JUPITER'S SYNCHROTRON RADIATION: OBSERVED VARIATIONS BEFORE, DURING AND AFTER THE IMPACTS OF COMET SL-9

M. J. Klein*, S. Gulkis*, and S. J. Bolton*

Abstract

Results of an observing program to monitor the synchrotron radio emission from Jupiter's inner radiation belts after the impact of Comet SL-9 are reported. The observations were made at 2295 MHz as part of the NASA-JPL Jupiter Patrol, a long term radio astronomy monitoring program begun in 1971. Data from the monitoring program illustrates the long-term variability of the synchrotron radiation with timescales of months to years. Jupiter Patrol observations taken during the period surrounding the Comet SL-9 impacts [Klein et al., 1995] indicate that the intensity of the synchrotron emission at 13 cm wavelength increased by 27 percent within a few days after the comet impacts and the magnetic latitude beaming curves flattened after the week of the impacts. In this paper we report new observations made in 1995-96 showing that the microwave brightening following the comet impacts has decayed with an e-folding time of approximately 170 days and that a new outburst, presumably unrelated to the SL-9 impacts, may have occurred in August 1995.

1 INTRODUCTION

Responding to predictions that periodic comet Shoemaker-Levy-9 (SL-9) would impact Jupiter in July of 1994, radio astronomers worldwide carried out an observing campaign to monitor the synchrotron emission from the Jovian radiation belts. Substantial and rapid increases in the planet's synchrotron emission were reported by several research teams during the week of July 16-23 at numerous wavelengths spanning the decimetric spectrum (see de Pater et al., [1995] and references therein).

The NASA-JPL Jupiter Patrol, a long term radio astronomy monitoring program begun in 1971 [Klein et al., 1972], participated in the campaign to monitor the effects of the SL-9 impacts. The Jupiter Patrol observations are made at 2295 MHz (13 cm wavelength) using the large filled-aperture antennas of NASA's Deep Space Network (DSN). The observations were typically made several times a month in the first decade and several

* *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA*

times a year in the second decade. The observations since 1991 have been made with the 70-m and 34-m diameter antennas. In preparation for the impact event, the DSN observing program was intensified in January 1994 and procedural changes were made to improve the precision of the data.

Jupiter's radio emission near 13-cm wavelength is dominated by synchrotron radiation from electrons with relativistic energies spiraling around magnetic field lines in the planet's magnetosphere. The intensity of the observed emission depends on the orientation and strength of the magnetic field as well as the number, pitch angle and energy distribution of the relativistic electrons. Models of the synchrotron emission require multiple populations of electrons with pitch angles that range from approximately 90 degrees, to account for the emission peaks that are observed when the magnetic equatorial plane crosses the line of sight, to electrons with steeper pitch-angle distributions, to account for emission at higher magnetic latitudes (see reviews by Berge and Gulkis, [1976]; Carr et al., [1983]; and de Pater, [1990]).

The synchrotron emission is confined to the inner magnetosphere where radio interferometer maps show that the maximum flux occurs near 1.5 Jovian radii (R_J) from the planet and very little emission is observed beyond $3\,R_J$. Single-dish radio telescopes, like those used for the Jupiter Patrol, measure the integrated intensity of the synchrotron emission because the solid angle of the antenna beam is typically much larger than the angular dimensions of the emitting region. The single-dish intensity data are traditionally represented by the average of the two peaks in the intensity beaming curve that is observed during one Jupiter rotation.

2 THE OBSERVATIONS

2.1 Flux Density Measurements

To establish a set of baseline measurements before the predicted impact date of Comet SL-9, observations began in December 1993 and continued throughout the spring of 1994 using the 70-meter diameter antenna at NASA's Goldstone Deep Space Communication Complex. Beginning in June of 1994 a 34-meter antenna located at the Research and Development site at Goldstone became the primary observing site because it is more available than the 70-m antenna for radio astronomy research. Intensive observations were made from July 17 through August and a follow-up program to monitor the intensity of the synchrotron emission at approximately two week intervals began in September 1994. The initial effects of the SL-9 impacts have been reported [Klein et al., 1995; de Pater et al., 1995].

The new observations reported here extend the measurements from January 1995 through August 1996. The 34-m antenna remains the primary site with occasional observations using the 70-m antenna. The receiving systems were operated as total power radiometers using a method [Stelzried and Klein, 1994] that intersperses system calibrations with traditional OFF-ON-OFF measurements of Jupiter and calibration radio sources. Details of these procedures are described in Klein et al. [1995]. The intensity measurements are calibrated relative to the flux density scale established by Baars et al. [1977] and updated by Ott et al. [1994]. The radio sources Virgo A, 3C286 and 3C295 are the primary calibrators. The respective flux densities at 2295 MHz are 138.64 jy, 11.50 jy, and 14.31 jy.

The intensity of Jupiter at centimeter wavelengths is comprised of thermal emission from the atmosphere and synchrotron emission from energetic electrons in the planet's magnetic field. The atmosphere radiates with an equivalent temperature of 305 K at 13 cm wavelength [de Pater and Massie, 1985] and the corresponding flux density* at 4.04 au is 2.02 jy.

Jupiter's flux density was measured about six times per hour throughout each observing session from pairs of OFF-ON-OFF samples taken in the azimuth and elevation coordinates. Each flux measurement was multiplied by a normalization factor, $f_d = (d/4.04)^2$ where d is the distance of Jupiter from Earth in astronomical units (au). Next the thermal component (2.02 jy at 4.04 au) was subtracted and the residual non-thermal component was multiplied by a polarization adjustment factor f_p to account for the slight difference between total flux and the measured fluxes, which were made with circular polarized feeds (RCP 34-m; LCP 70-m). The circular polarization of Jupiter's synchrotron emission varies with System III longitude and magnetic latitude but is never large ($0.988 < f_p < 1.012$).

2.2 The Synchrotron Beaming Curves

The synchrotron component is known to vary as the geometry of the radiation belts changes with Jupiter's rotation. When the intensity of the synchrotron emission is plotted against System III longitude, the familiar double-peaked beaming curve is produced.

An example of the beaming curve early in 1994 before the cometary encounter is shown in Figure 1. The data represent a composite set of measurements taken on four nights to acquire coverage of all System III longitudes. The dashed curve is a Fourier series representation with amplitudes and phases derived from a least-squares fitting process. The phases and amplitudes have been found to be stable over the 25-year history of the Jupiter Patrol with values that vary predictably with the parameter D_e, the Jovicentric declination of the Earth [de Pater and Klein, 1989; Klein et al., 1996].

A recent analysis by Hood [1993] suggests that the observed long-term variations may be influenced by viewing geometry (e.g., D_e) as well as intrinsic changes in Jupiter's synchrotron emission. Fortunately the viewing geometry changed very little ($-3.4 < D_e < -3.0$) throughout 1994 when most of the SL-9 activity occurred. The effects of viewing geometry on SL-9 results are at least partially removed by the baseline observations made in 1995-96 and described below.

Beginning in 1994 the Jupiter Patrol observations were scheduled on two or more adjacent dates so data could be combined to produce composite beaming curves that uniformly sampled the ten-hour magnetospheric rotation period. Estimates of the two peak flux values were then derived by fitting the measured fluxes to a "template" Fourier series

*1 jy = 1 jansky = 10^{-26} W m^{-2} Hz^{-1}

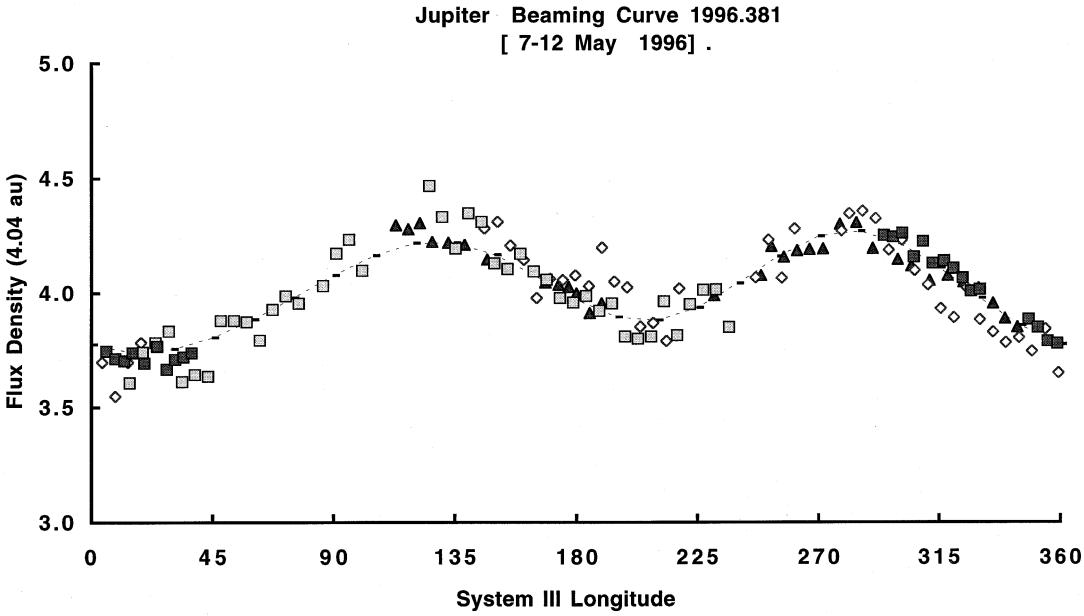

Figure 1: A composite beaming curve of Jupiter's synchrotron emission at 2295 MHz from four nights of observations at Goldstone in May 1996.

beaming curve calculated for the appropriate value of D_e. The precision of the resulting peak flux values is improved because measurements from all System III longitudes are used and not only those few measurements that are made near the longitudes of the two peaks. This method has become the standard procedure, although additional analytical procedures were used from July 16 to August 15, 1994 when the Jovian synchrotron emission was dramatically changing during and immediately after the SL-9 impacts.

3 VARIATIONS IN JUPITER'S SYNCHROTRON FLUX DENSITY

3.1 The Aftermath of the Shoemaker Levy 9 Impacts

The Goldstone observations from the 70-m and the 34-m radio telescopes are shown in Figure 2. The data points represent the average intensities of the two peaks in the composite beaming curves derived from successive observing sessions typically spaced from one to a few days apart. Each observing session consisted of 20 to 40 individual measurements that typically spanned four to six hours of the 10 hour period of the beaming curve. (Note that Jupiter's declination was too far south to provide northern observers with view periods much greater than six hours with the planet $>$ 2 degrees above the horizon.) The relative error on each data point is approximately $\pm$1.5 percent, with the exception of some of the 1996 data described below.

The sudden increase in Jupiter's flux density during the week of the Comet SL-9 impacts is evident in Figure 2. The synchrotron flux at 13-cm increased 27 percent during the week of the impacts in July 1994 and was followed by a monotonic decline that began in

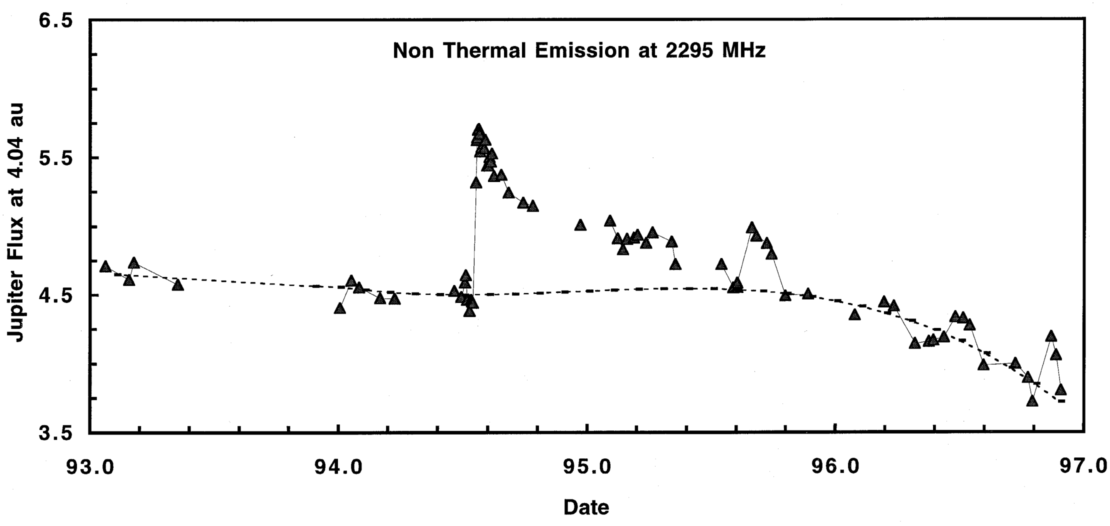

Figure 2: The intensity of Jupiter's synchrotron emission observed at 2295 MHz and normalized to a distance of 4.04 au.

August and continued through the summer of 1995. The dotted curve in the Figure is an estimate of the baseline made by fitting a second order polynomial to the data taken before July 15, 1994 and after September 30, 1995.

3.2 The Exponential Decline of the SL-9 Enhancement

It is clear from the history of long-term variations that Jupiter's synchrotron emission would have changed significantly from 1994 to 1996 had the SL-9 impacts never occurred. One of the objectives of the observations reported here was to estimate Jupiter's "baseline" emission. During the analysis of the 1996 data we discovered that some of the Jupiter measurements were adversely affected as the planet's orbital motion carried it near the center of the Milky Way Galaxy. Jupiter crossed the galactic equator on January 4, 1996 and the planet remained within 16 degrees absolute galactic latitude for most of the year.

Continuum radio emission from the galactic plane at 13-cm wavelength is non-uniform, diffuse and comparable to the antenna temperature of the planet. The DSN data were scrutinized and the most severely affected were deleted. Observations when Jupiter's absolute galactic latitude, $|b_J|$, was greater than 10 degrees were unaffected and most observations when $|b_J|$ was between 5 and 10 degrees were usable after compensating for non-uniform background emission in the off-source sky positions. A two percent error was added to the error budget for these particular data to account for the uncertainty of the adjustment factors, which were typically less than five percent.

The decline in synchrotron emission following SL-9 can be seen in Figure 3 where the DSN data are plotted after subtracting the polynomial baseline. Data taken when Jupiter's absolute galactic latitude was less than 12 degrees are represented by the open circles, which are more likely to be affected by residual systematic errors than the data (filled triangles) taken farther from the galactic plane. The best exponential fit with an e-folding

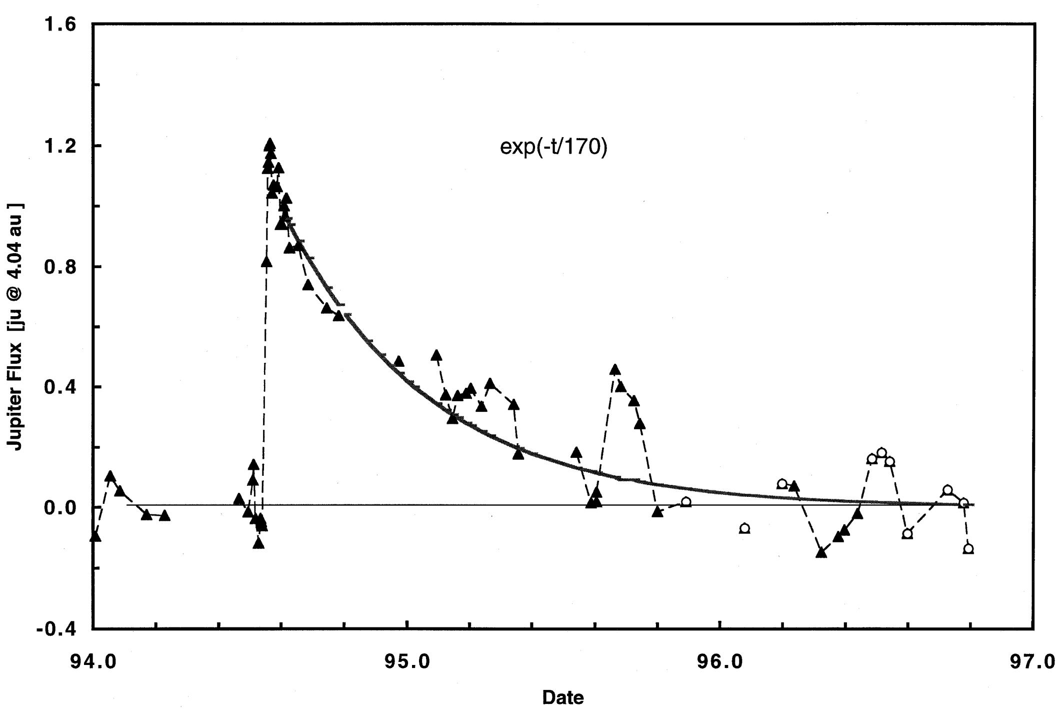

Figure 3: The rapid increase and slow exponential decay of Jupiter's synchrotron emission at 2295 MHz following the impacts of Comet Shoemaker-Levy 9 in July 1994. The baseline shown in Figure 2 has been subtracted. Open-circle data were adjusted, as described in the text, for the influence of Jupiter's proximity to the Galactic plane.

time of 70 days is plotted in the Figure. The average scatter in the data about the exponential curve is 0.112 jy. The greater-than-average scatter in the 1996 data can be explained by Jupiter's proximity to the galactic plane, but the four measurements near 1995.7 that lie approximately 0.35 jy above the exponential may have a different explanation.

3.3 Evidence for a short-term outburst?

The observations made in late summer 1995 were examined for possible sources of error to explain the higher-than-average fluxes that were recorded between August 30 and September 30. Follow-up observations made after Jupiter had moved several degrees to the east showed no evidence that one or more background radio sources could have produced spurious results. The system calibration data were examined and found to be consistent and nominal.

The observed increase in 1995 may be evidence for a short-term outburst in Jupiter's synchrotron emission. If this explanation can be verified, then the DSN data indicate that: (a) the increase occurred between August 11 and August 30; (b) and the magnitude at 13 cm wavelength was approximately 0.35 jansky (normalized to 4.04 au), which would have been ~ 8 percent of the Jupiter's synchrotron flux at the time; (c) the risetime was less than 20 days; and (d) the decay time could have been as short as two months.

However, this decay time might be a minimum estimate because the baseline in late 1995 may be distorted by the galactic plane emission that was discussed above.

4 DISCUSSION AND CONCLUSION

The sudden rise and slow decline in synchrotron emission seen in the NASA-JPL Jupiter Patrol observations from 1994 through 1996 has also been reported by other microwave observing programs at several wavelengths, but the cause of the increase has not been identified [de Pater et al., 1995]. A rapid injection of energetic particles into the trapped radiation belts is a plausible explanation, however it is not understood how the energetic electrons could be produced or accelerated in times as short as a few days. Radial diffusion times appear to be much too long to account for the rapid rise in emission. Shock related acceleration processes (e.g., Ip, [1994]; Brecht et al., [1995a,b]) may be required if indeed the increased emission is caused by the injection of energetic particles.

Other mechanisms to explain the rapid increase should also be considered. Synchrotron emission depends on the product of the magnetic field strength and the differential number of electrons in a specified energy range and pitch angle distribution. Because the observed emission is integrated spatially throughout the magnetosphere, it is possible that the differential number of electrons can be changed as a result of the impacts (without changing the electron energies) in such a way as to cause the observed increase in total emission. Pitch-angle scattering by whistler-mode shocks [Bolton and Thorne, 1995] is one such mechanism. Changes in the magnetic field itself could produce the increase, but this explanation seems unlikely unless the dynamo responsible for the field was disturbed by the impact.

Following the impact, the 13-cm emission declined very slowly following an exponential law with a decay time (1/e) of 170 days. The most significant feature of the decay is that it is very slow; only half of the excess emission had disappeared 118 days after the impact. The observed decay is suggestive of a diffusive process which results in a gradual loss of the energetic radiating electrons. The loss of geomagnetically trapped electrons by scattering and atmospheric interactions has been studied for many years and may be applicable to this problem. Numerical integration of the Fokker-Planck equation, including suspected scattering processes may be used to interpret physical conditions in the radiation belts following the impact.

The suspected enhancement of emission in August 1995, which is barely three times greater than the estimated error, would be more convincing if the outburst were recorded by independent observations. If confirmed, the 1995 outburst will likely generate speculation about its relation, if any, to the impact of the Comet SL-9. New observations may be able to sort this out. If the outburst is not related, the observations suggest that sudden enhancements of Jovian synchrotron emission may not be rare. If the outburst is related, the challenge will be to find an explanation of the year-long time lag between impact and outburst.

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