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# A SEARCH FOR RADIO PULSES OF ASTROPHYSICAL ORIGIN

by

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## Preface

This thesis contains a description of experimental work carried out by the author at Glasgow University between 1969, October and 1972, September.

In the introductory chapter, the search for radio pulses of astrophysical origin is justified. Generating mechanisms and specific sources which might give rise to bursts of radio energy are examined. Previous observations of isolated radio pulses are also noted. Most of this chapter is based on the relevant literature. The original proposal that a search be made for radio pulses from supernovae or in association with gravitational radiation was due mainly to Dr. J.V. Jelley (Harwell), while the studies of the Crab Nebula were prompted by a comment made by Dr. G.G. Fazio (Smithsonian Observatory, U.S.A.). However, the searches for pulses from novae and from the possible black hole in Cygnus X-1 were at the suggestion of the author. This chapter also contains a description of the Colgate theories for radio emission during supernova eruption. The specific energy predictions relevant to the present work were determined from these theories by the author, who has also presented a critical review of the quantitative results derived by Colgate et al from their revised model.

Chapter 2 contains an account of the methods used by the author and others, to investigate the possibility that isolated VHF radio pulses might be emitted by cosmic sources. The experiment was of necessity a collaborative effort in that a search for coincidences between widely spaced sites (Cambridge, Dublin, Glasgow, Harwell and Jodrell Bank) was carried out in order to discriminate against local interference. The decision to use phase-switched dipole interferometers tuned to VHF wavelengths was due to others in the collaboration and

much of the Glasgow electronics was designed by Dr. R.W.P. Drever. Dr. Drever was also largely responsible for getting the Glasgow VHF systems into working order. The setting up and alignment with the Greenwich Meridian of all the Glasgow interferometer dipoles was due to the author, and from 1970, August to 1972, August, he was solely responsible for the operation and maintenance of the Glasgow observing station at Cochno Farm, 8 miles from the city centre. The discussion of the effects of the interstellar and intergalactic media on the choice of bandwidth and integration time was also the author's work, although it leans heavily on actual electron density estimates published by others. The author was entirely responsible for considering the influence of the antenna radiation patterns on the threshold sensitivities and sky coverage.

In the following chapter, an analysis of the VHF dipole observations is presented. About 50% of the Glasgow data was measured by the author, who also carried out the correlation of the data from the five groups and deduced the constraints on the radio emission from novae and supernovae. In addition, the precise repetition of F.G. Smith's early experiment at 45 MHz was largely at the author's instigation.

Chapters 4 and 5 describe directional studies of the Galactic Centre and Crab Nebula at 151.5 MHz. The high gain antennae used in these experiments were designed by Dr. P.F. Scott (Cambridge) and built mainly by the author. The initial testing of these antennae was carried out by the author who drew the attention of the other collaborators to the effects of ground reflections during low elevation observations of the Galactic Centre. The Glasgow Galactic Centre data was measured by the author and correlated with data from the other stations. The chance rates and overlap times were

determined by Dr. G.A. Baird (Dublin), who also compared the radio data with the "gravitational radiation" events obtained by J. Weber during this experiment.

The entire correlation of the Crab Nebula results was performed by the author, who also placed upper limits on the energy of the strong pulses from the Crab Pulsar NP 0532. Constraints were also established by the author for the prompt radio emission from the Crab which might occur in association with Weber's events or with phase fluctuations in NP 0532.

The penultimate chapter describes a pulse search at 10 GHz, involving a collaboration between the author and Dr. Jelley. This study was at the instigation of Dr. Jelley who also chose the radiometer circuit. Dr. Drever designed the phase-switching, phase-detection and sidereal drive units used at Glasgow. The physical arrangement and construction of the radiometer and its equatorial mount were performed by the author, who also designed the drive gearing unit. The author was responsible for the initial testing of the microwave system and the alignment of the equatorial mount with the polar axis. Observations were made of the Galactic Centre, the Coma Cluster of galaxies and possible black holes in Beta Lyrae and Cygnus X-1. In each case, the analysis of the Glasgow data and its correlation with the Harwell results was due to the author.

In the concluding chapter, reasons are considered for the negative results and suggestions are made as to the form which future studies should take. Interesting events obtained during the VHF experiments are discussed. This chapter is mainly the work of the author, although it does rely to some extent on published material.

Publications

Spaced Receiver Observations of Radio Pulses.

W.N. Charman, J.V. Jelley, J.H. Fruin, E.R. Hodgson, P.F. Scott, J.R. Shakeshaft, G.A. Baird, T.J. Delaney, B.G. Lawless, R.W.P. Drever, W.P.S. Meikle, R.A. Porter and R.E. Spencer.
Nature 228, 346, (1970).

Search for Isolated Radio Pulses from the Galactic Centre at 151.5 MHz.

W.N. Charman, J.H. Fruin, J.V. Jelley, R.F. Haynes, E.R. Hodgson, P.F. Scott, J.R. Shakeshaft, G.A. Baird, T.J. Delaney, B.G. Lawless, R.W.P. Drever and W.P.S. Meikle.
Nature 232, 177, (1971).

A Search for Isolated Radio Pulses from the Crab Nebula at 151.5 MHz.

W.P.S. Meikle, R.W.P. Drever, R.F. Haynes, J.R. Shakeshaft, W.N. Charman and J.V. Jelley.
Monthly Notices Roy. Astron. Soc. 160, Short Communication 5P, (1972).

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The author would like to thank the other members of the collaborative effort including:-

Drs. R.F. Haynes, E.R. Hodgson, P.F. Scott and J.R. Shakeshaft of the Cavendish Laboratory, Cambridge.

Dr. G.A. Baird, Mr. T.J. Delaney, Miss R. Kavanagh and Dr. B.G. Lawless of the Physics Department, University College, Dublin.

Dr. W.N. Charman and Mr. J.H. Fruin of UKAERE, Harwell.

Drs. R.A. Porter and R.E. Spencer of NRAO, Jodrell Bank, Cheshire.

The author wishes to express his gratitude to Miss M.L. Fitzpatrick and Dr. J. Hough, for considerable scientific assistance and advice. Much of the Glasgow equipment was built by Mr. A. McKellar to whom the author also wishes to convey his thanks. About 50% of the Glasgow data was measured by Mr. J. McDaid, Mrs. H. Shaw and the scanners of the Glasgow University High Energy Physics group and the author is very grateful for this assistance.

Finally, the author wishes to express his gratitude to the following people:-

Mr. J. Baird and the workshop staff, and Mr. E. Donaldson and the stores staff, for technical assistance.

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# Chapter 1

## Introduction

> "We have been so much impressed by the integrating properties, first of the human eye and then of the photographic emulsion, that there has been a concentration - a very large concentration - on exploring further by increasing integrating times. But of course this has almost completely excluded observation of transient effects ..... I think it is sometimes overlooked that perhaps we are missing a whole continent. I do not know exactly what I am looking for : it may be that one might discover that there are brick ends flying about space and obscuring stars every now and then for very brief moments; and it may be that there are bits in the interstellar medium that suddenly just flash up like a neon light. I just do not know."
>
> H. Bondi, 1970.

Astronomy is a passive science. Contemporary man cannot actively probe the stars. Nor can he vary the controlling parameters of the galaxies in order to produce observable changes in their behaviour. Most other exact sciences progress through the interpretation of man-made changes in the materials found on this planet, but the astronomer is forced to use only the effects which Nature

freely provides. It is for this reason that transient astrophysical phenomena might be so important. The rapidly changing conditions which occur in violent events such as supernovae, provide natural experiments in which the structure of astrophysical objects can be observed to CHANGE.

In addition, the impulsive signals which might be released during such events could provide a valuable probe for investigating otherwise unobservable regions of the Universe. It is possible that most cosmic matter is invisible. The detection of this material is essential for determining the future of the "expanding" Universe. The critical density (at present) above which contraction must ultimately occur is

$$5 \times 10^{-27} \text{ kgm m}^{-3}$$ (Burbidge, 1972)

(Note:- This assumes a value of $H_o = 50$ km $s^{-1}$ $Mpc^{-1}$ for the Hubble constant (Sandage and Tammann, 1972). This figure is adopted throughout the present work).

Much of the Universal matter may be in the form of a highly ionised intergalactic gas. According to Burbidge (1972), if the soft X-ray background is regarded as being caused by bremsstrahlung in the intergalactic plasma, then the plasma density cannot exceed

$$\sim 10^{-27} \text{ kgm m}^{-3}$$

However, absorption of the X-rays in the vicinity of the Galaxy complicates this interpretation. The detection of dispersed radio pulses from supernovae in distant galaxies might yield less ambiguous information about the density of matter in intergalactic space.

Another form which invisible material could take is that of black holes. While they are not directly detectable except through their gravitational fields, the formation of these objects, or

matter accretion by them could possibly release brief bursts of energy.

Burbidge (1972) has also pointed out that if all galaxies are emitting gravitational radiation at the rate of > 1000 solar masses per year, as Weber's results (Weber, 1969, 1970b) suggest might be the case, then the majority of mass-energy is currently in this form. Weber's events last for 10-20 s so that any investigation of other associated energy forms should clearly be sensitive over similar timescales.

## 1-1 Historial Note

The present work is a description of a search carried out by the author and others for transient RADIO emission of astrophysical origin. This investigation was stimulated by three main considerations:-

1) In 1968, Colgate proposed a mechanism whereby a relativistic shock wave produced during a supernova eruption, could give rise to a "flash" of $\gamma$-rays and X-rays. Subsequently, Dr. J.V. Jelley (1969, private communication) suggested that relativistic electrons present in this model might also produce a pulse of radio energy detectable at the Earth.

2) Just before this suggestion, Weber(1969) reported the detection of pulses of gravitational radiation. Dr. Jelley realised that if only a very small fraction ($\sim 10^{-21}$) of the energy apparently present in Weber's events appeared in the form of electromagnetic radiation, it would be detectable by the same techniques as those which might be used to search for radio pulses from supernovae.

3) At a meeting in Cambridge (1969, October) Dr. Jelley's suggestions prompted Sir Martin Ryle to recall that F. G. Smith (1950)

had reported the detection of rare radio pulses apparently of extraterrestial origin.

Following the Cambridge meeting, observing stations were set up at Cambridge, Dublin, Glasgow, Harwell and Jodrell Bank. The reason for building systems at these five, widely spaced sites was to allow discrimination against man-made interference which could produce pulses at single locations. Observations began in 1970, January.

## 1-2 Generating Mechanisms

Before possible specific sources of pulsed radio emission are discussed, it is interesting to consider briefly what mechanisms might allow the production of large bursts of radio energy. In the present work, radio pulses of duration 0.1 s to $10^3$ s were considered. The reasons for this were largely experimental. To record pulses of duration less than 100 ms would have required more sophisticated recording techniques than the simple pen-recorders used. In addition, in view of the VHF bandwidths employed, typical interstellar and intergalactic electron densities could be expected to disperse intrinsically brief radio pulses to time-widths exceeding 0.1 s. Pulses which lasted longer than $10^3$ s were in danger of being confused with the interference patterns produced by the sources Cassiopeia A and Cygnus A (see Chapter 2). It could also be argued that events which appeared and vanished on timescales exceeding an hour, would already have been noticed in radio astronomical investigations using the more standard long integration times.

The restriction of observations to pulses less than $10^3$ s in width immediately puts a constraint on the size of the emitting object provided that it radiates roughly isotropically and that the

source itself is not moving or expanding at relativistic velocities with respect to the observer. Under these restrictions, it is unlikely that the duration of a pulse will be less than the light travel time across the source. A time-width of $10^3$ s implies that the source probably does not exceed $\sim 3 \times 10^8$ km in diameter i.e. objects liable to give rise to pulses less than $10^3$ s wide must be of stellar dimensions, or smaller.

Thermal bremsstrahlung radiation from a hot gas is quite inadequate to produce a detectable radio pulse with the sensitivities used in the present work, even at a distance of only 1 pc. According to the Rayleigh-Jeans Law, for $10^8$ Hz radiation to be observed from a $3 \times 10^8$ km diameter star, 1 pc distant, would require a surface temperature exceeding $10^{10}$ $^o$ K. Enormous problems would be involved in creating a mechanism whereby the surface of a star could rapidly heat up to this temperature.

Studies by Cavallo and Ventura (1972a), also imply that at a frequency of $\sim 10^8$ Hz, incoherent synchrotron radiation from an object of diameter $< 3 \times 10^8$ km, would be just detectable at a distance of only 30 pc. Indeed, this represents a virtually unattainable upper limit. To produce an observable pulse from 30 pc away, would require a cloud of mono-energetic electrons whose optical depth at the peak frequency (due to synchrotron re-absorption processes) just happened to equal the physical size of the source. In addition, the observer would have to be fortunate enough to be tuned to the peak frequency. Any attempt to improve the source emission by raising the electron density, would increase the optical thickness more rapidly than the energy output at the original turn-over frequency.

Cavallo and Ventura concluded that only COHERENT emission

might produce detectable radio pulses from sources at distances $\gg$ 1 pc. They considered three possible mechanisms - Antenna Radiation, Synchrotron Maser Radiation and Amplification by Plasma Wave Scattering in a Turbulent Plasma. The second and third mechanisms were found to be rather unpromising at VHF, in each case the particle density being limited by the demand that

$$\nu_{obs} > \nu_p$$

where $\nu_{obs}$ = frequency of observation.

$\nu_p$ = plasma frequency of the source.

However, reasonably intense emission was obtainable at 10 GHz, allowing detection at distances of up to $10^3$ Mpc.

The most efficient mechanism was found to be one in which Antenna Radiation could arise. This effect demanded a "blob" of electrons of size $\approx \lambda$, radiating in phase, where $\lambda$ was the observation wavelength. Huge amounts of energy could be emitted at any single radio frequency, but again the observer had to be lucky enough to be tuned to the emission wavelength. Also, Cavallo and Ventura pointed out that this mechanism was very unlikely and that it would be extremely difficult to maintain coherence in the "blob" for any length of time.

Although predictions from the above mechanisms are rather pessimistic, other less understood sources might give greater energies in the radio spectrum. In particular, it is known that "beamed" sources exist (pulsars) and it will be shown later that relativistic expansion of a star might give rise to a fast, intense radio pulse, detectable at distances > 100 Mpc.

In sections 1-3 to 1-6, specific astrophysical phenomena are considered, in which large amounts of energy are thought to be generated over very short timescales. Possible sources discussed are Supernovae, Novae, Black Holes and Pulsars. Radio emission in

association with Gravitational Radiation is also considered.

## 1-3 Supernovae

### 1-3-1 Observed features

Supernovae are stars which suddenly flare up in timescales of about a day to an absolute magnitude of $\sim -20$. They can be divided into two groups known as Type I and Type II. Type I supernovae form a group of objects of relative similarity, whereas those of Type II exhibit widely varying characteristics. It is quite possible that Type II supernovae will eventually be re-classified into smaller groups. However, in the present work, all supernovae not of Type I are assumed to be of Type II.

Type I supernovae reach a maximum absolute magnitude of -20.5. They have a well-defined light curve which falls to $\frac{1}{2}$-maximum in 20-30 days. The luminosity then decreases more slowly, and approximately linearly for several hundred days. They generally occur among population II stars. The quantity of ejected material is 0.1-1.0 $M_\odot$, the kinetic energy being about $10^{41}$-$10^{43}$ joules. The progenitors of Type I supernovae are thought to have masses of between 1.12 and 2 $M_\odot$. Little or no hydrogen is ejected during the explosion of this type of supernova.

Type II supernovae have a maximum absolute magnitude of $\sim -19.2$. However, their light curves vary greatly although they tend to remain at maximum for a longer period and then fall more rapidly than do those of Type I. They occur among population I stars, and are generally thought to be more massive (2-10 $M_\odot$) than Type I supernova A large quantity of material (1-10 $M_\odot$) is ejected with energies in the range $10^{43}$-$10^{45}$ joules and a considerable amount of hydrogen is present in the expanding shells.

Tammann (1970) has attempted to correlate the frequency of supernovae with the type of galaxy in which they are found. He showed that a very high rate occurs in Supergiant ScI and ScI-II systems, (more than 1 per 16 years) probably due to the greater rate of star formation in such galaxies. He found that the ratio of Type I to Type II supernovae was 1:2. However the problem of determining the absolute rate of supernova occurence is complicated by selection effects. Not all regions of the sky are regularly checked, and certain types of galaxy tend to be better studied than others. In addition, there is the possibility that the brighter Sb galaxies tend to conceal their supernovae more effectively that Sc galaxies.

In a volume of 6,380 $Mpc^3$, 26 supernovae were found in 10 years. Tammann put the correction factor for "missed" supernovae in this time at 1.2-2. In view of this, the author has adopted a supernova rate of

$$0.58 \times 10^{-3}\ yr^{-1}\ Mpc^{-3}$$

in future discussions.

Many ideas have been put forward to account for the phenomenon of supernovae, but as yet no theories show outstanding promise, and much theoretical work is still being carried out. In the section which follows, a short summary of suggested mechanisms for supernovae is given, but few of these models are without problems.

1-3-2 Supernova Theories

Attempts to account for the observed properties of supernovae can be divided into two groups depending on whether or not the explosion is triggered by the gravitational collapse of the core. Earlier theories depended predominantly on an implosion trigger and so this is discussed first.

(i) Implosion - Trigger Theories

According to Chandrasekhar (1939), the pressure balance in a degenerate star cannot be wholly maintained by the cold electron degeneracy pressure if the mass M of the star exceeds a critical mass $M_{cr}$ where

$$M_{cr} = \frac{5.75}{\mu_e^2} M_\odot \qquad \text{(Equ 1-1)}$$

and $$\mu_e = \frac{\text{Number of nucleons per unit volume}}{\text{Number of electrons per unit volume}}$$

Hoyle and Fowler (1960) have stated that $\mu_e$ can be as large as 2.23 in which case $M_{cr} \gtrsim 1.16\ M_\odot$. Thus, stars larger than this limit are potentially unstable. Two principal theories involving implosion have been suggested.

According to Fowler and Hoyle (1964) and earlier papers, a reasonably large star ($>10\ M_\odot$) will evolve without disruption until a large core ($\sim 3M_\odot$) of iron has been built up. When a central temperature of $5 \times 10^9$ °K and a central density of $10^{10}$ kgm $m^{-3}$ are reached, the iron undergoes highly endoergic photodisintegration into helium and neutrons

i.e. $$^{56}Fe \rightarrow 13\alpha + 4n - 124.4 \text{ MeV}$$

The energy for this reaction is supplied by the gravitational collapse of the star. The implosion is assumed to be "free-fall" and so takes place in a time $t_{imp}$ where

$$t_{imp} = \left\{\frac{4}{3\pi G\rho}\right\}^{+\frac{1}{2}} \qquad \text{(Equ 1-2)} \qquad \text{(Burbidge et al, 1957)}$$

$$= 0.2 \text{ s.}$$

where G = Gravitation constant

$\rho$ = Central density at beginning of collapse.

This theory can be criticised on the grounds that the assumption of free-fall makes a detailed analysis of the actual dynamics of the implosion impossible. Its reliance on a large initial mass also poses problems since such stars evolve rapidly and so are unlikely

to be associated with the population II stars among which Type I supernovae are found. However, Hoyle and Fowler (1960) have suggested that the association of this mechanism with Type II supernovae is not too implausible.

Nevertheless, difficulties have been encountered in trying to explain how such an implosion results in an explosion of the energy observed.

Finzi and Wolf (1967) have proposed that a white dwarf containing high concentrations of $^{24}Mg$ or $^{40}Ca$ could eventually collapse due to the inverse beta-decay of these nuclei. Consider, for example, a star of mass 1.395-1.400 $M_\odot$ which has evolved to the stage where its core contains a large amount of $^{24}Mg$. Electron capture takes place in the reaction,

$$^{24}Mg + e^- \longrightarrow {}^{24}Na + \nu - 5.52 \text{ MeV}$$

the energy being supplied by gradual gravitational contraction. This transition can proceed when the density exceeds $1.6 \times 10^{12} \mu_e$ kgm $m^{-3}$ but as it is fourth-forbidden, the lifetime is long ($\sim 3 \times 10^7$ years $\pm$ an order of magnitude). However, once the density exceeds $2.0 \times 10^{12} \mu_e$ kgm $m^{-3}$, the fast allowed transition from the $0^+$ ground state of $^{24}Mg$ to the $1^+$ excited state of $^{24}Na$ becomes possible. Rapid contraction over a timescale of less than a year then takes place, until the star finally collapses. Details of the final collapse have not been investigated.

The interesting aspect of this theory is that a supernova can be produced in an old star and so might account for the association of Type I supernovae with Population II stars. However, several criticisms have been directed at the beta-decay models. It is difficult to explain how high concentrations of $^{24}Mg$ or $^{40}Ca$ could be accumulated. According to Rose (1969) and Paczynski (1970), in stars of the masses considered by Finzi and Wolf (1.2-1.4 $M_\odot$), carbon

burning would not commence before the white dwarf stage was reached, with the result that $^{24}Mg$ or $^{40}Ca$ enriched interiors could not be built up. Also, in order to associate this mechanism with Type I supernovae, it is necessary to restrict the presupernovae to a very narrow mass range (1.395-1.400 $M_\odot$ for $^{24}Mg$ stars) in order that evolution occurs within a timescale of $10^7$ to $10^{10}$ years. It seems improbable that a sufficient number of old stars exist having the correct mass to give rise to the observed incidence of Type I events.

Neither of the above implosion models directly give mechanisms whereby the observed supernova explosion can result. However, two main collapse induced explosion theories have been suggested. Fowler and Hoyle (1964) proposed that after implosion, the outer layers of oxygen collapse, heat up and ignite. Colgate and White (1966) criticised this idea. They argued that URCA-process neutrinos produced near the centre by the imploding core are deposited in the outer layers, causing a shock wave to travel radially outwards. This rarefaction wave completely attenuates the thermonuclear explosion. Colgate and White suggested that the explosion is actually caused by the deposition of the high-energy neutrinos in the stellar envelope.

Since 1966 there has been considerable debate as to which of these two explosion mechanisms is more likely. The outcome of this discussion would seem to hinge on the value which is finally adopted for the opacity of stellar material to high-energy neutrinos. Work by Arnett (1967) and J.R. Wilson (1971) implies that most of the neutrinos produced during the implosion of a star escape and no explosion occurs. At present, the neutrino deposition theory has less popularity than thermonuclear theories of energy production. However, it may be that neutrino physics is just not sufficiently understood to compete with the fusion models.

(ii) Non-Implosion - Trigger Theories

In an attempt to explain Type I supernovae, Hoyle and Fowler (1960) suggested that they might be caused by highly evolved stars of intermediate mass. A star just above the Chandrasekhar limit evolves to the stage where it contains a large degenerate core of $^{12}C$ or $^{16}O$. The pressure in such a core is relatively independent of temperature so that as contraction proceeds, the temperature rise does not stop this process. Eventually carbon or oxygen ignition takes place. These particular mechanisms for the explosion of a supernova have been developed by Arnett (1968, 1969) who proposed that after the initial ignition, a detonation front travels through the star from the centre, resulting in its total disruption, no imploded remnant remaining. However, in order to account for the presence of pulsars, Colgate (1971) pointed out that at the high densities and temperatures found in the material immediately after detonation, rapid electron capture occurs producing a rarefaction wave which follows the detonation front out of the star. The result of this is that a considerable amount of material collapses to form a neutron star.

Truran and Cameron (1971) have adopted this model for the final stage of stars in the mass range 4-8 $M_\odot$. However, they have suggested that it should in fact be associated with Type II rather than Type I supernovae.

Evolutionary calculations by Rakavy and Shaviv (1967) have shown that for oxygen stars of mass $> 25\ M_\odot$, as oxygen burning proceeds, dynamical instabilities occur due to the formation of electron-positron pairs. Although their computations were not continued beyond the point of instability, it is conceivable that a supernova could be subsequently produced. The main problem with this mechanism is that

the small number of very massive stars implies a much slower rate of supernovae eruptions than that observed.

Wheeler and Hansen (1971), and Truran and Cameron (1971) have pointed out that in a binary system with components of unequal mass, the more massive star will reach the white dwarf stage first. Later, the lighter star may lose matter to the white dwarf, possibly when going through the red giant phase. Eventually the white dwarf star will exceed the Chandrasekhar limit and explode due to helium or carbon ignition, producing a Type I supernova. Hartwick (1972) has suggested that Type I supernovae could be produced in a binary system, by mass transfer to a very light (0.1 $M_\odot$) degenerate hydrogen star, leading to hydrogen ignition. However, it is difficult to see how the necessary non-ejection of hydrogen could be brought about in such a model.

In conclusion, it would appear that the trend in supernova theory is moving away from massive progenitors (>10 $M_\odot$) and the consequent implosion triggers. The number of massive stars is relatively small and so alone, could not give rise to the observed supernova rate. Truran and Cameron (1971) have argued that the very massive stars, which Hoyle and Fowler and others suggested might give rise to Type II supernovae, would in fact have collapsed to form black holes at a very early epoch of the galaxy. Indeed, they maintain that ~90% of the galactic mass is in the form of black holes. They have also pointed out that the pulsars, generally accepted as supernova remnants, never have masses exceeding ~2 $M_\odot$. The production of a 2 $M_\odot$ neutron star from, say, a 20 $M_\odot$ progenitor would imply a rather large amount of explosive nucleosynthesis necessary to eject ~90% of the star into space. The products of this nucleosynthesis would by far exceed the observed solar system abundances of elements between carbon and iron.

Perhaps the most important point in common with all supernova theories is that they involve a sudden catastrophic event taking place in a timescale of less that $10^2$ s. Thus, the eruption of supernovae would appear to be a valid study for short time-constant techniques.

1-3-3 Radio Emission During Supernova Explosions

Theoretical investigations concerning the emission of bursts of electromagnetic energy during supernova eruptions have only been carried out by S. A. Colgate and his collaborators. Their original model for coherent radio emission from expanding supernova shells (Colgate and Noerdlinger, 1971) indicated that radio pulses from supernovae at a rate of over 100 per day should have been detectable by the equipment used in the present work. However, more recent calculations (Colgate, McKee and Blevins, 1972) have drastically reduced the expected radio energy. Nevertheless, the theoretical model to which Colgate, McKee and Blevins referred was qualitatively the same as that originally proposed by Colgate and Noerdlinger. This model is now described, and is followed by specific predictions from both the original and revised theories, of the energies to be expected at the frequencies of the present work.

Regardless of the mechanism responsible for the triggering of a supernova, shortly after this event, a spherical shock wave accelerates outwards through the body of the star attaining relativistic velocities (Colgate, 1968). Eventually the material exterior to the shock becomes too rarefied to allow its continued propagation. At this point, the photons behind the shock break through and eject the outer layers. A highly ionised shell of gas expanding with a relativistic velocity $V_s$ is emitted from the star. If the star has a magnetic field, the effect of the shell moving through this field

is to induce a transient current sheet in the conducting surface (Fig. 1-1). The current pulse produces a burst of coherent electromagnetic radiation. The energy, spectrum and direction of emission of this radiation are now investigated.

Relativistic hydrodynamic theory indicates that the Lorentz factor $\gamma_s$ of the matter immediately behind the shock is such that

$$\gamma_s \propto F^{-\alpha} \qquad \text{(Equ 1-3)}$$

where $\gamma_s = \left[1 - \frac{V_s^2}{c^2}\right]^{-\frac{1}{2}}$

$c$ = velocity of light

$F$ = mass fraction external to the shock

$\alpha$ = a constant depending on the hydrodynamic theory used.

In order to calculate the effect of the expanding shell on the magnetic field, the following assumptions are made.

A) When the fluid behind the shock "breaks out" at some radius $r_o$, the resulting conducting surface expands with a constant velocity $V_B$. The corresponding Lorentz factor $\gamma_B$ is given by

$$\gamma_B = \left[1 - \frac{V_B^2}{c^2}\right]^{-\frac{1}{2}} \qquad \text{(Equ 1-4)}$$

B) Anything happening in the interior of the conducting surface is irrelevant.

C) The initial exterior magnetic field is of dipole form, having a magnetic moment $\mu$.

The radiation field and time dependent induction field produced at a point $(r, \theta, \phi)$ due to a disturbance in a magnetic dipole field centred at the origin can be most conveniently expressed in terms of the Fourier transforms $\underset{\sim}{B}_1(\omega)$ and $\underset{\sim}{E}_1(\omega)$, of the disturbance.

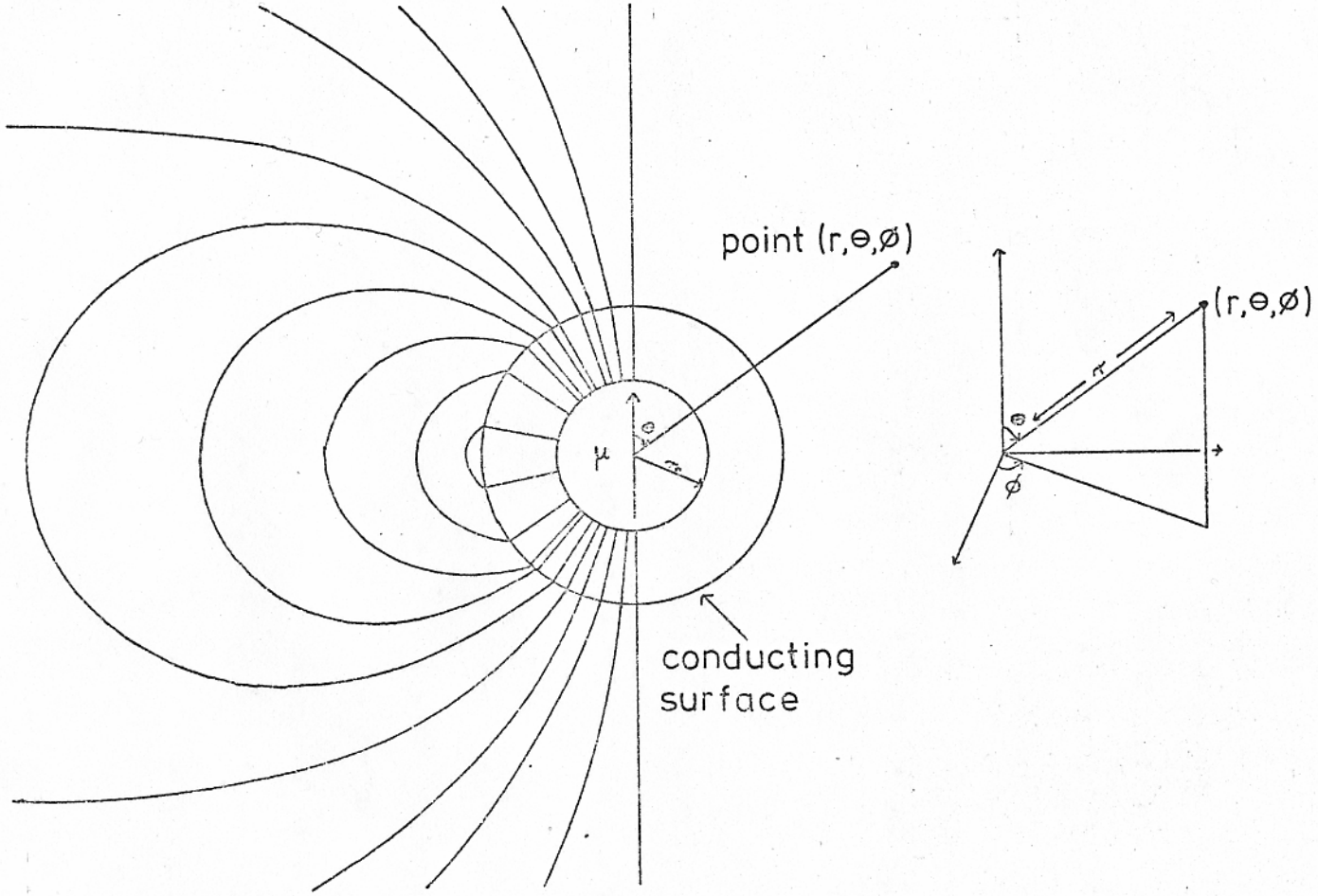



Fig.1-1 Expansion of a Conducting Surface in the Magnetic Field of a Supernova. (For clarity, only the projection of the Current Surface and Field Lines on the plane of the paper are shown).

For a magnetic dipole field,

$$\underset{\sim}{B}_1(\omega) = \mu f(\omega)\exp\left(\frac{i\omega r}{c}\right)\left[2\hat{\underset{\sim}{e}}_r\frac{\cos\theta}{r^2}\left(1+\frac{ic}{\omega r}\right) - \hat{\underset{\sim}{e}}_\theta\frac{i\omega\sin\theta}{cr}\left(1+\frac{ic}{\omega r}-\frac{c^2}{\omega^2 r^2}\right)\right] \qquad \text{(Equ 1-5)}$$

$$\underset{\sim}{E}_1(\omega) = \mu f(\omega)\exp\left(\frac{i\omega r}{c}\right)\hat{\underset{\sim}{e}}_\phi\frac{i\omega\sin\theta}{cr}\left(1+\frac{ic}{\omega r}\right) \qquad \text{(Equ 1-6)}$$

where $f(\omega)$ is the value of the Fourier coefficient at angular frequency $\omega$, and $\hat{\underset{\sim}{e}}_r$, $\hat{\underset{\sim}{e}}_\theta$ and $\hat{\underset{\sim}{e}}_\phi$ are the unit vectors appropriate to the spherical co-ordinates used (Fig. 1-1). $f(\omega)$ can be determined by the applying boundary conditions (i)-(iii) to Equs 1-5 and 1-6.

(i) Since the shell is assumed to be a perfect conductor, the tangential electric field must vanish at the surface.

Hence $$E_\phi + \frac{V_B}{c}B_\theta = 0 \qquad \text{for } t > 0 \qquad \text{(Equ 1-7)}$$

(ii) From assumption A,

$$r = r_o + V_B t \qquad \text{for } t > 0 \qquad \text{(Equ 1-8)}$$

(t = "laboratory" time with respect to the instant of initial eruption)

(iii) As the conducting surface moves through the dipole field, the induced currents produce a tangential magnetic field which BEHIND the surface is equal and opposite to the tangential dipole field. Thus, the expanding surface "combs" the dipolar lines into radial lines (Fig. 1-1), yielding the condition

$$B_r = \frac{2\mu}{r_o\xi^2}\cos\theta \qquad \text{for } t > 0 \qquad \text{(Equ 1-9)}$$

where $\xi = r_o + V_B t$

In fact it can be shown that this condition is redundant with that given in Equ 1-7.

Having determined $f(\omega)$, convolution of its inverse Fourier transform with those of Equs 1-5 and 1-6 gives the radiation field

$\underset{\sim}{B}_{rad}$ in the form

$$B_2(r,\bar{t}) = \frac{2\mu V_B \gamma_B^2}{crr_o^2}\left[1 + \frac{2V_B\gamma_B^2 t^*}{r_o}\right]^{-1} \qquad \text{(Equ 1-10)}$$

where $\underset{\sim}{B}_{rad} = \sin\theta\, \hat{\underset{\sim}{e}}_\theta B_2(r,\bar{t})$

$$\bar{t} = t + \frac{r_o}{c}$$

$$t^* = \bar{t} - \frac{r}{c} > 0$$

$$\gamma \gg 1$$

Equ 1-10 defines the form and intensity of the emitted pulse. In order to determine the spectrum of the energy $E(\nu)$ released, the Fourier transform of $\underset{\sim}{B}_{rad}$ is integrated over the range $0 \leq t^* \leq \infty$ giving

$$E(\nu)d\nu = \frac{\mu^2}{2\pi r_o^2 c}\int \Psi \sin^2\theta \, d\Omega \qquad \text{(Equ 1-11)}$$

where $\Omega$ is the solid angle into which the radiation is emitted, and

where $\Psi = \Psi(q)$, $q = \frac{\pi r_o \nu}{c\gamma_B^2}$, $\nu$ = frequency of emission in Hz.

For $q \ll 1$, $E(\nu)d\nu \doteq \frac{4\mu^2}{3cr_o^2}\, d\nu$ (Equ 1-12)

For $q \gg 1$, $E(\nu)d\nu \doteq \frac{4\mu^2 c}{3\pi^2 r_o^4}\cdot\frac{\gamma_B^4}{\nu^2}\, d\nu$ (Equ 1-13)

Thus, for low frequencies, a flat spectrum is obtained, while at high frequencies the energy decreases as $\nu^{-2}$. It can also be shown that low frequency emission is isotropic, but as $\nu$ exceeds $\frac{c\gamma_B^2}{\pi r_o}$, the radiation is concentrated towards the poles.

In order to make specific predictions for the energy released at the observation frequencies, values for $r_o$, $\mu$ and $\gamma_B$ must be obtained.

$\underline{r_o}$ :- Presupernova models generally depend upon dense cores ($\sim 10^{13}$ kgm $m^{-3}$) of degenerate matter. For a star of mass $\sim 1 M_\odot$ this gives

$$r_o \approx 10^6 \text{ m}$$

for a polytrope of index 3.

$\underline{\mu}$ :- The association of pulsars with supernova remnants (Nature Editorial, April 21, 1972) suggests that it is reasonable to assign a magnetic field to the pre-supernova star such that the subsequent neutron star would have a field appropriate to that observed in pulsars. Assuming

$$B_{\theta max} \propto \frac{1}{r_*^2} \qquad \text{(Equ 1-14)}$$

where $B_{\theta max}$ = maximum value of the tangential magnetic field at the star's surface.

$r_*$ = radius of star,

this gives

$$\mu \approx 10^{22} \text{ amp } m^{-2}$$

$\underline{\gamma_B}$ :- As the conducting surface expands, the combined total energy of the shell of material and the tangential magnetic field $B_\theta$ must be conserved.

Thus

$$B_\theta^2 \gamma_B^2 = \text{constant}$$

or

$$\gamma_B = \frac{\gamma_S}{\sin\theta} \qquad \text{(Equ 1-15)}$$

Also, according to Equ 1-3

$$\gamma_S \propto F^{-\alpha}$$

Colgate and Noerdlinger assumed that "breakout" occurs when the thickness of the shell above the shock has decreased to only a

few Compton mean free paths for the radiation behind the shock. This corresponds to an area density of $10^2$ kgm $m^{-2}$ yielding

$$F = 0.62 \times 10^{-15}$$

for a mass of 1 $M_\odot$. Studies of Tycho's supernova indicate that the shock becomes relativistic when

$$F = 3 \times 10^{-5}$$

Colgate and Noerdlinger adopted a value of 0.33 for $\alpha$ giving

$$\gamma_s = \left[\frac{0.62 \times 10^{-15}}{3 \times 10^{-5}}\right]^{-0.33} = 3{,}600$$

Thus, for equatorial emission,

$$\gamma_B = 3{,}600$$

Applying these figures to Equs 1-10 and 1-11 gives, for $\tau \ll 1$

$$E(\nu)d\nu \approx 4.5 \times 10^{30}\, d\nu \text{ joules} \qquad \text{(Equ 1-16)}$$

and with $\tau \gg 1$

$$E(\nu)d\nu \approx 6.8 \times 10^{48} \nu^{-2}\, d\nu \text{ joules} \qquad \text{(Equ 1-17)}$$

Also, from Equ 1-8, it can be shown that most of the energy is emitted in a time of about $10^{-10}$ s. Thus an exceedingly brief and energetic pulse can be produced by a relativistically expanding shell.

However, in the revised theory of Colgate et al (1972), the value for $\alpha$ was reduced to 0.178 and the shell area density at breakout to 10 kgm $m^{-2}$ with the result that

$$\gamma_s \doteqdot 70$$

In addition, Colgate et al (1972) stated that the expanding shell shares its energy with the compressed magnetic field. Since the initial equivalent energy density of the magnetic field is considerably less than the initial rest mass density of the outer layer, $\gamma_B$ is generally larger than $\gamma_s$, the relationship being

$$245 \times \gamma_B^4 \approx \nu\gamma_s^2 \qquad (\theta = 90^\circ) \qquad \text{(Equ 1-18)}$$

The effect of the reduction in $\gamma_B$ is to decrease the total energy emitted. Also, most of the energy is emitted below 1 MHz and so could not be observed from the Earth. The pulse width is increased to about $10^{-6}$ s.

Colgate et al (1972) have made a specific estimate for the energy to be expected at 1.4 GHz, assuming a dispersion measure of 30 $cm^{-3}$ pc. They argued as follows :-

Total energy in the pulse $= 2.5 \times 10^{34}$ joules

Delay D due to dispersion at 1.4 GHz $= 0.1$ s

For a bandwidth of 80 kHz, the dispersed pulse width = $t_D$ $= 12.5$ microseconds

Therefore the fraction of the total energy appearing in this band at 1.4 GHz is simply $\frac{t_D}{D} = \frac{12.5}{10^5} = 1.25 \times 10^{-4}$

The energy in the 80 kHz band is therefore $1.25 \times 10^{-4}$ x the TOTAL energy over all wavelengths $= 3.1 \times 10^{30}$ joules

However, it is the opinion of the author that this is incorrect, as it is at variance with their earlier statement:-

> "that the lowest-frequency band that might contain the bulk of the emitted energy corresponds to a frequency $\approx \frac{\gamma_s^2 c}{r} \lesssim 8 \times 10^5$ Hz, which is below the cutoff of the ionosphere. We therefore accept the rapid reduction of emitted power with $\gamma$ at high frequencies ....."

In view of this, the author has made an additional energy estimate by simply applying the revised parameters to the original Colgate-Noerdlinger model. Table 1-1 gives the energies expected

Table 1-1 Radio Energies Expected from Supernova Eruptions.

| Frequency (MHz) | Predictions of Colgate and Noerdlinger (J $Hz^{-1}$) | Author's predictions using revised parameters of Colgate, McKee and Blevins (J $Hz^{-1}$) | Predictions of Colgate, McKee and Blevins (J $Hz^{-1}$) |
|---|---|---|---|
| 47 | $5.8 \times 10^{30}$ | $1.8 \times 10^{28}$ | $1.1 \times 10^{27}$ |
| 80 | $5.5 \times 10^{30}$ | $1.0 \times 10^{28}$ | $6.2 \times 10^{26}$ |
| 151.5 | $4.9 \times 10^{30}$ | $5.5 \times 10^{27}$ | $3.3 \times 10^{26}$ |
| 10,000 | $9.0 \times 10^{28}$ | $8.3 \times 10^{25}$ | $5.0 \times 10^{24}$ |

at the observation frequencies of the present work (47 MHz, 80 MHz, 151.5 MHz and 10 GHz). In each case, three values are given corresponding to

(i) The original Colgate-Noerdlinger predictions.

(ii) Predictions obtained by applying the revised parameters to the Colgate-Noerdlinger model.

(iii) Predictions made by Colgate, McKee and Blevins.

## 1-4 Novae

### 1-4-1 Observed Features

Novae are stars which flare up by 12-13 magnitudes, probably within a few hours to absolute magnitudes of -6.1 to -8.4 (Payne-Gaposchkin, 1958). However, they are far less energetic than supernovae, releasing only $\sim 6 \times 10^{37}$ joules during an explosion. Spectral studies of the remnant of a nova usually reveals a blue type A subdwarf star. Novae also differ from supernovae, in that total disruption of the pre-nova does not occur. Only about $10^{-5}$-$10^{-3}$ of the mass is ejected and the pre-nova appears to be very similar to the post-nova. This together with the fact that some novae recur, implies that the effect of the eruptions on this type of star is relatively superficial. Galactic novae seem to cluster towards the Galactic Centre, populating a flattened spheroidal region composed of stars intermediate between the extremes of populations I and II. Although only 1 or 2 new novae are observed in the Galaxy each year, many are not detected, and it is estimated that about 25 Galactic novae per year occur. Thus, although the energy of a nova is only $\sim 10^{-6}$ of that of a supernova, the closest supernovae occurring in a reasonable observing time ($\sim$1 year) would be at least

$\times 10^3$ further away than the nearest novae which would erupt in the same period.

The light-curve of a nova shows a rapid initial rise, followed by a pause before a final slower rise to maximum. The fall to half-maximum varies greatly, from only ~1 day to over 100 days. About 20 days after an outburst, the nova often undergoes fluctuations in brightness. The final decline to its original state can take many years. Spectroscopic studies indicate that at the initial outburst, one or more shells of material are ejected into space at a velocity of $\sim 3{,}500$ km $s^{-1}$.

Recent observational work has shown that novae are probably contained in binary systems, each consisting of a bright white dwarf and a larger, cooler star. In addition, Starrfield (1971b) has argued on theoretical grounds, that if a nova is caused by hydrogen ignition in the outer envelope of a white dwarf, then it could not, by itself, build up sufficient hydrogen in the outer layers to give rise to a violent explosion. A material transfer process in a binary system therefore appears to be necessary.

### 1-4-2 Nova Theories

Most recent theoretical work has assumed that the nova occurs in a binary system, where a hydrogen-rich envelope is built up on a white dwarf component due to mass transfer from its cooler companion. The hydrogen at the bottom of this layer is increasingly compressed and heated, resulting in ignition.

The mechanism whereby the ejection of a shell of material occurs has been the subject of considerable study in the last few years. Sparks (1969) has considered the effect of injecting a "square" pulse of energy into a concentric zone at some depth in the envelope of a 1 $M_\odot$ star. He found that two types of ejection can occur. Radiation

pressure ejection takes place when the energy is injected in a time interval which is long compared to the sound traversal time across the zone. When the energy is injected in a time shorter than the sound traversal time, shock ejection occurs. He identified the pressure ejection case with ordinary, slower novae and showed how it could explain the pre-maximum halt, as well as produce the ejection of a definite shell. The shock ejection case he identified with the faster "flash" novae. No recognisable shell or pre-maximum halt is produced in this case, although post-maximum oscillations are obtained.

An interesting consequence of Sparks' studies, was that in both cases, following the injection of energy, a shock wave travels outwards through the star. As it penetrates the outer zones, the resulting sharp rise in temperature produces a fast spike in the light curve $\sim 5$ hours before the initial rise. The width of this spike at $\frac{1}{2}$-maximum is only a few seconds and its magnitude is of the same order as the final maximum. Sparks also found that the initial rise is exceedingly rapid in both cases. A rise of 5 magnitudes in the pressure ejection case, and 8 magnitudes in the shock ejection case occurs in only a few minutes.

Starrfield (1971a, 1971b), has investigated the possibility that thermal runaway in the hydrogen rich envelope of a white dwarf can produce the sudden energy injection required by Spark's theory. Models of mass range 0.12-1.0 $M_\odot$ were studied. In light stars ($\sim$0.12 $M_\odot$) it was found that thermal runaway which produces sufficient energy is only possible if an accretion shock is present due to material from the companion arriving "supersonically". However, in the more massive 0.5 $M_\odot$ and 1.0 $M_\odot$ stars, sufficient energy is obtained from hydrogen ignition in the envelope, to eject shells

with the energy observed. In all the ejection models examined by Starrfield, the final rise to maximum energy production is very rapid. In one 1.0 $M_\odot$ model, the energy production rate increases 10-fold in the last 5 minutes.

Rose and Smith (1972) have also investigated a matter accretion model, and have included the effects of the fast CNO hydrogen burning cycle, ignored by Starrfield. They concluded that most novae do NOT eject their envelopes by a single, shock-wave mechanism, although this may be the case for fast novae. It was found however that high rates of nuclear energy generation cause the star to become pulsationally unstable, a significant amount of energy being stored in the pulsations. Rose and Smith suggested that shock waves produced by the pulsations, gradually heat the surface, producing an extended envelope. The ejection velocities and light curves produced in this model, were found to agree better with observation, than do the shock ejection predictions. However, one drawback of their model is that only $\sim 10\%$ of the required energy can be stored in the pulsations.

Perhaps the most interesting nova model to date, is that due to Starrfield, Truran, Sparks and Kutter (1972). Again, a hydrogen accretion model was considered. However, they realised that the fast CNO cycle responsible for energy production never attains equilibrium during the outburst because the timescale is too short. The result is that the $\beta^+$-unstable nuclei $^{13}N$, $^{14}O$, $^{15}O$, and $^{17}F$ become the most abundant nuclei in the envelope next to H and $^4He$, and the energy released during their decay is responsible for the luminosity increase and shell ejection observed in the nova outburst. Once the temperature at the bottom of the envelope reaches $9 \times 10^7$ K, rapid conversion (in about 95 s) of all the CNO nuclei to $^{13}N$, $^{14}O$, $^{15}O$ and $^{17}F$ takes place and the rate of energy production increases

by a factor of $3.5 \times 10^4$. Near the peak of this process, the pressure jumps by x2 in $\sim\frac{1}{2}$ s causing a shock wave to move outwards and deposit $8 \times 10^{38}$ joules in the outer layers, ejecting about $10^{-7}$ $M_\odot$. The arrival of the shock wave at the surface causes the bolometric magnitude to jump from +7.0 to -11.5 in ONLY 30 ms. Convection then brings the $\beta^+$-unstable nuclei rapidly to the surface where they decay in a few minutes (corresponding to their $\frac{1}{2}$-lives) releasing a further $6 \times 10^{40}$ joules and ejecting $3 \times 10^{-5}$ $M_\odot$.

The importance of this model lies in its correct prediction of the energies and relative abundances observed in nova outbursts. Its light-curve shows a very rapid initial decline, characteristic only of fast novae, but the computation was only taken to a few hours beyond maximum luminosity.

In conclusion, it can be seen that although novae have been observed to flare up in a duration of several hours, recent theories demand processes of a considerably shorter timescale than this. In particular, it is interesting that most models involve the production of a shock-wave deep in the envelope, which on reaching the surface, causes an initial luminosity rise in only minutes or seconds. It is tempting to recall the Colgate-Noerdlinger supernova theory in which a shock wave results in the compression of the star's magnetic field, producing radio emission. However, it must be borne in mind that the results of Colgate and Noerdlinger demand that the shock accelerates the material to RELATIVISTIC velocities. Such velocities do not occur in the above nova theories. The shock-ejected material in Starrfield et al (1972) only had a velocity of $\sim 0.025c$.

### 1-4-3 Radio Emission from Novae

The detection of radio emission from novae which had previously erupted, has been reported in only the last 3 years. Hjellming and

Wade (1970), Wade and Hjellming (1971) and Herrero, Hjellming and Wade (1971) have observed fluxes of up to ~0.5 f.u. from Nova Delphini 1967, Nova Serpentis 1970 and Nova Scuti 1970 several months after they erupted at wavelengths of between 0.35 cm and 11.1 cm. The simplest interpretation of the observed spectra and variation with time of the radio emission is that it is caused by the bremsstrahlung of thermal electrons in a dense ionized envelope about the nova.

There have been no reports of impulsive radio emission from novae, nor have there been any quantitative predictions as to the radio energy which might be expected during the initial outburst.

## 1-5 Weber Events and Black Holes

### 1-5-1 The Weber Experiment

Weber (1969) has reported the occurrence of a significant number of coincidences between gravitational radiation detectors over a baseline of 1,000 km. The possibility that these events are caused by seismic, electromagnetic or cosmic ray disturbances has apparently been eliminated (Weber, 1970a; Ezrow et al, 1970). Weber's conclusion was that his results are consistent with the excitation of his detectors by gravitational radiation. He has also found (Weber, 1970b) that the coincidences vary sidereally, and that a sidereal-time histogram of his data exhibits an anisotropy of at least 6 standard deviations from the mean. Following a study of the radiation pattern of his detectors, Weber concluded that the anisotropy is consistent with his events being caused by unpolarised gravitational radiation emitted from the direction of the Galactic Centre. This deduction has been confirmed by Douglass and Tyson (1972) who have pointed out that if the source is randomly polarised then it could

also lie in three other small regions of the sky, one of which contains the Crab Nebula.

Initially Weber's detectors had a centre frequency of 1,660 Hz and a bandwidth of 0.016 Hz. However he later set up systems operating at 1,580 Hz and again obtained coincidences (Weber, 1971a). A reasonable deduction from this is that his events extend over a band of at least 80 Hz. Weber (1969) has estimated that if his events are caused by gravitational radiation then the energy flux associated with each coincidence is

$$\sim 10 \text{ J m}^{-2} \text{ s}^{-1}$$

in a 0.016 Hz band, so that over 80 Hz the energy flow during each pulse must be at least

$$5 \times 10^{4} \text{ J m}^{-2} \text{ s}^{-1}.$$

The burst of "gravity-waves" probably lasts for less than 10 s since after each event the oscillation of the detector decays with its natural 10 s decay time.

Considerable discussion has taken place as to how much energy must be deposited in Weber's detectors in order to produce a pulse above threshold. According to Field, Rees and Sciama (1969), Thorne (Zeldovich and Novikov, 1971), and Kafka (1972), during the early part of Weber's experiment the energy deposited in the detectors during an event was about 1/20 kT, where kT is the energy required to displace the detectors by an amount equal to the mean thermal amplitude. However, several authors (Thorne in Zeldovich and Novikov, 1971; Gibbons and Hawking, 1971a; Kafka, 1972) have pointed out that for most of the time the thermal motion of the detectors is probably sufficiently out of phase with incident gravity waves to prevent the detection of events of such small energy. Thorne has suggested that only ~10% of all 1/20 kT events are detected, while Gibbons and Hawking estimate an efficiency of ~6% for 1/12 kT events. Kafka

however, has indicated that for 1/16 kT events only 0.6% would be detected. According to Thorne (Zeldovich and Novikov, 1971), for an energy of 1/20 kT to be deposited it would be necessary to have a gravitational radiation flux at the earth of

$$7 \text{ J m}^{-2} \text{ event}^{-1}$$

in a 0.016 Hz bandwidth. Adopting Thorne's optimistic efficiency factor of 10% at a 1/20 kT threshold, Weber's initially observed rate of 1 event per 45 hours (Weber, 1970a) must correspond to a real rate of at least 1 per 4.5 hours. If each pulse extends over 80 Hz, then the total energy in each event must be at least

$$3.5 \times 10^{4} \text{ J m}^{-2}.$$

Allowing for an equal amount of energy in the other polarisation, which Weber does not observe, we have

$$7 \times 10^{4} \text{ J m}^{-2}$$

as the minimum energy associated with each event. At a rate of 2000 events/year this implies a gravitational radiation flux at the earth of

$$\sim 1.4 \times 10^{8} \text{ J m}^{-2} \text{ yr}^{-1}.$$

If the source of this flux lies at the Galactic Centre, and radiates isotropically, then it would have to emit at least 1000 $M_{\odot}$ per year in the form of gravitational radiation.

Attempts have been made to reduce this apparent mass loss by introducing "beaming" mechanisms. However, the proposed synchrotron mode emission (Misner, 1972) or focussing effects (Lawrence, 1972) appear to be rather improbable. According to Field, Rees and Sciama (1969) 21 cm line studies have indicated that the Galaxy could be losing mass at a rate of $\sim 70$ $M_{\odot}$ per year. However, observations of stellar motions near the sun imply that the average rate of Galactic mass loss cannot have exceeded 200 $M_{\odot}$ per year over the last $\sim 10^{8}$ years.

It therefore appears that at the time of writing, the simplest explanation of Weber's events - a source of quadrupole gravitational radiation at the Galactic Centre - leads to an impossible rate of mass loss from the Galaxy. Further experimental investigations will undoubtedly solve this problem, but for the remainder of the present work, the flux deduced above is assumed to be approximately correct.

A simple VHF dipole system, such as will be described later, has a threshold of

$$\sim 10^{-22} \text{ J m}^{-2} \text{ Hz}^{-1}$$

for an event of 1 s duration in a 1 MHz band. Thus, if only about $10^{-21}$ of the energy associated with Weber's events were radiated into this band of the electromagnetic spectrum in $\gtrsim$ 1 s, then its detection would be possible. Apart from this perhaps rather naive energy consideration, justification of a search for radio emission associated with Weber's events must inevitably include suggestions of potential sources. In sections 1-5-2 to 1-5-4, one such source is considered.

1-5-2 Black Holes - Theory

Aside from the problem of galactic mass loss there exists the question as to what mechanism at the Galactic Centre could produce such large fluxes of gravitational radiation. The principal explanation has been to suppose that one or more black holes exist at the Galactic Centre and that gravity waves are produced by collapse, collision or matter accretion in these objects. It is therefore of interest to consider the nature of black holes.

In 1939, Oppenheimer and Volkoff estimated that if the mass of a non-rotating neutron star exceeds 0.7 $M_\odot$ , then it must collapse. Since then, the Oppenheimer-Volkoff limit has been somewhat increased owing to recent allowance for the effects of hyperons in the star.

Present estimates for the critical mass are as high as 3 $M_\odot$. The question as to what happens to a star of mass exceeding this limit was dealt with by Oppenheimer and Snyder (1939). They showed that such a star contracts asymptotically in time towards its gravitational or "Schwarzchild" radius $R_G$ where

$$R_G = \frac{2MG}{c^2} \qquad \text{(Equ 1-19)}$$

where M = mass of star

G = Gravitation constant

c = velocity of light

To an external observer, the star never in fact shrinks to $R_G$, but after a finite time, the light from such a star undergoes such a large gravitational redshift that the actual electromagnetic energy escaping is negligible, rendering the star invisible i.e. a "black hole". Such an object cannot be directly detected, except by its gravitational field.

As many stars of considerably greater mass than $\sim 3\ M_\odot$ exist, the possibility cannot be dismissed that some of these stars ultimately collapse to form black holes.

The huge flux of gravitational energy which is necessary to explain Weber's events if their source is at the Galactic Centre, demands a highly efficient mechanism for converting matter into gravitational radiation. Hawking (1971) has pointed out that nuclear reactions release only $\sim 1\%$ of the rest mass in the form of energy. However, the efficiency is considerably higher for the collision and coalescence of two black holes. If two such objects of equal mass combine, as much as $\sim 30\%$ of the total mass can be radiated away in the form of gravitational radiation. It is because of this high efficiency that there have been many suggestions that one or more

black holes at the Galactic Centre are responsible for the pulses detected by Weber. Such objects are also attractive because of their small size. A 3 $M_\odot$ black hole has $R_G$ = 9 km so that its coherent movement can produce a 60 microsecond burst of gravitational radiation. Such a pulse can contain Fourier components corresponding to 1,660 Hz, the frequency of Weber's observations.

According to Davis et al (1971), if a particle of mass m falls radially into a black hole of mass M, then the spectrum of the emitted gravitational radiation has a peak frequency $\nu$ and bandwidth $\Delta\nu \approx \nu$, where

$$\nu = \frac{0.32c^3}{2\pi GM} \qquad \text{(Equ 1-20)}$$

$$\approx 3 \text{ kHz for } M = 3\ M_\odot$$

Thus, matter accretion by a black hole can also produce gravity waves of the frequency necessary to explain Weber's results. However, in this case the mass conversion efficiency is only $\sim \frac{m}{M}\%$ of m which is considerably less than for the coalescence of two black holes. The same is true for a star undergoing collapse. In fact unless the collapse is spherically asymmetrical, no gravitational radiation can be produced. According to de la Cruz et al (1970) the asymmetrical implosion of a body of mass M produces a gravity-wave pulse of width $\tau_G$ where

$$\tau_G \approx \frac{2GM}{c^3} \qquad \text{(Equ 1-21)}$$

It therefore seems reasonable to expect the association of "short time-constant" phenomena with black holes, provided that they exist.

### 1-5-3 The Detection of Black Holes

In view of the above theoretical arguments, it is interesting to summarise possible experimental evidence for black holes.

Wyller (1970) has suggested that the excess brightness observed at the centres of concentrated globular clusters could be explained by a central black hole which would affect the stellar spatial distribution. Such a black hole might be detected by observing Doppler shifting in the spectra of stars whose orbits approach closely to it. However, the predicted shift is at the limits of present observing techniques.

Wolf and Burbidge (1970) and Mathews (1972) have discussed the possibility that black holes exist at the centres of elliptical galaxies. According to Wolf and Burbidge, studies of the dynamics of these galaxies and the spectra of the component stars imply that $\sim$75% of the galactic mass is invisible. They deduced that either an exceptional number of dim dwarf stars are present, or else the excess mass is in the form of black holes. However, the explosive phenomena observed in the nuclei of such galaxies cannot be explained by the presence of large numbers of low mass stars. The explosions suggested to Wolf and Burbidge that large masses ($10^9$-$10^{10}$ $M_\odot$) are present in small volumes and as such objects are unstable, they must collapse rapidly to form black holes. Mathews pointed out that the gas observed at the centres of elliptical galaxies does not seem to lead to star formation. He argued that the fate of this gas must be to collapse in the gravity field of the central stars. Stability considerations of this collapsing gas suggests that most of it is ultimately contained in elements having masses $> 500\ M_\odot$, which could implode to form black holes. Mathews remarked, however, that the effects of heating as the gas collapses might cause re-expansion. Also, if the gas has a large angular momentum, this could affect the formation of black holes due to self-gravitational fragmentation.

In the above, extra-galactic black holes of masses $\gg 1\ M_\odot$ were considered. More recently, suggestions have been made that

certain binary systems in the Galaxy may contain black holes of stellar-mass dimensions.

Cameron (1971a) has proposed that the unusual eclipsing binary system Epsilon Aurigae might contain a black hole or "collapsar". His argument was as follows. The primary is an F2 supergiant of 35 $M_\odot$. As such a massive star evolves rapidly, it must already be at a post-main sequence stage. The secondary, which is invisible, has a mass of 23 $M_\odot$. Normally a star containing this quantity of material would be visible. It cannot be at its pre-stellar non-luminous stage, as its companion must be highly evolved. A remnant mass of 23 $M_\odot$ is too large to correspond to a stable white dwarf or neutron star. The secondary must therefore be a black hole.

One problem with this argument is that for the secondary to be at a more advanced stage than the primary, it must at one time have been more massive than 23 $M_\odot$. Cameron assumed that it underwent extensive mass loss in the red giant stage. However, Demarque and Morris (1971) have criticised Cameron's argument, and pointed out that a less exotic explanation of Epsilon Aurigae is that it consists of an F2 supergiant transferring material to its less massive companion which is still near the main sequence. Part of this mass is in the form of a disk around the secondary, thus rendering it invisible.

Devinney (1971) has proposed that the eclipsing binary system Beta-Lyrae also might contain a black hole. From photometric and spectroscopic arguments, he showed that the binary probably consists of a 10 $M_\odot$ visible primary and a 20 $M_\odot$ invisible secondary. The argument was then the same as Cameron's, that the 20 $M_\odot$ component must be a black hole. According to R.E. Wilson (1971) recent observations of the light curve of Beta-Lyrae by OAO 1 have shown that the secondary emits faint light, but "peaked" in the blue-ultraviolet region implying a high temperature. He maintained that for such a hot

source to be so underluminous, the secondary must consist of a black hole surrounded by a cloud of material, and that the emission from the secondary is being caused by matter accretion.

Gibbons and Hawking (1971b) have suggested that the highly eccentric, short-period spectroscopic binaries HD 176318 and HD 194495 might contain black holes. However, their reasoning, which was based largely on statistical considerations, has been criticised by Batten and Clowin (1971) who pointed out that the measured eccentricities of short period binaries are not reliable. In addition, Evans and Bath (1972) have found that the anomolous eccentricity distribution of single-line spectroscopic binaries found by Gibbons and Hawking also occurs in single-line eclipsing systems, which are not thought to be able to contain collapsed objects.

Perhaps the most interesting suggested black hole is the X-ray source Cygnus X-1. The X-ray flux from this object is known to undergo rapid fluctuations occurring at a rate of several times a second and having an amplitude which sometimes exceeds 25% of the average source intensity (Oda et al, 1971). In addition, Dolan (1971) has shown that long term observations of this object indicate SLOW variations in intensity, which are consistent with a period of 2.9850 days. To account for this he suggested an eclipsing binary model of small angular extent, surrounded by an X-radiating plasma, in which one X-radiating component revolves about a non X-ray emitting companion.

According to Webster and Murdin (1972), a spectroscopic binary containing a B-type blue supergiant lies within 3" arc of Cygnus X-1. The period of this binary is 5.6075 days, and they have shown that this would also be consistent with the X-ray data analysed by Dolan i.e. the X-ray system might in fact have a 5.6 d period. However,

the "eclipse" of the X-ray star occurs at a time when the companion to the B-star is BETWEEN the earth and the visible star. For this reason, Webster and Murdin rejected Dolan's simple model. They assumed that the X-ray source is associated with the companion of the visible star and that material ejected by the B-star onto the invisible component causes non-isotropic X-ray emission. They also suggested that the origin of the fast X-ray fluctuations lies in this mass transfer process. Dynamical and spectroscopic considerations indicate that the mass of the blue supergiant is 10-30 $M_\odot$ and that of the companion is 2.5-6.0 $M_\odot$. The small distance scale associated with the rapid X-ray fluctuations implies that the companion is of small volume. As its mass apparently exceeds 2.5 $M_\odot$, it might possibly be a black hole.

This suggested connection between a possible black hole and an X-ray source is particularly interesting in view of the prediction by de la Cruz et al (1970), that black holes in close binary systems might be detectable by the accretion of matter causing thermal X-ray bremsstrahlung.

If Cygnus X-1 is the source of Weber's events, its small mass implies that the emitted gravitational radiation must be beamed preferentially towards the earth. Synchrotron mechanisms (Misner, 1972) appear to result in highly polarised emission. It may therefore be significant that the anisotropy observed by Weber, could not be produced by a polarised source at the Galactic Centre, but it WOULD be consistent with such a source lying in the direction of Cygnus X-1. (Douglass and Tyson, 1972).

### 1-5-4 Radio Emission from Black Holes

Even if black holes are not associated with Weber's coincidences, bursts of radio emission from these objects might nevertheless occur

during collapse or matter accretion. However, no detailed models have been produced for the release of electromagnetic radiation from collapsed bodies.

According to Cameron (1971b) unpublished calculations by Schwartzman have indicated that a magnetised plasma falling into a black hole is heated by compression and emits synchrotron radiation with a spectrum sloping gently from the optical to radio wavelengths.

De la Cruz et al (1970) have considered a model in which a magnetic dipole lies at the centre of a thin hollow spherical shell undergoing gravitational collapse. It was found that 4% of the magnetic field energy is radiated to infinity in the form of electromagnetic radiation, but the spectral behaviour was not predicted. An interesting conclusion of de la Cruz et al was that any initial magnetic field at the time of collapse must ultimately decay to zero. This follows from the demand that all externally detectable properties of a black hole must vanish, except for its gravitational field. Thus the accretion of matter cannot give rise to radio emission unless the in-falling material is itself magnetised.

One other proposed mechanism whereby a black hole can give rise to a pulse of electromagnetic energy is the "black hole bomb" (Press and Teukolsky, 1972). A rotating black hole of mass M is surrounded by a spherical mirror (e.g. a shell of ionised gas) of radius $L \approx 10^3$ km. Thermal noise within the mirror ensures that electromagnetic waves of small amplitude are initially present. While most radiation incident on the hole is partially absorbed, waves in the frequency range

$0 < \nu < 2_{\pi} n \nu_o$ where n = corresponding mode of the wave in the cavity.

$$\nu_o = \frac{a}{4_{\pi} M R_G}$$

aM = angular momentum

extract rotational energy each time scattering off the hole takes place ("superradiant scattering"). Most amplification occurs at low modes, and for a maximally rotating black hole of 1 $M_\odot$,

$$\nu_o \doteq 15 \text{ kHz}.$$

Owing to reflections off the spherical mirror, a series of interactions of the waves with the black hole occur, gradually increasing the electromagnetic energy inside the shell. Eventually the radiation pressure causes the mirror to explode, releasing the energy in a time $\frac{L}{c} \doteq 1$ ms.

The main problem with this model is that most of the amplification takes place at a frequency well below the plasma frequency of the ionosphere. However, some emission at frequencies $\gtrsim 30$ MHz would probably take place due to the amplification of higher modes.

In conclusion, it appears that the possibility of large pulses of radio energy from black holes is not as strong as in the case of supernovae. Nevertheless, in view of the huge energies which must be released when matter accretion takes place, a search for radio pulses from such objects can be considered worthwhile, particularly as there may be many black holes within the Galaxy, possibly containing 90% of its mass (Truran and Cameron, 1971).

## 1-6 Pulsars

### 1-6-1 Current Understanding

Following the discovery of the pulsars in 1967, two main theories were proposed, in order to account for the rapid, regular bursts of radio emission from these objects. One of these ideas, that of a radially pulsating white dwarf, is no longer considered acceptable as it cannot explain NP 0532, the fastest pulsar so far discovered. The alternative theory, is that of a rotating neutron star and this is generally believed to be the nature of all pulsars.

At the time of writing, nearly 100 pulsars have been discovered (New Scientist, 1972, October 19). There is some evidence that they are the collapsed cores of old supernovae. Although the Crab Nebula is the only supernova remnant known to contain a pulsar, it is thought that most pulsars might be ejected away from the exploding shell, with the result that they have no obviously associated remnants. This explanation is consistent with the observed high velocities of pulsars. Also, three supernova remnants (The Vela Remnant, the Crux Remnant, and IC443) are known to have pulsars lying closer to them than would be expected by chance.

Pulsars are, as yet, the only successfully studied short time-constant phenomena. Despite the fact that their radio emission led to their discovery, they are nevertheless, rather weak radio sources. Although the flux density of individual pulses may be as high as 100 f.u. (ter Haar, 1972) this is still well below the threshold sensitivity of the dipole experiment ($\sim 10^4$ f.u.) described later. The relevance of the pulsars to the present work was due to certain effects which possibly involve the release of much greater energy than do the normal periodic emissions. These effects include frequency jumps ("glitches"), phase fluctuations and "strong" pulses. Frequency jumps have been observed in the Crab and Vela pulsars, and strong pulses have been detected from the Crab pulsar and PSR 1237 +25. The Crab pulsar alone is known to undergo phase fluctuations. As only the Crab pulsar exhibits all three of the above effects, the remainder of this section is confined to this object.

1-6-2 Frequency Jumps

The Crab pulsar has shown three sudden increases in frequency, since its discovery. (Boynton et al, 1969; Richards et al, 1969;

Lohsen et al, 1971; Nelson, 1972; Lohsen, 1972). The magnitude of these frequency jumps are a few parts in $10^9$, and happen about once a year. The actual occurrence of one of these sudden changes has never been observed, and frequency measurements before and after the events have only pinpointed the times of the glitches to within ~1 day. According to Baym and Pines (1971), the energy released during the first (and largest) frequency jump could have been as much as

$$7 \times 10^{33} \text{ J}$$

It was this sudden tremendous release of energy which provided one of the arguments in favour of conducting extended observations of NP 0532. If emitted isotropically, the energy at the earth would be

$$\sim 1.5 \times 10^{-7} \text{ J m}^{-2}$$

Thus, if only $\sim 10^{-9}$ of this energy were radiated into a 1 MHz band at 151.5 MHz, it would have been detectable by the techniques described in Chapters 2 and 5. (The fraction of pulsed energy emitted by the steady pulsar into the above VHF band is in fact $\sim 10^{-9}$). The above maximum energy released during a frequency jump was estimated from its magnitude on the basis of changes in rotational, gravitational and strain energy in the pulsar. However, two other observations also indicate that large quantities of energy are released during glitches.

According to Scargle and Harlan (1970), the "wisps" close to the pulsar brightened and extended, 6-10 weeks after the first frequency jump in 1969, September. They estimated from this, that the total energy released during the glitch could have been as much as $10^{38}$ joules, implying that the frequency jump was probably a rather minor consequence of a much more energetic event in the nebula. They suggested that the energy released by the pulsar over ~2 years is stored in a surrounding magnetic plasma until an instability developes, releasing this energy. The frequency jump could be caused by a torque

conveyed to the pulsar via the magnetic field.

Fazio et al (1972) have found increases in the $\gamma$ -ray flux (Energy $\geq 2.5 \times 10^{11}$eV) from the Crab Nebula 8-17 weeks after each fequency jump. The $\gamma$ -ray energy released during these periods was $\sim 10^{34}$ joules - comparable to the energy loss estimated by Baym and Pines.

If the energy emission during a glitch occurs gradually over several hours, detection by the methods of the present work would have been unlikely. Scargle and Harlan made no estimate for the timescale of their proposed energy release mechanism, although they pointed out that the frequency jump could be produced by turning off the secular slow-down of the pulsar for only 200 s, an effect which might be produced by a transient disruption of a surrounding plasma.

Pines and Shaham (1972), have criticised the mechanism proposed by Scargle and Harlan, pointing out that such a model would encounter severe difficulties in providing a plasma which was stable for $\sim 1$ year. They suggested rather, that the wisp brightening was due to enhanced magnetospheric activity triggered by changes at the pulsar surface. In their opinion, the most promising line of thought is the "crust-cracking" theory originally proposed by Ruderman (1969). In this, a neutron star has a superfluid degenerate neutron interior surrounded by a solid crust of nuclei. The formation of the crust is due to the exceedingly high energy of the electrons. This has the effect of preventing the normal screening of the positive nuclei from each other so that they arrange themselves into a cubic lattice owing to their mutual repulsion. As the pulsar slows down, gravitational forces near the equator are no longer balanced by centrifugal forces, and eventually the crust "cracks", taking up a new equilibrium configuration. The resulting decrease in the moment of inertia causes the pulsar rotation to increase in frequency.

According to Baym et al (1969), the time scale for the cracking and initial spin-up is of the order of 0.01-0.1 s, the time for a shear wave in the crust to propagate a stellar radius. The spin-up of the crust is then communicated to the charged particles in the interior by the strong magnetic field over a timescale of several hundred seconds. The release of a large amount of energy in a short time therefore seems possible.

An interesting aspect of this theory is that during the crust-cracking, a large quantity of matter will fall inwards in a region where there exists a very strong tangential magnetic field. ($\sim 10^8$ Tesla). It may be that this material could give rise to a large coherent radio pulse in a manner analogous to the Colgate-Noerdlinger model for radio emission from supernovae.

According to Baym and Pines (1971) the rate of build-up of strain in the crust, $\dot{S}$, is such that

$$\dot{S} \propto \frac{\Omega^2}{T} \qquad \text{(Equ 1-22)}$$

where $\Omega$ = angular velocity

$$T = -\frac{\Omega}{\dot{\Omega}}$$

i.e $\dot{S} \propto$ rate of loss of rotational energy.

They concluded that frequency jumps due to starquakes in pulsars other than the Crab and Vela pulsars, are unlikely to occur with sufficient frequency to be observed. It therefore appears that while the timescale and energy involved in the Crab pulsar glitches make it seem quite reasonable that strong radio emission occurs during these events, observations of other pulsars hardly seem worthwhile in this connection.

### 1-6-3 Phase Fluctuations

Precise timing of the optical pulses from NP 0532 have continued for over 2 years. The overall slowdown of the pulsar can be

adequately described by a cubic polynomial whose coefficients are suitably chosen time derivatives of the pulsar frequency. However, in order to describe precisely, the phase and frequency of the pulsar at any time, small "phase residuals" have to be added or subtracted. Considerable effort has been put into finding a function which describes the residuals (Boynton et al, 1972), but these attempts have not met with success and have been abandoned. However, Boynton et al have found that if the frequency is assumed to undergo completely random jumps following a Poisson distribution about the phase predicted by the cubic polynomial, then a reasonable fit to the data is obtained.

Earlier work by Nelson et al (1970) suggested that the residuals could be explained by "mini-glitches" of magnitude $\sim 1$ in $10^9$ occurring about once every 25-30 days. Boynton et al criticised this idea, arguing that such large, sudden changes would give rise to observable alterations in the pulse shape. In fact, no changes in shape have been detected. However, in the "frequency noise" model the pulse shape is not affected by detectable amounts, the random jumps being much smaller and more frequent.

Boynton et al suggested that the most plausible origin of the frequency noise is due either to the accretion of lumps of material, or crust-cracking. Pines and Shaham (1972) have developed the crust-cracking idea, suggesting that the phase fluctuations are caused by small localised crust-crackings, rather than the entire crust disruptions which may occur in major glitches. Whether matter accretion or "microquakes" are responsible for the frequency noise, small jumps, each occurring over a timescale of less than a few seconds, would be expected. Boynton et al suggested that these proposed "noise" mechanisms would have to take place at a rate of several events a day, to account for the data. Thus, although the

energy involved in one of these events would be much smaller than in a major glitch (~1%) the risk of missing them due to insufficient observing time is greatly reduced.

1-6-4 Strong Pulses

While the emissions from all pulsars have amplitudes which vary greatly from pulse to pulse, NP 0532 is exceptional in that at VHF, it occasionally produces a pulse several hundred times larger than the mean pulse energy. Indeed it was this property which led to its discovery (Staelin and Reifenstein, 1968). Most of the strong pulses are associated with the main pulse component, although occasionally, a "giant" interpulse is obtained (Heiles et al, 1970; Gower and Argyle, 1972). No giant precursor pulses have ever been observed, so that it is unlikely that the strong pulses are caused by the interstellar medium, as this would presumably affect all three components equally.

Sutton et al (1971) have suggested that the strong pulses are caused by a beaming effect, in which the direction of the beam changes slightly from pulse to pulse, the strong pulses being observed when the beam maximum coincides with the line of sight. They proposed that the mechanism involved is wideband maser amplification in which the direction of maximum amplification varies due to refraction in the amplifying plasma. Manchester (1971) has suggested that the strong pulses may be associated with the fact that the radio emission from NP 0532 originates at the magnetic pole of the star.

At the commencement of the present work, little was known about the pulse height spectrum of the strong pulses, and it was argued that occasional exceptionally strong pulses (perhaps 1 per day) might occur. Such pulses would have been observable even with the relatively small collecting areas used in the spaced-receiver technique

described in Chapter 2.

## 1-7 Early Spaced-Receiver Experiments

Since much of the stimulus for the present work was provided by the observations of Smith (1950), early spaced-receiver experiments are now described.

Around 1950, studies were being carried out in the U.K. and Australia in order to determine the origin of intensity fluctuations at metre wavelengths in the radio sources Cygnus A and Cassiopeia A. It is now known that these variations are not intrinsic to the sources, but are in fact caused by irregular refraction processes due to patches of varying ionisation in the F layer of the ionosphere.

In the course of these early experiments, a search was made for correlations between the fluctuating signals received simultaneously at sites of various distances apart. For several weeks in the autumn of 1949, Smith conducted observations of Cassiopeia A using receivers tuned to 45 MHz at sites separated by 160 km. The simple dipole interferometer systems which he used, were very similar to those employed in the present work. While the usual scintillation phenomena showed no correlations between the sites, occasionally (about once a week) simultaneous bursts of large amplitude and 10-20 s duration were received at night. Smith concluded that in view of the wide separation of the observing stations, it seemed unlikely that the bursts were of terrestrial origin. He suggested that the pulses were due to genuine variations of the emission from the sources and pointed out that the brevity of the bursts implied that their origins were of stellar dimensions. However, owing to the rarity of these events, it was not possible to relate their direction of origin with the positions of any of the

radio sources known at the time. In any case, it has since been shown that the diameters of Cygnus A and Cassiopeia A are $10^5$ light years and 13 light years respectively so that 20 s variations in the intensity of either object are very unlikely. No bandwidth information was given by Smith, but for a reasonable choice of 0.1-1 MHz, a dispersed width of 10 s would imply a dispersion measure to the source of 10-100 $cm^{-3}$ pc, which is typical for objects lying within the Galaxy.

Other considerations argue against the suggestion that the origin of Smith's events lay beyond the solar system. Simultaneous observations at 81 MHz carried out by Smith at Cambridge and by Little and Lovell (1950) at Jodrell Bank produced no coincidences between the two sites (210 km apart). This implies that the source of the 45 MHz bursts had a spectrum which was either very narrow (e.g. a man-made transmitter) or which fell away sharply at high frequencies.

At about the same time as these observations were made, similar experiments were in progress in Australia. Stanley and Slee (1950) investigated scintillations over the frequency range 40-160 MHz. In one of their experiments, receivers were placed on the east coasts of Australia and New Zealand (separation $\sim$2,000 km) but no correlations between the records made at the two sites were obtained. No large coincident bursts were reported. However, no details were given of the observing duration and exact frequency of this spaced-receiver experiment.

Observations using a single 45 MHz system at Cambridge continued from 1949, October to 1950, September, for 15 hours a night. Two 45 MHz systems 1 km apart were then operated between 1951, January to 1951, April for 5 hours a night (Hewish, 1952). Again, no large

coincident bursts were reported.

Ryle and Hewish (1950) have remarked that Smith's events were suggestive of bursts of solar radiation. Indeed, 1949 was a time of high sunspot activity so that the possibility cannot be ruled out that the coincidences at 45 MHz were caused by Type III solar bursts which had undergone anomalous reflection due to unusual ionospheric activity.

Despite the likelihood that these events were man-made or solar in origin it was decided that as the precise conditions under which Smith had carried out his observations had never been repeated, a pulse search at 45 MHz should be made (Chapter 3, part 2). The experiments described in the present work represent the first attempts to observe rare radio pulses since the time of the above early investigations.

CHAPTER 2

## Techniques for Observing Rare Radio Pulses

### 2-1 Discrimination against Man-made Interference

Undoubtedly, the largest problem encountered in attempts to observe transient radio pulses of extraterrestrial origin lies in the discrimination between these events and artificial transmissions. However, typical man-made interference has certain properties which allow it to be distinguished from natural electromagnetic emission:-

(i) Reception of interference at frequencies > 30 MHz from sources below the physical horizon is unusual. Hence, by carrying out simultaneous observations with widely spaced receivers, local transmissions can be eliminated since they would generally be received at only one station. Events of interest would be those which produced simultaneous pulses at several stations.

(ii) Signals > 30 MHz received from terrestrial transmitters have usually propagated horizontally. By designing the receiving antennae so that they have minimum sensitivity (or even a null) in a horizontal direction, the effects of local interference can be reduced.

(iii) Intentional transmissions are normally confined to a narrow band whereas, natural radio emission usually extends over at least several octaves of the spectrum. Observation by several receivers tuned to slightly different frequencies can make possible the identification of narrow-band interference.

(iv) Even when artificially produced VHF radio signals are

broad-band, they do not usually show the characteristic dispersion of a pulse from a source at least several parsecs distant. This fact has been employed by many workers, to make possible single-station searches for pulses from astrophysical sources. In particular, pulsar hunters have achieved considerable success by searching for single dispersed pulses rather than by analysing radio noise for periodicities. For example, the pulsars NP 0527 and NP 0532 were discovered (Staelin and Reifenstein, 1968) by monitoring a 5 MHz band at 50, 0.1 MHz intervals. Dispersed events appeared at successively later times with decreasing channel frequency and so were distinguishable from local interference, whether narrow or broad-band. M.I. Large and his collaborators have discovered several pulsars using a similar technique (Davies and Large, 1970). More recently, a search has been made for dispersed pulses from supernovae (Colgate et al, 1972) using frequency-tracking receivers at a single station.

As a technique for pulsar investigations, utilisation of the pulse dispersion to discriminate against interference is effective partly because repeated observations of the pulsar can be made. However, in a search where only one pulse from a particular source might be detected, the presence of "dispersion" cannot provide completely unambiguous information concerning the origin. Indeed, it was found by Colgate et al that "lock-in" of their receivers with nearby sources considerably reduced their sensitivity and observing time. In addition, for typical interstellar and intergalactic electron densities, negligible dispersion would occur at microwave frequencies.

It is therefore likely that in a search for rare radio pulses of astrophysical origin, the single station dispersed pulse technique is less effective than spaced-receiver observations, such as were carried out in the present work. Nevertheless, three systems operating at 151.5 MHz, 80 MHz and 47 MHz were constructed at Glasgow, so that dispersion information about any interesting coincidences might be obtained.

## 2-2 Other Types of Interference

Broadband pulses can be caused by lightning discharges and cosmic-ray showers. However, such phenomena are generally local and so can be eliminated by the spaced-receiver technique. It is also unlikely that pulses of geophysical origin would exhibit dispersion.

Shortly after the beginning of the present work, it was found that many day-time coincidences were caused by Type III solar bursts (Kundu, 1965). This effect occurs about 3 times per hour during a sunspot maximum but less frequently at other times. During this type of disturbance, the VHF emission characteristically sweeps from high to low frequencies and so could possibly be mistaken for a dispersed event. At 151.5 MHz, a sweep rate of about 100 MHz $s^{-1}$ occurs. A similar rate would be caused by a dispersion measure of about 5 $cm^{-3}$ pc which is quite possible for an object $\gtrsim$ 100 pc away.

For Type III solar bursts at a frequency $\nu$,

$$\frac{d\nu}{dt} \propto \nu \text{ Hz } s^{-1} \text{ (approximately)} \qquad \text{(Equ 2-1)}$$

while for genuinely dispersed events

$$\frac{d\nu}{dt} \propto \nu^3 \text{ Hz } s^{-1} \qquad \text{(Equ 2-2)}$$

Hence, in principle, the two effects can be distinguished from each other by simply observing the sweep rates over a range of frequencies. In practice, it was decided to confine VHF investigations to times

when the sun was below the horizon, thus minimising the possibility of mistaking a Type III pulse for a genuine event.

## 2-3 Choice of Antenna Collecting Area and Operating Frequency

Given that impulsive events (e.g. supernovae) are occurring at a uniform rate, evenly distributed throughout space, the best antenna size and wavelength for observing such events must be examined. It is assumed that a constant quantity of energy is released during each eruption, and that it has a flat spectrum and is emitted isotropically.

Let $\lambda$ = wavelength of observation.

$D_a$ = diameter of antenna.

R = maximum distance at which an event can be detected using an antenna of diameter $D_a$.

$\Omega$ = solid angle observed with a sensitivity exceeding the $\frac{1}{2}$-maximum sensitivity.

Volume of universe observed above threshold

$$\propto \text{Rate of events observed} \propto \Omega R^3 \qquad \text{(Equ 2-3)}$$

But $\Omega \propto \lambda^2 D_a^{-2}$ and $R \propto D_a$

$$\therefore \text{Rate of events observed} \propto \lambda^2 D_a \qquad \text{(Equ 2-4)}$$

It is interesting to note that the expected event rate is proportional to $D_a$ and not $D_a^2$. Nevertheless, it is clearly advantageous to use as large a collecting area as possible. However, owing to the practical problems involved in the construction of large antennae at several stations, it was decided to carry out the initial observations using simple dipoles of collecting area $\sim\lambda^2$. (The use of several large established radio telescopes in conjunction was ruled out owing to the large amount of observing time required.)

The above dependence of the event rate on $\lambda$ (Equ 2-4) ignores the effects of receiver noise, sky noise, interstellar scintillation

and dispersion. Below frequencies of $\sim 300$ MHz, it is possible to construct relatively simple transistor preamplifiers which contribute less noise to the system than does the sky background. According to Kraus (1966), the flux $S_{gal}$ received from the sky background is such that

$$S_{gal} \propto \lambda^{2.5} \qquad \text{(Equ 2-5)}$$

The rms fluctuation $\Delta S_{gal}$ in the sky noise therefore follows the approximate relationship

$$\Delta S_{gal} \propto \lambda^{2.5} \qquad \text{(Equ 2-6)}$$

Thus, for a sky noise limited system

$$\text{Rate of events observed} \propto \lambda^{-0.5} D_a \qquad \text{(Equ 2-7)}$$

The spectrum of the noise generated in the receiver is approximately flat so that for a receiver noise limited system

$$\text{Rate of events observed} \propto \lambda^{2} D_a \qquad \text{(Equ 2-8)}$$

These results apply to a pulse whose intrinsic time width $t_I$ has been negligibly affected by scintillation or dispersion broadening, assuming that $t_I$ does not vary with $\lambda$ . As will be seen later, at VHF $t_I$ is generally "spread" by scintillation to a width $t_s$, or by dispersion to a width $t_D$, where

$$t_s \propto \lambda^{4} \qquad \text{(Equ 2-9)}$$

$$t_D \propto \lambda^{3} \qquad \text{(Equ 2-10)}$$

For the optimum detection of a pulse arriving at the earth, the integration time $\tau$ of the system should be set equal to the duration of the pulse. For a system which has been optimised in this way, the dependence of the event rate on $\lambda$ is determined by the factors which influence the pulse width and system noise. Details of this dependence are given in Table 2-1.

Table 2-1 Criteria Determining Dependence of Event Rate on $\lambda$.

| Principal noise source | Duration determination factor | Dependence of event rate on $\lambda$ |
|---|---|---|
| receiver | intrinsic width | $\lambda^{2}$ |
| galactic background | intrinsic width | $\lambda^{-0.5}$ |
| receiver | dispersion | $\lambda^{0.5}$ |
| receiver | scintillation | $\lambda^{0}$ |
| galactic background | dispersion | $\lambda^{-2}$ |
| galactic background | scintillation | $\lambda^{-2.5}$ |

It can be seen from Table 2-1 that for pulses whose time widths have been determined by the interstellar or intergalactic medium, it is advisable to reduce the observation wavelength until the receiver noise becomes comparable to the sky noise. Further increase of frequency beyond about 300 MHz is not profitable, unless very low noise systems such as parametric amplifiers or masers are used. In the present work, such devices were not available, and so transistor preamplifiers were employed. Thus, the choice of 151.5 MHz as the principal observing frequency was quite close to optimum, under the above conditions.

In the following section, the detailed effects of scintillation and dispersion broadening at VHF are considered.

## 2-4 The Effects of the Interstellar and Intergalactic Media

### 2-4-1 Scintillation

Inhomogeneities in the interstellar and intergalactic electron densities may result in pulse broadening due to multipath scattering. For interstellar scintillation at VHF, pulsar studies have shown that the spreading follows a $\lambda^{4}$ law (Rankin et al, 1970; Sutton et al, 1971; Lang, 1971) According to Lang (1971) the value of $t_s$ is given

by

$$t_s \approx 2 \times 10^{26} \frac{(DM)^2}{\nu^4} \text{ s} \qquad \text{(Equ 2-11)}$$

where DM = dispersion measure in $cm^{-3}$ pc, to the emitting object.

$\nu$ = frequency of observation in Hz.

This empirical result was obtained from measurements of the decorrelation frequencies for 14 pulsars. It assumes that the width $t_s$ of the pulse at $e^{-1}$ of the maximum height is given by

$$t_s = \frac{1}{\text{decorrelation frequency}} \qquad \text{(Equ 2-12)}$$

The expected values of DM will be discussed later.

2-4-2 Dispersion

When an electromagnetic wave travels through an ionised gas, the effect of the free electrons is to reduce the group velocity U of the signal such that

$$U = c\left[1 - \frac{e^2 n_e}{\epsilon_o m_e \omega^2}\right]^{\frac{1}{2}} \qquad \text{(Equ 2-13)}$$

where c = velocity of light in vacuo.

e = electronic charge.

$n_e$ = free electron density.

$\epsilon_o$ = permittivity of free space.

$m_e$ = electronic mass.

$\omega$ = angular frequency of electromagnetic wave.

The interstellar and intergalactic plasma cause a delay D in the arrival time of a pulse, where

$$D = 4.14 \times 10^{15} \frac{DM}{\nu^2} \text{ s} \qquad \text{(Equ 2-14)}$$

where $\nu$ = frequency in Hz.

Thus, if an intrinsically fast, broadband pulse is observed with a

system of bandwidth $\Delta\nu$, the pulse appears to "sweep" through the band from high to low frequencies in a time $t_D$, where

$$t_D = 8.28 \times 10^{15} \frac{DM}{\nu^3} \Delta\nu \, s \qquad \text{(Equ 2-15)}$$

## 2-5 Interstellar and Intergalactic Electron Densities

### 2-5-1 The Interstellar Plasma

Within the galaxy, the most reliable information with regard to free electron density has been obtained from pulsar dispersion measures. However, the diversity of methods used to determine pulsar distances has resulted in a considerable range of estimates for the mean free electron density $\langle n_e \rangle$. Details are given in Table 2-2.

Table 2-2 Mean Free Electron Density Estimates

| $\langle n_e \rangle$ ($cm^{-3}$) | Author(s) | Date |
|---|---|---|
| 0.02 | Bridle and Venugopal | 1969 |
| 0.04 | Prentice and ter Haar | 1969 |
| 0.04 | Gunn and Ostriker | 1970 |
| 0.06 | Mills | 1970 |
| 0.03-0.12 | Grewing and Walmsley | 1971 |
| 0.03 | Lang | 1971 |
| 0.15 | (Cavallo and Ventura) | 1972b |

The last value in the table was determined by the author using pulsar distance estimates published by Cavallo and Ventura (1972b) and dispersion measures given by Manchester and Taylor (1972). In view of the tabulated values, the author has adopted a figure of $\langle n_e \rangle = 0.05$ $cm^{-3}$ for the mean free electron density within the Galactic disc. However, it must be emphasized that this value is only approximate, since variations in $\langle n_e \rangle$ within the Galaxy are large. For the 37 pulsars

considered by Cavallo and Ventura, $< n_e >$ varied from 0.006 $cm^{-3}$ to 0.66 $cm^{-3}$. It should also be pointed out that in view of the typical pulsar distances, the adopted value (0.05 $cm^{-3}$) is only strictly applicable to regions within about 2 kpc of the sun. It is assumed that similar electron densities would be obtained throughout the outer regions of most galaxies.

Considerably higher values of $< n_e >$ probably occur in the central regions of the Galaxy. Studies of the 166$\alpha$ recombination line (Davies et al, 1972) emitted by $H_{II}$ clouds within 7 kpc of the centre indicate an average density of $< n_e > \approx 0.5$ $cm^{-3}$. The actual 166$\alpha$ emitting clouds may have electron concentrations of up to $\sim 10$ $cm^{-3}$.

For an average electron density of 0.05 $cm^{-3}$, the dispersion measures to most Galactic objects (0.1-10 kpc from earth) lie in the range

$$5\text{-}500 \text{ cm}^{-3} \text{ pc}$$

2-5-2 The Intergalactic Plasma

Compared with interstellar space, much less information is available concerning the density of intergalactic electrons. Conversely, much of the importance in attempts to detect pulses of extragalactic origin lies in the fact that such observations could give more precise values for the intergalactic $< n_e >$. Extragalactic matter can be categorised according to whether it occurs within galactic clusters or outside them.

(i) Matter within Galactic Clusters

Observations of neutral hydrogen apparently falling into the Galaxy have led to density estimates of $\sim 2 \times 10^{-4}$ $cm^{-3}$ for hydrogen in the vicinity of the Galaxy (Oort, 1970). However, this gives no measure for the plasma density, which could conceivably exceed the

concentration of neutral hydrogen. Attempts have been made to determine the free electron density within the Local Group by interpreting the soft X-ray background as being thermal X-rays emitted by an intergalactic plasma. According to Hunt and Sciama (1972a), X-ray measurements could imply a density of $\sim 3 \times 10^{-4}$ cm$^{-3}$. In addition, recent observations of M87 by the UHURU satellite have shown that it emits soft X-rays compatible with an intergalactic plasma density of $\sim 2\text{-}3 \times 10^{-4}$ cm$^{-3}$ within the Virgo Cluster (Hunt and Sciama, 1972b).

The apparent gravitational instability of galactic clusters is removed if it is assumed that a large mass of intergalactic ionised hydrogen is present within these groups. Application of the virial theorem to nearby clusters (Chamaraux et al, 1972) has shown that the minimum particle density necessary to achieve stability is $0.6\text{-}6 \times 10^{-5}$ cm$^{-3}$. However, Goldsmith and Silk (1972) have used the virial theorem to show that the intergalactic density within the Coma Cluster must be $\sim 4 \times 10^{-4}$ cm$^{-3}$, which is considerably larger than the $3 \times 10^{-5}$ cm$^{-3}$ obtained by Chamaraux et al.

In view of these considerations the author has adopted a value of $3 \times 10^{-4}$ cm$^{-3}$ for the free electron density between galaxies but within clusters. Assuming that typical groups have radii $\approx 3$ Mpc, this yields a dispersion measure of about 900 cm$^{-3}$ pc.

(ii) Matter outside Galactic Clusters

The situation here is complicated by the possible presence of the plasma considered in (i). However, as stated in Chapter 1, if the soft X-ray background is interpreted as being due to a universal plasma then the electron density within a Friedman universe is less than $\sim 6 \times 10^{-7}$ cm$^{-3}$. The radius of observation which is necessary to yield a reasonable rate of supernova occurrence is about 100 Mpc. The corresponding dispersion measure for intercluster space is there-

fore $\gtrsim 60$ cm$^{-3}$ pc.

It appears that for pulses of extragalactic origin, the largest dispersion measure is encountered in galactic cluster space. Such pulses will generally experience comparatively small dispersion measures within the source parent galaxy or the Galaxy. Assuming a galactic disc thickness of $\sim 200$ pc, and that the incidence of extragalactic events is isotropic, then 50% of the pulses from these events will experience galactic dispersion measures of $\gtrsim 30$ cm$^{-3}$ pc.

## 2-6 Bandwidth and Integration Time

From the previous discussion, it can be seen that for most possible sources of impulsive radio emission, dispersion measures in the range 10-1,000 cm$^{-3}$ pc are likely. The optimum observation bandwidth can now be considered.

If the pulse duration is determined by either the intrinsic width or by scintillation, then the observed time width is independent of the bandwidth. Thus, for a broadband pulse, the bandwidth $\Delta\nu$ should be made as wide as possible, since under these conditions,

$$S/N \propto \frac{F \Delta\nu t}{\sqrt{\Delta\nu \tau}} \qquad \text{(Equ 2-16)}$$

where S/N = signal to noise

F = flux per Hz during pulse

t = pulse duration = $t_I$ or $t_s$

$\tau$ = integration time = $t_I$ or $t_s$ (the integration time is assumed to be optimised)

However, when $t_D > t_I$ and $t_D > t_s$, the flux F is independent of the bandwidth, and optimum detection occurs when the integration time is set equal to the time $t_D$ for the dispersed pulse to sweep through the band $\Delta\nu$. In this case,

$$S/N \propto \frac{F t_D}{\sqrt{\Delta\nu \tau}} \qquad \text{(Equ 2-17)}$$

$$\propto F \quad \text{since } t_D \propto \Delta\nu \text{ and } t_D = \tau$$

Thus, once the time width is dominated by dispersion, further increase in the bandwidth is not worthwhile. In addition, unnecessary expansion of the band is not good practice due to the increased probability of detecting interference as well as the loss of spectral information. Hence, an optimum bandwidth is one for which

$$t_D \approx t_s \qquad \text{when} \qquad t_s > t_I$$

or

$$t_D \approx t_I \qquad \text{when} \qquad t_s < t_I.$$

At 151.5 MHz, $t_s$ has the range 10 ms to 1 s for dispersion measures of 10-1,000 $cm^{-3}$ pc. According to Colgate et al (1972), an intrinsic width of $\sim 10^{-6}$ s for a supernova pulse is likely. Assuming therefore, that $t_s > t_I$ in general, then from Equs. 2-11 and 2-15, $t_D \approx t_s$ when

$$\Delta\nu = 160 \times DM \text{ Hz} \qquad \text{(Equ 2-18)}$$

The corresponding optimum bandwidths lie in the range 1.6 kHz to 160 kHz. Clearly it is best to operate with $\Delta\nu$ around 160 kHz, since this ensures that for dispersion measures in the above range, the pulse width is always dispersion dominated.

It is impossible to optimise the integration time $\tau$ for all values of DM, but it should be set between 10 ms and 1 s.

In practice, the bandwidths and integration times were largely controlled by the availability of equipment. Nevertheless, at VHF, the values used were

$$200 \text{ kHz} \gtrsim \Delta\nu \gtrsim 1 \text{ MHz}$$

and

$$300 \text{ ms} \lesssim \tau \lesssim 3 \text{ s}$$

and so were reasonably consistent with the above considerations.

## 2-7 The Simple Horizontal Dipole Interferometer

It was decided to carry out observations using phase-switched interferometers (Ryle, 1952) at each site for several reasons:-

(i) Since only the signals from the antennae are correlated in such a system, voltage-gain instabilities in the receiver do not affect the sensitivity.

(ii) The daily drift of known radio sources such as Cassiopeia A, through the interferometer fringes provided a regular and reliable sensitivity calibration. This was important in view of the many months during which the systems were required to operate.

(iii) In order to make the above calibration possible, it was necessary that the interferometer should respond to a DC signal, and so subtraction of the background radiation by AC coupling was ruled out. However, a phase-switched interferometer has the property that it responds only to sources of angular diameter $\gtrsim \frac{\lambda}{d}$, where d = antenna separation. Thus, by making the interferometer spacing sufficiently large, severe drifting and saturation of the receiver output owing to rotation of the system with respect to the Galaxy, was eliminated.

An interferometer spacing of $5\lambda$ was chosen, as this was found to be sufficiently large to remove most of the Galactic background. A wider separation was not worthwhile since reduction in fringe width would have simply reduced the pulse duration for which confusion might have arisen with the pattern produced by Cassiopeia A or Cygnus A. At a $5\lambda$ spacing, the $\frac{1}{2}$-period of the pattern was 1,350 s so that pulses of up to $\sim 10^3$ s could be unambiguously identified. In

addition, as the interferometers were positioned at several points on the earth's surface, it was convenient to keep the fringes as wide as possible so that the patterns at the different stations could be more easily aligned, for reasons given later.

The distances of the sites (Cambridge, Dublin, Glasgow, Harwell and Jodrell Bank) from each other ranged from 110 km to 500 km. For two stations 500 km apart, line of sight can only be obtained above heights of 5 km. Thus, the only interference sources liable to produce spurious coincidences were high-flying aircraft or satellites. Details of all the dipole systems used in the collaboration are given in Table 2-3. The remainder of this chapter refers principally to the Glasgow interferometers. These systems were set up at a relatively remote site at Cochno Farm (about 8 miles from the centre of Glasgow), in order to reduce the reception of man-made interference.

The 151.5 MHz antennae were designed by Dr. W.N. Charman at Harwell, and the Glasgow 80 MHz and 47 MHz antennae were designed by the author. Each interferometer consisted of two horizontal half-wave dipoles each placed $\frac{\lambda}{4}$ above a plane metal reflector (Figs 2-1 and 2-2). The power radiation pattern of this type of antenna (assuming an infinite, perfectly conducting reflector) has the form

$$\frac{\cos^2(\frac{\pi}{2}\cos\theta)\,\sin^2(\frac{\pi}{2}\sin\theta\cos\phi)}{\sin^2\theta}$$

where $\theta$ and $\phi$ are as shown in Figs. 2-1 and 2-3. It can be seen that for any horizontally propagating signal, the sensitivity is zero, thus minimizing the reception of most forms of man-made interference. The $\frac{1}{2}$-maximum sensitivity beamwidths in the planes parallel and perpendicular to the dipole are respectively $72^\circ\ 40'$ and $120^\circ$. This gives a sky coverage above $\frac{1}{2}$-maximum sensitivity of about 0.17 of $4\pi$.

Table 2-3 Details of Dipole Interferometers and Running Times

| Site | Frequency (MHz) | Bandwidth (MHz) | Operating periods until 1/1/72. |
|---|---|---|---|
| Cambridge | 151.5 | 1 | 6/1/70 – 10/9/70<br>1/5/71 – 1/1/72 |
| | 80 | ? | 19/1/70 – 24/2/70<br>1/3/70 – 8/4/70<br>13/4/70 – 1/6/70 |
| Dublin | 151.5 | 1 | 1/2/70 – 18/5/70<br>14/9/70 – 1/1/72 |
| | 70 | 20 | 11/3/70 – 5/5/70<br>2/8/70 – 1/1/72 |
| | 45 | 4 | 15/9/70 – 15/6/71 |
| Glasgow | 151.5 | 1 | 24/1/70 – 1/1/72 |
| | 80 | 0.35 | 28/1/70 – 1/1/72 |
| | 47 | 0.2 | 24/1/70 – 28/1/70<br>11/2/70 – 9/5/70<br>14/10/70 – 1/1/72 |
| Harwell | 151.5 | 1 | 6/1/70 – 1/1/72 |
| Jodrell Bank | 151.5 | ? | 6/1/70 – 11/2/70<br>19/2/70 – 29/4/70<br>10/12/70 – 1/1/72 |
| | 43 | 0.8 | 26/1/70 – 11/2/70<br>17/12/70 – 9/4/71<br>17/12/71 – 1/1/72 |

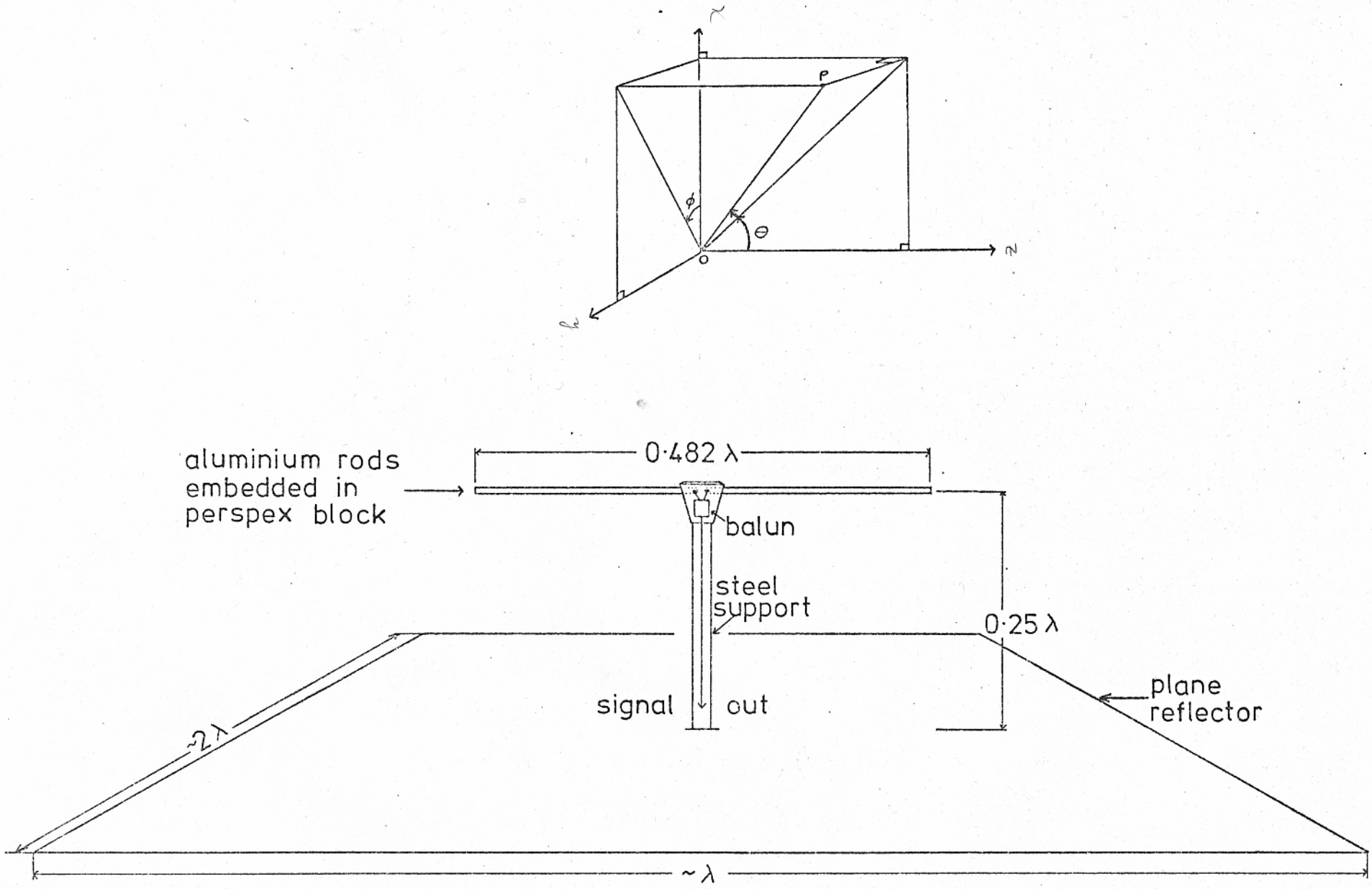
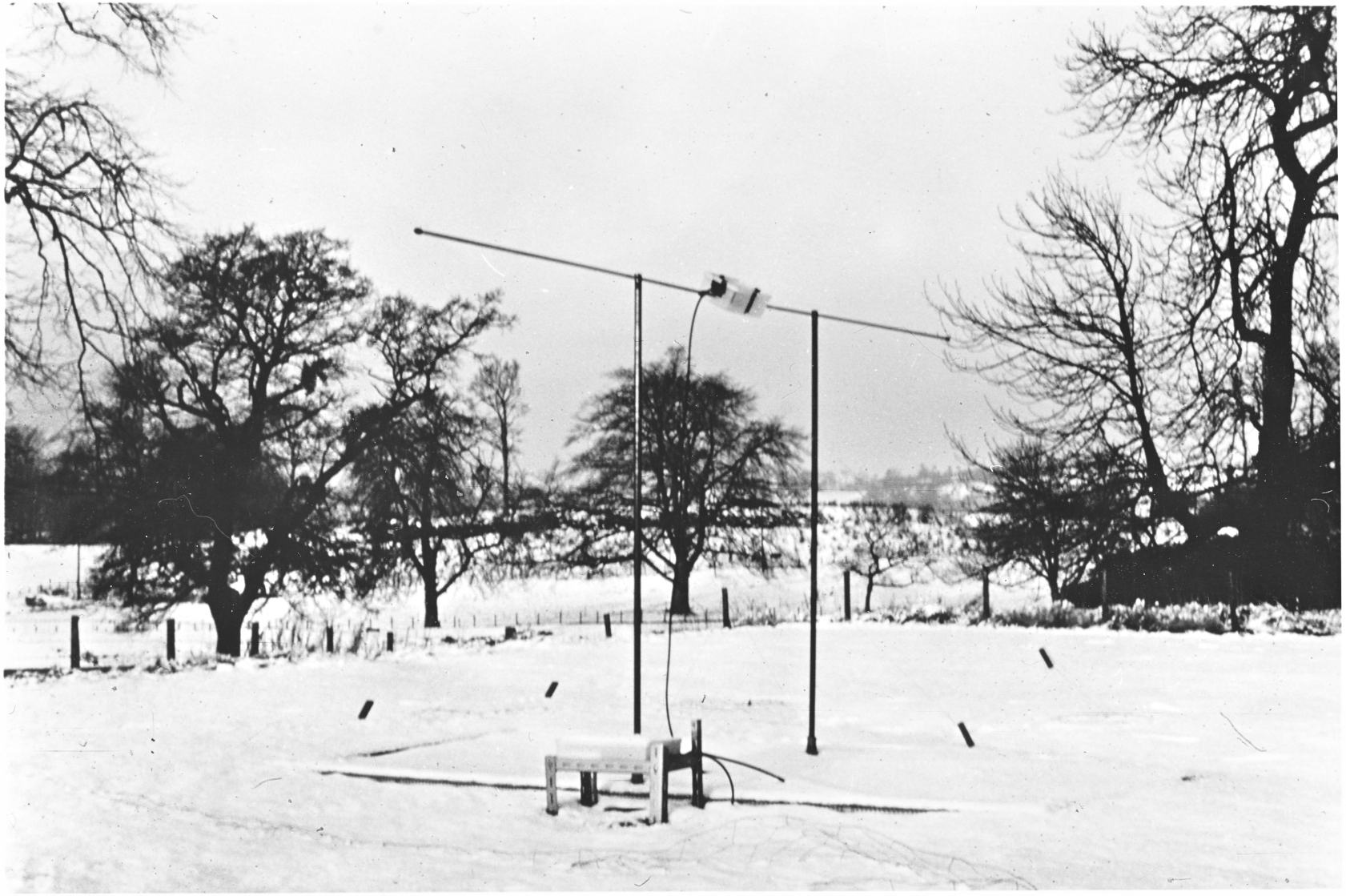



Fig.2-1 Glasgow dipole design. The expression on p.60 gives the sensitivity in the direction OP (θ,Ø).

Fig.2-2 47 MHz Glasgow Dipole. This was the first antenna to be built at Glasgow, and it was supported by two "Tufnol" rods rather than the single steel post which was used for the later dipoles (Fig.2-1).



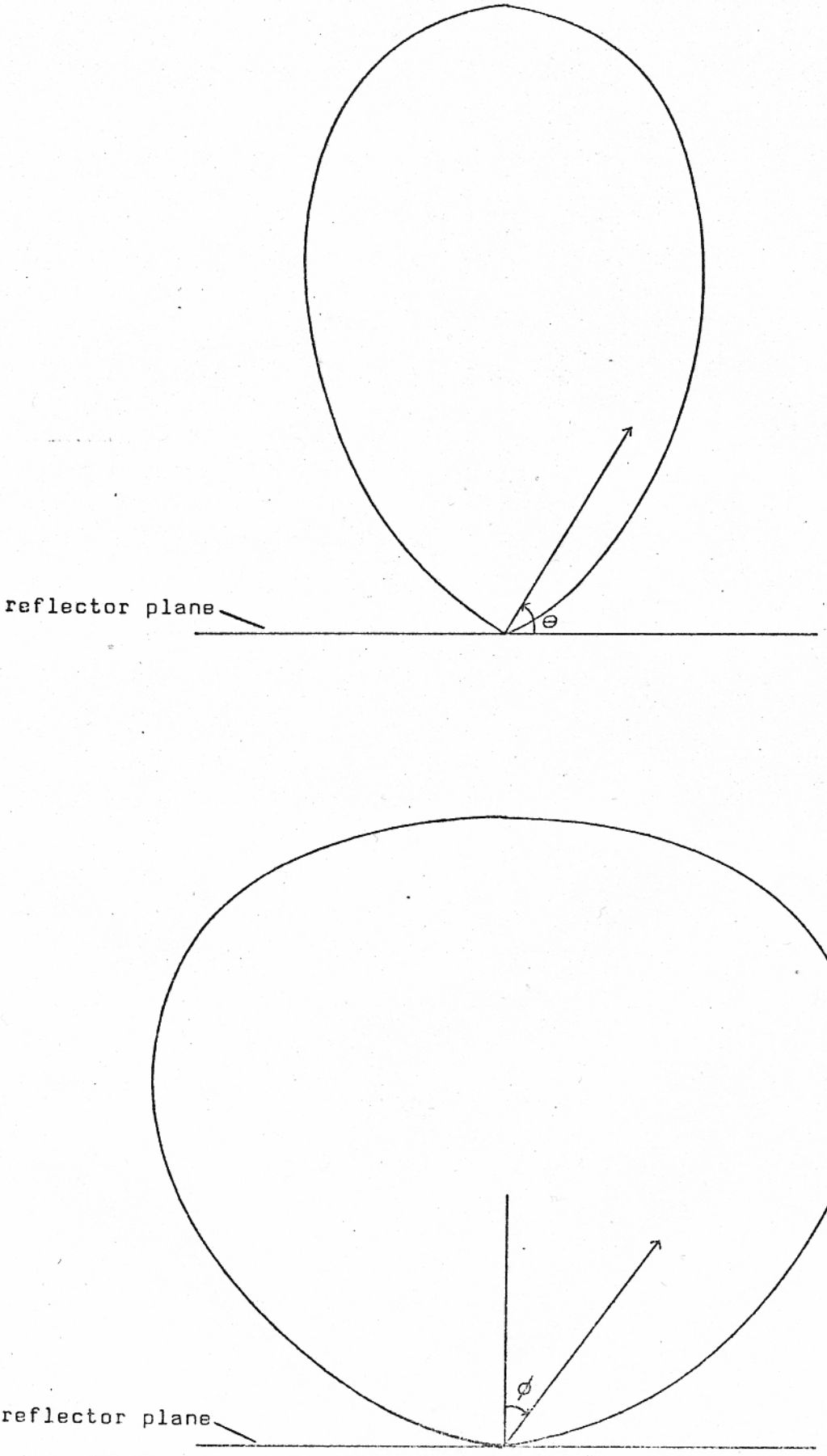



Fig.2-3 Dipole Sensitivity Patterns.
The upper diagram gives the response in the plane of the dipole and the lower diagram gives the response perpendicular to it.

In practice, the horizontal reflectors were of length $\sim 2\lambda$ perpendicular to the dipole and $\sim\lambda$ along the parallel side. However, according to Moullin (1949), the use of a finite reflector of this size results in a radiation pattern which is not greatly different from the ideal pattern shown in Fig 2-3. The 151.5 MHz reflectors were composed of sheet aluminium, while chicken wire netting was used at the other two frequencies. The 80 MHz and 47 MHz dipoles were made of aluminium tubing and had a length to diameter ratio of ~ 150:1 yielding a free space impedance at resonance of ~ 62 ohms (Huntoon, 1964). The presence of the reflector increased the impedance to ~ 70 ohms (Moullin, 1949) thus providing a good match to the 80 MHz and 47 MHz systems, which had 70 ohm input impedances. The dipoles were designed to resonate at the operating frequencies, and so owing to the finite thickness of the tubing the necessary physical length was $0.482\lambda$ (Huntoon, 1964).

The 151.5 MHz dipoles, constructed at Harwell, were designed to have a radiation resistance of 50 ohms, and so each had a length to diameter ratio of 32.5:1 and were placed $0.17\lambda$ above the reflector.

In order to prevent the coaxial signal cable from behaving as an antenna and so distorting the dipole radiation pattern, a "balun" was used to couple the balanced dipole to the unbalanced feeder. The 80 MHz and 47 MHz antennae were fitted with broadband balanced to unbalanced transformers constructed by the author. Each consisted of several turns of wire wound on a small ferrite toroid, and had an impedance ratio of 1:1 (Ruthroff, 1959). Initially, the 151.5 MHz dipoles were fed into Hatfield baluns (Type AT 62N), but these became lossy due to moisture and so were replaced by $\frac{\lambda}{4}$-$\frac{3\lambda}{4}$ cable baluns (Cocking, 1950).

The dipoles were placed parallel to the interferometer baseline so that the interferometer power radiation pattern had the form

$$\frac{\cos^2(\frac{\pi}{2}\cos\theta)\ \sin^2(\frac{\pi}{2}\sin\theta)\ \cos(10\pi\cos\theta)}{\sin^2\theta}$$ in the dipole plane (Fig 2-4)

and

$\sin^2(\frac{\pi}{2}\cos\phi)$ in the plane perpendicular to the dipoles.

Thus, the resulting pattern was a series of "fan" beams, each fan being at right angles to the baseline. 11 regions of sky, each roughly elliptical in shape, were observed above $\frac{1}{2}$-maximum sensitivity (Fig 2-5) and the total sky coverage above this threshold was $\sim 0.085$ of $4\pi$.

At the beginning of the experiment, the interferometers were placed on east-west baselines at each station. However, about 3 months after the commencement of observations, it was decided to position the interferometers so that they were parallel with a hypothetical east-west interferometer on the Greenwich Meridian. This was necessary to ensure that each system had roughly the same sensitivity to the same sky areas so that a pulse originating from a particular direction could be detected with equal likelihood at all sites. Following discussions with Dr. R.W.P. Drever and Dr. J. Hough, the necessary changes in azimuth $\Delta A$ and altitude $\Delta a$ were calculated by the author. For a site of latitude $\phi$ and longitude L, the adjustments are

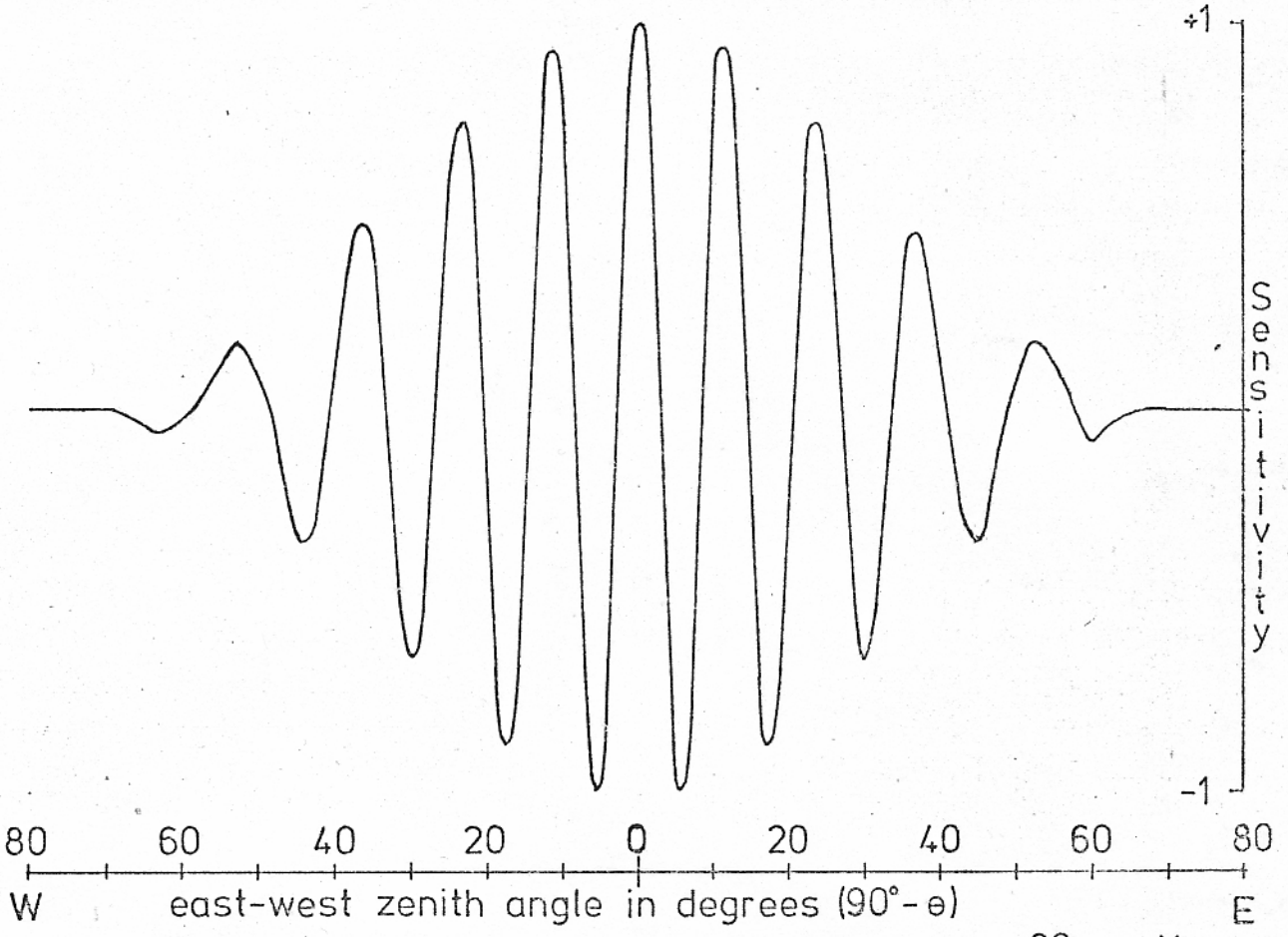
$$\Delta A = \sin^{-1}(\sin\phi \sin L\ (1 - \sin^2 L \cos^2\phi)^{-\frac{1}{2}}) \qquad \text{(Equ 2-19)}$$

and $$\Delta a = \sin^{-1}(\cos\phi \sin L) \qquad \text{(Equ 2-20)}$$

In the British Isles, for sites west of Greenwich the west antenna must be moved south through a distance $d\Delta A$ and raised to a height of $d\Delta a$. For sites east of Greenwich, this operation is performed on the east antenna.

At Glasgow, adjustments of $d\Delta A = 0.317\lambda$ and $d\Delta a = 0.215\lambda$ were carried out. The alignments were then empirically checked by comparing the transit time of the sun at Greenwich with the times at which the

Fig.2-4 Dipole Interferometer Sensitivity Pattern.
The sensitivity is in arbitrary units, and the spacing is 5λ.



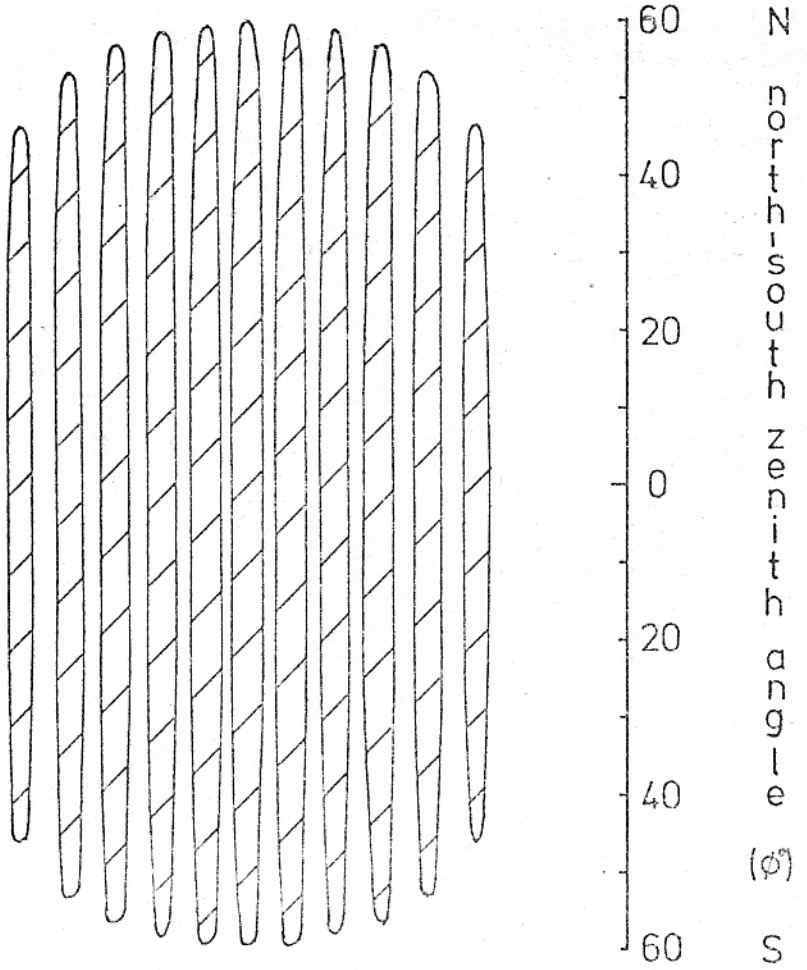




Fig.2-5 Regions of the Sky (shaded areas) which were observed by the Dipole Interferometer with a Sensitivity Exceeding $\frac{1}{2}$-Maximum.

sun passed through the centres of the radiation patterns. Small phase errors were removed by adjusting the lengths of cable in the interferometer arms. With the antennae in their final positions, measurment of the solar interference patterns indicated that the Glasgow systems were parallel to the Greenwich standard with an accuracy of better than 15' arc.

The basic layout used for each Glasgow system is shown in Fig. 2-6. Similar arrangements were employed at the other stations. The phase-switch (Fig 2-7) for 151.5 MHz was designed at Harwell, and it had an insertion loss of 0.15 dB. Similar designs were used for the 80 MHz and 47 MHz systems. The three Glasgow interferometers differed slightly in detail (Table 2-4).

Table 2-4 Details of the Glasgow Dipole Interferometers

| Frequency | Antennae-Preamplifier Matching Device | Preamplifier | Receiver |
|---|---|---|---|
| 151.5 MHz | $\frac{\lambda}{4}$-transformer | FET Cascode | "Phase-Switch E" (Cambridge) |
| 80 MHz | Hybrid ring | Transistor cascode | AN/APR-4 (Ex-USAF) |
| 47 MHz | "T" Matching section | Transistor (Band I TV preamp) | Eddystone (Type 990 R) |

The noise figures of the preamplifiers varied between 2 dB and 5 dB. The best noise figure (2 dB) was obtained in the 151.5 MHz FET pre-amplifier which was of Jodrell Bank design (Fig. 2-8). However, at 151.5 MHz, attenuation in the cables and baluns reduced the sky background contribution to only 20% of the total system noise. At 80 MHz and 47 MHz, most of the noise at the output was Galactic in origin.

At 151.5 MHz, phase-switching and detection was carried out by

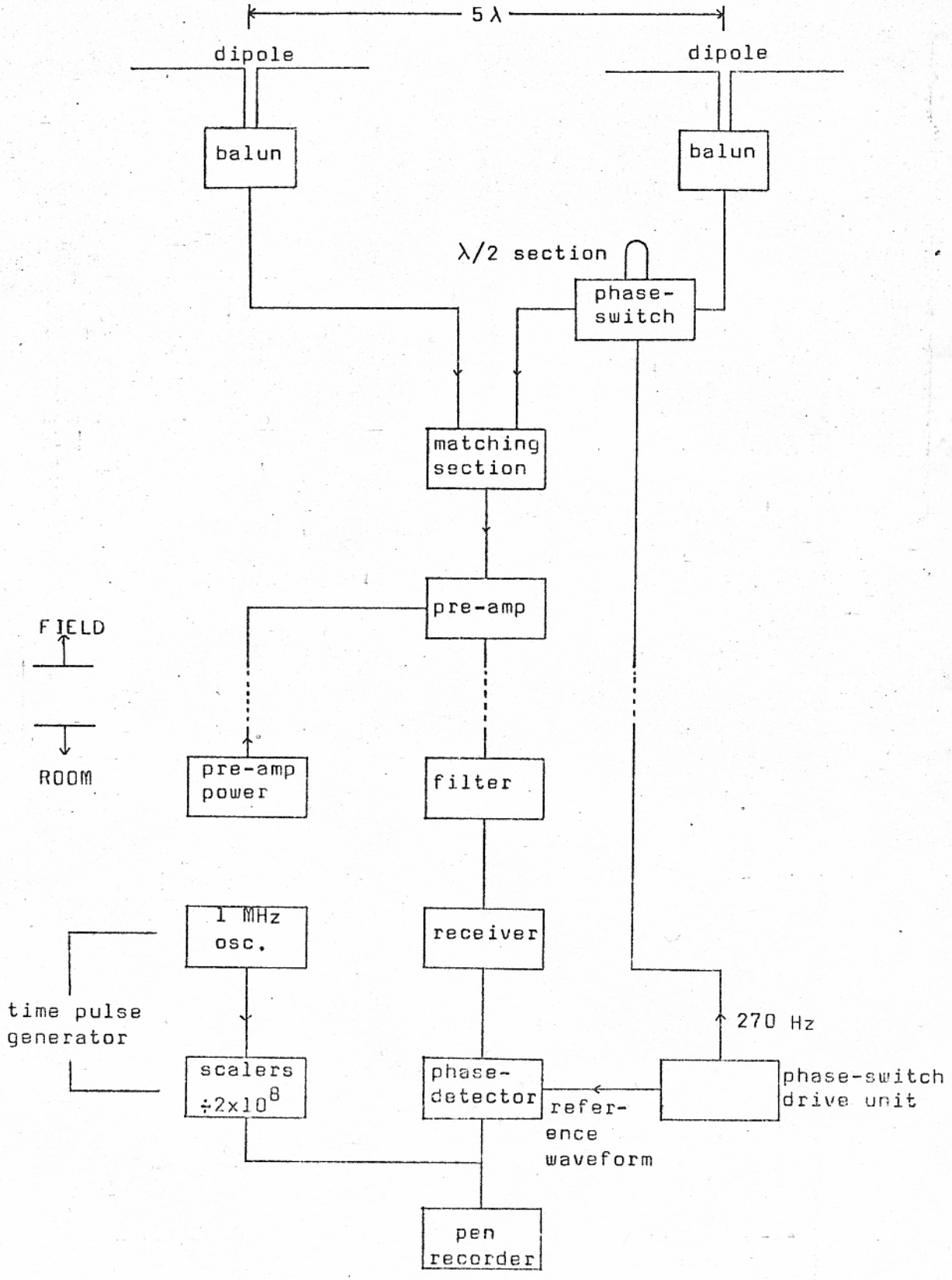



Fig.2-6 Interferometer System Block Diagram.

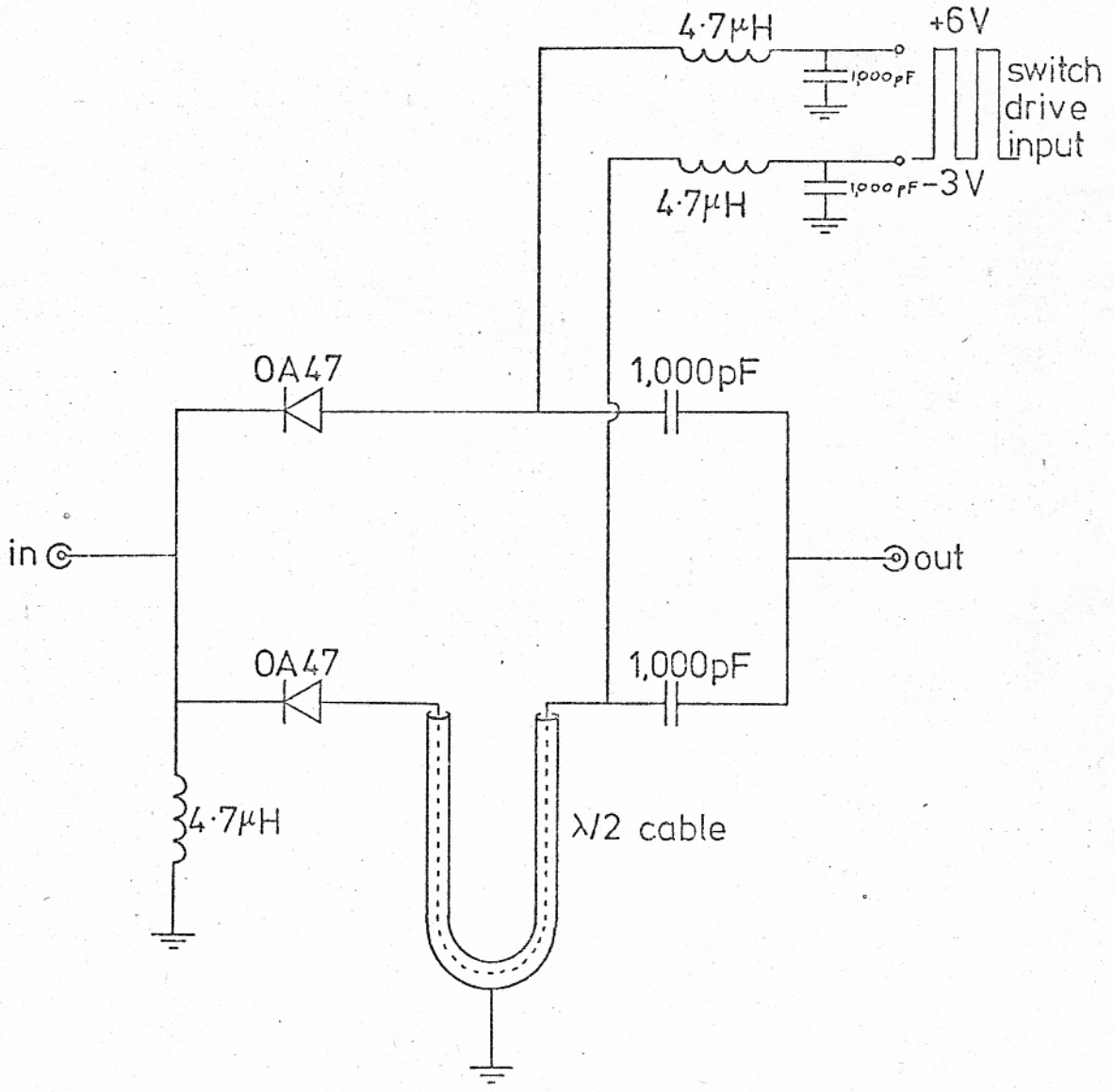



Fig.2-7 The Phase Switch.

L1 3·5turns 14swg tapped 1:4

L2 3 turns 18swg

L3 5 turns 16swg tapped 4:1

L4 5 turns 16swg tapped 1:4

all FET's :- 2N4416

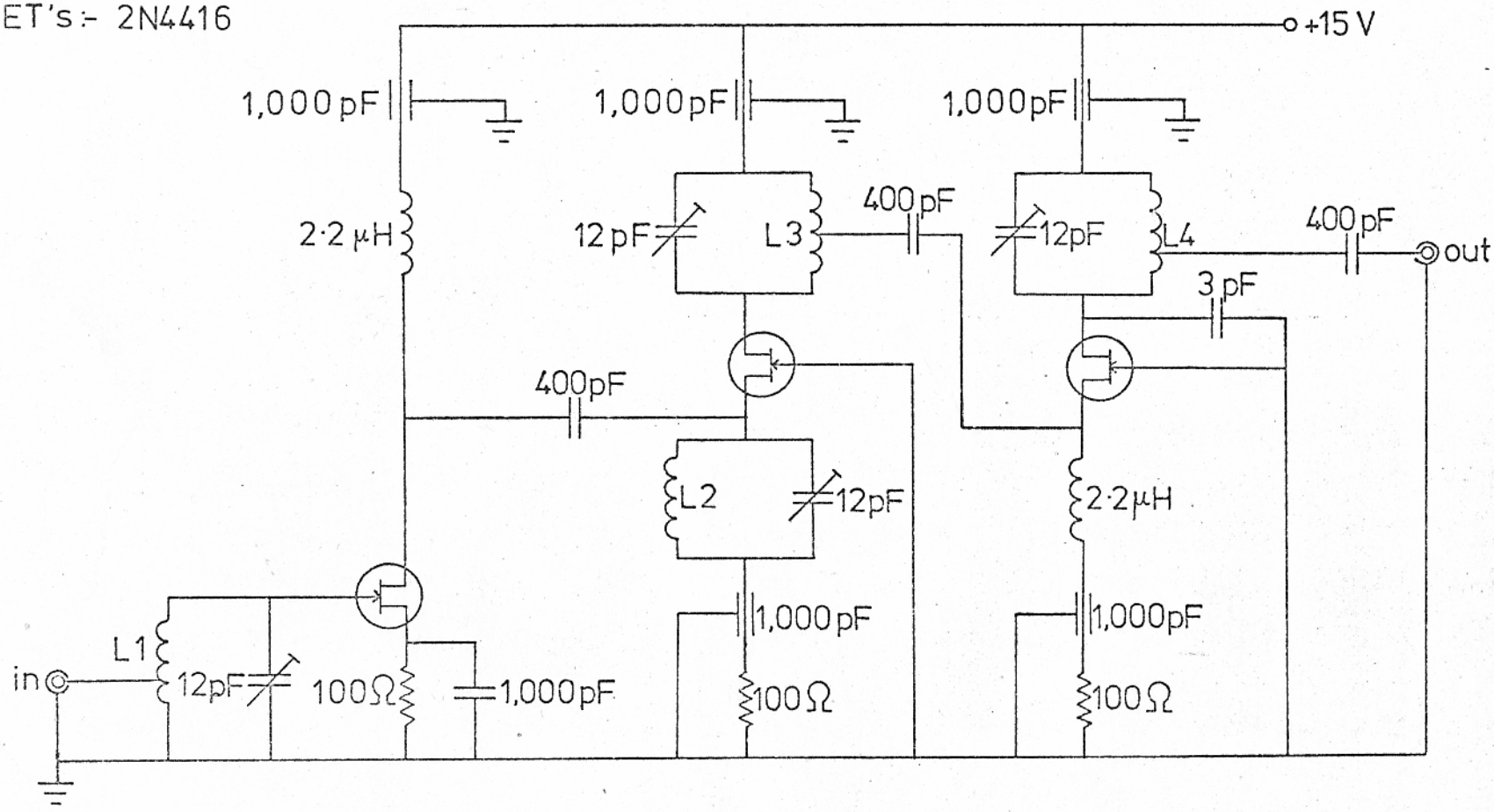



Fig.2-8 151.5 MHz Preamplifier (Jodrell Bank Design)

the Phase-Switch E system, while at 80 MHz and 47 MHz, separate phase-switch drive and phase-detector units designed by Dr. Drever, were used (Figs. 2-9 and 2-10). The outputs of all three systems were displayed on Record pen-recorders, at a chart speed of 12" $hr^{-1}$. Time marks were put on the traces at 200 s intervals. The timing was controlled by a quartz crystal oscillator, and was never wrong by more than $\pm$ 2 s. With the above chart speed, pulse times could be measured with a ruler to an accuracy of $\pm$ 5 s.

The sensitivities of the Glasgow interferometers were determined by measuring the amplitude of the interference pattern produced by Cassiopeia A near transit time. This was a particularly convenient source owing to its large intensity and the nearness to which it approaches the Glasgow zenith ($\sim 2\frac{1}{2}^{\circ}$). In the analysis of the charts, only pulses whose amplitudes were not less than three times the "peak to peak" noise width on the trace were considered. In practice, this corresponded to an amplitude $\gtrsim 12\sigma$, where $\sigma$ is the rms noise fluctuation amplitude. Table 2-5 gives the maximum sensitivities of the three systems.

Table 2-5 Glasgow Dipole Interferometer Maximum Sensitivities

| Frequency | Minimum Flux Required to produce a Deflection = 3 x "peak to peak" noise |
|---|---|
| 151.5 MHz | $1.1 \times 10^{-22}$ W $m^{-2}$ $Hz^{-1}$ |
| 80 MHz | $2.6 \times 10^{-22}$ W $m^{-2}$ $Hz^{-1}$ |
| 47 MHz | $2.7 \times 10^{-22}$ W $m^{-2}$ $Hz^{-1}$ |

Note: The tabulated values refer to unpolarised fluxes.

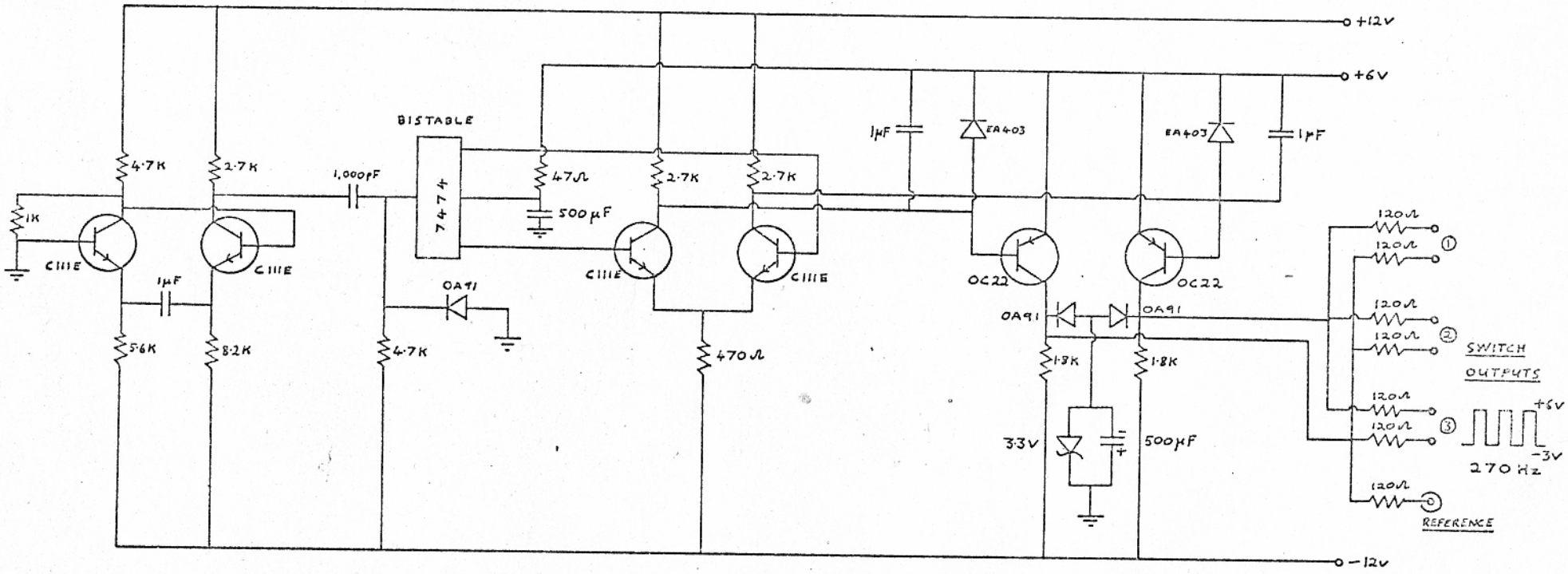



Fig.2-9 Phase-Switch Drive Unit.

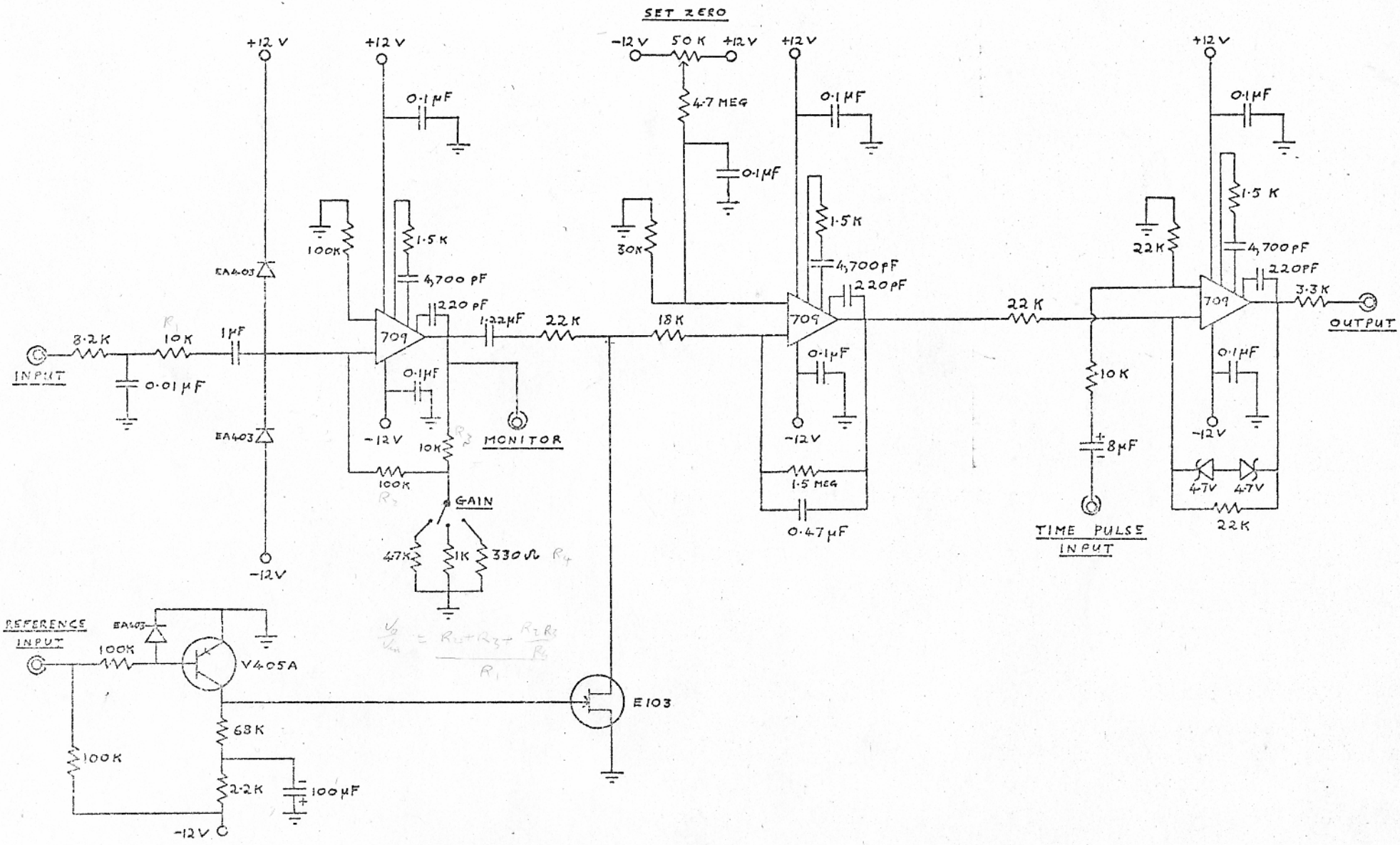



Fig.2-10 Phase Sensitive Detector.

CHAPTER 3

## A Search for VHF Radio Pulses of Unknown Direction of Origin

In the following account, several series of observations of the sky are considered, in which the simple dipole interferometers were used. The actual operating periods at the different sites were never precisely coincident. However, three substantial overlap runs were obtained, and for this reason, the experiment divides naturally into three parts.

All five stations operated at 151.5 MHz which was the principal observing frequency. Systems tuned to longer wavelengths were also set up by some groups. (Details of all the simple dipole interferometers are given in Table 2-3). Single station event rates were typically 1 per hour with the result that the expected 2-fold chance rate within a 1 minute resolution was ~ 1 per 30 hours. Thus if some impulsive phenomenon occurred less frequently than this, two-fold statistics alone would have been unable to reveal such an effect. Reduction of the resolving time to 10 s was just feasible, but this would have still produced about 25 chance events during the experiment. In view of this, the 151.5 MHz analysis presented here, is confined principally to 3-fold data, although in Part 1, some 2-fold data is also included in order to illustrate the large number of spurious 2-fold coincidences obtained. The entire 3-fold overlap time at the principal frequency was 3,620 hours and only about 2 chance 3-fold events would have been expected within a 1 minute resolving time. Thus, examination of the 3-fold statistics alone (ignoring other factors such as pulse shapes and widths) made it possible to detect a real pulse rate of only ~ 1 per month.

A smaller number of stations operated at around 80 MHz and

45 MHz, and so in order to increase their effective overlap time, 2-fold data recorded at these frequencies was analysed in addition to the 3-fold information.

3-1 Part 1 1970, January 6 to 1970, May 31.

Initially, the interferometers at the different sites were not aligned, and dipole spacings varied from $5\lambda$ to $20\lambda$. However, at a collaborative meeting at Jodrell Bank on 1970, March 19-20, it was decided to standardise the spacing at $5\lambda$ and to align the interferometers with a hypothetical system on the Greenwich meridian as already described. By 1970, April 1, this decision had been put into practice at every site.

The receiver outputs were recorded on paper charts at all the stations, with speeds of between 6" $hr^{-1}$ and 24" $hr^{-1}$. Bandwidths varied from 200 kHz to 1.5 MHz, and all integration times lay in the range 0.3 s to 1.0 s. The chart recordings made at each station were scanned by the corresponding group. Data obtained from the three Glasgow systems during Part 1, was measured by the author. Pulse acceptance was carried out on the basis of amplitude as described in Chapter 2, the threshold of $\sim 12\sigma$ making extremely unlikely the occurrence of a chance noise spike exceeding this level. In general, pulses of width $< 10^{3}$ s were considered. The time at which a pulse began was measured and listed, as well as the amplitude, width and sign. Qualitative descriptions of unusual events were also noted. The data sheets were then circulated to each group, and the results presented here are derived from correlations of these lists performed by the author. (List comparisons were also independently carried out by other group members, particularly Dr. W.N. Charman who acted as principal co-ordinator during Part 1 of the

dipole experiment).

In the examination of the event times, searches were made for pulses occurring at 2 or more stations within 1 minute of each other. The effect on the 2-fold coincidence rate of reducing the resolving time to 20 s, 10 s and 6 s respectively was also investigated. The number of chance 2-fold events was determined by searching for coincidences after a 3 minute delay had been inserted into the data from one station. This procedure was then repeated for the other station, and the average number of coincidences obtained was assumed to be representative of the chance rate. The delay method had the advantage of making allowance for variations in time of the single station counting rates. The 3-fold chance rate was obtained by adding 3 minutes to the data from one site and 6 minutes to the data from a second site and then searching for 3-fold events. This was repeated for the six permutations possible within any 3-station group, and the mean number of 3-fold coincidences obtained over the six searches was adopted as the chance rate. In practice, a chance 3-fold event within a 1 minute resolving time was NEVER obtained during the "all-sky" dipole experiments.

In addition to the 151.5 MHz systems, during Part 1, Glasgow and Cambridge operated dipole interferometers tuned to 80 MHz while Dublin carried out observations at 70 MHz. A search for 2-fold and 3-fold coincidences between these systems was carried out. However, it should be pointed out that the investigation of the Cambridge-Glasgow data was probably more significant than the correlation of Cambridge-Dublin or Dublin-Glasgow lists, since a coincidence within 1 minute between systems at 80 MHz and 70MHz would imply a dispersion measure of less than 300 $cm^{-3}$ pc.

The Glasgow data was also examined for "delayed coincidences" between pulses at 151.5 MHz, 80 MHz and 47 MHz. 80 MHz pulses which

occurred up to 1 hour after an event at 151.5 MHz were investigated, this delay corresponding to a maximum dispersion measure of 7,700 $cm^{-3}$ pc. For a dispersed pulse,

$$\frac{\text{Delay between pulses at 80 MHz and 47 MHz}}{\text{Delay between pulses at 151.5 MHz and 80 MHz}} = 2.60$$

Thus, whenever a pulse occurred on the 80 MHz system at some time t seconds after a pulse on the 151.5 MHz charts, the 47 MHz trace was examined for a deflection 2.60 t seconds after the 80 MHz event time.

The results of the above analyses are shown in Table 3-1. At 151.5 MHz, no 5-fold or 4-fold coincidences were obtained. Four 3-fold events were found in 1,510 hours and these are shown in Figs. 3-1 to 3-4. Three of these coincidences occurred in March within 10 days of each other, and exhibited highly dissimilar component pulses. Of these three events, two contained slow, bipolar pulses typical of the effect obtained when a transmitting satellite moved through the interferometer fringes. In addition, during two of the March events, other stations were operating, and yet detected nothing. This almost certainly implies that they were either of relatively local origin, or else were narrow-band so that slight frequency differences between stations resulted in deflections occurring only at sites tuned to the transmission frequency. The simplest explanation of the three 3-fold coincidences detected in 1970, March, is that for a few days a satellite happened to be transmitting at a wavelength not allocated to it, possibly due to a technical fault.

The event obtained on 1970, January 11 (Fig. 3-1) occurred before 151.5 MHz systems were operating at Glasgow and Dublin. It consisted of a series of fast spikes, several coincidences being detected at Cambridge, Harwell and Jodrell Bank. These three sites have a common point less than 60 miles from each of them, making this combination of stations less effective for discrimination against

Table 3-1 Results of Simple Dipole Experiment - Part 1.

(A) 151.5 MHz data - 1 min. resolving time

| | 5-fold | 4-fold | 3-fold | 2-fold |
|---|---|---|---|---|
| No. of coincidences observed | 0 | 0 | 4 | 45 |
| No. of coincidences expected by chance | 0 | 0 | 0 | 39 |
| Overlap time (hours) | 470 | 1,050 | 1,510 | Not estimated |

(B) 151.5 MHz 2-fold data - effect of resolving time variation

| Resolving time | 60s | 20s | 10s | 6s |
|---|---|---|---|---|
| No. of coincidences observed | 45 | 27 | 18 | 16 |
| No. of coincidences expected by chance | 39 | 18 | 9 | 4 |

(C) 80-70 MHz data (Cambridge, Dublin and Glasgow) - 1 min. resolving time

| | 3-fold | 2-fold |
|---|---|---|
| No. of coincidences observed | 0 | 16 |
| No. of coincidences expected by chance | 0 | 15 |
| Overlap time (hours) | 340 | 1,110 |

(D) 80-70 MHz 2-fold data - effect of resolving time variation

| Resolving time | 60s | 20s | 10s | 6s |
|---|---|---|---|---|
| No. of coincidences observed | 16 | 6 | 4 | 3 |
| No. of coincidences expected by chance | 15 | 4 | 2 | 1 |

(E) 80 MHz only (Cambridge and Glasgow) - effect of resolving time variation

| Resolving time | 60s | 20s | 10s | 6s |
|---|---|---|---|---|
| No. of coincidences observed | 8 | 4 | 2 | 1 |
| No. of coincidences expected by chance | 2 | 1 | 1 | 0 |

Overlap time = 950 hours.

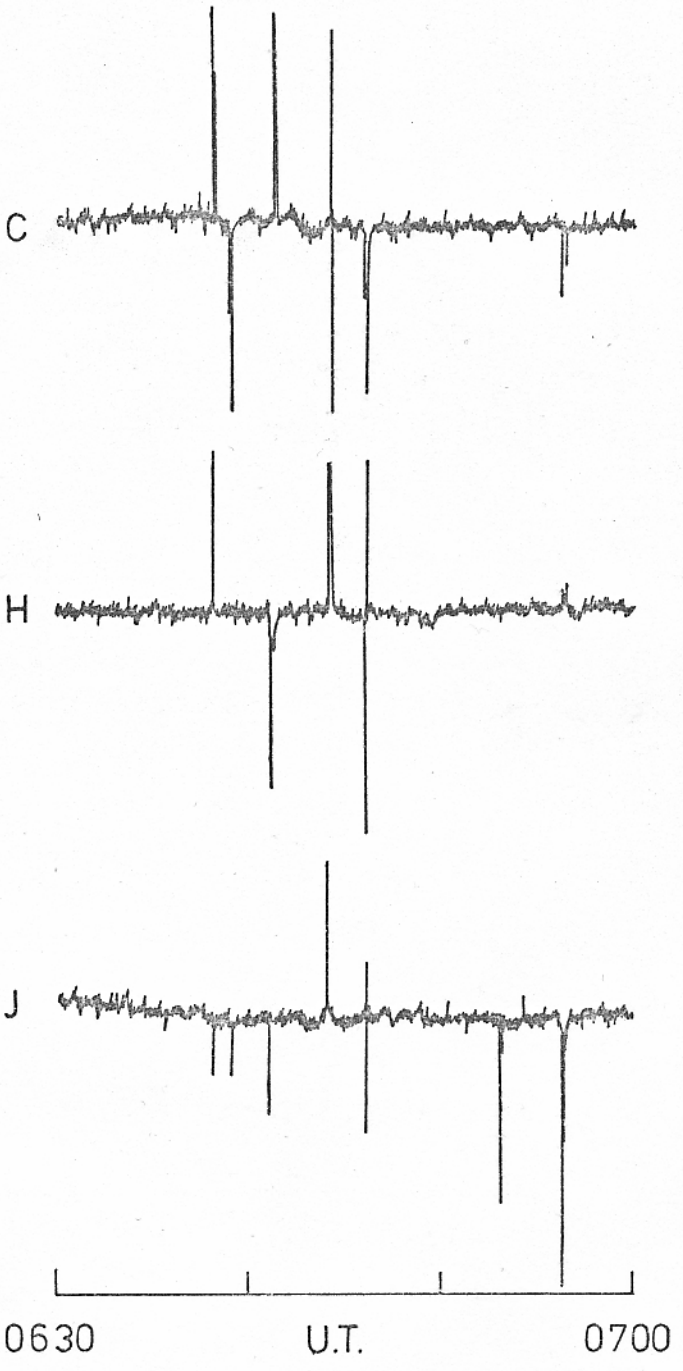



Fig.3-1 3-fold coincidence obtained at 151.5 MHz on 1970 January 11. The stations involved were Cambridge, Harwell and Jodrell Bank.

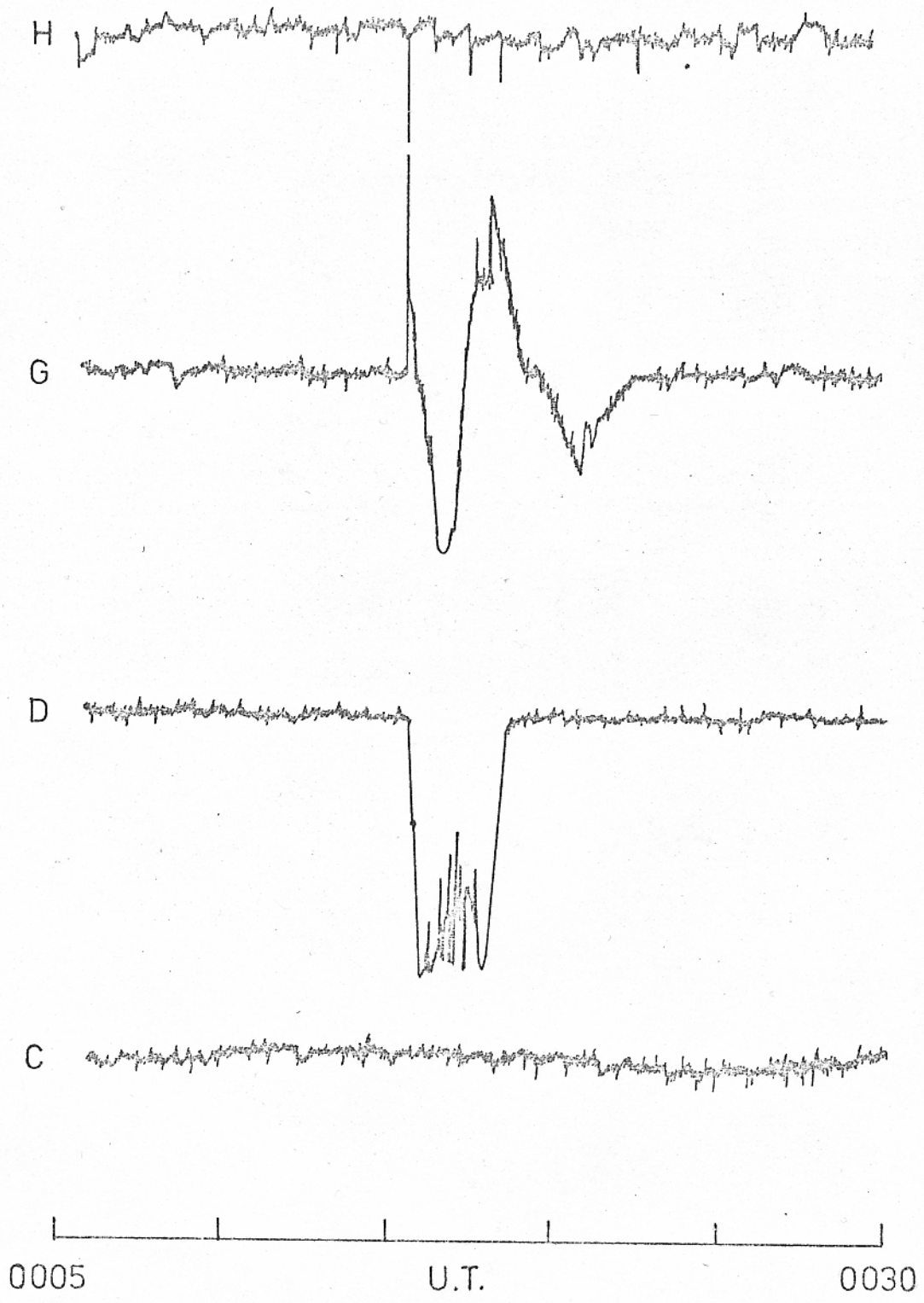



Fig.3-2 3-fold coincidence obtained at 151.5 MHz on 1970 March 16. The stations involved were Dublin, Glasgow and Harwell.

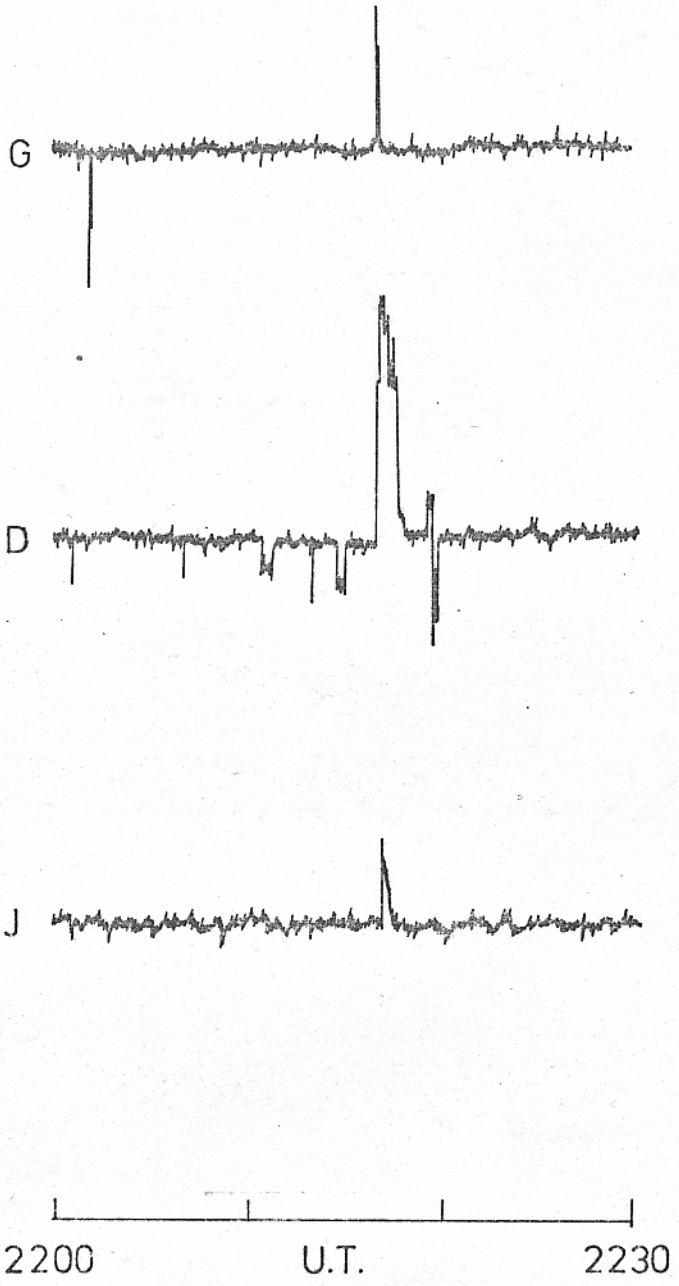



Fig.3-3 3-fold coincidence obtained at 151.5 MHz on 1970 March 23. The stations involved were Dublin, Glasgow and Jodrell Bank.

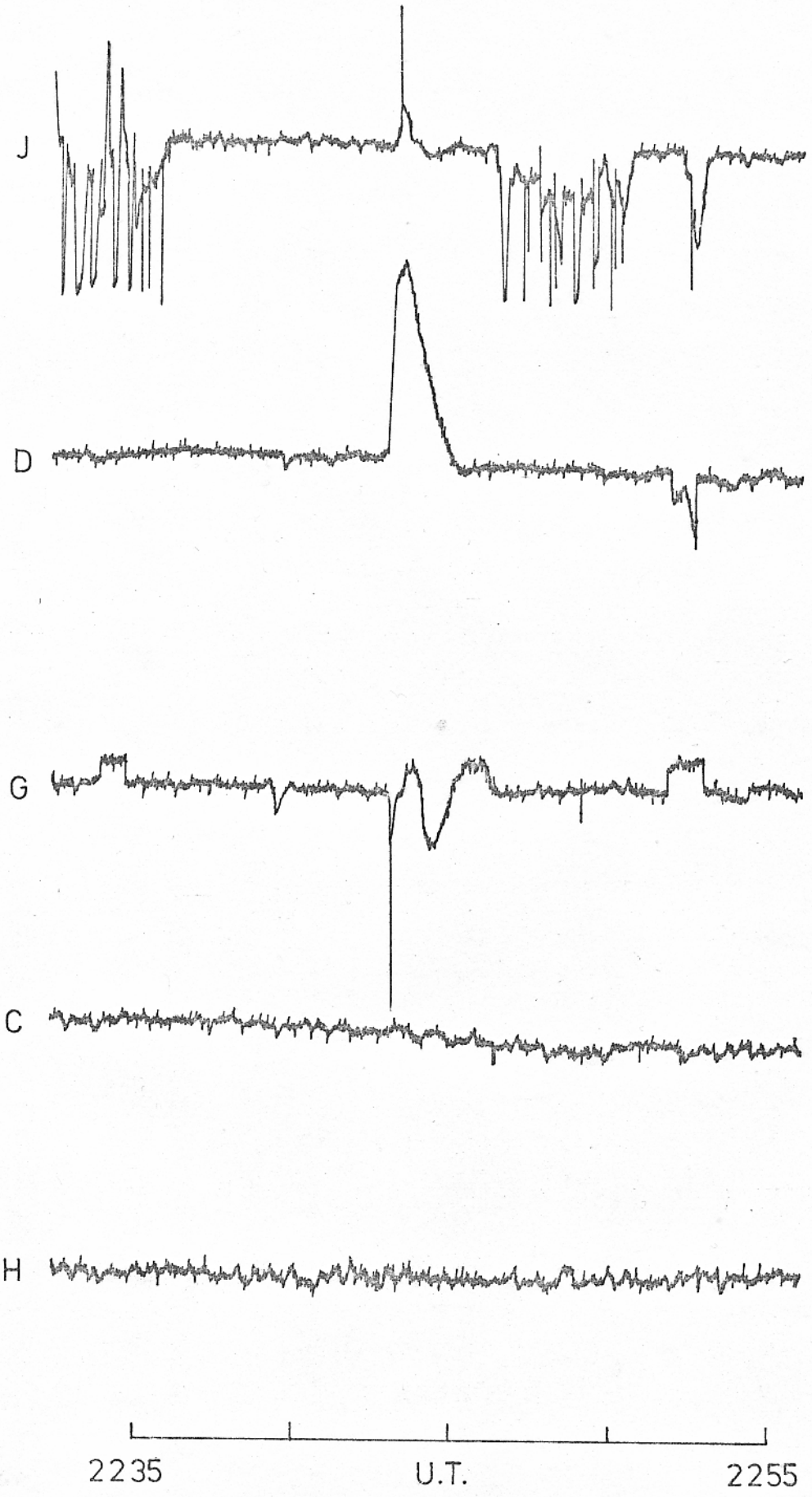



Fig.3-4 3-fold coincidence obtained at 151.5 MHz on 1970 March 26. The stations involved were Dublin, Glasgow and Jodrell Bank.

local interference than those involving the more distant observation points of the collaboration. The possibility that this event was of local origin must therefore be considered. Some of the component pulses were bipolar, and sign changes occurred which were not consistent with a source lying beyond the solar system. The coincidence was probably narrow-band, since 80 MHz and 47 MHz systems operating at Cambridge and Glasgow failed to detect similar pulses either during or several hours after the event at 151.5 MHz.

It is possible that a satellite emitting occasional radio bursts could have caused the multiple coincidence. The shortest time taken at any station for the pulses to change sign twice places a lower limit of $3^{\circ}$ per minute on the angular velocity of the source. However, this does not rule out the above explanation, since satellites can have angular velocities of up to $4^{\circ}.5$ per minute.

Although this event was possibly man-made, it was nevertheless unique within the simple dipole experiment. However, a similar multiple coincidence was obtained during high gain observations of the Crab Nebula, and this will be discussed in Chapter 5.

Analysis of the 2-fold data at 151.5 MHz yielded a prompt excess of 9 or 10 over the random number expected. However, the four 3-fold coincidences are contained within the 2-fold data in the form of twelve 2-fold events. Thus, the entire excess was probably caused by satellite transmissions.

No 3-fold coincidences were obtained between the 80 MHz and 70 MHz systems, and the total number of 2-fold events at these frequencies was not significantly in excess of the chance number. A separate analysis of the Cambridge-Glasgow data showed that for a 1 minute resolving time, the number of prompt 2-fold coincidences exceeded chance by a factor of 4. However, reduction of the resolving time resulted in a prompt rate comparable to the chance rate.

In view of the very small numbers involved (see Table 3-1), it is unlikely that the excess obtained for a 60 second resolution is significant. Individual examination of the eight Cambridge-Glasgow coincidences showed that three were composed of dissimilar pulses. The remaining five contained pulses which were in no way different from other, non-coincident deflections. It can therefore be concluded that the 80 MHz and 70 MHz systems gave no evidence for events of extraterrestrial origin in about 1000 hours of observation.

The Glasgow search for dispersed events was negative. The nearest observed value to the necessary delay ratio was 2.62:1, the corresponding dispersion measure being 3,600 $cm^{-3}$ pc. However, no other stations detected pulses simultaneously and so this event was probably spurious. In conclusion, for dispersion measures in the range 20-7,700 $cm^{-3}$ pc, no dispersed events were detected in 840 hours.

## 3-2 Part 2 1970, December 10 to 1971, March 31

Although the 3-fold coincidences obtained in Part 1 were probably of man-made origin, the possibility that they were produced by geophysical effects could not be completely ruled out. In order to further investigate any 3-fold events detected, it was decided at a meeting in Dublin, on 1970, November 4-6, to attempt the acquisition of crude directional information about these coincidences. It was agreed to change the 151.5 MHz interferometer spacing to $\frac{\lambda}{2}$ and to insert a $\frac{\lambda}{4}$ section into one arm. The resulting interference pattern was such that pulses arriving from a source east of the meridian plane would be opposite in sign to pulses incident from the west (Fig. 3-5). Only Dublin, Glasgow, Harwell and Jodrell Bank took part in this experiment, since the Cambridge effort was being applied to the design and construction of the high resolution direction finding

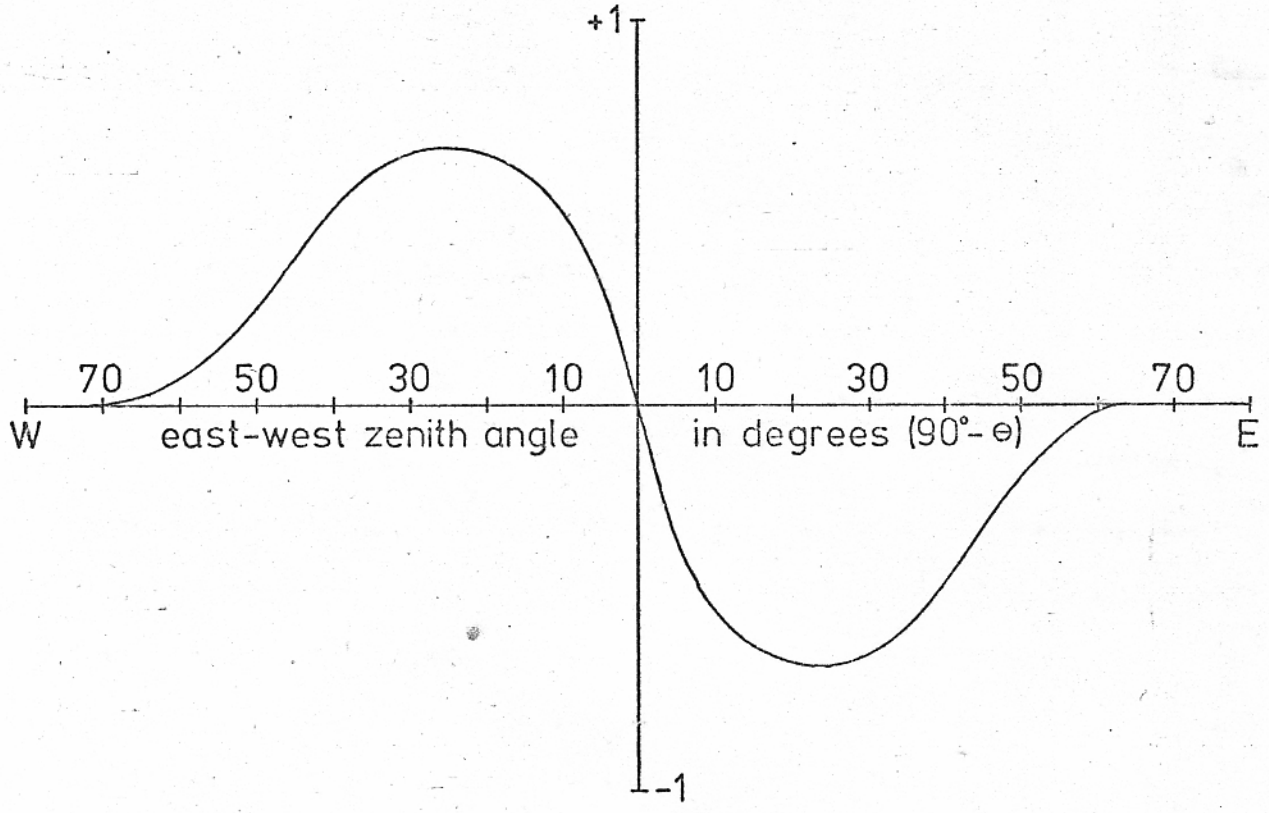



Fig.3-5 Dipole Interferometer Sensitivity Pattern.
The sensitivity units are the same as those used in Fig.2-4.
The spacing is $\frac{1}{2}\lambda$ with a $\frac{1}{4}\lambda$ section added to one arm.

system used during Part 3.

At Glasgow, immediately following the modification to the 151.5 MHz system, it was found that pulses due to solar bursts switched sign about 30 minutes before the sun crossed the meridian. However, with slight alterations to the electrical length of one interferometer arm, the central null-plane was brought to within $3^{o}$ of the meridian-plane. As expected, the close spacing of the dipoles resulted in saturation of the system for several hours a day, due to the flux from the unresolved Galactic plane. Even with a decreased gain, this problem considerably reduced the effective overlap running time between the four groups.

During Part 2, a deliberate attempt was also made to repeat the experiment of Smith (1950). Systems were set up at Glasgow (47 MHz), Dublin (45 MHz) and Jodrell Bank (43 MHz). The slightly differing frequencies at the three stations were necessary in order to avoid local narrow-band interference. The bandwidths at Dublin and Glasgow were respectively 4 MHz and 200 kHz so that their high frequency limits were almost identical. Thus, the leading edge of a genuinely dispersed pulse would have been detected simultaneously within a 1 minute resolving time at these two stations, unless the dispersion measure to the corresponding source exceeded 7,600 $cm^{-3}$ pc. For this reason, no examination was made for "delayed" coincidences between Dublin and Glasgow. However, as the Jodrell Bank bandwidth was only 800 kHz, a dispersed pulse could quite possibly have been detected at this site some time after its detection at the other two stations so that a search for "delayed" events in this case was necessary. For a dispersion measure > 180 $cm^{-3}$ pc, a pulse would not have been detected simultaneously at Jodrell Bank and the other two stations within a 1 minute resolving time. Such an event would have been at least 15 s wide in the Jodrell Bank band, and so all pulses exceeding

this width were individually examined. In each case the assumption was made that the measured pulse duration at Jodrell Bank was caused by dispersion, and from this, the expected delay between events at Jodrell Bank and the other two sites was calculated. The Glasgow and Dublin records were then searched for pulses occurring $\pm$30 s of the times obtained in this way, from the Jodrell Bank data.

The results of Part 2 are shown in Table 3-2. At 151.5 MHz, no 4-fold coincidences were obtained, although the 4-fold overlap time was only 90 hours, mainly due to a lack of Harwell data. In 790 hours, two 3-fold events were detected (Figs. 3-6 and 3-7). During the coincidence of 1970, December 11 (Fig. 3-6), Jodrell Bank was still operating with a 5$\lambda$ spacing, and its component exhibited the slow oscillatory pattern characteristic of satellite interference. The event of 1971, February 4 (Fig. 3-7) had very different shapes and widths between the stations involved. It is almost certain that this coincidence was also caused by a satellite transmission, but the usual slow, bipolar trace was absent owing to the $\frac{\lambda}{2}$ spacing at all the sites. It can therefore be concluded that no 3-fold coincidences caused by pulses of astrophysical origin, were detected at 151.5 MHz during Part 2.

At 43-47 MHz, no 3-fold coincidences were obtained within a 1 minute resolving time in 390 hours (Table 3-2). Examination of the 2-fold data showed that as the time resolution was reduced from 1 minute to 6 seconds, a small excess of prompt 2-fold events over random, occurred for Dublin-Glasgow and Glasgow-Jodrell Bank coincidences. (No such excess was apparent for the Dublin-Jodrell Bank combination) In view of this excess, an individual examination was made of the 23 prompt 2-fold coincidences which occurred within a 10 s resolving time. 4 of these events were Glasgow-Jodrell Bank coincidences, and could be eliminated on the basis of dissimilar

Table 3-2 Results of Simple Dipole Experiment - Part 2.

(A) 151.5 MHz data - 1 min. resolving time

| | 4-fold | 3-fold |
|---|---|---|
| No. of coincidences observed | 0 | 2 |
| No. of coincidences expected by chance | 0 | 0 |
| Overlap time (hours) | 90 | 790 |

(B) 47-43 MHz data (Dublin, Glasgow and Jodrell Bank) - 1 min. resolving time

| | 3-fold | 2-fold |
|---|---|---|
| No. of coincidences observed | 0 | 105 |
| No. of coincidences expected by chance | 0 | 100 |
| Overlap time (hours) | 390 | 1,768 |

(C) 47-43 MHz 2-fold data - effect of resolving time variation

(i) Dublin - Glasgow

| Resolving time | 60s | 20s | 10s | 6s |
|---|---|---|---|---|
| No. of coincidences observed | 85 | 33 | 19 | 16 |
| No. of coincidences expected by chance | 85 | 27 | 13 | 7 |

(ii) Glasgow- Jodrell Bank

| Resolving time | 60s | 20s | 10s | 6s |
|---|---|---|---|---|
| No. of coincidences observed | 15 | 8 | 4 | 3 |
| No. of coincidences expected by chance | 10 | 3 | 1 | 0 |

(iii) Dublin - Jodrell Bank

| Resolving time | 60s | 20s | 10s | 6s |
|---|---|---|---|---|
| No. of coincidences observed | 5 | 1 | 0 | 0 |
| No. of coincidences expected by chance | 5 | 3 | 2 | 2 |

Table 3-2, continued

(D) 47-43 MHz Delayed Events

| Date | Time (UT) at 47 MHz. h. | m. | s. | Time (UT) at 43 MHz. h. | m. | s. | Duration at Jodrell Bank | Corresponding Dispersion Measure ($cm^{-3}$ pc) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 29/12/70 | 00 | 36 | 05 | 00 | 37 | 30 | 30s | 255 | No pulse at G. |
| 15/1/71 | 00 | 00 | 30 | 00 | 05 | 00 | 1 min. | 810 | Sawtooth shape at J.B. No pulse at G. |
| 16/2/71 | 07 | 28 | 29 | 07 | 33 | 48 | 1 min. | 960 | Bipolar at J.B. No pulse at G. |
| 15/3/71 | 05 | 52 | 05 | 05 | 56 | 00 | 1 min. | 705 | ~15 s wide at G. D. not operating |

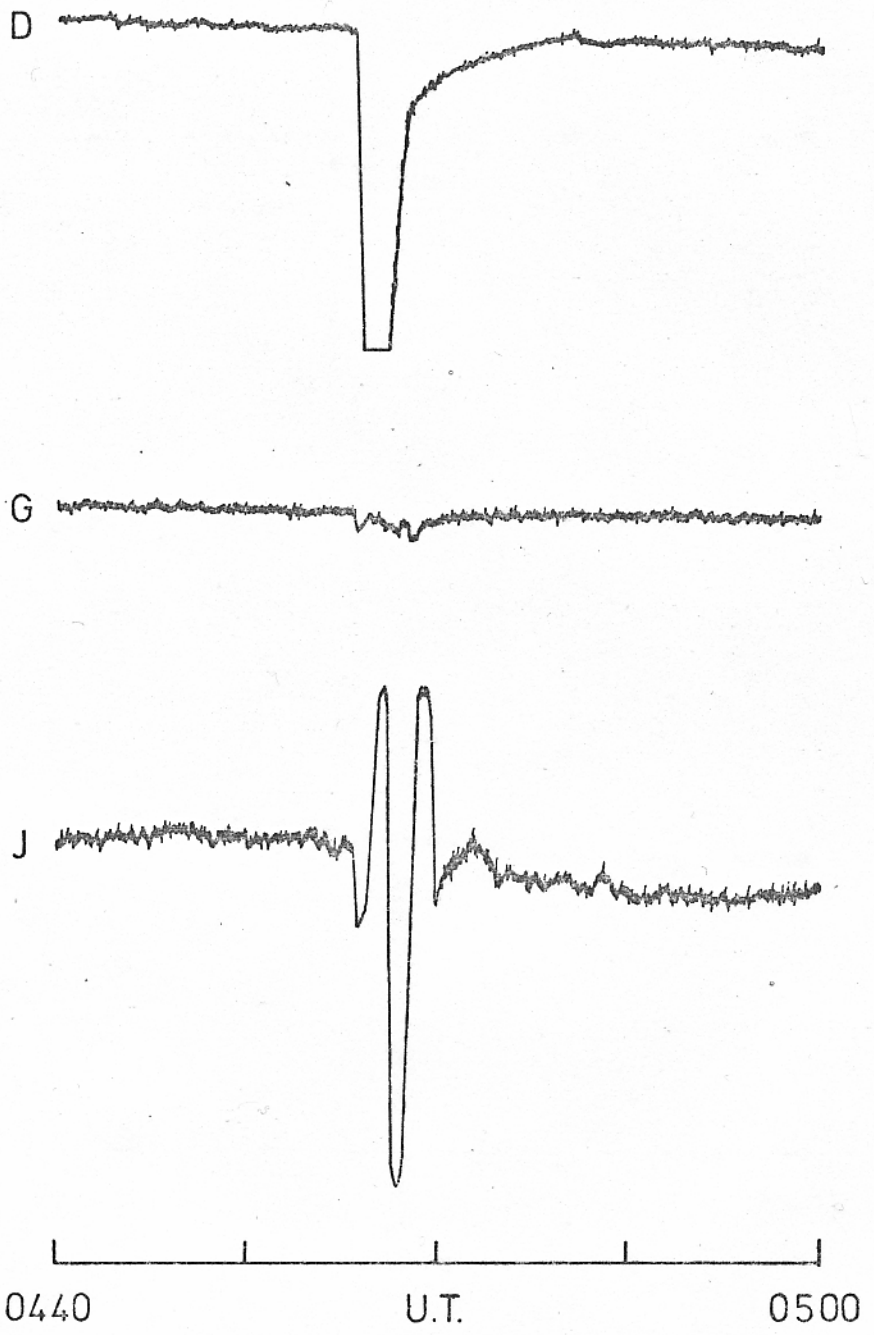



Fig.3-6 3-fold coincidence obtained at 151.5 MHz on 1970 December 11. The stations involved were Dublin, Glasgow and Jodrell Bank.

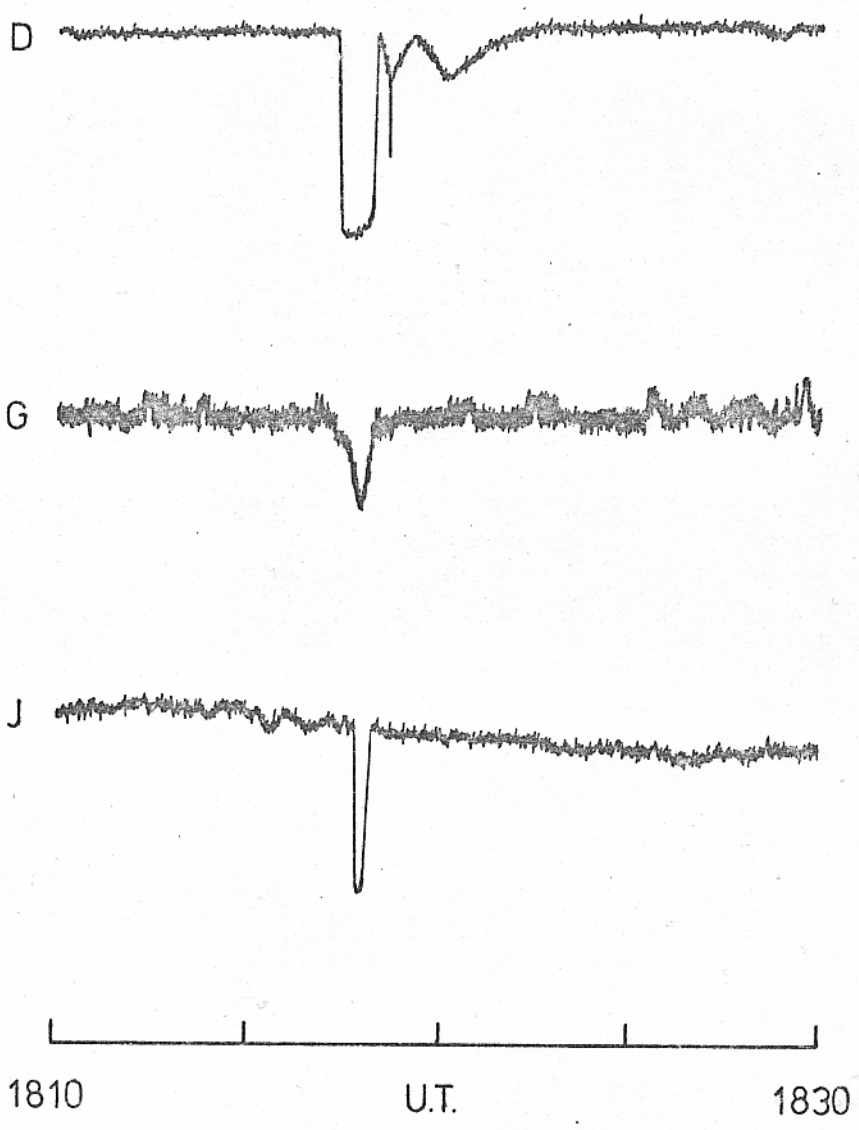



Fig.3-7 3-fold coincidence obtained at 151.5 MHz on 1971 February 4. The stations involved were Dublin, Glasgow and Jodrell Bank.

component pulse shapes, and the non-detection of pulses at Dublin. A further 2 events (Dublin-Glasgow coincidences) could also be discarded as no deflections occurred at Jodrell Bank near the relevant times. The remaining 17 prompt 2-folds occurred between Dublin and Glasgow at a time when Jodrell Bank was out of action. No pulse shape data for the Dublin events were available to the author, and so closer scrutiny of these 17 events was not possible. However, it can be stated that none of the Glasgow components of these events was particularly different from other non-coincident pulses detected. All the Glasgow events were less than 20 s in width and of $S/N \gtrsim 5$.

The search for delayed coincidences between Jodrell Bank and the other 2 stations yielded 4 events (Table 3-2). 3 of these occurred between Dublin and Jodrell Bank, during which times no corresponding pulses were detected at Glasgow. The remaining event was a Glasgow-Jodrell Bank coincidence and was recorded when the Dublin system was not operating. The delays in the 4 events had corresponding dispersion measures in the range 250-1,000 $cm^{-3}$ pc. 2 chance events would have been expected between Jodrell Bank and either of the other two stations. It seems unlikely that any of these delayed coincidences were caused by genuinely dispersed pulses.

In conclusion, if the excess of real events over the chance number was due to genuine coincidences, then the rate of these events was less than 1 in 200 hours. Smith (1950) detected large bursts of width 10-20 s at a rate of about 1 per 200 hours. None of the 23 prompt coincidences obtained between Dublin and Glasgow in 1,680 hours, was of this type.

## 3-3 Part 3 1971, September 10 to 1972, January 1

In order to acquire improved directional information about pulses detected, Dr. R.F. Haynes set up a multiple total-power

interferometer at Cambridge. The system consisted of five 151.5 MHz interferometers of various spacings, two lying north-south and three east-west. All the outputs were AC-coupled, the differentiation time being 10 minutes, while an integration time constant of 0.3 s was used. The signal from each interferometer was recorded both directly and also after the insertion of a $\frac{\lambda}{2}$ section into one arm, thus yielding ten channels in all. The system response pattern was calibrated using the sun. By measuring the relative amplitude of a pulse in each channel, its direction of origin could be determined to an accuracy of

$\pm 6^{\circ}$ in the north-south plane

and

$\pm 3^{\circ}$ in the east-west plane.

By the time the Cambridge system came into operation, it was becoming increasingly clear that few pulses, if any, of genuinely astrophysical origin had been detected. Indeed it could be argued that ultimately, the chief importance of the direction-finding apparatus lay in its ability to detect LOCAL events. Nevertheless, it was decided to carry out simultaneous observations at Dublin, Glasgow, Harwell and Jodrell Bank in order to cover the possibility that occasional pulses originated beyond the solar system. At the four stations other than Cambridge, the simple 151.5 MHz dipole interferometers were operated. It was decided to revert to a $5\lambda$ spacing so that satellite interference was more readily recognisable from the oscillatory pattern which only occurred if the spacing was at least several wavelengths. In addition, with the longer baseline, the saturation problems encountered in Part 2 were eliminated.

In the analysis, the Cambridge data was regarded as primary, and Dr. Haynes circulated lists of event times ( and directions of origin) which were compared with pulse times at the other stations.

For this reason, complete systematic analysis of data taken at Dublin, Harwell and Jodrell Bank was not carried out as in Parts 1 and 2. This restricted the 3-fold overlap data to the period 1971, September 10 to 1972, January 1, although observations continued until 1972, April 30.

The results of Part 3 are shown in Table 3-3. No 4-fold coincidences were detected in 320 hours, and in 1,320 hours, only two 3-fold events occurred, both on 1971, December 1. Individual examination of the component pulses revealed that these two coincidences had almost certainly been caused by satellite transmissions. Thus, Part 3 of the "all-sky" dipole experiment gave no evidence for pulses produced by astrophysical events. The results of the Cambridge investigation of pulses of local origin will be discussed in Chapter 7.

A summary of the results obtained at 151.5 MHz during Parts 1-3 is given in Table 3-4. Perhaps the most significant conclusion which can be drawn from the huge amount of data accumulated is as follows:-

At 151.5 MHz, 8.5% of the celestial sphere was observed for 3,620 hours at a threshold sensitivity which was never poorer than

$$2 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}.$$

No radio pulses of astrophysical origin were detected.

## 3-4 Constraints on Radio Emission during Nova and Supernova Outbursts

The failure to detect any VHF pulses from beyond the solar system can now be used to place upper limits on the emission of pulsed radio energy during the eruptions of novae and supernovae.

Table 3-3 Results of Simple Dipole Experiment - Part 3

151.5 MHz data - 1 min. resolving time

| | 4-fold | 3-fold |
|---|---|---|
| No. of coincidences observed | 0 | 2 |
| No. of coincidences expected by chance | 0 | 0 |
| Overlap time (hours) | 320 | 1,320 |

Table 3-4 Summary of 151.5 MHz Dipole Data

| | 5-fold | 4-fold | 3-fold |
|---|---|---|---|
| No. of coincidences observed | 0 | 0 | 8 |
| No. of coincidences expected by chance | 0 | 0 | 0 |
| Overlap time (hours) | 470 | 1,460 | 3,620 |

Note:- It is unlikely that any of the eight 3-fold coincidences were of astrophysical orgin.

### 3-4-1 Upper Limits for Impulsive Radio Energy from Novae

During the VHF dipole experiment, 3 galactic novae are known to have erupted, and their details are given in Table 3-5. A fourth nova, Nova Scuti 1970 is also described. Although it did not erupt during the dipole observations, it may have some relevance to an event discovered during the Galactic Centre studies (see Chapters 4 and 7).

In order to estimate the upper limits to the radio energy emitted during their eruptions, the maximum distances of the novae were calculated from their maximum apparent magnitudes using the result of Payne-Gaposchkin (1958) that the absolute magnitude of a nova never exceeds -8.4. It was found that the 3 novae could not have been more remote than 3.7 kpc, 9.5 kpc and 37 kpc respectively (Table 3-5).

The probability (the "observation probability") was calculated for each nova, that it exploded when it was above the horizon at night and so might have been detected (Table 3-5). It was found that if all three novae had produced radio pulses of sufficient energy, then there was a 58% probability that at least one pulse would have been observed. However, in establishing the energy constraints, it was necessary to make some allowance for the variation with direction of the interferometer sensitivities. The $\frac{1}{2}$-maximum sensitivity zones had a threshold of

$$\sim 2 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$$

at 151.5 MHz, but the probability that any of the novae erupted within one of these zones at night was only $\sim 15\%$. However, if the threshold was relaxed by another factor of ten, to

$$2 \times 10^{-21} \text{ W m}^{-2} \text{ Hz}^{-1}$$

it was reasonable to assume that any flux exceeding this value and originating above the horizon would have been detected.

Table 3-5 Galactic Novae Discovered during the VHF Observations

| Name | Position | | Observation Probability | Maximum Observed Magnitude | Maximum Distance | Date First Observed |
|---|---|---|---|---|---|---|
| | RA | Dec | | | | |
| Nova Serpentis 1970 | $18^h\ 28^m$ | $+2^\circ 35'$ | 21% | +4.4 | 3.7 kpc | Feb. 13 (absent on Feb. 12) |
| Nova Aquilae 1970 | $19^h\ 22^m$ | $+4^\circ 08'$ | 23% | +6.5 | 9.5 kpc | April 12 (absent on Apr. 6) |
| Nova Cygni 1970 | $20^h\ 51^m$ | $+35^\circ 48'$ | 31% | +9.4 | 37 kpc | May 24 (absent on May 7) |
| Nova Scuti 1970 | $18^h\ 43^m$ | $-8^\circ 36'$ | 13.5% | +6.9 | 11.5 kpc | July 28, $16^h.15$ UT (absent on Jul. 28, $0^h$ UT) |

Note:- "Observation Probability" is the probability that the eruption occurred at night while the nova was above the horizon.

The energy upper limits depended on the distances of the novae, and the observation probabilities on their positions. From the various permutations of energy constraints and probabilities available, the author selected the three most informative combinations (Table 3-6). In each case allowance for dispersion was made assuming a uniform interstellar electron density of 0.05 $cm^{-3}$. Isotropic emission was also assumed.

Table 3-6 Novae Observation Probabilities and Energy Constraints

| Possible Origin | Observation Probability | Upper Limit for Impulsive Energy Emitted |
|---|---|---|
| Nova Serpentis 1970 | 21% | $1.2 \times 10^{20}$ J $Hz^{-1}$ |
| Nova Serpentis 1970 or Nova Aquilae 1970 or both | 41% | $2.2 \times 10^{21}$ J $Hz^{-1}$ |
| Nova Serpentis 1970 or Nova Aquilae 1970 or Nova Cygni 1970 or any combination of the 3 | 58% | $1.4 \times 10^{23}$ J $Hz^{-1}$ |

Explanatory Note:- Column 2 gives the probability that one of the combinations in column 1 erupted while above the horizon at night.

In conclusion, it seems unlikely that an energy burst exceeding

$$\sim 10^{23} \text{ J Hz}^{-1}$$

at 151.5 MHz, is emitted during a nova flare-up, unless the generation timescale is considerably greater than $\sim 1$ s.

### 3-4-2 Upper Limits for Impulsive Radio Energy from Supernovae

The limits on radio energy produced by exploding supernovae were examined using both statistical considerations, and direct optical observations.

a) Energy Constraint based on Supernova Statistics

It has been shown that at 151.5 MHz, 8.5% of the celestial sphere was observed for 3,620 hours with a sensitivity better than

$$2 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$$

without any pulses of convincingly astrophysical origin being detected. According to Tammann (1970), the nearest supernova to explode within the $\frac{1}{2}$-maximum sensitivity zones during the above time would have been at a distance of $\sim$ 10 Mpc. Assuming isotropic emission, and a dispersion measure of $10^3$ cm$^{-3}$ pc, the upper limit for the radio energy emitted is therefore

$$5.4 \times 10^{26} \text{ J Hz}^{-1}$$

b) Energy Constraint based on Optical Observations

According to the IAU Circulars, and Kowal et al (1971), a total of 30 extragalactic supernovae were reported as having occurred between 1970, January and 1972, January. 16 of these supernovae probably erupted during the dipole experiment, and in addition were above the horizon in the British Isles for some time each day. Of the 16, 13 were of sufficiently high declination to pass daily through the $\frac{1}{2}$-maximum sensitivity zones, and descriptions of these 13 are given in Table 3-7. Also given in Table 3-7 are details of Supernova 1970g, which occurred during the Galactic Centre experiment, and which will be referred to in Chapter 7. For each supernova, the probability that it erupted at night while within a $\frac{1}{2}$-maximum sensitivity zone, was estimated.

Distances were found in two ways. One of the 13 listed supernovae occurred in a galaxy whose redshift was known, so that its distance could be obtained using the Hubble law ($H_o$ = 50 km s$^{-1}$ Mpc$^{-1}$) The maximum distances of the remaining 12 supernovae, were found using their maximum apparent magnitudes, on the assumption that the maximum absolute magnitude of a supernova never exceeds -20.5

Table 3-7 Supernovae of Dec>-4° Discovered during (or shortly after) the VHF Observations.

| Date Discovered | Position | | Observation Probability % | Maximum Observed Magnitude | Maximum Distance (Mpc) |
|---|---|---|---|---|---|
| | RA | Dec | | | |
| 15/2/70 | $12^h\ 30^m$ | $+14°19'$ | 6 | +11.0 | 12.6 |
| before 17/3/70 | $10^h\ 50^m$ | $+14°21'$ | 6 | +15.5 | 100 |
| 7/4/70 | $10^h\ 35^m$ | $+11°01'$ | 5 | +17.0 | 200 |
| 31/5/70 | $12^h\ 01^m$ | $+52°12'$ | 12 | +18.5 | 396 |
| 31/5/70 | $11^h\ 48^m$ | $+53°20'$ | 12.5 | +19.0 | 500 |
| (30/7/70) | ($14^h\ 01^m$) | ($+54°29'$) | -- | (+11.0) | (8.0*) |
| 31/1/71 | $11^h\ 16^m$ | $+28°33'$ | 10 | +16.5 | 159 |
| 22/2/71 | $11^h\ 12^m$ | $+26°12'$ | 9 | +19.5 | 630 |
| 15/4/71 | $12^h\ 10^m$ | $+13°31'$ | 6 | +13.0 | 31.4 |
| 15/11/71 | $01^h\ 19^m$ | $+0°41'$ | 2.5 | +15.5 | 100 |
| 23/11/71 | $02^h\ 44^m$ | $-0°27'$ | 2 | +16.0 | 126 |
| 16/12/71 | $10^h\ 46^m$ | $+26°51'$ | 9 | +15.0 | 79 |
| 10/1/72 | $10^h\ 13^m$ | $+73°38'$ | 25 | +15.5 | 57.5* |
| 20/1/72 | $15^h\ 13^m$ | $+27°50'$ | 7 | +17.0 | 200 |

Notes

(i) * denotes that the distance was determined from the redshift of the parent galaxy.

(ii) "Observation Probability" is the probability that the eruption occurred at night when the supernova was within a $\frac{1}{2}$-maximum sensitivity ellipse.

(iii) The supernova of 30/7/70 (Supernova 1970g) did not erupt during the simple dipole observations. It may, however, be of some relevance to an event detected during the VHF Galactic Centre experiment (see Chapters 4 and 7).

(Shklovsky, 1968). In order to check the accuracy of the magnitude method for distance estimation, the same procedure was applied to 11 supernovae which occurred in galaxies of known redshift, between 1969 and 1972. It was found that for 8 out of 11, the distances obtained from magnitude considerations did not exceed the redshift distances by more than a factor of two. Maximum distances and observation probabilities are given in Table 3-7.

In placing an upper limit to the radio energy emitted during a supernova eruption, the observation probabilities had to be considered, as in the section on novae. (For the supernovae, however, the observation probability refers to the time spent within a $\frac{1}{2}$-maximum sensitivity zone at night, rather than the total time spent above the horizon at night). The nearest maximum distance obtained was 12.6 Mpc, but the corresponding observation probability was only 6%. To obtain a more informative result, the 6 supernovae which exploded within 100 Mpc of the earth were examined. The probability that at least one of this group erupted at night within a $\frac{1}{2}$-maximum sensitivity zone, was $\sim 45\%$. The corresponding upper limit on the radio energy emitted is

$$5 \times 10^{28} \text{ J Hz}^{-1},$$

again assuming isotropic emission and a dispersion measure of $10^3$ cm$^{-3}$ pc.

Predictions by Colgate et al (1971, 1972)

In the original paper by Colgate and Noerdlinger (1971), the energy expected at 151.5 MHz from a supernova eruption was

$$4.9 \times 10^{30} \text{ J Hz}^{-1}$$

which is clearly in disagreement with the observations. However, the implications of the dipole results for the revised theory of Colgate, McKee and Blevins (1972), depend critically on its interpretation. The author's predictions from this theory yielded a

value of

$$5.5 \times 10^{27} \text{ J Hz}^{-1}$$

for the radio energy emitted at 151.5 MHz. However, the value obtained by Colgate et al (1972), was considerably less than this, being

$$3.3 \times 10^{26} \text{ J Hz}^{-1}$$

Thus, the observations are consistent with the energy predicted by Colgate et al (1972), but are in some conflict with the author's energy derivation from the revised theory.

It should be pointed out that the occurrence of regions of high electron density either in the vicinity of the supernovae or in the intervening space, could have greatly reduced the VHF flux. This possibility is discussed in Chapter 6.

# CHAPTER 4

## A Search for Radio Pulses from the Direction of the Galactic Centre at 151.5 MHz.

Some time after the commencement of Part 1 of the dipole experiment, Weber (1970b) reported that his coincidence rate was showing a sidereal anisotropy consistent with his events originating in the direction of the Galactic Centre. It was therefore decided to design an experiment to search for possibly associated radio pulses from this direction. The main problem involved in carrying out such observations from the British Isles concerns the low maximum altitude attained by the Galactic Centre. At Glasgow, this object reaches $5^{\circ}$ above the horizon and is "visible" for only about 4 hours a day. For this reason, the simple dipoles were relatively insensitive to signals from the Galactic Centre, having a sensitivity in that direction of $< 1\%$ of their zenith response. In order to perform high gain, low altitude observations, more directional antennae for operation at 151.5 MHz, were constructed.

### 4-1 The Galactic Centre Antennae

The Glasgow antennae were built by Mr. A. McKellar and the author, and were copied directly from a Cambridge design provided by Dr. P. F. Scott. Each antenna consisted of a stack of 8 horizontal half-wave, folded dipoles, $\frac{\lambda}{2}$ apart, placed quarter of a wavelength in front of a plane, $\frac{1}{2}$" mesh, chicken wire reflector (Figs. 4-1 to 4-3). The dipoles were fed by two wires passing down the centre of the array, with a $180^{\circ}$ twist between each section so that signals arriving at the output from all the dipoles, would be in phase for a flux arriving at right angles to the line of the array. (Broadside

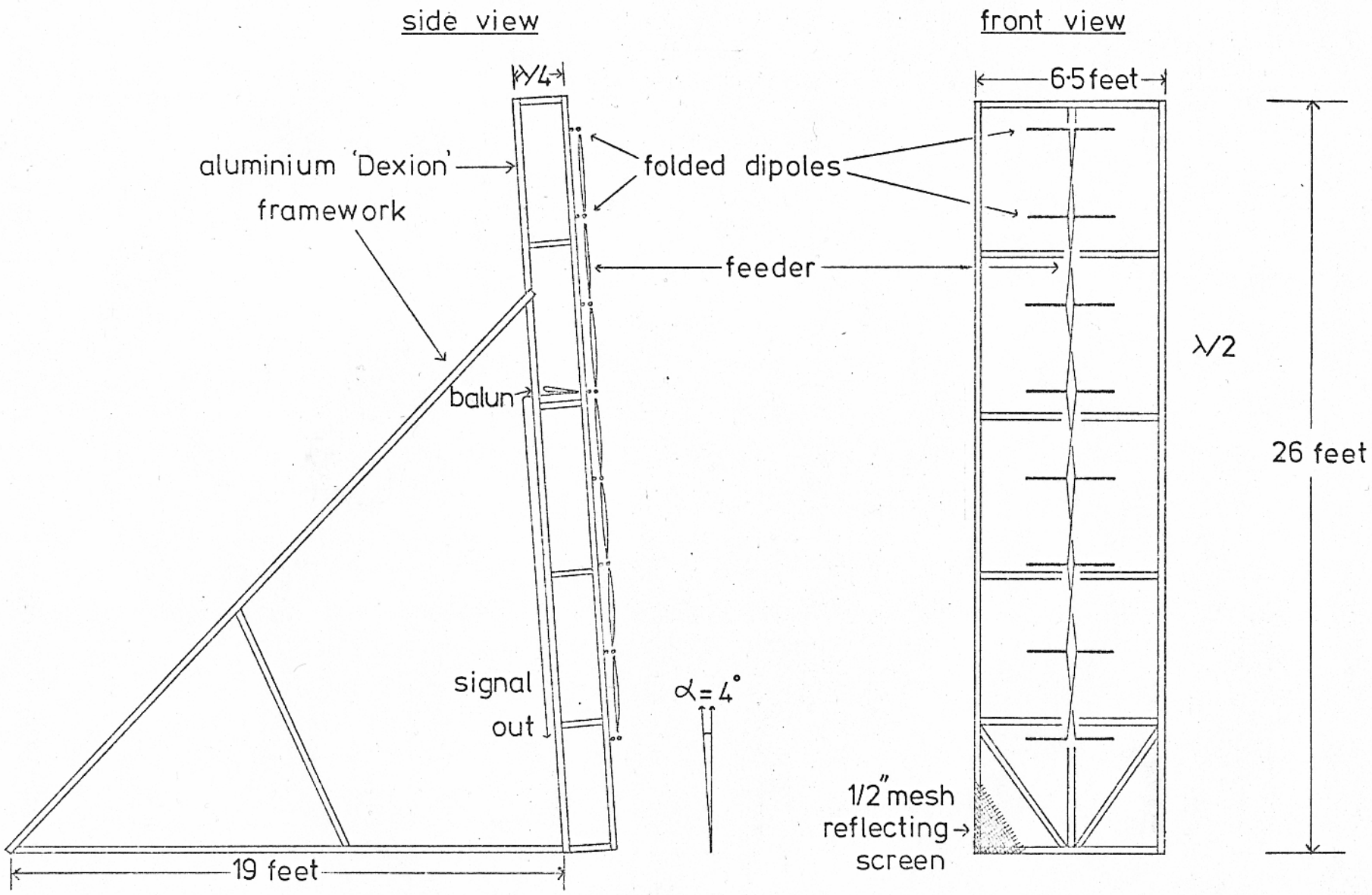



Fig.4-1 Broadside array used to observe the Galactic Centre at 151.5 MHz. The same antennae were subsequently used to monitor the Crab Nebula.

Fig.4-2 151.5 MHz broadside arrays, forming a directional interferometer of 5$\lambda$ spacing. The antennae are shown in the position used for Galactic Centre observations.

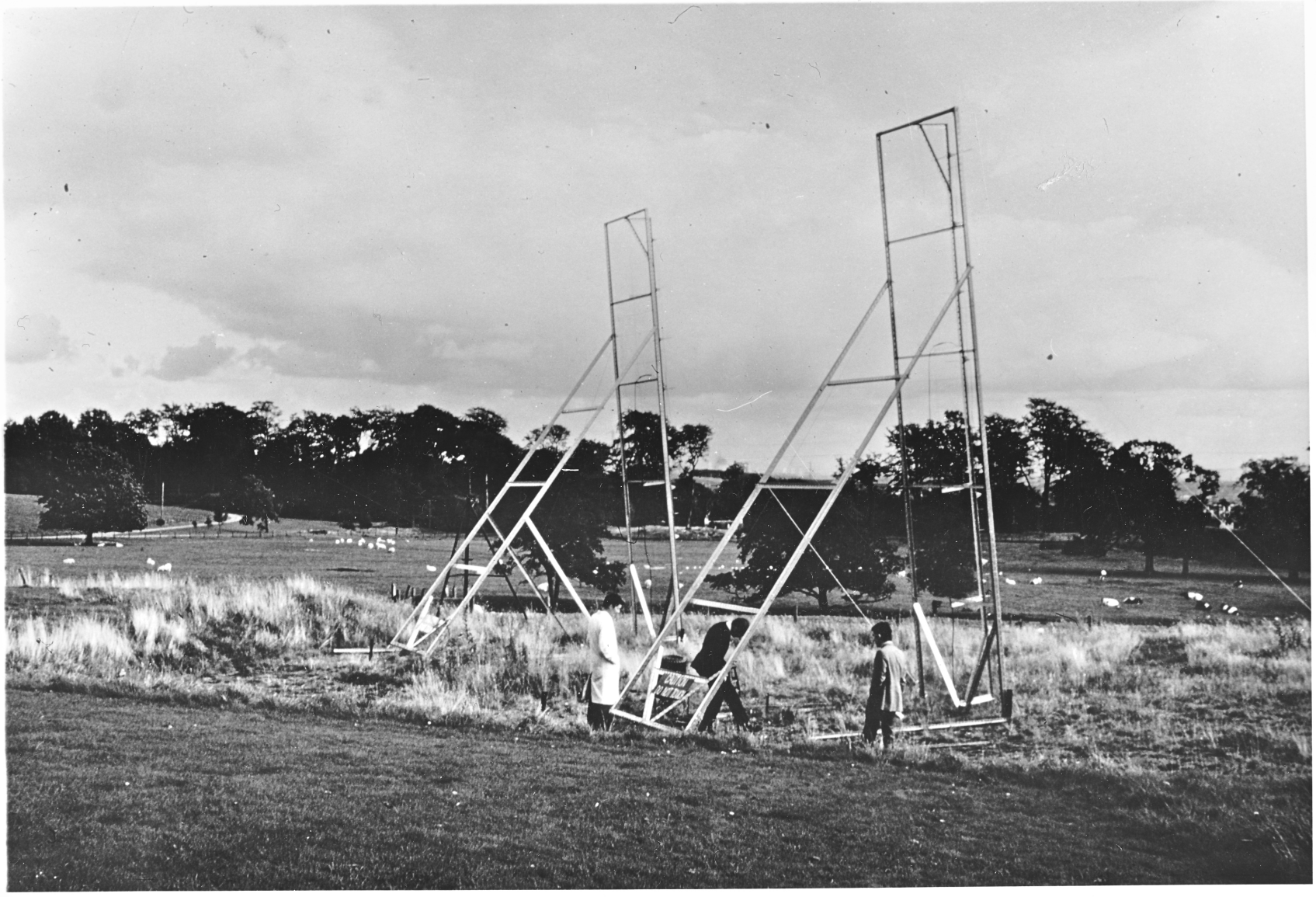
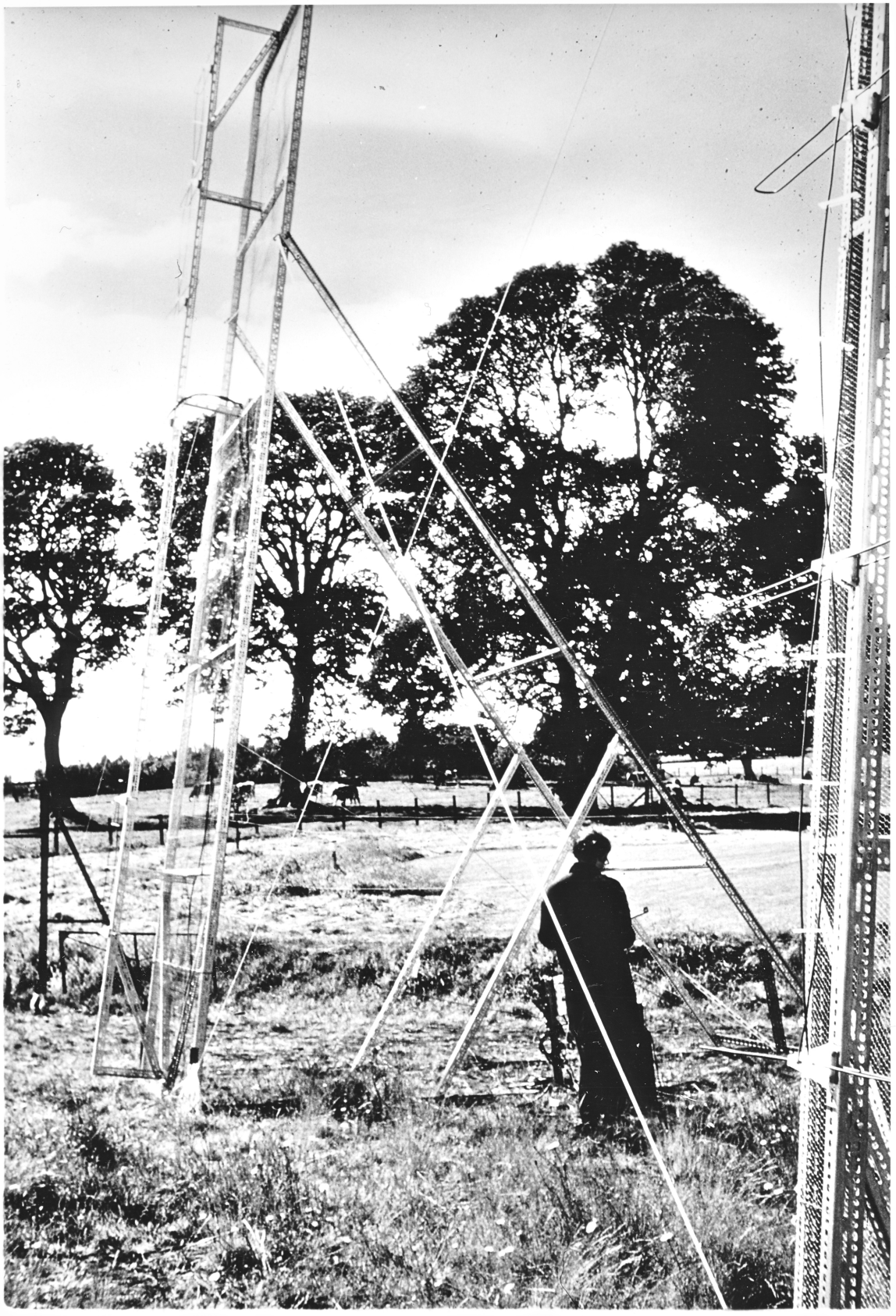


Fig.4-3 Detail of the 151.5 MHz broadside arrays. The double dipoles and feeder can be seen.



Mode). The $\frac{\lambda}{2}$ spacing of the dipoles eliminated the problem of matching the feeder to each antenna. Placing a reflector screen $\frac{\lambda}{4}$ behind the array had the effect of providing a greater operating frequency range. It also increased the gain and impedance of the antenna as well as making the reflector distance less critical in its effect on the impedance (Wheeler, 1948). The output was tapped off at the fifth dipole above the ground in order to minimise cumulative errors in the dipole spacing. The balanced output was transformed to an unbalanced signal using a $\frac{\lambda}{4} - \frac{3\lambda}{4}$ cable balun.

Two arrays were constructed, and operated as a phase-switched interferometer (on an east-west baseline) of $5\lambda$ spacing, for reasons similar to those given for the simple dipole systems. Although ultimately, the parameters describing the performance of these antennae were determined empirically, the design itself was based on the following theoretical considerations.

For the antennae described above, the power radiation pattern in the plane perpendicular to the dipoles and reflector has the form

$$\frac{\sin^2(4\pi\sin\phi)\ \sin^2(\frac{\pi}{2}\cos\phi)}{\sin^2(\frac{\pi}{2}\sin\phi)} \qquad \text{(Moullin, 1949)}$$

where $\phi$ is the angle which the incident ray makes with the normal to the plane of the arrays (Fig. 4-4). The response in the plane parallel to the dipoles and perpendicular to the reflector is simply that of a single dipole $\frac{\lambda}{4}$ above a plane reflector (see Chapter 2) viz.

$$\frac{\cos^2(\frac{\pi}{2}\cos\theta)\sin^2(\frac{\pi}{2}\sin\theta)}{\sin^2\theta}$$

where $\theta$ is the angle which the incident ray makes with the plane of the dipoles (Fig. 2-3 ). Thus, the radiation pattern of this antenna

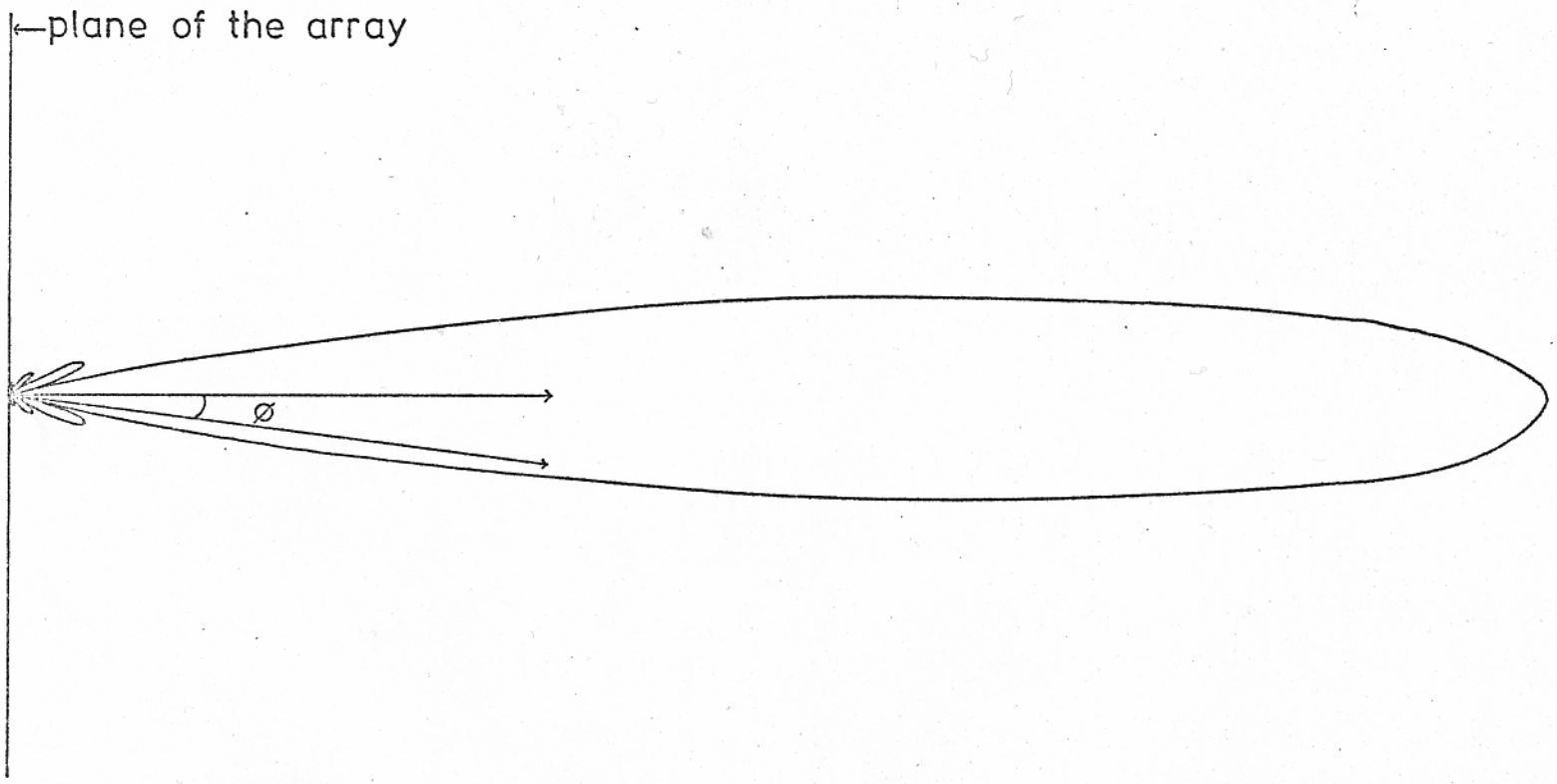



Fig.4-4 Sensitivity pattern of an 8-dipole broadside array placed $\frac{\lambda}{4}$ in front of a plane reflecting screen.

consists of a narrow beam in one plane and a broad beam in the other. The $\frac{1}{2}$-maximum sensitivity widths of these beams are $12^{\circ}.8$ and $72^{\circ}.7$ respectively. Six side-lobes in the narrow-beam plane are also produced although they are reduced in size by the presence of the reflector. The largest side-lobes have maxima at $\pm 21^{\circ}.2$ to the main beam, but have only 5% of the sensitivity of the principal maximum.

Without the reflector, the array would have a gain of 10.2 dB relative to a single dipole (Moullin, 1949). It is assumed that the gain of the array with the reflector is also about 10 dB relative to a single dipole + reflector.

If 8 unfolded, half-wave dipoles are connected in parallel as above, then in the absence of a reflecting screen, the net impedance is only $\sim 7$ ohms, including the effects of mutual impedance (Kraus, 1950). By using folded dipoles, the impedance is increased to 27 ohms, providing a better match to 50 ohm signal cable. The presence of a reflector probably increases the impedance further still, although the precise change is difficult to estimate. Wheeler (1948) has shown that for an individual half-wave dipole, $\frac{\lambda}{4}$ above a plane reflector, in an infinite array of dipole density 1 per $\frac{\lambda^2}{4}$ $m^2$, the radiation resistance is about twice that of a dipole in free space. While this result is clearly not directly applicable to a finite, 8-element array, some increase of impedance due to the reflector is still likely.

With the arrays in their observing position, ground reflections probably altered their impedance. In order to check that the antennae were reasonably matched to the 50 ohm signal cable, direct measurements of their output impedances were made using an admittance bridge (Wayne-Kerr type B901), shortly after Galactic Centre observations began. Resistances of 43.1 ohms and 40.7 ohms and reactances of 2 pF and 4 pF were found for the west and east arrays

respectively, which was satisfactory.

The gain and beamwidth were measured at Cambridge and Glasgow by performing drift-scans of Cassiopeia A and Cygnus A. At Glasgow the gain was somewhat disappointing, being only about 7.5 dB instead of the expected 10 dB relative to the single dipoles. The $\frac{1}{2}$-maximum sensitivity width of the narrow beam was $16^{o}\pm2^{o}$ rather than the $12^{o}.8$ predicted above. Both of these results may have been caused by losses in the feeders, which would reduce the signal contributions of the outer dipoles. Some loss probably also occurred in the coaxial signal cables, which were longer than in the case of the single dipoles. By timing the transit of the above radio sources, it could be deduced that the maximum of the narrow beam lay within $1^{o}$ of the normal to the plane of the array. The antennae constructed at Cambridge were found to have a $\frac{1}{2}$-maximum sensitivity beamwidth of $14^{o}$ and a gain similar to that obtained at Glasgow.

## 4-2 The Effect of Ground Reflections

When the arrays were placed on end in order to observe the Galactic Centre, the effect of ground reflections on the main beam became important. It was therefore necessary to make allowance for these reflections, in choosing the optimum angle to the vertical at which the arrays were to be set. According to Williams (1966) radio signals (E-Vector horizontal) reflected from level ground undergo a phase change of $180^{o}$ regardless of angle of incidence or soil quality. In addition, if the incident signal is at an angle of less than $10^{o}$ to the horizontal, then more than 70% of the signal is reflected. Thus, for a radio pulse from the Galactic Centre, the ground behaves approximately as an infinite conducting sheet placed in front of the arrays. In order to investigate the effect of the ground on the

radiation pattern, the author performed a numerical analysis for an 8-element array (without a backing reflector) placed at a range of angles to the vertical with the lowest dipole $\frac{\lambda}{2}$ above a perfect reflector. Using the method of images, the power radiation pattern was found to have the form

$$\left[\frac{\sin 4\psi}{\sin \frac{\psi}{2}}\right]^2 + \left[\frac{\sin 4\eta}{\sin \frac{\eta}{2}}\right]^2 - 2\left[\frac{\sin 4\eta}{\sin \frac{\eta}{2}}\right]\left[\frac{\sin 4\psi}{\sin \frac{\psi}{2}}\right] \cos \frac{9}{2}(\psi - \eta)$$

where $\psi = \pi \sin(\alpha - \beta)$

$\eta = \pi \sin(\alpha + \beta)$

$\alpha$ = angle which array makes with the vertical.

$\beta$ = angle which incident ray makes with the horizontal.

Computation of the radiation patterns for different values of $\alpha$, showed that the presence of the ground altered the shape and size of the main beam, and also tended to deflect it upwards. With the antenna vertical, the maximum made an angle of $6^{\circ}.4$ with the horizontal. For values of $\alpha > 0^{\circ}$, the main beam pointed higher still. It was also found that for $\alpha = 0^{\circ}$, the $\frac{1}{2}$-maximum beamwidth was reduced by a factor of $\sim x4$ and the forward gain was increased by 6 dB. These results ignored the effect of the mutual impedance between the array and its image, but according to Kraus (1950) this does not appreciably affect the result.

In practice, some attenuation of the ground-reflected rays would occur, causing the radiation pattern to have a wider beam, smaller gain, and lie closer to the ground than in the case of a perfect reflector.

At the beginning of the experiment, the effects of reflections were ignored, the arrays being placed so that in the absence of the ground, the beams would have pointed a little above the Galactic Centre. With this arrangement, the Galactic Centre would have spent most of its time within the beams, while above the horizon. However, after the Glasgow system became operational, the

author noticed that the maximum signal received during the night occurred about 45 minutes AFTER the transit of Sagittarius A. A similar effect was subsequently observed at other sites. At Harwell and Cambridge, the maximum flux was obtained $1\frac{1}{2}$ hours and 2 hours respectively, after the transit of the Galactic Centre. It was realised that if the beam was pointing at a higher declination than intended, this would result in the reception of signals from a section of the Galactic plane of larger Right Ascension than Sagittarius A, thus accounting for the "lateness" of the observed flux. Following this, Dr. W.N. Charman made some direct measurements of the radiation pattern of the Harwell arrays using a transmitter of variable height. He found that with the antennae at $15^{\circ}$ to the vertical, the beam pointed at an angle of $20^{\circ}$ to the horizontal. Bringing the arrays to the vertical, the beam elevation was reduced to $\sim 5^{\circ}$, which was consistent with the author's calculations.

At Glasgow, the arrays were positioned on the side of a southward facing hill so that the effect of ground reflections was probably less here than at other sites. As a compromise, the Glasgow antennae were placed at $4^{\circ}$ to the vertical, although the precise effect of the ground reflections at this site was never determined.

It should be pointed out that even with the beam pointing in the correct direction, the maximum signal observed could still occur after the transit of Sagittarius A, owing to radio emission from higher declination regions of the Galactic plane (and also Cygnus A) entering the sidelobes. This could produce a net "source" having a larger RA than the Galactic Centre. Indeed at Harwell, even with the beam measured to be at the correct elevation, the time of maximum signal was still somewhat later than would have been expected for an isolated point source at the Galactic Centre.

## 4-3 The Effect of the Ionosphere

Another problem which the author considered might be important, concerned the possibility that signals from the centre of the Galaxy might be totally reflected by the F2 layer of the ionosphere. The exact value of the plasma frequency of the F2 layer at night varies with season and sunspot activity, but is typically $\sim 5$ MHz in the British Isles. Signals of considerably greater frequency can be reflected if they strike the ionosphere at a large angle of incidence and it is this fact which allows world-wide communication using frequencies of up to 30 MHz. However, at night, the F2 layer is at a height of $\sim 250$ km so that the angle of incidence which terrestrial transmissions make with the ionosphere, can never exceed $\sim 75^{\circ}$. The situation is different for signals arriving at the ionosphere from outer space since angles of incidence of up to $90^{\circ}$ can occur, thus making it possible for it to reflect at frequencies higher than 30 MHz.

In order to determine the importance of reflection at 151.5 MHz, the author submitted the problem to the Radio and Space Research Station, Slough, for investigation. At this establishment, Mr. P.A. Bradley calculated the path of a radio signal through a model ionosphere with the aid of a ray-tracing program. The critical frequency adopted was 10 MHz, which was slightly larger than any observed in the relevant part of the world (Spain) during the Galactic Centre experiment. It was found that there was no cut-off at 151.5 MHz due to ionospheric reflection, even at an elevation angle of $0^{\circ}$. Refraction at this frequency was also found to be quite small ($\sim 0.3^{\circ}$). It could therefore be concluded that the Galactic Centre was "visible" at the frequency of this experiment, for the entire time that it was above the horizon. In addition, it was found that other factors such

as sporadic-E and ionospheric tilts never reached sufficiently extreme values to upset these conclusions.

## 4-4 Receiving System and Sensitivity

After pre-amplification, the signal from the Glasgow arrays was fed into two Eddystone receivers (Type 990R) which had bandwidths of 200 kHz. They were usually operated ~1 MHz apart in order to discriminate against narrow band interference, as well as provide information about any highly dispersed events. The dispersion measure to the Galactic Centre is uncertain, but is probably large. Davies et al (1972) have indicated that it might be as high as 3,500 $cm^{-3}$ pc. In addition, UHURU X-ray observations (Kellogg et al, 1971) suggest that the neutral hydrogen column density to the centre of the Galaxy is 20,000 $cm^{-3}$ pc. If a further 10% of ionised hydrogen is also present (Grewing et al, 1970) then the resulting dispersion measure of 2,000 $cm^{-3}$ pc would produce a frequency sweep-rate equivalent to 200 kHz in 1.4 s. The integration times of the two systems at Glasgow were 0.7 s and 3.5 s respectively, the fast time constant being included, in case of lower density channels towards the Galactic Centre.

Directional interferometers were set up at Cambridge, Dublin, Glasgow, Harwell and Malta. The Maltese site was operated by the Dublin group, and was considerably better placed for observing the Galactic Centre owing to its lower latitude ($36^{\circ}$N). All stations operated at, or near to, 151.5 MHz. The Cambridge system also contained two receivers tuned to frequencies 1 MHz apart. Among the five stations, bandwidths varied from 200 kHz to 1 MHz, and integration times ranged from 0.3 s to 3.5 s. Chart recordings were made at speeds of between 6" $hr^{-1}$ and 24" $hr^{-1}$. At Glasgow, the first

month's observations were carried out with Yagi antennae, after which the broadside arrays were used.

Only an approximate estimate could be made of the sensitivity with which the Galactic Centre was observed, owing to the uncertainty as to the contribution of Sagittarius A to the total observed signal. The Galactic disc near the centre presents an elongated source which has a width at $\frac{1}{2}$-maximum of $\sim 10^{\circ}$ across its narrow dimension. This means that such a source would be partly unresolved by a phase-switched interferometer of only $5\lambda$ spacing. Calibration of the system by performing drift scans of Cassiopeia A with the arrays horizontal also only gave a rough estimate for the sensitivity, since it did not allow for the presence of ground reflections during Galactic Centre observations.

With the arrays at $4^{\circ}$ to the vertical, a sine wave was obtained having a "peak to peak" signal to noise of 10 to 1, near the transit time of Sagittarius A (time constant = 0.7 s). Observations of Cassiopeia A implied that the signal to noise of the sine wave produced by Sagittarius A should only have been 7.5 to 1, indicating the additional detection of ground reflections and other parts of the Galactic disc.

If it is assumed that at least 50% of the observed signal was due to emission from the Galactic Centre, then the smallest unpolarised pulse from that direction, giving a 3 to 1 "peak-to-peak" signal to noise would have been

$$\sim 4 \times 10^{-23} \text{ W m}^{-2} \text{ Hz}^{-1}$$

Thus, for a dispersion measure of say 2,000 $\text{cm}^{-3}$ pc and a 0.7 s integration time, the smallest detectable energy would have been

$$\sim 6.5 \times 10^{-23} \text{ J m}^{-2} \text{ Hz}^{-1}$$

## 4-5 Observations

The Galactic Centre was monitored between 1970, June 1 and 1970, August 16, during which time it was above the horizon at night. Interference was found to be much greater than in the dipole experiment, owing to the low elevation at which the observations were carried out. This problem was particularly severe at Glasgow, where the arrays pointed directly over Clydebank with the result that the data taken before midnight at this site was frequently unusable.

As in the dipole experiment, pulses having an amplitude of at least 3 times the "peak to peak" noise were measured and listed. Comparisons of the data lists were made by several of the collaborating groups, correlations at Glasgow being performed by the author. Estimations of the chance rates and overlap times were carried out by Dr. G.A. Baird at Dublin, who also made a direct comparison of the Galactic Centre radio data with the times of coincidences recorded by Weber during this period. The chance rates were determined as before, by inserting delays of various magnitudes into the data from the different stations, and then re-examining the lists for coincidences.

## 4-6 Results

Coincidences obtained between two or more sites within 2 minute and 1 minute resolving times are shown in Tables 4-1 and 4-2, together with the relevant chance rates and overlap periods. No 5-fold or 4-fold events were obtained, the 4-fold overlap time being 209 hours. Within a 2 minute resolving time four 3-fold coincidences occurred, but individual examination of the component pulses allowed them all to be eliminated as spurious. It can therefore be concluded that in 368 hours of 3-fold overlap time, no events were detected

Table 4-1 151.5 MHz Galactic Centre Data - 3, 4 and 5-fold events obtained when the G.C. was above the horizon.

| | | 5-fold | 4-fold | 3-fold |
|---|---|---|---|---|
| No. of coincidences observed | 2 min. resolving time | 0 | 0 | 4 |
| No. of coincidences expected by chance | 2 min. resolving time | 0 | 0 | 2 |
| No. of coincidences observed | 1 min. resolving time | 0 | 0 | 1 |
| No. of coincidences expected by chance | 1 min. resolving time | 0 | 0 | 0 |
| Overlap time (hours) | | 78 | 209 | 368 |

Note:- This data does not include the triple coincidence of 1970, July 28. This event was found by re-examining the Glasgow charts around the times of 2-fold coincidences between other stations.

Table 4-2 151.5 MHz 2-fold data obtained during the Galactic Centre experiment, including times when the G.C. was below the horizon.

| Resolving time | 2 min. | 1 min. |
|---|---|---|
| No. of coincidences observed | 237 | 137 |
| No. of coincidences expected by chance | 236 | 139 |

Overlap time = 1,114 hours.

Note:- The Galactic Centre was above the horizon for 57% of the 2-fold overlap time given above.

from the direction of the Galactic Centre. The expected number of chance 3-fold coincidences in this time was two.

An analysis of all the 2-fold data taken in this experiment (including times when the Galactic Centre was below the horizon) showed that in 1,114 hours, the number of observed events did not differ significantly from the number which would have been expected by chance (see Table 4-2). The Galactic Centre was above the horizon for 57% of this time.

## 4-7 The Event of 1970, July 28.

Owing to the severe interference problems at Glasgow, the amount of data which was analysed was generally less than at other stations. In order to partially compensate for this loss of overlap time, the author re-examined the Glasgow charts at the times of coincidences between other sites. This procedure included Glasgow traces which had never been systematically analysed. As a result, one event emerged which was unique within the entire present work. It was located in a period for which the data obtained at Glasgow had not been measured, and so it does not figure in Table 4-1.

The event occurred at about 20.09.25 UT on 1970, July 28 and it is shown in Fig. 4-5. It was composed of a coincidence between receivers at Cambridge, Glasgow and Harwell, the Dublin and Malta 151.5 MHz arrays being out of action at the time due to local interference. The pulses saturated the systems at all three sites involved, and as deflections appeared on both channels at Glasgow and Cambridge, narrow band interference could be ruled out. In view of the unusual nature of this occurrence, the author carried out a re-measurement of all the data recorded during this event, and the results of this are now presented. The description of the coincidence

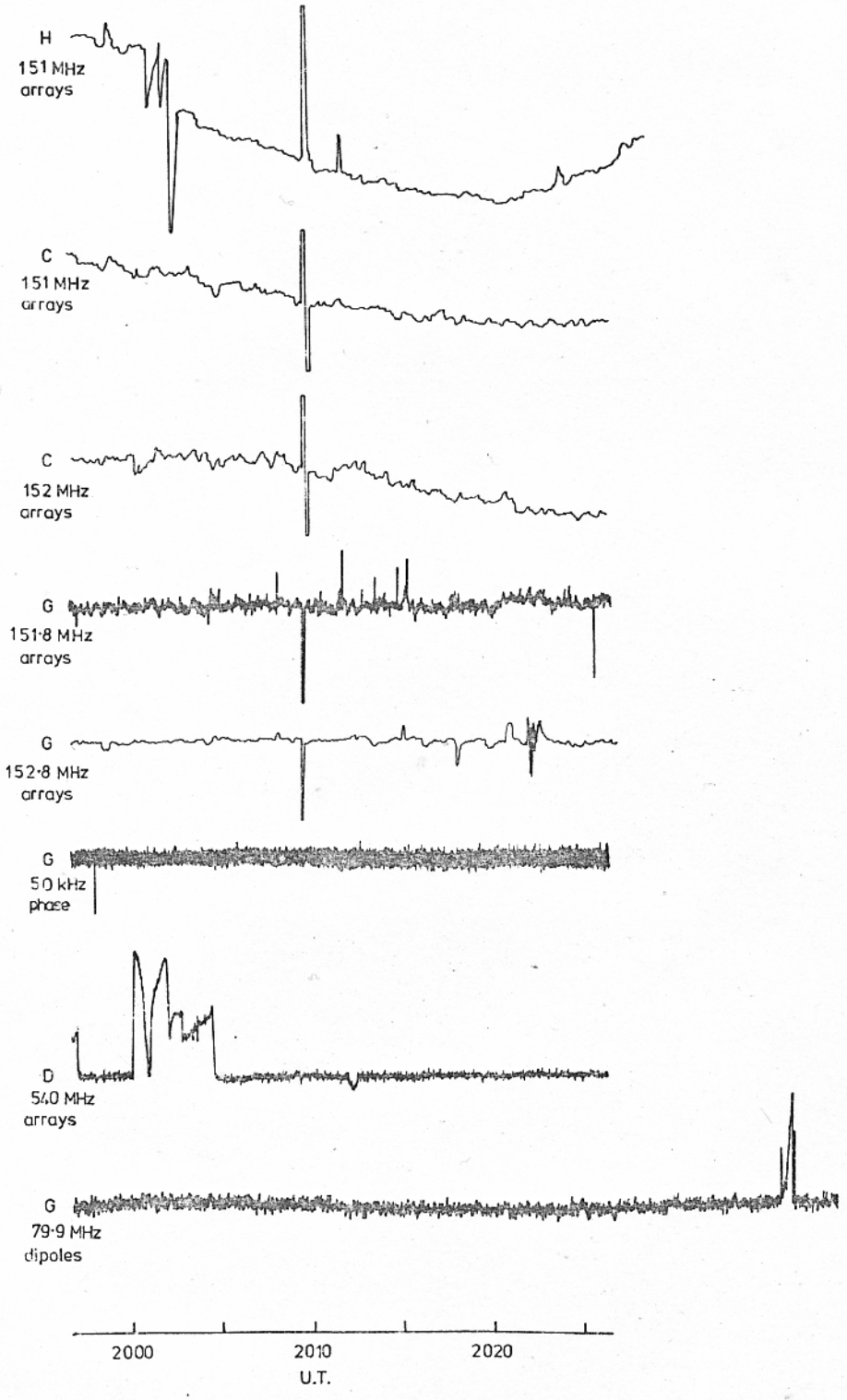



Fig.4-5 Coincidence obtained during Galactic Centre observations on 1970 July 28.

is divided into two parts, arguing respectively for and against its having an astrophysical origin.

Argument in favour

The event extended over at least 1.2 MHz implying that it could not have been caused by narrow-band transmissions from satellites or high-flying aircraft. It had a very large amplitude and similar shape at all three stations. As it was also coincident between these sites to within 3 s, this argues strongly against the possibility that it was a random effect.

As well as the arrays, four other systems were operating during the event. At Dublin an additional array tuned to 540 MHz was running, while at Glasgow, horizontal dipole systems at 151.8 MHz and 79.9 MHz were in action. Also at Glasgow, a record was being made of phase fluctuations in a 50 kHz standard frequency transmission from Czechoslovakia.

At 540 MHz, no deflection was detected at the time of the principal event. However, about $9\frac{1}{2}$ minutes before, a large, multi-structured pulse of width≈5 minutes appeared on this system. This disturbance at 540 MHz was very unusual.

No pulse was visible on the 151.8 MHz dipole record implying that the event originated in a direction of small elevation or, possibly, that it arrived along one of the dipole interferometer nulls.

At 79.9 MHz, again no pulse was observed at the time of the coincidence, but a deflection WAS observed 27 minutes 5 seconds later. It is interesting to note that the dispersion measure which would produce this delay is $3,475 \pm 20$ cm$^{-3}$ pc.which would be reasonable for emission at the Galactic Centre. In addition, the delay which this dispersion measure would cause between pulses at 540 MHz and 151.5 MHz

is 9 minutes 36 seconds, which is in good agreement with the observed time lag.

Since the bandwidths of the systems are known, the pulse widths due to the above dispersion can be predicted, assuming the intrinsic event duration to be short. At Cambridge ($\Delta\nu$ = 1 MHz), Glasgow ($\Delta\nu$ = 200 kHz) and Harwell ($\Delta\nu$ = 1 MHz) respective widths of 8.2 s, 1.7 s, and 8.2 s would be expected. At Harwell the measured width was $8.5\pm1$ s and at Glasgow it was $3\pm1$ s. Poorer agreement was obtained at Cambridge, where a duration of $20\pm1$ s was observed. However it must be recalled that all the pulses at $\sim$151.5 MHz saturated the systems, so that the points on the leading and trailing edges corresponding to the 3 dB points of the band, could not be determined i.e. the widths at $\frac{1}{2}$-maximum height were un-measurable. (The widths were in fact measured at the saturation levels). At 79.9 MHz ($\Delta\nu$ = $350\pm50$ kHz), the observed $\frac{1}{2}$-maximum width was $15\pm1$ s which can be compared with a predicted value of $19.5\pm3$ s. The pulse duration at 540 MHz will be discussed later.

The 50 kHz phase record was clean during the main event, but 11 minutes 23 seconds before, a sudden phase advance of 1 micro-second was recorded. The phase returned to normal about 2 s later. The fast recovery made this disturbance very unusual, no others like it being found throughout the Galactic Centre observations. If this phase jump was caused by an X-ray burst striking the ionosphere and if the X-rays had the same source and were emitted at the same time as the 151.5 MHz pulse then the expected delay between the two events due to the above dispersion measure would be 10 minutes 25 seconds. Although this is not in perfect agreement with the observed delay, simultaneous emission of X-rays and radio cannot necessarily be assumed, since their respective generating mechanisms may differ

(Colgate, 1968; Colgate and Noerdlinger, 1971).

The discussion presented so far, indicates that the coincidence was caused by an intrinsically fast, but highly dispersed pulse extending over a large region of the electromagnetic spectrum. Evidence against this conclusion is now detailed.

Argument against

The events recorded at 540 MHz and 79.9 MHz had shapes which differed considerably from each other and from the 151.5 MHz pulses. Although the event at 540 MHz was rare over a timescale of three months, several other similar pulses occurred a few minutes beforehand. The width at 540 MHz was about 5 minutes, and is considerably greater than the value which would be produced by the dispersion measure adopted above. The event at 79.9 MHz contained a precursor which was not evident at 151.5 MHz. In addition, several similar pulses at 79.9 MHz were recorded throughout the night and as they all had the same sign it is likely that the source was probably a local stationary transmitter.

At $\sim$151.5 MHz, a dispersion delay of 8 s between the pulses on the two channels (151.8 MHz and 152.8 MHz) at Glasgow would have been expected. A similar delay between the two frequencies at Cambridge should have also occurred. No delay $\lesssim$ 3 s was observed at either station implying an upper limit to the dispersion measure of 1,260 $cm^{-3}$ pc. In addition, absolute timing measurements to an accuracy of less than 2 s were carried out at Glasgow and Harwell. Within this error, the pulses at these two sites were coincident despite their tuning separation of 0.8 MHz which would have resulted in a 6.6 s delay for a dispersion measure of 3,475 $cm^{-3}$ pc.

At Harwell, the pulse sign was opposite to that of the observed

sine wave. However, owing to the confusion produced by signals from other parts of the Galactic disc, as well as ground reflections, the Galactic Centre cannot be eliminated as the possible source of the event on the basis of pulse sign alone.

At Cambridge, the pulse was bipolar on both channels which could imply that the source moved rapidly across the interferometer and therefore was not astrophysical in nature. Conversely, the bipolarity might simply have been caused by the saturation of the electronics.

In concluding this discussion, it should be remarked that the Glasgow dipole records for 1970, July 28 showed that the sun was exceptionally strong at VHF (probably due to sunspot activity). As the triple coincidence occurred just after sunset, it is possible that an exceptionally large solar burst coupled with unusual atmospheric conditions could have resulted in its detection at all three stations.

In the opinion of the author the evidence for dispersion is very unconvincing. However, it is difficult to prove that the event did not originate in a source to which the dispersion measure was $\gtrsim 10^3$ cm$^{-3}$ pc. In Chapter 7, unusual astrophysical phenomena which were detected near the time of the coincidence, will be considered.

## 4-8 Conclusion

Subject to the assumption that at least 50% of the observed steady signal was due to Sagittarius A, it has been stated that the maximum sensitivity of the Glasgow system to pulses from this direction was

$$\sim 6.5 \times 10^{-23} \text{ J m}^{-2} \text{ Hz}^{-1}$$

for a dispersion measure of 2,000 cm$^{-3}$ pc. However, for most of the

time that the Galactic Centre was above the horizon, the sensitivity was poorer than that quoted above, owing to the interferometer radiation pattern. Nevertheless, it is reasonable to assume that during this period, the sensitivity was seldom worse by more than a factor of ten relative to the maximum.

It can therefore be concluded that in about 350 hours of observation, no pulses exceeding an energy of

$$\sim 6.5 \times 10^{-22} \text{ J m}^{-2} \text{ Hz}^{-1}$$

were detected from the direction of the Galactic Centre. While this threshold was derived specifically from Glasgow data, a similar sensitivity was obtained at the other stations.

During the period of the above experiment, Weber detected 31 coincidences within 1 hour of a 2-fold VHF event. The expected number of Weber events occurring by chance within 1 hour of a VHF 2-fold coincidence was 27. Reduction of the resolving time to less than 1 hour did not significantly alter the ratio of "reals" to randoms. None of the 3-fold events lay within 1 hour of a Weber coincidence.

Weber originally classified his events into four groups (Weber, 1970a) depending on the amplitudes of the component pulses relative to the noise at around the time of the coincidence. About 80% of the events fell into the two lower classes only. Within these two classes, the coincidence rates were 1 per 45 hours and 1 per 58 hours respectively. It can therefore be stated that for Weber events lying outside the two upper classes, there are probably no associated radio pulses at 151.5 MHz from the direction of the Galactic Centre, exceeding the above threshold and subject to the conditions already given.

Recently, by using an improved sensitivity Weber (1972) has obtained an event rate of 1 per 10 hours. These events were not

classified as in Weber (1970a), but about 35 would have been expected during the Galactic Centre observations. Possible explanations for the failure to detect any associated radio pulses will be presented later.

CHAPTER 5

## A Search for Radio Pulses from the Direction of the Crab Nebula at 151.5 MHz.

During the search for VHF radio pulses from the Galactic Centre, it was pointed out to us (G.G. Fazio, private communication) that the sidereal anisotropy in Weber's events could be explained if they were caused by gravity-waves arriving from the direction of the Galactic Anticentre. This possibility resulted from the axial symmetry of the quadrupole radiation pattern of Weber's detectors. By a remarkable coincidence, the Crab Nebula lies within $8^{\circ}$ of the Anticentre and so the possibility that this was the source of Weber's events could not be ruled out.

In addition, the Crab Nebula Pulsar NP 0532 is known to undergo phase fluctuations and frequency jumps in its period, as well as emitting occasional "strong" pulses (see Chapter 1).

In view of the large transient energy emission associated both with detectable gravitational waves as well as irregularities in the pulsar behaviour, it was decided that radio observations of the Crab Nebula would be worthwhile.

### 5-1 Observations

Possessing a declination of about $+22^{\circ}$, the Crab Nebula is considerably more suited to observation from the British Isles than is the Galactic Centre. Three groups took part in this experiment at Cambridge, Glasgow and Harwell. The broadside arrays used in the Galactic Centre observations were rotated about the East-West base-line so that the main beam pointed at a declination of $+27^{\circ}$. With the arrays in this position, the Crab Nebula spent about $5\frac{1}{4}$ hours

per day within the $\frac{1}{2}$-maximum sensitivity points of the narrow beam.

The receiving systems were similar to those used in the Galactic Centre experiment. At Cambridge and Glasgow only one channel was used. This was partly because the much smaller dispersion measure to the Crab ($\sim$57 $cm^{-3}$ pc compared with $\sim 10^3$ $cm^{-3}$ pc to the Galactic Centre) meant that a 1 MHz separation of two channels at 151.5 MHz would not produce a measurable delay in a pulse from this source, between the two frequencies. Also, the new position of the arrays greatly reduced the interference problem at Glasgow so that it was not necessary to have two channels in order to discriminate against narrow-band transmissions.

The systems at the three sites were tuned near to 151.5 MHz and had bandwidths of between 1 MHz and 1.2 MHz. As the dispersion measure to the Crab Nebula is known, in principle the time constants could have been optimised for pulses whose time-widths were effectively determined by the dispersion. The bandwidths at Glasgow and Harwell were 1 MHz, so that the optimum integration time was 0.135 s. In practice the pen recorders used were not capable of responses as fast as this and time constants of 0.27 s at Glasgow and 0.3 s at Harwell were in fact used. At Cambridge where the bandwidth was 1.2 MHz, the time constant was not optimised and it varied between 1 s and 2.9 s. As before, recordings were made on paper charts.

At Glasgow the Eddystone receivers used in the Galactic Centre experiment were replaced by a Decca receiver (type 7211) followed by a 60 MHz IF amplifier (Decca type 91543A). The greater bandwidth of the Decca receiver ( 1 MHz compared with 200 kHz in the Eddystone) meant that the pen recorder time constant of 0.27 s was much nearer to optimum for pulses from the Crab than it would have been, had the Eddystone been used. In addition, the reduced interference problem

at Glasgow allowed observations over a wider bandwidth.

Observations took place between 1970, September 23 and 1971, March 3 when the Crab was above the horizon at night. Charts were analysed according to the usual criteria that for a pulse to be accepted it had to equal or exceed three times the "peak to peak" noise. In general, only pulses of duration less than 5 minutes were considered.

## 5-2 Sensitivity

The sensitivities of the systems to pulses arriving from the Crab Nebula were estimated (by the author) by measuring the amplitude of the sine wave produced by Taurus A as it moved across the interferometer fringes. This estimate lacked the ambiguity present in the Galactic Centre experiment since unlike Sagittarius A, Taurus A is in a relatively "cold" part of the radio sky and presents a point source to the low resolving power systems used.

The smallest flux which could give a deflection of S/N = 3 to 1 was

$$3.6 \times 10^{-23} \text{ W m}^{-2} \text{ Hz}^{-1}$$

for an unpolarised signal. However, since the antennae were fixed, the sensitivity to radio pulses from the direction of the Crab varied as it moved across the sky, and was in general poorer than that quoted above. In order to make a more useful statement about the effective observing time and sensitivity, a less demanding flux value of

$$1.4 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$$

was chosen as a threshold sensitivity. This value was obtained by considering the sensitivity to signals from the Crab's direction when it was on the $\frac{1}{2}$-maximum sensitivity points of the narrow beam.

In these positions the Crab was also approximately at the $\frac{1}{2}$-maximum sensitivity points of the wide beam, parallel to the dipoles. Thus the net sensitivity in these situations was about $\frac{1}{4}$ of maximum. As the Crab spent $5\frac{1}{4}$ hours per day within the $\frac{1}{4}$-maximum sensitivity zone, a reasonable amount of observing time could be obtained with a sensitivity better than threshold.

## 5-3 Results

Pulse description lists were made at each site and then sent to the author who acted as principal co-ordinator for this experiment. The lists were then correlated, and the results of this comparison which are now described were entirely the work of the author.

The 2-fold and 3-fold overlap times when all pulses above threshold from the Crab's direction were detectable, were determined empirically by superimposing the sine wave traces recorded at each site. The times during which the steady signal from Taurus A was simultaneously above threshold at two or three sites, were added up.

During the 178 hours that all three stations were simultaneously sensitive to signals from the Crab, one 3-fold coincidence was obtained within a resolving time of 1 minute (Fig. 5-1). The event at Glasgow was multiple and bipolar, whereas the Harwell trace showed a simple monopolar doublet. Also, the Glasgow pulse occurred 10 s after the Cambridge and Harwell pulses and the Cambridge event was of opposite sign to the Crab sine wave and so could not have originated in that direction. It seems likely that this coincidence was spurious. The number of chance 3-fold coincidences expected in this period was 0.

A separate examination of 2-fold coincidences was also carried out for the entire running time of the experiment, including times

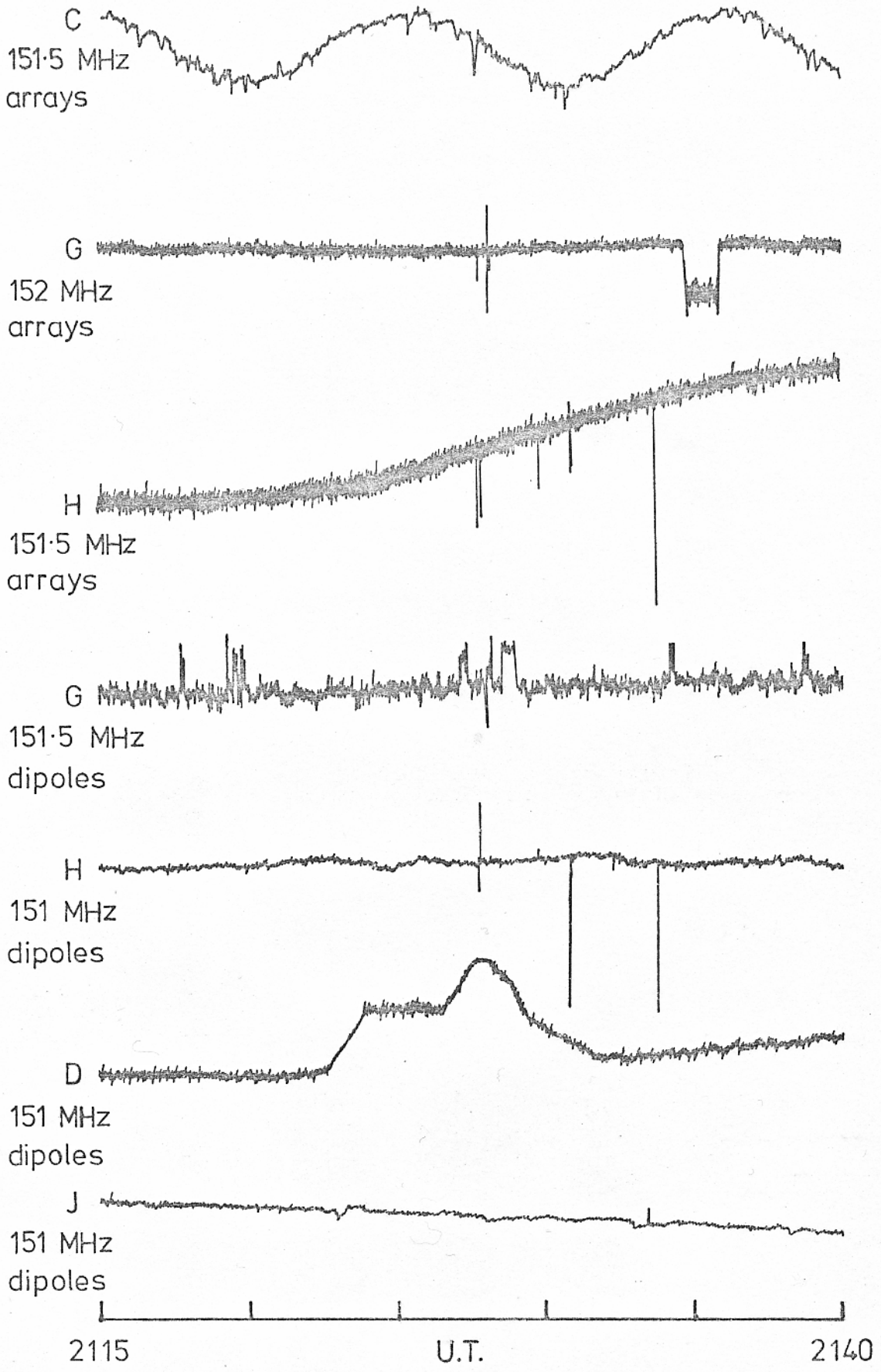



Fig.5-1 Coincidence obtained at 151.5 MHz on 1971 January 19, during observations of the Crab Nebula.

when the arrays were not sensitive to signals coming from the Crab's direction. (In fact, the Crab was observed above threshold for 27% of the total 2-fold overlap time). The results of this analysis together with the corresponding overlap timesare given in Tables 5-1 and 5-2. The random rates were found by the usual method of inserting a delay into one data list and then re-examining the lists for coincidences. From Table 5-1 it can be seen that a definite excess of real coincidences over random events occurred. However, closer inspection revealed that practically all of this excess was due to Cambridge-Harwell coincidences. It would therefore seem likely that the excess was due to some local effect near Cambridge and Harwell. In order to further investigate this, the data was re-analysed for NON-BIPOLAR events only, in view of the possibility that bipolar events were caused by local interference sources moving rapidly through the interferometer fringes. The results of this analysis are given in Table 5-2. It can be seen that the ratio of reals to randoms for Glasgow-Harwell and Cambridge-Glasgow coincidences remained unchanged. By contrast, in the Cambridge-Harwell data the subtraction of bipolar events reduced the excess factor from $\sim 7.5$ x random to $\sim 4.5$ x random, thus adding weight to the argument that the excess was caused by local interference (e.g. satellites) near Cambridge and Harwell.

Of the 137 2-fold coincidences which occurred within a 1 minute resolving time during the entire experiment, 41 events were detected when the Crab was within the $\frac{1}{4}$-maximum sensitivity zone. The number of events which would have been expected by chance while the Crab was within this zone was 21. All 41 real coincidences were individually re-examined to see if any might have been caused by pulses originating in the direction of the Crab Nebula. 14 events contained at least one pulse which had a sign opposite to that of

Table 5-1 151.5 MHz Crab Nebula Data - All 2-fold data (including times when the Crab was outside the $\frac{1}{4}$-maximum sensitivity zones of the arrays).

(i) Glasgow - Harwell (Overlap time = 2,014 hours)

| Resolving time | 60s | 20s | 10s | 6s |
|---|---|---|---|---|
| No. of coincidences observed | 65 | 23 | 16 | 14 |
| No. of coincidences expected by chance | 51 | 22 | 13 | 9 |

(ii) Cambridge - Harwell (Overlap time = 835 hours)

| Resolving time | 60s | 20s | 10s | 6s |
|---|---|---|---|---|
| No. of coincidences observed | 55 | 31 | 19 | 12 |
| No. of coincidences expected by chance | 12 | 3 | 2 | 2 |

(iii) Cambridge - Glasgow (Overlap time = 752 hours)

| Resolving time | 60s | 20s | 10s | 6s |
|---|---|---|---|---|
| No. of coincidences observed | 17 | 6 | 2 | 0 |
| No. of coincidences expected by chance | 19 | 8 | 4 | 4 |

(iv) All 2-fold Data (Overlap time = 3,601 hours)

| Resolving time | 60s | 20s | 10s | 6s |
|---|---|---|---|---|
| No. of coincidences observed | 137 | 60 | 37 | 26 |
| No. of coincidences expected by chance | 82 | 33 | 19 | 15 |

Note:- (i) The 2-fold overlap times quoted above include periods when a 3rd station was running. The time during which ONLY two stations ran was 1,514 hours.

(ii) The Crab Nebula was within the $\frac{1}{4}$-maximum sensitivity zones of the arrays for 27% of the total 2-fold running time.

Table 5-2 151.5 MHz Crab Nebula Data - Non-Bipolar 2-fold events only.
(including times when the Crab was outside the $\frac{1}{4}$-maximum sensitivity zones of the arrays).

(i) Glasgow - Harwell

| Resolving time | 60s | 20s | 10s | 6s |
|---|---|---|---|---|
| No. of coincidences observed | 54 | 19 | 13 | 11 |
| No. of coincidences expected by chance | 45 | 17 | 9 | 8 |

(ii) Cambridge - Harwell

| Resolving time | 60s | 20s | 10s | 6s |
|---|---|---|---|---|
| No. of coincidences observed | 22 | 13 | 11 | 6 |
| No. of coincidences expected by chance | 7 | 2 | 2 | 2 |

(iii) Cambridge - Glasgow

| Resolving time | 60s | 20s | 10s | 6s |
|---|---|---|---|---|
| No. of coincidences observed | 13 | 6 | 2 | 0 |
| No. of coincidences expected by chance | 12 | 5 | 3 | 3 |

(iv) All Non-bipolar 2-fold Data

| Resolving time | 60s | 20s | 10s | 6s |
|---|---|---|---|---|
| No. of coincidences observed | 89 | 38 | 26 | 17 |
| No. of coincidences expected by chance | 63 | 24 | 13 | 12 |

the Crab sine wave while a further 14 contained pulses having the slow, bipolar form characteristic of satellite interference. Among the remaining 13 2-fold events, 5 occurred when there was severe interference at one of the stations involved. These 5 were therefore probably chance coincidences due to the high single station rate when they occurred. Another 5 events were not precise coincidences, there being a delay of at least 20 s between the pulses at the two stations. This left 3 coincidences of which 2 were detected when a third station was sensitive to signals from the Crab's direction and yet did not detect a pulse. The last remaining coincidence exhibited very different forms at the two stations, being composed of a fast, bipolar pulse at one site and a monopolar triplet at the other. It therefore seems unlikely that this event was of extraterrestrial origin.

The Crab Nebula was observed with a sensitivity better than threshold by at least two stations for 605 hours, and according to the above discussion, no pulses from its direction were obtained in this time.

During the experiment, a further two 3-fold coincidences occurred when the arrays were relatively insensitive to signals from the Crab's direction. One of these was recorded at a time when the Crab was below the horizon. In addition, the pulse detected at Glasgow during this event occurred 30 s before the pulses at Cambridge and Harwell, and so this coincidence was almost certainly spurious.

The other 3-fold event was detected around 21.20 UT on 1970, December 4, and is shown in Fig. 5-2. It consisted of a fast spike at all three stations. In addition, two other precise coincidences between Glasgow and Harwell occurred near this time. They also consisted of fast spikes. Two of the Harwell pulses were doublets but only single pulses were detected at Glasgow and Cambridge.

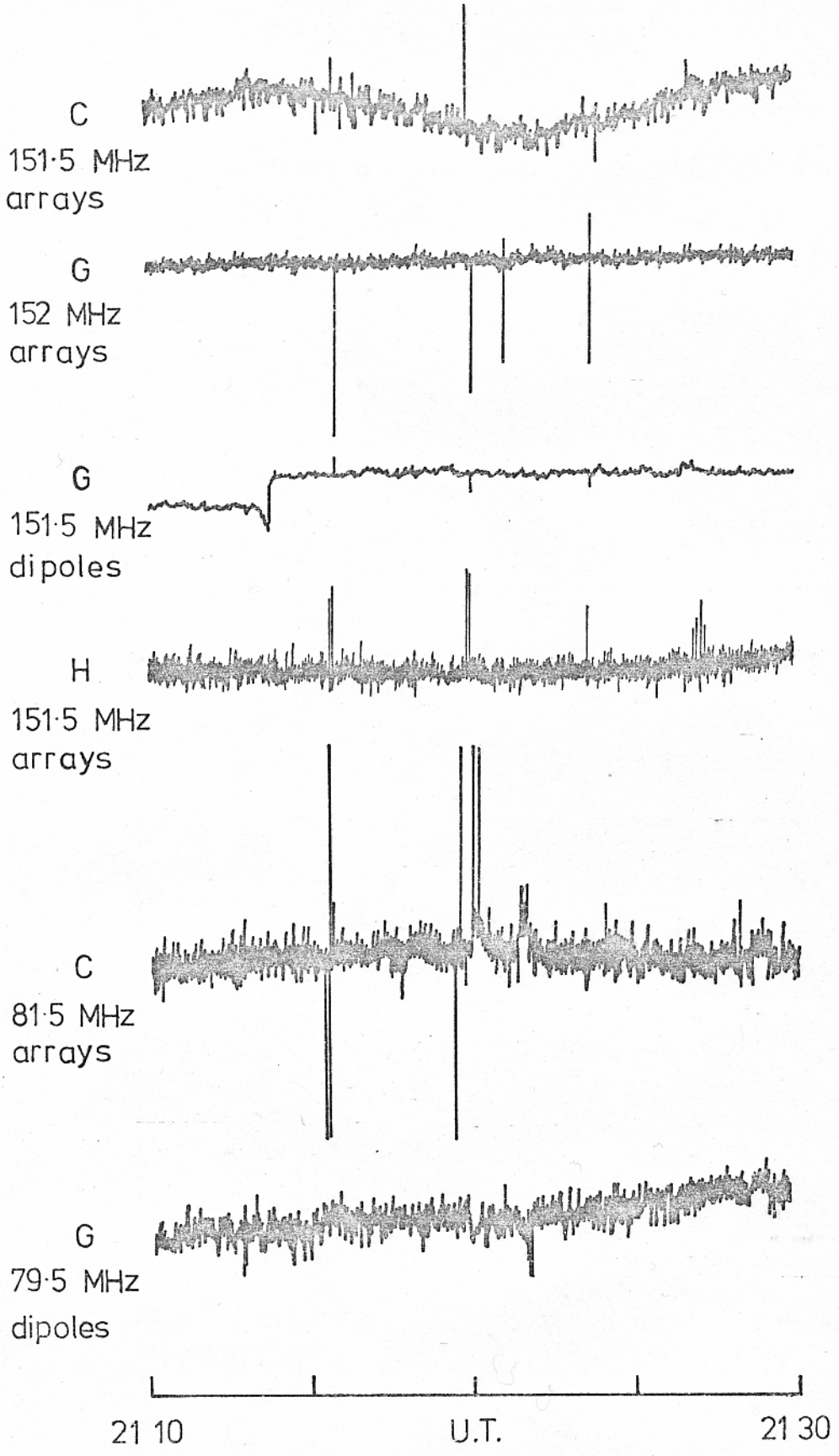



Fig.5-2 Coincidence obtained on 1970 December 4 during observations of the Crab Nebula.

Coincident pulses also appeared on the 151.5 MHz single dipole systems at Glasgow and Harwell. At the time of this event, Cambridge was operating arrays at 81.5 MHz, pointing at the Crab Nebula. Several coincident pulses were recorded on this system, making the occurrence very unusual. If the low frequency Cambridge events are ignored then the coincidence could be accounted for if a satellite transmitting occasional pulses at 151.5 MHz happened to have been in the beam at the time. At Glasgow the pulses changed sign on the 151.5 MHz dipole system while one of the pulses detected by the arrays was bipolar. It may also be significant that Dublin was operating 151.5 MHz dipoles at this time and detected nothing. Neither was anything detected on the Glasgow 79.5 MHz dipoles.

This event has a striking similarity to the multiple coincidence detected on 1970, January 11 (Fig. 3-1), but owing to the pulses at 81.5 MHz, it cannot be so easily dismissed as being caused by a satellite. Had the event originated at the Crab Nebula, a delay due to dispersion of 27 s would have been present between the pulses at 151.5 MHz and 81.5 MHz. No such delay was detected. The failure of Dublin to detect the event seems to imply that it was of local origin, but this leaves unexplained why events at around 80 MHz should be detected at Cambridge and yet not at Glasgow. The author tentatively suggests that if the event had been of geophysical origin and therefore relatively localised, and if the 81.5 MHz arrays at Cambridge happened to have been pointing in the direction of origin then this might explain why the Glasgow 79.5 MHz dipoles with their much smaller gain, failed to detect the event.

## 5-4 Conclusion

In 605 hours of observation, no pulses exceeding a flux of

$1.4 \times 10^{-22}$ W $m^{-2}$ $Hz^{-1}$

were detected from the direction of the Crab Nebula.

Although the times and amplitudes of events detected by Weber during the above observing time were not acquired, certain statistical conclusions can nevertheless be reached. In Weber's classification of events (Weber, 1970a), his first class contains his largest coincident pulses and comprises 5% of all his coincidences. The probability of at least one of these rare events occurring in the 605 hours observing time is 56%. Therefore the possibility cannot be ruled out that there occur radio pulses from the Crab's direction, associated with these unusually large events. However, the rate of occurrence of Weber's events outside his first class is such that 13 would have been expected in 605 hours. It therefore seems probable that for 95% of Weber's events, there are no associated radio pulses at 151.5 MHz emitted by a source in the direction of the Crab Nebula and having a flux exceeding the sensitivity threshold. (It must be pointed out that Weber's recent revision of his event rate (Weber, 1972) implies that with his new threshold he would have detected about 60 events during the Crab Nebula observations, rather than the 13 or 14 quoted above).

It should be emphasized that the mass-energy contained in the Crab Nebula is quite insufficient to produce the gravity-wave flux necessary to explain Weber's events, unless some very efficient beaming mechanism is operating.

The upper limit on the rate of large, isolated radio pulses from the Crab Nebula can also be viewed with regard to phenomena such as "strong" pulses, phase fluctuations and frequency jumps in the pulsed emission from NP 0532. Table 5-3 summarises the VHF measurements available up to 1972, January on the "strong" pulses from NP 0532. More recently a detailed study of the energy spectrum of

Table 5-3 Summary of VHF Observations of "Strong" Pulses from NP 0532.

| Frequency (MHz) | Pulse Energy Threshold ($10^{-26}$ $Jm^{-2}$ $Hz^{-1}$) | Approximate Rate above Threshold ($hr^{-1}$) | Reference |
|---|---|---|---|
| 74 | 20 | 120 | Comella et al. (1969) |
| 146 | 10 | 23 | Gower & Argyle (1972) |
| 111 | 15 | 14 | Heiles & Rankin (1971) |
| 160 | 28 | 6 | Sutton et al. (1971) |
| 170 | 14 | 4 | Goldstein & Meisel (1969) |
| 146 | 65 | 0.5 | Gower & Argyle (1972) |
| 151.5 | 4000 | $\lesssim$ 0.002 | Present Work |
| ********** | ********** | ********** | ********** |
| 151.5 | 0.4 | $1.2 \times 10^{5}$ | Rankin et al. (1970) |

The last entry in the table is an interpolated value for the average pulsed energy per period at 151.5 MHz.

the "strong" pulses at 146 MHz has been carried out by Argyle and Gower (1972), and the pulse height spectrum which they obtained is shown in Fig. 5-3.

The 2.9 s time constant of the Cambridge system rendered it unsuitable for the study of the "strong" pulses. However, the sensitivity of the Glasgow and Harwell systems, having time constants of about 0.3 s, to pulses of this type was never poorer than

$$\sim 4 \times 10^{-23} \text{ J m}^{-2} \text{ Hz}^{-1}$$

and the 2-fold overlap time of Glasgow and Harwell was 442 hours. The corresponding upper limit on the rate of "strong" pulses $\gtrsim 10^4$ times the average pulsed energy per period is $\sim 0.002$ hr$^{-1}$ (Table 5-3 and Fig. 5-3). According to Argyle and Gower (1972), the pulse energy spectrum of the "strong" pulses associated with the main pulse component is given approximately by

$$N = 500 S^{-2.5} \text{ min}^{-1}$$

where N = number of strong pulses per minute exceeding a threshold S, where S is measured in units of the average main pulse energy.

This expression was only tested for values of S up to about 300, but if it is extrapolated to the threshold of the present work ($S \approx 1.5 \times 10^4$) it predicts a pulse rate of the order of 1 in $3 \times 10^5$ hours which is certainly consistent with the upper limit quoted above.

It can also be concluded that if the departure of the phase of NP 0532 from a cubic polynomial slow-down law is caused by small, sudden fluctuations in phase (Nelson et al, 1970; Boynton et al, 1972) more often than once every 25 days, then there is probably no radio emission of a flux exceeding the threshold sensitivity associated with these changes.

No major changes in period were reported as having occurred

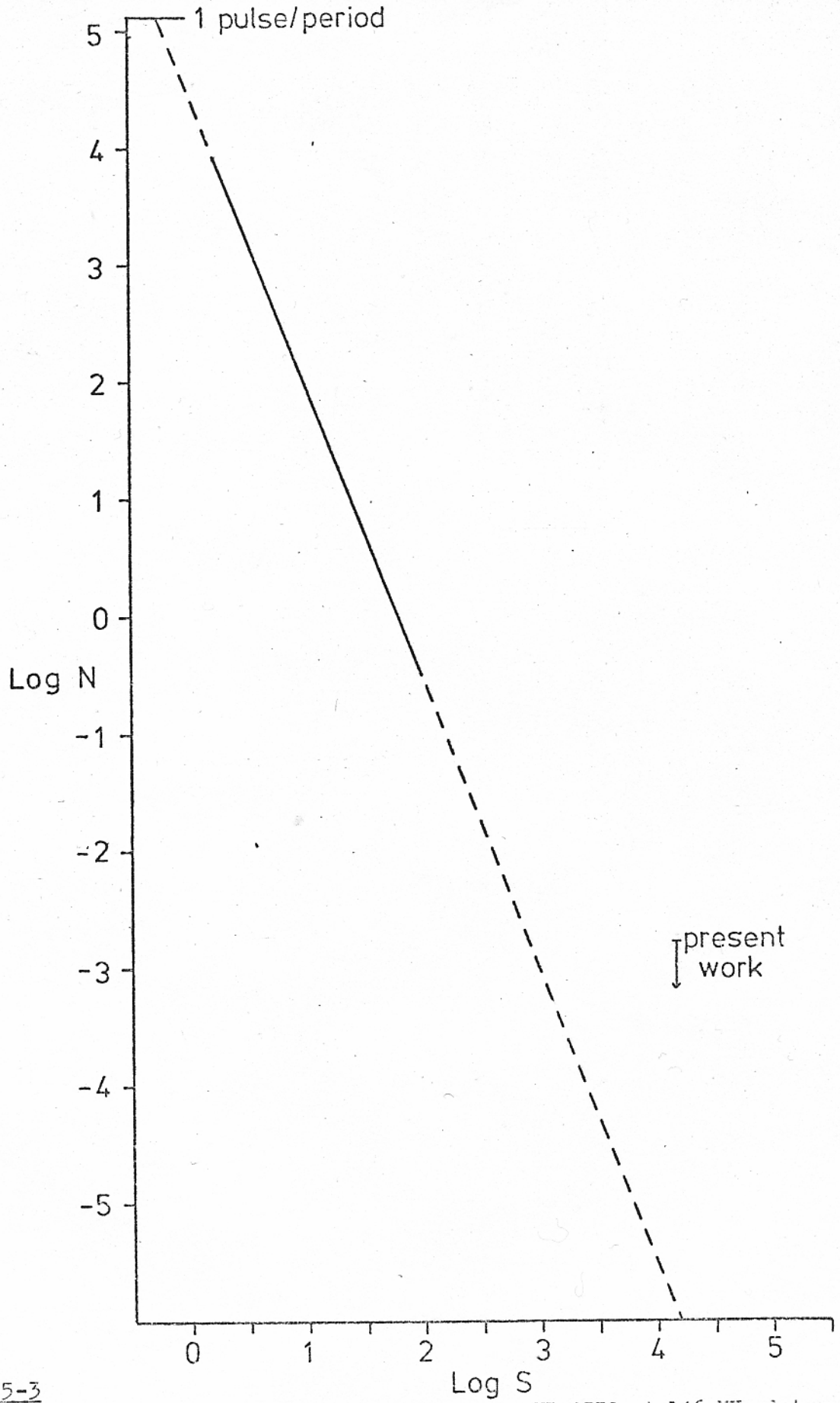



Fig.5-3
Pulse height spectrum of the strong pulses from NP 0532 at 146 MHz determined by Argyle and Gower (1972). The vertical axis is in terms of log N where N is the number of pulses per hour exceeding a threshold S. The horizontal axis is in terms of log S where S is the threshold in units of the average main pulse strength. The broken lines are extrapolations of the measured (solid line) pulse height distribution. The upper limit obtained from the present work at 151.5 MHz is also shown.

during this experiment, and so nothing can be said with regard to radio emission during such events.

# Chapter 6

## Observations at 10 GHz

The decision to conduct a series of observations at microwave frequencies was based on a combination of astrophysical and experimental factors.

### 6-1 Astrophysical Considerations.

The negative results obtained in the VHF experiments could conceivably have been caused by unusually high electron densities in the surrounding media of possible sources, so that the plasma frequency exceeded 151.5 MHz resulting in the complete screening of emission at metre wavelengths. Even if this had not been the case, exceptionally large dispersion measures to potential sources could have produced pulse "spreading" within the VHF bandwidths, to durations of hours or days. Events of this length would not have been detected in the data analysis.

By observing at 10 GHz, these two problems were considerably reduced. The electron density required to screen 10 GHz radiation exceeds the cut-off density at 151.5 MHz by a factor of 4,350. Dispersion broadening is also reduced by this factor for the same fractional bandwidths. The electron column density required to disperse a 10 GHz pulse in a 20 MHz bandwidth to more than $10^3$ s (and so have been ignored in the analysis) is $5.8 \times 10^9$ cm$^{-3}$ pc. If the Galactic Centre is considered as a case where high electron column densities might occur, it can be pointed out that recent X-ray observations (Kellogg et al, 1971) indicate a hydrogen column density of only 20,000 cm$^{-3}$ pc. Thus it is likely that dispersion of 10 GHz radiation from sources in the Galactic Centre would be unimportant for an integration time of $\sim$1 s.

In addition to plasma considerations, it must be borne in mind

that the spectra and intrinsic time widths of the suggested radio bursts are generally unpredicted. It is possible that the spectra of such pulses would be unlike those of "normal" sources and have negative spectral indices. Also, if intrinsic durations of 1 ms were expected, then the reduced broadening due to dispersion and scattering at 10 GHz would allow shorter integration times and correspondingly better sensitivity.

## 6-2 Experimental Considerations.

The most important factor here was that solar and man-made interference was considerably less at 10 GHz than at 151.5 MHz. This allowed observations to be continued throughout daylight hours and made low elevation studies more feasible. Problems connected with ground reflections were also reduced, as the antenna could be placed at a greater number of wavelengths in height than in the VHF experiments. In addition, reflected signals at 10 GHz were more severely attenuated and had much poorer coherence than at metre wavelengths.

The main drawback in observing at 10 GHz was that an antenna of beamwidth similar to that of the VHF dipoles, has a collecting area which is smaller by a factor of $\sim 4 \times 10^3$. Consequently it was decided to observe specific objects using an antenna of aperture roughly equal to the VHF aperture, but which therefore had a much narrower beamwidth. This was no disadvantage where studies of the Galactic Centre or black holes were concerned, but it did reduce the area of sky which could be continuously monitored for supernovae. To allow this aspect of the experiment to continue, the beamwidth of the antenna was deliberately chosen to be wide enough to contain

entire clusters of galaxies such as those found in Coma and Perseus. These considerations led to the choice of a parabolic dish having a $\frac{1}{2}$-maximum sensitivity beamwidth of about $2^{\circ}.5$.

The narrow radiation pattern of this antenna had the additional advantages of allowing the acquisition of directional information concerning any pulses detected, as well as further reducing the effects of off-axis interference sources.

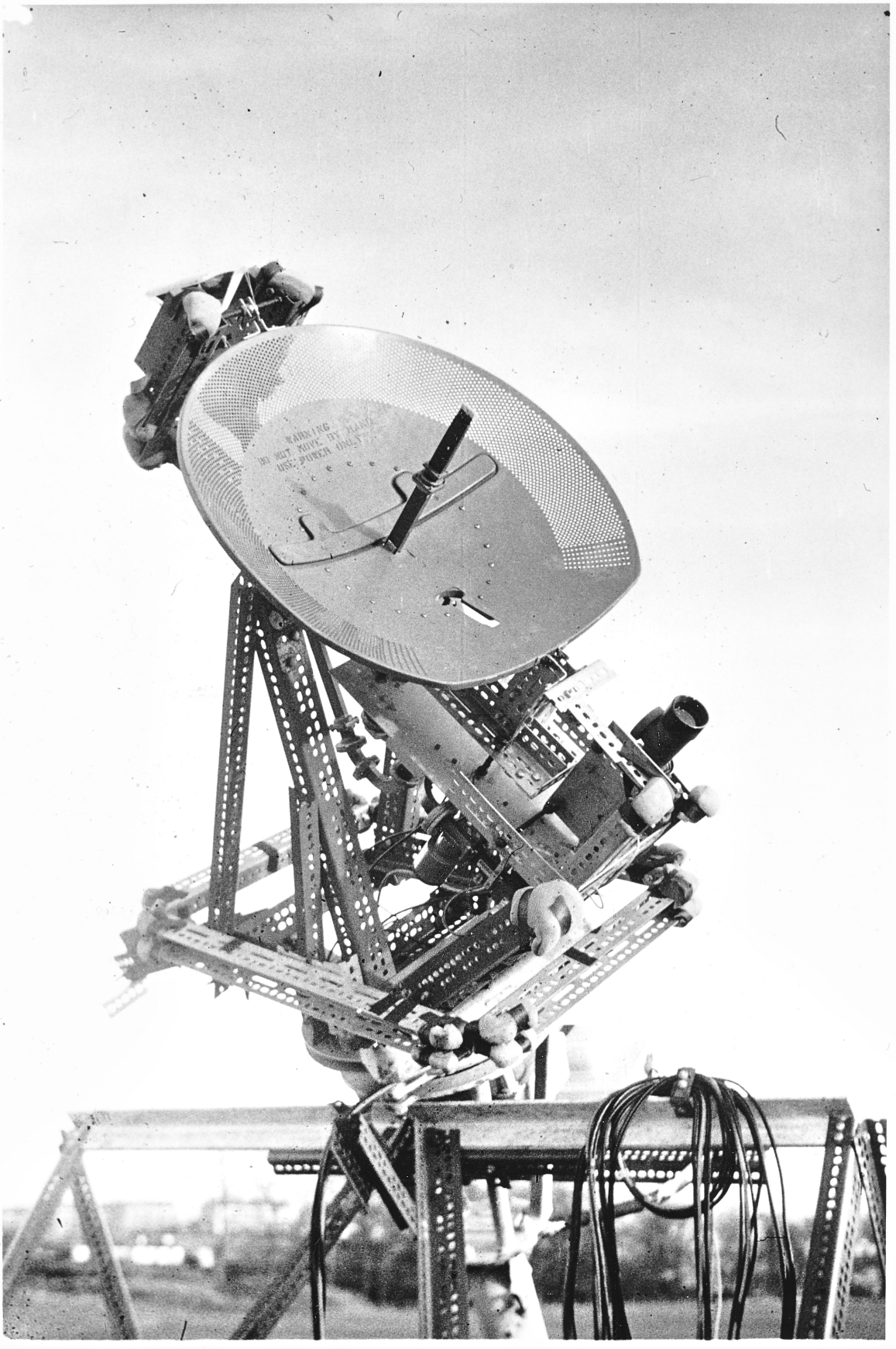
As in the VHF experiments, simultaneous observations at widely spaced sites were carried out in order to discriminate against local interference. Initially, systems at Glasgow and Harwell were operated. At the latter site, the experiment was set up by Dr. Jelley whose original idea it was to perform microwave observations using the system now described.

## 6-3 The Design and Construction of the Microwave Radiometer.

### 6-3-1 The Antenna

An almost circular, parabolic reflector of diameter 0.75 m and F 0.4 aperture was used (Fig. 6-1). In its original function as a radar dish, an $80^{\circ}$ segment had been removed resulting in a net surface area of 0.413 $m^2$. When acquired, the reflector was fitted with a horn feed of American EIA type WR112 which has an operating range of 7.05-10.00 GHz. However, it was intended to use British RCSC type WG16 waveguide after the antenna, this having an operating range of 8.20-12.40 GHz. Tests were carried out by the author, in which the efficiency of the original horn feed was compared with that of a double dipole feed of type WG16. It was found, that for the frequency range liable to be used in this experiment (9.7-10.3 GHz), the signal extracted by the dish-feeder system for a constant incident flux was larger for the double-dipole feed than for the

Fig.6-1 10 GHz radiometer.


WARNING
DO NOT MOVE BY HAND
USE POWER ONLY

horn. A double-dipole feeder was therefore chosen. An advantage in using this type of feeder is that its position with respect to the focus is relatively non-critical (Harvey, 1963). In addition, the angle subtended by the dish at the focus was $130^{\circ}$, which is quite close to the optimum of $140^{\circ}$ for double-dipoles (Cutler, 1947).

The feeder was positioned in the following way. A transmitter, composed of a Gunn diode oscillator feeding into a horn antenna, was placed at a considerable distance from the dish so that it behaved approximately like a source at infinity. The feeder position was then varied until the output from the parabolic antenna reached maximum. The double-dipole was then clamped in position.

After completion of the radiometer (see below), it was possible to obtain more information about the antenna. The beamwidth was measured by performing solar drift scans, (Fig. 6-2) which gave

$\frac{1}{2}$-maximum sensitivity beamwidth = $2^{\circ}$ 22' $\pm$ 2'

This can be compared with a theoretical value of $2^{\circ}$ 12'. The 10' discrepancy can probably be explained by

a) Finite angular width of the sun ($\sim$30').

b) Tapered illumination of the dish by the feeder.

c) Possibly slightly incorrect alignment of the dish with respect to the sun.

It can also be seen from Fig. 6-2 that the antenna had a small secondary maximum on only one side of the main beam. This may have been due to slightly asymmetric feeder illumination of the dish. The gain of the antenna for directions $> 4^{\circ}.5$ off-axis was at least 17 dB below the on-axis gain.

An approximate measurement of the aperture efficiency was also carried out by comparing the signal from the sun with that from an Argon-filled, noise source tube. The power from the tube was fed into the receiver (tuned to 10.0 GHz) via a -29.3 dB directional

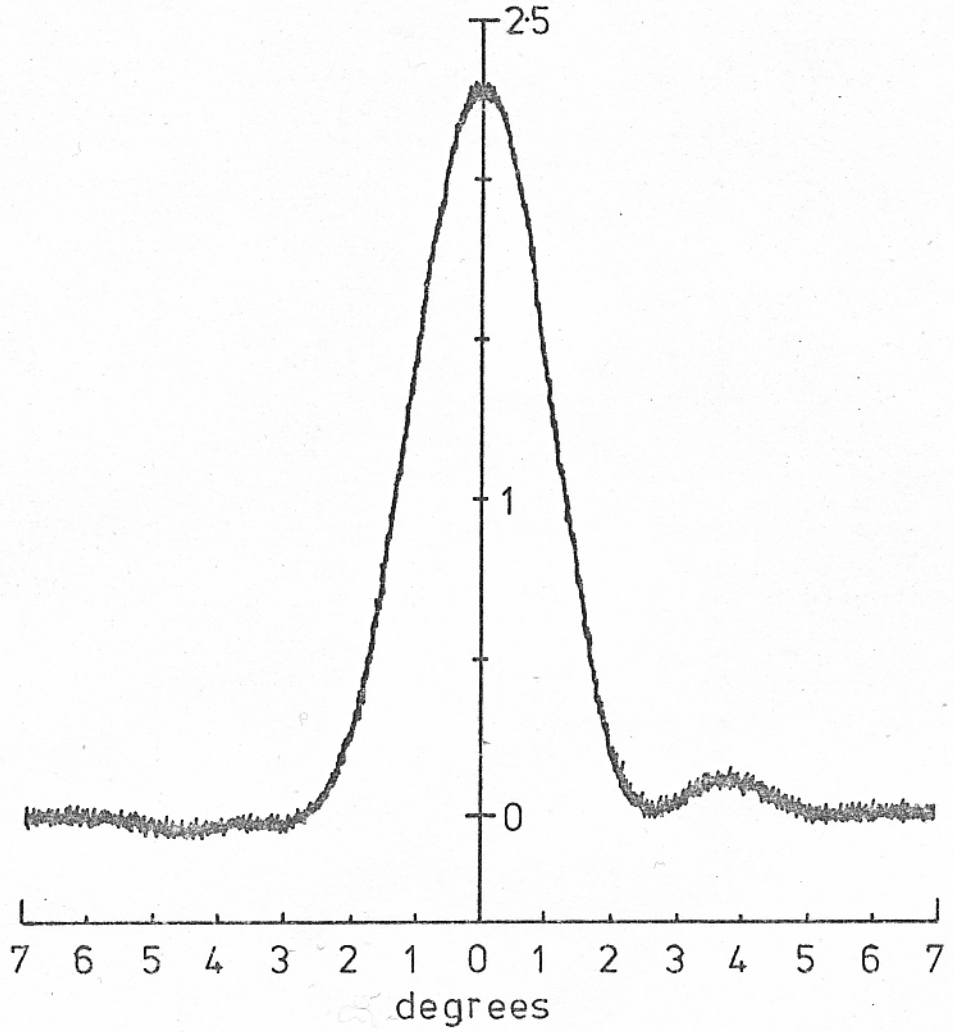



Fig.6-2 Solar drift scan obtained with the 10 GHz radiometer. The vertical scale is calibrated in units of $10^{-20}$ W $m^{-2}$ $Hz^{-1}$ and gives the deflection produced by an on-axis source.

coupler. The equivalent noise temperature of the discharge tube was 10,100° K so that the signal which entered the receiver was equivalent to a temperature increment $\Delta T$ of +11.9° K.

It was found that the ratio

$$\frac{\text{Power entering receiver from discharge tube}}{\text{Power entering receiver from sun}} = \frac{P_t}{P_s} = 0.071 \quad \text{(Equ 6-1)}$$

In order to determine $\frac{P_t}{P_s}$ for an aperture efficiency of 1, a solar temperature of 15,000° K was assumed. This value was somewhat approximate since the temperature of the solar disc at $\lambda$ = 3 cm varies with sunspot activity, and lies in the range 12,000° K to 17,000° K (Kundu, 1965). When these measurements were made (1972), the sun was roughly midway between a sunspot maximum and minimum, which was the reason for the assumed temperature value. However, the error in this figure may be as much as ±10%.

The aperture efficiency was obtained thus:-

Solar power striking dish (polarised in plane of double-dipole)

$$= (0.47 \pm 0.04) \times 10^{-20} \text{ W Hz}^{-1}$$

Power entering receiver from noise tube = $k\Delta T$ W Hz$^{-1}$

$$= 1.64 \times 10^{-22} \text{ W Hz}^{-1}$$

where k = Boltzmann's constant

$\Delta T$ = +11.9° K

Therefore, for an aperture efficiency of 1

$$\frac{P_t}{P_s} = \frac{1.64}{47 \pm 4} = 0.035 \pm 0.003$$

Hence, aperture efficiency $= \dfrac{0.035 \pm 0.003}{0.071}$

$$= 0.49 \pm 0.04$$

6-3-2 The Microwave Receiver

The microwave circuit (Fig. 6-3) was chosen by Dr. Jelley, but the physical arrangement and construction of the Glasgow version was performed by the author. Owing to the narrow beamwidth of the

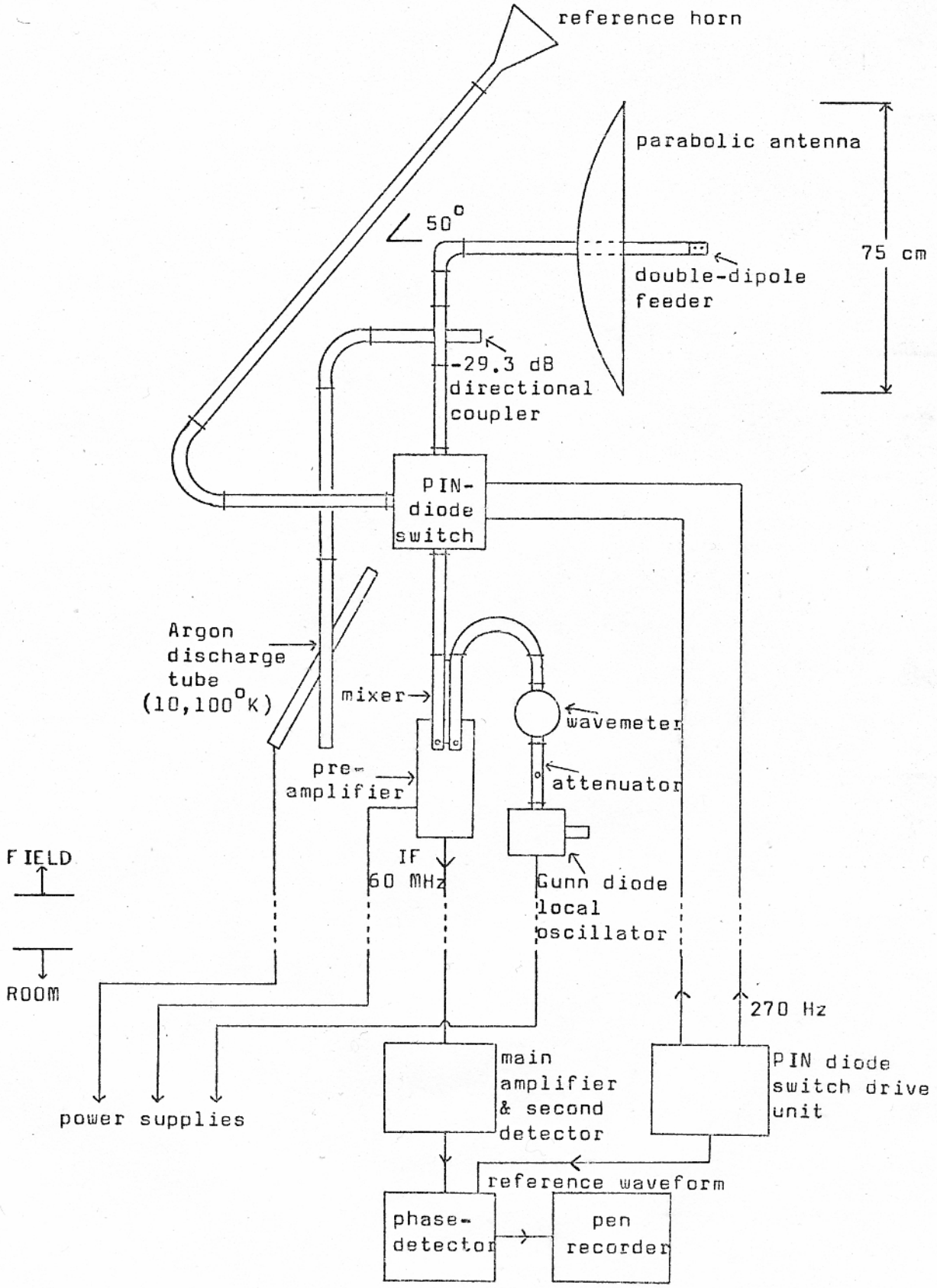



Fig.6-3 10 GHz radiometer circuit.

antenna, it was necessary to "track" the objects under observation by arranging that the dish rotated at the correct speed, on an equatorial mount. By mutual agreement between Dr. Jelley and the author, it was decided that the entire microwave assembly should be fixed to the dish, allowing the IF signal cable to move as the system rotated. This was preferred to a rotatable microwave section immediately after the feeder as it was unknown as to whether or not such a joint might produce spurious pulses while in motion.

For stability against gain fluctuations, the receiver input was switched between the main antenna and a reference horn. The horn had an aperture of 0.103m x 0.085m, giving a gain of 17 dB, and a $\frac{1}{2}$-maximum sensitivity beamwidth of about $24^{\circ}$ in both planes. The horn was positioned with its axis about $50^{\circ}$ above that of the dish (Fig. 6-3). Thus, for most of the objects observed ($+28^{\circ} < \delta < +42^{\circ}$) the horn pointed close to the North Pole, so that it always observed roughly the same path of "reference sky" as the radiometer rotated.

The switching was accomplished by a PIN diode switch (Decca type MWS 354), which had a centre frequency of 10.0 GHz and an operating range of $\pm$300 MHz, thus allowing the system to be tuned over a range of 600 MHz. This was important since it was decided to tune the systems at Glasgow and Harwell to slightly differing frequencies in order to eliminate the possible simultaneous reception of narrow-band transmissions from satellites or high flying aircraft. The switching time of the PIN diode was $< 10$ microseconds so that pulses of duration $\sim 1$ ms could be detected by using a chopping waveform of frequency $\gg 1$ kHz. Initially, however, the switching frequency was set at 270 Hz. The switch drive unit (Fig. 6-4) was designed by Dr. Drever, and constructed by Mr. McKellar.

After passing through the PIN diode, the signal was fed into a crystal mixer (Decca type MW19-16B) where it was mixed with the

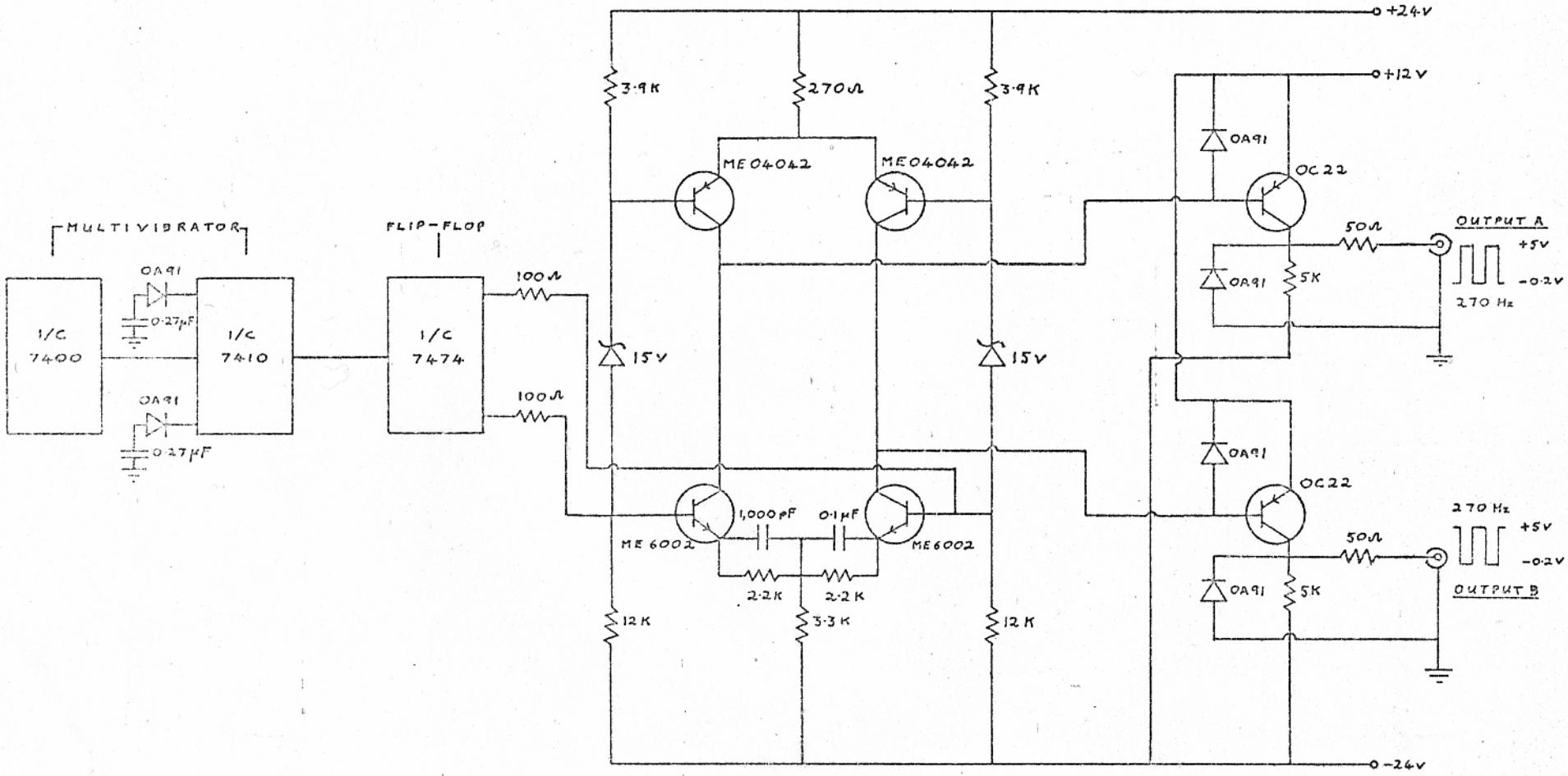



Fig.6-4 PIN-Diode switch drive unit.

local oscillator signal derived from a Gunn diode (Marconi type 6061). The local oscillator was tuneable over the range 8.5-12.0 GHz. As the mixer contained no selective circuits, the receiver also responded to the image signal. The IF was 60 MHz, and the preamplifier and main amplifier together gave a bandwidth of 20 MHz at both the signal and image signal frequencies. The system temperature $T_s$ was measured at a local oscillator frequency of 10.0 GHz, using the Argon discharge tube. The value determined was

$$T_s = 3{,}500^\circ \text{ K}$$

Following amplification in the preamplifier (Decca type 2426) which was attached to the rear of the antenna, the IF signal was brought from the radiometer mount into the recording room where further amplification took place. After the second rectification, the signal was correlated with the phase of the switching waveform, in a phase detector unit (Fig. 2-10), and then displayed on a pen recorder. The final RC time constant was 0.3 s yielding an effective integration time $\tau$ of 0.6 s. Thus, the minimum detectable temperature increment $\Delta T_{min}$ was

$$\Delta T_{min} = \frac{\sqrt{2}T_s}{\sqrt{2\Delta\nu\,\tau}} \qquad \text{(Equ 6-2)}$$

$$= 1^\circ\text{.4 K}$$

where $T_s = 3{,}500^\circ$ K

$\Delta\nu = 20$ MHz

$\tau = 0.6$ s

(The $\sqrt{2}$ in the numerator allows for the fact that the receiver only "observed" the signal for half the total time due to the switching. The $\sqrt{2}$ in the denominator allows for the presence of an image signal). A $1^\circ$ K temperature change corresponds to a power increment of

$$1.4 \times 10^{-23} \text{ W Hz}^{-1} \qquad \text{(unpolarised)}$$

Allowance for the collecting area and aperture efficiency of the antenna gave

$$\text{Minimum detectable flux} = 1.0 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1} \qquad \text{(unpolarised)}$$

For weather protection, the antenna and microwave assembly were contained in a large, 1000 gauge polythene cover. Observations of the sun showed that attenuation and beam distortion effects due to the cover were negligible.

6-3-3 The Equatorial Mount.

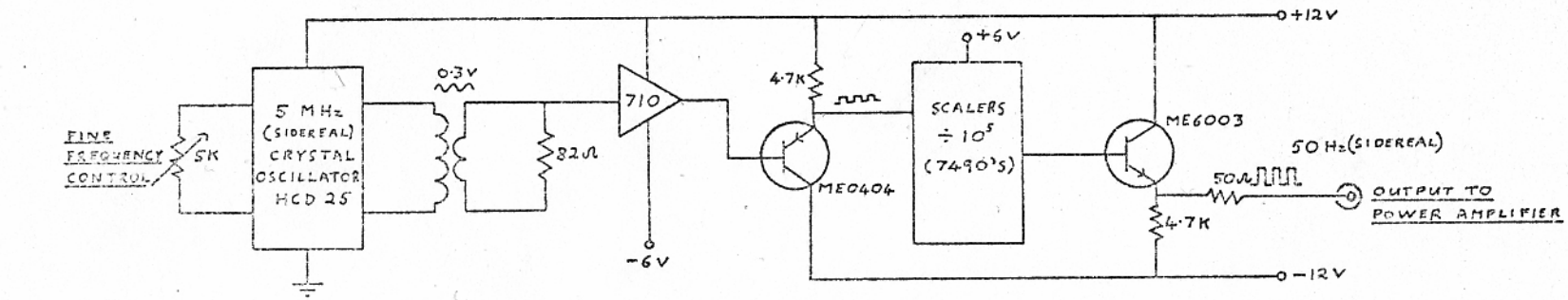
The design, construction and alignment of the equatorial mount were carried out almost entirely by the author. The control of the rotation speed by a sidereal crystal was at the suggestion of Dr. Jelley, while the designs for the motor drive frequency generator and power amplifier were accomplished by Dr. Drever.

The equatorial mount consisted of an old radar mast held in a steel Dexion frame. This was constructed so that the angle of the mast could be adjusted to bring it parallel to the earth's axis with an accuracy of about 1' arc. The antenna and microwave assembly were mounted on a declination axis at the mast head, allowing the observation of any astronomical object in the range $-31^{\circ} \leq \delta \leq +90^{\circ}$ (Fig. 6-5). Balance about the right ascension and declination axes was achieved with appropriately placed lead counterweights.

As in the VHF experiments, it was decided to perform observations at Cochno in order to reduce the reception of man-made interference. It was therefore important that the radiometer could rotate about the polar axis for several days, without resetting. This was achieved by controlling the motor drive speed with a 5 sidereal MHz crystal oscillator (Type HCD 25) which had a stability of probably better than 1 part in $10^8$. The signal frequency of the oscillator was divided down by a factor of $10^5$ using a series of scalers (Fig. 6-6) and the resulting output (50 sidereal Hz or 50.136895 Hz) was used to control the frequency of the motor power amplifier.

Fig.6-5 10 GHz radiometer and equatorial mount.

Fig.6-6 Drive frequency generator.



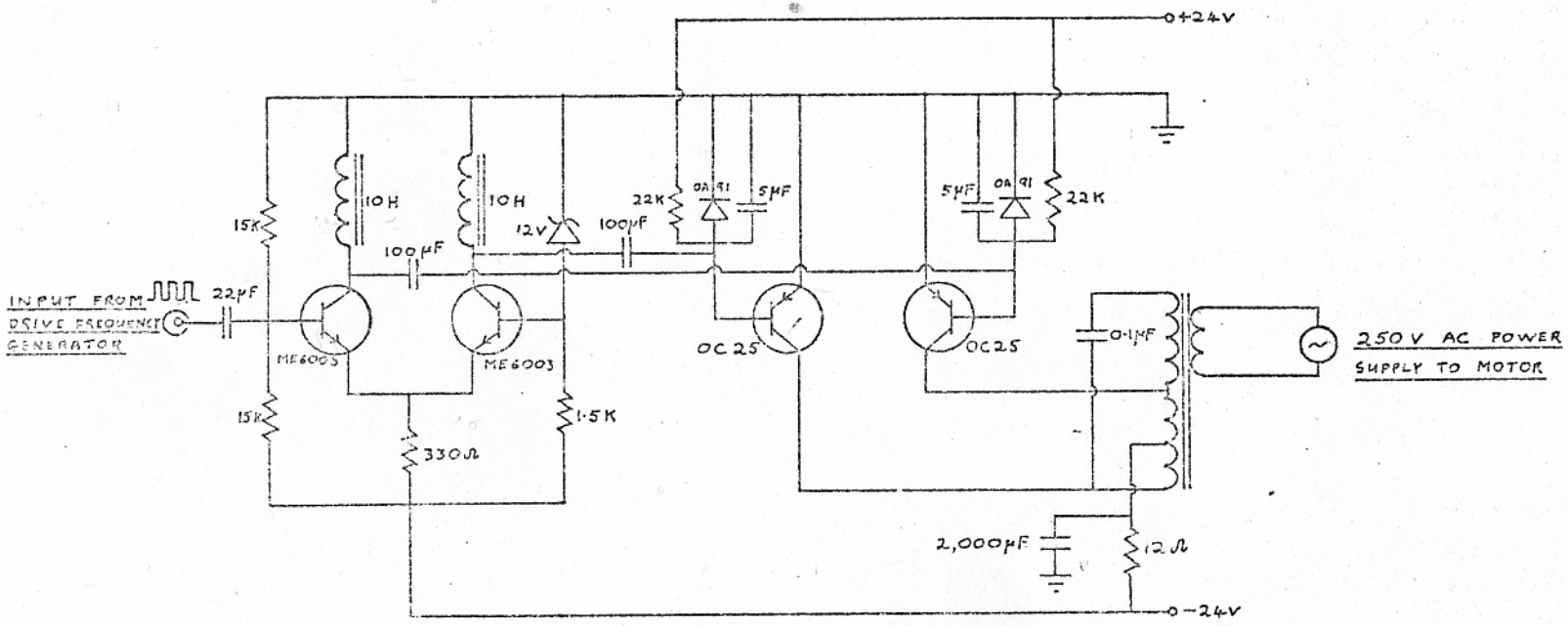




Fig.6-7 Motor power amplifier.

(Fig. 6-7). The mount was driven by a small, 250 V AC synchronous electric motor, running at 1 revolution per sidereal minute. The original radar mast contained gearing giving a reduction ratio of 60 to 1, and so a further reduction of 24 to 1 was acquired by placing a chain and sprocket assembly between the motor shaft and the mast drive shaft. The cables for the signal, power, PIN diodes and noise tube were allowed to unwind from and then rewind on to a drum placed immediately beneath the rotating section. This made it possible for the system to revolve for 6 days without attention.

A small, finder telescope ($7^{\circ}.5$ field of view) was attached to the dish and its optical axis was set parallel to the antenna beam axis by observing the sun.

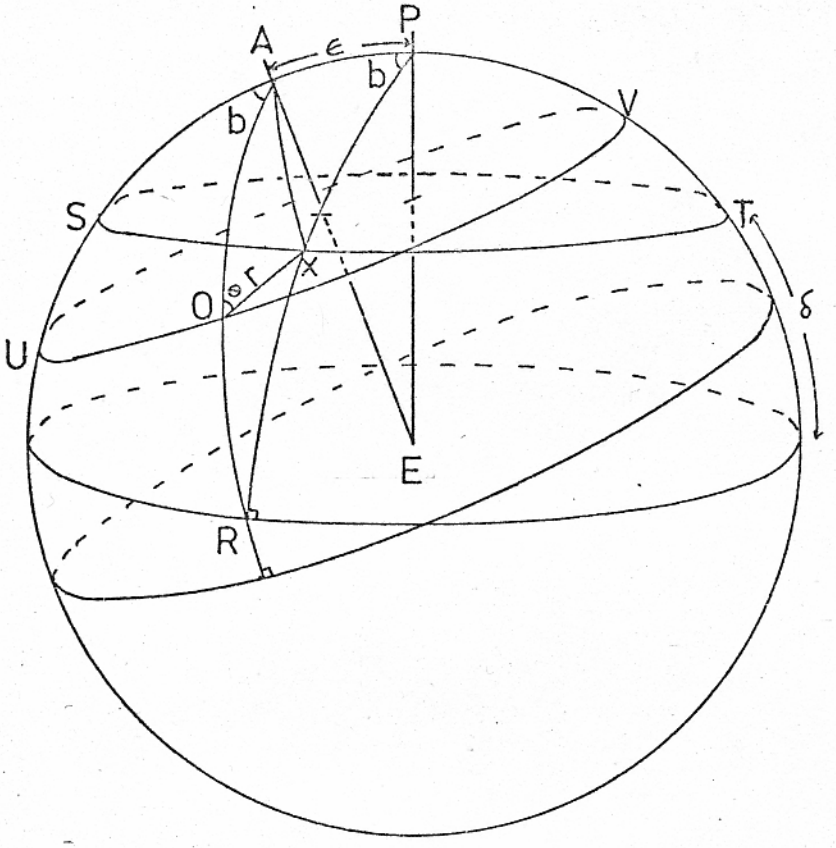
By using rough geometrical measurements and compass bearings, the mast axis was brought to within about $2^{\circ}$ of the polar axis. More precise alignment was achieved by using the following method devised by the author.

Let Fig. 6-8 represent the celestial sphere, with the radiometer mast AE making a small angle $\in$ with the polar axis PE. Let ST be the circle described by a star X of declination $\delta$. Since the mast was already roughly aligned with the pole, the dish and finder telescope could be directed at X so that it remained within the field of view throughout the sidereal day. Let UV be the circle described by the dish about AE such that UV would coincide with the circle ST if the axes AE and PE coincided. O is the point in the telescope field, fixed relative to the cross-wires, which coincides with X when X crosses the circle UV.

Since the dish and telescope rotate with precisely the same angular velocity as the celestial sphere, we have, at any moment,

$$S\hat{A}O = A\hat{P}X = b \qquad \text{(Equ 6-3)}$$

Fig.6-8 The celestial sphere, where AE represents the radiometer mast making a small angle $\epsilon$ with the polar axis PE.



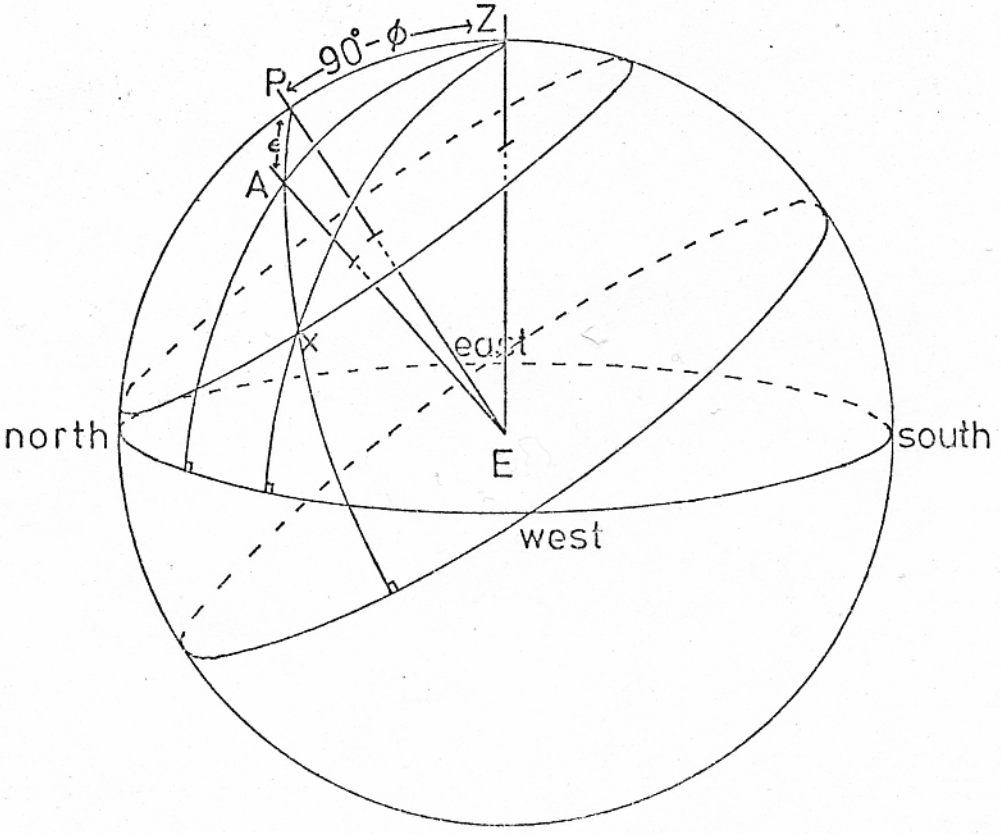




Fig.6-9 The celestial sphere at latitude $\phi$ at the instant that P, A and X lie on the same great circle.

Also, since $\epsilon$ is small, the great circles through AO and PX intersect at R where

$$PR \approx 90^{\circ}$$

Thus, by making the additional approximation $\sin\epsilon = \epsilon$

and $\cos\epsilon = 1$

we have:-

In $\Delta$ RAP, $\sin A\hat{R}P = \epsilon \sin b$ (Equ 6-4)

In $\Delta$ AXP, $\cos AX = \sin\delta + \epsilon\cos\delta\cos b$ (Equ 6-5)

In $\Delta$ AXO, $\cos AX = \sin\delta + r\cos\delta\cos\theta$ (Equ 6-6)

where $r = OX$

and $\theta = A\hat{O}X$

Combining Equs 6-5 and 6-6 gives

$$\frac{r}{\epsilon}\cos\theta = \cos b \qquad \text{(Equ 6-7)}$$

In $\Delta$ ROX $\sin O\hat{R}X = r\frac{\sin\theta}{\sin\delta}$ (Equ 6-8)

Combining Equs 6-4 and 6-8 gives

$$\sin b = \frac{r\sin\theta}{\epsilon\sin\delta} \qquad \text{(Equ 6-9)}$$

Squaring and adding Equs 6-7 and 6-9 gives

$$\frac{r^2\cos^2\theta}{\epsilon^2} + \frac{r^2\sin^2\theta}{\epsilon^2\sin^2\delta} = 1 \qquad \text{(Equ 6-10)}$$

which is the equation for an ellipse centred on O, of semi-major axis $\epsilon$ and semi-minor axis $\epsilon\sin\delta$.

Hence, viewed in the finder telescope, the star X describes an ellipse about the point O, the semi-major axis giving the magnitude of the error in the mast alignment. The extent by which the mast must be adjusted in azimuth and altitude to bring it parallel to the polar axis can now be estimated.

When the star X is at S in Fig. 6-8, this situation can be redrawn as in Fig. 6-9 where Z is the zenith of the observer at a site of latitude $\phi$, and P, A, and X lie on the same great circle.

At the instant shown in Fig. 6-9,

$$\hat{APZ} = \hat{XPZ} \qquad \text{(Equ 6-11)}$$

where $\hat{XPZ}$ = Hour Angle of X.

Therefore in $\triangle$ APZ

$$AZ = \cos^{-1}(\sin\phi + \epsilon\cos\phi\cos\hat{XPZ}) \qquad \text{(Equ 6-12)}$$

Hence, mast altitude correction = $AZ - (90^\circ - \phi)$ (Equ 6-13)

Also, in $\triangle$ APZ,

$$\hat{PZA} = \epsilon \cdot \frac{\sin\hat{XPZ}}{\sin AZ} = \text{mast azimuth correction} \qquad \text{(Equ 6-14)}$$

In the procedure adopted by the author, the star Epsilon Aurigae was observed over a period of ~12 hours, and its positions on the ellipse were noted at different times. From this, the sidereal time was interpolated at which the star reached the upper vertex of the ellipse. After calculating the Hour Angle of Epsilon Aurigae at this time, the necessary corrections were obtained. In this way, the mast was aligned with the pole to an accuracy of better than 10' arc.

Subsequent observations showed that the dish remained pointing at any object of interest for periods of weeks without any sign that it was drifting off target.

## 6-4 Observations

The microwave radiometers at Glasgow and Harwell became operational in 1972, January. At first, the Glasgow system contained only a DC output channel. However, it was found that when the gain was sufficient to give a reasonable noise "width" on the trace, large amounts of running time were lost due to the pen being driven off-scale by changes in the temperature difference between the horn and the dish. This was usually caused by clouds. In order to compensate

for this, the DC gain was reduced so that the trace stayed on scale for most of the day, and an AC channel with a higher gain was added. The differentiation time of this new channel was 10 s.

In general, man-made interference was found to be much less than in the VHF observations. However, during periods of rain, the data was unusable due to rapid temperature fluctuations caused by rain-drops falling on the dish and reference horn.

Before beginning a supernova search, involving runs of several months on the Coma and Perseus Clusters, it was decided to carry out several shorter periods of observation of Galactic objects which might produce sudden outbursts of energy. The Galactic Centre, and two possible black holes (Cygnus X-1 and Beta Lyrae) were selected for these early studies.

6-4-1 The Galactic Centre

At the time that this experiment was performed, (1972, January 21 to 1972, February 11), only one report of a search for microwave pulses from the Galactic Centre had been published (Partridge, 1971). The threshold sensitivity used by Partridge was ~ x70 higher than that used in this experiment and so it was hoped at least to improve on his constraints by this factor. However, following the observations of the Galactic Centre described here, Partridge and Wrixon (1972) reported negative observations at a threshold which was ~ x50 LOWER than that of the present work (see Chapter 7).

Simultaneous observations of the Galactic Centre were carried out at Glasgow and Harwell for a total of 70 hours. Owing to the reduced interference at 10 GHz, the pulse selection threshold could be reduced to the width of the "peak to peak" noise or $\sim 4\sigma$. During the above observing time, no pulses exceeding a flux of

$$5 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1} \qquad \text{(unpolarised)}$$

were detected from the direction of the Galactic Centre. According to Weber (1972), he would have detected about 7 coincidences during the above running time. It is therefore unlikely that there are microwave pulses exceeding the above flux, associated with these events.

6-4-2 Beta Lyrae

Following the suggestion by Devinney (1971) that the eclipsing binary system Beta Lyrae might contain a black hole, microwave observations were made of this object from 1972, January 7 to 1972, January 19. In 56 hours of simultaneous running time, 1 coincidence was obtained. The pulse shapes at the two stations were highly dissimilar, and so it was probably a chance coincidence. The number of coincidences expected in the above observing time was $\frac{1}{2}$. The sensitivity threshold at Glasgow was somewhat higher than in the Galactic Centre observations, being

$$10^{-21} \text{ W m}^{-2} \text{ Hz}^{-1} \quad \text{(unpolarised)}$$

6-4-3 Cygnus X-1

In view of the fast fluctuations in the X-ray flux from this object, and the suggestion by Webster and Murdin (1972) that it might contain a black hole, the author proposed that a series of microwave observations of Cygnus X-1 should be carried out. Just after this proposal, Douglass and Tyson (1972) pointed out that if Weber's events were being caused by linearly polarised gravitational waves, then the observed sidereal anisotropy would be consistent with a source lying in the direction of this X-ray object.

Before observations began, it was already known that Cygnus X-1 contains a microwave source which is strongly variable over a time-scale of several days (Braes and Miley, 1971; Hjellming and Wade,

1971), but searches for pulsed VHF emission had proved negative (Mohanty et al, 1971; Taylor et al, 1972). However, these searches only lasted for about an hour, and so would have been unlikely to detect pulses of greater time separation than this.

Cygnus X-1 was observed at 10 GHz from 1972, March 7 to 1972, March 20. The Glasgow-Harwell overlap times on the DC and AC channels were respectively 105 hours and 170 hours. No coincidences were obtained within a 1 minute resolving time. The expected number of chance events in each channel was 1, and the threshold sensitivity was

$$8 \times 10^{-22} \text{ W m}^{-2} \text{ Hz} \qquad \text{(unpolarised)}$$

6-4-4 The Coma Cluster

It was decided to begin extended searches for microwave pulses from supernovae by observing the Coma Cluster, since this object contains about 1000 galaxies within a $6^{\circ}$ diameter field. Observations took place between 1972, April 19 and 1972, September 5, and the total overlap time amounted to about 850 hours. For pulses arriving within $2^{\circ}$ of the beam axis, the sensitivity threshold was never poorer than

$$8 \times 10^{-21} \text{ W m}^{-2} \text{ Hz}^{-1} \qquad \text{(unpolarised)}$$

10 coincidences within a 1 minute resolving time were detected, which can be compared with a chance number of 8. Individual scrutiny of these 10 prompt events has not yet been carried out, but the chance rate would seem to imply that the genuine pulse rate cannot exceed about

$$1 \text{ event per } 10^{3} \text{ hours.}$$

The fraction of the cluster which was observed above threshold amounted to $\sim 50\%$, so that if variations in galaxy density are ignored, about 500 galaxies were included in this study. If a super-

nova rate of 1 per galaxy per 37 years is assumed then about 1 supernova should have occurred in the Coma Cluster during the above observing time. However, it is known that a high proportion of the cluster members are elliptical galaxies which have a much lower supernova production rate than the average rate for all galaxies derived by Tammann (1970). It is therefore very likely that no supernovae occurred during the observations. Clearly, however, much longer observing times are necessary to obtain a significant excess of real events over random, even for clusters having average supernova production rates.

# Chapter 7

# Conclusion

## 7-1 Implications of the Negative Results

### 7-1-1 Radio Emission from Supernovae

The failure to detect VHF radio pulses from supernovae can be interpreted in several ways:-

(i) If the Colgate model for radio emission is qualitatively correct, the shock acceleration of the outer shell may simply have been overestimated. To some extent, this was anticipated by Colgate et al (1972), but the results of the present work imply that the radio energy predicted even by the revised theory is probably too large.

(ii) The predictions of the Colgate theory are derived from an initial presupernova star which has a magnetic field, but is not rotating. The existence of a star having zero angular momentum seems rather unlikely. LeBlanc and Wilson (1970) have considered the history of a rotating magnetised star of 7 $M_\odot$ , which undergoes gravitational collapse. In their model, the magnetic and angular momentum axes are coincident. They found that during the collapse, a vortex is formed on the axis, and a toroidal swirl is produced at the centre. This swirl has the effect of concentrating the magnetic field along the axis, which in turn gives rise to the axial ejection of a jet of material 2-3 s after collapse begins. The importance of this result is that a shell of material is NOT radially ejected and so the coherent radio pulse mechanism predicted by Colgate et al, cannot arise. Even if in general, the magnetic and rotation axes are

not parallel, it seems likely that the effect of rotation will reduce the magnitude of a radially expanding current sheet.

(iii) The possibility has already been discussed, that excessively high electron densities could cause screening or extreme dispersion of VHF events. As yet, insufficient observations have been made at microwave frequencies to resolve this question. However, the rapid decline of the spectrum at high frequencies predicted by Colgate et al, implies that microwave pulse detection can only be accomplished by using systems of much greater sensitivity than that described in Chapter 6. It must also be pointed out that for screening or dispersion to have been directly responsible for the negative results, much higher electron densities than those generally encountered, would have to be present.

7-1-2 Radio Pulses Associated with Weber's Events

The apparent absence of radio emission associated with Weber's coincidences could also have several explanations:-

(i) The point of origin of Weber's pulses may never rise in the British Isles. However, there are no likely sources which fit into this category.

(ii) There may exist gravitational wave generators which produce remarkably little electromagnetic radiation. Hawking (1972) has remarked that the only possible process which could emit such "pure" gravitational radiation would be in the collision of black holes. This would be consistent with the requirement that

if Weber's events are caused by gravitational radiation, then the source must be able to convert matter into this form with very high efficiency.

(iii) The same arguments as those given above concerning plasma screening or high dispersion, can be applied to possible sources of gravitational radiation.

(iv) Associated electromagnetic radiation may be emitted over timescales $>> 10^3$ s and so might not have been detected in the present work.

(v) Weber (1971b) has argued that gravitational emission would be expected to be limited to frequencies below $10^6$ Hz since only large masses are involved, whereas the available bandwidth for radio emission is the entire electromagnetic spectrum. In reality, this argument appears to be rather unreasonable. If pulses of electromagnetic energy, comparable in magnitude to the gravitational energy required to produce Weber's events were spread evenly over the spectrum to the extent that they would not have been detected in the present work, then their bandwidth would have to be at least $10^{30}$ Hz. No pulse sources capable of radiating evenly over this frequency range are known (e.g. NP 0532 possibly does not radiate above $\sim 10^{27}$ Hz (Fazio et al, 1972) and its spectrum falls off rapidly at high frequencies).

(vi) Finally, the possibility must be raised that Weber's events are not astrophysical in origin. The strongest argument in favour of gravitational waves originating in a cosmic source lies in the sidereal anistropy which Weber observed. At the time of writing, there are no reports describing the successful repetition of this

experiment.

### 7-1-3 Smith's Events

In view of the results presented in Chapter 3, Part 2, it seems probable that the 45 MHz bursts detected by Smith were not astrophysical in origin. The most likely explanation of these early observations is that they were produced by brief transmissions from aircraft.

## 7-2 Interesting Events Observed

### 7-2-1 Coincident Events

During the VHF experiments, three exceptional coincidences were obtained (Figs 3-1, 4-5 and 5-2). The multiple events detected on 1970, January 11 and December 4 were probably not of extra-terrestrial origin, although geophysical causes for these pulses cannot be ruled out.

Two astrophysical events of distinction occurred near the time of the coincidence of 1970, July 28. On this day between $0^h$ UT and $16^h.15$ UT, Nova Scuti 1970 flared up (Table 3-5). In addition, a few days before 1970, July 30, Supernova 1970g exploded in the M101 cluster (Table 3-7). The eruption of this supernova occurred at a distance of 8 Mpc, making it the nearest of the entire VHF experiment. The maximum distance of the nova was 11.5 kpc. The light curves of these two objects are shown in Fig. 7-1. At the time of the radio event, the nova and supernova were above the horizon and within $\sim 2$ hours of transit. It is therefore interesting to consider the possibility that either eruption gave rise to the coincidence.

The detected pulse had a S/N $\gtrsim$ 20/1 and lasted for $\sim 10$ s. The lower limit to the incident energy is therefore

$$\sim 3 \times 10^{-22} \text{ J m}^{-2} \text{ Hz}^{-1}.$$

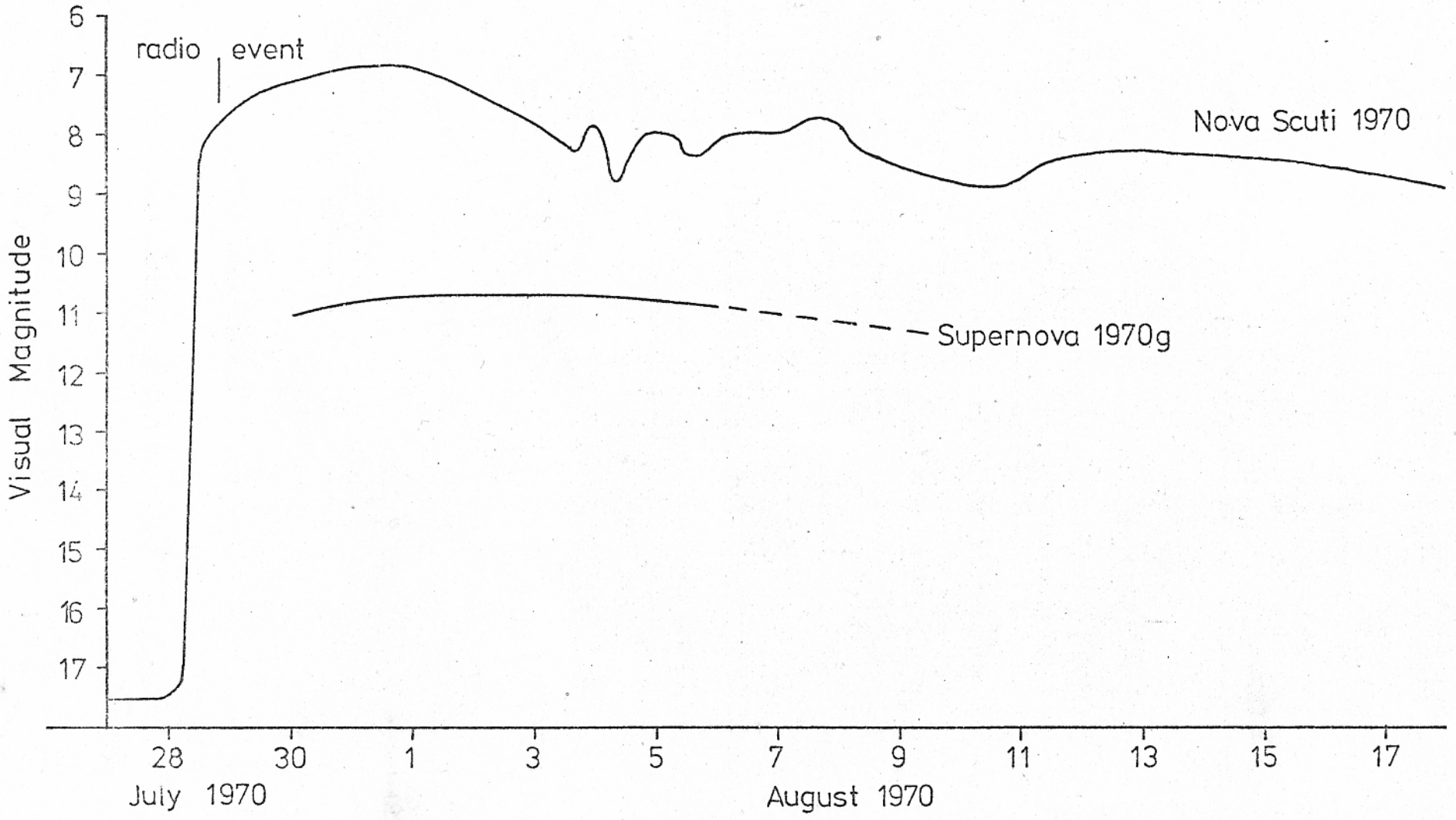



Fig.7-1 Light curves of Nova Scuti 1970 and Supernova 1970g. The time of the event of 1970 July 28 is also shown. The supernova curve has been extrapolated (broken line).

Assuming isotropic emission, the minimum energy release necessary to produce the observed pulse was

$4.5 \times 10^{20}$ J $Hz^{-1}$ for Nova Scuti 1970

and

$2.2 \times 10^{26}$ J $Hz^{-1}$ for Supernova 1970g.

Neither of these lower limits conflict with the constraints determined in Chapter 3. However, neither the nova nor the supernova was of sufficiently low declination to enter the main beam of the arrays. Thus if the pulse was caused by either object, the energies involved must have been considerably greater than the above values.

Nova Scuti 1970 was first observed about 4 hours before the radio event, which probably means that it was not the source. In addition, if the dispersion measure of $\sim 3{,}500$ $cm^{-3}$ pc is accepted (see Chapter 4) then this value is rather large for a Galactic nova. For Nova Scuti 1970, a uniform electron density of 0.05 $cm^{-3}$ would result in a dispersion measure of $\sim 500$ $cm^{-3}$ pc. For these reasons it appears that the supernova is a better candidate for the pulse source. Also, the probability that it exploded while above the horizon at night was 33% compared with only 13% for the nova. However, owing to the pulse saturation and lack of information concerning the sidelobe size, a definite energy estimate is not possible.

7-2-2 Non-Coincident Events

The directional studies at Cambridge indicated that 15% of all the local events detected, originated within $55^{\circ}$ of the zenith. It therefore seems unlikely that all the pulses obtained at any one station were man-made in origin. Suggestions have been made that many of these localised emissions might be attributable to atmospheric electrical discharges or cosmic-ray bursts striking the upper ionosphere. Further investigations of these possibly geophysical events

should be carried out. Spectral information and meteorological correlations might provide clues as to their source.

## 7-3 Other Searches for Radio Pulses

Subsequent to the commencement of the present work, several other investigators conducted experiments similar to those described herein.

(i) Searches were made for microwave pulses which might be correlated with Weber's events (Partridge, 1971; Partridge and Wrixon, 1972). It was found that in 90 hours observation at 16-19 GHz, no associated pulses of a flux exceeding

$$9.6 \times 10^{-25} \text{ W m}^{-2} \text{ Hz}^{-1}$$

were detected from the direction of the Galactic Centre. Indeed, no pulses at all, exceeding

$$10^{-23} \text{ W m}^{-2} \text{ Hz}^{-1}$$

were received from this object.

(ii) Hughes (1972) performed drift scans of the Galactic Centre at 858 MHz using an 18.3 m antenna. In 270 hours observation, 97 pulses of amplitudes

$$8\text{-}50 \times 10^{-25} \text{ W m}^{-2} \text{ Hz}^{-1}$$

were detected. The experiment involved only a single station so that some of the events may have been caused by interference. However, Galactic Centre observations produced a 5-fold increase in the pulse rate relative to that obtained at other times. As yet, no prompt coincidences with any of Weber's events have been found but Hughes claims that the possibility of some correlation cannot be excluded.

(iii) Colgate et al (1972) searched for dispersed pulses (~0.1-100 s duration) from supernovae, using single frequency-tracking receivers at two frequencies. The 400 MHz system had an

antenna of $\frac{1}{2}$-maximum sensitivity beamwidth $\approx 100^{o}$, and a 60 kHz bandwidth, yielding a threshold sensitivity of

$$\sim 2 \times 10^{-19} \text{ W m}^{-2} \text{ Hz}^{-1}.$$

At 1.4 GHz the beamwidth was $30^{o}$ and with a bandwidth of 500 kHz, a sensitivity of

$$\sim 4 \times 10^{-20} \text{ W m}^{-2} \text{ Hz}^{-1}$$

was obtained. No dispersed events were detected with either system in 100 hours observing time.

## 7-4 Future Work

At 10 GHz, the time spent observing clusters of galaxies will have to be increased by a factor of x10 at least, before any definite constraints can be placed on microwave emission during supernova eruptions. However, if this measure produces negative results, then it appears that for any future pulse search to be successful, the threshold sensitivities must be improved.

It is reasonable to expect that broadband microwave pulses of intrinsically short duration (~1 ms) would preserve their widths during the traversal of space. Thus, a logical step would be the construction of recording systems with response times in the region of 1 ms. By this procedure, the sensitivity to such brief pulses could be increased by a factor of about x10. It is the author's intention to attach a short time constant recording system to the radiometer described in Chapter 6.

Sensitivity improvements by factors of over x100 would be possible at microwave frequencies by the use of low noise preamplification devices such as parametric amplifiers or masers. Thus, under ideal conditions, reduction of the integration time and system noise

might produce a sensitivity increase of $\times 10^3$. For the radiometer described in the present work, this would allow the detection of pulses of energy

$$\gtrsim 10^{-25} \text{ J m}^{-2} \text{ Hz}^{-1}$$

However, the improved sensitivity to rain, clouds and man-made interference would probably result in a higher threshold than this. Larger collecting areas would clearly allow further threshold reduction.

At VHF, sensitivity increases are possible only by using antennae of greater gain. Among the most energetic VHF pulses received from a source definitely beyond the solar system are the strong pulses from NP 0532 observed by Gower and Argyle (1972) using a 25 m antenna. Nevertheless, their largest recorded pulse had an energy of only

$$1.2 \times 10^{-24} \text{ J m}^{-2} \text{ Hz}^{-1}$$

which would have been undetectable by any of the VHF systems used in the present work. In addition, the apparently positive results of Hughes (1972) were achieved with an 18.3 m dish. It is therefore likely that in studies of transient events, as in conventional radio-astronomy, large antennae are necessary.

The pulsars remain as the only sources beyond the solar system known to emit radio bursts of duration $< 1$ s. These objects could have been detected 15 years before their actual discovery if short integration times had been used. Notwithstanding, it is probably significant that their existence was finally revealed by the use of one of the largest collecting areas in the world at the time.

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