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RESULTS OF DECAMETRIC MONITORING OF THE COMET COLLISION WITH JUPITER

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Abstract. Decametric observations of Jupiter were made at frequencies from 16.7 to 32 MHz from the Maipu Radio Astronomy Observatory in Chile, the University of Florida Radio Observatory, and the Owens Valley Radio Observatory in California before, during, and after the collision of comet Shoemaker-Levy 9 with the planet. No significant change in the general level of Jovian decametric activity that might be attributed to the comet was observed. However, single bursts of possibly Jovian origin appeared at two of the 12 fragment impact times during which we were observing. We are attempting to establish more definitely whether these two bursts really were Jovian, and assuming that they were, we are tentatively modeling the circumstances of their emission.

Introduction

The terrestrially observable spectrum of Jupiter's decametric radio emissions extends from a lower limit set by the transparency of Earth's pre-dawn ionosphere (usually between about 5 and 15 MHz) and an upper limit of about 40 MHz. The radiation is believed to result from the cyclotron maser instability (CMI) in the lower magnetosphere, most of the radiation being in the X mode. It presumably originates in Jupiter's auroral regions (largely in the northern one) at magnetospheric altitudes at which the frequencies of emission are roughly 10% higher than the local electron cyclotron frequencies (f_c). Much of the radiation observed at Earth appears in the so-called source B region of central meridian longitude (CML) when Io's orbital phase is near 90°, or in the source A or C regions of CML

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when Io's phase is near 240°. These are the Io-related emission components; they are designated Io-B, Io-A, and Io-C, respectively. There is another Source A component that is independent of Io's orbital position; it is called Non-Io-A. At times the Non-Io-A activity can considerably exceed that of the Io-A component. See *Carr et al.* [1983] for a review of the Jovian decametric emission.

Io-related radiation is supposedly emitted near one foot of a magnetic flux tube that has been carried by Jupiter's rotation across Io a relatively short time previously. The precise nature of this excitation of the flux tube by Io, its transfer down the flux tube to the radio emission site, and the manner in which it can stimulate the CMI emission process remain the primary mystery in the continuing search for an explanation of Jupiter's decametric radiation. Another part of the mystery is how the Io-unrelated emissions are stimulated. Prior to the encounter of the comet with Jupiter it was clear that if decametric activity was observed that could convincingly be attributed to the incoming fragments, gas or dust, new observational constraints would be available for guiding further theoretical investigations into the details of the origin of the Jovian decametric emission. We therefore conducted the program of monitoring Jupiter's decametric radiation before, during, and after the week of the comet impacts. This paper is a report to date of our analysis of the data obtained from the search.

The observations were made at three observatories. They were the Maipu Radio Astronomy Observatory (MRAO) of the University of Chile, the University of Florida Radio Observatory (UFRO), and the Owens Valley Radio Observatory (OVRO) of the California Institute of Technology. About 11 frequencies were monitored, ranging from 16.7 to 32 MHz. Descriptions of the four types of antennas that were used and the interference problems encountered in making the observations are given in *Carr et al.* [1994]. With one exception, the minimum detectable flux densities for Jovian radiation ranged from about 50 to 200 kJy, depending on antenna type and Jupiter's hour angle (1 kJy = 1 kilojansky = 10^{-23} w m^{-2} Hz^{-1}). The exception was the 640-dipole 26.3 MHz antenna array at UFRO, for which the minimum detectable flux density (for these observations) was about 2 kJy.

Effect of the Comet on the General Level of Decametric Activity

Our daily radio observations at UFRO began about six months before the first comet fragment impact (July 16, 1994) and continued until about a week after the last impact (which was on July 22). Observations at the other two stations were made each day from about a month before the first impact to a week after the last, those at OVRO continuing intermittently thereafter until September 9. We thus have an ample amount of data obtained before and after the impacts to serve as a baseline for the determination of the level of relative activity and its distribution in CML and Io orbital phase during impact week. Figure 1 provides, for all three stations and all frequency channels (except for the 26.3 MHz 640-dipole array channel at UFRO), comparisons of activity during impact week with that occurring outside impact week. Figure 1a shows the locations on the Io phase–CML plane of the Jovian activity that was detected during impact week, and the sloping lines in 1b indicate the parts of the plane that were covered by the observations made during this period. Similarly, Figure 1d indicates the Io phase–CML locations of activity detected during the comparison period outside impact week (beginning a month before the first impact), and 1e is the corresponding coverage plot for this period. The central areas of the three main Io-related source regions are indicated by rectangles on each of these four panels, and the values of Io phase and CML at the times of fragment impacts are indicated very approximately in Figure 1b by their letter designations.

It is apparent from Figure 1d that during the relatively long comparison period significant amounts of activity were observed in regions Io-B, Io-A, and Io-C, and also in Non-Io-A (which is within or near the CML range of the Io-A rectangle but outside its Io-phase range). Figure 1a indicates that there was very little activity during impact week. The occurrence probabilities of activity within 90° by 90° squares on the Io phase–CML plane for impact week and for the month before impact week are shown in Figures 1c and 1f respectively. The expected rms statistical deviations (σ) in these probabilities ranged from 0.05 to 0.08 for the impact-week values, and were either 0.03 or 0.04 for the month before the impacts. It is immediately obvious that there was no significant increase in the occurrence probabilities due to the comet fragment impacts. The probability values for corresponding 90° by 90° squares in Figures 1c and 1f agree to within their 1σ uncertainties except for the square containing the Io-A rectangle. Before the impacts, we detected Io-A emission with a probability of about 0.19 ± 0.03, but during impact week the corresponding detection probability was 0 ± 0.05. This apparent decrease in impact-week Io-A activity is about four times the larger σ value. Although this decrease is higher than one would expect from purely random statistical fluctuations, we consider it most unlikely that the impacts had anything to do with it. It has long been known that the occurrence times of Jovian activity at a given set of values of frequency, CML, and Io phase are not completely randomly distributed; there are one or more other unknown modulating factors that can either suspend or intensify the activity over relatively long time intervals. Our conclusion is therefore that the entries of the comet fragments into the Jovian magnetosphere and ionosphere had no observable effect on the general level of decametric activity. However, the possibility of single brief low-intensity bursts that might have been emitted close to the impact times of some of the fragments must be looked into separately; this is done in the next section.

Possible Brief Fragment-Triggered Emissions Near Impact Times

After making the above general survey of our data, we took a closer look at what had happened on each channel at approximately the accepted impact times. Fragment impacts that occurred while at least one of our antennas was in operation were A, B, C, F, H, L, Q2, Q1, R, T, U, and V; the total is 12. The only impact times at which our high-sensitivity antenna (the 640-dipole array at UFRO) was operating were those of F and L, the other impacts listed above having been monitored only by the low-sensitivity antennas. No bursts were detected by the 640-dipole array near the F and L impact times. This high-sensitivity antenna also monitored parts of the passage of 9 other fragments through the Jovian magnetosphere, but largely because of its limited hour angle coverage of only 3.5 h, their actual impacts were missed. A careful recheck of all the low-sensitivity recordings revealed possible Jupiter emission activity occuring within ± 20 min of the impact times of only two of the fragments; these were Q2 and Q1. These two emission events are of great interest, and are the subject of the remainder of this paper. To summarize the statistics of our search for radio bursts approximately coinciding with fragment impacts, we can state that a) no bursts were detected coinciding with the two impacts that were monitored with a flux density detection sensitivity of about 2 kJy, and b) for 10 other impacts monitored at a sensitivity of about 100 kJy, bursts were detected in coincidence with two of them.

We shall refer to the bursts observed at the Q2 and Q1 impact times as bursts A and B respectively. They were observed at UFRO at several frequencies with both LH and RH circularly polarized antenna arrays, each of which consisted of four log-spiral elements. A distant thunderstorm was in progress at the time, and every few seconds a large but brief burst would appear on all frequency channels due to a lightning discharge, the duration of which was usually less than a second or two. Fortunately, there were quiet intervals between lightning bursts of sufficent length in which we could usually have detected extraterrestrial bursts with flux densities greater than 200 kJy and durations longer than about 3 s each. In our processing of the data, the lightning burst excursions could not be eliminated by usual methods of low-pass filtering because of their extreme intensities. Consequently, we developed a filtering method in which the lightning bursts have been largely eliminated by means of a purely objective clipping process—one in which no decisions had to be made as to which of the abrupt deflections were or were not due to the lightning. Figure 2 shows the resulting low-pass filtered plots of flux density vs. time for bursts A and B. Burst A (panels *a* and *b* of Figure 2) was observed from 18 to 26 MHz, reaching a flux density of 920 kJy at 22 MHz. Its duration was 54 s. It was LH elliptically polarized; its degree of circular polarization was about +0.42, corresponding to an axial ratio of +0.22 (assuming zero unpolarized component). Burst B (panels *c* and *d*) was observed only at 28 and 32 MHz. It was RH elliptically polarized with a maximum flux density of about 700 kJy at 32 MHz and a duration of 75 s. The degree of circular polarization was about -0.45, corresponding to an axial ratio of about −0.24. These bursts had more than 10 times the duration of typical single Jovian L bursts, and in this respect they resembled solar bursts. The antenna gain in the direction of the sun at the times of bursts A and B was about 10 db less than that in the direction of Jupiter. None of the solar bursts identified from the Ulysses observations by *Desch et al.* (paper in this issue) coincided with bursts A or B. The strongest evidence we have that these bursts were of Jovian origin, however, is the remarkably close agreement of their times of peak intensity with the accepted impact times of fragments Q2 and Q1. The burst A peak occurred at 19:50 UT on 7/20/94, while the accepted impact time of fragment Q2 was 19:44, the value of σ for the impact time being 6 min [*Yeomans and Chodas, University of Maryland Bulletin Board, 1994*]. Burst B peak was at 20:13 (same day) and fragment Q1 impact was at 20:12 UT, with $\sigma = 4$ min. Each burst thus occurred within 1σ of the corresponding impact time. We did not observe any bursts at all resembling A and B at any other time or on any other channel. If they had been solar bursts, it would have been a remarkable coincidence that they happened to agree so closely with fragment impact times.

If it could be definitely established that bursts A and B were indeed Jovian, it could then be concluded that they were almost certainly triggered in some way by the two fragment entries into the magnetosphere or ionosphere of the planet. The fact that the elliptical polarization sense of burst A was LH suggests that it might have been emitted from near the southern foot of a magnetic flux tube through or near which fragment Q2 had passed (X-mode emission from the southern foot of a Jovian flux tube would be polarized in the LH sense.) Here we assume that the flux tube was excited by the fragment (or perhaps by material surrounding it or ejected by it from below), in a manner more or less analogous to Io's excitation of flux tubes causing X-mode radio emission from near their two feet. In the case of burst B, however, it at first appeared possible that the RH polarized radio emission caused by it could have been emitted either in the *X mode* from near the *northern* foot of a flux tube that had been intersected by fragment Q1, or in the *O mode* from near the *southern* foot of such a flux tube. We found that the magnetic field was probably sufficently strong to provide high enough f_c values to support CMI emission at the observed frequencies for either of these alternatives. At present, however, we favor the second alternative, because we have found that for the northern branches of all flux tubes intersected by fragment Q1, the altitudes at which f_c approximately equals the observed frequencies were probably behind the planet as seen from Earth. We have also made the interesting discovery that the southern foot of the *Io flux tube* was located at a great circle distance of less than 15° from the impact point of each of the two fragments. We will investigate both the possibility that the Io flux tube was involved in the emission process and the possiblity that it was not.

If we are correct in assuming that the two bursts originated at Jupiter, our modeling of the chain of events leading up to and including their emission might well provide important new information pertaining to the unsolved mysteries of the Jovian decametric radiation in general. At the same time, however, we will continue our efforts to settle the question whether the two bursts really were Jovian.

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Figure 1. *a)* Jovian decametric emission activity from all three observatories during impact week displayed on the Io phase vs. CML plane.The flux density threshold for the detection of activity was about 100 kJy. Boxes indicate the central regions of sources *Io-B, Io-A,* and *Io-C. b)* Coverage diagram for preceding plot. Values of Io phase and CML at fragment impact times are indicated very approximately by the positions of the letters. *c)* Values of occurrence probability during impact week for 90° x 90° squares on the Io phase vs. CML plane. Occurrence probability for each square is the ratio of the total Jovian activity within the square to the total observing time within the square. *d)* Jovian activity on the Io phase vs. CML plane for the comparison period before and after impact week. *e)* Coverage diagram for preceding plot. *f)* Values of occurrence probability during the month preceding impact week for 90° x 90° squares on the Io phase vs. CML plane.

Figure 2. Plots of flux density vs. time *a)* for the RH circularly polarized component of burst A at each of several frequencies, *b)* for the LH polarized component of burst A at the same frequencies, *c)* for the RH polarized component of burst B, and *d)* for the LH polarized component of burst B. Frequencies in MHz are indicated. In each panel the flux density scale applies to the lowest-frequency plot, each of the higher frequency plots having been successively offset on this scale. No measurement was made of the LH polarized flux density at 32 MHz (hence its omission from panel *d*). Bursts A and B were observed only from UFRO. A typical error bar of 1σ height for the curves in *a)* and *b)*, determined from the pre-burst background, is shown in the lower right-hand corner of *b)*. Error bars for *c)* and *d)* are about one-third as high.