AN INVESTIGATION INTO THE DECAMETRIC RADIO EMISSION BY THE PLANET JUPITER

A thesis presented in partial fulfillment of the requirements for the degree of Doctor of Philosophy of Rhodes University

by

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To

Glen, my wife

and

Doc and Mama, my parents

C O N T E N T S

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INTRODUCTION

Jupiter is the largest planet in the solar system. Its distance from the Sun is five times that of the Earth and its mass is nearly two and a half times that of all the other planets added together. Jupiter turns about its own axis rather rapidly, once in just under ten hours, and it completes one revolution about the Sun in just under twelve years. Thus Earth has to pass almost directly between the Sun and Jupiter once every thirteen months. When this happens Jupiter is said to be in "opposition", as its position is then opposite to that of the Sun, when viewed from Earth. Around this time the planet will be most favourably placed for observations, as it is at its closest to Earth and up in the sky for a large part of the night. During the day observations on radio frequencies are more difficult, as the Sun is a source of great interference.

Besides being an emitter of thermal electromagnetic radiation, as one would expect, Jupiter also emits two kinds of non-thermal radiation, one in the decimetre wavelength range and the other in the decametre wavelength range. A large number of scientists have worked on the problems of decimetre and decametre radiation. This thesis deals with some aspects of decametre radiation.

It is usually thought that radio astronomy involves the use of rather expensive equipment. However observations in the decametre wavelength region can be carried out without having to budget for large sums.

The sort of research reported in this thesis was done for a fraction of the amount required for decimetre observations. Our Jupiter research project was started in 1961, using second-hand world war II equipment. The total initial costs of all apparatus needed was certainly less than R300.

In the early days of Jupiter observations on radio frequencies, most observations were made around 20 Mc/s. For this reason our first observations were attempted at 18 Mc/s and 22 Mc/s. This equipment was set up in a hut built near the Jameson water reservoir, about eight miles from Grahamstown. During July 1962 the author was able to record his first observation of signals which were definitely coming from the "Giant Planet". Although this was seven years after the discovery that Jupiter emits electromagnetic radiation in this frequency range, the feeling of achievement was still very exciting.

The results of the year's observation which showed the dependence upon rotational period of the planet, confirmed previous observations by other observers. After publication we were invited by Professor C.H. Barrow of Florida State University, Tallahassee, to collaborate with him in a joint program, as we could observe Jupiter, when it was unobservable from Florida, due to the rotation of the Earth.

At the beginning of 1964 a new site was chosen closer to the town and near a better road. On account of this we could think of extending our observations and since theoretical considerations at that time indicated that observations of polarization of Jupiter bursts were most important in the frequency region 15 Mc/s to 25 Mc/s, it was decided upon to construct a swept frequency polarimeter covering this frequency range. This instrument's primary function was to determine the sense of polarization of Jupiter's radiation and its possible variation with frequency.

Initial tests were carried out during 1964. For the 1965 observing season a completely redesigned receiver was constructed, as described later, and definite observations were carried out. During the time between completion of the apparatus and the start of the observing season, the author's interest was directed towards results published in an International Geophysical Year report. In this report results obtained by an American group of Scientists during five years of observations were presented.

A remark by Professor Gledhill, my supervisor in this research project, led me to do some statistical investigation using these results. As one thing leads to another, interesting conclusions snowballed and some completely new aspects were obtained. These are presented in Chapter V of this thesis and, should the author be correct, influence future observations of decametric radiation emanating from the planet Jupiter.

CHAPTER I

Some aspects of Jupiter's decametric radiation

It was purely by chance that one of the strongest sources of decametric radiation was discovered (Burke and Franklin 1955; Franklin, 1959). During the first few months of 1955, Burke and Franklin were improving the receiver and auxiliary equipment attached to the 22.2 Mc/s Mills Cross, an antenna which had been built to produce a survey of the sky at that frequency. In order to judge the results of their improvements, they decided to direct the pencil beam (about 2.5° wide at half-power points) to the declination of the Crab Nebula, the strong radio source in Taurus, and compare records before and after each modification. They also decided to build up a two dimensional picture of this part of the sky, during which they arbitrarily directed the antenna beam southward by about 1° at three to four week intervals.

The records showed the characteristic hump as the Crab Nebula passed through the antenna beam. At times the recordings showed a feature which appeared to be one of interference. They joked that it was probably due to faulty ignition in the car of a farm hand returning from a date.

Investigating this interference more fully, Burke discovered that this was turning out to be "some strange romance". The "swain" was returning home earlier each evening. Upon further investigation it was found that whenever this "interference" was received, Jupiter was in the reception beam of the antenna. Not only did this source have the same direction in space as Jupiter, but it also exhibited the same change of direction as this planet during its retrograde loop of 1955. From this it was concluded that Jupiter must be the source of the decametric radiation.

They determined the power density received on Earth at 22.2 Mc/s to be of the order of $5x10^{-23}w.m^{-2}.cps^{-1}$. From this they suggested that the radiated peak power per burst must be at least 300 watts per cps of bandwidth.

Since that time 10 years have passed and a lot of observations have been carried out. Theoreticians as well as practical workers have applied themselves to the problem of Jovian decametric radiation.

To attempt relating, even in a very superficial manner all the research work that has been done on Jupiter's decametric radiation would be far beyond the scope of this investigation. As certain aspects of Jupiter's radiation are to be discussed, we will show what is known about them in some detail.

1.1 The longitude dependence of Jupiter's decametric radiation

Following Burke and Franklin's discovery, Shain (1955, 1956), who found traces of Jupiter radiation on some of his recordings going back as far as 1951, plotted burst activity versus longitude of the Central Meridian (CML), using System I as well as System II co-ordinates. These two systems of co-ordinates describe the mean rate of rotation of the clouds seen in the equatorial and temperate zones of the planet. Although there was a definite drift with respect to System I co-ordinates, Shain found that when System II co-ordinates were used, there was little drift. He concluded that the source of radiation rotated with the planet, at a rate approximately equal to the System II rate, but, as indicated by a slight negative drift with respect to those co-ordinates, somewhat faster. He also plotted a histogram, allowing for the slight drift rate. This shows the characteristic appearance Jupiter Observers know so well.

These results were confirmed by a number of workers, (e.g. Barrow et al, 1957; Carr et al, 1958; Gallet, 1957; Burke, 1961; Franklin and Burke, 1958).

Carr et al (1958) proposed the so-called "System III", which had a rotation equal to that of the radio sources. Three years later they published a revised equation (Carr et al 1961) which gives the relationship between System III (L_{III}) and System II (L_{II}) co-ordinates and the Julian date (J). This equation is

$$L_{III}^{(1957)} = L_{II} + 0.2747\ (\ J - 2435839.5)$$

This means that System III rotates with a period of $9^h 55^m 29.37^s$ and coincided with System II longitudes at 0^h UT on January 1st, 1957.

It is now generally accepted that the period of rotation of System III is the probable rotation period of the magnetic field of Jupiter.

Histograms, showing the probability of occurrence as a function of System III CML of the planet, have been published by many investigators for virtually the whole frequency range, over which Jupiter noise has been observed.

Jupiter's decametric radiation, which is generally very burstlike in nature has to date been observed on all frequencies from 3.5 Mc/s (Zabriskie et al, 1965) to 43 Mc/s (Kraus 1958). The last mentioned limit was however only an aural observation and has not been confirmed by any other observer. Warwick (1963) shows spectograms, which do indeed show beyond doubt, that Jupiter emits decametric radiation beyond 38 Mc/s.

The largest number of observations can be made in the vicinity of 18 Mc/s. Fig. 1. shows the histogram constructed from data obtained by the author at 18 Mc/s at our local observatory (Gledhill et al. 1963). It shows the usual characteristic features. The various peaks are generally called "Sources". The following nomenclature for source regions on Jupiter was adopted by the Jupiter Observers Conference at Goddard Space Flight Centre during April 1965.

System III longitude range in degrees	Designation
0 - 70	D
70 - 190	B
190 - 280	A
280 - 360	C

Histograms constructed for different years and frequencies practically all show a prominent peak between 200° and 280° CML and a secondary peak between 90° and 160° CML, as well as one around 320° CML. Franklin and Burke (1958)

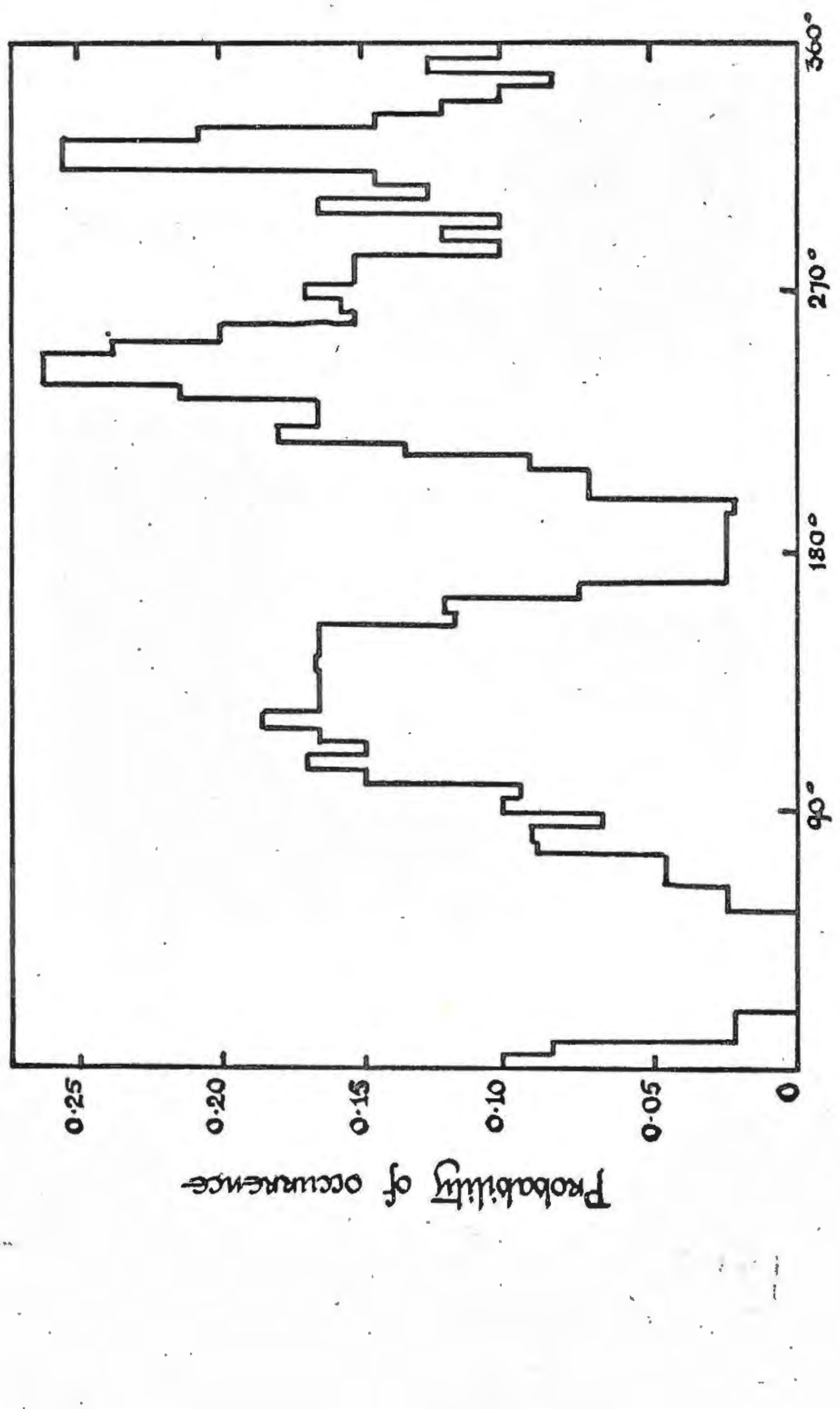


Fig. 1 Histogram of Jupiter noise at 18 Mc/s

and Gardner and Shain (1958) noticed that the main peak was narrower at higher frequencies.

Since 1960 a swept-frequency receiver (Lee and Warwick, 1964) has been operating at the High Altitude Observatory at Boulder, Colorado. (Warwick 1961, 1963a). From the recordings it was established that the emissions occur over a range of frequencies throughout a storm. It was also noticed that there was a tendency for positive frequency drifts to occur at what is now known as Source B and negative frequency drifts to occur at large values of L_{III}, now known as Source A. These characteristic features of the spectra tend to be repetitive and have durations of several minutes to an hour. Finer details do not repeat.

Fast recordings (Gardner and Shain, 1958; Gallet, 1960) show that the bursts come in groups. Ellis (1964b) found that the stronger bursts seemed to be superimposed on a fairly weak background signal. Short pulses have been reported by Gallet and Kraus (reported by Douglas and Smith 1961) and confirmed by Douglas and Smith (1961). Recently Baart et al (1966) reported having observed very short pulses, the occurence of which is also dependent upon System III longitude.

There is another interesting feature, which must be mentioned. Ellis (1962b), when reporting his observations at 4.8 Mc/s showed, that while the number of occurrences of Jupiter storms at that frequency was uniformly distributed over the System III longitude co-ordinates, the relative average power was indeed greatly dependent upon the System III CML position. The histograms show two distinct peaks, one just below 180° CML and another one just below 360° CML.

In a recent paper (McCulloch andEllis 1966) it is shown that there is little difference in histograms, irrespective whether the relative power or the probability of occurrence is considered for events which take place at frequencies above 20 Mc/s. If, however, frequencies below 20 Mc/s are considered, it is found that for frequencies above 10 Mc/s histograms of probability of occurrence tend to lose their characteristic appearance of three peaks. The histograms plotted using relative power tend to become more distinct in their characteristic appearance. This indicates that weak events can occur over a wide range of longitude, while the stronger events are confined to narrow longitude intervals corresponding to the peaks in the power longitude profiles. The longitude profiles obtained for the probability of occurrence by including only strong events can be very different from that obtained by including all events strong or weak.

These results are in agreement with those published by Stone et al (1964), who reported that when using high sensitivity instruments the peaks in their histograms are somewhat broadened in comparison to results of other workers at the same frequency. Even though the sources are "broadened", they were unable to detect any activity whatsoever in the longitude interval from 330° to 70° CML. They reported that this preliminary analysis of the intensity distribution at 26.3 Mc/s suggests two components of emission. If this suggestion is supported one would have to consider the possibility that the radiation is emitted in two modes, from two radiation belts or even by two different mechanisms.

Until 1963 most observers, who attempted to establish estimates of the rotational period, found no significant departure from the adopted mean period (System III (1957.0) - $9^h55^m29.37^s$). However in September 1963, Douglas and Smith (1963b) reported that from observations which they had carried out during 1961 - 1963 at a frequency of 22.2 Mc/s, it appeared as if the rotational period of the radio sources had lengthened by approximately 0.8 sec. This was confirmed by Smith et al (1965). An interesting feature of this occurrence was the fact that a similar change in period of the Great Red Spot was also reported at the same time. The conclusion was therefore drawn by some workers that the rotational period of the whole planet may have changed. However Warwick, using his method of "landmarks", did not find such a deviation for the System III period for the same observing seasons.

Since most theories, which try to explain the origin of Jupiter's decametric radio emission, link the emission to the planets magnetic field and thus by presumption to the core, such observations are very important in formulating models of the planet.

In a rough draft of a paper to be published by Gulkis and Carr (1966), it is pointed out that upon critical re-examination of the available data of 18 Mc/s observations of Jupiter, it can be concluded that the apparent rotation period drifts cyclically about a constant mean value. The most probable drift period appears to be 11.9 years, Jupiter's orbital period. They find that the mean rotational period during one revolution is about 0.3^s longer than the accepted System III period. This agrees closely with determinations of the rotational period using decimeter results. It is pointed out that this probably represents the true rotation period of the magnetic field. They also point out, that the inverse sun-spot relationship, which has puzzled observers for many years, might be due to the variations of the emission cone with the variation in the declination of the earth as seen from Jupiter. This had previously been pointed out by the author (Gruber 1962), but never carried further.

Smith et al (1966) in another draft publication use results for four different frequencies, 15 Mc/s, 18 Mc/s, 22.2 Mc/s and 27.6 Mc/s. They find that there is evidence that the observed source drift is frequency dependent. This implies that the drift may be a virtual effect which might perhaps be related to the mechanism of escape of the radiation.

1.2 <u>The Io dependence of Jupiter's decametric radiation</u>

Some of the earliest Jupiter workers (Carr et al, 1958) had already noticed that Jupiter's activity seemed to occur in cycles consisting of 3 or 4 days of sporadic radiation followed by a like period of relative inactivity. They found the average period of this effect to be 8.0 days. They suggested that it might arise from tides in Jupiter's ionosphere due to one of the satellites (Ganymede; period 7.17 days). However Carr (1959) reports that Douglas and Smith of Yale have pointed out that it is much more likely to be a stroboscopic effect between the rotational period of the active areas on Jupiter and the observers rotational period on Earth.

Six (reported by Dulk, 1965c) noted in his Ph.D thesis that a seven-day cycle appeared in the 60 days of data centred on 1961 opposition, but that a similar cycle was absent in the 1960 data.

Warwick (1964) states that observations at the HAO indicate that spectra are often of startling similarity. These similar spectra do not necessarily occur in the same year, but several events have been observed where pairs of similar spectra had occurred with a time interval of approximately one month.

Dulk (1965c) pointed out that all these effects can be explained by the beat phenomenon between Jupiter's period, Io's period and the one-day observational period due to the Earth's rotation.

The fact that Jupiter's largest Galilean satellite Io affects the emission pattern of the decametric emission was pointed out by Bigg (1964). Arguing that since the moon exerts at least some control on the Earth's magnetic field through the electrons in or beyond the Ionosphere, it might be possible that Io influences the signals coming from Jupiter.

Using the results of Warwick and Kreiss (1964), Bigg calculated and plotted the product of total intensity times the duration in each 10 minute interval versus the departure of Io from Superior Geocentric Conjunction (SGC). Using all the data independent of frequency, he found that there is a maximum at 93° and at 246° from SGC. Using data cases where the top frequency of the storm exceeds 30 Mc/s, he showed that the apparent control is far more complete. Bigg also showed that it is mainly source B which emits when Io is in the vicinity of 90° from SGC and mainly source A when Io is in the vicinity of 240° from SGC. He pointed out that although there is a possibility that the other satellites may contribute to this effect it would require much more sophisticated treatment to reveal the extent of their influence, as the ratio of their period is approximately 1 : 2 : 4 : 8. His treatment does at least predict with certainty that Io's period has the strongest influence. Bigg also showed that the effect depends on the position of Io with respect to the Earth - Jupiter line and not the Sun - Jupiter line.

Lebo et al, (1965) examined the data obtained at Gainesville. They find, that their results, obtained at a variety of frequencies since 1957, confirm Bigg's observation. The correlation is weaker when only the number of storms is included in the analysis. Evidence is also presented of a similar influence by the satellites Europa and Ganymede, using their results at 18 Mc/s, obtained during 1962. A similar study based on data for 18 Mc/s from 1957 through to 1963 failed to show up any peaks.

Alexander and Stone (1965) show that their observations at 26.3 Mc/s are also influenced by the position of Io.

Dulk (1965a) reported an analysis of HAO spectrograph data for the years 1960 to 1964. He shows that Io affects both the probability of emission and the character of the emission spectrum. The emission probability is shown to approach 1.0 when Io's position and Jupiters longitudes are simultaneously favourable.

In a very recent paper, Bigg (1966) reports a systematic search for periodicities in Jupiter's decametric radio emission and discusses their statistical and physical significance. He shows that while there is no detectable influence by the satellites Ganymede (III), Callisti (IV) and Amalthea (V), Europa (II) does seem to reduce Jupiter's decametric emission when it is in the vicinity of 40° past the Sun - Jupiter line. It is also shown that certain claims by Lebo et al (1965) and Duncan (1965) are questionable. Lebo et al had suggested that the simultaneous conjunction of the first three Galilean satellites affects the emission, while Duncan thought that a period of 0.5397 days may be detectable in the data. This period represents the time between successive sweeps of a given meridian past Io. Bigg also suggests that the radiation is triggered off, by some tidal effect in the magnetosphere.

1.3 Polarization of Jupiter's decametric radiation

Already the earliest Jupiter observers had been attempting to measure the polarization of Jupiter's radio emission, although the experiments were of secondary importance compared to the determination of occurrence probability, spectrum and intensity. Franklin and Burke (1958) and Gardner and Shain (1958) reported observing right hand (in the radio sense) elliptical polarization. Carr et al, (1961) report having made polarization observations both in Florida and Chile on a frequency of 22.2 Mc/s. Right hand polarization was observed at both stations. This was interpreted as evidence that the observed polarization was due to conditions on Jupiter and not an effect of the terrestrial ionosphere.

Barrow (1962) reports observations at 18.3 Mc/s and 24 Mc/s. He found that a smaller proportion of R.H. bursts was to be found at the lower frequency. In a later paper, Barrow (1964b) reports having observed L.H. polarized bursts at 16 Mc/s. In another paper, Barrow (1964a) describes the observations he made during 1963. Operating on the frequencies of 16 Mc/s, 18 Mc/s, 22 Mc/s and 26 Mc/s he found that for that observing season most of the radiation received at the two higher frequencies were right hand polarized, while at the two lower frequencies an appreciable proportion of the observed bursts were left handed. Analysing his data according to the source emitting the radiation, he found that most left-hand activity was emitted by source C. He also suggests that the changes in polarization mode observed from one frequency to another may indicate magnetic and ionospheric conditions on Jupiter. This would allow parameters to be deduced to within quite narrow limits.

Barrow's observations are confirmed by Sherrill and Castles (1963) who reported polarization observations at seven different frequencies ranging from 15.2 Mc/s to 24.2 Mc/s. They found that there was a significant trend towards left hand and mixed polarization at frequencies below 20 Mc/s.

Source B appeared to emit significantly more elliptically than source A. Barrow suggests that the observations of mixed polarized events below 20 Mc/s implies the existence of highly unstable propagation conditions in the interplanetary medium or in Jupiter's magnetosphere.

Dowden (1963) took polarization measurements at 10.1 Mc/s. He finds that frequency bursts of both senses of polarization are readily observable. The algebraic mean axial ratio is found to be a strong function of Jupiter's longitude, while bursts of the two senses of polarization, which are analysed separately, show no such variation.

Carr et al, (1965a) give a detailed report of the work done at the University of Florida. Using the observations made at their stations at Chile and at Florida they show that the lower the observing frequency the more sinusoidal the variation in mean axial ratio becomes. They also report a very unusual effect noticed in their observations from a valley near Cerro La Peineta, about 650 km north of Maipu, Chile. They found that as the critical frequency of the ionosphere increased, the right circular component of Jupiter's radiation grew progressively weaker relative to the left circular component. Thus they conclude that polarization observations at lower frequencies might be misleading unless they are corrected for ionospheric effects.

During the later part of 1964, Warwick and Gordon (1965) operated a swept frequency receiver at Arecibo in Puerto Rico. Using the 1000 ft dish they observed in the frequency range 24 Mc/s to 36 Mc/s. They find the radiation to be right hand elliptical with roughly constant axial ratio and orientation as a function of frequency above 24 Mc/s. Extremely fast drifts from high to low frequencies, varying between 5 Mc/s^2 to 35 Mc/s^2, are also reported. It is also suggested that more than one mechanism is responsible for the emission.

CHAPTER II

A short survey of past and present theories

The knowledge gained to date from both decametric and decimetric observations suggests that the origin of the radiation is to be found in acceleration processes of electrons in a magnetic field. Especially observations of the polarization of the emission gave valuable clues. It is therefore thought advantageous before going into the description of theories to discuss shortly various radiation mechanisms and the polarization those mechanisms are likely to produce. Only those radiation mechanisms of interest to astronomy will be discussed.

2.1 Radiation mechanisms and polarization

(a) Gyro- and Synchrotron radiation

As electrons moving in a magnetic field describe helical paths, and are therefore constantly accelerated, they will emit radiation. There are two cases to be considered relativistic and non-relativistic electrons. The latter case corresponds to a type of emission usually refered to as gyro- or cyclotron emission. In this case the emitted radiation will have a frequency, the gyro-frequency f_G,

$$f_G = \frac{eB}{2\ m}$$

(Note: theory assumes emission by a single particle)

where e = charge of the electron

B = magnetic field

m = mass of the electron

If the electron is slightly relativistic, the emitted frequency will be f_G

plus harmonics, which increase in number and magnitude as the velocity becomes greater.

The radiation emitted will in general be elliptically polarized, but the observed polarization will depend on the observing geometry. The radiation emitted parallel to the magnetic field line will be circularly polarized, while the radiation observed at right angles to the magnetic field line will appear to be linearly polarized, the plane of polarization lying in the plane of the electron orbit.

As the electron velocity approaches the velocity of light, the observed radiation is called synchrotron emission. In this case the radiation is emitted in a continuum. The radiation is beamed along the direction of motion, i.e. perpendicular to the magnetic field line, and is emitted into a narrow cone, the half-angle of which decreases as the electron velocity increases. The cone of emission from these relativistic electrons produces linear polarization, whose plane of polarization is orientated parallel to the plane of the orbit.

(b) Cerenkov radiation

If an electron enters a medium, it is decelerated and will emit radiation. Should the electron velocity have been greater than the group velocity of light in the medium, then the radiation is emitted in the Cerenkov mode. The radiation is emitted into a cone with axis parallel, and in the same direction, as the electron velocity. When the group velocity falls to zero, which happens for certain electron concentrations, directions of propagation and frequency in an ionosphere, we get reflections of electromagnetic radiation. (cf. Warwick's theory discussed later).

No intrinsic polarization characteristic can be defined, as the details of the emitted Cerenkov radiation are determined by the mode of excitation and the properties of the medium. For example if, in a certain medium, only one characteristic wave can propagate, then highly circular polarization would be observable.

(c) Plasma oscillations

An ionized plasma consists of electrons and ions. Since there is a very large difference in mass, it is relatively easy to displace the electrons. Should this occur through the influence of some external force, then the electrons will attempt to return to the equilibrium position. They will oscillate about this position. Electromagnetic radiation will be given out at the so-called plasma frequency f_p

$$f_p = \left(\frac{N e^2}{m} \right)^{\frac{1}{2}}$$

where e = charge of the electron

N = electron density

m = mass of the electron

Also for this process no characteristic polarization can be defined and any observed polarization will depend upon the properties of the medium where it is generated, as well as the media through which the radiation travels on its way to the observer. The latter is a very important point to consider and will therefore be discussed later on.

2.2 Theories of Jupiter's decametric radiation

There are at present two theories, which appear to explain Jupiter's decametric radiation to a certain extent. One was proposed by Warwick (1961; 1963a; 1963b), the other by Ellis (1962a; 1963) and Ellis and McCulloch (1963a). As we shall see presently, the latter one is the only one worked out in any detail. Before actually discussing the abovementioned theories we shall shortly survey other theories so far proposed.

After an initial assumption that the decametric emission can be attributed to thunderstorms in Jupiter's atmosphere (Shain 1955), it was thought that the radiation was due to plasma oscillations in Jupiter's ionosphere (Zheleznyakov 1958; Gardner and Shain 1958; Gallet 1961).

Landovitz and Marshall (1962) discuss the possibility of stimulated electron spin-flip transitions. They suggest that the radiation is a maser-like phenomenon. The emission is caused by electrons making spin-flip transitions in the perturbed magnetic field of Jupiter. The solar particles are supposed to impinge on Jupiter's magnetic field and stimulate perturbations which in turn cause very sudden changes in the magnetic field. The incidence of a cloud of solar particles subjects an electron population in a static magnetic field to an oscillating magnetic perturbation causing the electron population to emit radiation at the Lamor (gyro) frequency, characteristic of the static magnetic field.

Strom and Strom (1962) suggested that the decametric radiation does not actually originate on or near Jupiter, but comes from a distant background of discrete sources of radio stars. Jupiter's ionosphere is said to act like a gigantic spherical lens focussing energy onto Earth, when these sources are temporarily occulted by Jupiter. This theory was discounted by Smith et al (1963) and Jelley (1963).

Hirschfield and Bekefi (1963) proposed that the radiation might be due to cyclotron radiation emitted by the electron stream itself. Assuming that the radiation is generated in the magnetosphere in the region of zero plasma density, they show that this process produces radiation intensities similar to those observed. No attempt was made by them to account for any other property.

Chang (1963) describes how amplified whistlers could be the source of Jupiter's decametric radiation. Starting with the assumption that the decimeter radiation is due to synchrotron emission, he shows that there is a possibility of whistler generation and amplification.

(a) <u>Warwick's radiation model</u>

Warwick based his model on a group of dynamic spectra, most of which were later proved to be Io related. This implies therefore that even if Warwick's model should be correct, it only explains the spectrum of the Io related emission.

Warwick assumes that the radiation is produced by fast electrons which originate from the radiation belts located at a distance of between 2 and 3 Jupiter-radii. These electrons enter the ionosphere along the magnetic field line, where they enter regions of low propagation velocity and will therefore emit Čerenkov radiation. This is supposed to occur slightly below the local plasma gyro-frequency. The radiation is beamed down towards the planet in a narrow cone (about 10°). The lower ionosphere or the planetary surface reflects the radiation and it is received on Earth only for favourable orientations of the magnetic field lines and the surface. It is the geometry of these reflections which accounts for the observed spectrum of the longitude profile. The emissions are supposed to be initiated by magnetic disturbances of the radiation belts.

The magnetic field is said to be a dipole field with the dipole inclined to the rotational axis at 9°. This was based upon a deduction by Morris and Berge (1962) who observed the polarization of the microwave emission.

Using these assumptions, Warwick found, by trial and error, that profiles similar to the observed ones require the dipole to be located:

1) near the axis of rotation but well away from the equatorial plane to achieve a slowly varying spectrum;
2) south of the equatorial plane and towards the Earth, when the CML is 200°, to achieve the correct senses of frequency drift either side of CML 200°;
3) displaced slightly from the $L_{III} = 200^{\circ}$ plane to achieve the small asymmetry of the spectra about CML 200°

To fit the frequency scales a magnetic moment of 4.2×10^{30} gauss.cm^3 was chosen. The resulting synthetic spectra reproduced quite closely the observed (Io-related) spectral features (source A and source B). To account for the polarization it is supposed that the emitted radiation is generated in the extraordinary mode, i.e. right hand, and the northern pole of Jupiter must be a magnetic north-seeking pole. This implies that Jupiter's magnetic field has the opposite sense to the Earth's field with respect to the direction of the rotation of the planet. It is also pointed out that the other sources could be explained by a second inner radiation belt.

In the derivation of his theory, Warwick bases his estimates upon the behaviour of a single particle. Further unsatisfactory features are the highly asymmetric dipole position, and the fact that Cerenkov radiation is not emitted in the direction of particle motion, as Warwick assumed, but rather at an angle to it. For emission near the gyro-frequency the refractive index is high, which implies that substantial refraction will take place when the ray emerges into free space. This means that the radiation is emitted in a fairly large cone, a fact which seems to be wrong (Gulkis and Carr 1966).

At the time Warwick proposed his theory, polarization observations were still rather few. Warwick's theory cannot explain at all the present observations of variation of axial ratio with frequency and longitude. (cf. 2.1b)

(b) Doppler cyclotron model

The history of this model is complicated. Field (1960) discussed cyclotron radiation as a source of Jupiter's decimetric emission. Dowden (1962) discusses Doppler shifted cyclotron radiation from electrons as the possible source of the VLF emission from the Earth's exosphere. Ellis (1962a) takes the cyclotron model a bit further and finds that it can explain the rising and falling frequency-time characteristics, the average intensity variation with CML, a high frequency spectral cut-off and the general variation of polarization sense with planetary rotation. The following year Ellis (1963) discusses some further properties of cyclotron radiation from bunches of electrons trapped in Jupiter's exosphere, taking into account a magnetic field at the poles of 15 gauss and an inclination of the magnetic axis of 10^{o} to the rotational axis. Later the same year, Ellis and McCulloch (1963a) publish a fairly polished version of their theory of doppler shifted cylotron emission. We shall survey this theory to a certain extent and show how much this particular model can explain. It considers the radiation only of a single particle, but Fung (1966b) shows that Ellis and McCulloch findings still hold if radiation from electron populations are taken into account.

Starting with the assumption that Jupiter is surrounded by an extensively ionized exosphere, the density of which, like that of Earth, is roughly proportional to the magnetic field intensity, they consider bunches of electrons which are disturbed near the outer regions of the exosphere. These electrons are accelerated and will therefore emit radiation. During this process they are travelling down high latitude field lines.

Assuming that the electron emitting the radiation (<u>Note:</u> single particle) is relativistic then the gyro-frequency changes to

$$f_G' = f_G \, (1 - v^2/c^2)^{\frac{1}{2}} \qquad 1)$$

While spiralling along the magnetic field lines, the frequency will shift (Doppler effect) and the observed frequency will be

$$f = \frac{f_G'}{1 - (v/c)\, n\cos\phi \cos\Theta} \qquad 2)$$

where ϕ = pitch angle

v = velocity of the electron

n = refractive index of the magneto-ionic medium

Θ = wave normal direction of the emitted radiation with respect to the magnetic field vector

It should be noted that $n = f\,(\Theta, B, N, f)$, all variables.

where N = electron density

B = Magnetic field intensity

f = wave frequency

In the forward direction the emission of radiation is limited to a cone given by

$$\sin \alpha = n . \sin\phi \qquad 3)$$

i.e. the cone angle depends on the ratio of the local gyrofrequency to the local plasma frequency and on the pitch angle of the electron. The medium limits the propagation and it escapes only in the extraordinary mode.

If the rearward radiation is considered, no cone limitation exists and radiation will always occur. Both Cyclotron and Cerenkov radiation are possible, however propagation conditions are such that the radiation cannot escape from the planetary exosphere.

It was also assumed that the bunches of electrons occur with equal probability in all magnetic longitudes and to be zero at magnetic latitudes less than 75^o, increasing linearly from 75^o to 85^o. The lines at a latitude of 85^o are supposed to extend to the magnetopause, so that they are likely to be affected by solar disturbances. In all their calculations they use the fact that the observer's magnetic latitude changes by about $\pm 10^o$ during one revolution.

Using the above assumptions theoretical probability calculations are carried out. Since this theory, based on a simple dipole, obviously gives a sinusoidal variation of probability, it was necessary to introduce modifications to fit the observations at higher frequencies. These modifications are taken to be magnetic anomalies from the dipole field close to the planet. It is interesting that Roberts and Komesaroff (1964) do indeed report some sort of asymmetry of Jupiter's van Allen belts.

The theory also predicts the distribution of the polarization of bursts, since the axial ratio of the polarization ellipse will depend mainly on the angle of the emission cone (α). It is given that the axial ratio A

$$A = \pm \cos \alpha \qquad (4)$$

Since the cone angle is a function of the pitch angle, which is itself a function of the number of bunches, the axial ratio is a function of the bunch number. If one integrates this over pitch angle, latitude and longitude, one gets the result that the summed axial ratio is a function of the total number of observable bunches.

This has actually been found to be true by two independent observers (Sherrill, 1965a; Dowden, 1963).

Theory also predicts that the integrated power should be proportional to the 1.3th power of the number of bursts. Dowden (1963) did actually find that such a power relationship exists, but that the exponent was 1.51. Ellis (1965) suggests that this discrepancy may be due to the incorrect pitch-angle function for the radiated power or due to failing to take account of superimposed bursts in counting the number.

This theory of Ellis and McCulloch, having been adjusted to the probable magnetic field distribution, does predict with very reasonable accuracy the shape of the frequency-time variation of the Io-controlled emission.

It also predicts some fine structure within this spectrum. In the derivation of the theory it had also been assumed that the radiation cones from the individual electron bunches are all of negligible angular thickness. If this assumption is dropped, then the theory predicts, assuming electron energies in the range 30 - 60 keV, fine frequency-time structures with drift rates in the vicinity from 30 Mc/s^2 to 50 Mc/s^2.

Ellis (1965) suggests that, before the theory can be successfully developed further, it is necessary to obtain frequency-time spectra with time resolution of less than 10^{-2}sec. He also points out that in order to explain the influence of the satellites a general theory of a rapidly rotating magnetosphere has to be investigated in detail.

CHAPTER III

We have so far discussed some of the properties of Jupiter's decametric radiation, as an experimenter on Earth would observe it and we have surveyed shortly present ideas of how this radiation can be accounted for. Whatever the process responsible for the radiation, the emission will still have to pass through some parts of Jupiter's ionosphere, the interplanetary medium and finally the Earth's ionosphere, each of which will affect the radiation to a greater or lesser extent.

Since the observed sense of polarization of Jupiter's bursts are the same in both hemispheres of Earth, the polarization must be an intrinsic feature of the decametric radiation. This is generally accepted, as the interplanetary medium is thought to be unable to impose the features usually observed.

Warwick and Dulk (1964) report that some of the decametric radio emission from Jupiter observed by them exhibits effects which are attributable to Faraday rotation within the Earth's ionosphere. This effect was noticed on their spectrograms as alternate light and dark bands, which in most cases were lying parallel to the time axis. The bands appeared to be unrelated to the more prominent interferometer fringes and were more closely spaced at lower frequencies. They are also not affected by a change in the delay line. Riihima (1966) reports Faraday rotation observations in his spectrographs which slowly drift in frequency, indicating that the total electron content over the ray path is slowly changing.

Warwick and Gordon (1965) report the construction of a receiver which by observing Jupiter's decametric radiation in the extraordinary and ordinary mode, is capable to allow for the effects of the Earth's ionosphere. They do this by arranging their antenna connections in such a way, as to immitate a dipole antenna, rotating at the same rate as the incoming radiation ellipse. The results they obtain seem to indicate that they have observed a Faraday effect which was not due to the Earth's ionosphere but may have been due to Jupiter's ionosphere.

Smith and Douglas (1962) reporting results obtained with a spaced site experiment suggest that diffraction patterns of interplanetary irregularities might affect the reception of Jupiter's radiation.

It seems therefore indicated that propagation effects should be looked at, to enable one to appreciate the difficulties of interpreting observed results.

3.1 Mode of propagation in the terrestrial ionosphere

(Ratcliffe 1959; Kelso 1964)

Considering a plane electromagnetic wave of small intensity propagating in a slowly varying, absorbing, ionized medium in the presence of a magnetic field, which is constant in space and time, various equations relating to the behaviour of the wave may be deduced. The two most important forms which specify the properties of a given ionized medium in the presence of an electromagnetic field, are the "Appleton-Hartree polarization equation" and the "Appleton-Hartree dispersion equation". These equations are named after E.V. Appleton, who with M.A.F. Barnett was the first to establish experimentally the existence of the ionosphere and D.R. Hartree who derived the equation for the refractive index for an isotropically absorbing medium and for the general magnetic field problem.

Both the equations mentioned above may be reduced to one describing the polarization of the wave $R = H_y/H_x$

$$R = \frac{Y_T^2 \pm \quad Y_T^4 + 4(1-X-jZ)^2 Y_L^2}{2j(1-X-jZ)\, Y_L}$$

where $Y = f_G/f$ = ratio of gyro frequency to observing frequency

$X = f_P^2/f^2$ = square of the plasma frequency to the square of the observing frequency

Θ = angle between the external magnetic field and the wave normal

$Y_T = Y \sin \Theta$

$Y_L = Y \cos \Theta$

j = square root of (-1)

Z = ratio of frequency of collision of electrons with heavy particles to the angular wave frequency ω $(= 2\pi f)$.

The above equation describes the two self consistent waves that exist in the magneto-ionic medium. The polarization associated with the one sign is that of the ordinary mode and that of the other sign the extraordinary mode. Any wave entering the medium described by the above equation with different polarization to either of these characteristic waves will split into these components, the relative amplitudes depending on the polarization of the incoming wave. Both the resulting waves will then travel with their polarizations unchanged, provided the parameters of the transversed medium vary only slowly. They will have different phase velocities.

If collisions are neglected and observations take place during the night at frequencies above 15 Mc/s and the gyrofrequency of the Ionosphere is in the vicinity of 1.5 Mc/s and the critical frequency is close to 2 Mc/s, an approximation can be made since in that case $X \ll 1$ and $Y \ll 1$.

i.e. $$\left| \frac{Y_T^4}{4\,(1 - X - jZ)^2} \right| \ll \left| Y_L^2 \right|$$

This defines the quasi-longitudinal approximation and the two Appleton-Hartree equations reduce to the relatively simple form

$$n_{QL}^2 = 1 - \frac{X}{(1 - jZ \pm Y_L)}$$

and $R_{QL} = \pm j$

This implies that when the QL approximation is valid the two characteristic waves are circularly polarized.

3.2 The effect of Faraday rotation (Kelso, 1964; Riihimaa, 1966)

The two characteristic waves propagating through the ionosphere would be detected by an antenna as the vector sum of the two individual waves. Since any elliptical polarization can be represented as the sum of two circularly polarized waves of opposite sense of rotation, it is clear that in the general case of elliptical polarization the major axis of the polarization ellipse will rotate as the wave transverses the magneto ionic medium. The sense of rotation will be the same as that of the component of larger amplitude.

If the ionosphere is assumed not to vary horizontally, then the Faraday rotation is given by

$$\Psi = Kf^{-2} \int_{o}^{h} NB_L \sec \chi \, dh$$

where Ψ = total angle through which the plane of polarization is rotated

K = constant = 2.97×10^{-2}

N = electron density

B_L = component of the magnetic field along the ray-path

χ = angle between the ray and the vertical

dh = element of ray-path

h = upper extreme of the one end of the path

Thus the total angle of rotation of the plane of polarization is a measure of the integrated electron content. It is also seen that the spectrum of radiation disperses into a continuum of waves, with their polarization ellipses in different orientations at the receiving plane. If the observations are made with a swept-frequency polarimeter using a linearly polarized antenna, then constant frequency minima will occur at intervals of 180°. The spacing of these Faraday fringes is inversely proportional to the square of the frequency.

Faraday rotation takes place in any magneto-ionic medium. It will therefore also take place in the interplanetary medium. However, Gordon (1966) performs the calculation for a wave frequency of 26 Mc/s and he finds the rotation to be of the order of 17°, which taken relative to the rotation due to the Earth's ionosphere (approximately $50\,\pi$ radians) is negligible.

3.3 The effect of ionospheric and interplanetary scintillation

In the previous two sections we have been considering two kinds of effects which are due to the plasma characteristics. The various parameters were taken to be slowly varying. If however this is not the case and there are irregularities present, then these will affect the signals received.

The first experiments on the role of scintillation in Jupiter's radiation were carried out by Gardner and Shain (1958). They used receivers at two stations 25 km apart. They concluded from their observations that the ionosphere can have a very pronounced effect on the short-term characteristics of the received radiation.

Other observers, Douglas and Smith (1961), Smith and Douglas (1962) and Carr et al (1961) reported having carried out correlation experiments with baselines from a few kilometers to several thousand kilometers. These experiments show that all degrees of correlation can be experienced. Barrow et al (1964) report considerable differences in day-by-day frequency of occurrence between stations located at Tallahassee-Florida, St. Osyth-England and Grahamstown-South-Africa.

While this shows that the Earth's ionosphere is capable of introducing large variations, Douglas (1964) reports observations of a phenomenon which he interprets as due to interplanetary scintillation produced by irregularities in the solar wind. One particular record taken at 22.2 Mc/s on the 1st November 1963 shows almost perfect envelope correlation, except that the signals, arriving at two stations 100 km apart, were recorded with a time lag of approximately $\frac{1}{2}$ sec. This correlation lasted for 15 minutes. The observations over the whole observing period showed that this lag reversed at opposition. The suggested drift velocity for the hypothetical diffraction pattern cast on Earth, is between 200 km/sec and 500 km/sec.

The above observations suggest that the decametric source on Jupiter has a small angular width, a fact which seems to be borne out by recent investigations by Slee and Higgins (1963; 1965; 1966).

Therefore it is important that care be taken when drawing conclusions about the actual conditions at the origin of Jupiter's decametric radiation.

3.4 Polarization and its detection

Elliptical polarization can be considered to be the resultant of either

a) two linear polarized waves of the same frequency, or

b) two oppositely polarized circular waves of appropriate relative intensity and phase difference.

To specify the polarization ellipse completely, we would have to know the ratio of the magnitude of the minor axis to the major axis, usually termed the "axial ratio" and the angle of tilt of the major axis relative to some system of co-ordinates of the observer. Often however there is also an unpolarized component, which complicates matters. It is found that to completely specify the state of partially polarized radiation quantitatively four numbers are required. These are the Stokes parameters.

Cohen (1958) treats this problem in detail. We shall just highlight some of the derivations as far as they will help our further discussion.

Suppose that the receiver of known bandwidth receives a signal which is partially polarized. The total intensity I is made up of the two components I_p, the polarized and I_u, the unpolarized component, so that

$$I = I_p + I_u \qquad (1)$$

The electric vector $E_o e^{j(\omega t + \delta_o)}$ can be resolved into two components along two arbitrarily chosen axes X and Y. Suppose that the major axis of the ellipse is inclined to the X axis at an angle θ.

The object of the analysis is to derive sufficient parameters to describe the polarization completely, i.e. ellipse and unpolarized component, in terms of the observables of the wave.

The axial ratio is defined as

$$\tan \phi = \pm \frac{\text{minor axis}}{\text{major axis}} = \pm r \tag{2}$$

Sherrill (1964b), going through the treatment in a way similar to that found in most advanced optics textbooks, derives the Stokes parameters:

$$I = I_p + I_u = I_x + I_y \tag{3}$$

$$Q = I_{xp} - I_{yp} = I_x - I_y = I_p \cos 2\phi . \cos 2\theta \tag{4}$$

$$U = I_p \cos 2\phi . \sin 2\theta \tag{5}$$

$$V = I_p \sin 2\phi \tag{6}$$

where

$$\tan 2\theta = U/Q \tag{7}$$

$$I_p = (Q^2 + U^2 + V^2)^{\frac{1}{2}} \tag{8}$$

$$m = \text{polarization fraction} = I_p/I \tag{9}$$

$$\sin 2\phi = \frac{V}{(Q^2 + U^2 + V^2)^{\frac{1}{2}}} \tag{10}$$

The following limits are placed on the angles θ and ϕ

$$-\pi/2 \leq \theta \leq \pi/2 \quad \text{and} \quad -\pi/4 \leq \phi \leq \pi/4 \tag{11}$$

Radio astronomy adopts the "radio" convention when discussing polarization. This convention states that a wave is left hand (right hand) polarized if the approaching wave rotates in a clockwise (counterclock wise) fashion, when observing from a fixed plane along the direction of propagation.

To detect the radiation antennas are used. The Stokes parameters can then be rewritten to take the form of the detectors into account. It was stated above that any elliptical polarization can be represented as two opposite circular components. Suppose these can be represented by "R" and "L" and that they differ in phase by an amount (RL). Let the phase reference be taken at the instant R is along the "X" axis. From this one can obtain the Stokes parameters for circularly polarized components.

$$I = I_p + I_u = I_L + I_R \tag{13}$$

$$Q = 2\ R.L \cos\ (RL) \tag{14}$$

$$U = 2\ R.L \sin\ (RL) \tag{15}$$

$$V = I_L - I_R \tag{16}$$

(Note that the above set of equations is similar to equations (3) - (6), except that the definitions of Q and V are interchanged).

$$m = \frac{\left\{ (I_L - I_R)^2 + 4\ R^2 L^2 \right\}^{\frac{1}{2}}}{I_L + I_R} \tag{17}$$

$$\sin 2\phi = \frac{I_L - I_R}{\left\{ (I_L - I_R)^2 + 4\ R^2 L^2 \right\}^{\frac{1}{2}}} \tag{18}$$

$$\theta = \tfrac{1}{2}\ (RL) \tag{19}$$

$$r = \tan \phi$$

The measurements required for complete determination of the polarization with the aid of a polarimeter are, as seen from above

I_R, I_L, R.L, and (RL)

However, if the incoming radiation is 100% polarized, i.e. no random component is present, results showing the axial ratio only are meaningful (Sherrill and Castles, 1963; Carr et al. 1961; Dowden, 1963). We shall therefore follow their example and assume that Jupiter's decametric radiation is completely polarized.

The axial radio is then given by

$$r = \frac{L - R}{L + R} \qquad (20)$$

The values will vary between +1 (left-hand) to -1 (right-hand).

Fig. 2 shows an antenna connection which is capable of detecting circular components of polarization. A and B are two linear dipoles. A' and B' are two output points. The antennas A and B are mutually perpendicular and interconnected with a cable introducing a phase change of $\pi/2$.

Suppose right hand circular polarization is incident upon the antennas. This will produce a signal of the form $E \cos \omega t$ in antenna A and a signal $E \cos (\omega t + \pi/2)$ in antenna B. The signals at the outputs A' and B' will then be

At A' -- $E \cos \omega t$ plus $E \cos (\omega t + \pi/2 + \pi/2)$, i.e. ZERO. (21)

At B' -- $E \cos (\omega t + \pi/2)$ plus $E \cos (\omega t + \pi/2) = 2 E \sin \omega t$

If the signal is left hand circularly polarized then the two outputs will be reversed, i.e. the output at A' will be $2 E \sin \omega t$ and the output at B' will be zero.

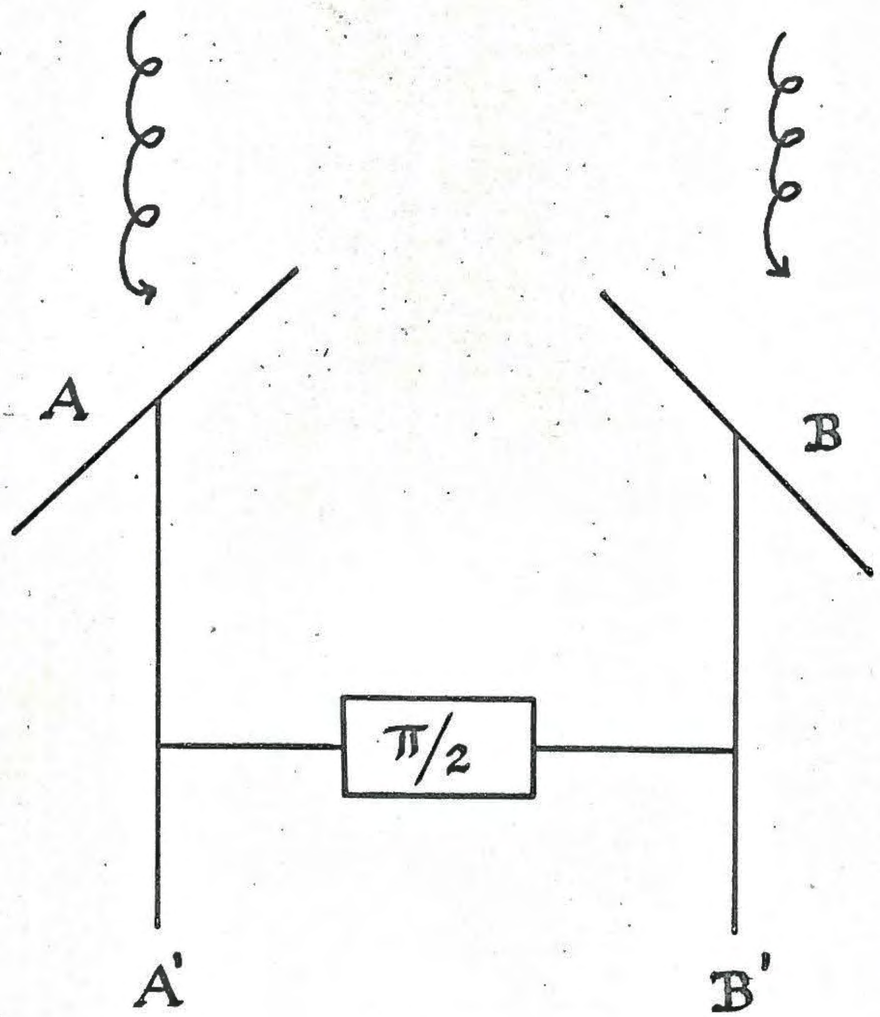


Fig. 2 Antenna arrangement

Therefore the antenna connections as shown in Fig. 2, will allow, assuming complete polarization, the determination of sense of polarization and ellipticity, both described by the same quantity r, the axial ratio.

CHAPTER IV

The swept frequency polarimeter

4.1 Apparatus: General outline (Fig. 3)

The receiver was designed to receive radiation in the frequency range 15 Mc/s to 25 Mc/s. Its main objective was to determine the sense of polarization and its variation with frequency over the designed range. Determination of axial ratios was to be of secondary importance, as Barrow (1964a) had suggested that one should look for possible changes in polarization mode with frequency and that the axial ratio is not necessarily a very significant quantity, when observed at an antenna on Earth. It was therefore not thought necessary to include a correlator.

The radiation was received by two log-periodic antennas arranged in such a way that two outputs were provided, one sensitive to RH circular, the other sensitive to LH circular polarization. The radiation was then fed via RG 8/U - 50 ohm coaxial cables to the wide-band preamplifiers, which also switched between the two antennas. By switching the receiver between the two different inputs, one representing right hand, the other left hand polarization, it was possible to use the same receiver to amplify both signals. This meant that the result displayed on the oscilloscope screen would be unaffected by any possible differences in gain, which would have upset any form of analysis.

The antenna system was made sensitive to the mode of polarization by

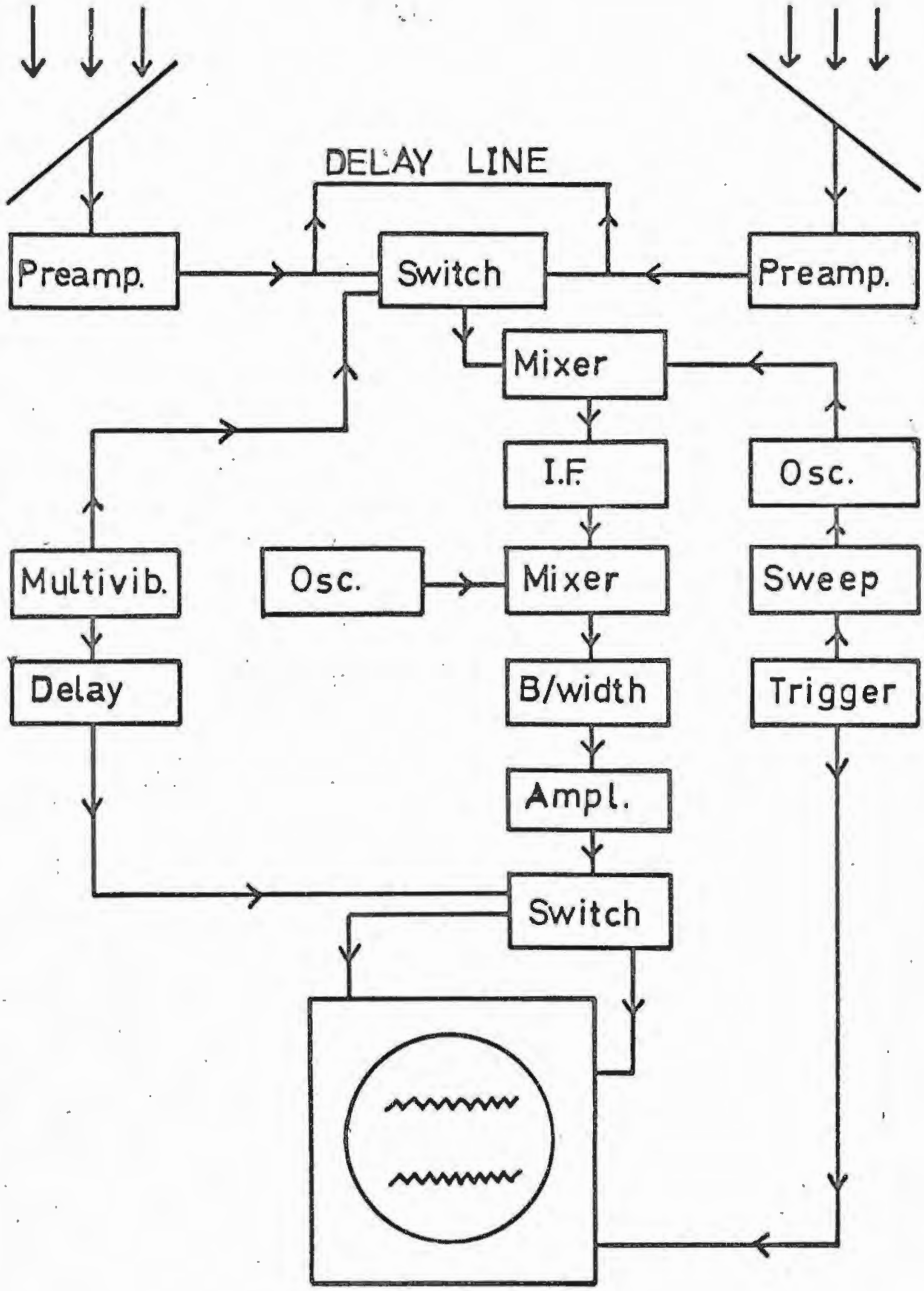


FIG. 3 GENERAL OUTLINE.

interconnecting the two log-periodic antennas, mounted mutually perpendicular, with a line whose length was $\lambda/4$ for one particular frequency. Although there were varying lengths of delay line on hand, only the 18 Mc/s delay line was used. This does indeed introduce an error, which will be discussed in detail later in this thesis.

From the switch, the signals were fed into a mixer, where they were mixed with a signal varying in frequency between 45 Mc/s and 55 Mc/s. The 30 Mc/s IF was then picked out and amplified by a tuned amplifier, before being mixed once more with a frequency of 29.4 Mc/s. The resulting beat frequency was further amplified and passed through an adjustable band-pass filter and a voltage linear detector circuit of variable time constant. The output voltage of the receiver is therefore proportional to the input voltage. A second switch distinguished between signals of left hand and right hand polarization and fed these to the appropriate inputs of a double beam oscilloscope.

This receiver had an output which was proportional to the input voltage, due to the inclusion of a voltage linear detector. Since the mixer circuits will also give a linear output provided the oscillator voltage input is much larger than the signal input, deviations from linearity will only result from the input of very large signals, when some of the tubes would tend to saturate. This design facilitates the immediate determination of axial ratios without having to know the exact background noise level, provided the input is not too large.

Originally there were supposed to be two wide hand pre-amplifiers, with a gain of 30 dB and a low noise figure, connecting antenna and switch. They were commercially manufactured by an American firm. Unfortunately one of the two amplifiers was burned out accidentally during the testing stage of the equipment and replacement transistors arrived too late to repair the amplifiers before the close of the last observing season.

4.2 The log-periodic antenna

The log-periodic antenna system was based on a design by Robert Carrel of the University of Illinois. The antenna consists of a number of parallel elements arranged side by side in a plane. The lengths of the dipole elements and the spacings between the elements form geometric progressions. Adjacent elements were connected in an alternating fashion to the two parallel pipes, which formed a transmission line (Fig. 4). The coaxial cable, which connects the antenna to the receiver, is fed up one of the pipes. At the top (higher frequency) end the outer conductor is led to the other pipe and connected to it. In this way the antenna becomes its own balun. At any given frequency, within the designed range, there is then a unique electrical center of the antenna which is located near the appropriate resonant dipole element. The other elements are then passive and tend to act as reflectors and directors similar to a multi element Yagi array.

The characteristic impedance of the antenna is controlled by the ratio of the half length of element to element radius, as well as the ratio between the separation of the two pipes, constituting the feeder, and the radius of the pipes. In the operating frequency region the antenna receives radiation end

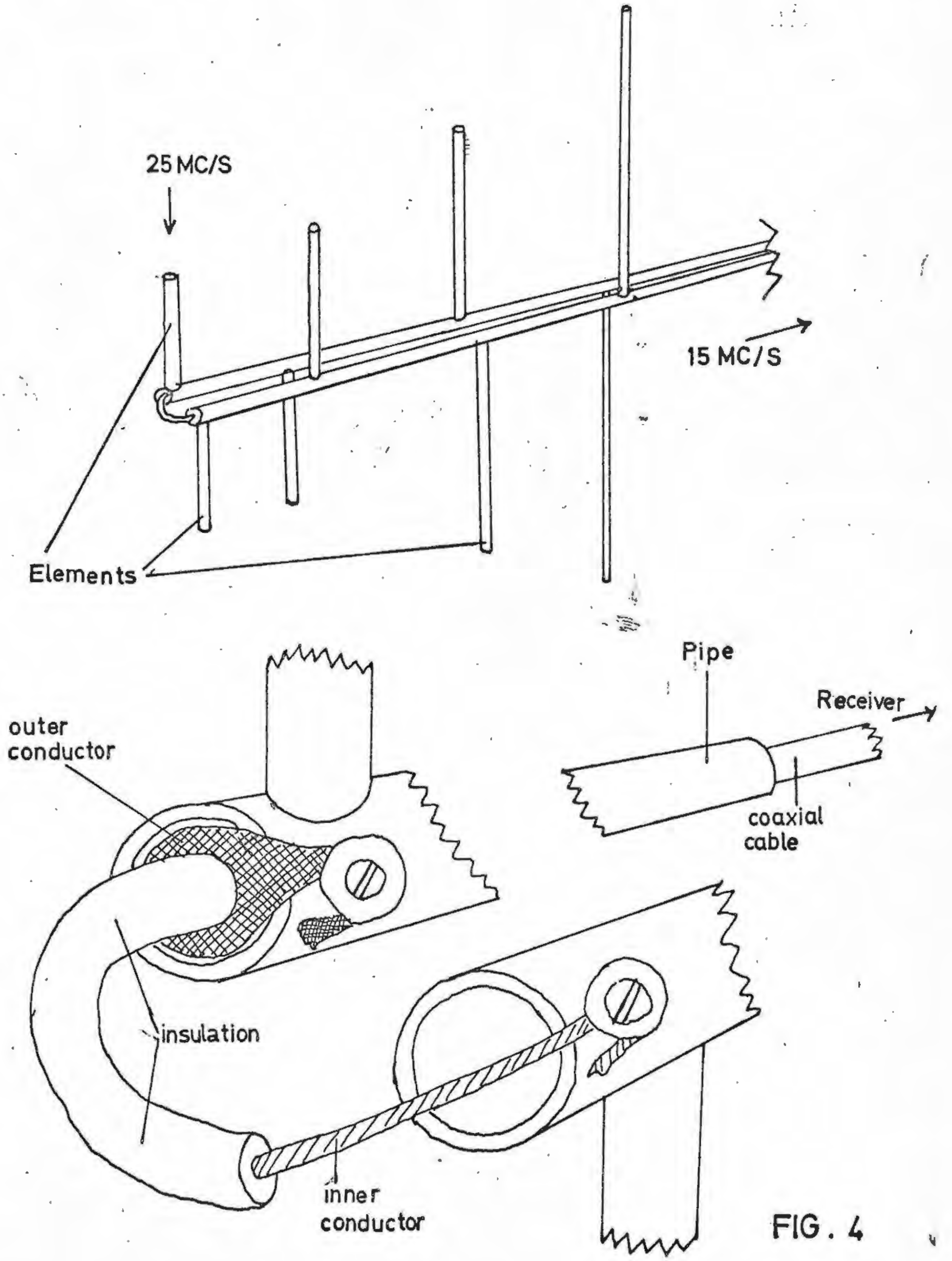

25 MC/S
15 MC/S
Elements
Pipe
Receiver
coaxial
cable
outer
conductor
insulation
inner
conductor

FIG. 4

on from the direction in which the smaller elements are pointing.

The antenna design is as follows:

Lowest frequency	15 Mc/s
Highest frequency	25 Mc/s
Geometric progression ratio	0.84
Angle subtended between axis of antenna and ends of the elements on one side	30°
Input impedance	50 ohms
Number of elements	8
Ratio of half length of elements to radius	800
Ratio of separation of feeder pipes to radius of pipes	2.3 .

The above design gives an antenna with a total theoretical forward gain in the region of 7 dB. The nominal gain is given as 7.5 dB, but this is decreased by about 0.2 dB for every doubling of the ratio of half length of elements to radius over the ratio of 125. The beamwidth of the antenna is given as about 60°. (The values specified above were determined by Carrel from a model built to operate in the microwave region.)

Two such antennas were constructed and mounted, with their planes of polarization at right angles, in a structure made of creosoted telephone poles and 2x2in wooden beams (cf. plate A). The whole structure was rotatable on a semi-circular track on solid rubber wheels. The drive was manual and had to be adjusted to follow the movement of the planet Jupiter

PLATE A : The antenna

through the sky. With this set up it was possible to observe Jupiter for a period of over four hours, two hours each side of meridian transit. The meridian, i.e. the direction of north was marked, so that should the sky be overcast the antenna could still be pointed into the right direction.

Fig. 5 shows the VSWR curve for the two separate antennas. This gives some idea of the operating efficiency of the instrument.

No verification of the theoretical radiation-pattern was attempted, as the physical size of the antenna made any experimental determination too difficult.

4.3 The spectrograph

In this section, we shall only describe the overall characteristics of the instrument. A detailed description of the polarimeter electronics is given in Appendix A. We shall subdivide this discussion into four sections, one dealing with the actual receiver, one dealing with the sweeping circuitry, the third dealing with the switching circuitry and the fourth with the recording equipment.

a) The receiver

The signals from the two antenna outputs A' and B' (cf. Fig. 2) were each fed into a wide-band low noise pre-amplifier of voltage gain just less than eight. The amplifiers were designed to amplify uniformly to beyond 25 Mc/s, but to cut off rapidly after that, in order to reduce any signal coming through at the IF of 30 Mc/s.

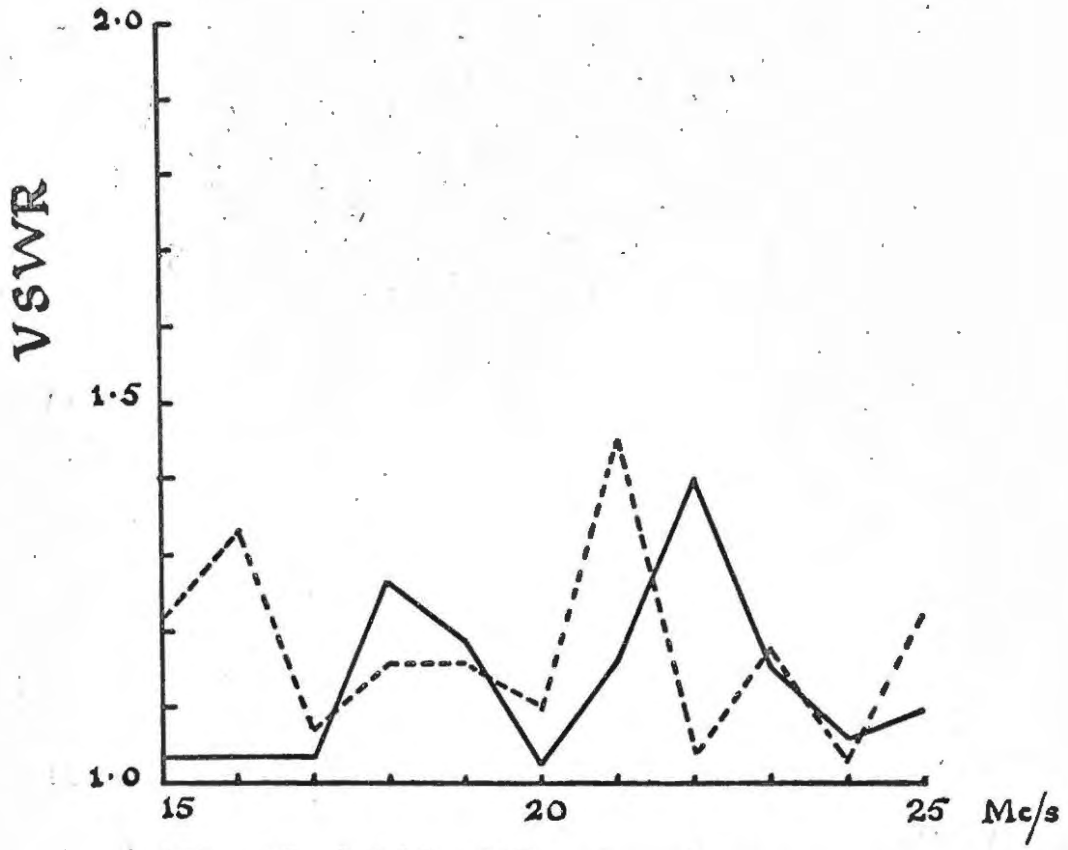


Fig. 5 VSWR of antennas

In the mixer the signals were mixed with a varying frequency from a voltage-tuned oscillator so that an IF of 30 Mc/s contained all the required information. Since design difficulties prevent selection of suitable bandwidths at that frequency, the 30 Mc/s signal was beaten again with a fixed frequency signal. The difference frequency was then passed through an M-derived low-pass filter with rather sharp cut-off. Three cut-off frequencies could be selected to give bandwidths of the order of 100 kc/s, 200 kc/s and 400 kc/s.

The passed band was then amplified once more and fed through a switch to the oscilloscope, where the signals were displayed and photographed.

Selection of the bandwidths and time constant in the detector circuit is governed by the amount of noise variation the observer wishes to detect.

It can be proved that the ratio of the detectable noise variation to the total noise is related to the receiver characteristics by

$$\frac{\Delta N}{N} = \sqrt{\frac{1}{B\tau}}$$

where B = bandwidth of the receiver

τ = time constant of the detector

Sometimes 1/B is also referred to as the pre-detection time constant and τ the post detection time constant.

τ was selected in such a way as to be small compared to the time it took to sweep over the equivalent of the bandwidth. Our instrument had, in its usual operating condition, a bandwidth of 100 kc/s and a time constant of 10^{-3}sec. This means that the swept-frequency receiver could detect a variation of about 10% of the background noise. For comparison, the fixed frequency receivers we operated at the same time could detect a variation of about 3% of the background noise. (The sky temperature in our operating range amounts to approximately 50.000°K)

The choice of bandwidths is however not only governed by the above considerations. There are two effects which define an upper and a lower limit to the suitable bandwidths.

Should the bandwidth be too low "ringing" will occur. This effect results from the inability of the receiver to pass sufficient frequency components of the Fourier frequency representation of a sharply pulsed signal, to permit the reconstruction of the accurate pulse shape in the time domain after detection.

There are two possible sources of sharp pulses. One is the sharp pulses received by the antenna and the other source is of our own making. In operating our instrument on a time-shared basis we are switching between two different inputs at a rate of 5 kc/s. This switching is done using a square wave from a multivibrator. This means that whenever the cycle changes, very sharp pulses have to be passed by the receiver. In order to partly overcome this problem, the switching waveform was adjusted to give a longer rise time than would normally be possible. This reduces the higher frequency components. Interference from actual signal pulses would have been negligible compared to the first mentioned problem.

The minimum bandwidth requirement is

$$B = 1 / 2 \pi \Delta t$$

where Δt = the rise time of the sharpest pulse.

In our case, where the rise time of the square wave had been adjusted to be of the order of 5% of the cycle, the minimum bandwidth would have to be of the order of about 5 kc/s. This condition is more than sufficiently complied with in our case.

The second limit applies to the maximum bandwidth. In a polarimeter where the four Stokes parameters have to be determined there is an upper limit to the bandwidth. Since Faraday rotation is a function of frequency, the bandwidth of the receiver must be so small that the dispersion within one bandwidth due to Faraday rotation is negligible. For a bandwidth of 100 kc/s the dispersion is approximately $\pi/20$, which we shall neglect. At a bandwidth of 400 kc/s this effect would have to be corrected for in calculating the axial ratio. The dispersion effect increases the observed axial ratio.

b) <u>The sweeping circuitry</u>

In this section we shall shortly describe the functions of the triggering and sweeping circuit.

The trigger circuit was employed to start the sweeping of the ramp circuit, supplying the varying voltage to the voltage tuned oscillator, and the double beam oscilloscope. This ensured that any particular position on the oscilloscope screen corresponded to a certain determinable frequency.

Sweeping was done at a rate of 4 sec^{-1}.

c) <u>The switching circuitry</u>

This part of the apparatus provided the signal which operated the switch between the two possible inputs A' and B' and directed the output to the receiver into the right channel. Since there was a slight phase delay in the actual receiver, this had to be allowed for by delaying the signal operating the output switch with respect to the signal operating the input switch.

The switching was done at a rate of 5 kc/s. This allowed each polarization to be sampled a number of times, during the time it took the receiver to sweep a band equal to the bandwidth of the receiver.

d) <u>The recording equipment</u>

The signals coming from the separator switch were fed into a double beam oscilloscope, Telequipment Type D47, triggered externally from the multivibrator, which also triggered the voltage sweep. The traces on the blue screen were photographed on Kodak positive safety film, type 5302, with a continuous feed camera Type C/F/100, made by D. Shackman and

Sons. This camera took 100 ft of film at one time and the film could be run at speeds varying from 1 in/sec to 36 in/sec. The speed was set to about 5 in/sec, as the sweep repetition frequency was in the region of 4 sec^{-1} and this speed gave sufficient space between the traces.

4.4 Calibrating and operating procedure

The swept frequency polarimeter was kept operating continuously during the total period over which observations were attempted. Only the double beam oscilloscope was switched off, outside scheduled observing periods.

Each night observations were attempted the following procedure was adopted to test the equipment.

After arrival at the field station the auxiliary equipment was switched on. Then the antenna was aligned, either visually or by calculating the correct position from information obtained from the Astronomical Ephemeris. Tests were carried out to determine whether any leakage existed between the two antennas due to dampness in the supports.

The next step was to check through the performance of the instrument. First the switching circuits were checked and aligned to allow for possible phase delays in the receiver. The gain of the instrument was checked using a Hewlett-Packard signal generator, type 606A. Any difference between the two channels was adjusted with the fine control of the oscilloscope amplifiers. The linearity of the gain was also checked and usually found to be within 10% over the dynamic range, for a range of input frequencies.

The overall gain was adjusted until the noise level occupied about 2 to 3 mm of screen. It should be remembered at this point that the sensitivity of the instrument was limited by the amount of noise the input switch introduced into the circuit. Therefore any checks of the gain were carried out to establish, whether any deterioration of the gain relative to the noise level had taken place. The main object of the check of the individual channels, was to ensure balanced amplification, so that later evaluations of axial ratios were a true reflection of the input characteristics. The sweep rate was adjusted to roughly 4 sec^{-1} and the frequency range adjusted and calibrated.

During the course of the observation, the position of the antenna was adjusted to follow Jupiter. In this way the maximum deviation of Jupiter from the antenna axis was never more than 10^{o}, ensuring minimum possible error with the system in determining axial ratios. This maximum deviation was at the end points of the possible observation period of 2 hours each side of meridian transit.

Fixed frequency recordings apparatus operated throughout the watch at 16 Mc/s, 18 Mc/s, 20 Mc/s and 22 Mc/s. When any indication was given at any of these fixed frequencies that Jupiter radiation was being received, the film recorder was switched on for short periods. Continuous operation of the film recorder was uneconomic as the film speed was in the region of 5 in/sec (100 ft/4 min), and Jupiter storms are likely to last for anything up to a few hours.

4.5 Results and their analysis

Before attempting to present any results obtained, we have to stop a moment and consider the corrections that have to be applied due to the characteristics of our particular instrument. It was pointed out that the instrument had a voltage linear detection characteristic. This implies that the signal visible above the noise fluctuation is proportional to the voltage variation at the input of the receiver.

There was, however one major failing of the instrument, which could not be rectified without completely redesigning the receiver. Switching between the two inputs introduced so much noise into the system that only very strong bursts were recorded as deflections large enough for any quantitative interpretation.

It has been mentioned in the section describing the receiver, that the two log-periodic antennas were interconnected with a $\lambda/4$ line to make the system responsive to the sense of polarization. This line introduced a phase difference of $\pi/2$ at a frequency of 18 Mc/s, above this frequency the phase angle was larger, below this the phase angle was smaller. This means that for circular polarization of one sense, the cancellation and addition was not complete. We shall consider this point now in a little more detail.

a) Correction to the axial ratio

Let us consider the case depicted in Fig. 2, when the phase difference introduced is not $\pi/2$. (Previously discussed in section 3.4).

Suppose right hand circular polarization is incident upon our antenna system. The antenna "A" will receive a signal E cos ωt and the antenna "B" E cos $(\omega t + \pi/2)$. The phase delay introduced by the "$\lambda/4$ line" will now depend upon the frequency of the incoming radiation in a manner such that the phase angle will be

$$\theta = \frac{f \cdot \pi}{18.2}$$

where f is the wave-frequency.

We may now make use of some A.C theory and add the two resulting signals in vector form.

The output at A' will now not be zero, but will be the vector sum of E cos ωt plus E cos $(\omega t + \pi/2 + \pi f/36)$, and have an amplitude

$$E \sqrt{2(1 - \sin \theta)} \qquad (1)$$

The output at B' will be less than before. It will be the vector sum of E cos $(\omega t + \pi/2)$ plus E cos $(\omega t + \pi f/36)$, and have an amplitude

$$E \sqrt{2(1 + \sin \theta)} \qquad (2)$$

If the received radiation is left hand circular the voltage formerly at A' will appear at B' and the voltage formerly at B' will appear at A'.

As the received Jupiter emission is elliptically polarized, there will normally (unless circular) be an output at both A' and B'. Due to the phase being different from $\pi/2$ the outputs will be changed. The output at B' will contain some of A' output and vice versa.

We can therefore calculate the real axial ratio in terms of the observed axial ratio. The correction graph is shown in Fig. 6.

b) Appearance of recorded bursts

It will be realized that due to the bandwidth, time constant and sweeping, resulting traces on the oscilloscope screen may not be what they seem to be.

Two subdivisions have to be made in this discussion, pulses which have short duration in time and pulses which have narrow frequency bands. We shall discuss each in turn.

Consider a pulse, lasting for at least a couple of sweeps, appearing between the frequency limits f_1 and f_2 (Fig. 7a), f_2-f_1 being very much larger than the bandwidth of the receiver. After this pulse has been detected by the instrument, it will appear as shown in Fig. 7b on account of having passed through a circuit of time constant RC. In this case, although the edges have been deformed, the bandwidth of the pulse will still be reasonably represented by the bandwidth as shown by the distorted pulse. The amplitude will be truly represented. A pulse whose width is of the same order as the bandwidth of the receiver would appear as shown in Fig. 7c. If the pulse has a still narrower bandwidth it will hardly be detected by the receiver and will appear as a "weaker" signal.

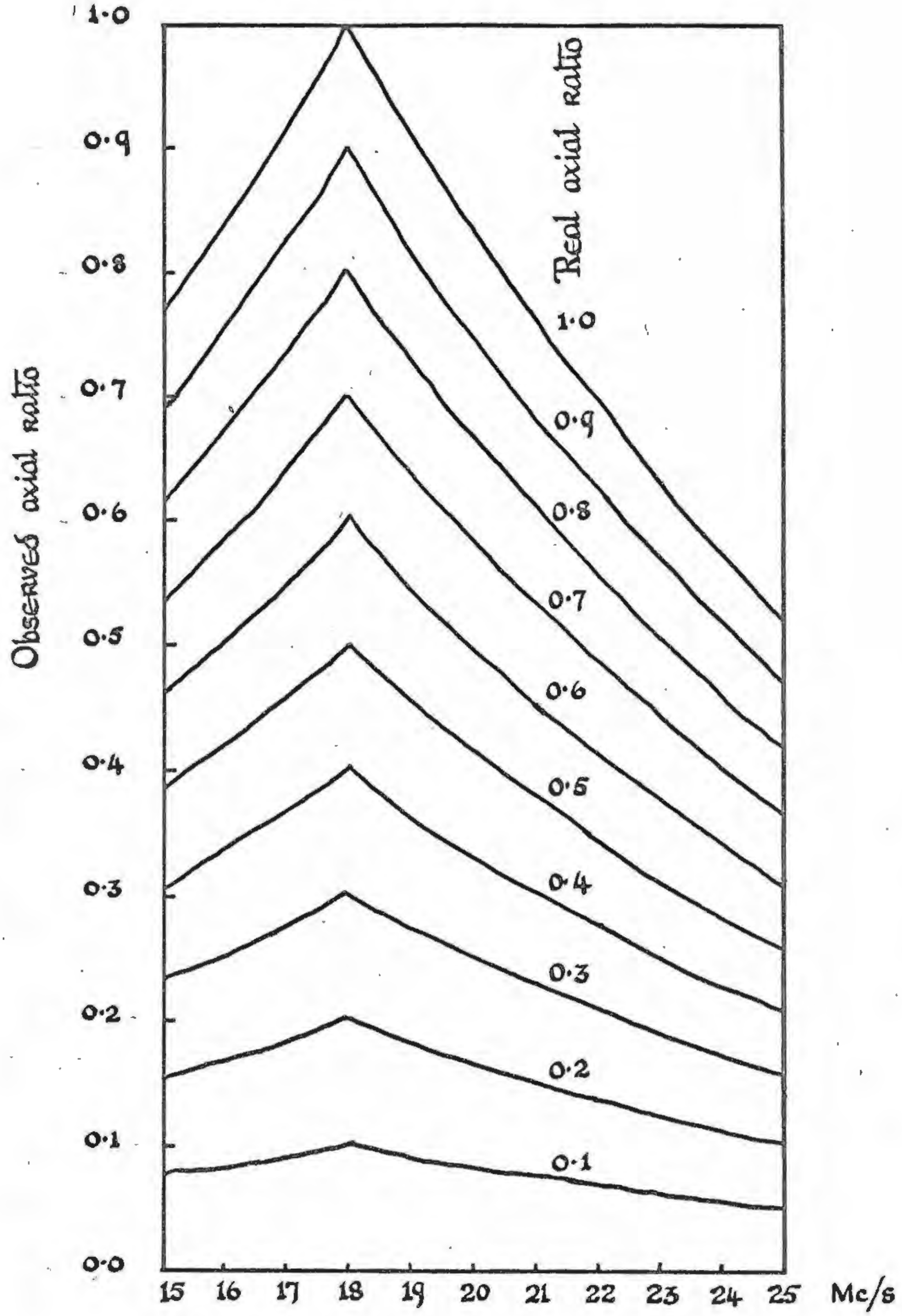


Fig. 6 Axial ratio correction curves

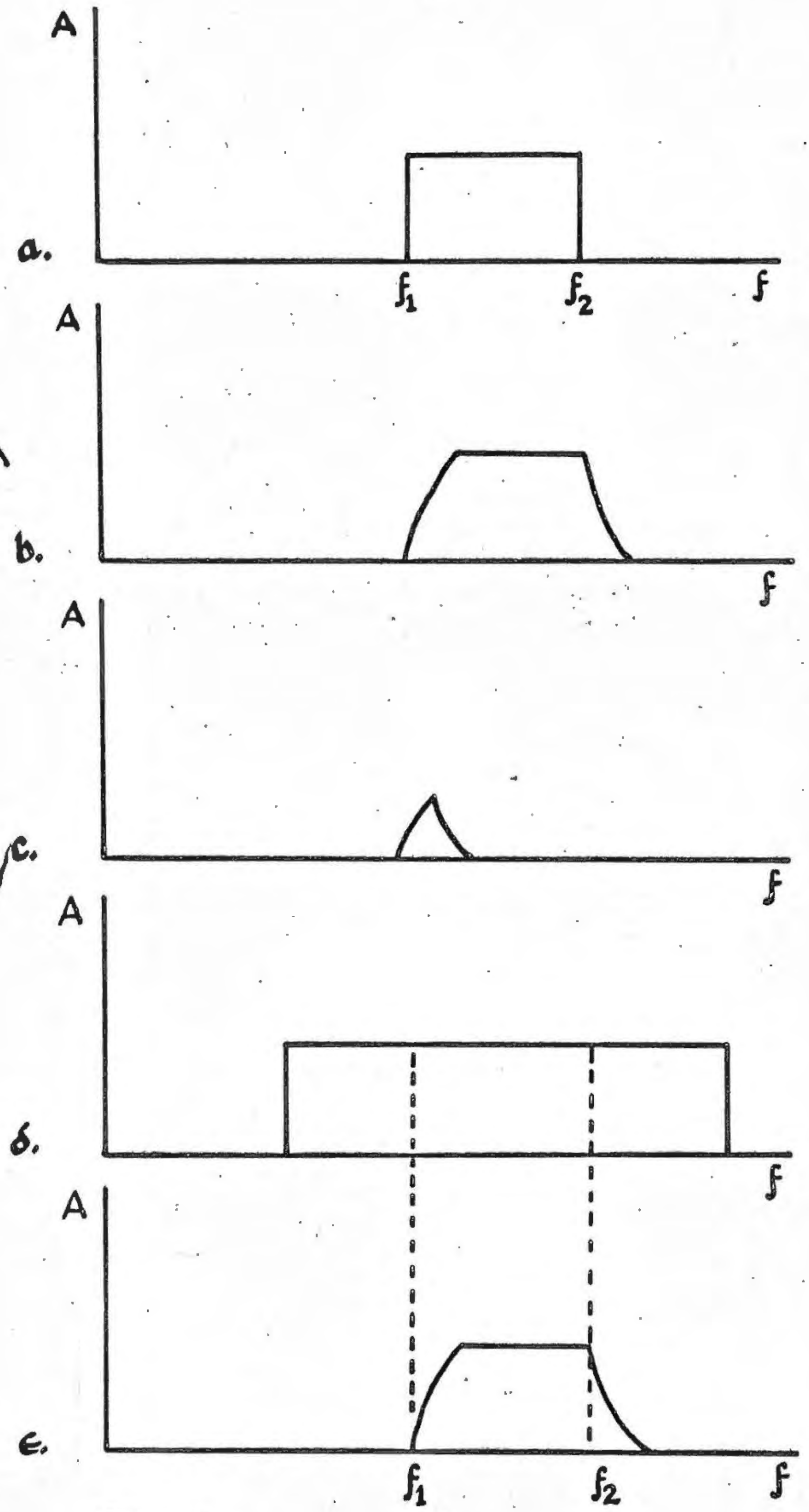


Fig. 7

If we have a pulse which is emitted over a large range of frequencies (Fig. 7d) but which last for only a short time, then this pulse will only be visible on the film if it is received during the time that the receiver was actually sweeping across the frequency band. If we assume that this pulse appeared while the receiver was in the middle of its frequency sweep, and that the pulse lasted while the receiver swept from frequency f_1 to the frequency f_2, then the film will show a trace as shown in Fig. 7e. It should be noted that in this case it is impossible to tell the difference between the two traces shown in Fig. 7b and Fig. 7e. Both will have the same appearance. But as the pulse shown in Fig. 7b will appear in more than one trace, because it lasted for a time long compared to the repetition rate, we may conclude that in this case the frequency limits were correct. The only thing we may conclude in the case of the short pulse is that the frequency range extended at least from f_1 to f_2, and may have been larger.

There is a second question that must be answered before samples of the records and some analysis can be presented. This is how certain is it that these traces actually represent Jupiter signals. To do this it is best to describe how the author chose these photographs from over 1000 ft of recorded film.

It should be remembered that the oscilloscope camera was only switched on to take samples, when activity, which had the usual Jupiter-characteristics, was shown on any of the four fixed frequency receivers.

Jupiter's decametric radio emission has a very characteristic sound, very much like the breaking of a wave on a pebbly beach, as some noted scientist once described it. This can only seldom be confused with terrestrial interference or distant radio stations. Although the storms are sometimes not unlike thunderstorm activity it is virtually impossible to confuse the two as thunderstorm activity would give a very close burst for burst correlation over a wide band of different frequencies, while Jupiter activity usually was a bandwidth of the order of half a megacycle.

For proper identification of weak signals they have to be at least three times the RMS value of the noise to be accepted.

When the photographs were developed it was established whether there was any continuous interference noticeable. If this was the case then no attempts were made to analyse that part of the film. If there was no interference then the film was scanned trace by trace for any evidence of Jupiter activity. (It should be remembered here that the sensitivity of this instrument was very much inferior to the fixed frequency receivers) Whenever such activity could be ascertained the film was marked for later analysis.

At the end of the observing season all marked film was compared and the most interesting sections enlarged and copied. These will be shown and discussed later.

When adjusting the receiver matters were arranged in such a way that two traces, one representing left hand, the other right hand polarization, were close together. It was usual for the left hand polarization to be represented by the upper trace and the right hand polarization by the lower trace. The sweep rate was 10 Mc/s in 60 msec, repeated every 250 msec.

The work described here is new, as no-one has as yet observed Jupiter emissions on a swept frequency polarimeter in this particular frequency region. It has recently come to the author's notice that Gordon (1966) has operated such an instrument covering the frequency range 24 Mc/s to 36 Mc/s. The only other swept frequency instrument, sweeping over more than a few Mc/s, is a swept frequency interferometer operating at the High Altitude Observatory (HAO) at Boulder, Colorado and it does not distinguish between the various forms of polarization. Some results obtained at the HAO will be discussed later on in this report. Riihimaa, in Finnland, also operates a swept frequency receiver. It is a phase-switched panoramic interferometer, sweeping the range from 15 Mc/s to 20 Mc/s once every 6 secs. He also operates a high-resolution multi-channel spectrograph operating in the vicinity of 19 Mc/s. (Riihima, 1961; 1964a, 1964b, 1966b)

We are now in a position to show some of the results obtained. It will be appreciated, that not all successful photographs of Jupiter activity can be shown here. We will show a few which may show something of the characteristics of the observed emission. Some of the more prominent bursts recorded, shown and not shown, have been investigated for values of axial ratios and these will be compared with the work of other observers.

Fig. 8 shows some activity recorded during the night of the 6th November 1965. During this activity source A (238^{o} - 265^{o} CML) was pointing towards Earth and Io was in the vicinity of 220^{o} from SGC. The total duration of this burst group was about 2.5 sec. Although activity may have been all over the band, two main regions of activity can be seen to be well above the noise level, one activity region is in the vicinity of 16 Mc/s and the other is in the vicinity of 23 Mc/s.

For comparison and easy surveyance Fig. 9 was prepared to show the activity of the right hand trace only. It can be seen that both bursts are stable in frequency, no appreciable drift in frequency could be established. The structure and amplitude seems to vary. Axial ratios were determined for the maximum peak of each burst in each sweep. The accuracy is of the order of 20%.

The lower frequency burst varied in axial ratio from -0.15 to -0.66 and for the higher frequency burst the axial ratio varied from -0.17 to -1.0. The mean axial ratio for the burst amounted to -0.40 and -0.46 respectively.

There appears to be a division of the lower frequency pulse into two sections. Comparing traces b and c, it seems possible that the division may be due to another pulse having drifted up from lower frequencies, the pulse not being noticeable in trace b, while trace c shows them both.

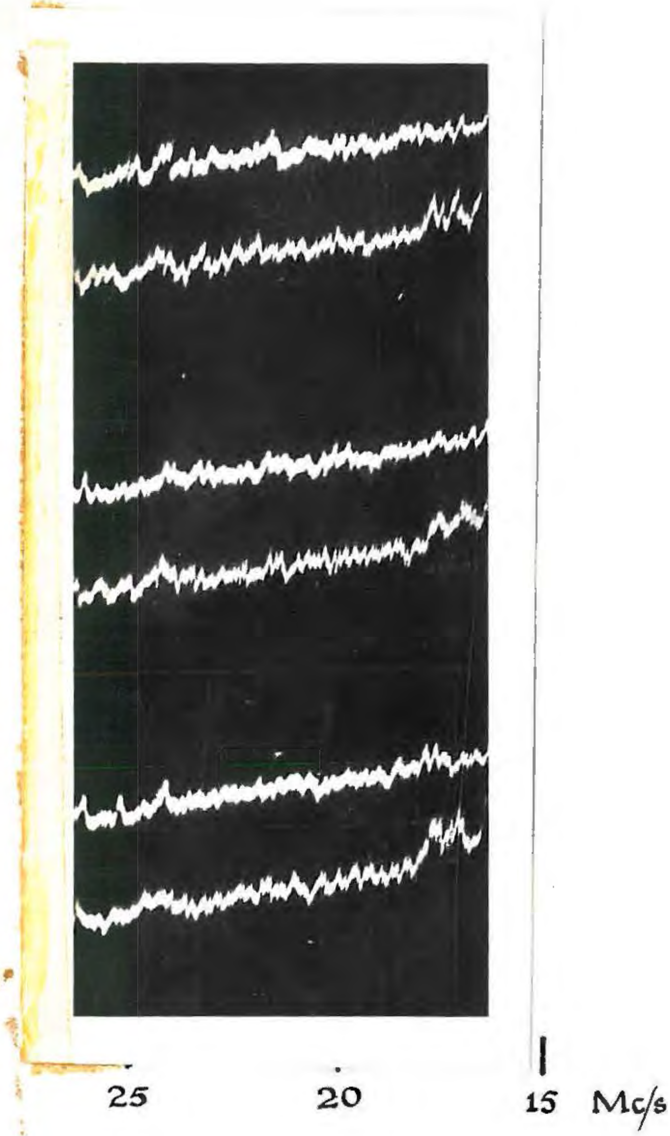


Fig. 8

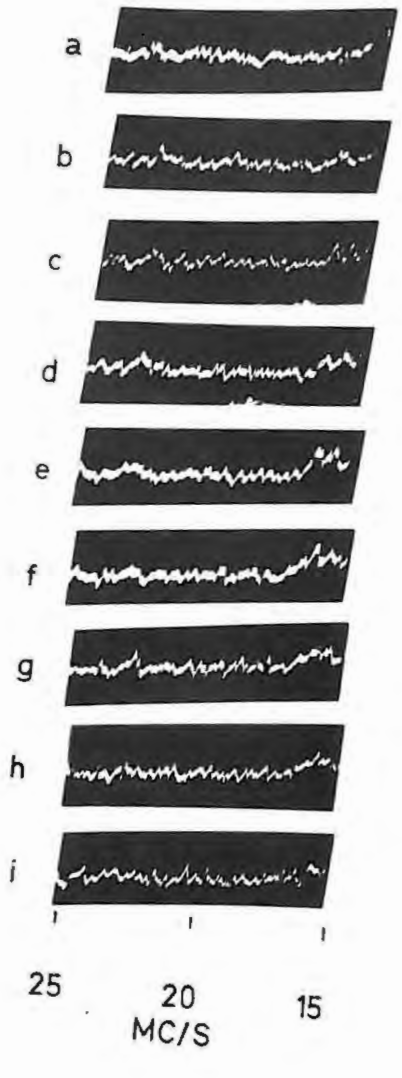


Fig. 9

There is also a second explanation. The pulse observable in trace b just above 16 Mc/s could have split by the next sweep, remaining at a slightly lower frequency until trace f, after this drifting to lower frequencies.

Pulses drifting to lower frequencies have actually been observed on more occasions and will be described a little later.

The higher frequency pulse is less intense and its bandwidth is also less. It is possible that the higher frequency activity is the third harmonic of a fundamental, whose second harmonic is the lower frequency activity. The suggested harmonic relationship would then be 8 Mc/s, 16 Mc/s and 23 Mc/s. This suggestion appears more plausible in the light of two recent publications. Carr et al (1965) report that the activity of Jupiter appears to be greatest between 5 Mc/s and 10 Mc/s, while Dulk and Carr (1966) report almost continuous radio emission at 8.9 Mc/s and 10 Mc/s.

Fig. 10 shows four pictures (I, II, III, IV) each presenting three sweeps across the frequency band. At that time source B was pointing towards Earth. Io was at that time in the vicinity of 300° from SGC. Traces Ia and Ib show the build up of a left hand polarized pulse (axial ratio +1) around 16 Mc/s. By the time sweep Ic took place the emission was over. Since there was no trace on the sweep before Ia (not shown), the total duration was in the region of half a second and the bandwidth about 200 kc/s. It will be seen later that it is unusual for left hand pulses to be recorded at such longitudes. Barrow (1964a) does report bursts in that vicinity, which are left hand polarized.

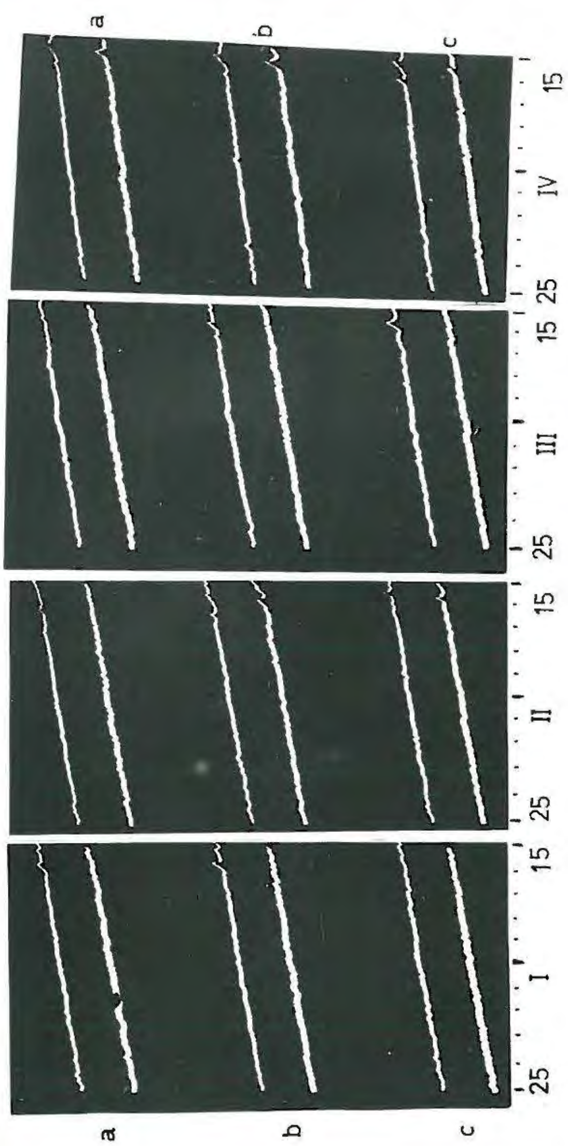


Fig. 10

In the second picture we see left hand activity in trace a. This can still be seen in the second trace (AR = +1) at a frequency of 17 Mc/s. However there is also some RH activity to be seen at a slightly lower frequency (16 Mc/s) extending downwards, out of the range of the instrument. When the third trace was taken activity is noticeable in both traces. It appears as if the RH pulse might be at a slightly higher frequency. Picture II was taken a few seconds after picture I. The axial ratio of the RH pulse in IIb is of the order of -0.2.

Picture III also shows a left hand pulse (AR = +1), while the fourth picture shows activity with a bandwidth of approximately 1 Mc/s at a frequency of 16 Mc/s. The axial ratio is about +0.13. In the same picture, we can also make out some activity around 16.5 Mc/s which is completely left hand (AR = +1).

Fig. 11 shows four pictures, each of which might exhibit the phenomenon of travelling pulses. Pictures I, II, III were taken during a storm on the night of the 7th November 1965, picture IV on the night of the 22nd November 1965. On the 7th November CML longitudes were about 100° during this emission and Io about 90° from SGC, while on the 22nd November 283° CML was pointing towards Earth and Io was about 266° from SGC. We shall see from the discussion which follows in the next chapter, that both these occurrences may have been Io-related. We cannot be certain as we do not know the highest frequency these storms attained.

It is not at all certain that these pulses do indeed represent travelling

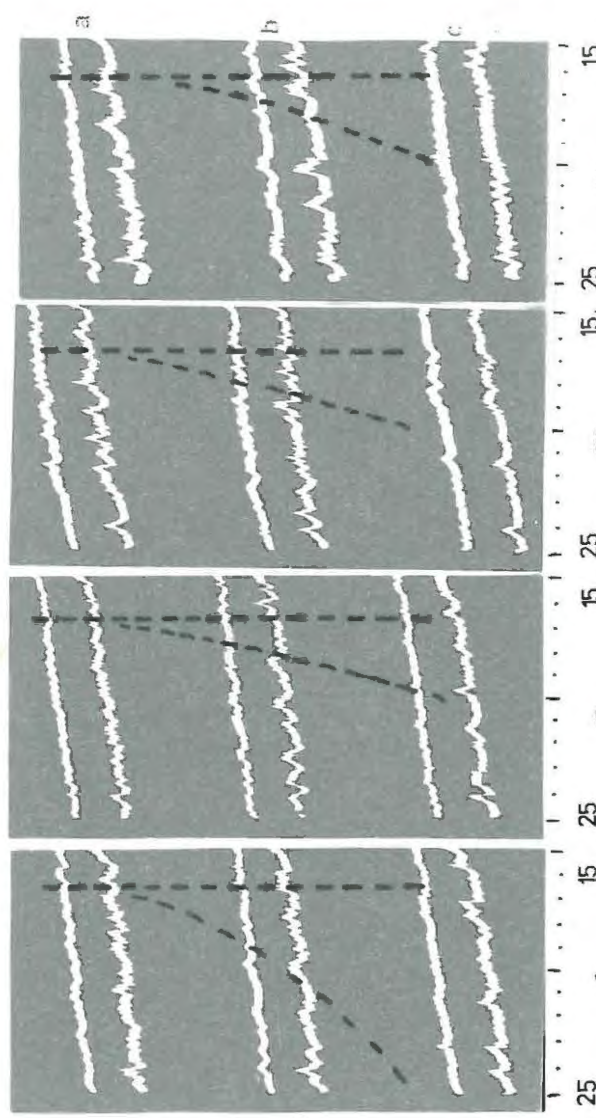


Fig. 11

phenomena, as the evidence is much too scanty. The only way in which we could have been certain is if the sweeping rate had been higher. This possibility and its advantages will be discussed in due course. However picture III seems, in the author's opinion, to be the clearest cut case for partially proving the existence of travelling pulses. If we look at IIIa we note that a right hand polarized pulse is evident at 24 Mc/s. No other activity can be seen until about 22 Mc/s. In IIIb we note two pulses of equal strength separated by about 1 Mc/s and in IIIc two pulses, also of equal strength, one at about 24 Mc/s the other 21.5 Mc/s, with no detectable emission in between.

It is interesting to note that similar patterns could be attributed to pictures I, II and IV. If this had occured only once, it would have been put down to chance. This multiple occurrence of similar patterns is taken to be evidence, for the existence of travelling pulses. Theory also predicts them. In a lot of other groups of traces no possible patterns were detectable. Therefore it was decided to interpret these traces as travelling pulses and see how they do fit in with evidence collected by other observers. The suggested paths are outlined on the covering tracing paper. It is also interesting to note that the suggested travelling pulse changes the axial ratio from -1 in IIIa to -0.4 in IIIc. If we average the axial ratios for the nine traces and plot them against the frequency we get the graph shown in Fig. 12. Although the axial ratio seems to vary considerably, we can still see that the polarization is definitely right hand. The suggested drift rate reaches at least 8 Mc/s^2, it increases with time. If picture IV can also be interpreted as drifting

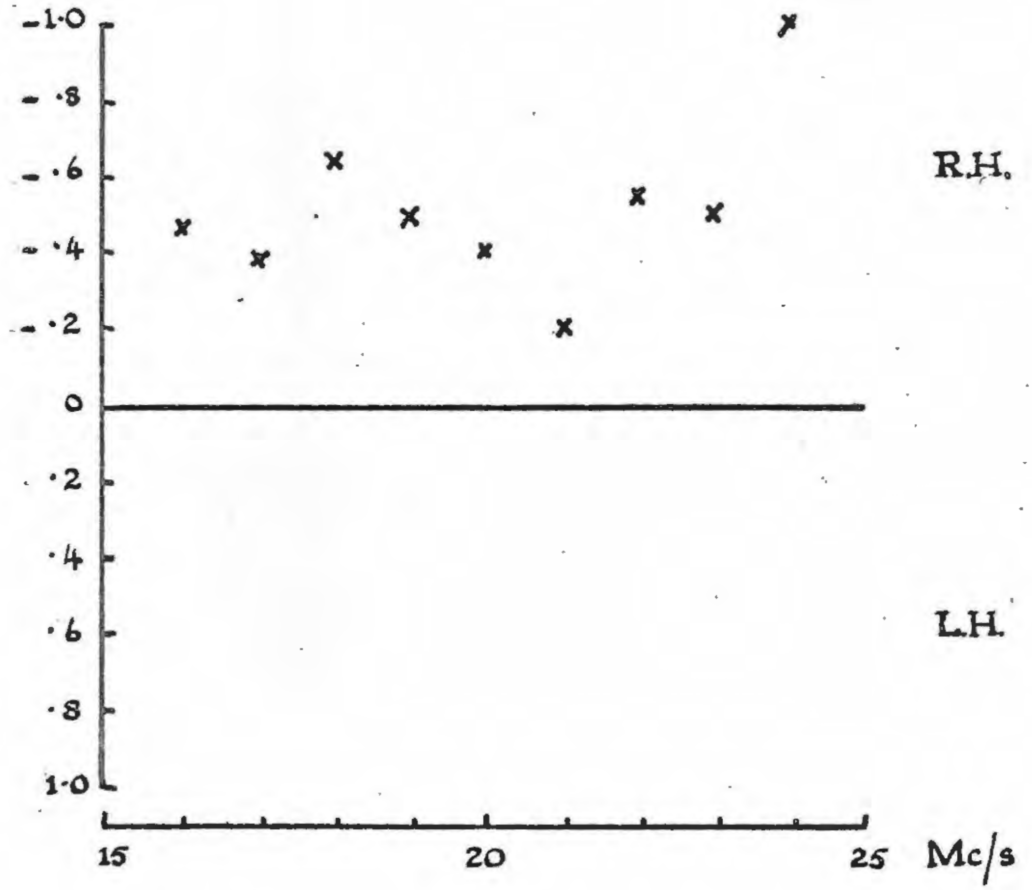


Fig. 12 Axial ratios of bursts shown in Fig 11

pulses, then this drift rate is still higher. (Ellis's theory predicts drift rates of over 30 Mc/s^2). It is also interesting to note that the axial ratios in the fourth picture are much more closely spaced. The actual determined values vary from -0.48 to -0.56 over the whole frequency range. In all four pictures, most of the emission noticeable is of short duration relative to the repetition rate.

Fig. 13 shows three pictures taken also on the 7th November 1965. (CML = 100°; Io = 90° from SGC). In picture I we can see a group of pulses (marked X) between 18 Mc/s and 20 Mc/s. In Ia they seem to be circular polarized, changing into elliptical (AR = -0.3). In Ib we can also see another RH pulse just above 22 Mc/s. Comparing Ia and Ib it appears as if, in the vicinity above 16 Mc/s, a RH pulse can be seen in Ia and a LH pulse in Ib. Both seem to be circular polarized and they seem to be related in some fashion. In picture II activity is noticeable throughout the band, but little correlation seems to exist between the three sweeps. In the third picture broad-band activity is noticeable in III b reaching as far as 19 Mc/s. The axial ratio is in this case undeterminable, as it is virtually impossible to locate the levels accurately. It is however clear that the burst is strongly right hand polarized.

Fig. 14 shows some further traces. Pictures I and III were taken on the 22nd November 1965, picture II on the 7th November 1965. Picture I shows some short burst activity in sweep b, with virtually nothing visible in trace a or c. The activity seems to take place throughout the observed

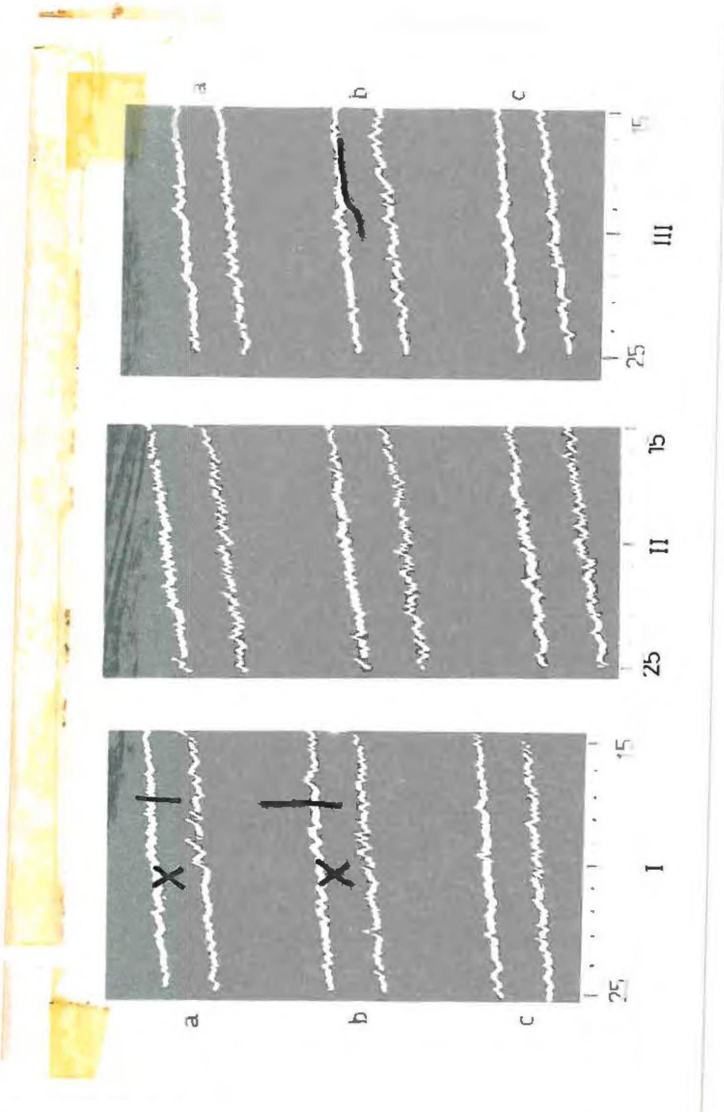


Fig. 13

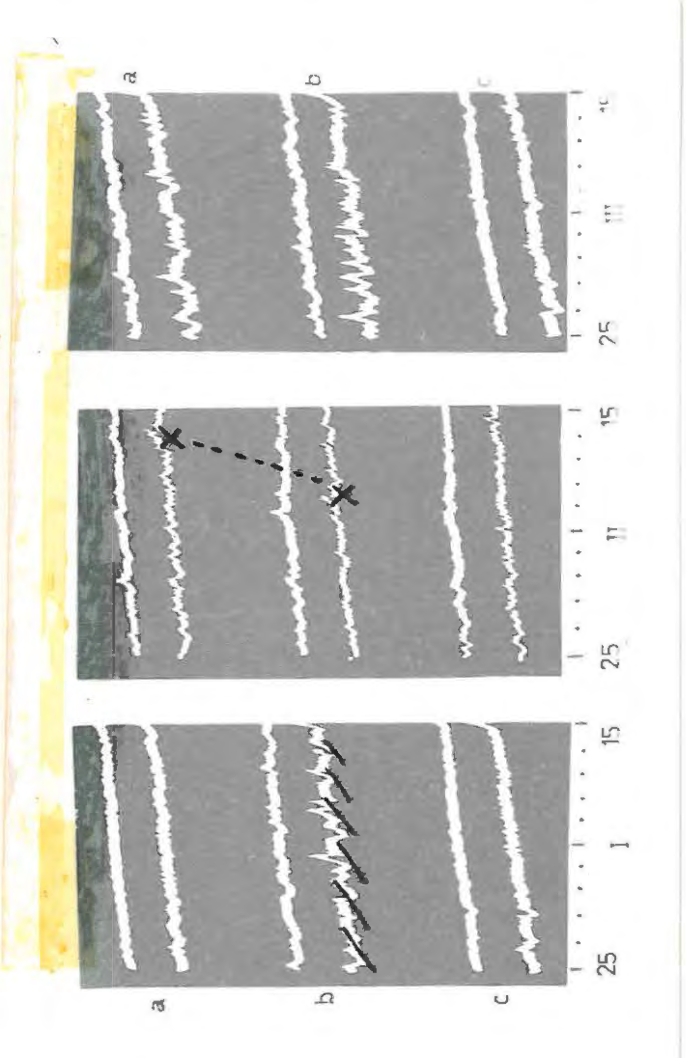


Fig. 14

frequency band. The polarization seems to be complete circular. In IIa RH activity is seen at about 16 Mc/s and in IIb at about 19 Mc/s. The shape of the two pulses appears to be similar, could it be a drifting pulse? If it is the drift rate is in the vicinity of 10 Mc/s^2. In IIIa and IIIb activity is seen in the higher frequency region, but gone by trace IIIc. The axial ratio seems to vary, from about -1.0 at 24 Mc/s to about -0.5 at about 20 Mc/s.

In the following pictures (Fig. 15) we can detect what may be an interesting phenomenon, definite and sudden changes in the axial ratio within quite narrow frequency limits. These pulses are marked with an "X". In Ib we see two pulses around 20 Mc/s. The one has an AR close to zero (exact value undeterminable) while about 500 kc/s higher the polarization seems to be circular (AR = -1.0). In IIb we see a similar effect close to 18 Mc/s. In this case it appears as if the polarization might change from -1.0 to +1.0 and back to -1.0 within less than 1 Mc/s. It seems possible to interpret the activity around 18 Mc/s in IIIb in a similar way. Other, weaker activity is noticeable in all three pictures. These sweeps were also excepts of the storm recorded on the 7th of November 1965.

Fig. 16 shows some pictures of what might be termed general activity. A few of the pulses can be seen in more than one sweep staying fixed in frequency. The third picture shows some fairly strong activity. Most of the pulses are strongly RH polarized.

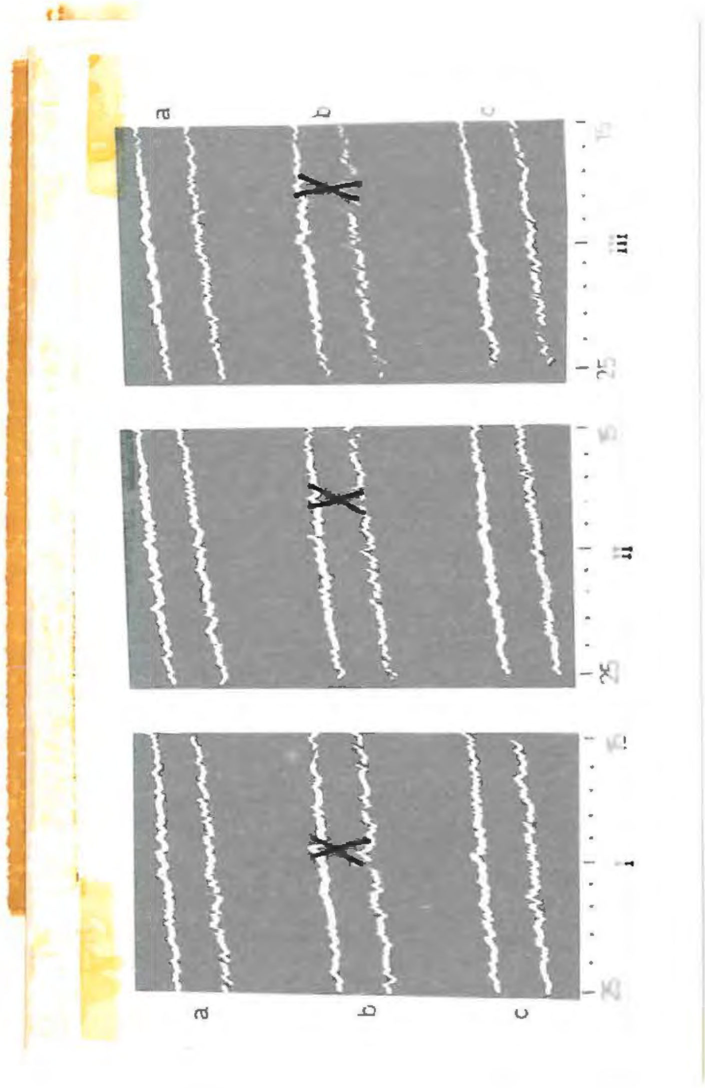


Fig. 15

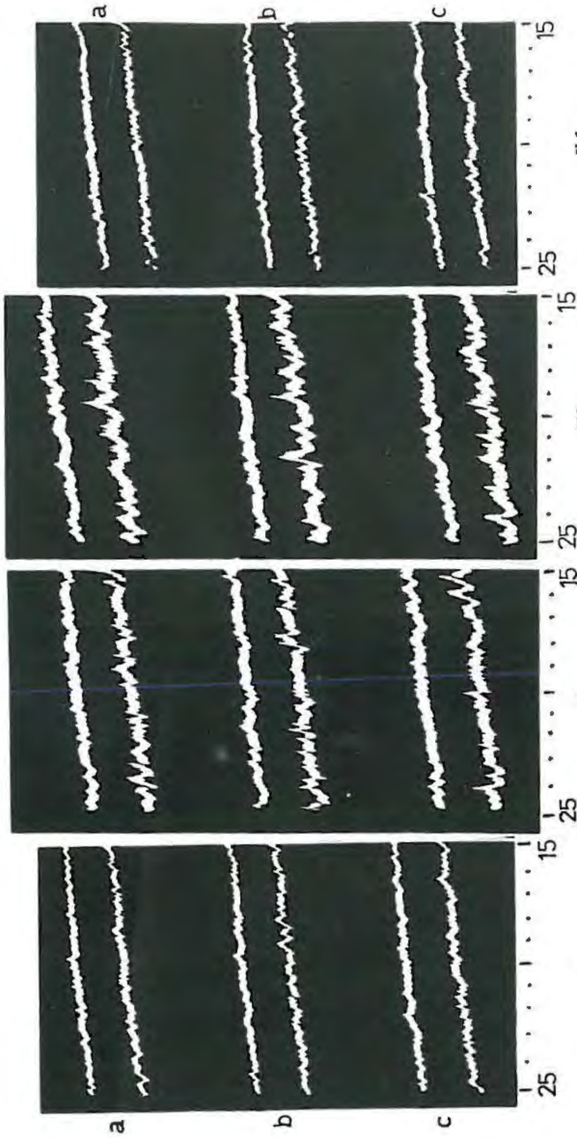


Fig. 16

The last three pictures are to be seen in Fig. 17. Picture I shows some unrelated short activity. The second picture also shows some unrelated activity. In the last picture some stationary pulses are evident. These are marked X. The pulses marked + are thought to be interference.

4.6 Discussion

The time duration of Jupiter's decametric emission varies from bursts lasting for a few seconds, down to bursts lasting less than 0.05 sec. The latter pulses have sometimes been referred to as "spitting" pulses.

The Jupiter observers conference held in 1964 at GSFC proposed that the pulses be grouped as follows:

Burst type	Time scale in sec	NASA class.	name
long	greater than 2.0	3	L
normal	0.2 - 2.0	2	N
short	less than 0.2	1	S

Baart et al (1966a) have recently proposed that the "S-group" be subdivided into short pulses (range 0.05 - 0.2) and very short pulses (less than 0.05 sec). The latter type they named "I-pulses".

This classification covers all the types of bursts we are likely to observe

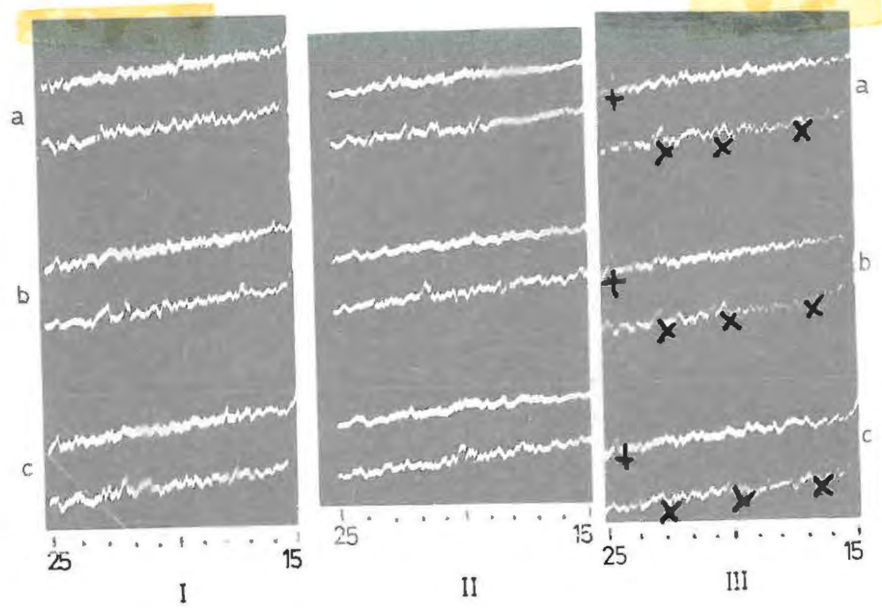


Fig. 17

from Jupiter. In the light of this classification, we have to ask ourselves what the capabilities of our instrument were.

It was said that the receiver swept the frequency range in approximately 60 msec once every 250 msec. This means that only pulses which last longer than roughly 310 msec are likely to be recorded on two successive sweeps, while pulses which last longer than 500 msec are definitely recorded on two successive sweeps.

To be able to interpret any characteristics of a pulse we would have to see it in at least three sweeps, and even then this may be difficult. We may however, say with certainty that any pulses which last longer than 1 sec, can be investigated properly, provided they stay reasonably fixed in frequency. Should the pulse drift, then we have further difficulties.

We have seen in Section 3.5 (Fig. 11), that certain pulses were detected which were thought to drift at a rate of approximately 8 Mc/s^2. This means that between each successive sweep, the pulse will have shifted in frequency by about 2 Mc/s. In that case, although we have said that these pulses were drifting in frequency, one cannot be certain at all. A frequency drift of the order of 0.5 Mc/s^2 could be interpreted as such, without much doubt, but once the drift exceeds 1 Mc/s^2 the argument becomes weak, if an instrument of such low time resolution is used.

To sum up, we may conclude that this particular instrument may be sufficient to investigate class 3 pulses, provided they do not drift in frequency by more than 1 Mc/s^2.

However if we consider the latest publications in this field (Warwick and Gordon, 1966; Riihimaa, 1966), we find that they have observed phenomena which drift in frequency at a much higher rate. Warwick and Gordon report having observed drift phenomena moving from high to low frequencies at a rate varying between 5 Mc/s and 35 Mc/s, while Riihimaa reports drifts of about 0.5 Mc/s^2. (His instrument was incapable of detecting higher drift rates). We may therefore conclude that all types of drift rates can be observed. Theory predicts drifts varying from 30 Mc/s^2 to 50 Mc/s^2, but the limits are only imposed by the choice of electron energies.

We can deduce the electron energy of our observed drift pulses from relatively simple geometrical considerations. Davis and Chang (1961) have determined from decimetric observations of Jupiter, that the planets magnetic moment is 4.24 x 10^{11} weber.meter. For the purpose of this calculation, let us assume that the drift velocity is 8 Mc/s^2 at 20 Mc/s and that the radiation is emitted at the gyro-frequency.

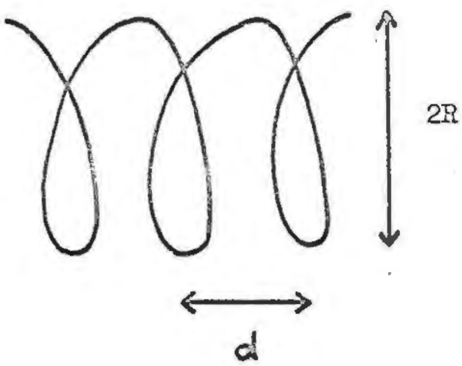
With the above dipole moment, a difference of 2 Mc/s corresponds to a difference of height of 3250 km in the magnetic field along the magnetic polar axis. The drift rate of 8 Mc/s^2 therefore corresponds to a linear velocity of 13,000 km/sec, and a bandwidth of 0.5 Mc/s corresponds to a length, of the electron cloud emitting the radiation, of 800 km. The negative drift rate implies that the electron cloud is travelling into the direction of decreasing magnetic field, i.e. away from the planet, since the gyro-frequency is decreasing. The assumption of gyro-frequency emission means that the electrons, when emitting the radiation of 20 Mc/s, are gyrating about the magnetic field line at a rate of 20 Mc/s. Due to the drift velocity of 13,000 km/sec they will travel along a helical path. If these electrons have velocity "v", and pitch angle θ, then

$$v \cos \theta = 13{,}000 \text{ km/sec} \qquad (1)$$

since the component of their velocity along the field line must equal the drift velocity.

The electrons, gyrating at 20 Mc/s, will drift a distance

$$d = \frac{13.000}{2 \times 10^7} \text{ km/cycle}$$



If the radius of the helical path is R, then it follows from the diagram on the left, that there is a relation between the pitch angle and the radius. We may therefore write

$$\tan \theta = \frac{2\,R}{\frac{1}{2} \times 13{,}000/2 \times 10^7} \qquad (2)$$

We may also derive a third relationship, if we consider that the total velocity is the sum of the drift velocity and the velocity along the circumference of a circle of radius R, i.e.

$$v = 2 \times 10^7 \left\{ 4\pi^2 R^2 + \left(\frac{1}{2} \frac{13.000}{2 \times 10^7} \right)^2 \right\}^{\frac{1}{2}} \qquad (3)$$

Solving between the three equations given above, one obtains the value for the velocity and radius

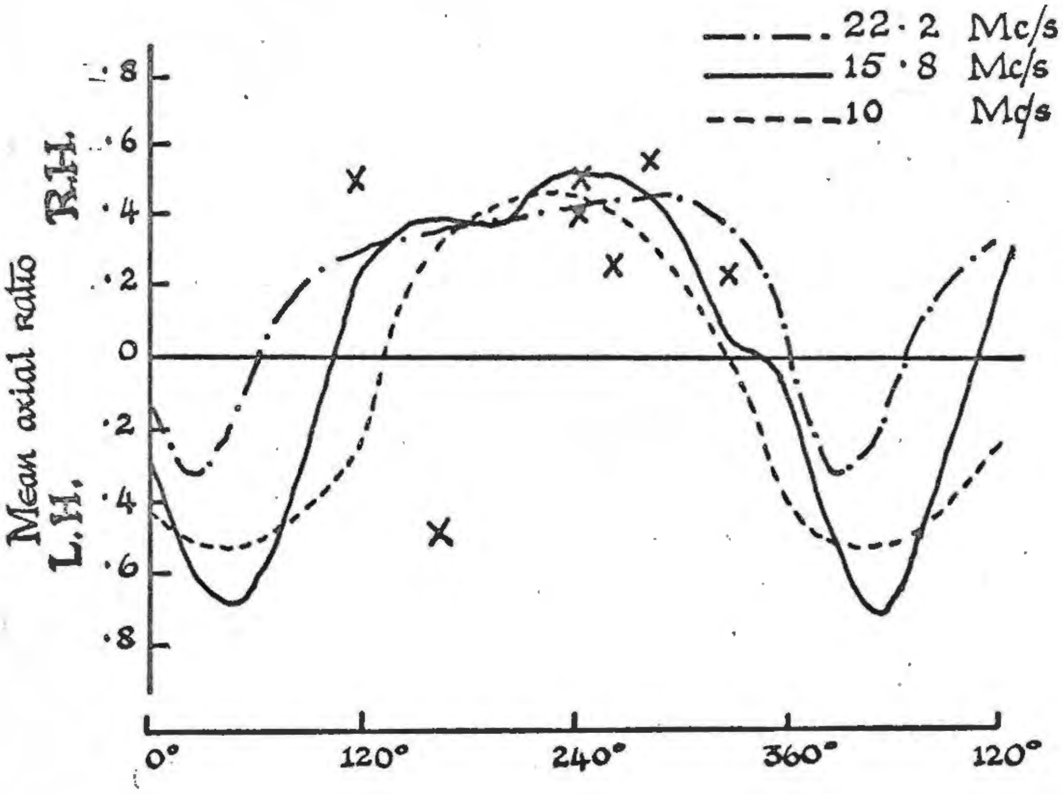
$$v = 16{,}000 \text{ km/sec} \; ; \; R = 1.2 \text{ m}$$

This implied that the electron emitting this drifting phenomenon is travelling at five per cent of the velocity of light. They are therefore probably non-relativistic. The energy of such electrons is of the order of 5 kev.

The reason why only negative frequency drifts are observed can be two fold, either no electron clouds drift into regions of stronger magnetic field, or if they do, this radiation is unobservable. Ellis and McCulloch's theory does indeed have an explanation for this effect, because according to their theory, emission can only take place in the forward direction and is emitted into a narrow cone only. Emission in the direction opposite to that of the emitting electrons has no narrow cone limitation, but can also not escape.

Fig. 18 shows the smoothed curves obtained by Carr et al (1965a) showing the longitude variation of polarization at three frequencies. Superimposed upon this graph marked (X), are the few measurements we were able to make successfully.

There is only one result which seems to be outside the limits of error. The point corresponding to AR = +0.5 in the vicinity of 180° CML. However we have to remember that the graph upon which these points were superimposed is one of mean axial ratio and the point in question is only the mean of four observations. The method of sampling may have precluded



X = our observation

Fig. 18 Mean axial ratio versus CML (Carr et al, 1965 a) observation before and after which would have put the point into the right position on the graph. However it may also be pointed out, that both Barrow and Sherrill have reported having observed LH polarized pulses in similar CML positions. Barrow (1964a) reports having observed LH at 16 Mc/s at some slightly higher CML values during 1963, while Sherrill (1965b) reports observations of LH polarized pulses at 16 Mc/s at similar CML values.

Sudden variations of axial ratios similar to those observed will be discussed in the next chapter, when a suitable model will have been introduced to explain various phenomena. The other pictures which showed generalized activity have been included in our analysis of axial ratios. To say much more about them would be futile at this point, as neither the apparatus nor the statistics would allow a more detailed analysis.

The general trend of our observations appears to correlate with previous observations. This is in spite of the fact that our apparatus was only able to detect strong Jupiter bursts and the difficulty of correlation due to the method of recording. The first mentioned fact resulted in the difficulty of observing Jupiter-bursts in the background noise. It can be seen on a number of traces that this was a most serious complication. The influence of the second major defect was the inability of determining trends in the records, due to the large distance between sweeps, and the large amount of film per storm.

All the same we may conclude that the apparatus has actually performed the task for which it was intended. We have been able to determine the sense of polarization, and in addition we were able to determine the axial ratio and its variation for a number of bursts. To be able to determine much more than that would require a much more sophisticated instrument. We have learned by our mistakes and the instrument, at present in its completing stages will improve upon the one used during the last observing season. Its sweep rate will be 100 sweeps/sec and the former switching has been eliminated, thereby increasing the sensitivity greatly. The instrument will sweep through the frequency range amplifying during alternate sweeps first the left hand channel, then the right hand channel. The phase difference between the two inputs is provided by a hybrid ring which adds all frequencies between 15 Mc/s and 25 Mc/s with phase differences of 90° and 270° thereby producing two outputs, one representing left-hand circular the other right hand circular polarization. Finally the recording is to be done on film using Z-modulation. This will allow us, while still being able to determine some axial ratios, to determine trends and characteristics on a basis of high resolution. We will also be able to record continuously, a fact which will improve the system. A large number of bursts were certainly missed with the past method of sampling during activity.

We shall not go into detail of interpretation at this stage, as in the next chapter additional evidence will be introduced. This evidence will allow us to postulate, with the aid of Ellis and McCulloch's theory, a model which exhibits some of the characteristics of present observations of the decametric radiation.

CHAPTER V

A statistical analysis

5.1 Introduction

In this chapter we shall attempt to analyse data obtained by Warwick's group (Warwick and Kreiss, 1964; Warwick and Dulk, 1965) at the High Altitude Observatory at Boulder, Colorado. The data published contained:

(a) Date of observation;

(b) Time during which observation took place;

(c) Time during which Jupiter activity was observable on the frequency-time recordings;

(d) Intensity of a storm on a scale 3,2,1;

(e) Burstiness of the emission;

(f) Frequency range over which the storm was observed;

(g) System III CML co-ordinates of observed emission.

These data were obtained with a swept-frequency interferometer sweeping from 7.6 Mc/s to 41 Mc/s. The equipment integrates over about 600 kc/s of spectrum, and had a sweep recurrence rate of 1.30 sec from January 1960 through to July 1963 and 0.65 sec from August 1963 on. The equipment permits identifying each Jupiter event lasting more than 2 or 3 minutes, or covering more than one or two Mc/s. Its sensitivity is high enough to record the bright radio stars Cassiopeia A and Cygnus A.

The observations were carried out over such a large period of time, that it may be assumed that each part of Jupiter was pointing towards Earth an equal number of times. The resulting information would therefore correspond to that obtained by a random sampling process. It is therefore unnecessary, from a distribution point of view, to calculate probability of occurrence, as an analysis with respect to number of occurrences gives similar results.

Table I gives a summary of Warwick's data which was used for the analysis.

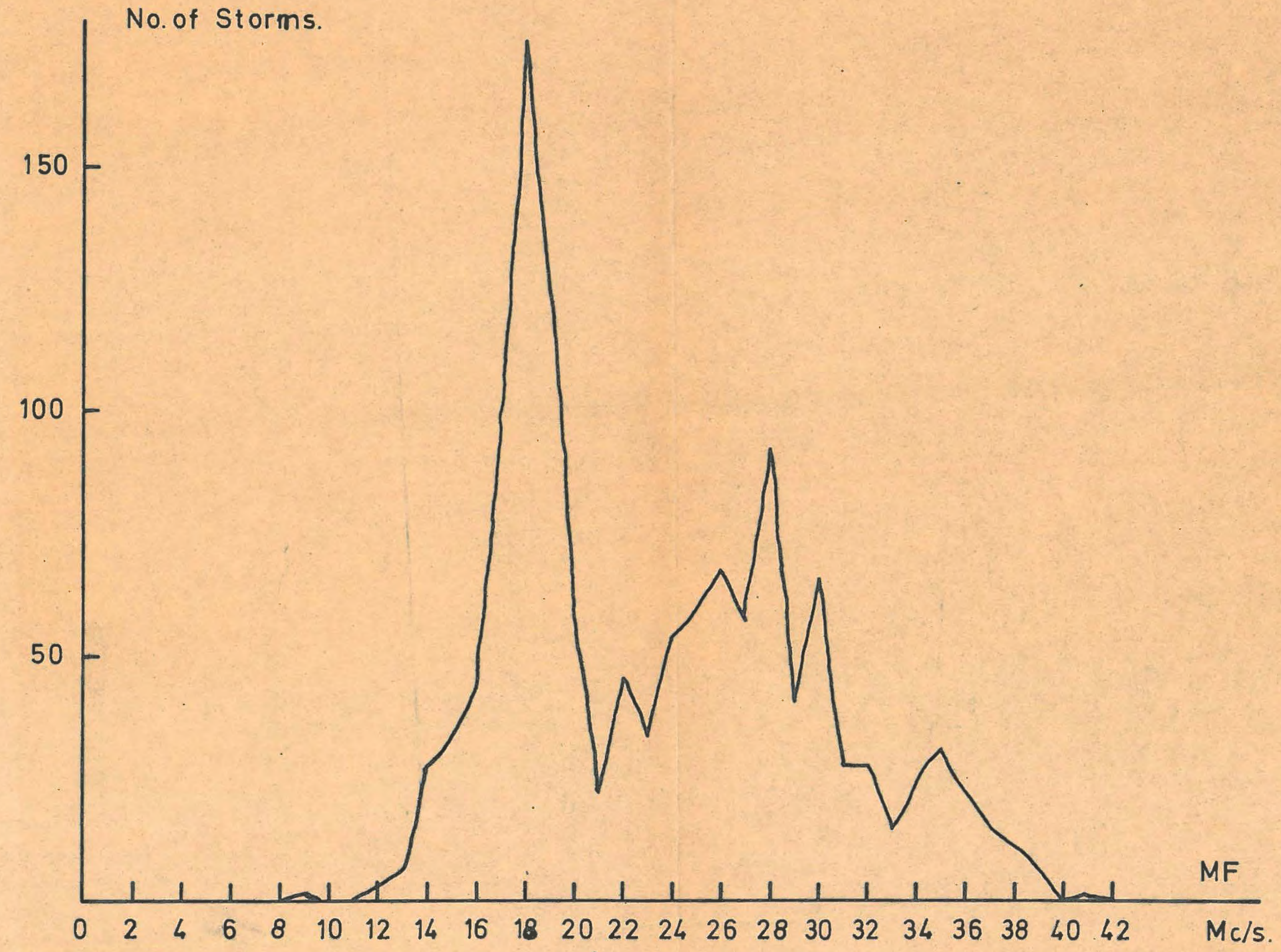
The analysis which is about to be presented, was designed to determine whether any significant variation can be found, when analysing the data on a basis of "Maximum Frequency" (MF). This MF was the top frequency an emission from the planet Jupiter reached during one particular event. Suppose, for example, during an observation on one particular day Jupiter emission was recorded by the HAO spectrometer between the frequency limits 15 Mc/s and 31 Mc/s, nothing having been observed above 31 Mc/s. In this case 31 Mc/s is the MF.

Furthermore it must be realized that such an analysis could not be performed by an observer, who observes Jupiter on a few fixed frequencies. This observer, supposing he operates a set on 18 Mc/s, will observe ALL storms, which have a "frequency component" of 18 Mc/s.

Fig. 19 shows a graph of all the 1304 storms used in this analysis plotted versus the MF observed during each storm. It is seen from this graph,

	Apparition			Number of events	Total time (min)	Average time per event (min)	Observing time (min)	Average Percentage Probability
	Beginning	End	Opposition					
1960	2.12.59	5.1.61	20. 6.60	57	1397	25.0	-	-
1961	6. 1.61	8.2.62	25. 7.61	244	9008	37.0	187201	4.8
1962	9. 2.62	16.3.63	31. 8.62	352	17411	49.5	197384	8.8
1963	17. 3.63	22.4.64	8.10.63	430	28625	66.6	231992	12.3
1964	23. 4.64	29.5.65	13.11.64	229	11341	49.5	192220	6.0
			Total	1312	67782	51.7	808797	8.4

Table I : Summary of Jupiter events, apparitions 1960 - 1964.



No. of Storms.
150
100
50
MF
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42
Mc/s.

FIG. 19

that the largest number of storms had a MF in the vicinity of 18 Mc/s. There is a second peak at an MF of 28 Mc/s and a third peak appears at 35 Mc/s. There are also two definite minima, one at 21 Mc/s and another one at 33 Mc/s. The latter one is not as obvious as the former, most probably due to the smaller number of storms recorded with a high MF.

The observations were analysed for relationships to the angular position from Superior Geocentric Conjunction (SGC) of Io, the first Galilean satellite, and for relationships to System III Central Meridian Longitude co-ordinates (CML). The variation of emission with "apparition phase" is also investigated.

5.2 The Io-relationship

Bigg's discovery and the subsequent work along similar lines were reported in Chapter I. Bigg in his calculation had originally only used observations for the three apparitions of 1961 to 1963, and had also used an intensity weighting. He multiplied the time of Jupiter storms by factors ranging between 3 and 1, depending on the strength of the emission, as published by Warwick. As a first step in this investigation, Io-relationships were recalculated using data published for the five apparitions 1960 to 1964 and omitting this intensity weighting used by Bigg.

The published information was transferred onto punched cards and fed into a computer (I.C.T.1301) programmed to work out the number of times Jupiter storms occurred for each 1° interval of departure of Io from SGC. The results were plotted as a graph, which is shown in Fig. 20.

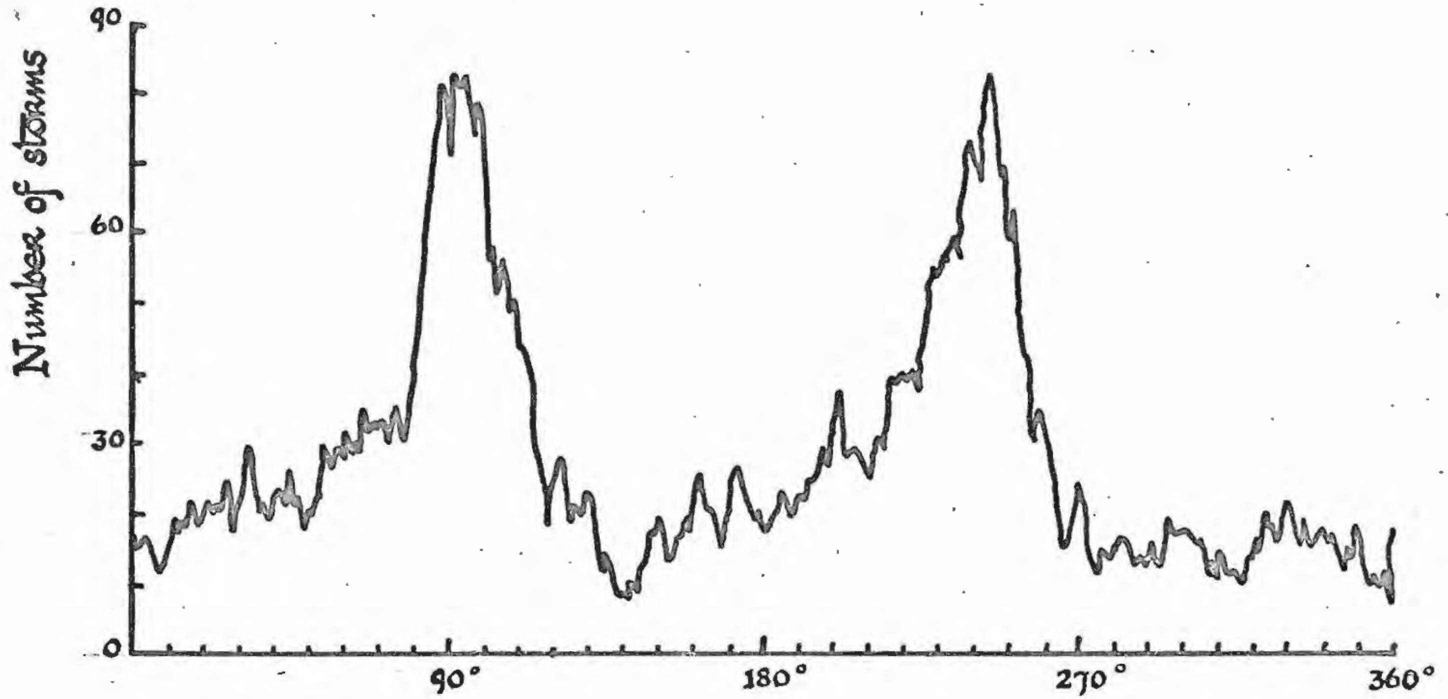


Fig. 20 Number of bursts versus departure of Io from SGC

The maximum peaks are located at 94° and 245°. This is similar to the results of Bigg who obtained peaks at 93° and 246°. However it may be seen quite readily when comparing the two individual graphs, that when Bigg included the intensity weighting, he obtained much sharper peaks. A comparison of the ratio of maximum to minimum of the graphs is very interesting. In Fig. 20 this ratio comes to 9.34, while in Bigg's graph the ratio amounts to 15.41. Comparison therefore reveals that when including intensity weighting the ratio of maximum to minimum is increased roughly in the ratios 5 : 3. It may therefore be concluded that we have here definite evidence that the intensity of Jupiter's decametric radiation is also related to the position of Io from SGC.

Since there is sufficient information so that reasonable subdivision still gives statistically significant results, it was decided to divide the data according to the 2 Mc/s interval in which the MF observed during a complete storm fell. The dependence of emission upon the position of Io was calculated in each interval. The results are shown in Fig. 21. (For convenience Fig. 21 and Fig. 24 have been placed at the back of this thesis)

It can be seen from the graph that while for certain MF ranges Jupiter's decametric radiation is strongly dependent upon the relative position of Io, there are others where it does not seem to matter much in which position Io is.

Whenever emission of Jupiter's decametric radiation has been recorded at the HAO at frequencies higher than 30 Mc/s, then Io was in either the vicinity of 90° or 250° from SGC. Storms which had a maximum or cut-off frequency between 20 Mc/s and 30 Mc/s are relatively unaffected by the position of Io. We see that emission with a MF in the range between 18 Mc/s and 19 Mc/s does, once again, depends in a more pronounced fashion upon the relative position of Io. It may be significant that the one region of Io-dependent activity (30 - 39 Mc/s) contains the second harmonic of the other (18 - 19 Mc/s). However this aspect will be discussed further after other results have been presented.

It is interesting to note that whenever emission takes place with an MF higher than 31 Mc/s, Io is above a certain region of Jupiter longitudes. Fig. 22 shows the geometry of lo relative to Jupiter when emission in the higher frequency regions takes place.

5.3 Dependence on Jupiter longitude

It was reported in Chapter I that, soon after the discovery of Jupiter's decametric radiation, the dependence of emission probability upon the CML position was noticed. Fig. 23 shows Warwick's data plotted in a fashion which indicates the variation of number of emissions with relatice CML. The graph shows the usual pattern obtained.

It is seen that most emissions takes place when Jupiter's longitudes around 240° are pointing towards Earth. There are two minima to be seen, one around 190° and one around 50°. The general appearance of the graph does suggest a tilted dipole field as used by Warwick and Ellis

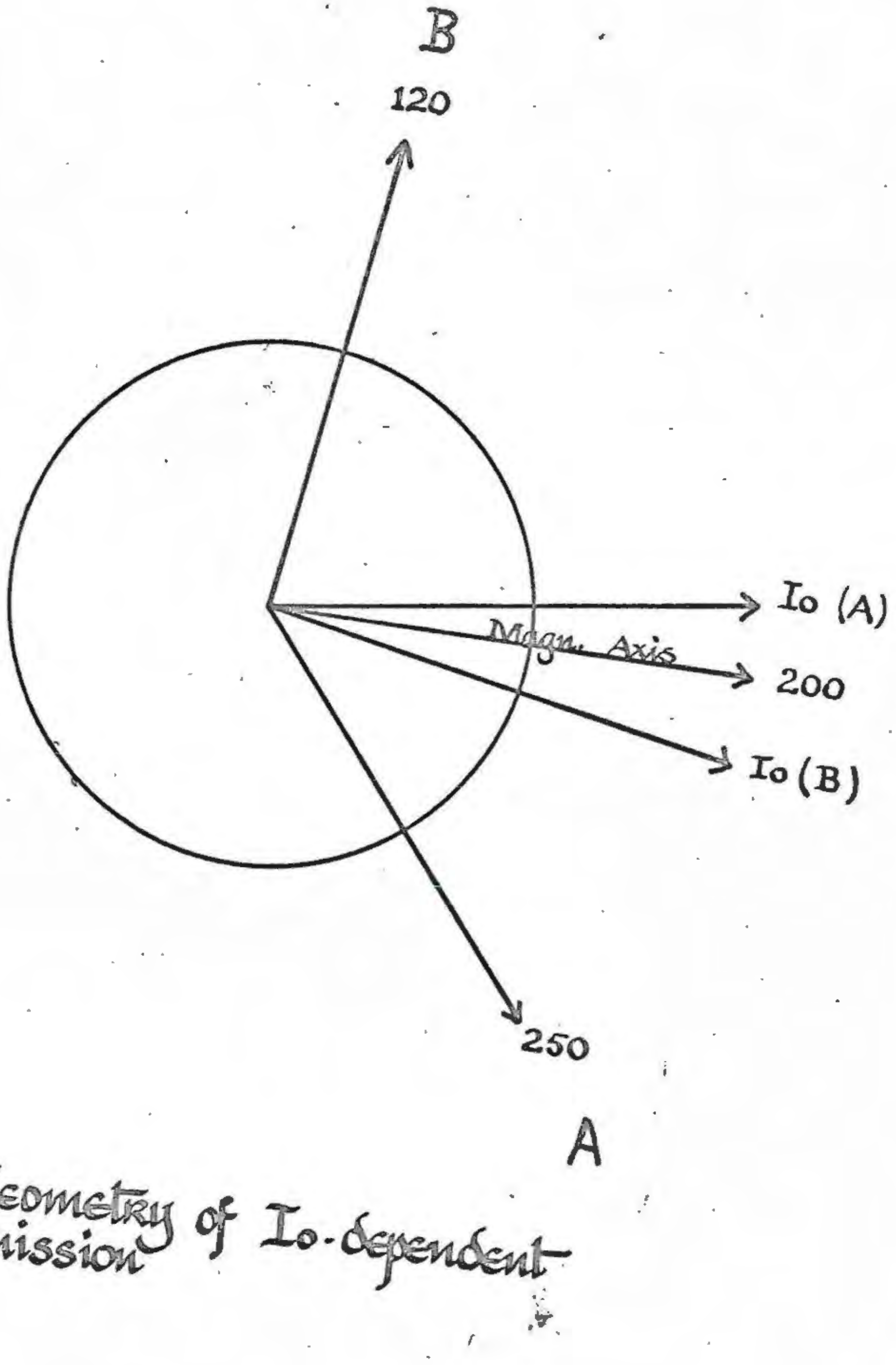


Fig. 22 Geometry of Io-dependent emission

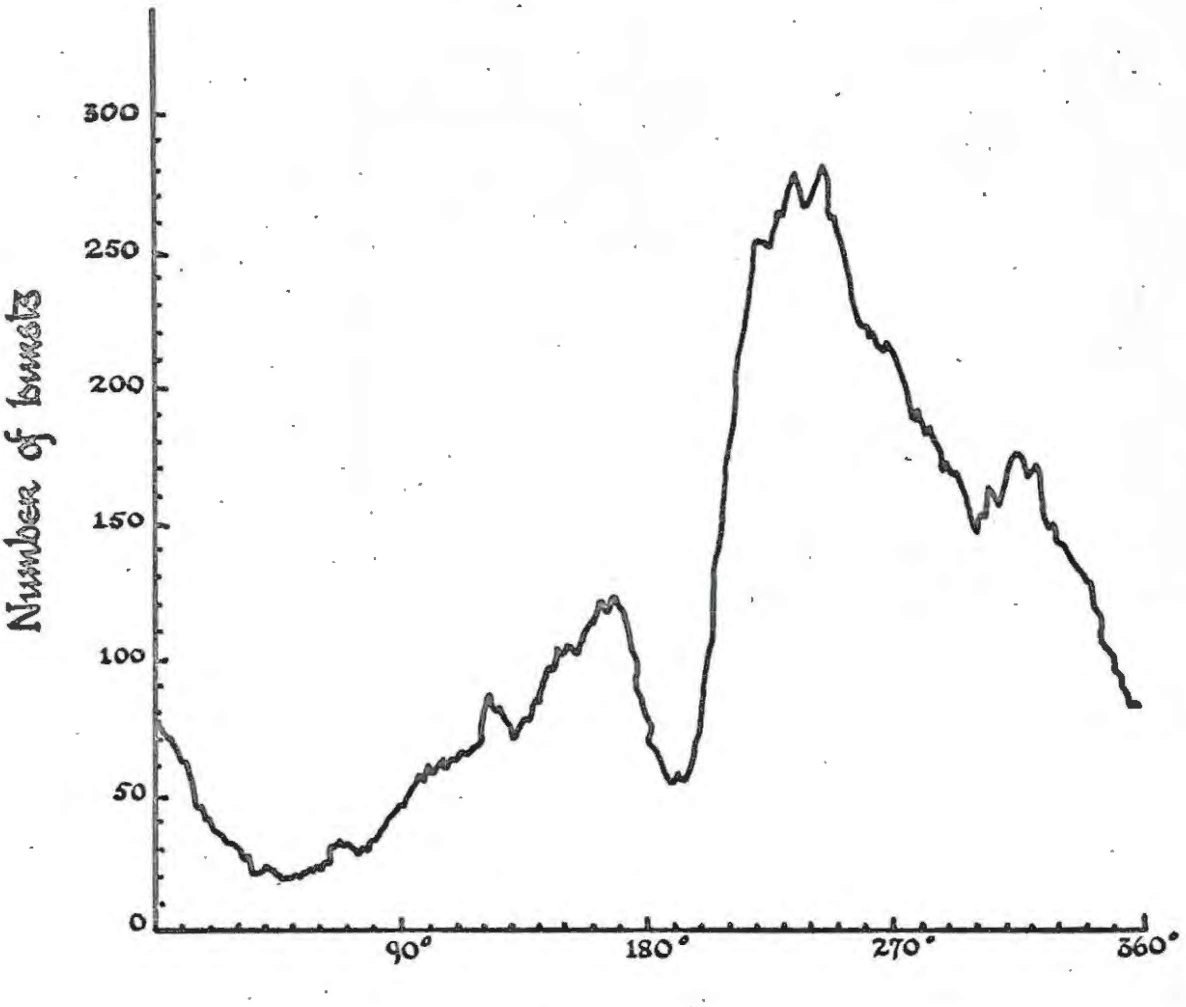


Fig. 23 Number of bursts versus system III longitude

and McCulloch in their theories. It is also seen that the hump around 320°, usually called source C, is relatively small.

The investigation of the longitude dependence according to the MF observed does give some very interesting results. (Fig. 24) We see that source A emits a large number of storms which have an MF in the region of 28 Mc/s or 29 Mc/s. Source B emits largely with MFs in the range above 31 Mc/s and Source C emits virtually only below 21 Mc/s. Emission by source D appears to be only an extension of the emissions by the source C region. It is also noted that the MFs of source B go to higher frequencies than those of source A.

It may be significant that source C and the emission peak around 170° in the 18 - 19 Mc/s MF interval are nearly 180° apart.

5.4 Comparison between Io and System III dependence

We shall now attempt to compare and contrast between the Io and System III dependence in the various MF intervals. For the convenience of the reader the two graphs have been plotted side by side, in order that he may follow the argument and appreciate the importance of these results. We shall discuss each subdivision separately.

a) 40-41 Mc/s MF interval

There was during the five apparitions only one record which went beyond 39 Mc/s. This was in spite of the recorder being able to examine the spectrum up to and including 41 Mc/s. This emission was due to source B and Io was in the vicinity of 100° from SGC.

b) 38-39 Mc/s MF interval

Here we see, that while Jupiter emission was received over wide CML values of source B virtually all the emission took place when Io was within quite narrow limits. These are from below 80^{o} to above 110^{o}. Source A shows virtually no activity.

c) 36-37 Mc/s MF interval

The pattern of source B emission in this interval is still very similar in outline to the one discussed above, but more storms were recorded. There seems to be also a little more activity by source A, with Io apparently within narrow SGC limits.

d) 34-35 Mc/s MF interval

In this interval we see a sudden increase of emission due to source A. By comparison with the previously discussed intervals we may conclude that emission from A will only take place if Io is in the vicinity of 240^{o} from SGC, while emission from source B will take place if Io is in the vicinity of 90^{o} from SGC. It is also interesting to note that for emission from source A, Io seems to have a far wider "Bandwidth" of allowed deviation from SGC, while the emission pattern with regards to L_{III} seems to be very much the same as in (c) above.

e) 32-33 Mc/s MF interval

The activity of source B seems to decline in this interval, while the activity of source A remains at about the same level as in (d). However there seems to be a slight shift of the Io position w.r.t. SGC, to a smaller angle for the higher SGC values, while the lower values show no such change.

f) 30-31 Mc/s MF interval

Most of the emission is from source A and is still Io dependent. A shift to lower values of Io's departure from SGC is once again noticed for the values around 240°.

g) 28-29 Mc/s MF interval

There is very little emission from source B. However a curious effect can be noticed on careful scrutiny. With decreasing MF intervals, the L_{III} position of source B seems to shift to higher values of Longitudes. By the 18-19 Mc/s interval, source "B" seems to have shifted to a longitude close to 180°.

The dependence of emission upon the position of Io seems to have been almost completely smeared out. Although there are still a number of positions of Io where there is more emission than at positions close by, this effect may purely be due to statistical fluctuations. On the other hand it could be possible, that Io-control "splits" in this interval. This could be deduced from the indication of a minima in the 30-31 Mc/s interval at 230° from SGC and the possible minima at 215° from SGC in this interval

h) 26-27 Mc/s MF interval

The general shape of the number of emissions versus L_{III} plot seems to broaden out towards larger values of L_{III}. Hardly any Io dependence can be noticed, a possible peak appearing in the vicinity of 250° from SGC.

i) 24-25 Mc/s MF interval

The L_{III} dependence is very similar to (h) and from the Io dependence plot we can deduce more a position for which it is unlikely that radiation is received than to say radiation will be received if Io is in a certain vicinity.

j) 22-23 Mc/s MF interval

The L_{III} pattern is broadened still further and no real Io dependence can be deduced.

k) 20-21 Mc/s MF interval

In this interval we can notice that source A and source C patterns may be "splitting". Io control seems to become a little more prominent again. This is deduced from the disappearance more than the appearance of deflections on the Io dependence graph.

l) 18-19 Mc/s MF interval

In this section there are quite a few changes as compared to the last few sections discussed above. Emission from source B becomes a bit more prominent, although the source region has shifted to higher L_{III} longitudes, as pointed out above. Emission from source C is very prominent, while emission due to source A has increased too, but not as much as source C. Since it is not obvious what the CML is of those storms where Io is in the range $90^\circ - 115^\circ$ i.e. the reappearance of Io-dependence, a separate check was carried out. It was found that this Io-dependence, when expressed as emission of CML, can be attributed as follows: Source A was emitting for 17 events, source B for 11 and source C for 20 events. This latter result is thought to be very significant and will be discussed again at a later stage.

m) 16-17 Mc/s MF interval

The activity seems to be smaller on the whole, but a very noticeable decline can be observed for emission from source A. Source C is still very active. Emission from source "B" has shifted a bit further towards the 180° mark.

n) Below 15 Mc/s MF interval

There is too little information available and no real trend, different from the above, can be established. The lack of data is due to the decrease in useful observations at lower frequencies, due to the increase of interference from the Earth's ionosphere.

5.5 Percentage probability of decametric emission

The calculations in this section were carried out with the intention of determining whether there was any noticeable difference in the rate of observed emissions during the apparitions. This was originally done with the idea of determining a possible influence of Jupiter's magnetospheric tail (Gruber, 1965) It has recently come to the author's notice that Six et al (1963) had noticed this effect, of decrease after opposition, in their fixed frequency data. They explained it as an eclipse of Jupiter by the Earth's magnetosphere.

For the purpose of this investigation the period between two superior geocentric conjunctions was divided into 27 intervals each of 15 days, except for the first and the last which may have less than 15 days. The intervals were numbered from 1 to 27; interval 14 was centred on the day of opposition. For each of these intervals the total time for which Jupiter was observed was computed as well as the total time during which Jupiter events occurred. The ratio of the latter to the former gives the percentage probability of occurrence in that particular interval. This was initially done without taking into consideration the frequency distribution of the bursts. The results are shown in Figs. 25 to 29.

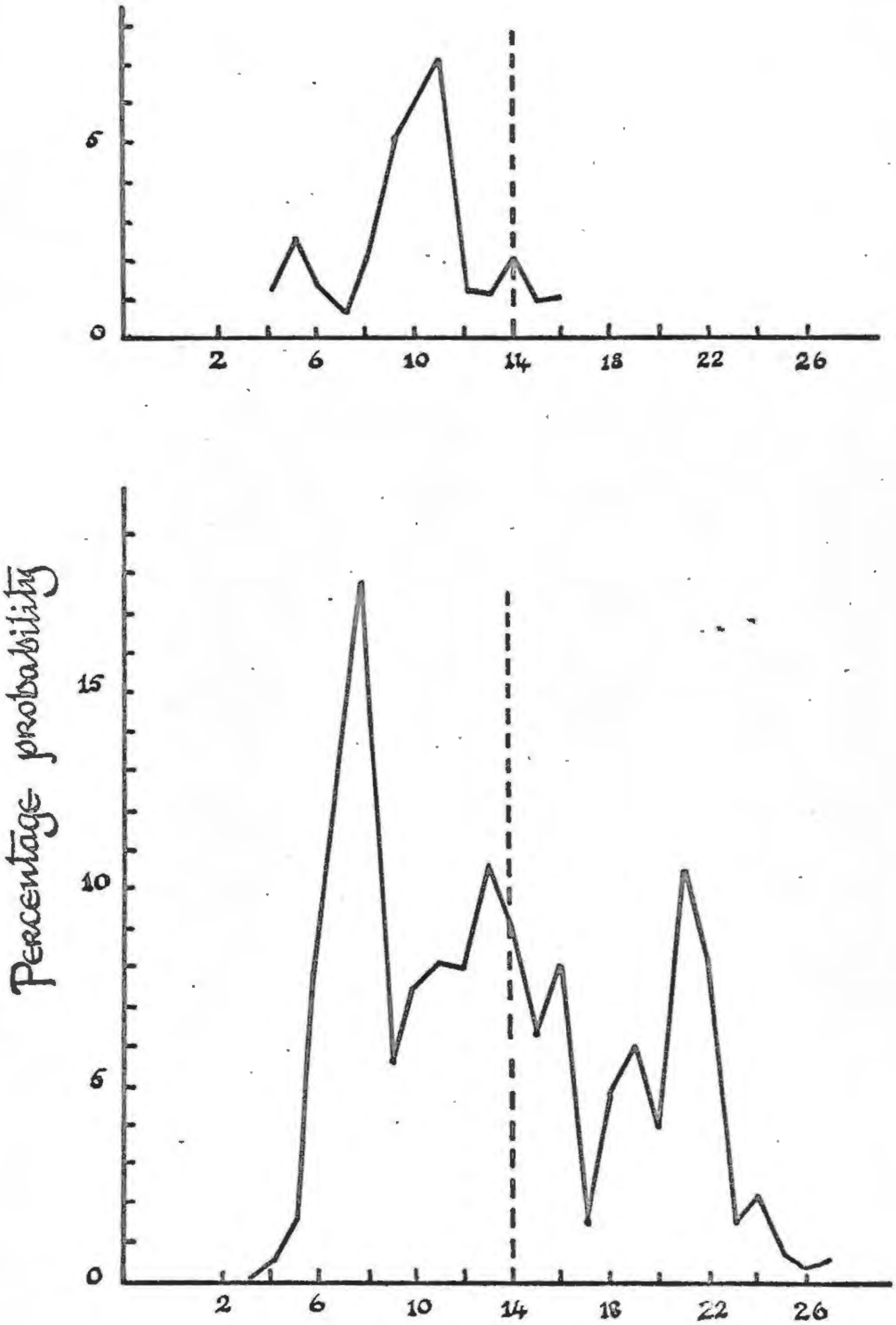


Fig. 25 Percentage probability versus interval number for 1960/1961

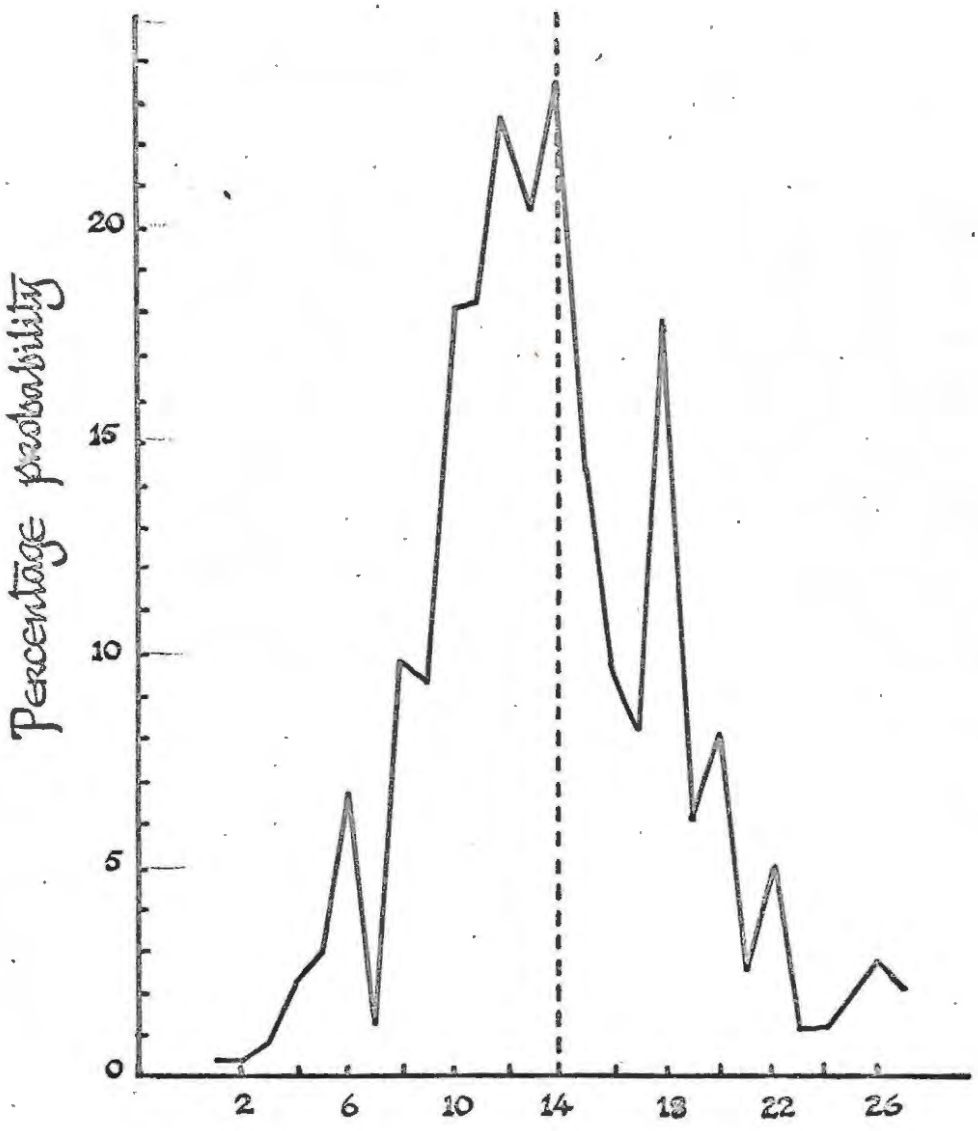


Fig. 26 Percentage probability versus interval number for 1962

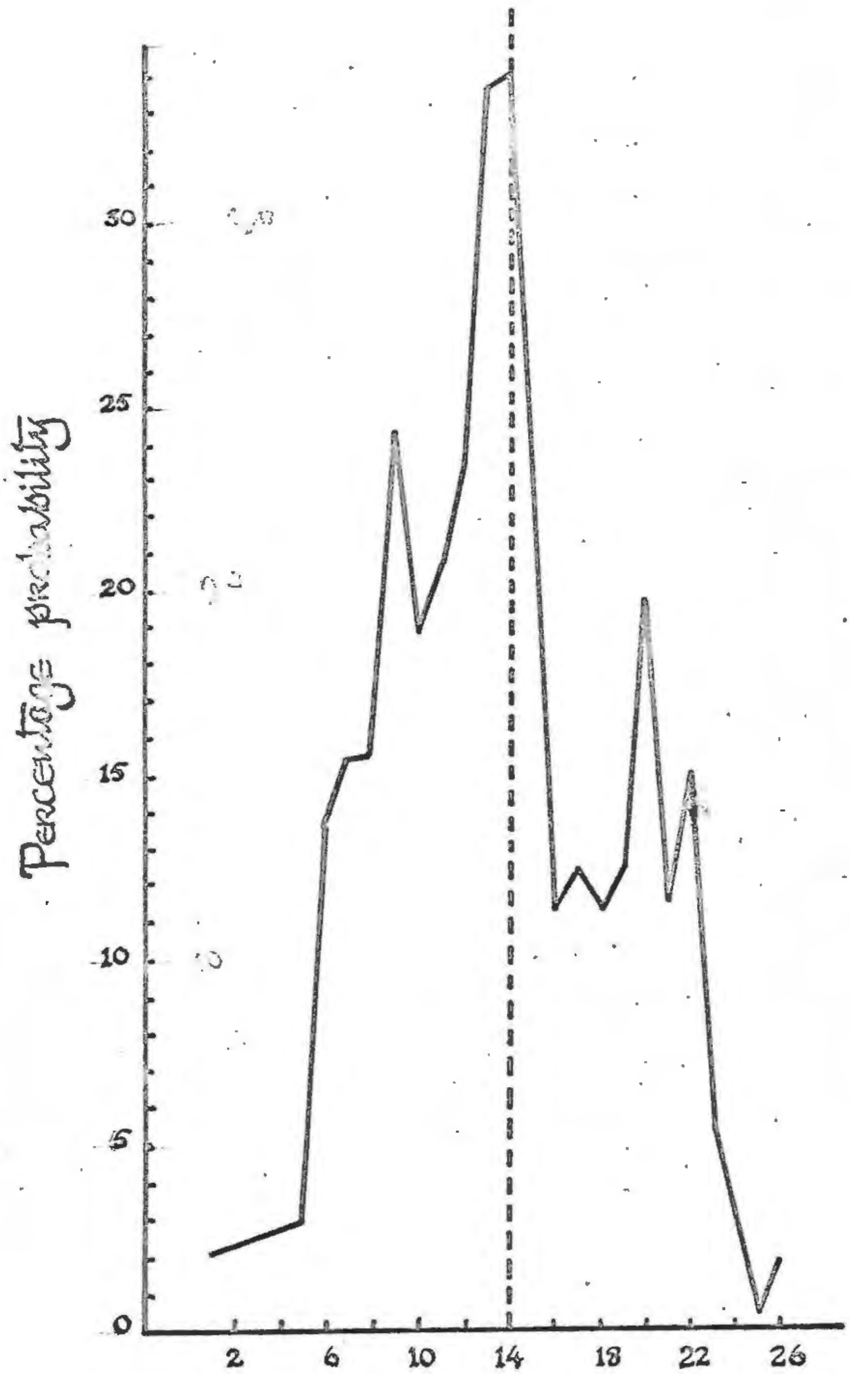


Fig. 27 Percentage probability versus interval number for 1963

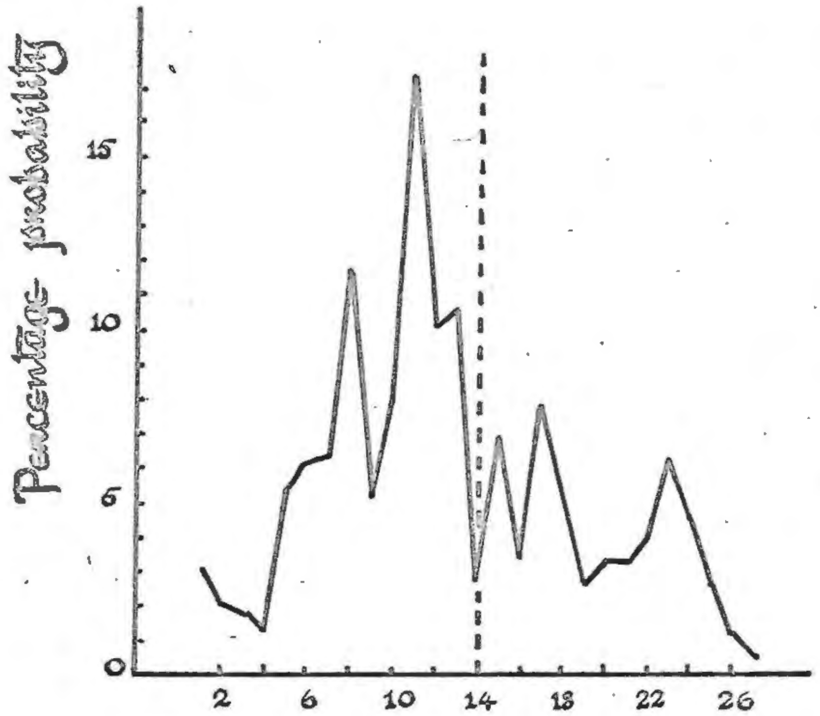


Fig. 28 Percentage probability versus interval number for 1964

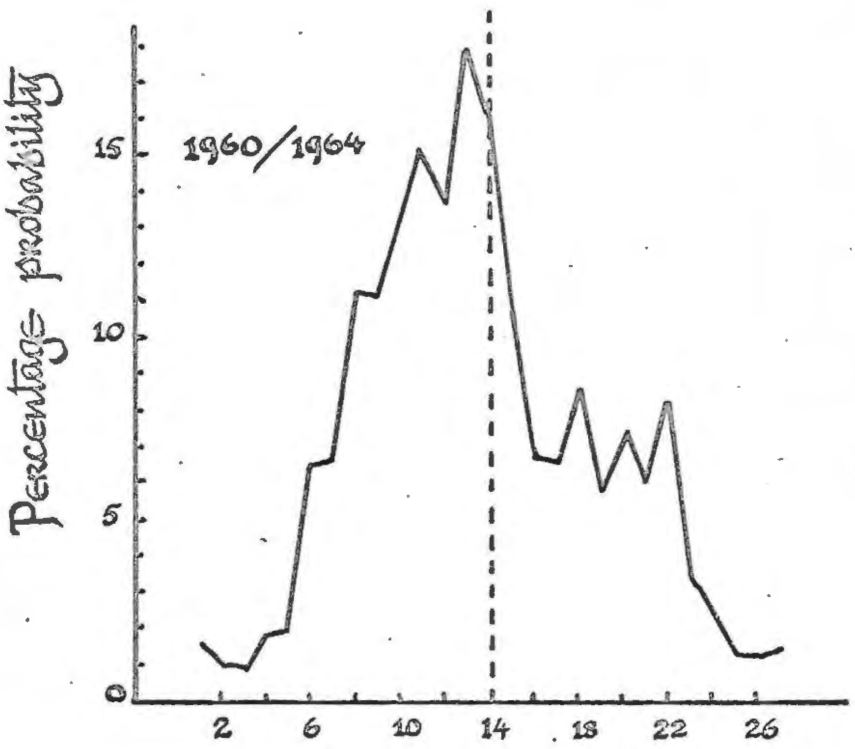


Fig. 29 Percentage probability versus interval number for the five year period 1960/1964

It can be seen from these graphs that there is a tendency for Jupiter emissions to take place before opposition rather than after opposition. Combining the values for the five apparitions, that is, calculating the average percentage probability for the correspondingly numbered intervals, this tendency becomes much more pronounced.

From the graphs it appears that the rate of emission before opposition to the rate of emission after opposition is approximately in the ratio 3 : 2. Furthermore a rather sharp cut off is apparent immediately after opposition.

Dulk (1965b) noticed this effect when drawing histograms separately for the period before and after opposition for the apparitions 1964 and 1965. He suggested that this effect might be due to the influence of the maximum usable frequency of the Earth's ionosphere on Jupiter reception. However, I think, that this is most probably not the case. Let us consider this a bit further.

The ionosphere determines the lowest frequency which can be observed coming from outside Earth. Therefore, if variation of ionospheric conditions is responsible for the sudden decrease of percentage probability, one would expect that during the same period there would be an increase in the lowest possible frequency one can observe. To check this point, the "mean lowest frequency" observed was calculated for each interval for the five apparitions. This was done by noting the lowest frequency of each storm and finding the average for the fifteen day interval. The result for all five apparitions is shown in Fig. 30.

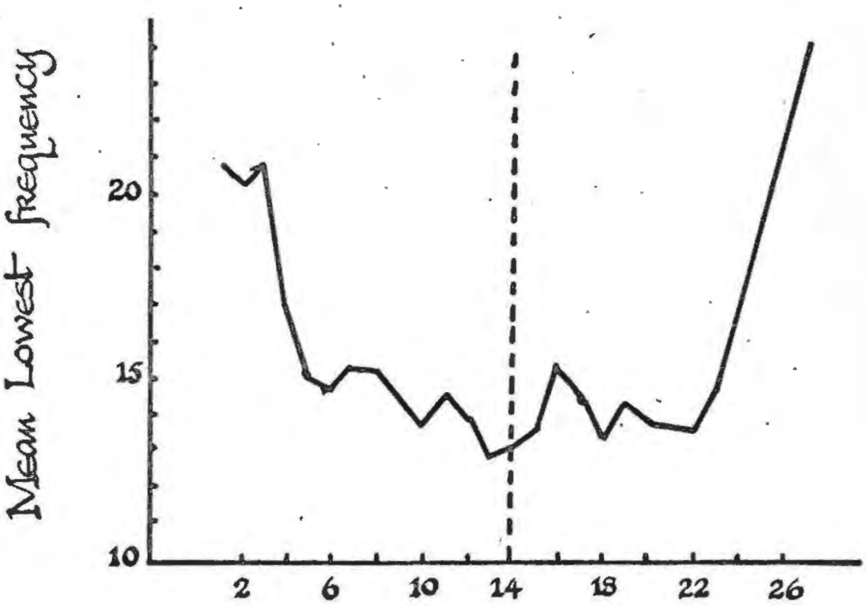


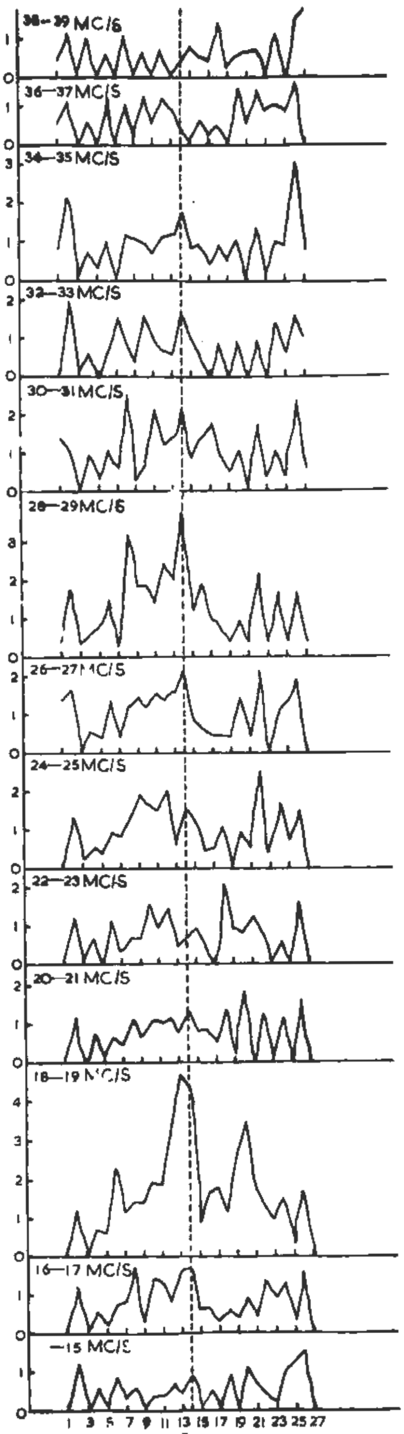
Fig. 30 Mean lowest frequency versus interval number for the five year period 1960-1964

From the graph it seems obvious that the variation of ionospheric conditions is not likely to be responsible for the observed decrease of percentage probability after opposition. If it were we would expect the graph to show a sudden change on or after interval 14. The graph however shows little variation. The cause of this effect must therefore lie somewhere else.

Comparing Fig. 29 and Fig. 30, it can be seen that the rise in percentage probability starting at interval 5 and the fall of percentage probability starting at interval 22 may be explained by the fall and rise of the lowest observable frequency, i.e. an ionospheric effect.

Fig. 31 shows the percentage probability versus interval number when the MF observed during a storm is taken into consideration. The fall of percentage probability after opposition is most noticeable in the 18-19 Mc/s interval. It can also be seen quite strongly in the MF region from 26 Mc/s to 29 Mc/s. It is difficult to say whether the effect is less in the other intervals, due to the fact that in the particular intervals, where the effect is most noticeable, there are also more storms recorded than in the remainder. The variation may therefore only be due to statistical influence.

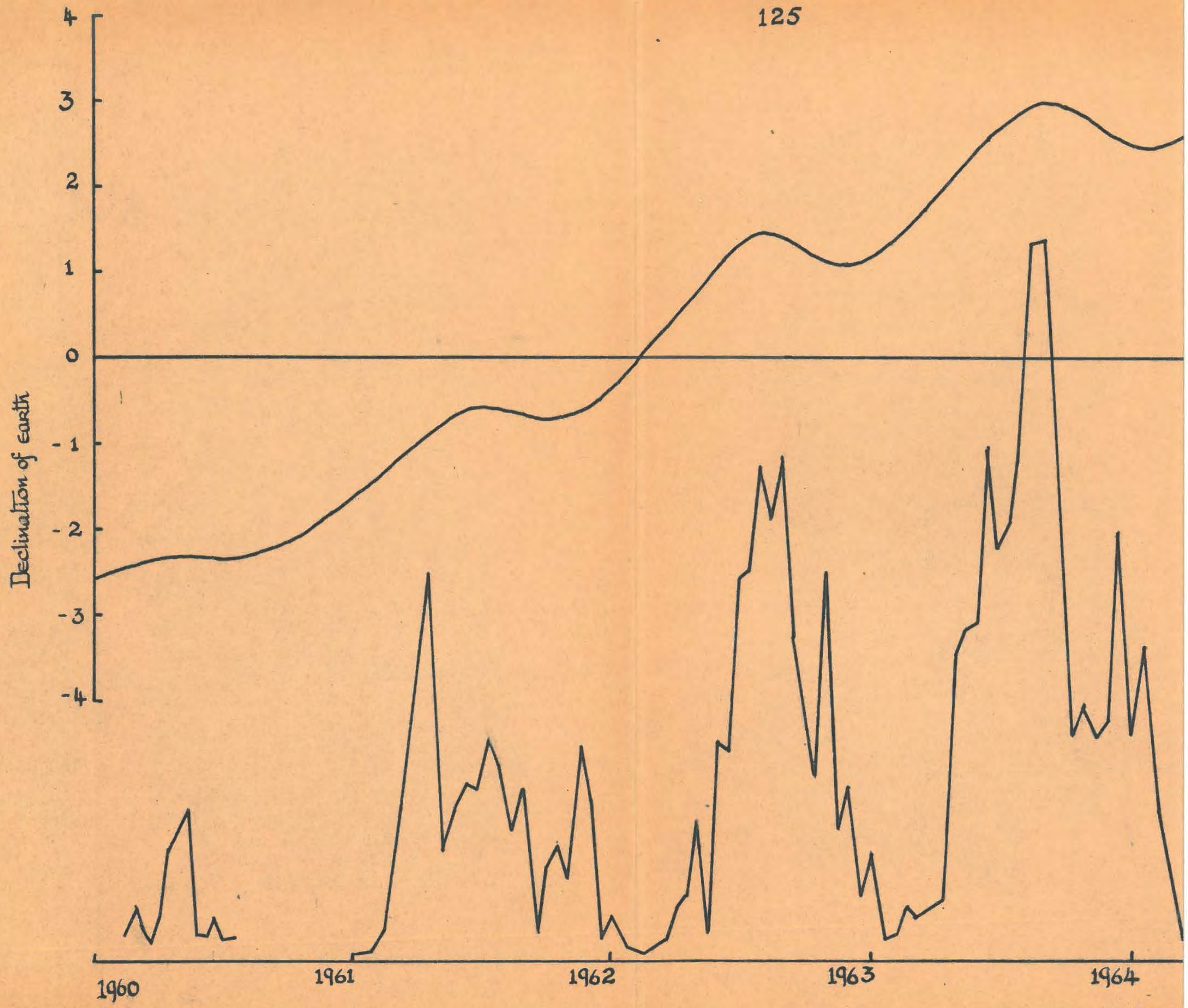
Since a relatively large amount of data was available in the 18 - 19 Mc/s interval it was decided to determine whether any variation of percentage probability could be determined with the two major sources in that interval, i.e. source A and source C. This is shown in Fig. 32. The


38–39 MC/S
36–37 MC/S
34–35 MC/S
32–33 MC/S
30–31 MC/S
28–29 MC/S
26–27 MC/S
24–25 MC/S
22–23 MC/S
20–21 MC/S
18–19 MC/S
16–17 MC/S
–15 MC/S
1 3 5 7 9 11 13 15 17 19 21 23 25 27

drop is noticeable in both sources. However there is a very interesting phenomenon noticeable in the graph illustrating the variation in the 19 Mc/s interval. The percentage probability drops after interval 13, but does come back to the original value at interval 19. This means some process apparently cuts off emission, with a maximum frequency of 19 Mc/s, for a period of close to 10 weeks. Similar trends are noticeable in the graphs representing the total percentage probability for the apparitions 1961, 1962 and to some extend for the apparition 1963. In the 1964 apparition a drop is noticeable in the corresponding intervals. This might account for the relatively equal values after opposition in the graph representing the average for the five year period.

One further significant detail, which becomes apparent when comparing the figures for the five years, is the fact that there was a maximum number of emissions during the apparition 1963. (This is also obvious when scanning table 1.) This is additional evidence that the sources emit into very limited ranges of declination.

There is another way of looking at these phenomena. During one Jupiter year (11.9 Earth years) Jupiter's position relative to Earth changes and with it the declination of Earth, as seen from Jupiter. During the observing periods Earth itself moves, so that Earth's apparent declination changes considerably with time. This variation is given in the Ephemeris as D_E. Fig. 33 shows the various graphs of percentage probability plotted versus the time of observation and superimposed on the same graph are the variations of D_E.


4
3
2
1
0
-1
-2
-3
-4
Declination of earth
1960
1961
1962
1963
1964

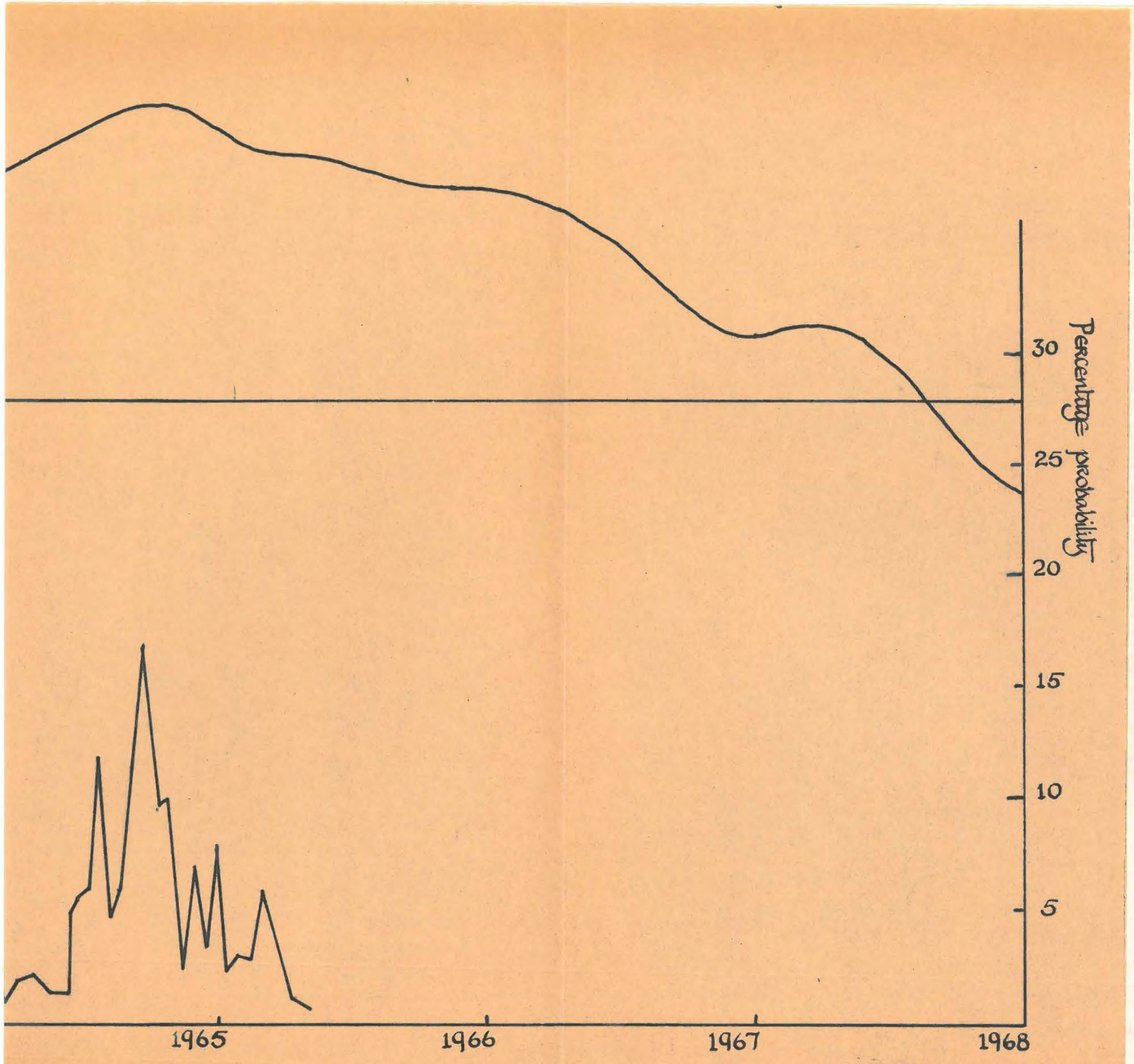


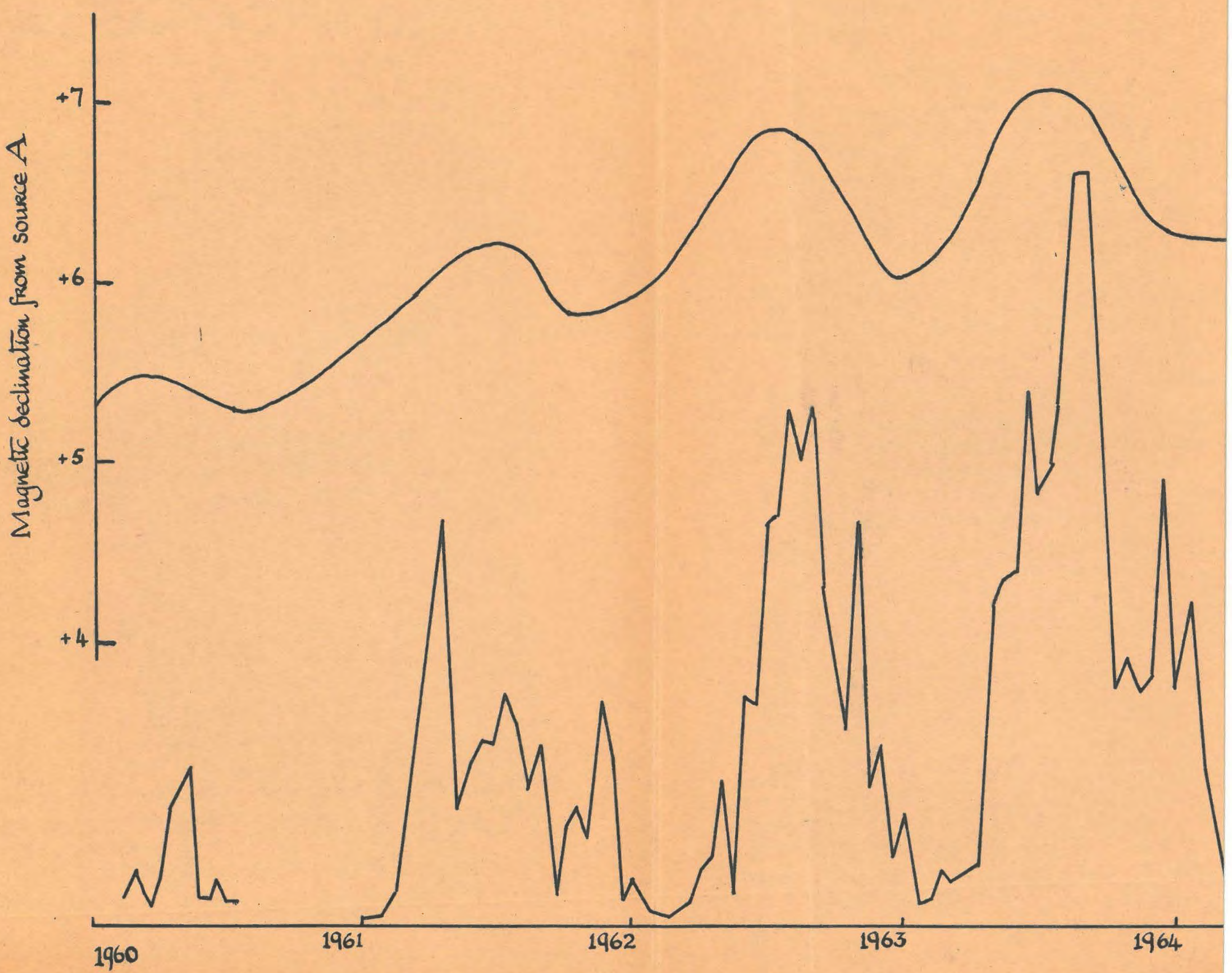
Fig. 33

We can deduce from this graph that as the axis of rotation of Jupiter changes and Jupiter's North pole becomes more visible, the percentage probability increases. There is however one point which shows that this argument does not hold throughout. On the above argument we would expect the percentage probability to have increased further, also during the apparition 1964. This is however not the case, as the percentage probability is seen to have decreased quite rapidly during the apparition 1964.

We have mentioned before that decimeter observations have suggested that the magnetic axis of Jupiter is inclined to the rotational axis by about 10° and that the magnetic axis is located in the plane containing longitude 200°. This implies that during one revolution of Jupiter the magnetic equator will wobble heavily as observed from Earth.

We can express this movement as the variation of the apparent magnetic declination of Earth. The magnetic declination is the position angle Earth occupies as seen by an observer located at the magnetic equator on the CML. This means that Earth will have a different magnetic declination for every value of CML and these values will change throughout one Jupiter year.

Fig. 34 shows the percentage probability variations plotted against the magnetic declination as observed from that value of CML where most emission appears to come from in source A. The variation of source A CML values have been calculated from the formula given by Gulkis and Carr (1966).


Magnetic declination from source A
+7
+6
+5
+4
1960
1961
1962
1963
1964

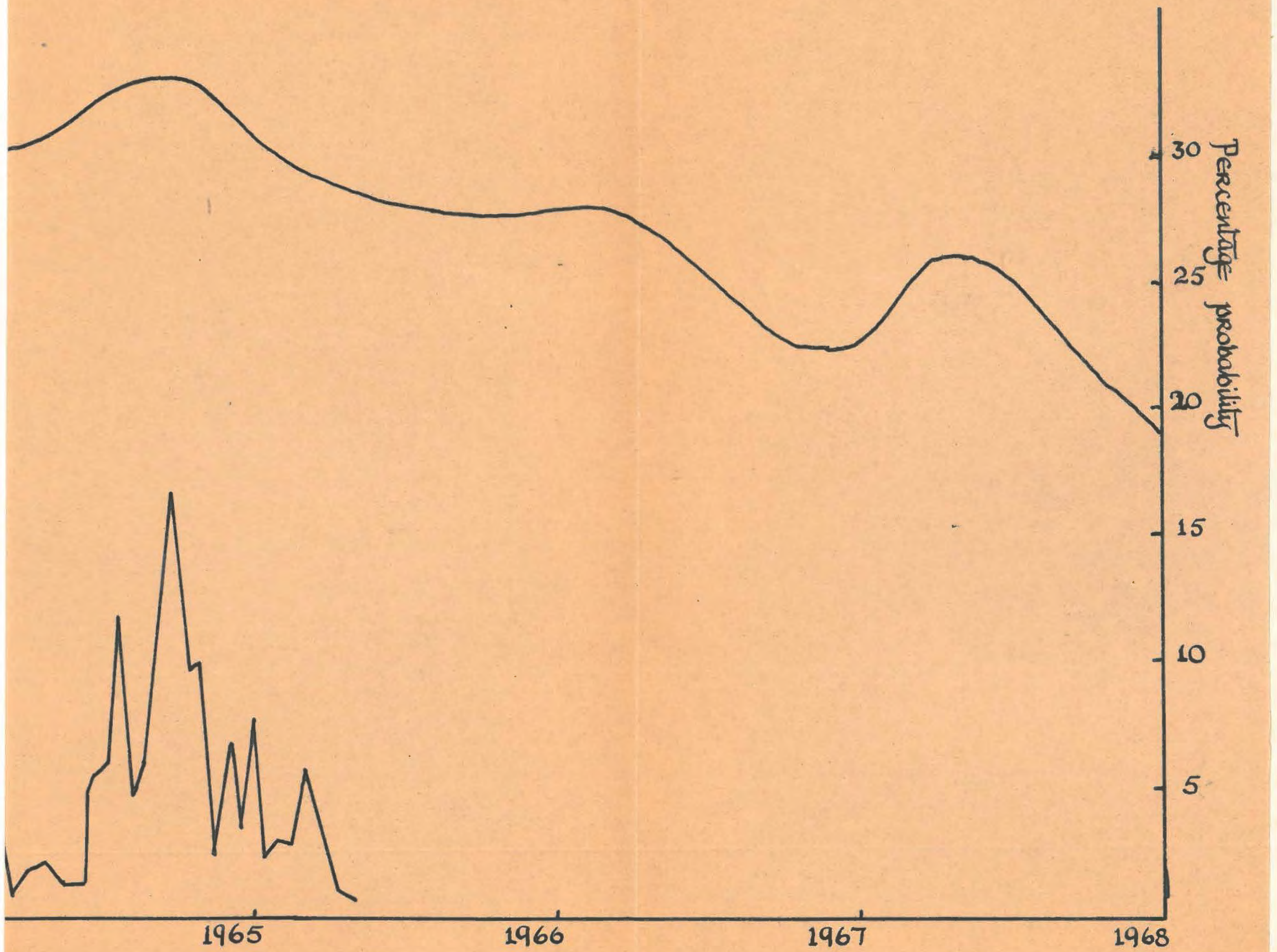


Fig. 34

$$L_{III_A} = 253.5 - 17.8 \sin \left\{ \frac{(\text{Year} - 1956.25)}{11.9} \, 2\pi \right\}$$

We see immediately that the previous paradox has disappeared. When the maximum number of emissions were recorded on Earth then the Earth was at its largest magnetic declination, i.e. the furthest north relative to the magnetic zenith. The fall-off either side of the 1963 apparition is also in accordance with the variation of the magnetic declination. For the production of Fig. 34 source A was used, as any variations will be most noticeable in it, seeing it is responsible for the largest number of emissions.

We may conclude from Fig. 34 that it appears probable that the variations of magnetic declination and the emission probability are related.

5.6 Influence of other Jupiter satellites

Fig. 35 shows a plot of number of storms versus departure from SGC for the second largest satellite Europa. Europa is nearly two-third the size of Io, both in mass and in volume, and its orbit is fifty percent further from the planet than that of Io. It appears, from the graph, that this satellite does not have any appreciable influence upon Jupiter emission in this frequency range. There is however some indication of a drop in emissions, when Europa is 40° from SGC. This phenomenon was noted by Bigg (1966).

No correlation could be detected with the remaining two large satellites

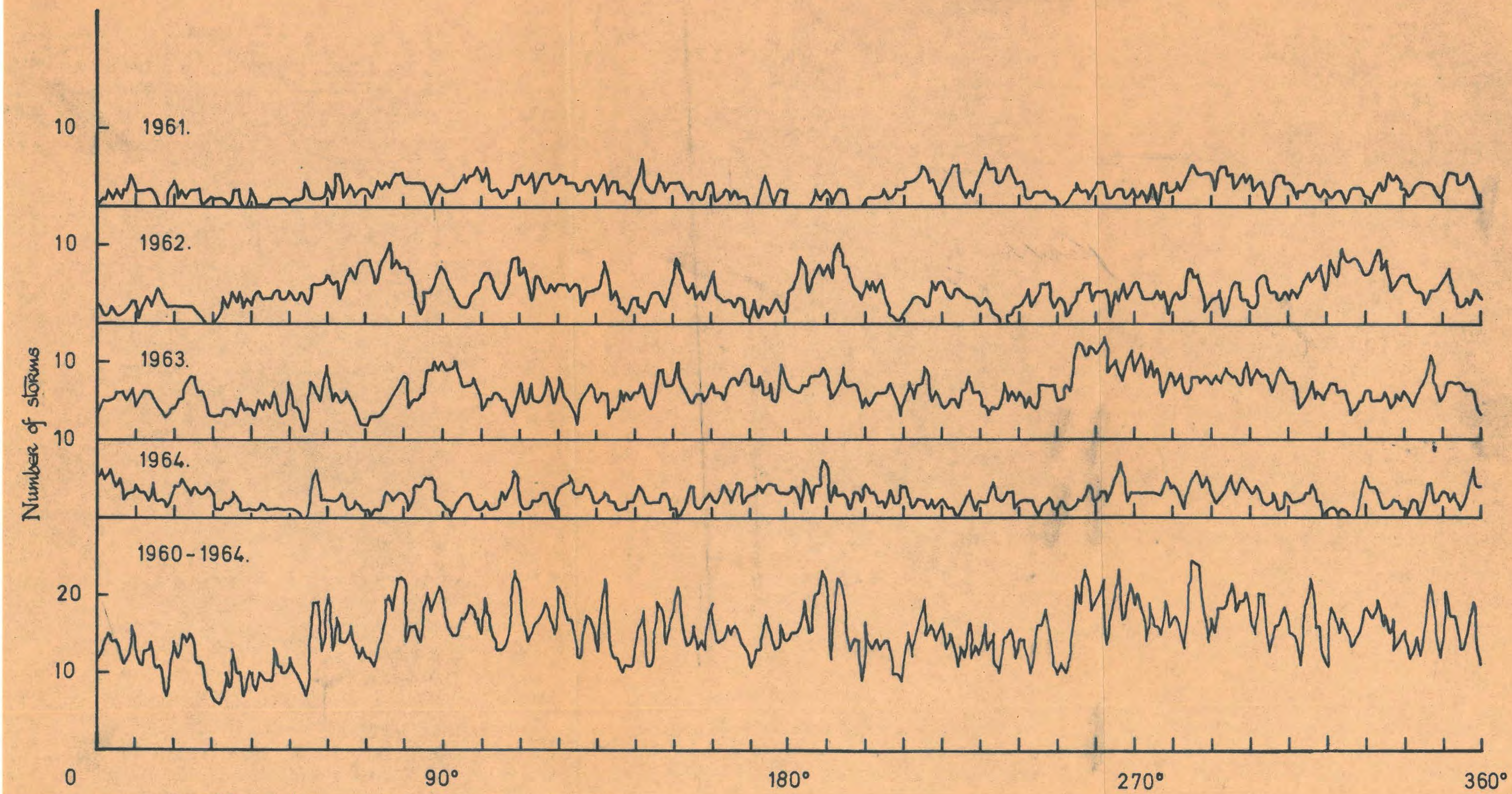


FIG. 35 Departure of Europa from SGC

of Jupiter. The fact that Lebo et al (1965) did find some correlation for one particular year is most probably due to insufficient data, as a similar study for six years shows a negative result.

5.7 A dipole model

Before we attempt a discussion of the effects observed in this analysis, it may be informative to discuss what radiation we would expect from a perfect dipole field. This would then allow us to introduce possible corrections to the field, to explain the observed phenomena.

Fig. 36 shows a magnetic dipole field. In calculating this field we have assumed that the magnetic field strength at the poles is 15 gauss. We are choosing values which, according to various workers, are likely to be applicable in Jupiter's case. Assuming gyrofrequency emission the positions were calculated and indicated where emission of a certain constant frequency is taking place.

For the purpose of this model, let us suppose that a van Allen type of particle belt surrounds this hypothetical model of a planet. We further suppose, that gyro-radiation is emitted into a narrow cone in the forward direction only, i.e. in direction of particle velocity. It is also supposed that the magnetic axis is inclined to the rotational axis at an angle of about 10°.

At 5 Mc/s radiation will be emitted at least into latitudes within the angle defined by A from the northern hemisphere and latitudes defined by A' from

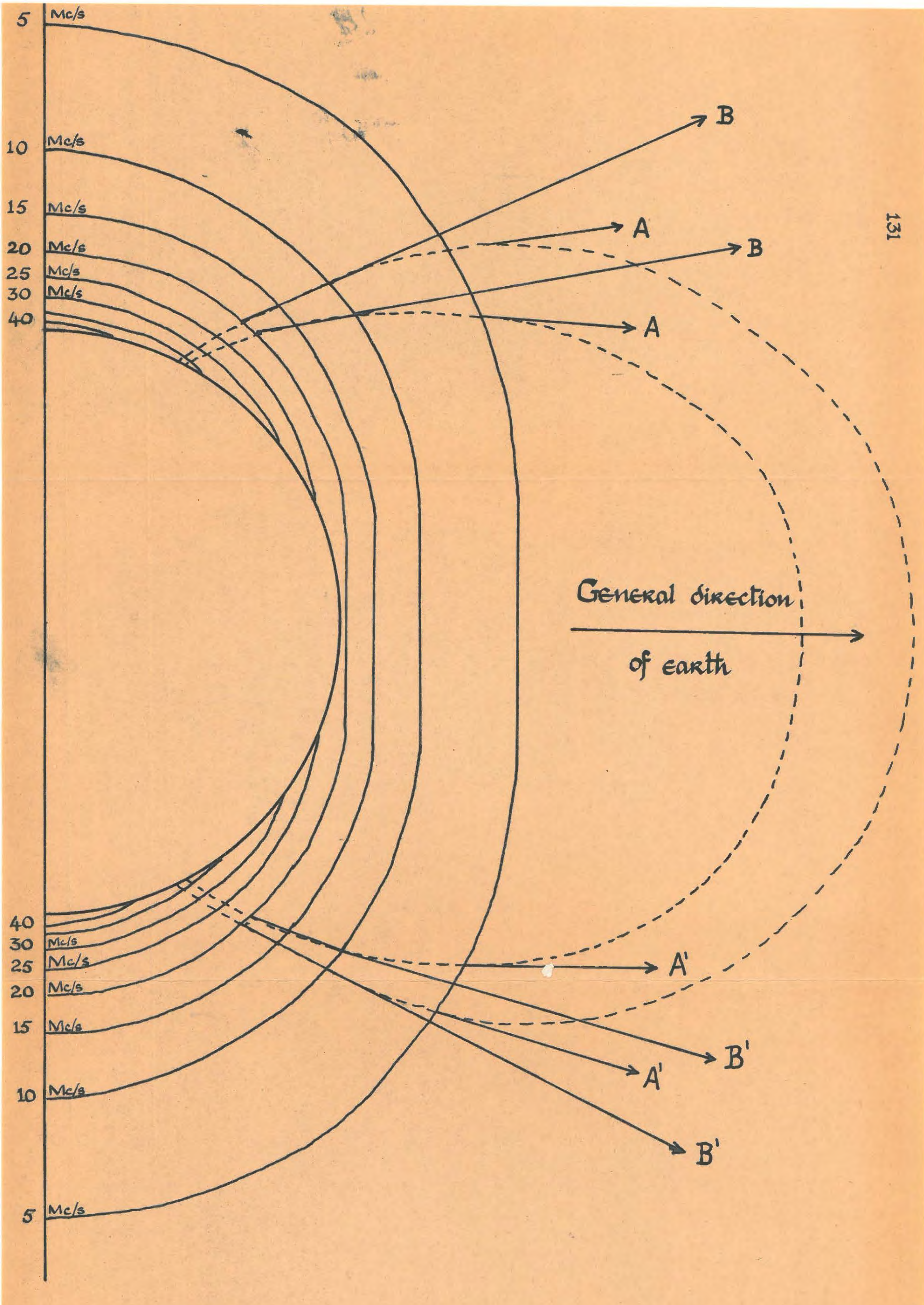


Fig. 36 A dipole field

the southern hemisphere. The actual angle will depend also upon the cone angle into which the radiation is emitted. The radiation from the "north" pole will be right hand polarized, if the emitting particles are electrons and the emission from the southpolar regions will be left hand polarized. This assumes a field direction identical to that of Earth.

As the planet rotates, we will see different proportions of northern and southern emission. When the north pole is pointing towards the observer, he will observe more radiation with right hand polarization. 180° degrees later, he will observe more radiation with left hand polarization. If the observer calculates the mean axial ratio, he will deduce that the axial ratio changes between two limits, one denoting mostly RH, the other denoting mostly LH polarization.

The observer could also detect a variation of intensity, but this will depend upon the variation of intensity with declination of the observer. If the directions of maximum intensity are located along declination values greater than 10°, and the intensity varies fairly rapidly over the emission region, then the observer will most probably observe a variation of intensity during one rotation of the planet.

However, if the observer should attempt to analyse the results on a basis of emission probability, then assuming the particle belt is uniform he will find no such variation with longitude.

This result has actually been observed. No probability variation with longitude, but a strong longitude dependence of polarization and, to a lesser extend, intensity dependence have been detected in the radiation received below 10 Mc/s. (Fig. 37)

If we now assume that in addition to the magnetic axis being tilted to the rotational axis, the rotational axis is tilted to the ecliptic, then we do get additional complications. Let us assume that this inclination is 3°.

Since the angle of emission is relatively large compared to the angle of tilt, we would not expect much variation at lower frequencies.

If however we consider emission at a higher frequency, say 20 Mc/s, we see that the emission angle is smaller and is also pointing further away from the planet. These emission regions have been denoted by B and B' in the northern and southern hemisphere respectively. (Fig. 36)

For the observer to record emission at that frequency he would have to be in the direction of these emission latitudes, i.e. his declination has to be high enough. If the emission angle is small enough, then an observer might observe two sources located symetrically about the magnetic meridian. This is due to the observer moving through the emission latitudes twice, as the planet rotates.

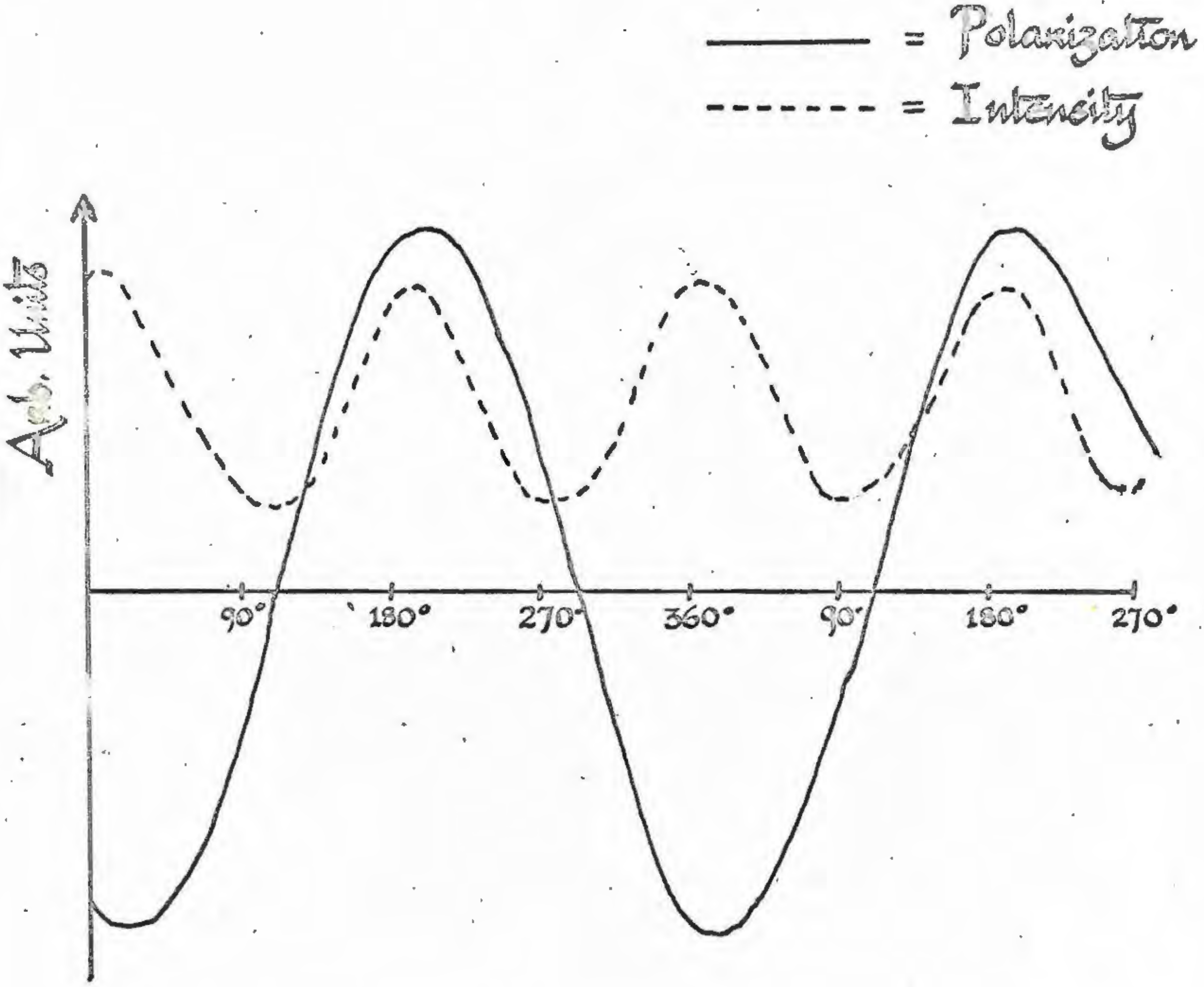


Fig. 37 Polarization and intensity variation versus CML at 4·6 Mc/s.

If we consider emissions at still higher frequencies, then we might get to a point where the observer will not come into the emission latitudes. In this case, although emission still takes place, the observer will have deduced a cut-off frequency, above which no further observations can be made.

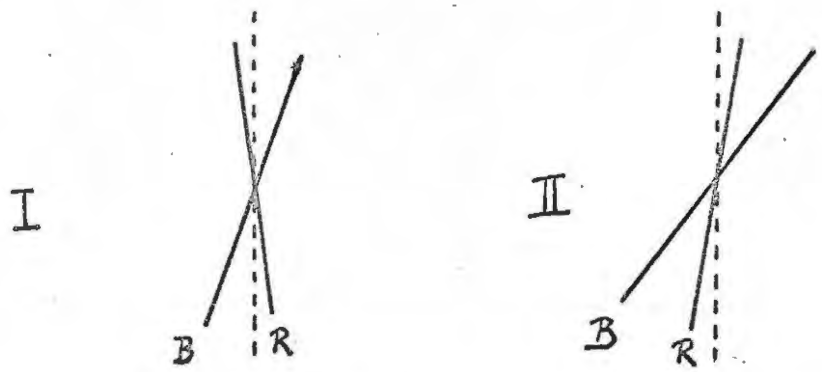
There is however another important point to consider. For emissions to take place the particle belt will have to reach down to those regions. If the particle belt has ended or become very thinly populated, then no emission will be observed. There is also the possibility of an Ionosphere, which will not pass frequencies below a certain value. This depends upon the electron density.

The closer we get to the planet, the less likely are we of obtaining emission as "end-effects" of the particle belts will become troublesome.

Another effect which will be noticeable is the gradual disappearance of emissions from one hemisphere with increasing frequency. This is due to the geometry of the observer. If the observer is in the ecliptic and he observes the longitude regions containing the magnetic axis, then he will only record at higher frequencies emissions from one hemisphere as emissions from the other hemisphere will be in a direction far off course from his position. Even when the geometric position is such that the rotational axis is at its maximum position on the other side, i.e. the angle of tilt of the rotational axis is subtracted from the angle of tilt of the magnetic axis, then the observer will still not be in a sufficiently southern position to observe emission from the southern part of the source lying around the longitude containing the magnetic axis.

As an example of this geometrical condition let us for the moment return to Jupiter. Jupiter's magnetic axis lies in the plane containing longitude 200°. The maximum tilt of the rotational axis is about 3°.* This has two maximum positions. One when the two tilts add, i.e. $10^\circ + 3^\circ = 13^\circ$, the other when they subtract, i.e. $10^\circ - 3^\circ = 7^\circ$.

e.g.



This means that during one Jupiter year the magnetic axis will occupy two extreme positions as seen from Earth. At any other time this apparent tilt will take up some value in between the two extremes. In position II we are more likely to observe emission coming from the northern regions, while in position I we will notice an increase of emission coming from the southern hemisphere. However we can also see clearly from the above sketch that on no occasion will we see as much from the southern hemisphere as we will see from the northern hemisphere, at least not around longitude 200°. (* This includes the effect of Earth's orbit)

If we apply a similar argument to the other side of the planet, i.e. the longitude $200^\circ + 180^\circ = 20^\circ$ the opposite argument holds. More will be seen from the southern hemisphere (cf sketch II).

But back to our model. We have seen above that it is likely that a specific cut-off frequency can be observed by an observer located in the ecliptic. This cut-off frequency could be varied if the magnetic field is somehow perturbed. Depending upon the geometry of the emitting region an apparent additional dip of the magnetic axis of 1° might produce the observed change in cut-off frequency (Io-control).

5.8 Discussion

In the previous sections we have presented an analysis of data collected over five apparitions. This analysis was based on a new grouping of the data and some additional facts are revealed. However if we combine some of the results of the previous sections, there are some further results.

We have seen in Fig. 19 that, if the observations are grouped w.r.t. the MF observed during a particular storm, the data falls into three sections, the MF below 21 Mc/s, the MF between 21 Mc/s and 33 Mc/s, and the last the MF above 33 Mc/s. For convenience sake, let us call these regions 3, 2 and 1.

From the discussion in section 5.4, we have determined that the Io dependence is not uniform over the MF range. Above 32 Mc/s the Io control is complete, between 20 Mc/s and 31 Mc/s Io control is weak and in the 18-19 Mc/s MF interval some definite Io control can again be detected. If we write this in terms of the three regions, we may say, that in region 1 Io control is complete, in region 2 Io control is very weak and in region 3 Io control can again be detected to a notable extent.

There is a third point which has to be called to mind, before the conclusion that is to be drawn makes sense. Carr et al (1965a) have published a paper wherein they state that Jupiter activity is greatest between 5 Mc/s and 10 Mc/s. For argument sake, let us assume that there is a peak in a hypothetical MF plot at 9 Mc/s. Since the activity is confined to the above limits, this assumption is not far fetched.

If we consider Fig. 19 along those lines, we have a maximum at 9 Mc/s, there is a very definite peak at 18 Mc/s, another one at 28 Mc/s and the last one at 35 Mc/s. We can now select a very interesting and perhaps important relationship, i.e. 9 Mc/s, 18 Mc/s, 27 Mc/s and 36 Mc/s. These are in the ratio of 1 : 2 : 3 : 4. There seems to exist a "harmonic" relationship.

We cannot apply the true term harmonic, as the different "harmonics" are NOT emitted by the same CML co-ordinates but the co-ordinates change (cf. Fig. 24 and discussion in section 5.4g).

However there is some further interesting comment to be made. Region 1, the fourth "harmonic", is strongly Io-related, region 2, the third "harmonic", is weakly Io-related and region 3, the second "harmonic" shows again some definite peak in Io-relationship.

The emission below 10 Mc/s is reported to be virtually continuous, and only the intensity is slightly Io-dependent (Dulk and Clark, 1966). We have, therefore, the interesting result, that "harmonic" emission takes place and that Io controls the even "harmonics", while the odd "harmonics" do not depend to any large degree upon the position of Io.

If we split the analysis of Fig. 19 and plot the number of storms with a particular MF for each opposition, then this "harmonic" relationship becomes less distinct in certain years than in others (Fig. 38). The data for the 1960 apparition is somewhat unreliable due to teething trouble in the HAO apparatus. During the 1961 apparition we note a maximum for 18 Mc/s and a broad MF band around 28 Mc/s. Both become very much more pronounced during the 1962 apparition and to a slightly lesser extent during the 1963 apparition. It is interesting to note that during the 1964 apparition the peaks have become considerably diminished.

Let us remember that most emission is due to source A and that it was shown in Fig. 34 that the variation in percentage probability for successive apparitions, can to a large extent be accounted for by the variation of magnetic declination of Earth, as seen from source A on Jupiter.

We observe from Fig. 38 that the variation of both "harmonics" follows similar trends. We may therefore conclude that during the variation of the magnetic declination Earth enters both emission angles by a similar amount.

This trend can be explained by assuming that Jupiter possesses two particle belts, an inner and an outer belt, which are located in such a way that an observer on Earth determines the cut-off frequencies as being in the vicinities of either 18 Mc/s or 28 Mc/s.

Io's influence is noted in the probability of emission of both belts.

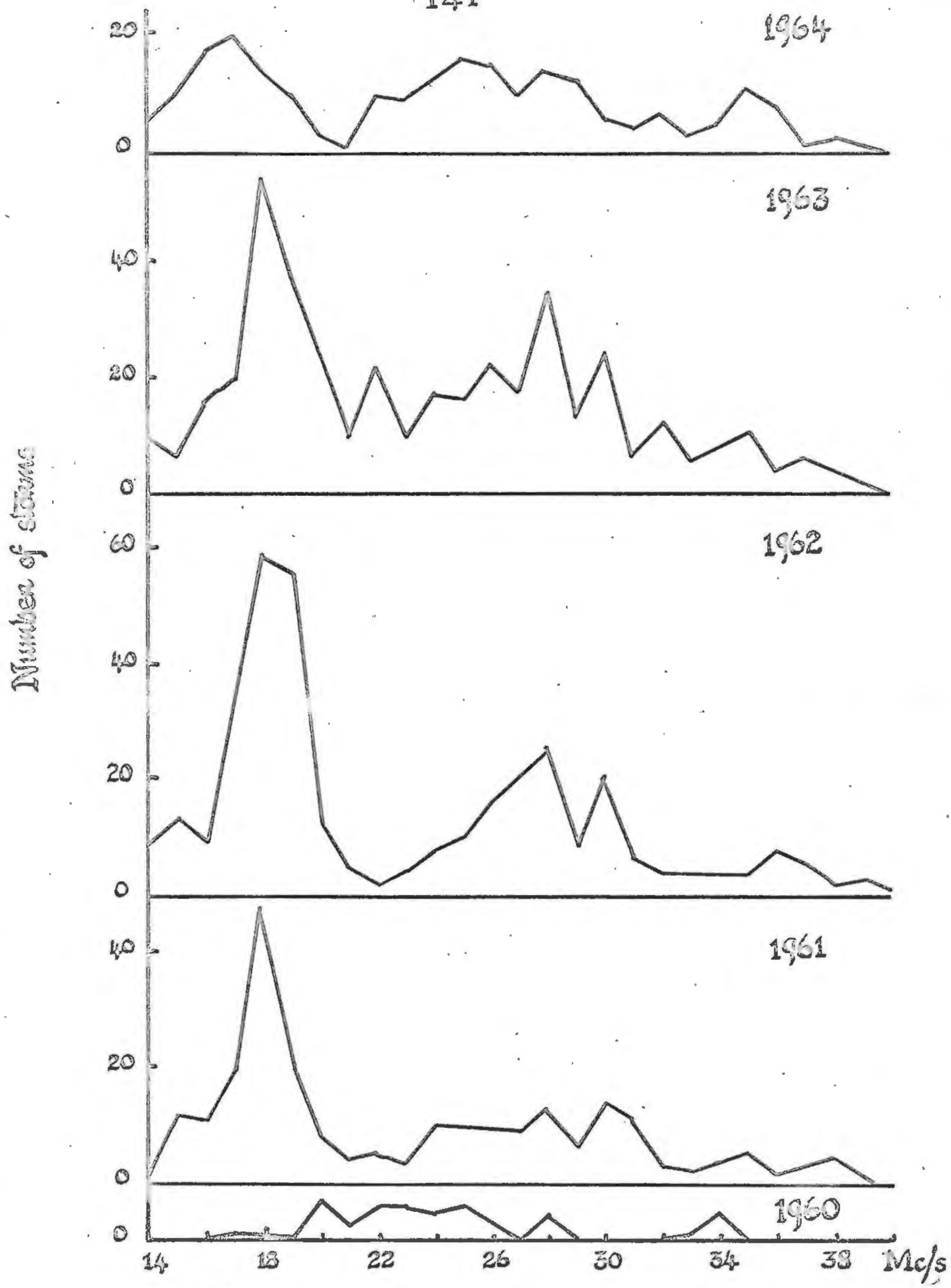

1964
1963
1962
1961
1960
Number of storms
0
20
40
60
14
18
22
26
30
34
38
Mc/s

Fig. 38

In the one belt Io's influence is such that it pushes up the MF to the regions beyond 30 Mc/s, while in the second belt Io's influence is felt only a little bit, pushing some of the MF up to 18 Mc/s. If this second belt, the outer one is also responsible for the lower frequency emissions, then this would explain why the 18 Mc/s Io-controlled bursts occur in the vicinity of 180^{o} CML, with a second peak of Io-controlled emission 180^{o} later when source C is affected.

We have mentioned before that the emission in the MF interval 18-19 Mc/s when Io is in the vicinity 90^{o} to 115^{o} from SGC can be split up into three source regions A, B and C in the ratio 17, 11 and 20. Let us consider for a moment the emission of source C. The peak of source C in that interval is around 320^{o} CML. If we reduce Io's SGC co-ordinates to System III longitudes it is found that 100^{o} SGC value corresponds to a value of 40^{o} system III longitude. This is close to the meridian opposite to the one containing the magnetic axis. (Fig. 39) We also know from polarization observations that source C has a large amount of emission which is left hand polarized. This implies that the emission is likely to come from the southern hemisphere. We have then the interesting phenomenon that Io appears to enhance emission from the southern hemisphere, when the satellite is close the meridian which contains the magnetic axis. This argument is derived from the fact that if the magnetic axis is tilted at 10^{o} in the northern hemisphere then we will also observe the "other end" 180^{o} later inclined at 10^{o} to the rotational axis.

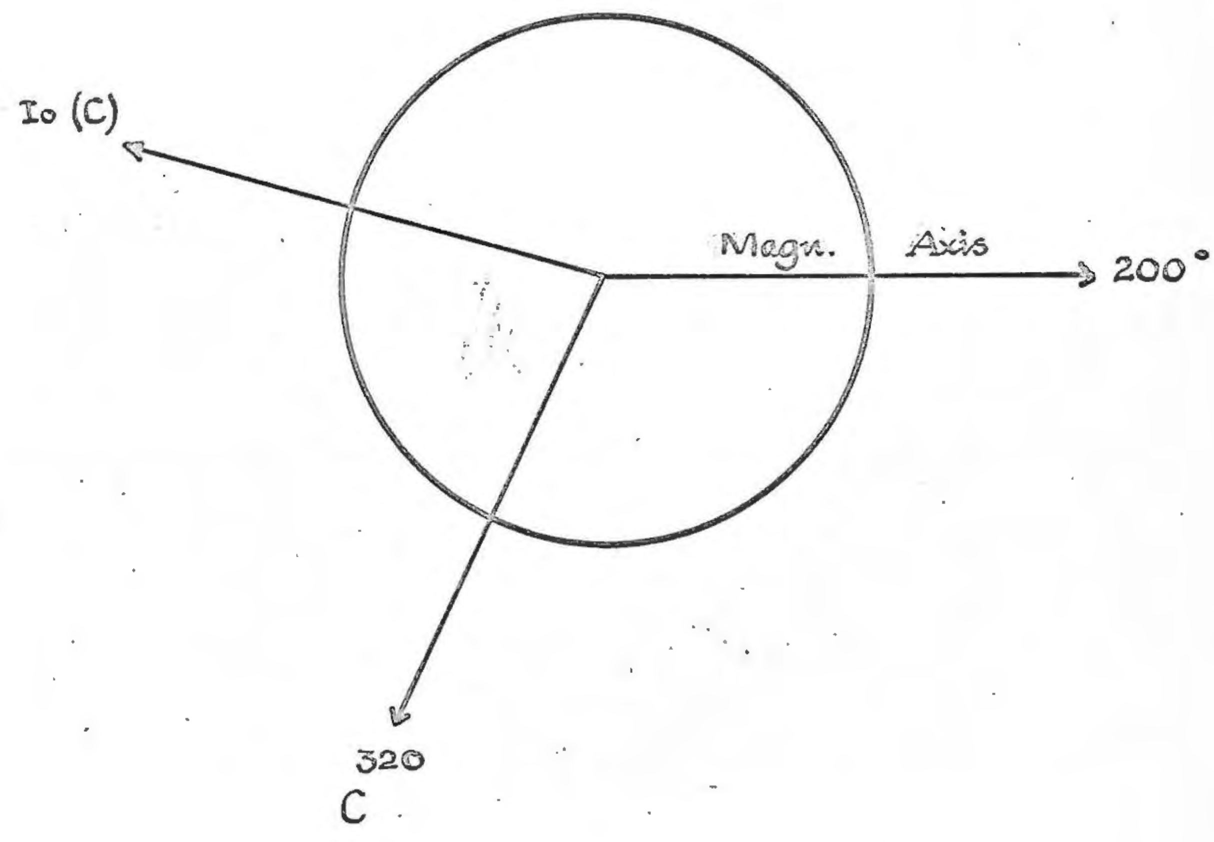


Fig. 39 Geometry of source C emission

From what has been said in the last few paragraphs we conclude that two separate particle belts may be responsible for the observed emissions, one for the emission having a cut-off frequency in the vicinity of 18 Mc/s, the other belt responsible for the emission with high MF, mostly around 28 Mc/s. If this is indeed the case then the apparent "harmonic" relationship is but a coincidence.

There is further evidence to be found in a recent publication of Riihimaa (1966e). He reports that there are indications of three types of high resolution dynamic spectra. These he calls A, B and S.

The type A emission occurs most often when source A is in the central meridian. Type B emission seems to favour source B, while type S emission, often referred to as "spitting" Jupiter seems to favour source B and source C. These observations were made with a high-resolution spectrograph and since no MF, i.e. upper cut-off frequencies were determined, it is difficult to relate these results to our analysis. However we shall attempt to draw some conclusions.

The S-type pulses seem to favour the late source B longitudes and source C longitudes. From our MF diagrams we can conclude that they have a fairly low MF, i.e. fall into the category of emission which has been attributed to emissions from the suggested outer particle belt.

While one cannot be sure that this argument holds, one may however conclude that it may be of considerable advantage if future observations of Jupiter characteristics of any kind are subdivided according to the MF reached during a particular event. This approach may allow us to divide the various characteristics into definite classes, such that present observations will fall into place and that further order may become apparent.

The results of this analysis show that Io has a very pronounced influence over certain Jupiter events. This division is sharp when analysing on a basis of MF. It is also apparent that the Io-control may split below 30 Mc/s and become fairly weak.

It had been suggested that the Io-effect may be due to Io breaking through the boundary of Jupiter's magnetosphere. However calculations reveal that the boundary of Jupiter's magnetosphere lies far outside the path of Io's revolution around the planet. Calculated values, using a range of parameters, ranged between 40 and about 400 Jupiter radii for the distance of the magnetospheric boundary, while Io's orbit is just under 6 Jupiter radii.

It has been suggested (Bigg, 1966) that it may be a possible tidal effect in Jupiter's ionospheric regions. While we agree to a possible tidal effect produced by Io being responsible for some of the emissions, there are some difficulties which any detailed explanation will have to disperse.

Io controls, as we have seen, the probability of emission of the highest frequency emission of the two suggested particle belts. But it has also been pointed out by various workers (e.g. Dulk and Clark, 1966) that Io controls the intensity output at the low frequency end of the decametric spectrum (to 10 Mc/s). The emission in the 4 Mc/s region takes place, according to our simple dipole model, at a height of approximately 1 Jupiter radius. We have also seen that emission seems to be beamed into the higher magnetic declinations. From this it can be deduced that a uniform change in the position of the particle belt would explain such phenomena. This implies that the apparent magnetic declination of Earth is sometimes increased, when Io is in certain positions. It is significant, as has been pointed out earlier, that for the emissions above 30 Mc/s, i.e. the highly Io dependent radiation, Io's position is always near the meridian containing the magnetic axis. This is also true for type S pulses of Riihima (1966e), to a lesser degree for type B, while no definite relationship was established for type A pulses.

It is suggested here that the possibility should be taken into account that Io affects the position and direction of the magnetic field. This suggestion seems somewhat farfetched, however we should remember that magnetic observations on Earth have determined a cyclic departure in the degree of magnetic disturbance on a given day. This average level of disturbance tends to repeat itself, usually in a diminished degree, 27 or 28 days later. (Moon 29.53 days)

Chapman (1964) states that for a time this was interpreted by some observers as an indication of lunar influence. This view is however not longer taken as there is only a very limited influence that the moon can exert upon the Earth.

We can apply the same argument to Io's influence upon Jupiter's decametric emission; there is little reason to believe that Io should excert a large physical influence. However we have here two phenomena which could be explained by the influence of a moon upon the magnetic field of the planet.

Chapman also states that todays observers attribute the 27-day recurrence tendency to the rotation of the sun relative to the moving Earth. It is agreed that as the sun appears to rotate with a similar period, the distinction is not easy to make. But we have here a different phenomena which recurs at a rate similar to the rate of rotation of Io, Jupiter's largest moon, and the sun is definitely not directly responsible for the Io-relationship.

There is still further evidence that can be added to the argument. Bigg (1966) reported that when Jupiter's second biggest satellite is in the vicinity of 40° from SGC, then a decrease of activity can be noticed. Since source A is the most active one, we shall investigate how Europa could influence decametric emission. Fig. 40 shows the geometry at the time source A is active. The longitude containing the magnetic axis is 200°. Therefore this longitude will be 40° to the East of CML. This means that the position of the longitude containing the magnetic axis and the position where Europa hinders emission are 180° apart.

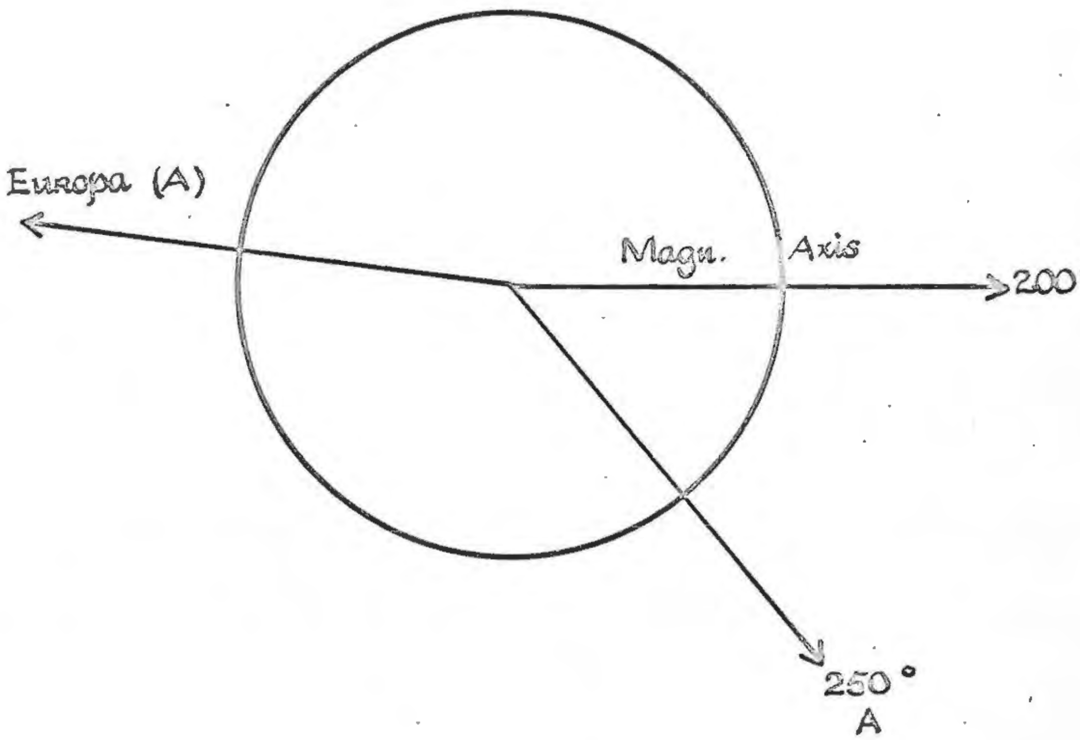


Fig. 4.0 Geometry of source A to Europa position

We then have the phenomena that source A emission (northern hemisphere) is enhanced when Io is in the vicinity above the meridian containing the magnetic axis and emission of source A is reduced when Europa is 180^{o} away from this position.

We have also seen above that emission from the southern hemisphere is enhanced when Io is above the meridian containing the southern extremity of the magnetic axis, i.e. $200^{o} + 180^{o} = 20^{o}$.

It seems therefore possible, although difficult to understand, that there is an influence of the planet's satellites upon its magnetic field. This influence should definitely be investigated further. The influence could possibly be an internal perturbation upon the mechanism responsible for the magnetic field, but it could also be an external perturbation upon currents in the planet's magnetosphere.

The sudden decrease after opposition of the probability of occurrence is also very interesting. Six et al (1963) had also noticed this effect. They assumed the decrease to be due to an eclipse of Jupiter by the Earth's magnetosphere.

They reported that at opposition the terrestrial magnetosphere eclipses roughly 3% to 16% of the area of the solar disc. They say that a weak point in their hypothesis is the short duration of the eclipse compared to the period of low Jupiter activity around opposition. The noticed asymmetry about opposition could still be explained as due to the magnetospheric tail being swept back behind the path of Earth. However there is a noted increase again, at least in some years, after a low activity period of two months. Simple calculations give the extent of the magnetospheric tail as approximately 2 x $10^4 R_E$ if the above argument is true. If we compare this with the measured value of the forward boundary of approximately 10 R_E, then we realize that there is doubt about this hypothesis.

If we compare the data with the variation of the magnetic declination of Earth as seen from Jupiter, then we notice that some of the decline can be attributed to the decrease in the magnetic declination (Fig. 34). The increase after the low activity period is then still a mystery, as it does not coincide with a definite variation of the magnetic declination.

Ellis and McCulloch's theory predicts narrow cone emission by a small source. Interferometer observations, mentioned earlier (Slee and Higgins, 1963, 1965, 1966), showed that the source is smaller than the visible disk. We have shown using statistical methods that the source has, at least, very narrow limits. It was shown previously (Gruber 1962) that the minimum of Jupiter activity observed during 1959 coincided with the maximum angle of tilt of Jupiter's south pole. If we express this in terms of the magnetic declination of Earth as seen from source A, it is found that during that period of low activity Earth's declination was in the vicinity of 5^o. This value will again be reached during 1968.

We see therefore that it appears that a change of magnetic declination of

Earth of about 2^{o} changes the probability of occurrence by about threefold. This does indeed give additional evidence that the decametric emission from Jupiter is radiated into very limited latitude regions. This also implies that we are at present going through a period where Jupiter activity will be observed to be limited, at least from source A.

The emission appears to be due to two particle belts. The higher frequency emission of each belt is influenced by Jupiter's satellites. This was suggested to be due to a possible perturbation of the magnetic field. As yet we have not mentioned to any large extent the observations of polarization. We have shortly investigated what polarization phenomena we are likely to observe if the planet were surrounded by a perfect dipole field.

Right hand polarization was said to come from the planet's northern hemisphere, while left hand polarization would come from the southern hemisphere. The general drift of polarized pulses to lower frequencies only suggests that the theory of Ellis and McCulloch does explain the mechanism responsible, as their theory assumes doppler shifted cyclotron emission, which can only be observed when emitted in the forward direction. This means that observation can only be successful if the observer is located in the direction of electron travel. This implies in our case that the electron bunches we are observing must travel towards us, i.e. away from Jupiter. This also means they are travelling into regions of decreasing magnetic field and we will observe the emitted radiation as having a negative frequency drift.

The general characteristic of purely right hand polarization for the higher frequency emission can also be explained from the geometry. The inner radiation belt is non-uniform and is more prominent on the side containing the magnetic axis. We will therefore not get any emission from source C and D. Due to the geometry of the emission relative to the tilt of the magnetic axis we can only observe the emission belt of the northern hemisphere as at no time does Earth enter a sufficiently low magnetic declination to enter that emission region.

As the frequency of observations decreases, the emission latitude range becomes larger (cf. section 5.7; Fig. 36). Earth is therefore in such a position that, while still receiving the major share of the emission from the northern hemisphere, it also is in the boundary regions of the southern emission directions. With decreasing frequency therefore the amount of left hand polarization will increase. If the observer uses a high resolution instrument he will record a variety of pulses either left hand or right hand polarized. The axial ratio will not be unity, as this still depends upon the position of the observer relative to the emission cone. The mean axial ratio, when it is calculated, will give an indication of the effect of both observing geometry relative to the emission cone and geometry relative to the latitude range of emissions.

CHAPTER VI

Conclusions

6.1 An emission model

During the course of the last chapter, we have introduced bit by bit an explanation of Jupiter's decametric emission. We shall here attempt to put the various suggestions in some sort of logical order.

The basic assumptions are the following:

a) Emission takes place from electron bunches in such a way that only the emission which is radiated into the general direction of electron travel, reaches the observer. Ellis and McCulloch's theory of doppler shifted cyclotron emission is quite sufficient.

b) Jupiter possesses at least two particle belts. Each of these particle belts emit radiation in an intermittent manner. The outer belt is fairly uniform and is responsible for the radiation observed from the vicinity of 3 Mc/s up to about 18 Mc/s. This belt is located in such a way that the received radiation shows maxima of intensity and axial ratio when 170° and 320° CML are pointing towards Earth. The inner belt is responsible for the radiation usually known as source A and source B. Both belts are influenced by Jupiter's satellites in such a way that the higher the frequency the greater the influence.

c) It is suggested that Io affects the magnetic field. It was seen that small variations of magnetic declination affect the observed emission tremendously. The influence is most strongly felt, when satellites pass the meridians containing the magnetic axis. It appears as if gravitational perturbation might possibly account for the observed effect. We shall therefore assume that this pertubation results in an effective additional tilt of the magnetic axis.

d) The emission mechanism as such is not defined, but emission is thought to be dependent upon some external parameter, whose variation sets off the emission of a burst of radiation into certain limited regions.

We shall now attempt to build up this physical model. It was pointed out by Stone et al, (1964) that when more sensitive equipment is used, radiation is received over a wider range of longitudes. We shall take this to imply that Jupiter radiation is emitted into a certain range of magnetic latitudes value. A center band of intense radiation is bordered by weaker intensity emission.

Fig. 41 shows the limits L and L' between which radiation will be emitted. The intensity variation over the emission angle Θ is also shown. Emission comes from the particle cloud P.

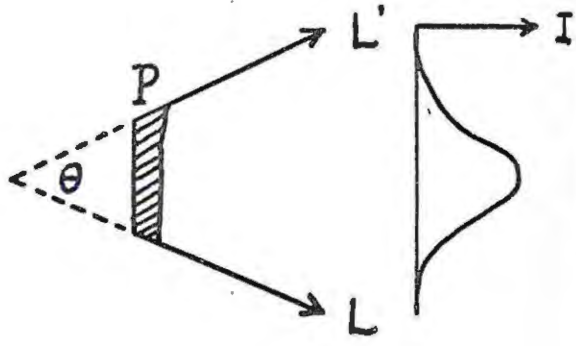


Fig. 41

We know that the magnetic axis of

Jupiter is inclined to the rotational axis by 10°. This means that as the planet rotates this emission angle will sweep across space. Depending upon the position of an observer, he will either receive radiation or not receive radiation. If θ is small enough the emission regions may sweep past the observer twice and emission will be symmetric about the meridian containing the magnetic axis.

We have seen from Fig. 36 that the higher the magnetic latitude the higher will be the maximum frequency that can be observed. This will continue until a certain latitude, when radiation will have ceased completely due to the termination of the particle belt. This type of emission geometry predicts one further phenomenon. As the latitude increases we should observe a decrease in the lower frequency emission. This would explain the lower frequency cut-off noticed in some of the Io-related emission from sources A and B. Fig. 42 shows the outline of the observed spectra.

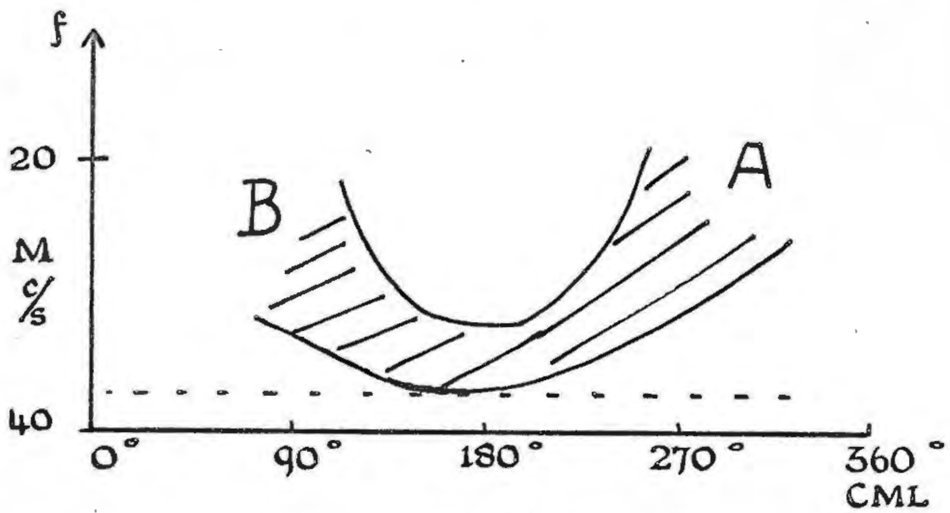


Fig. 42

We have stated that Io's influence "tilts" the magnetic axis. Maximum tilt would be expected when the satellite is above the two meridians containing the extremes of the magnetic axis. As the satellite approaches either meridian the axis would be tilted by a smaller amount. This implies that the maximum frequency we observe would be less. Fig. 43 shows the theoretical curves of number of storms versus Io position for the higher MF intervals. The observed minimum, which broadens as the frequency decreases is due to storms reaching a higher frequency when Io's position corresponds to those particular co-ordinates.

Such a tendency could be deduced from our MF curves. The number of observations is too small for a definite deduction, as this tendency could still be put down to a statistical variation. It is however an interesting thought. This argument is strengthened by an unexplained magnetic variation on Earth, with a recurrence period equal to that of our own moon.

The variation of polarization is also explainable on this model. The inner particle belt is situated in such a way that we can only observe the activity of the northern hemisphere. This would account for the right hand polarization at the higher frequencies. As the observing frequency is reduced we are able to receive more and more radiation from the southern hemisphere and the polarization will become mixed. Sudden changes in the axial ratio could be due to radiation being received simultaneously from both the northern and the southern hemisphere. At very low frequencies (about 5 Mc/s) equal amounts of the radiation belts are visible and as the planet rotates we are moved into regions of varying

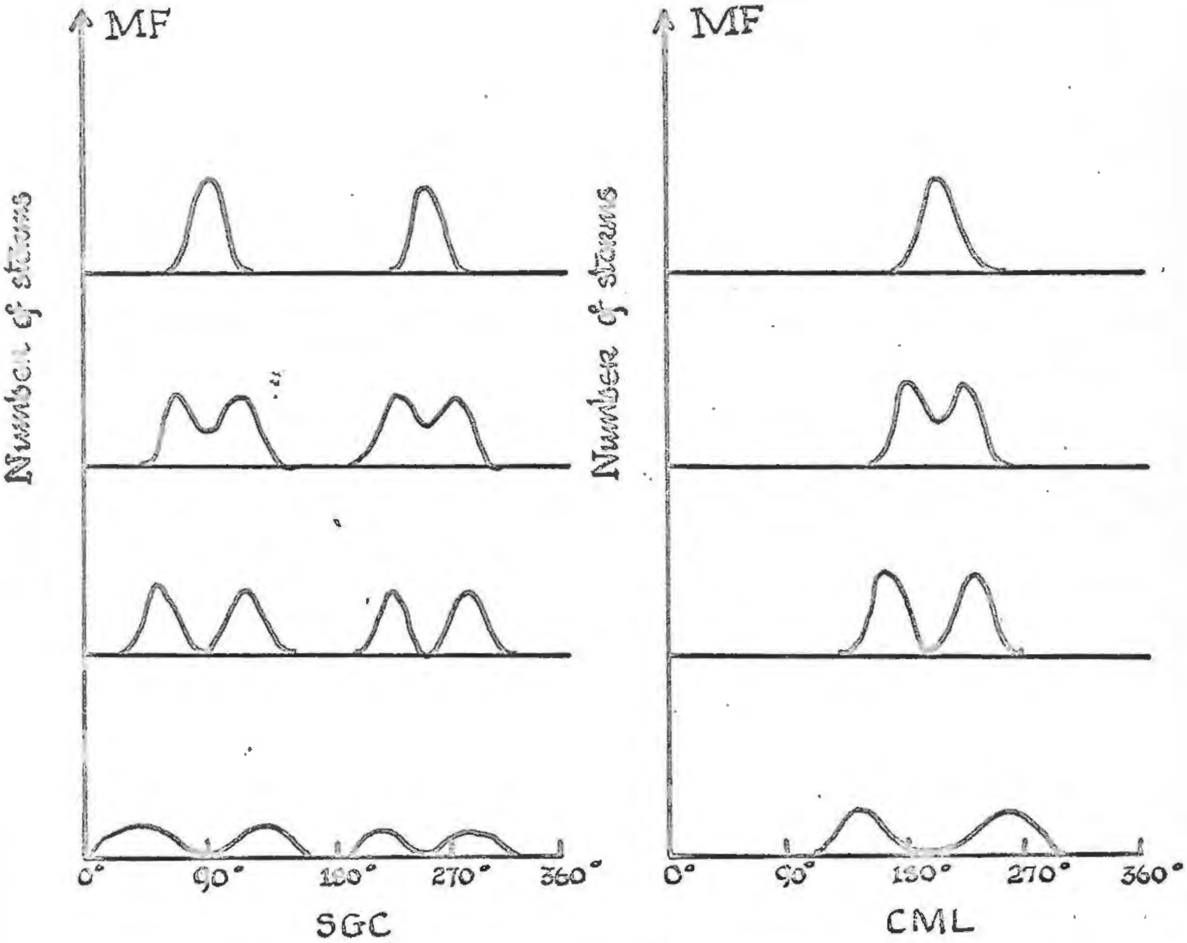


Fig. 43 Theoretical Io-dependence

polarization. As has been said in the previous chapter only mean axial ratio calculations will truly reflect this variation as in any position we are liable to receive radiation from both the northern and southern hemisphere.

The narrow emission angle hypothesis does also give a better value for the emitted peak power. For a burst of bandwidth $\frac{1}{2}$ Mc/s the maximum value of power lies in the vicinity of 10 kW.

6.2 Conclusions

The geometrical model we have been discussing will explain a considerable part of the observed characteristics of Jupiter's decametric radiation.

We have attempted to show that the variation of probability of occurrence varies in a way related to the variation of the magnetic declination of Earth as seen from source A on Jupiter.

It was seen that certain definite effects are observed when Io occupies particular positions.

Both the above observations have served to suggest that Jupiter's magnetic axis may be perturbed through influences of the first and second Jupiter satellites.

The variation of emission with frequency was put down to the probable existence of more than one radiation belt. It was possible to draw some conclusions as to their uniformity.

It was also possible to put forward a possible explanation for the variation of emission probability over part of a Jupiter year. This phenomenon had been previously described as the inverse sunspot relationship.

Observations can be classified into two classes. Firstly those that allow deductions to be made as to the physical conditions of the emission regions and secondly those observations which give us an insight into the basic emission mechanism or mechanisms.

The results of both sections of this thesis falls mainly into the first category. The instrument we are at present completing, a high resolution polarimeter, falls into the second class.

The analysis presented in chapter V has used the largest number of consistent results at present available. It is however seen, that although results from five apparitions give over 1000 pieces of data, this is not enough for the detailed analysis that is suggested by the results presented here.

There are some calculations which would be interesting to carry out:

a) Recalculations of all the data in the MF intervals according to the magnetic declination of Earth. This should give more detailed results which would allow further conclusions to be drawn as to the emission angles. These calculations should also be attempted distinguishing between the various sources, as it was suggested that the different sources emanate from different regions of the planet.

b) Calculations of Io and L_{III} relationships for the individual apparitions. This may prove difficult due to insufficient data. However it should be possible to establish some trends.

c) It would be interesting in the light of Io and Europa influences, to determine whether any relationship exists between emission and relative positions of Jupiter's satellites.

There are two types of experiments which would follow up this investigation.

a) Past and present records of the HAO spectrometer should be re-analysed stating the maximum frequency reached during, say, each 5^o of CML. In the present analysis the absence of the exact MF will have caused a broadening of the graphs. With the exact values one could then attempt constructing a more exact model of Jupiter's radiation belts.

b) Very high resolution swept frequency polarimeter observations analysed taking into account the various MFs reached, might provide further evidence of the existence of two individual particle belts. These observations should be able to distinguish individual pulses down to S-pulses, as Riihima calls them or I-pulses, as the FSU group calls them.

Although the existence of even "harmonics" controlled by the satellite Io is open to doubt, it should nevertheless be investigated further, until definite evidence is obtained, one way or the other.

There would be another interesting investigation to carry out. It is not directly connected with Jupiter research but has, as we have seen, possible connections. As the influence of more than one satellite is evident and due to the altering of the radiation directions which our geometrical model suggests, it might be profitable to investigate again the possibility of lunar influence upon the magnetic field of Earth.

An investigation of this sort may have far reaching results. As the possible physical influences are rather limited it would, should the perturbation definitely be proved, leave only a limited range of possible explanations. This would allow more definite conclusions to be drawn as to the possible origin of magnetic fields of planets.

APPENDIX A

Receiver electronics

A.1 Pre-amplifier and Switch

The pre-amplifier, described in this section, has a very low noise factor, which means it can be made use of to detect signals of small amplitude.

The pre-amplifier, whose circuit diagram is shown in Fig. 44 is based on the theory of distributed amplification. This form of amplifier structure was first proposed by W.C. Percivāl in 1935, but it was not until after 1948 that such amplifiers were constructed. The basis of this design is shown in Fig. 45. The networks L_1C_1 are the so-called gridline, a cascade of filter sections in which the capacitors C_1 are the input capacities of the tubes. Similarly, the networks L_2C_2 are the plate line, C_2 being the output capacities of the tubes. The two lines are designed to have the same phase velocity and are terminated by their characteristic impedances so that no reflections take place.

Within the limit of these idealized conditions, the following relationship holds:

$$R_{o1} = \sqrt{\frac{L_1}{C_1}} \quad \text{and} \quad R_{o2} = \sqrt{\frac{L_2}{C_2}} \qquad \omega = \sqrt{\frac{1}{L_1C_1}} = \sqrt{\frac{1}{L_2C_2}}$$

Plate current in each tube = $g_m V_1$

Because the phase velocity is the same in the grid and plate circuits, the plate currents in successive tubes are all in phase at the load.

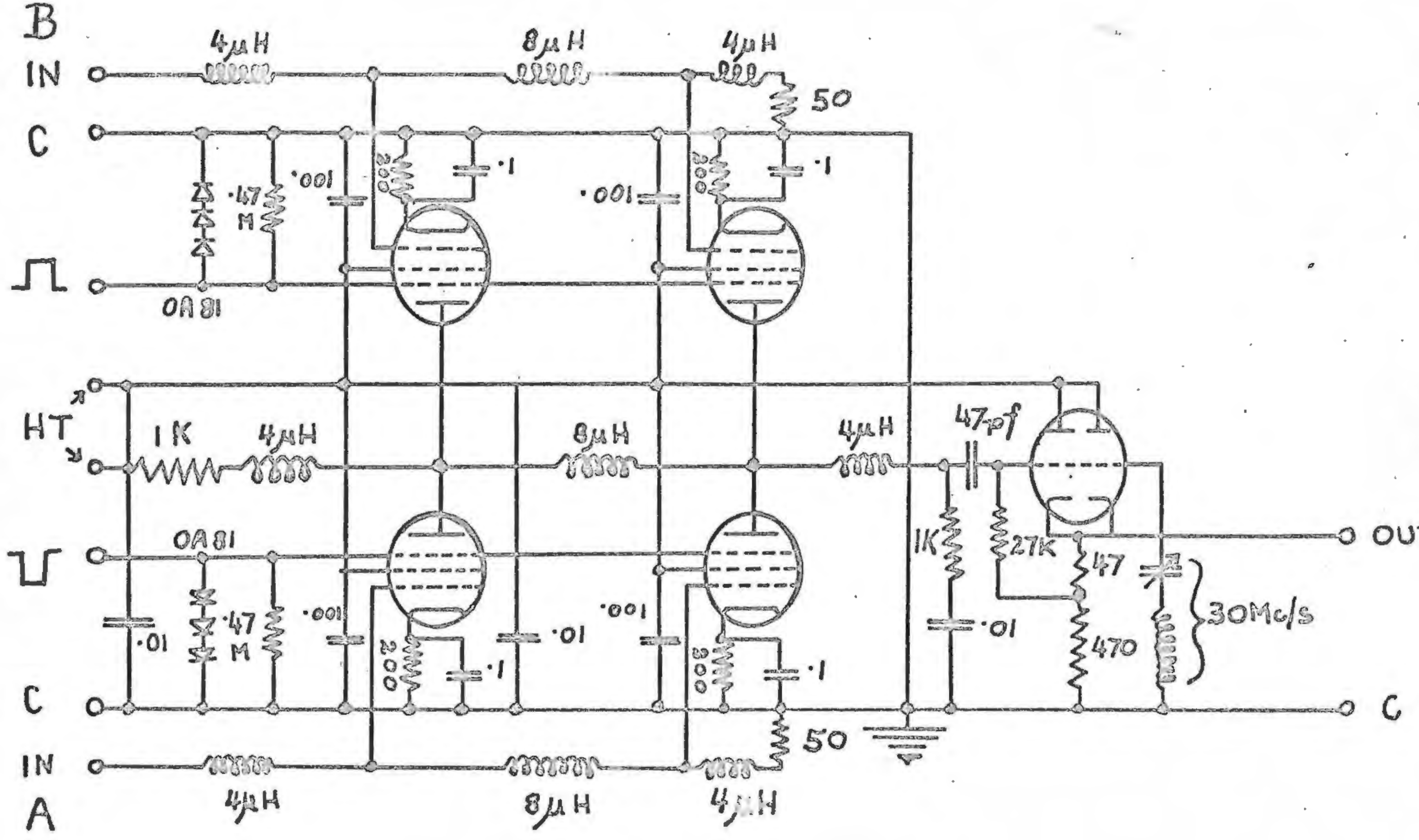


FIG. 44 PRE-AMPLIFIER AND SWITCH.

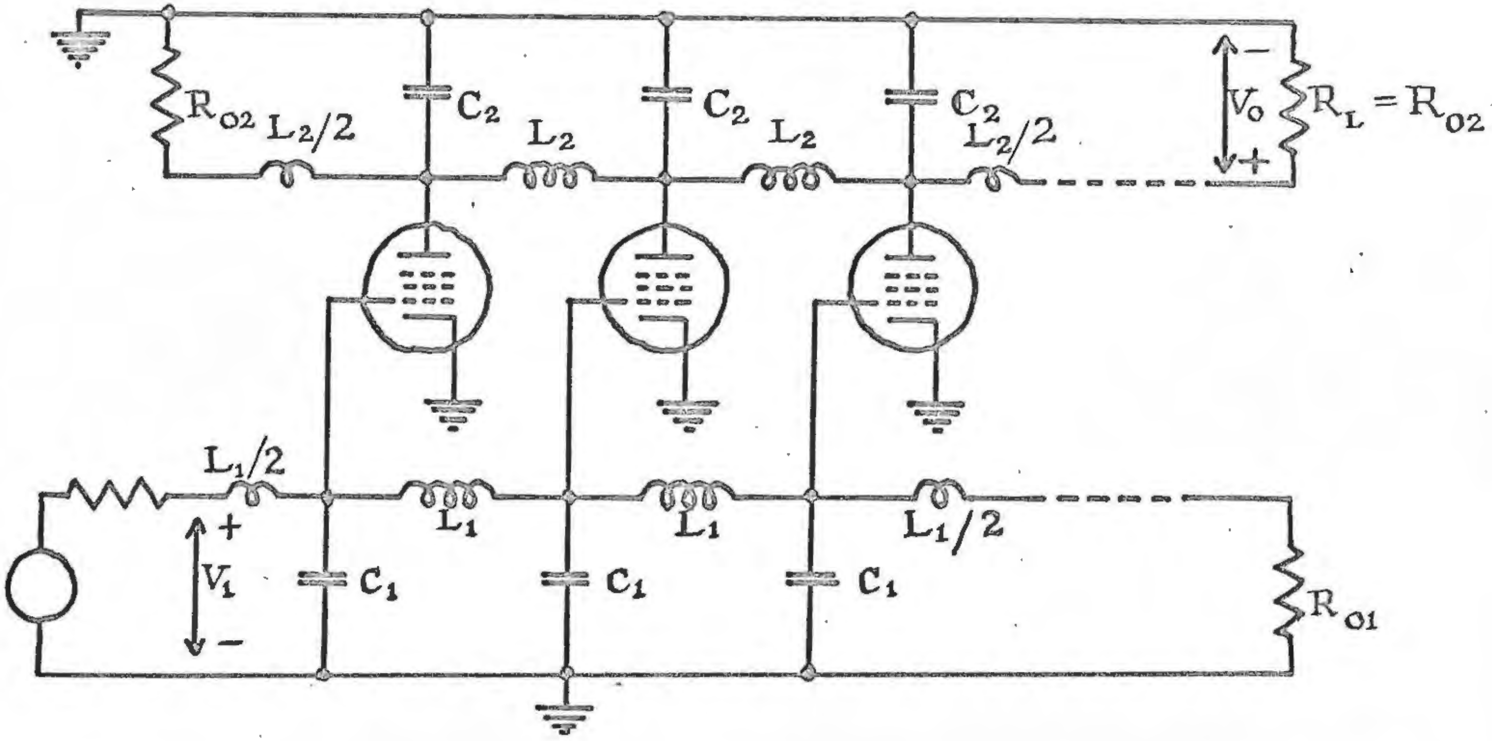


Fig. 45 Principle of Pre-amplifier

$$\text{Load current} = \frac{ng_m V_1}{2}$$

The factor 2 comes in because half the current contributed by each tube is lost, as it flows to the left and is lost in the terminating resistor R_{o2}. The resistor R_{o2} cannot be left out as otherwise waves are reflected from that end of the line and could cancel out, at certain frequencies, the wave travelling to the load.

The output voltage is given by $V_2 = \frac{-ng_m V_1}{2} R_{o2}$. We therefore get an amplification of $\frac{ng_m R_{o2}}{2}$. The amplification increases with the number of stages used, and the total gain can be made as large as required by adding a sufficient number of tubes.

The tubes used in constructing the pre-amplifier were two EF 184's, whose $g_m = 15$mA/V. This gives a theoretical gain of 15. The measured gain of the amplifier was in actual fact less than 8. The loss of gain is due to the insertion of a cathode follower-amplifier to match the pre-amplifier into the mixer stage. The series-resonant circuit in the cathode follower's grid circuit is designed to cut down any signal at the IF of 30 Mc/s.

Since the same amplifier was used to amplify the signals representing right and left handed polarization, the receiver input was switched between the two inputs A' and B' (see Fig. 2) at a rate of 5 kc/s. This was achieved by applying the 5 kc/s square wave to the suppressor-grids of the EF 184's of the pre-amplifier. The square wave was applied to the two pre-amplifiers out of phase. That means amplifier A, when it had the negative part of the square wave applied, was cut off and therefore not conducting, while amplifier B was conducting.

Thus the receiver was amplifying the signals from the two antennas alternately each for half a cycle.

The rejection ratio between the two channels was of the order of 20 dB.

A.2 Mixer and 30 Mc/s IF - amplifier (Fig. 46)

The mixer used an ECC 88. Both halfs of the tube were connected in parallel to give a higher current rating. In place of a grid-leak resistor a 2.5 mH inductance was used, in order to provide a low resistance dc path. This provided a higher signal to noise ratio and improved the performance as a mixer. The plate load of the triode was a parallel resonant circuit tuned to the IF of 30 Mc/s. There were two inputs, one from the wideband amplifier-switch, the other from the swept-frequency oscillator (to be described in a later section).

Further amplification was then provided with three EF 91 pentodes, whose plate loads were also parallel resonant circuits tuned to 30 Mc/s. Gain control was provided by a variable resistor in the cathode circuit of the first amplifier stage.

A.3 Oscillators, Mixer and Filters (Fig. 47)

The oscillator was constructed with the triode part of an ECH 81. The

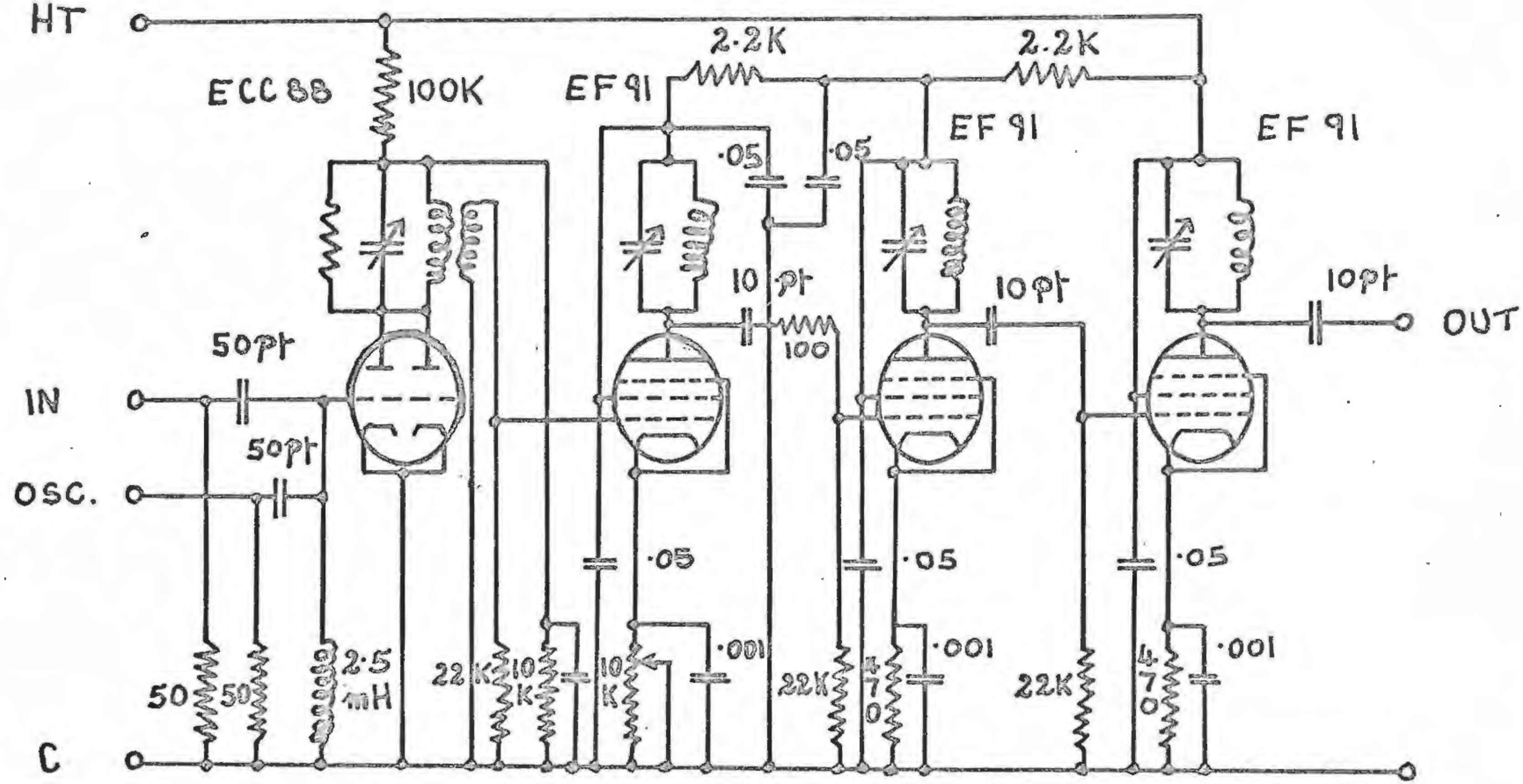


FIG. 46 MIXER AND 30Mc/s I.F. AMPLIFIER.

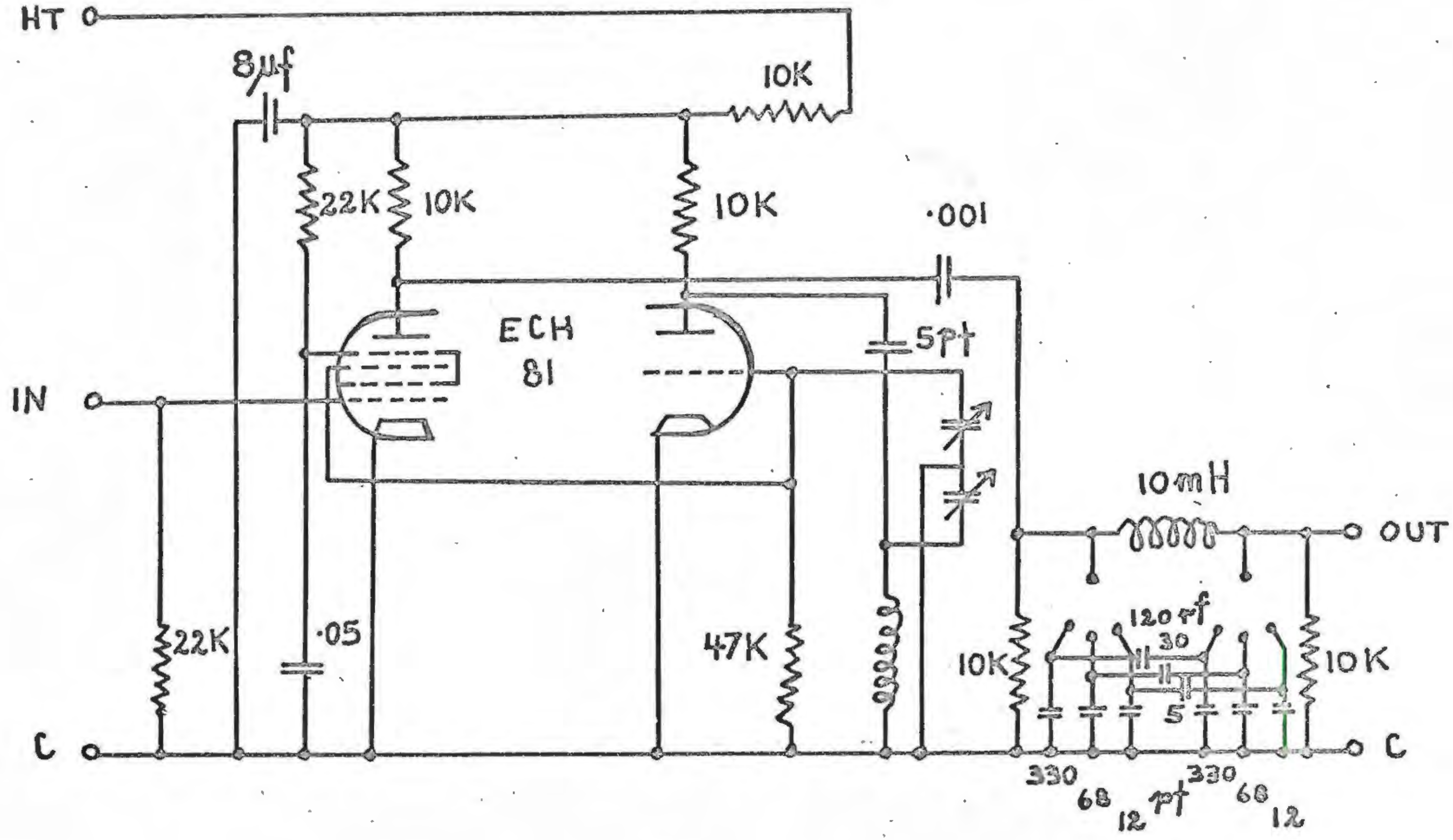


FIG. 47 OSCILLATOR, MIXER AND FILTERS.

output was fed into the hexode part of the same valve, where it was mixed with the 30 Mc/s IF.

The signals were then fed into a M-derived low-pass filter circuit, with a rather sharp cut-off. The design was such that three different values of cut-off frequency could be obtained, namely 100 kc/s, 200 kc/s and 400 kc/s. The response curves of the three filters are shown in Fig. 48. The lower cut-off was provided by the IF amplifier, which followed (cf next section).

A.4 Low-frequency amplifier

The Circuit diagram is shown in Fig. 49. The coupling capacitors and the grid resistors were chosen in such a way, as to give a lower cut-off frequency in the region of 1 kc/s. This was done to cut out low frequency interference. A potentiometer was put into the cathode lead of the second stage to act as a volume control.

A.5 Separator switch (Fig. 50)

This switch was necessary to sort out the signals representing one sense of circular polarization from those representing the other sense, directing each into a separate channel.

The circuit was made up with two silicon transistors of the type OC 203. They are high voltage transistors and more stable than germanium transistors, because of better temperature stability.

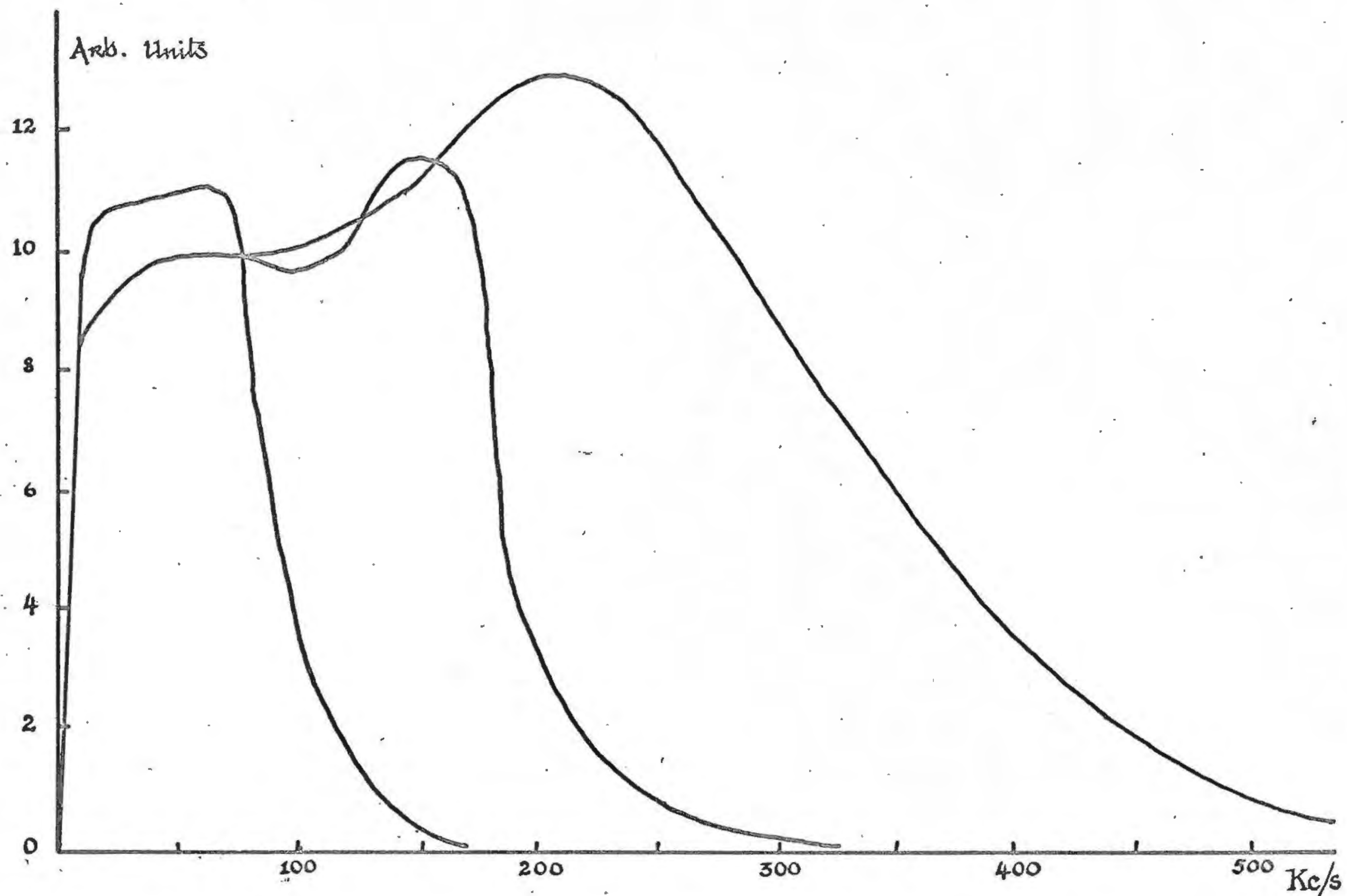


Fig. 48 Response curves of filters

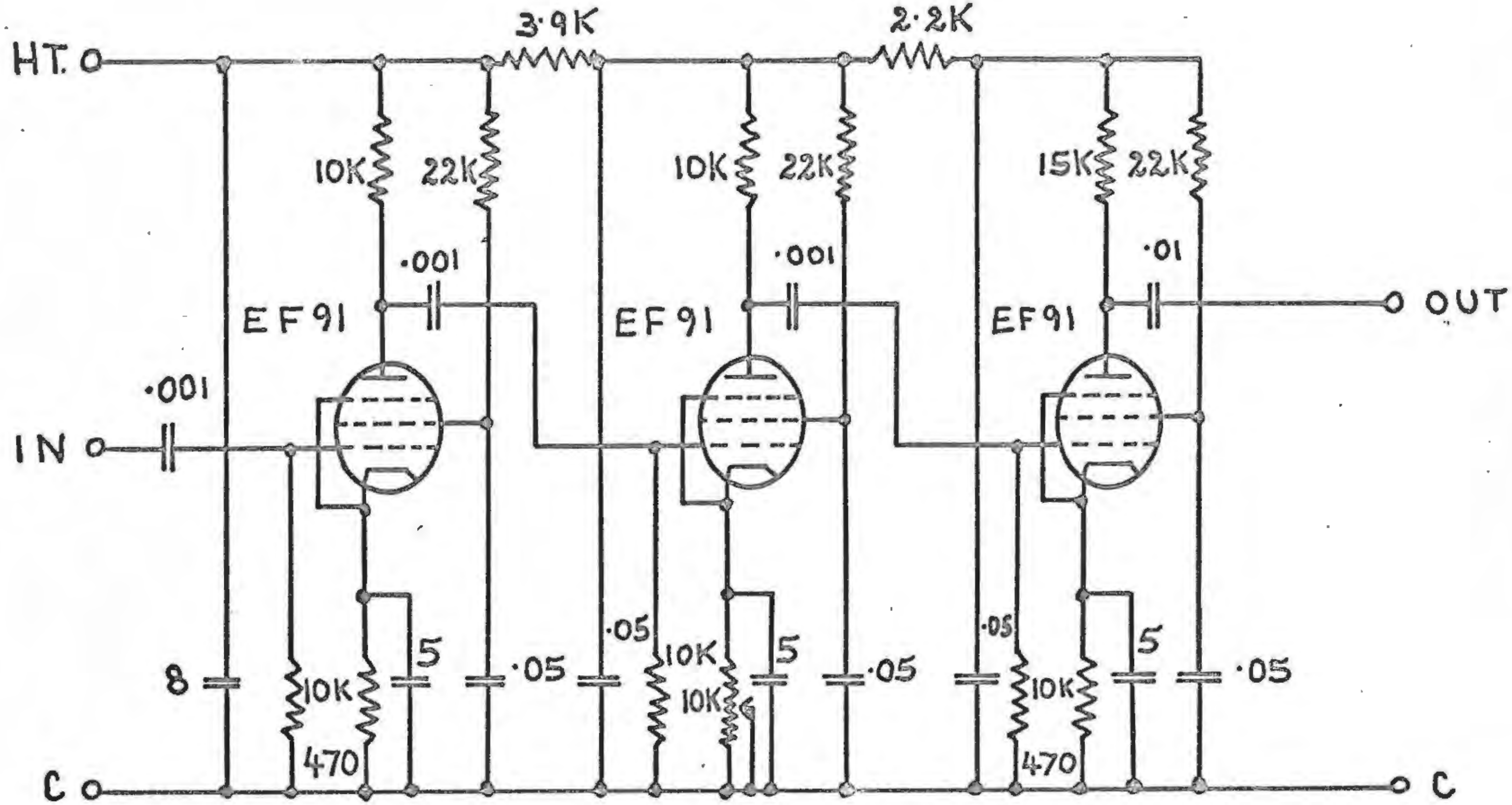


FIG. 49 L.F. AMPLIFIER.

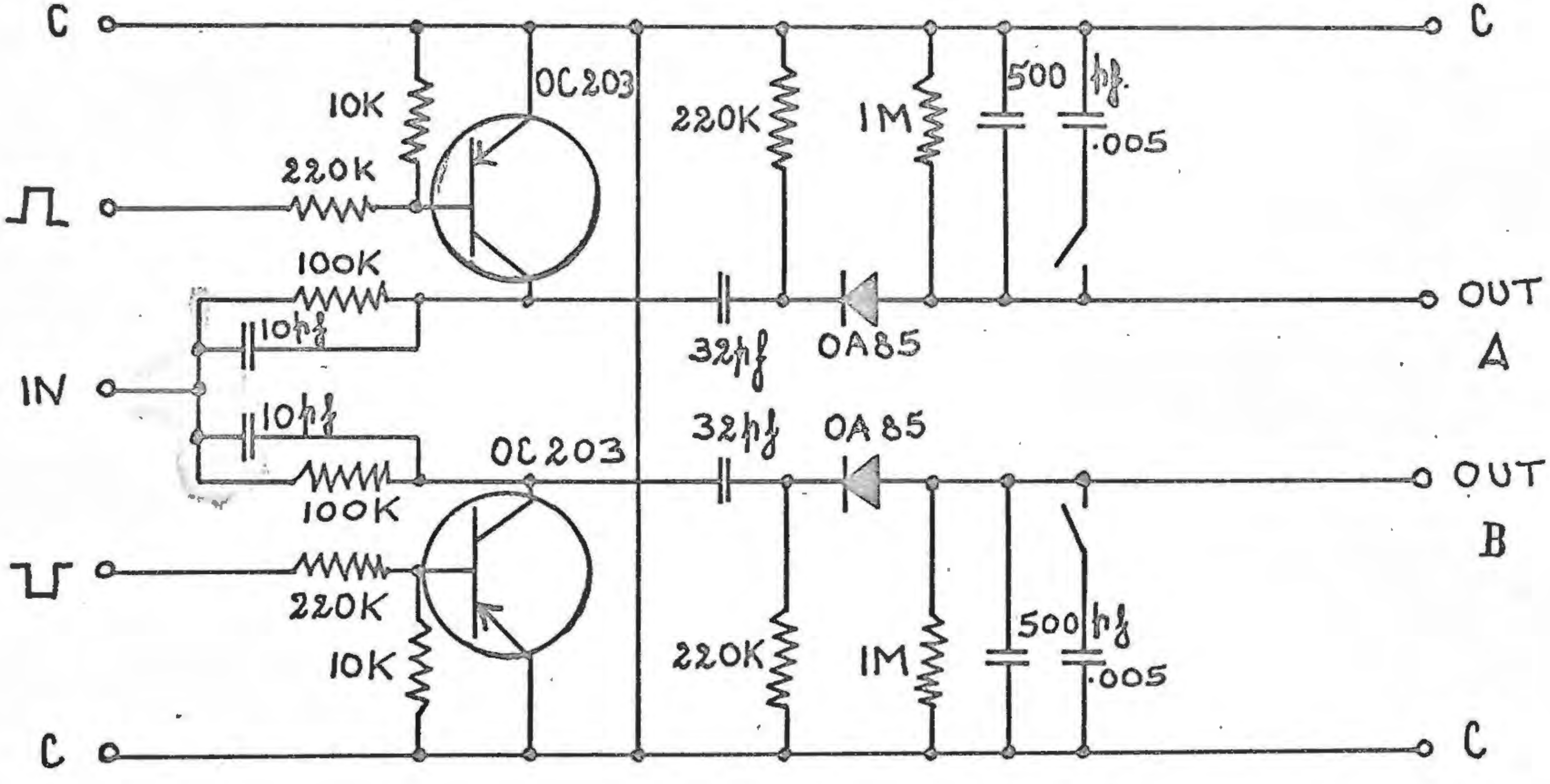


FIG. 50 SEPARATOR SWITCH.

When the transistor has a large positive signal applied to its base, the effective resistance between collector and emitter will be low, and the transistor will act like a short circuit. When a large negative signal is applied to the base the transistor will be cut off, and act as a high resistance. The biasing of the transistors is done with the square waves from both plates of the delay unistable multivibrator (described later). Thus when one transistor is in a state of low effective resistance the other is in a state of high effective resistance. When properly adjusted for possible delays in the receiver, switching the transistors will channel signals representing one sense of polarization into output A, while channeling the other into output B.

The OA 85 diodes detect the signal linearly provided the forward resistance of the diodes is very much less than the 1M resistor or the input resistor of the following piece of apparatus, whichever is the lower. The following time constant circuit smoothes the variation introduced by the switching. The switching frequency was chosen to be 5 kc/s so that switching would take place a few times in the time it took to sweep through the equivalent of one bandwidth, so that no information would get lost.

A.6 <u>Swept-frequency oscillator (Ames, 1949) (Fig. 51)</u>

This section of the apparatus was to provide the frequency varying between 45 Mc/s and 55 Mc/s, which was to be mixed with the incoming signals to give an intermediate frequency of 30 Mc/s.

In Fig. 51 valve A is the actual oscillator. It will operate at a

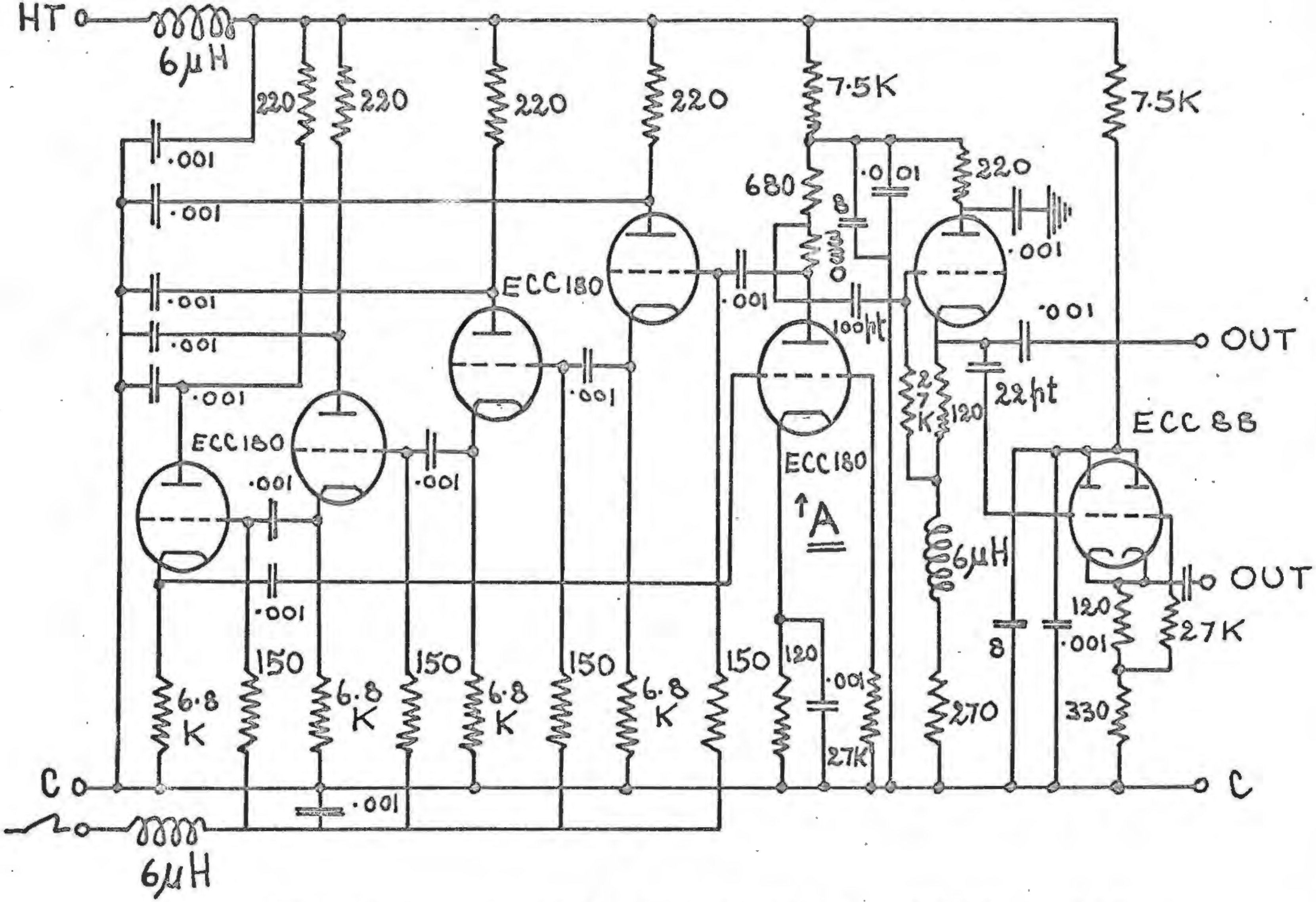


FIG. 51 SWEPT FREQUENCY OSCILLATOR.

frequency determined by the phase delay, due to the four cathode followers, i.e. at a frequency where the total phase change is 180° between the grid and plate of the oscillator. This phase change depends on the cathode resistor of the valves as well as the actual valve parameters. If one changes the voltage of the grids of the cathode followers, the valve parameters change and therefore the frequency.

The output signal is fed through two cathode followers to isolate the oscillating circuit, as any change in the external circuit system would affect the frequency.

Fig. 52 shows the graph of frequency versus applied voltage. It is seen that the variation of frequency given out by the oscillator is linear with respect to the applied potential.

A.7 <u>The sweep generator (Fig. 53)</u>

This was to provide the varying voltage necessary to sweep the frequency of the oscillator. The ECC 82 was wired up as a free-running multivibrator. The 1M potentiometer (A) allowed adjustment of the mark-space ratio, while the 47k potentiometer provided the frequency control. The output waveform was used to cut off the EL 86. The output voltage would then begin to rise from a value determined by the setting of the 4.7K potentiometer, at a rate determined by the setting of the 1M potentiometer (B), in the plate circuit of the EL 86, and the 2μF capacitor. When a positive pulse was applied to the EL 86, the valve would begin to conduct again and the plate voltage would drop to its

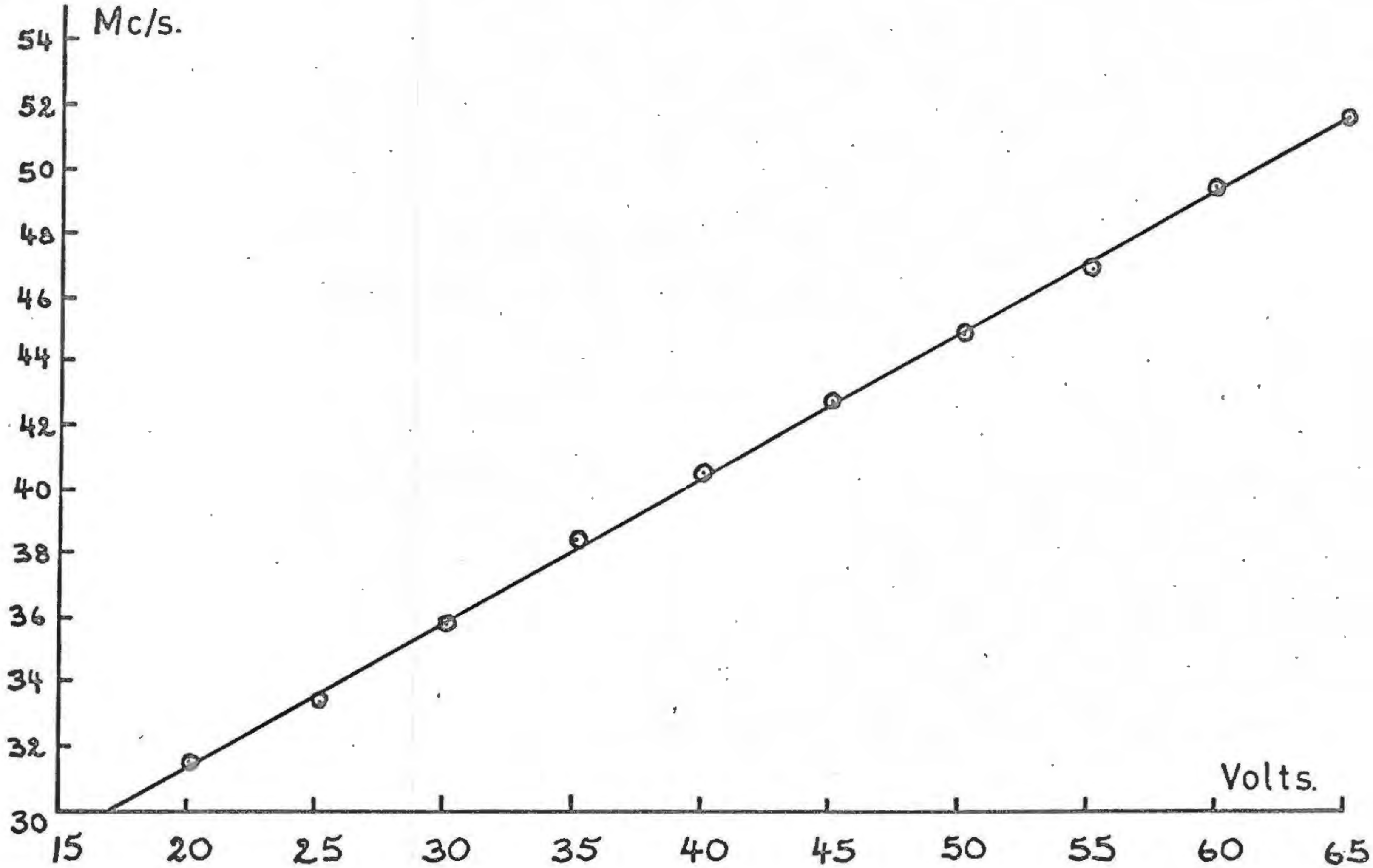


FIG. 52 FREQUENCY Vs. VOLTAGE OF OSCILLATOR.

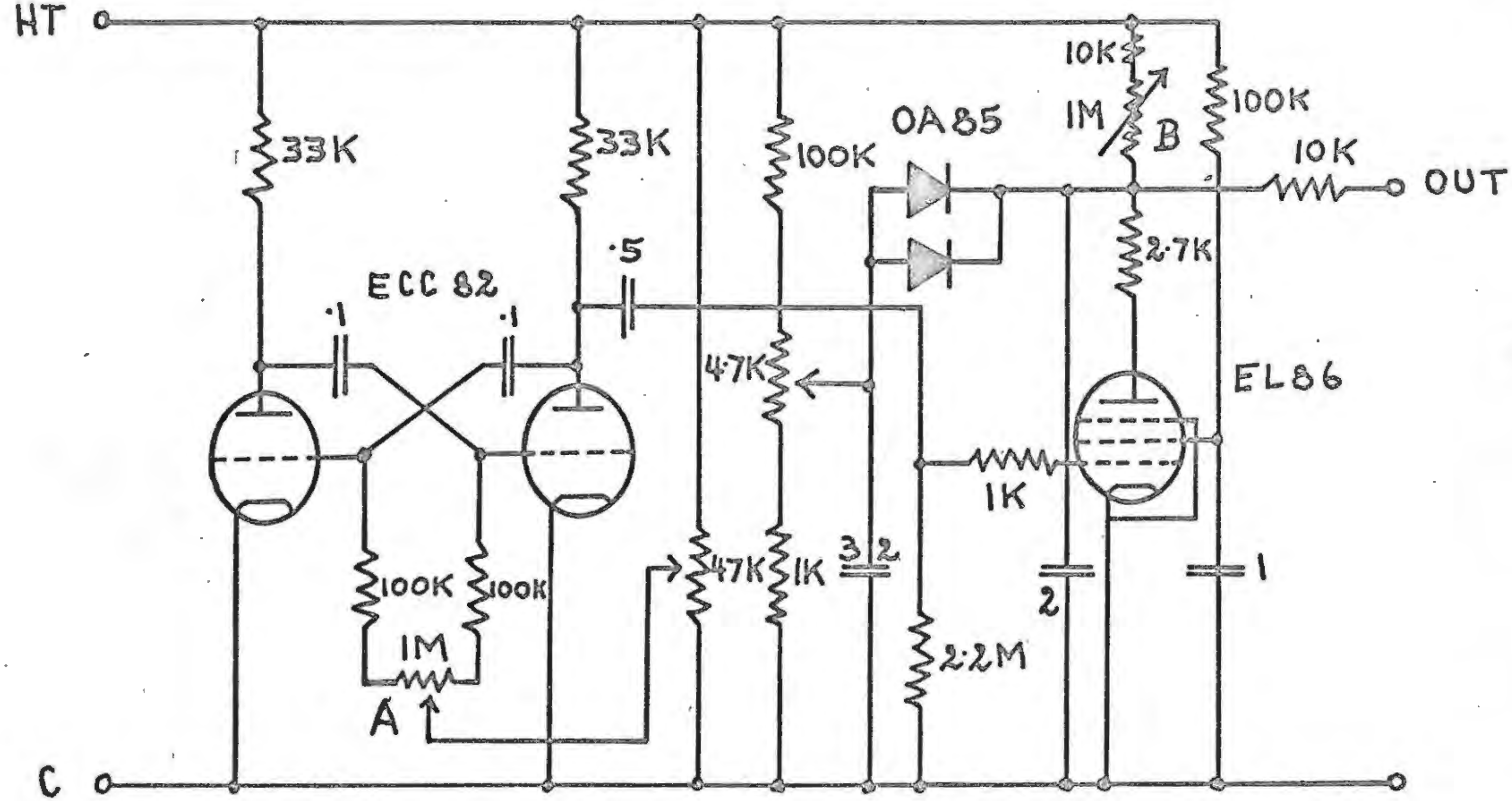


FIG. 53 SWEEP GENERATOR.

original value. The two OA 85 diodes in parallel clamp the plate to a voltage determined by the 4.7k potentiometer.

With the circuit components as shown, the frequency could be varied from about 1 cps to about 10 cps, while the voltage sweep could be varied from the lowest voltage of about 25V to the highest voltage of about 85 V. Since the sweep provided to be sufficiently linear no boot strap circuit was necessary.

A.8 Multivibrator and delay circuit (Fig. 54)

The multivibrator provided the square wave used to switch the pre-amplifier (discussed previously). To allow for delays in the receiver this square wave was delayed, using a unistable multivibrator whose return time could be controlled. This return pulse was then used to trigger a second unistable multivibrator. This multivibrator was therefore delayed by an amount determined by the return time of the unistable multivibrator. The outputs of the two plates of multivibrator C were then used to switch the separator switch (discussed previously).

The first two valves operated as a free-running multivibrator. Mark space ratio and frequency control were provided by the 100k and 47k (A) potentiometers respectively. Outputs for the switches were taken from the two plates. One output was differentiated and clipped, the negative pips being used to trigger off a unistable multivibrator, whose return time was determined by the setting of a 47k (B) potentiometer. The

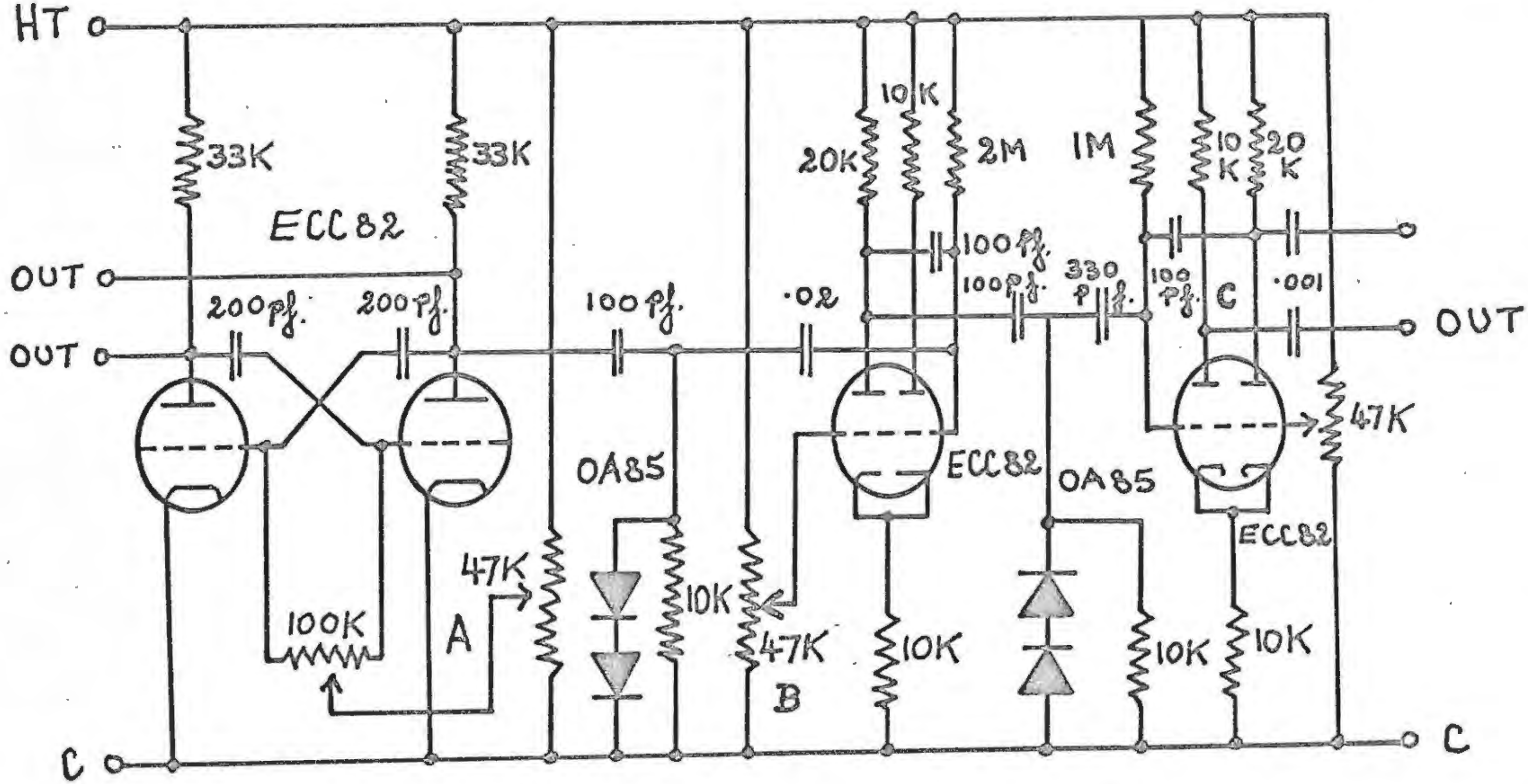


FIG. 54 MULTIVIBRATOR AND DELAY.

return pulse was used to trigger off another unistable multivibrator. The OA 85 diodes were used as clippers.

The free-running multivibrator was set to run at a frequency of 5 kc/s. The square waves could be delayed in excess of half a cycle.

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