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Flux Monitoring at 327 MHz during SL9-Jupiter Collision

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Abstract. Jupiter flux at 327 MHz was monitored using the Ooty radio telescope from July 12th to July 29th during the collision of comet Shoemaker-Levi 9 with Jupiter. Flux was found to increase steadily from July 17th to July 26th by ~ 2·5 Jy, after which it declined to its pre-event value. The comparison of 327 MHz observations with those at 840 MHz and 2240 MHz indicates that the enhancement was mainly due to the increased synchrotron emission and the contribution of thermal emission was very small at metric-decimetric frequencies. The enhancement in radio emission was found to be more at 840 MHz than at 327 or 2240 MHz. The steepening of the spectrum between 327 and 840 MHz as well as between 2240 and 840 MHz was also noted.

Key words: SL9-Jupiter collision—radio flux monitoring—Jupiter radio emission.

1. Introduction

Radio emission from Jupiter spans a wide frequency range from 0·01 MHz to 300 GHz. This radio spectrum consists of three distinct components. Thermal radiation from the cloud layer dominates at millimeter and centimeter wavelengths. At metric-decimetric wavelengths, the dominant component is the synchrotron emission by relativistic electrons trapped in the Jupiter’s magnetic field. At the low frequency end, below 40 MHz, the emission consists of sporadic bursts due to plasma instabilities in the inner magnetosphere that generate the emission at frequencies slightly above the local electron cyclotron frequency.

In the metric-decimetric band of interest to us, the emission is due to synchrotron process powered by electrons accelerated to 10–100s of MeV by radial diffusion from the outer magnetosphere into ~ 2 R_j. These high energy electrons are then trapped in a shell of ~ 2 R_j above the cloud top level and centered on the magnetic equator which is tilted by about 10° with respect to the spin equator. The mirror points of most of these trapped electrons are within ~ 1 R_j above and below the magnetic equatorial plane. The observed synchrotron source therefore is the projection of a toroidal source surrounding the planet. The width and height of this projection are approximately 6 R_j and 2 R_j respectively. The spectrum in the metric-decimetric band is nearly flat with the peak at around 1000 MHz. At higher frequencies, the thermal component dominates the synchrotron emission as shown in Fig. 1.

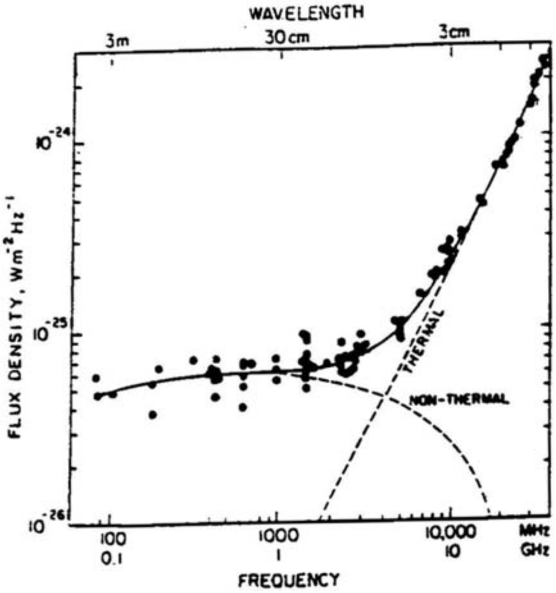

Figure 1. Radio spectrum of Jupiter observed over metric and decimetric frequency bands. The observed spectrum (solid line) is composed of emission due to thermal and non-thermal components (dashed lines), (Carr, T. D. *et al*. 1986, *Physics of Jovian Magnetosphere*, pp 235).

The passage of cometary fragments through the Jovian magnetosphere and the subsequent collisions were expected to affect Jupiter's metric-decimetric emission. Various scenarios for the change in the Jovian radio emission were thought of and are mentioned below.

- It was expected that the energy released in the impact could ionize the cometary material resulting in an enhancement in the electron density. These electrons could be accelerated to high energies in the shock waves that would have resulted from the, impact. The resulting increase in the number of relativistic electrons would enhance the emission.
- The emission could also be enhanced, if instead of producing new relativistic electrons in the impact, low energy electrons already existing in the synchrotron radiation belts were accelerated to sufficiently high energies thus resulting in a net enhancement in the density of high energy electrons.
- Enhanced thermal emission due to the heating up of the Jovian atmosphere by the impacts was also a possibility. Enhancement due to thermal emission was however expected to be seen for short durations after the impact because of short cooling time scales.
- On the other hand, increase in the dust grains and larger-sized material in the magnetosphere with the entry of the comet was expected to slow down the high energy electrons. As a result, the intensity was expected to decrease immediately after the cometary material entered the radiation belts. Inward diffusion of electrons through a dusty magnetosphere was therefore expected to result in a drop in emission for many months after the comet had entered the magnetosphere (de Pater 1994).

We briefly describe our observational results in section 2. Results are discussed in section 3, and section 4 concludes the paper.

2. Observational results

The observations were carried out using the Ooty Radio Telescope (ORT). The ORT consists of a 500 m long cylindrical parabolic antenna with an effective collecting area of about 8000 sqm situated in southern India at a latitude of + 12°. The telescope operates at 327 MHz. The telescope can be steered around its equatorial axis from – 4·5 to + 4·5 hours which allows one to monitor a single source for a stretch of 9 hours. In declination, the telescope can be pointed electronically from + 35 to – 35° by phasing the array of dipoles (Swarup *et al* 1971). The telescope can be operated

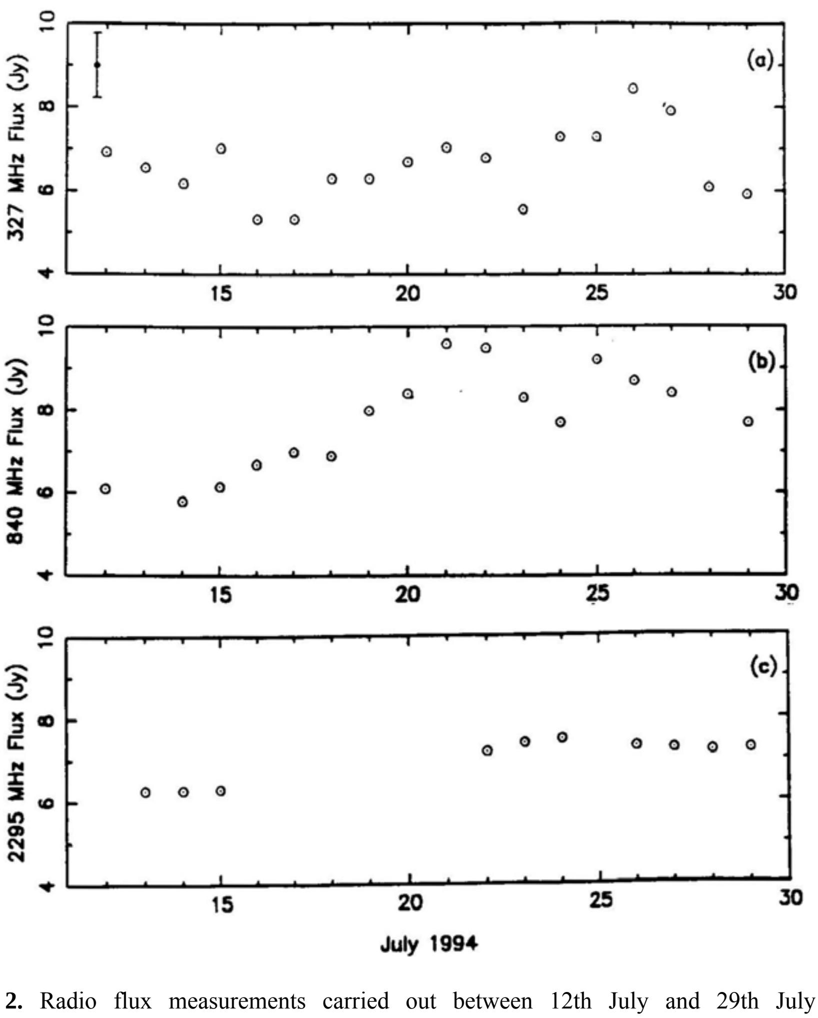

Figure 2. Radio flux measurements carried out between 12th July and 29th July 1994. Measurements at 327 MHz (**a**) were done using the Ooty radio telescope which we have compared with the reported observations at 840 MHz (**b**) and 2295 MHz (**c**) from Molonglo and J P L observatories, respectively. All the flux values were normalized to a distance of 4AU.

either in total power mode, where contribution from all the dipoles is added, or in phase-switched mode, where the signals from the north and south half of the telescope are correlated. In the phase-switched mode the ORT beam is 2·0° in the right ascension and 3′·5 sec (δ) in declination.

The observations for the Jupiter-Comet collision were started on July 12th and continued till July 29th, 1994, well after the collision had taken place. Jupiter observations were interspersed with observations of calibrators. A total of five calibration sources were used during the course of these observations, and at least three of them were observed on a given day (except for July 16th and 17th when the number was 2 and 1 respectively). The data found contaminated with interference were rejected. Observations were corrected for the effect of ORT beamshape as Jupiter drifted in the beam. For any Jupiter observation, confusion sources in the ORT beam down to 10 milli Jansky (1 Jansky = 10^{-26} Wm^{-2} Hz^{-1}) were subtracted. After calibrating it against the calibration sources observed that day, a daily average of the Jupiter flux was obtained. The daily variation of the Jupiter flux thus obtained is shown in Fig. 2(a).

As can be seen in Fig. 2(a) there was a systematic increase of about 2·5 Jy (after normalizing it to a distance of 4 AU) observed between 17th and 26th July which was greater than the limit of flux measurement for ORT. This is indicated by the vertical error bar in Fig. 2(a). This increase in flux started after the impact of the first cometary fragment. The maximum flux was observed on 26th July after which the flux steadily declined over the next 4 days of observations. The data from July 12th to July 16th, when the cometary fragments had entered the Jovian magnetosphere and were approaching Jupiter, show a gradual decrease in flux.

We have compared our results with the observations at 840 MHz (Huntstead & Campbell-Wilson 1994) and 2240 MHz (Klein *et al.* 1994) (Fig. 2b–c). The enhanced emission was more at 840 MHz than at the other two frequencies. There is evidence of progressive steepening of the radio spectrum between 327 and 840 MHz, and between 840 and 2240 MHz as a result of the impacts. As the radio emission declined after July 22nd (at 840 MHz) the spectra in these two frequency ranges also became less steep.

3. Discussion

The initial decrease in the emission level (July 12th to July 16th) could have resulted from the absorption of high energy synchrotron electrons by the dust added to the atmosphere by the comet. For the later enhanced radio emission we now explore two possible explanations – both enhanced thermal as well as non-thermal emission.

3.1 *Thermal emission*

The data show a day-to-day increase in the flux with a peak on July 26th (i.e. 4 days after the last impact). The impacts therefore seemed to have had a cumulative effect on the radio emission rather than just a transitory enhancement at the time of the impact. The optical depth τ for free-free absorption is (e.g. Benz 1993):

$$\tau \sim 0{\cdot}11\ n_e^2\ \nu^{-2}\ T^{-1{\cdot}5}\ \delta L, \qquad (1)$$

where n_e is in number of electrons per cm^3, ν is in Hz, T in degree Kelvin and δL is measured in cm.

In order to explain the enhanced emission at 327 MHz in terms of optically thick thermal emission, an enhanced electron density of the order of 10^8 cm^{-3} would be required, assuming $T \sim 5000$ K (since there is evidence that the temperature of the plumes resulting from the impact reached several thousand degrees, see Chapman 1994) and $\delta L \sim 1000$ km. (Note that we cannot account for the observations by assuming optically thin thermal emission since the increase in flux at 840 MHz is more than that at 327 MHz). However gas with density as high as indicated above, will cool very fast. For example, taking an analogy with HI or HII regions since the dominant component of the Jovian atmosphere is hydrogen, the cooling rate can be roughly estimated by (Spitzer 1978) $\Lambda/n_h^2 \sim 7 \times 10^{-26}$ erg cm^3 s^{-1} (assuming fraction of the H atoms ionized to be 10^{-2}).

The cooling time scale therefore would be $t_c \sim (3/2n_h\, kT)/\Lambda$. Taking $n_h \sim 10^{10}$ (for fraction of ionized H atoms $\sim 10^{-2}$) and $T \sim 5000$ K, we find that the cooling time would be ~ 1/2 hr. Even if the cooling time derived above is off by an order of magnitude compared to what may hold for the Jovian atmosphere, we find that it is still difficult to understand the slow and sustained rise in the emission seen at the metric-decimetric band. The thermal model however is more plausible for understanding the rapid variation in the emission reported at millimeter wavelengths.

Another difficulty with the thermal emission is that the electron density of $\sim 10^8$ cm^{-3} is required across the Jupiter disk in a shell of thickness ~ 1000 km. This is possible only if ALL the electrons from a typical cometary fragment spread out across the disk, which seems difficult to justify.

We can however use the shape of the frequency spectrum to constrain the thermal contribution to the observed enhanced emission. Assuming the thermal contribution to be optically thick at 2240 MHz, and further assuming that the increase of flux of ~ 1·56 Jy at 2240 MHz was purely due to thermal emission, in order to derive an upper limit on the thermal part of the enhanced emission, we find that the thermal contribution at 327 MHz would be ⩽ 50 mJy while at 840 MHz it would be smaller than 300 mJy because the thermal emission scales as $1/\lambda^2$ for optically thick emission.

3.2 *Synchrotron emission*

The peak of the Jovian synchrotron spectrum is determined by $\nu_{\max}$ (MHz) ~ 4·8 $(E)^2$ (B) sin (α), where energy and magnetic field is in MeV and Gauss respectively (Carr *et al.* 1986). Taking $\nu_{\max} \sim 1$ GHz, $\sin(\alpha) \sim 1$ and $B \sim 3$ Gauss we find that the energies to which electrons need to be accelerated are ~ 8 MeV to explain the enhanced emission. The power emitted by one electron is (Carr *et al.* 1986):

$$p \approx 6{\cdot}10^{-22} \left(\frac{E}{\text{MeV}}\right)^2 \left(\frac{B}{\text{Gauss}}\right)^2 \sin^2\alpha \sim 3{\cdot}10^{-19}\ \text{W}. \tag{2}$$

Assuming that the enhanced emission comes from a volume of scale size ~ 1000 km, we find that an excess electron density of the order of $2{\cdot}5 \times 10^2$ cm^{-3} accelerated to energies ~ 10 MeV is sufficient to explain the enhanced emission.

Considering the moderate increase in the number density, compared to that for thermal emission, of relativistic electrons required to explain it, the synchrotron process seems to be the source of enhanced emission. The requirement of electrons accelerated to relativistic speeds could be met by a variety of processes:

- Shock waves generated by the impact could have accelerated the low energy electrons existing in the inner regions of the Jovian magnetosphere.
- There is an evidence of production of new electrons as inferred from the increase in auroras seen in ultraviolet images obtained by HST soon after the impact. Therefore there is also a possibility that these newly generated electrons were accelerated and deposited in the inner regions of the magnetosphere.
- A third possibility would be the reconnection of magnetic field taking place behind the blob of ionized material as it arose after the impact and stretched the field lines.

All three of these scenarios would also explain the inward movement of the synchrotron belts.

4. Conclusion

We have observed the radio emission from Jupiter at the time of collision with comet Shoemaker-Levy at 327 MHz using the Ooty radio telescope. A careful analysis of the data indicates that there was a systematic but marginal increase of ~ 2·5 Jy in the Jovian radio emission at 327 MHz due to the cometary impacts. The flux continued to increase till July 26th after which it declined.

Comparison with observations carried out at 840 MHz and 2240 MHz indicates that the enhanced radio emission from Jupiter due to the cometary impacts was due to synchrotron emission. Acceleration of electrons in the inner regions of the magnetosphere either due to shock waves emanating as an after effect of the impact or due to magnetic reconnection could be the cause of the increase in emission.

Though the thermal emission cannot explain the sustained rise in the radio emission at meter-decimeter wavelengths, it is more plausible for ‘bursts’ seen at the time of impacts as e.g. in milli-metric wavelengths.

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