

THE EVOLUTION OF JUPITER'S SYNCHROTRON RADIATION ALONG THE SOLAR CYCLE

P. H. M. Galopeau* and E. Gerard†

Abstract

Since 1994, regular observations of Jupiter's synchrotron radiation have been performed with the Nançay Radio Telescope at 21 cm (1410 MHz), 18 cm (1666 MHz) and 9 cm (3300 MHz) wavelength. They suggest that natural variations do occur within the belts of trapped electrons in Jupiter's magnetic field. Klein and coworkers have suggested that long term variations of the Jovian synchrotron radiation might be controlled by the Solar wind which structures the magnetosphere. In order to understand the natural variations suggested by the Nançay observations, we have correlated the non-thermal radio flux density with some parameters characterizing the activity of the Solar wind measured at the Earth's orbit by the satellite IMP-8. The parameters that we have chosen are: the proton temperature, the flow velocity, the proton density, the kinetic energy flux, the ions thermal pressure, and the dynamic pressure of the Solar wind. A good correlation is obtained for a 245 day delay of the radio emission relatively to the above parameters. This delay corresponds to the reaction time of the relativistic electron belts against the Solar wind variations. Another correlation, but not so good, is possible for a lag time of 615 days. Moreover, the flux density does not seem to be controlled by the D_E parameter (jovicentric declination of the Earth) and the long term variations should not depend on the viewing geometry.

1 Introduction

We have observed the Jovian synchrotron radiation with the Nançay Radio Telescope (NRT) since April 1994 at 21.3 cm, 18.0 cm and 9.1 cm. The first aim was the study of the effects of the collision of comet SL9 with Jupiter [Galopeau et al., 1996]. Our observations revealed the presence of natural variations in the Jovian flux measurements

*Centre d'Étude des Environnements Terrestre et Planétaires, CNRS UMR 8639, 10-12 Avenue de l'Europe, F-78140 Vélizy, France

†Observatoire de Paris-Meudon, ARPEGES, CNRS UMR 8644, Place J. Janssen, F-92195 Meudon Cedex, France

independently of the effects induced by the collision [Galopeau et al., 1997a]. We present a study of medium (months) term and long term (years) variations in the synchrotron radiation and their dependence on the Solar activity. We extract several parameters (temperature, density, dynamic pressure, Solar energy flux...) and perform a correlation study of those parameters with the non-thermal Jovian flux density at 21.3, 18.0 and 9.1 cm. Our multi-wavelength monitoring also provides the spectral index of the non-thermal radio emission.

2 Observations at the Nançay Radio Telescope

The Nançay Radio Telescope is a large multi-frequency meridian instrument (7000 m²) allowing observations of a radio source one hour per day, with a point source efficiency of 1 K Jy⁻¹ at 21.3 and 18.0 cm and 0.5 K Jy⁻¹ at 9.1 cm. The system noise temperature is 45 K at 21 and 18 cm and 65 K at 9 cm. We observed at the three available wavelengths (21.3 cm, 18.0 cm and 9.1 cm) in H and V polarizations. Two frequencies were used for each wavelength: 1.404 and 1.416 GHz, 1.664 and 1.668 GHz, 3.263 and 3.335 GHz in protected radio astronomy bands.

The observing procedure consists of right ascensions (RA) scans centered on Jupiter. The scan duration is 3 min at 21 and 18 cm and 1.5 min. at 9 cm. Each daily Jupiter run lasts about one hour with typically three scans at 21 and 18 cm and six scans at 9 cm. In order to improve the signal-to-noise ratio, we only consider the total flux and the mean of the two nearby frequencies. Two calibrators are observed on the same day with an identical time sequence in order to monitor the antenna and receivers gains between 1994 and 1999. The relative fluxes of the calibrators are calculated from the observations with the NRT during the 5-year period. The absolute flux density scale is determined from 3C123 [Ott et al., 1994].

3 Data reduction and confusion effect

The data reduction consists of fitting Gaussians to each scan. Stringent criteria are used cumulatively (baseline noise, Gaussian fitting residual, RA position and Gaussian equivalent width) in order to eliminate spurious scans. On average, 40% of the scans were rejected mostly due to lightning, baseline ripples and confusion sources.

The Nançay Radio Telescope is very well suited to detect and discard confusion by background sources, first because the mean confusion limit is 0.02 Jy at 21 and 18 cm and 0.005 Jy at 9 cm, i.e. small compared to the minimum Jovian flux density of $\simeq 5$ Jy. Secondly, because of the daily apparent motion of Jupiter in RA (generally $\sim 5' \pm 10'$), the background confusion sources move relatively to the centre position. Hence, except when the planet is stationary, observing runs carried over several consecutive days show background sources pass behind Jupiter with a slowly varying antenna temperature. Most confusion cases are rejected automatically by at least one of the four criteria described above except when the RA of the confusing source is close to that of Jupiter. In that

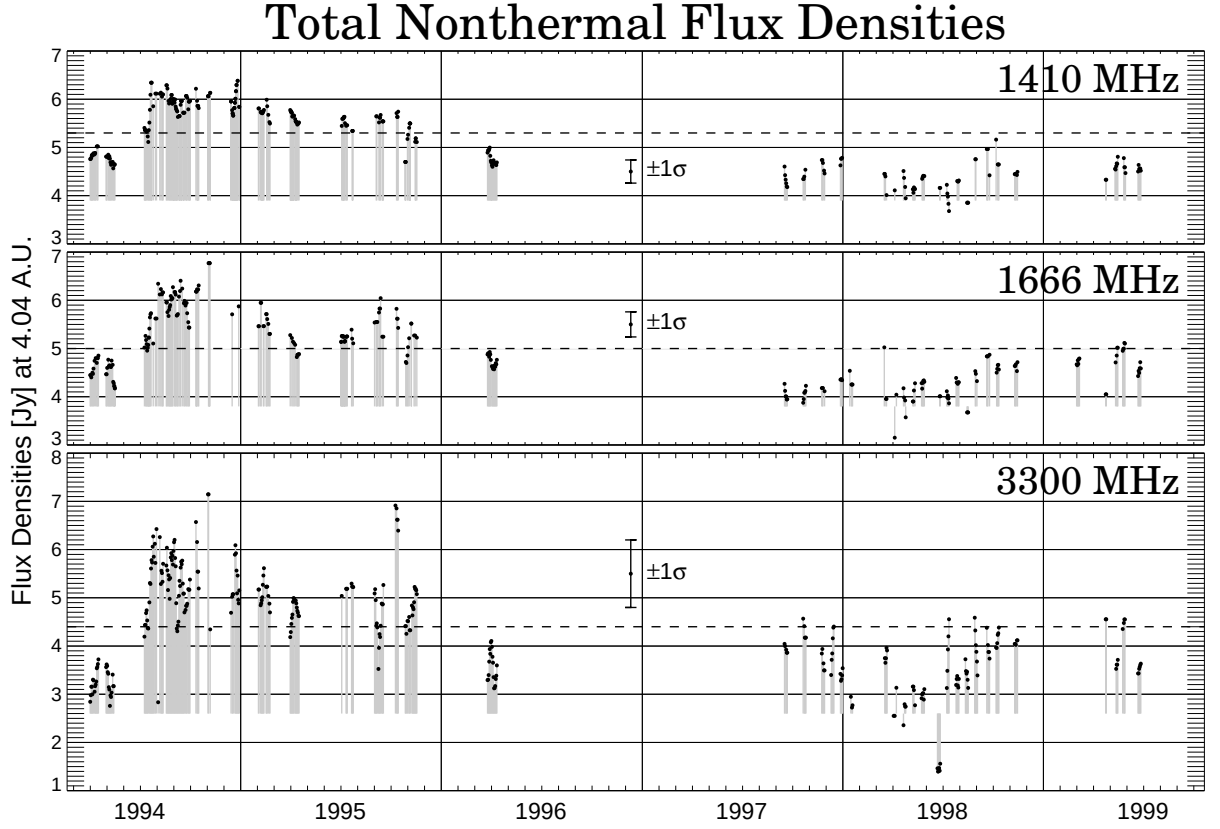


Figure 1: Total non-thermal flux density measured with the Nançay Radio Telescope between April 1994 and June 1999 at 21.3, 18.0 and 9.1 cm wavelength. A mean $1-\sigma$ error bar is drawn in the middle of the plots. The dashed horizontal lines represent the reference levels. The grey-shaded areas start from a minimum flux value defined as 3% of the area of the flux histogram.

case, we estimate the flux of the confusion source when it is far enough away from Jupiter and deduce the Jovian flux.

In order to remove the modulation effect due to the rotation of the planet, we performed a simple running average of the raw data over several consecutive days. The CML increases by $\sim 148^\circ$ from day-to-day. In 5 days, 12 days and 17 days, Jupiter performs respectively 12, 29 and 41 rotations. This stroboscopic effect provides nearly equal CML sampling intervals of $\sim 21^\circ$, 30° and 72° respectively and the corresponding error on the flux S becomes small. A running average over 5 days was applied over the entire 1994–1999 period.

The main causes of error affecting the measurements of total Jovian flux density are the pointing accuracy, the confusion by background sources and the beaming effect. When added quadratically, they amount on average to 4% at 21 cm, 4.5% at 18 cm and 8% at 9 cm. The non-thermal flux density is determined by subtracting the thermal contribution of the disk. The thermal brightness temperature was taken from de Pater and Massie [1985, and references therein] and interpolated to the current wavelengths. Figure 1 displays the non-thermal flux density at 21.3, 18.0 and 9.1 cm, normalized to 4.04 AU.

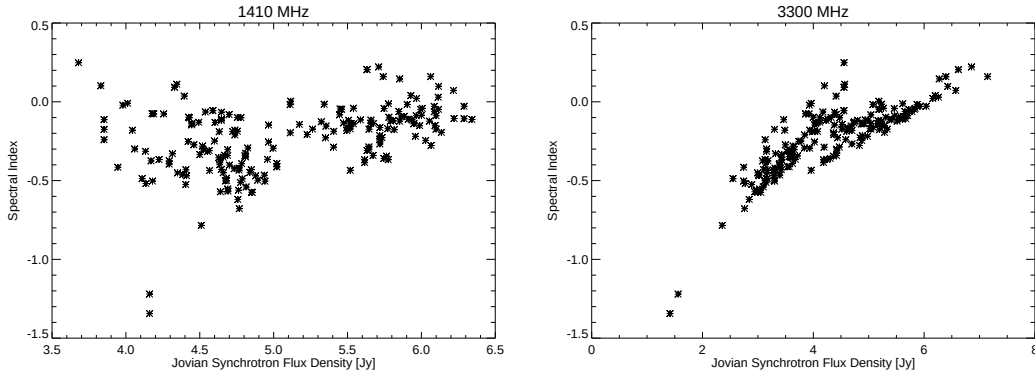


Figure 2: Spectral index of the synchrotron radiation versus flux density at 21 and 9 cm.

4 Results

4.1 Medium and long-term variations

The three curves in Figure 1 show a large increase in late July 1994 associated with the SL9 encounter followed by a long and irregular descent towards a deep minimum between April and July 1998 and a recovery between August 1998 and June 1999.

Immediately before the encounter, between 9 and 16 July 1994, the flux density values are respectively 5.3 Jy, 5.0 Jy and 4.4 Jy at 21.3, 18.0 and 9.1 cm. They are in good agreement with those used by Wong et al. [1996] at 20.3 and 21.9 cm and Funke et al. [1997]. They constitute our “reference levels”. However, the mean Jovian flux density for the periods 2–17 April and 1–17 May 1994 is significantly lower: 4.7 Jy, 4.5 Jy and 3.4 Jy (respectively 11%, 10% and 23% less than the reference levels) so that one cannot exclude a possible natural flux increase between mid-May and mid-July 1994. Between 20 and 31 July 1994, the non-thermal flux increases by 19%, 22% and 30% respectively, also in good agreement with other observers [de Pater et al., 1995; Wong et al., 1996; Funke et al., 1997; and Klein et al., 1995]. From August 1994 to April 1995, our data show a general decrease which is more pronounced between February and April 1995. In April 1995, the flux densities values are still above the reference values.

A natural surge of non-thermal radio emission seems to occur between April 1995 and April 1996: the flux starts to increase particularly at 18.0 and 9.1 cm in July 1995. A maximum is reached in September/October 1995 with flux levels comparable to those of early 1995, well above the reference levels. Between April 1995 and April 1996 increases of $\simeq 10\%$ at 21.3 and 18.0 and 20% at 9.1 cm can be noticed. Between April and July 1998, an absolute minimum is reached at all three wavelengths with $\simeq 4$ Jy at 21 and 18 cm and $\simeq 3$ Jy at 9 cm. It is comparable to the lowest flux densities recorded at 13-cm wavelength by the NASA JPL Jupiter Patrol over more than 20 years: Bolton et al. [1989] find flux minima of $\simeq 3.5$ Jy in early 1973 and early 1981.

4.2 Spectral index variations

In order to quantify the hardness of the non-thermal radio emission, we have computed the spectral index α of the flux density S between 21.3 and 9.1 cm according to the law $S = a \nu^\alpha$ where ν is the frequency and a a constant. The spectral index is plotted as a function of the 21.3 cm and 9.1 cm flux densities in Figure 2. The high frequency end of the non-thermal spectrum varies with an amplitude larger than that at low frequency. As a consequence, the spectral index appears to be well correlated with the 9.1 cm flux, while there is no obvious dependence of α on the 21.3 cm flux density. In fact, both spectral index α and constant a are correlated with the 9.1 cm flux density S_9 : $\alpha = -1.291 + 0.743 \ln S_9$ and $\ln a = 10.474 - 5.026 \ln S_9$, the correlation coefficient being respectively 0.871 and -0.829 .

5 Link with the Solar activity

The variations of the non-thermal flux density of Jupiter at 21.3, 18.0 and 9.1 cm between April 1994 and June 1998 cannot be ascribed solely to post-collision effects. Other causes of variation are needed and an obvious one is the Solar activity. The first evidence for long term variations of the decimeter non-thermal emission of Jupiter was discovered by Klein et al. [1972], Klein [1976], Klein et al. [1989] from an ongoing Jupiter Patrol Observational Program at 2295 MHz (13.1 cm) initiated in April 1971. From their data set as well as from observations prior to 1971, they found variability over a time scale of years and further suggested that those variations were correlated with many Solar wind parameters [Bolton et al., 1989].

We focus on medium- and long-term variations of the non-thermal radio emission at 21.3, 18.0 et 9.1 cm and study their possible correlation with various Solar wind parameters: the proton temperature, the proton density, the flow speed, the dynamic pressure, the ion thermal pressure and the energy flux. The variation of these parameters from 1992 until 1999 is displayed in Figure 3. Since no Solar wind continuous measurement is available in the vicinity of Jupiter during the period corresponding to our observations, the Solar data are taken from the NSSDC OMNIWeb (near-Earth heliosphere data from satellite IMP-8) and have been averaged over 3×27 days in order to discard the modulation due to the Sun's rotation.

Figure 4 displays the linear correlation coefficient of each Solar parameter with the Jovian flux density at 18.0 cm as a function of lag time (ranging from zero to four years). A corrected correlation coefficient (solid line) was calculated without the SL9 event by removing a period of three months following the impacts. Except for the proton temperature, all correlation curves are similar with a large peak $\simeq 0.8$ for a lag time of $\simeq 245$ days. Most correlation coefficients have a secondary peak near 615 days. In order to compare the quality of the two fits, the Jovian synchrotron flux density at 1666 MHz is displayed in Figure 3 shifted by 245 days and 615 days with respect to the Solar wind parameters. It is difficult to find a unique lag time matching all the variations in detail.

Such correlation studies between Solar wind parameters and the decimetric radio emission

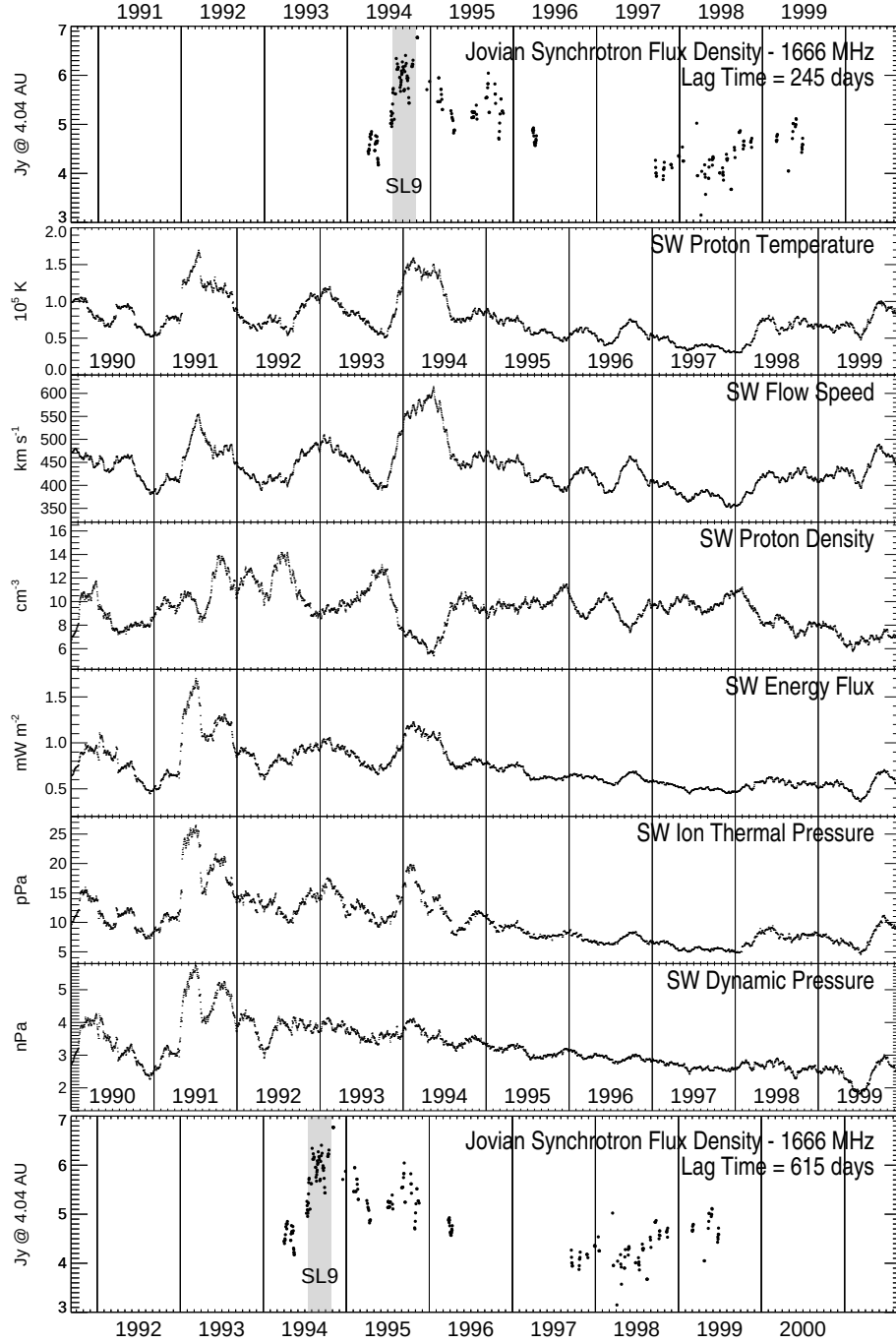


Figure 3: Eighty-one-day averages of the Solar wind parameters measured at the Earth's orbit. The Jovian synchrotron flux density at 1666 MHz is shown shifted by two different lags of 245 and 615 days. The shaded areas represent a 3-month period following the SL9 impacts.

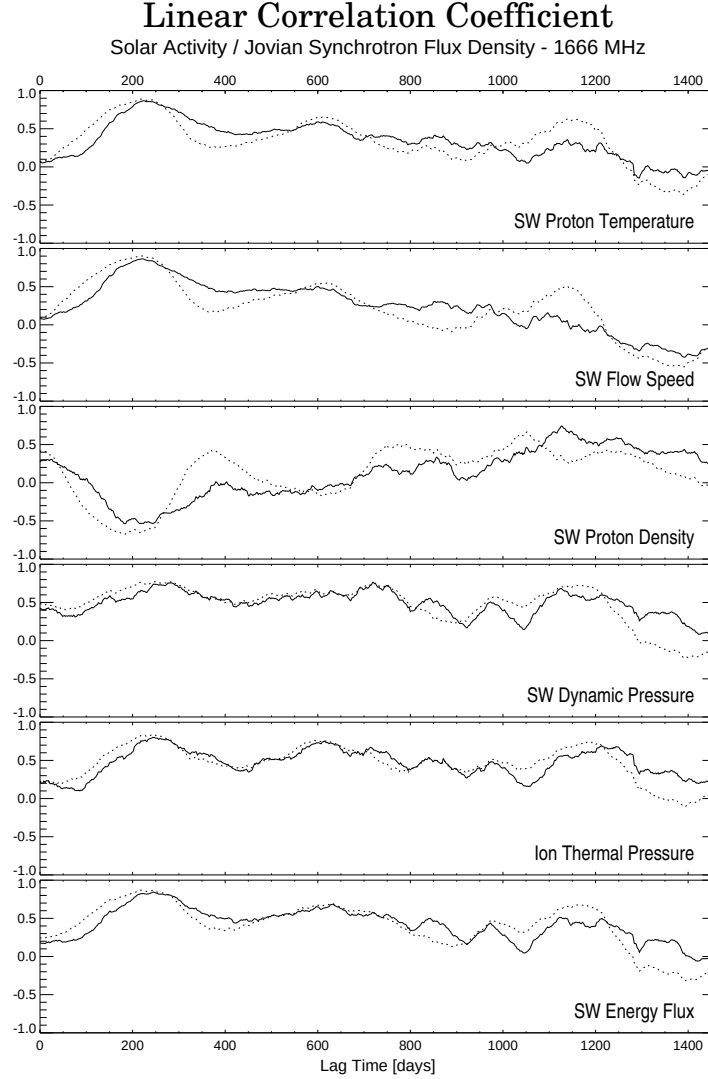


Figure 4: Linear correlation coefficient of the Solar parameters with the Jovian flux density at 18.0 cm as a function of lag time. The dotted line is calculated with the full (5-year) data set whereas the solid line is obtained after removing a 3-month window following the SL9 event.

from Jupiter were made by Bolton et al. [1989] for the period 1963–1985. They find high correlation coefficients (0.87) for the Solar wind dynamic pressure and the ion thermal pressure with respective lag times of 2.0 and 2.5 years. Their curves are different from ours and their lag time varies between 3 and 1 year with data from 1972 till 1982. Our data suggest smaller lag times in the range 0.7–1.7 year.

Another factor was proposed to explain the long-term variations of the Jovian synchrotron radiation: the joventric declination of the Earth D_E . Hood [1993] found a correlation between D_E and the long term 13-cm Jovian flux measurements of Bolton et al. [1989] with a phase lag of one year suggesting that these variations might be due mainly to the changes in viewing geometry. However the regression law derived by Hood [1993] ($S_{13}(t) = 4.7 + 0.18 D_E(t - 1 \text{ yr})$) does not allow to predict the flux variations recorded at Nançay between 1994 and 1999: an agreement is possible only for a time lag of 3 years instead of 1 year. A time lag so large does not seem very realistic and a dependence on the

viewing geometry should not present any phase lag at all. Moreover, the Solar activity cycle and the D_E cycle have neighbouring periods of 10.6 and 11.9 years respectively; thus the fact that we need to change the time lag in Hood's regression law implies that the dependence on the D_E is not the correct explanation.

6 Conclusions

From a five-year data set we have studied the medium- and long-term variations of the Jovian synchrotron radiation: natural variations clearly appear at 21.3, 18.0 and 9.1 cm wavelength in addition to the SL9 event. The spectral index of the non-thermal emission presents large variations and is strongly correlated with the 9.1 cm flux density. The flux density is grossly correlated with most parameters characterizing the Solar activity with a lag time of $\simeq 245$ days. A lag time of $\simeq 615$ days for the dynamic and ion thermal is also possible. The flux density is likely not controlled by the D_E parameter because it is difficult to find a satisfying physical reason for a large phase lag.

Recent observations have been obtained with the new optimized focal system of the Nançay Radio Telescope, which was installed a few months ago and allows to measure the full polarization of the incoming radiation with a sensitivity increased by a factor 2. Also, a fourth frequency was added: 2690 MHz (11 cm wavelength).

References

- Bolton, S. J., S. Gulkis, M. J. Klein, I. de Pater, and T. J. Thompson, Correlation studies between Solar wind parameters and the decimetric radio emission from Jupiter, *J. Geophys. Res.*, **94**, 121–128, 1989.
- de Pater, I., and S. T. Massie, Models of the millimeter-centimeter spectra of the giant planets, *Icarus*, **62**, 143–171, 1985.
- de Pater, I., et al., Outburst of Jupiter's synchrotron radiation following the impact of comet P/Shoemaker-Levy 9, *Science*, **268**, 1879–1883, 1995.
- Funke, O., M. K. Bird, J. Neidhöfer, and I. de Pater, Effelsberg observations of the evolution of Jupiter's radio brightness during and after the impacts of comet Shoemaker-Levy 9, *Planet. Space Sci.*, **45**, 1177–1181, 1997.
- Galopeau, P. H. M., E. Gerard, and A. Lecacheux, Long-term monitoring of Jupiter's synchrotron radiation with the Nançay Radio Telescope including the collision with comet P/Shoemaker-Levy 9, *Icarus*, **121**, 469–478, 1996.
- Galopeau, P. H. M., E. Gerard, and A. Lecacheux, Modifications of the synchrotron radiation belts of Jupiter: Evidence for natural variations in addition to SL9 effects, *Planet. Space Sci.*, **45**, 1197–1202, 1997a.
- Hood, L. L., Long-term changes in Jovian synchrotron radio emission: intrinsic variations or effects of viewing geometry?, *J. Geophys. Res.*, **98**, 5769–5783, 1993.

- Klein, M. J., S. Gulkis, and C. T. Stelzried, Jupiter: New evidence of long-term variations of its decimeter flux density, *Astrophys. J.*, **176**, L85–L88, 1972.
- Klein, M. J., The variability of the total flux density and polarization of Jupiter's decimetric radio emission, *J. Geophys. Res.*, **81**, 3380–3382, 1976.
- Klein, M. J., T. J. Thompson, and S. J. Bolton, Systematic observations and correlation studies of variations in the synchrotron radio emission from Jupiter, in *Time Variable Phenomena in the Jovian System*, edited by M. J. S. Belton, R. A. West and J. Rahe, NASA Special Publication Series 494, NASA, Washington, D. C., 151–155, 1989.
- Klein, M. J., S. Gulkis, and S. J. Bolton, Changes in Jupiter's 13-cm synchrotron radio emission following the impact of comet Shoemaker–Levy 9, *Geophys. Res. Lett.*, **22**, 1797–1800, 1995.
- Ott, M., A. Witzel, A. Quirrenbach, T. P. Krichbaum, K. J. Standke, C. J. Schalinski, and C. A. Hummel, An updated list of radio flux density calibrators, *Astron. & Astrophys.*, **284**, 331–339, 1994.
- Wong, M. H., I. de Pater, C. Heiles, R. Millan, R. J. Maddalena, M. Kesteven, R. M. Price, and M. Calabretta, Observations of Jupiter's 20-cm synchrotron emission during the impacts of comet P/Shoemaker–Levy 9, *Icarus*, **121**, 457–468, 1996.