A SEARCH FOR DECAMETRIC WAVELENGTH RADIO EMISSION FROM THE COLLISION OF COMET S-L 9 WITH JUPITER

F. Reyes*, T. D. Carr*, C. A. Higgins*,
J. A. Phillips†, L. Wang‡, W. C. Erickson§, K. Maeda¶,
N. Prestage‖, W. B. Greenman*, J. May**, J. Aparici**,
F. Olmos**, H. Alvarez**, L. Garcia*, C. Phillips§,
A. Vrana§, N. Tokimasa††, and T. Kuroda††

Abstract

We report results of an ongoing investigation of low frequency radio observations of the planet Jupiter made before, during, and after the collision of comet S-L 9. The observation were made in order to determine if the entry, passage, and collision of the comet may have generated low frequency radio emission or altered the normal Jovian decametric emission. We have investigated the variations in the occurrence probability of the normal decametric emission from several months before to several weeks after the collision. Our conclusion is that there were no detectable effects of the comet on the normal decametric emission. Using data from six different sites we are searching for possible bursts of emission associated with the collision of 19 fragments. No clear evidence of association of bursts with the collision of the fragments has been found so far. We are investigating the possible origin of a few bursts received almost simultaneously at two or more stations. An investigation of two short bursts of emission, received near the collision of fragments Q2 and Q1, reveals that there is a good possibility that the bursts could be associated with the fragments.

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*Dept. of Astronomy, P.O. Box 112055, University of Florida, Gainesville, FL 32611-2055, USA
†Antares Virtual Reality Systems, 233 Arcturis Circle, Bishop, CA 93514, USA
‡Applied Research Corporation, Landover, Maryland 20785, USA
§Dept. of Physics, University of Tasmania, GPO Box 252-21, Hobart 7001, Tasmania, AUSTRALIA
¶Dept. of Physics, Hyogo College of Medicine, Nishinomiya, Hyogo 663, JAPAN
‖IPS Radio and Space Serv., Culgoora Solar Obs., P.O. Box 611, Narrabri, NSW 2390, AUSTRALIA
**Dept. of Astronomy, University of Chile, Casilla 36-D, Santiago, CHILE
††Nishi-Harima Astronomical Observatory, Sayo-cho, Hyogo 679-53, JAPAN

1 Introduction

The remarkable phenomenon of the collision of the fragments of the comet S-L 9 with Jupiter unprecedented in modern times, provided a rare opportunity to observe the possible conversion of kinetic energy into radio waves as the cometary fragments entered a planetary magnetosphere. Calculations made before the collision predicted possible low frequency radio emission resulting from the interaction of the fragments and dust of the comet with the Jovian magnetosphere and the subsequent explosive disintegration in the atmosphere [Bolin and Brenning, 1994; Farrell et al., 1994; Ip and Prange, 1994; Kellogg, 1994]. Different types of mechanisms were proposed which would produce emission at different distances from the planet. The pre-collision estimates of the intensity of the emission depended strongly on the size of the fragments, and also to some degree on the amount of dust and the possible gas released. Since these parameters were poorly known, the uncertainties in the predicted intensity, frequency range, occurrence time, and time duration of the possible emission were large.

As a result of the enormous interest triggered by this event, several groups mounted a campaign to make coordinated observations of this unusual phenomenon at low radio frequencies. The goal was to provide an almost continuous coverage from different locations both in longitude and latitude. Preliminary reports available during the week of the collision, and in the few days after, indicated the detection of low frequency radio emission. Most of the emission was identified either as normal Jovian decametric emission or low frequency solar radio bursts. A few unusual bursts were received but the consensus was that further analysis was necessary in order to establish a possible connection with the collision of the fragments. Most of the ground based observations, in particular those made in the northern hemisphere, were plagued by terrestrial interference, mainly radio stations and impulsive radio noise from terrestrial lightning. Terrestrial interference seems to have been a source of confusion among some observers, who we believe to have incorrectly reported the association of these bursts with the collisions of several fragments.

Analysis performed in the last two years have resulted in the publication of several papers by Carr et al. [1994, 1995], Desch et al. [1995], Maeda et al. [1996], and Kellogg et al. [1997]. These reports concluded that with two possible exceptions, there was no detectable radio emission that could be directly associated with the entry of the comet's fragments or the collision. Particularly important was the report by Desch et al. [1995] based on data taken by the Ulysses spacecraft which was free from terrestrial interference. The exceptions were two bursts detected near the collision of the Q fragments and reported by Carr et al. [1994, 1995]. These two bursts will be discussed in section 5. Nevertheless, a few papers have been published claiming detection of very strong and unusual emission associated with the collision of the comet [Han et al., 1994; Zhang and Wang, 1994; Han et al., 1995; Oya, 1995].

In order to settle the question raised by the apparent contradictory reports between several groups of observers, we have made a combined effort of analyzing several data sets containing some the most reliable data gathered during the week of the collision. The data included in this analysis contains data collected at six different sites located in the USA, Chile, Australia, Japan, and Tasmania. Our search for possible low frequency emission related to the collision of the comet has concentrated in the following aspects:

a) Statistical analysis of the occurrence probability (OP) of the normal Jovian decametric radio emission (DAM) in search of possible effects of the passage and collision of the fragments.

b) Use of an extended data set in search of possible bursts of decametric radio emission that can be attributed to the collision of the fragments.

c) Investigation of the circumstances under which two bursts received near the collision of the fragments Q2 and Q1 could have been emitted.

2 The Observations and the Data Sets

The data sets used in this analysis were chosen on the basis of the frequency coverage, the length of the period covered by the observations, the latitude and longitude location of the observatories, and the experience of the observers in detecting and identifying low frequency radio emission from Jovian or solar origin. For the analysis of the OP, we used data collected at the University of Florida Radio Observatory (UFRO), the University of Chile Maipu Radio Observatory (MROA), and the Owens Valley Radio Observatory (OVRO). The data included in the search for bursts associated with the collision of the fragments were collected at the UFRO (USA), MRAO (Chile), OVRO (USA), Culgoora Solar Observatory (Australia), Nishi-Harima Astronomical Observatory (Japan), and Bruny Island Radio Observatory (Tasmania). Table 1 summarizes the frequency coverage at each observatory.

Table 1: Summary of frequency coverage during the period of observation of the collision of comet S-L 9 at the six radio observatories.

Radio observatory	Frequencies (MHz)
UFRO-MRAO-OVRO	16, 18, 20, 22.2, 24, 26.3, 27, 28.4, 32 26.3 MHz large array 18 – 36 MHz spectrograph
Bruny Island	5 – 36 MHz spectrograph
Nishi-Harima	18 – 36 MHz spectrograph 22 MHz interferometer 23.3, 24.4, 25.0, 25.3, 25.5 MHz radiometers
Culgoora	18 – 57 MHz spectrograph

Fragments A, B, C, D, E, F, G, H, J, K, L, N, Q2, Q1, R, S, T, U, and W were observed by at least one station. A total of 19 fragments were observed by the combined observations of the six stations.

3 Analysis of the occurrence probability (OP) in search for the possible influence of the collision in the DAM

Previous to the collision, there were no predictions regarding possible effects of the comet on the DAM. There was a possibility that the injection of dust and gas into the inner magnetosphere could have altered the mechanism responsible for the production of the DAM. A possible effect could be detected as either an increase or a decrease in the OP of the DAM. The behavior of the OP has been studied since the discovery of the DAM almost 40 years ago and is well known. The OP for the different sources of emission display natural variations having long and short term periodic and random components. The UFRO observed the DAM from January 5 to July 29 of 1994 as part of the regular program of study of the emission.

The results of the analysis of the OP for the period June 22 to September 8 were reported by Carr et al. [1995]. The analysis included data collected at UFRO, MRAO, and OVRO. No apparent effect was found with the exception of a marginally significant decrease in the OP for the Io-A source during the week of the collision.

For the study reported here we have expanded and modified this previous analysis by adding data collected at UFRO during the period January 5 to June 20, 1994. The addition provides a longer base line for the study of the OP. We have also modified the analysis by computing the OP for each individual source, instead of dividing the CML/Io Phase plane in 90 × 90 degrees squares [Carr el al., 1995]. For the source boundaries we have used the CML and Io phase values recently determined by Garcia [1996]. Computing the OP for each source avoids mixing activity coming from different sources which may behave differently before and after opposition [Barrow, 1981]. Table 2 summarizes the frequencies used at each station and the observing periods. The occurrence probability was computed, as usual, as the ratio of the activity time to the listening time. A value of OP was computed for each separated source (Io and non-Io related) at each separated frequency and also for the region outside of the sources. Our analysis covers the whole CML-Io phase plane and should detect any increase or decrease in the Jovian decametric activity. In order to increase the significance of the statistics, the 18, 20, and 22 MHz data were combined.

Table 2: Summary of frequency channels and observing periods used to compute the OP

Station	Frequencies (MHz)	Period (1994)
UFRO	18, 20, 22	Jan. 5 – July 29
MRAO	16, 18, 22	June 20 – July 29
OVRO	18, 20 – 30	June 22 – Sept. 8

The data for the period January 5 to June 22 was arbitrarily grouped in periods of one month. During the period June 22 to July 29, all the three stations, UFRO, MRAO and OVRO contributed with their data. During the period August 1 to September 8 only OVRO continued with the observations. We have used the combined data to calculate

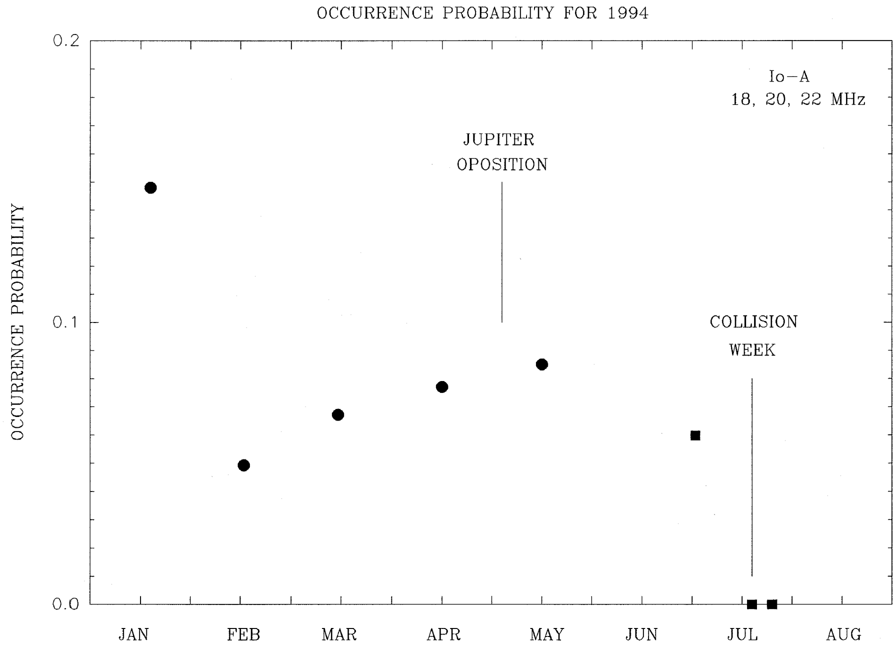

Figure 1: Occurrence probability (OP) for the Io-A source during the period January-July, 1994. The OP shows a smooth variation throughout the period, except for the month of January. The values began decreasing after opposition and dropped to zero for the week of the collision and the week after.

the OP for the periods June 22 to July 15 (three weeks previous to the collision), July 16 to 22 (week of the collision), July 23 to 29 (week after the collision), and August 1 to September 8.

Figure 1 shows an example of the variations in the occurrence probabilities for the Io-A source during the period January 5 to July 29. The OP shows a steady increase from February until May, where the value reached a maximum; during June and July there was a steady decrease. The values of the OP for the Io-B and Io-C sources show a steady decline from February to July, although the scatter of the values is much larger than those for the Io-A source. The OP for the Non-Io-A source was almost an order of magnitude smaller than for the Io-related sources. For the Non-Io-B, Non-Io-C, as well as for the region outside of the sources, the occurrence probabilities were about two orders of magnitude smaller. The values of OP for the region outside the sources show a small increase during June and July, with respect to previous months. However the values remained more than one order of magnitude smaller with respect to the Io-related sources. The increase cannot be considered significant due to the large scatter of the data throughout the period. The decline of the values of the OP for the Io related sources occur in a period that begins several months before the collision showing that the decline is not related to the collision of the comet. We attribute this behavior mainly to an opposition effect and to a lesser extent to an observational effect. The opposition effect manifest as a maximum of the values of the OP near or slightly after opposition and a decrease before and after that [Garcia, 1996]. For 1994, Jupiter's opposition occurred on May 3, the time when the Io-A source OP begins declining. The observational effect consists in a reduction of the chances of detecting the emission towards the end of the observing period. At the beginning of the season the observations took place in the early morning hours when the observing conditions were the best. In the last months (June-July) the observations took place in the evening when the interference was larger, thus reducing the chances of detecting the emission. The small values of the OP of the Non-Io related sources can be attributed to the large negative value of D_e (-2.94 degrees), an effect most recently reported by Garcia [1996].

It can thus be established more clearly now that the marginally significant decrease in the OP of the Io-A source during the week of the collision found by Carr et al. [1995] is not related to the comet. This decrease can be interpreted as a combination of an opposition and an observational effect. We have clearly demonstrated that there was a decrease in the OP of the Io-related sources which began well before the collision. The OP in the regions of the CML/Io phase outside of the Io related sources was extremely low during the whole period extending from January to September, including the week of the impacts. Our results do not support the claim made by Oya [1995] of an enhancement of the Jovian decametric activity associated with certain values of CML.

4 The search for possible emission associated with the collision of the fragments

A search made shortly after the week of the collision by each independent group in the data collected at UFRO, MRAO, OVRO, Culgoora, Nishi-Harima, and Bruny Island revealed no clear association of bursts with the collision of the fragments. A short report was sent to the Univ. of Maryland bulletin board right after the week of the collision. The exception were two bursts detected at UFRO which will be discussed in section 5. The results of the UFRO-MRAO-OVRO group were reported by Carr et al. [1994, 1995] and those of the Nishi-Harima Observatory by Maeda [1996]. Due to persistent reports associating emission with the collision of the comet, we have used the combined data collected at all six stations in search for bursts that could have been missed in the independent search. The search has focused on bursts that could have been received simultaneously with some of those reported as associated with the collision, and on bursts received simultaneously at two or more stations.

Two different types of emission associated with the collision have been reported. One type consists of a large enhancement of the intensity and number of bursts reported as having Jovian origin [Oya, 1995]. As we discussed in the analysis of the OP made in section 3, we do not find evidence to support this claim. The other type consists of the detection of isolated, mostly narrow band, strong bursts near the collision time of several fragments [Han et al., 1994; Zhang et al., 1994; Han et al., 1995].

We have searched the data from three of our stations (Culgoora, Nishi-Harima, and Bruny Island) which overlap with some of those strong, narrow band bursts reported by Han et al. [1994, 1995] and Zhang et al. [1994]. Although our search has not been completed yet, we do not find the counterpart of those bursts. As an example we refer here to an extremely intense burst (45 dB) detected at 26.0 MHz between 07:20–07:23 UT by Han et al. [1994]. We have examined the dynamic spectra obtained near the collision time of fragment G. We do not find evidence of this narrow band burst. Some short, wide band, much less intense bursts were received a few minutes later. They were originally identified as interference in the independent search. We are investigating the possible origin of this emission. These bursts are not unique; similar bursts were received at other times and they appear to be interference. The simultaneous reception of bursts at two or more stations is not of course, proof of their Jovian origin.

A few comments are in order regarding the reports of these very intense, narrow band bursts. Most of the bursts reported as associated with the fragments were detected between 26 to 28 MHz. This frequency range contains the highly congested CB band and two radio amateur bands which are well known sources of man-made interference. Another aspect is that some bursts were detected between one to one and a half hours before or after the collision. It is difficult to establish a causal relationship between these bursts and the fragments. Evidently, a more elaborate analysis will be necessary in order to establish such relationship.

It is a rather well known effect among the observers of the Jovian decametric emission that the emission can be detected at one station and missed (or partially missed) at another located a few thousand kilometers away. This happens even if both stations are observing at several common frequencies. This effect is believed to be caused by multipath refraction and scattering by inhomogeneities in the terrestrial ionosphere, and perhaps in the interplanetary medium. During the period June-July, 1994 we found several examples of such events in the data collected by the UFRO-MRAO-OVRO group. The station that detected most of the emission was located in the southern hemisphere and those that missed the emission, were in the northern hemisphere. The bursts reported as related to the collision, seem to have been completely missed at our three stations (two located in the southern and one in the northern hemisphere). The reports list around 30 bursts associated with a total of 8 fragments, a few of them with intensities that are at the limit, or well above the strongest bursts, of normal Jovian decametric emission ever detected [Han et al., 1994; 1995]. It is rather surprising that such large number of intense bursts received over a period of several days could have been completely missed by our stations.

5 Investigation of the circumstances under which two bursts received near the collision time of fragments Q1 and Q2 could have been emitted

Two short bursts were received at the UFRO on July 20, 1994, near the collision time of fragments Q2 and Q1 [Carr et al., 1995]. These two bursts were received within 1.5 and 1 standard deviations of the accepted impact times of fragments Q2 and Q1, respectively. The fact that they were received so close to the impact times of the Q fragments provides our strongest evidence that they were related to the fragments. As we explain later, additional evidence supporting the possibility that these bursts are of Jovian origin is that they cannot be identified as interference, solar bursts, or normal Jovian decametric emission. We have denominated these two bursts as burst A and B, respectively. Burst A was LH elliptically polarized and burst B RH elliptically polarized. Table 3 summarizes

Table 3: Characteristics of bursts A and B detected on July 20, 1994, near the collision time of fragments Q2 and Q1. S is the flux density. AR is the polarization axial ratio, (minor axis length)/(major axis length). It is assumed that there is no unpolarized component.

Burst	Arrival Time (UT)	Freq. (MHz)	S (kJy)	Duration	Polarization Sense	AR
A	19:50:10	18	850	54s	LH	+0.23
		20	620		LH	+0.21
		22	920		LH	+0.22
		24	840		LH	+0.26
		26	480		LH	+0.22
B	20:13:20	28	480	1m 15s	RH	−0.24
		32	700		(RH)[a]	

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[a] Only the RH polarization was being observed

the main characteristics of these two bursts.

These two bursts were detected with the low gain, log conical spiral (TP) array which has a broad beam and therefore cannot be used as a direction finder. The planet was out of range of the 26.3 MHz large array at the time of the impacts. The higher directivity of the large array would have provided a better way of determining the direction of arrival of the bursts. We first examine the possible origin of the bursts.

No other bursts similar to these two were found in the TP array data obtained during the week of the collisions. All the deflections can be identified as terrestrial lightning, radio stations, or normal Jovian radio emission. Terrestrial lightning pulses are much shorter, lasting about 1 second or less. The broadband characteristic of the two bursts, rules out the possibility of radio station interference. The bursts are clearly not part of the normal DAM as they do not display the characteristic scintillation present in the Jovian L bursts.

We compared the reception time of these two bursts with the time of reception of solar bursts detected by the Ulysses spacecraft [Desch et al., 1995]. During the week of the impacts, about 25 solar bursts were detected; no solar bursts were detected within 12 hours of the impact of the Q fragments. Apparently no ground based solar radio observatory was observing near the impact time of these fragments. The sun was well above the horizon at UFRO when these two bursts were received. We have computed the attenuation of the TP array in the direction of the sun. For the Q2 and Q1 impact times the attenuations were 18 and 14 dB respectively. The inferred flux density of the bursts, assuming they were from solar origin would be 2×10^{-19} and 0.75×10^{-19} W m^{-2} Hz^{-1}, respectively. These flux densities are very large and would have been easily detected by Ulysses.

These two bursts could not be found in the records of the MRAO. Recently, Kellogg [1997] published the results of the observations made by the Univ. of Minnesota station in South Africa. They find no evidence of these two bursts; the flux density of the bursts

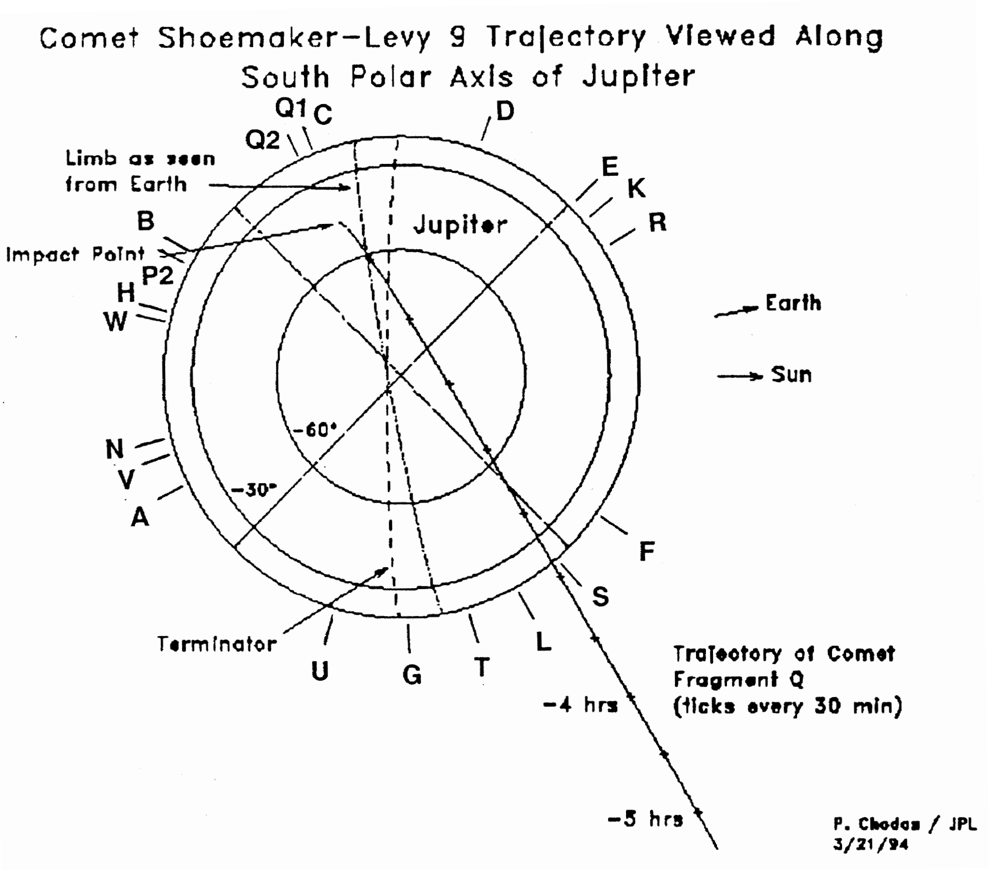

Figure 2: A view of the southern Jovian hemisphere, showing the trajectory of the comet and the direction of Io at the time of the impacts of the fragments. The letters mark the direction of Io at the time of the impact of the fragments designated by the letters. [Adapted from a figure distributed through the Internet by P. Chodas, JPL (reproduced with permission).]

were apparently well above the deduced detection threshold of their equipment. The question that arises is why they were not detected by the other stations? As we explained in section 4, it is not uncommon for two stations observing Jupiter radio emission, and separated a few thousand kilometers, to display a lack of correlation of the detected emission. Two short bursts lasting about 1 minute and separated by 20 minutes can easily be missed.

In summary, the two bursts cannot be identified as interference or as solar bursts. The fact that they were received within one standard deviation of the impact time, makes them very good candidates for being associated with the comet fragments. In what follows, we investigate if there was anything unusual in the orientation of the planet, the magnetic field, or the position of the satellite Io, with respect to the position of the fragments. Figure 2 shows the longitude of the satellite Io at the time of the impact of the major fragments. The letters mark the direction of Io at the time of the impact of the fragments designated with the corresponding letter. Figure 2 shows that near the collision time of the fragments Q2, Q1, and C, Io was located at about the same longitude of the impact site. No bursts were received at Nishi Harima radio observatory, the only station observing near the impact time of fragment C.

We have explored several possibilities in order to try to understand how these bursts may have been triggered. The possibility that the emission came from the region right above the impact site (or the conjugate points) can be quickly ruled out: the magnetic field is too weak for the emission to have reached the range of $18 - 32$ MHz. Another possibility is that the impact site of the fragments may have occurred close enough to the foot of an active Io flux tube. The O6 model for the magnetic field was used in order to locate the southern foot of the instantaneous Io flux tube (IIFT). The foot was located at about 15 degrees south in longitude of the impact time. This corresponds to a distance of about 18,000 km. Burst A was received 6 minutes after the impact time of Q2. Any material ejected from the impact site and interacting with the foot of the IIFT would need to travel at around 49 km/sec. This is a very large speed. This possibility can be ruled out for burst B since it was received 32 seconds before the collision of fragment Q1.

We explored the possibility that the trajectory of the fragments may have intersected an Io flux tube and that, in some way this may have triggered the emission. Using the O6 model for the magnetic field we traced the magnetic field lines south from the location of Io (and several degrees downstream from Io) looking for solutions that could intersect the trajectory. Our result shows that for the three fragments, Q2, Q1, and C there was a flux tube located a few degrees downstream from Io that was intersected by the trajectory of the respective fragments. Figure 3 shows an example of a plot of the trajectory and the flux tubes as function of longitude, latitude, and distance for the Q2 fragment. Table 4 shows some of the important parameters for the corresponding foot of the intersected IFT for the Q2 and Q1 fragments.

It can be seen that for fragment Q2, the magnetic field strength at the southern foot of the intersected IFT is strong enough to support emission at about 26 MHz. The maximum frequency at which burst A was received was 26.3 MHz. The angle Earth-Jupiter-Southern foot was 88 degrees therefore the foot was visible at the time burst A was received. The elliptical LH polarization of the burst is consistent with the emission being in the X-mode from the southern hemisphere. We don't find a consistent explanation for burst B. The southern foot of the intersected IFT was visible at the time at which the burst was received but the RH polarization is inconsistent with being emitted from the southern

Table 4: Parameters of the feet of the intersected IFT. The angle E-J-F is the angle Earth-Jupiter-Foot when the bursts were received. IIFT+10(s) is the southern foot of a flux tube located 10 degrees downstream from the instantaneous Io flux tube. f_c is the cyclotron frequency at the foot of the intersected IFT.

Fragment	IFT	Long. (deg.)	Lat. (deg.)	f_c (MHz)	Angle (E-J-F)
Q2	IIFT+10 (s)	40	−63	26	88
Q1	IIFT+5 (s)	59	−61	26	90
	IIFT+5 (n)	95	+75	27.5	103

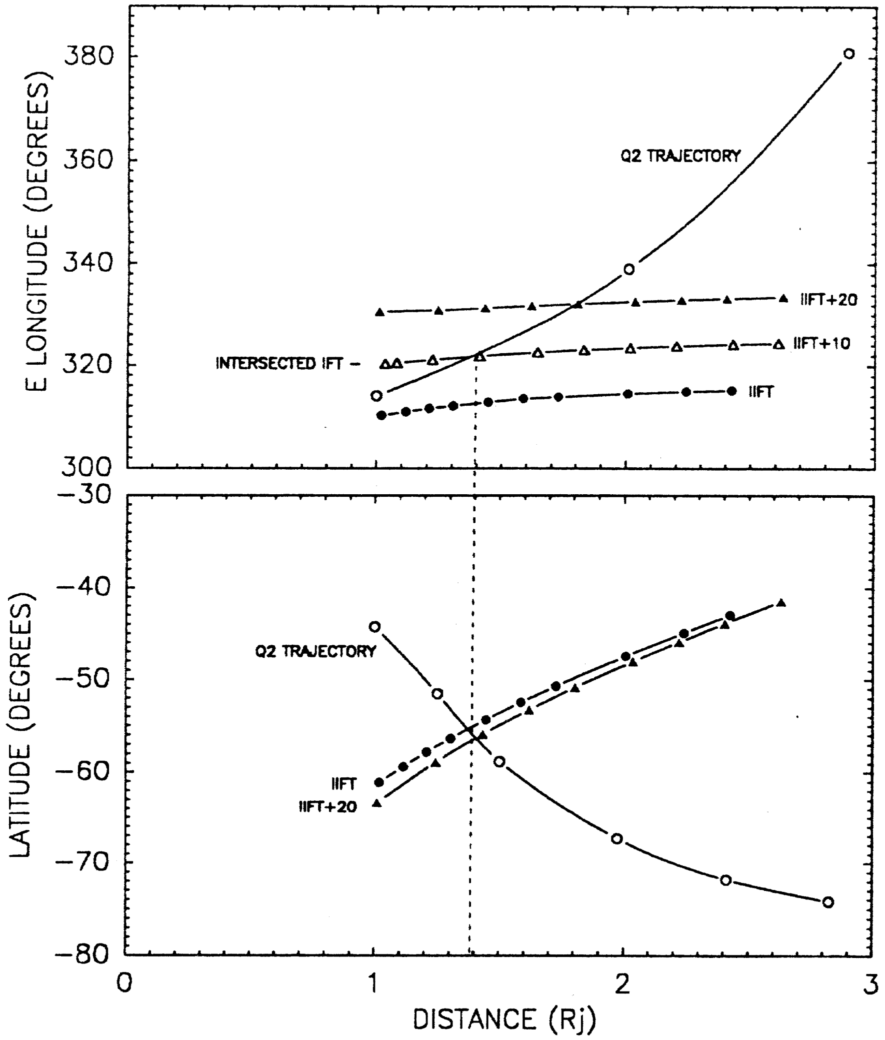

Figure 3: Plots of longitude and latitude as function of distance for fragment Q2, the instantaneous Io flux tube (IIFT), the IIFT+10 degrees, and the IIFT+20 degrees downstream from Io. The IIFT+10 degrees was intersected by the fragment at an approximate distance of 1.38 Jovian radii.

hemisphere. The polarization would suggest an origin in the northern hemisphere, except that the northern foot was about 13 degrees beyond the limb and was not visible from the Earth.

6 Conclusions

The analysis of the occurrence probability of the normal decametric emission for the period January 5 to September 8 shows that there was no effect that can be attributed to the collision of the comet. The occurrence probability for the Io-related sources show a steady decrease throughout the period. That for the non Io-related sources, as well as for the region outside of the sources, remained very low during the whole observing period.

An analysis of the circumstances under which two bursts received near the collision times of fragments Q2 and Q1 shows that they were probably associated with the collisions of these two fragments. Both fragments intersected an Io flux tube located a few degrees downstream from Io. The emission of burst A (Q2) is consistent with emission originating in the southern foot of the intersected IFT. No consistent explanation can be found yet for burst B (Q1). A search of the data from all six observing sites has not revealed evidence of any other fragment-associated bursts, although a few possible cases are still under investigation.

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