The Influence of comet SL9 on Radio Emissions from Jupiter

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Abstract: Radio emissions from Jupiter are observed over the entire spectral region from 10 kHz up to 300 GHz. The radiation is produced predominantly in three regions of the Jovian environment by different processes. The mechanisms producing this radiation are described and the effects on this radiation of the collision of comet SL9 with the giant planet are described. Observations made at HartRAO are discussed.

1 Introduction

Radio emission from Jupiter was discovered accidentally in 1955 by Burke & Franklin (1955) during testing of a radio interferometer that had recently been constructed. These observations were made at a frequency of 22.2 MHz which falls in the region of the radio spectrum designated the Short Wave band (SW band). The wavelength of this radiation is of the order of 10 metres and hence it is known as Jovian decametric radiation. Signals had been recorded by Shain during 1950 – 1951 at 18.3 MHz but had not been recognised as originating from the giant planet. From his archived data, Shain demonstrated that the radio energy came from a localised source on the Jovian disc. In 1964 Bigg (1964) announced that some of the decametric radiation is influenced directly by the Galilean satellite Io.

Jupiter has now been observed at frequencies from 10 kHz up to 300 GHz, its radio emission filling the entire spectral range. The average flux density spectrum of Jovian radio emissions is shown in Fig 1. Three distinct types of radiation are responsible for this impressive spectrum. Thermal emission (blackbody radiation) from the atmosphere accounts for virtually all the emission at high frequencies. Very energetic (relativistic) electrons spiralling around the magnetic field lines in Jupiter's magnetosphere produce the synchrotron emission observed between ~ 40 - 4000 MHz. Much of this radiation has wavelengths in the decimetre range and hence it is referred to as Jovian decimetric radiation. The third type of radiation is that seen below 40 MHz and is due to instabilities in the tenuous ionized medium of the inner magnetosphere. The source of energy for this radiation is a giant dynamo produced by the movement of Io across the magnetic field lines from the planet.

These emissions over the entire radio spectrum have been monitored for a few decades. After correcting the data for changing distances and changes with respect to the central meridian longitude and the magnetic latitude, it has been shown that the thermal component is constant. The synchrotron component undergoes changes of ~ 30% on time periods of years (see references in Carr, Desch & Alexander, 1982). The SW emissions are not continuous; outbursts occur sporadically.

From Fig 1 it is clear that the strongest signals are produced in the SW band by the plasma instabilities. It is possible to detect this emission with an ordinary communications receiver and has probably been heard by all ham radio operators as annoying interference. The synchrotron radiation provided the first indication of a magnetic field associated with Jupiter. The blackbody radiation has given valuable information on the thermal structure of Jupiter's atmosphere. The realization that comet Shoemaker-Levy 9 would collide with Jupiter in mid 1994 led to numerous predictions of what would happen to the Jovian magnetosphere and atmosphere as a result of this interaction. In particular, papers by Dessler & Hill (1994) and de Pater (1994) considered effects of dust from the comet

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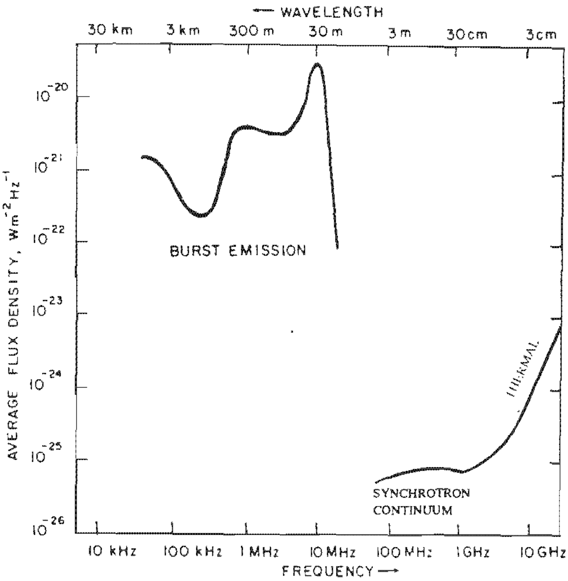

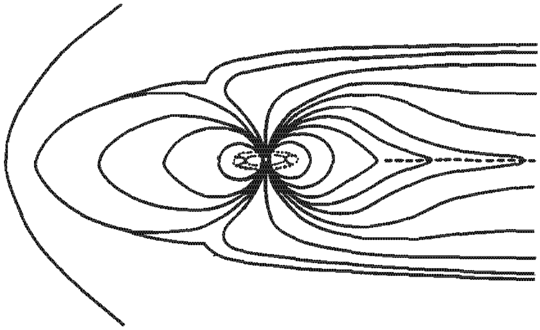

Figure 2 (above). An illustration of Jupiter's magnetosphere.

Figure 1 (left). A plot of the average flux density of Jovian radiation normalised to a distance of 4.04 AU as a function of frequency in the radio regime. The highest burst peaks attain values up to 2 magnitudes above the curve.

on the synchrotron emission. Both papers predicted that there would be a decrease in the synchrotron flux density due to the dust interacting with the relativistic electrons that produce the synchrotron emissions in the magnetosphere. There were also a number of predictions of the effect on the atmosphere and ionosphere of Jupiter due to the energy dissipated by the comet on entering the atmosphere.

2 The Magnetosphere

The magnetosphere of a planet or star can be defined as the region surrounding the body that contains ionized particles controlled by that body's magnetic field. In the case of planets in the Solar System, the region may be considered the magnetic sphere of influence of the planet whose domain is limited by the interaction between its magnetic field and the solar wind. A tenuous plasma consisting of charged particles such as electrons and protons is trapped in the magnetosphere. These particles follow helical trajectories along the field lines and emit radiation at the cyclotron frequency, $f = Be/2\pi m$, where B is the strength of the magnetic field, e is the charge and m the mass of the particle. Because electrons have a much smaller mass than protons, they are responsible for most of the observed emissions.

If the electrons have large energies (and hence have velocities close to the speed of light) the radiation is beamed in the direction of motion; this is called synchrotron radiation. The field strength B varies with position and hence radiation is produced at a range of frequencies.

Jupiter has a magnetic field that is about ten times stronger than the Earth's, with a magnetic moment second only in strength to that of the Sun in the Solar System. A schematic diagram of Jupiter's magnetosphere is shown in Fig 2; the torus indicates the position of Io's orbit. The magnetic field is believed to be produced by electric currents flowing in the interior of the planet, powered by the rapid rotation of the gas giant. Many of the gross features of the magnetosphere were first inferred from radio observations but with the *in situ* measurements of the Pioneer 10 & 11 and Voyager 1 & 2 spacecraft flybys, much new insight has been gained. Radio observations had determined that the field has Southward polarity, which is opposite to that of the Earth, and that to a first approximation it is dipolar. The tilt angle between the magnetic dipole and the spin axis is ~10° and points towards 202° in the System III northern hemisphere. The System III longitude co-ordinates are based on the sidereal rotation period of radio emissions which is $9^h 55^m 29\overset{s}{.}86$. The spacecraft data show that there are significant deviations from a dipole shape and that the magnetic axis does not pass through the planet's centre of mass. These are indications that complex structures occur in the deep interior. The effects to be discussed here are primarily concerned with the Jovian inner magnetosphere, defined as the region inside the orbit of Io which is at ~ 6 R_J, where R_J is the radius of Jupiter. The magnetic field generated by sources internal to the planet dominate in this region.

The synchrotron and low-frequency components provide a means of probing the inner magnetospheric regions. The synchrotron emission process, unlike the SW emission mechanism, is well understood, and hence provides an indispensable diagnostic tool for studying the Jovian radiation belts. Current research on the low-frequency emissions is trying to understand the mechanism producing the radiation and how it propagates through the magnetospheric plasma. Once this is accomplished, it too will serve as a diagnostic tool of the inner magnetosphere.

3 Properties of the Radiation

The thermal (high frequency) component is unpolarized, continuum emission. Because the optical depth of the Jovian atmosphere varies with frequency in the microwave region of the spectrum, different frequencies "see" to different depths in the atmosphere. The atmospheric temperature changes with altitude and hence the thermal contribution is dependent on the wavelength of observation. Much valuable information concerning the structure of the Jovian atmosphere has been gained from studying the thermal radio emission.

The main features of the decimetric component of Jovian radiation can be summarised as follows:

- continuous not sporadic
- spectrum flat extending into centimetric regime where it overlaps a thermal component
- periodic variation in total flux; 2 maxima and 2 minima per revolution
- 20 – 25 % linearly polarized
- plane of linear polarization varies quasi-sinusoidally by ±10°
- weak circular polarization, alternating between LCP and RCP as planet rotates

The relationships between the phases of these variations are illustrated schematically in Fig 3. The flux density is a maximum when the position angle of the linear polarization is zero and the circular polarization changes from one mode to the other at this point.

Radio maps have been made of this radiation, from which it can be seen that there is a distributed emission region centred on the planet, ~ 6 R_J E-W and ~ 2 R_J N-S, i.e. the radiation comes predominantly from a torus centred on the magnetic equator, about 2 R_J above Jupiter's cloud tops.

A first order explanation of the properties of the Jovian decimetric radiation is based on a changing viewing geometry of trapped relativistic electron orbits in the Jovian magnetic field as the planet rotates (Fig 4). The simplest approximation for the magnetic field is a dipole at the centre of the planet with its axis tilted by 10° with respect to the spin axis. This

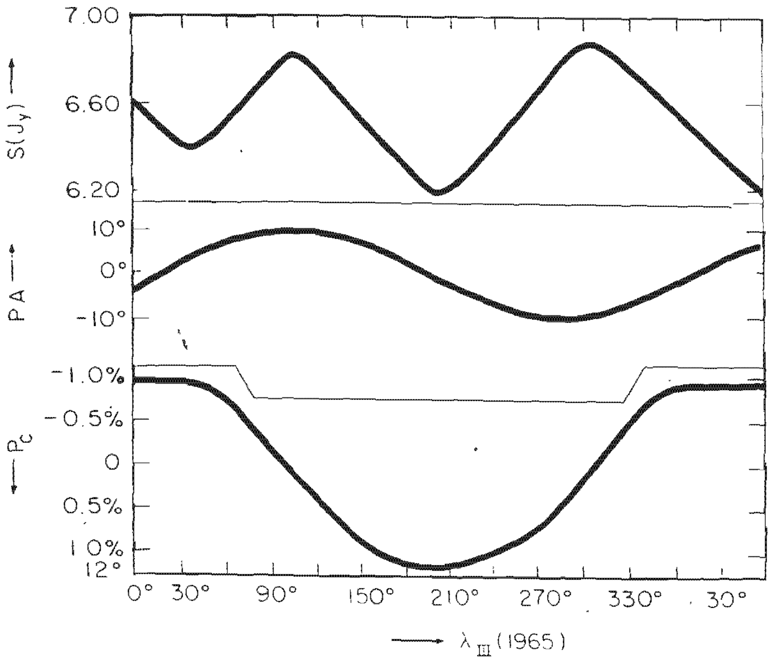

Figure 3. A schematic diagram of the variations of flux density S, position angle of linear polarization P.A., and degree of circular polarization P_c as functions of the System III longitude.

means that the magnetic equator is also tilted by 10° relative to the (spin) equator. Synchrotron emitting electrons having pitch angles of ~ 90° would have flat helical paths, with mirror points within 1 R_J of the magnetic equator. The polarization plane of the linearly polarized emission lies parallel to the magnetic equator (position angle = 0°) and hence rocks by ±10° as the planet rotates. Likewise, the weak LCP and RCP components would vary with the rotation, depending on which hemisphere is facing the observer.

The double peak in the flux density is a manifestation of the beaming of the synchrotron radiation. The beaming is a maximum along the plane of the magnetic equator and since this crosses the Earth-Jupiter line twice per rotation, a double peak is seen. The angle between Jupiter's equator and the line of sight to Earth is known as the Jovicentric declination D_E. When the Earth lies in the plane of Jupiter's spin equator, $D_E = 0°$. The model described above would produce two flux density maxima of equal magnitude and spacing per rotation. When $D_E \neq 0°$, which is the usual situation, there are asymmetries in the spacing between the maxima and in their peak fluxes. Further asymmetries are introduced by the non-dipole terms present in the Jovian magnetic field and by the fact that the dipole and other terms are offset with respect to the centre of the planet.

The decametric radiation occurs as bursts of continuum emission and has a large circular component of polarization. The energy for this emission is produced by the interaction between Io and Jupiter's magnetic field. Because Io's orbital period is longer than Jupiter's rotation period, the planetary magnetic field lines sweep across the moon with a relative velocity of 57 km s^{-1}. When a conductor is moved through a magnetic field, a potential difference is set up between the ends of the conductor. This is the principle behind a dynamo or electric generator. Io is a conductor and this giant dynamo produces a potential difference of ~ 500 kVolts across the diameter of Io, as illustrated in Fig 5 (overleaf). Because charged particles can move freely along lines of magnetic force and moving charges constitute a current, currents can flow along field lines. The Jovian ionosphere, like that of the Earth's, is a good electrical conductor and sets up a closed electrical circuit together with the field lines around which current flows, the potential difference across Io driving the current. ome of the energy in the electric circuit is dissipated by instabilities in the magnetospheric plasma and produces the observed bursts of decametric radiation. The precise mechanisms involved in producing these radio emissions are still poorly understood.

4 The effect of SL9

One of the surprising aspects of the collision of SL9 with Jupiter was that the microwave radiation, rather than decreasing as had been predicted, underwent an increase during the week of impacts. Subsequent analysis of the data has shown that it was the synchrotron component that increased while the thermal component remained constant. By separating the thermal and synchrotron components it has been shown by de Pater et al. (1995) that there was a frequency-dependent increase in the emission as listed in Table 1.

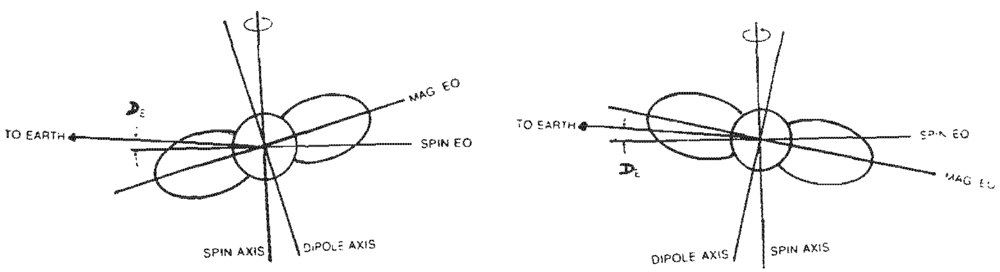

Figure 4. Geometrical relationships between the spin and magnetic axes and their equators. The jovicentric declination D_E is illustrated for the extreme cases when the observer's central meridian longitude is 200° and 20°.

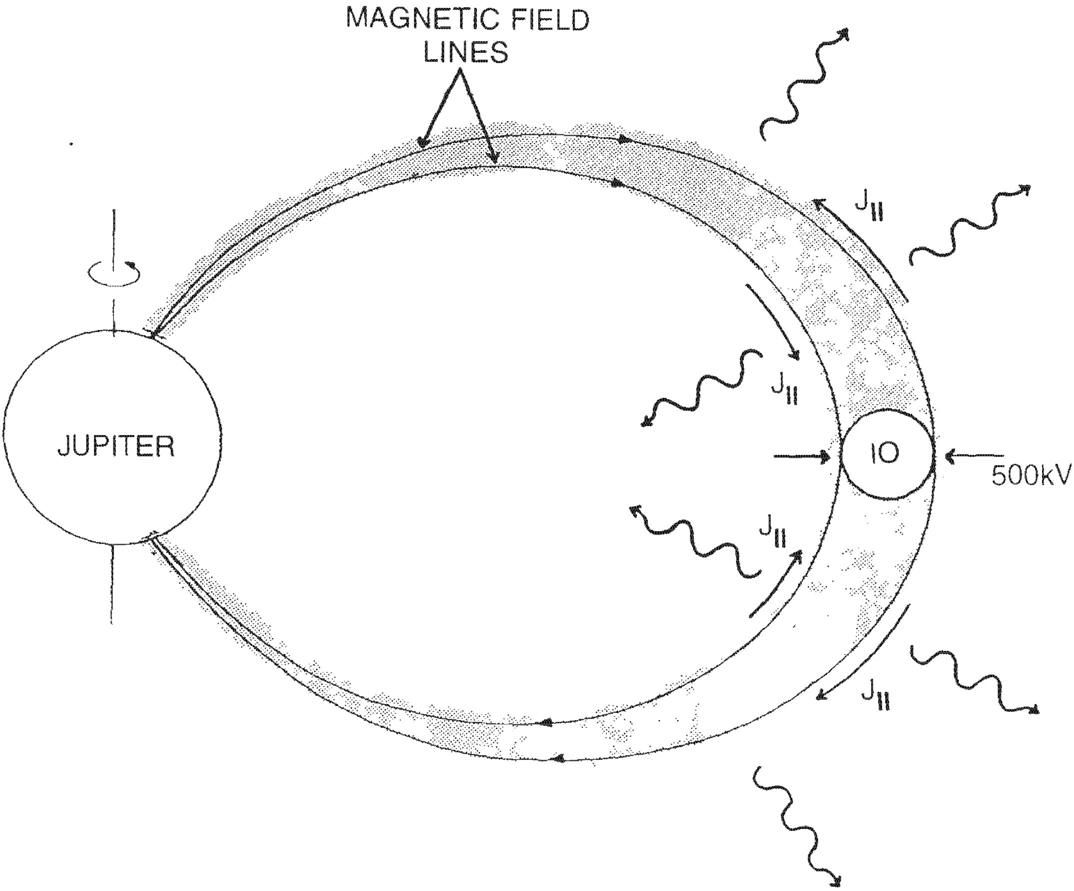

Figure 5. The Jupiter-Io dynamo.

Table 1. Wavelength versus percentage increase in flux of synchrotron component

Wavelength [cm]	Percentage increase
90 – 70	10 – 13
22 – 18	20 – 22
13 – 11	25 – 26
6	43

Following the week of impacts, the enhanced emission started to decline; the flux density at 70–90 cm started to decline about 2 days earlier than at other frequencies. The lower the frequency the faster the decay occurred. Three months after the impacts, the radiation levels were still declining at the high frequencies.

Radio images of Jupiter taken before and during the week of cometary impacts show that the brightness distribution of Jupiter's synchrotron radiation changed significantly during the week of impacts. There was a dramatic local enhancement in the radiation belts, concentrated near the magnetic equator.

5 Observations at HartRAO

The Hartebeesthoek Radio Astronomy Observatory (HartRAO), located in the Gauteng province of South Africa, is the only operational radio telescope on the African continent. The 26m telescope operates continuum receivers in bands between 1.6 GHz (λ= 18cm) and 8.4 GHz (λ= 3.5cm) and hence can detect emission from the decimetric synchrotron radiation and the low frequency end of the centimetric thermal radiation. Although HartRAO is not involved in any planetary observing programs, this unique event provided an opportunity to contribute to an international effort. The observatory has a latitude of -26° and therefore was well positioned to observe Jupiter, whose declination during the collisions was between -11° and -12°. The flexible weekly scheduling arrangements made it possible to include this target-of-opportunity project into the observation programme at short notice.

Continuum measurements of Jupiter's flux were made at wavelengths of 18, 13, 6 & 3.5 cm (frequencies of 1.6, 2.3, 5 & 8.4 GHz). To correct for any telescope pointing errors, the observing program stepped around the source measuring the flux at a number of nearby points as well as on the source. From these readings the on-source flux is calculated, taking into account any pointing inaccuracies. This observing technique requires 10 mins per datum point at 3.5 and 6 cm and 5 mins at 13 and 18 cm. During the collisions the flux density at all observed wavelengths increased and has subsequently been decaying. Observations of Jupiter's microwave emissions are continuing at HartRAO. This is the only station world-wide that has 3.5 cm data and the flux in September 1995 had still not returned to its pre-impact levels.

Once it was realised that the entry of SL9 into the Jovian atmosphere was producing spectacular effects in the infrared, we decided to look for changes in the microwave flux at the time of the collisions. For this a faster observing program was needed, so a new procedure was implemented. Rather than stepping around the source, only on and off source measurements were made at wavelengths of 6 & 3.5 cm. In this way a flux measurement was obtained every two minutes at both wavelengths. On days 201 and 202 (20/21 July), 1994 about the times of collision of fragments Q, S_1 and T with Jupiter this observing strategy was adopted. From the data it is clear that no short time-scale effects were produced in the radio regime by the impact of the comet fragments into the Jovian atmosphere.

Observations of the low-frequency emissions from Jupiter during the crashes were made by Prof P Kellogg and three colleagues from the Physics department, University of Minnesota who had come out to SA to observe the events. Taking advantage of the radio quiet conditions in the valley at HartRAO, they built 2 log-periodic antennae which they set up near to the 26 m telescope. The antennae were attached to receivers that swept through frequencies from 10 MHz up to 30 MHz in a couple of seconds. Prof Kellogg had predicted that burst-type emission, similar to that produced by Io, would occur when the comet fragments crashed into Jupiter. After some extensive analysis of the data, no obvious signatures are present. However, the data is still being analysed and it is possible that there is an unexpected type of response in their data that has not been recognized yet.

6 Conclusion

Jovian synchrotron flux densities increased by a few percent during the period of the comet collisions and are now decaying back to their pre-impact levels. The reason for this increase is not understood. The thermal and decametric components did not undergo any changes, contrary to various predictions. The response of the Jovian magnetosphere to the comet impacts was unpredictable. Clearly, our understanding of its complex environment is incomplete, but the new insights gained from the observations of this fortuitous event will greatly enhance our knowledge of the gas giant.

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