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Cassini-Jupiter Microwave Observing Campaign: DSN and GAVRT Observations of Jovian Synchrotron Radio Emission

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1. INTRODUCTION

The flyby of the Cassini spacecraft past Jupiter in December 2000 provided a unique opportunity to study Jupiter's radiation belts with high spatial resolution using a passive microwave radiometer that was built into the Cassini Radar Instrument. In a coordinated series of space-based and ground-based observations, named the Cassini–Jupiter Microwave Observing Campaign (Cassini-JMOC), Jupiter was observed at radio wavelengths during the Cassini encounter from November 2000 through March 2001. Cassini-JMOC has two objectives: (1) use ground-based observations to achieve in-flight calibrations of the Cassini radar receiver and thereby enhance the Cassini science at Saturn and Titan; (2) use the Cassini radar receiver to map Jupiter's synchrotron emission at a frequency above 10 GHz and thereby derive the spatial distribution of very high energy electrons (>20 Mev) for the first time. In addition to the scientific objectives, the project included an educational component which invited middle-school and high-school students to participate in the ground-based observations and data analysis.

Precision measurements of Jupiter's flux density relative to Venus and to a selection of radio sources were made in order to derive an accurate flux density for Jupiter at the spacecraft frequency (13.780 GHz). Precision measurements were also made at 2.3 GHz to monitor the time variability of the synchrotron emission from the Jovian radiation belts. These data are being merged with the ongoing NASA/JPL Jupiter Patrol [Klein et. al. 1989] to study the intensity of the synchrotron emission at the time of the spacecraft observations and throughout the Cassini-JMOC observing period.

The educational objective was to engage pre-college students in scientific research. GAVRT teachers want their students to understand that science is a process and not a collection of facts to be memorized. The GAVRT experience provides insight into the world of professional science and access to the scientific community because the students become active participants of the Cassini-JMOC science team.

2. THE OBSERVATIONS

2.1 Maps of Synchrotron Emission at 2.2 cm

On route to Saturn, the Cassini spacecraft flew past Jupiter and provided the first opportunity to observe the Jovian synchrotron radiation at a wavelength of 2.2 cm (13.8 GHz). Measurements were successfully carried out the first week in January near the time of closest approach to Jupiter using the radiometer subsystem of the Cassini Radar Instrument. The resulting data provide unique information on the highest energy electrons in the magnetosphere. Earth-based radio telescopes have difficulty measuring the synchrotron radiation at wavelengths this short because of the difficulty in separating atmospheric thermal emission from the synchrotron radiation, which becomes relatively weak at wavelengths shorter than ~ 6 cm.

The 2.2-cm radiometer was used to produce 20 maps covering a complete rotation of Jupiter in horizontal polarization and another complete rotation in vertical polarization. Synchrotron emission, although even weaker than anticipated, was clearly detected distinct from the thermal emission as evidenced by its polarization and spatial distribution. Preliminary maps of this radio frequency emission from Jupiter's radiation belts were reported by Janssen et. al. [2001].

2.2 DSN and GAVRT Observations at 13, 3.5 and 2.2 cm

In addition to the space observations, Cassini-JMOC included ground-based observations of Jupiter's synchrotron radiation at a variety of wavelengths using the VLA (operating at 20 and 90 cm) and a combination of the GAVRT antenna and NASA's Deep Space Network operating at frequencies in the 13-cm, 3.5-cm, and 2.2-cm bands. We anticipate that by combining these data and incorporating previous ground based measurements (6, 13 and 20 cm), a considerably more complete understanding of the energy spectrum and distribution of relativistic electrons trapped in Jupiter's radiation belts will be possible.

Jupiter's synchrotron emission is known to be time-variable and there is plausible evidence that the observed variations are correlated with changes in solar wind parameters, e.g., solar wind plasma density (Bolton *et al.*, 1989). The Cassini encounter with Jupiter occurred as Solar activity is reaching the peak in the current eleven-year cycle. The last large-scale (>20 %) increase in Jupiter's synchrotron flux density was observed in the winter of 1989-90, just about eleven years ago.

The GAVRT observations at 13-cm (2.295 GHz) were primarily made to monitor the time variations of the synchrotron emission from the radiation belts. The GAVRT data were merged with the ongoing NASA/JPL Jupiter Patrol to improve the sensitivity and time resolution of the resulting data. The results are shown in Figure 1.

FIGURE 1 Near Here

The lower panel in Figure 1 shows the thirty-year history of changes in the microwave radio emission from the radiation belts in the 11-13 cm bands. Changes up to thirty percent in the intensity of the microwave emission are clearly evident including the sudden outburst attributed to the impact of the Comet Shoemaker-Levy 9 in July of 1994. The upper panel is an enlarged view of the last two years of the data that includes the Cassini-JMOC observations. The open diamonds are NASA/JPL Jupiter Patrol observations made with DSN antennas with apertures of 70-m and 34-m. GAVRT team observations are represented by filled triangles. The relative 1-sigma uncertainty of the measurements is ~ two percent, which is about twice the size of the plotted data points. Note the excellent agreement between the two sets of data.

The GAVRT observations monitored the intensity of the synchrotron emission throughout the Cassini-JMOC observing period, but especially near the time of the spacecraft observations in the first week of January. The intensity of Jupiter's synchrotron emission leading up to the Cassini encounter tends relatively flat throughout 1999 and 2000 superimposed with modest intensity increases (~7-percent) in December 1999 and August 2000. The intensity was "near normal" from October through the first week in January when Cassini mapped the radiation belts at 2.2 cm. The 13-cm radio emission then appears to go through an eight-percent "dip" lasting from mid-January through mid-February. There is currently no explanation for this rather unique event.

The events of "modest" short-term intensity variations appear to be intrinsic to Jupiter and not caused by systematic errors in calibration or by discrete background radio sources the planet passes during its twelve-year orbital path along the ecliptic. A systematic search for background sources in the NASA Extragalactic Data Base (NED) is routinely made during the data processing, and data affected by discrete background confusion sources are edited from the data base. The events noted above were free of this source of error. Evidence of short-term variations in Jupiter's synchrotron radio emission have been reported in the past, most recently by Klein et. al. (1996) and by Galopeau et. al. (1996 and 1997). There is hope that the intensity fluctuation in January 2001 will reveal new insights about Jupiter's inner radiation belts when the Cassini-JMOC results are compared with the *in situ* particle and field measurements collected by the Cassini and Galileo spacecraft during the Cassini flyby.

2.3 GAVRT Observations of Jupiter at 13.8 GHz (2.2 cm)

The Cassini-JMOC ground-based observations of Jupiter at 13.8 GHz were made simultaneously with the spacecraft observations to permit the accuracy of ground-based radio astronomy flux calibration to be transferred to the Cassini radar receiver using Jupiter as a common reference source. Current estimates of the absolute uncertainty of the Radio Astronomy flux calibration scale tend to increase with frequency in the centimeter-to-millimeter radio astronomy bands. The goal of Cassini-JMOC was to calibrate the Jupiter flux density at 13.8 GHz with a one-σ absolute accuracy of 4 percent or better.

The GAVRT team supported a total of 167 observing sessions of Jupiter and calibration radio sources during the campaign. The team measured the ratio of Jupiter relative to six calibration sources that were selected to mitigate different sources of random and systematic errors. The calibration source selection criteria included the following:

a. Flux density greater than 3 Jy to ensure high signal-to-noise (5<SNR<10) for individual measurements.

b. Spectral Index is "known" with sufficient accuracy to interpolate flux density at 13.8 GHz
c. Angular size should be small compared to 0.039 degree (the 3-dB width of the 34-m antenna beam at 13.8 GHz). The source 3C405 (Cygnus A) was "exempted" for this selection criteria because it is one of the sources that is also being measured directly from Cassini during special calibration sequences in the fall of 2000 and the summer of 2001.
d. There is evidence that source does not vary with time
e. Circular polarization is small (<1%)
f. Proximity with Jupiter's location on the sky (Right Ascension and Declination)

All measurements of Jupiter and calibration sources were calibrated to remove sources of error caused by changes in system performance with antenna tracking in azimuth and elevation. System calibration checks were performed about three times per hour to monitor subtle changes in receiving system gain, stability and linearity.

The observed ratios of Jupiter to the six calibration sources were used to calculate the effective disk temperature of Jupiter for each calibrator. The results are shown in Figure 2. The error bars are 1-sigma errors calculated from the scatter of multiple ratio measurements for each calibration source. The average of the six values of the effective disk temperature shown in the Figure is 165.3 +/- 7.3 K.

Note that the effective disk temperature is slightly greater than the true disk temperature because no attempt has been made to subtract the emission from the radiation belts. For these preliminary results, the effective disk temperature T_d(eff), is calculated from the total flux density by assuming that all of the emission is coming from Jupiter's visible disk, i.e., $T_d(\text{eff}) = S \times [\lambda^2/2k] \times [\pi/4] \times [D_{eq}\, D_{pol})/d^2]$, where S is the total flux density (Janskys), λ is the wavelength (m), k is the Boltzmann constant, D_{eq} and D_{pol} are the equatorial and polar diameters of the planet, and d is the distance from Earth at the time of each measurement.

FIGURE 2 Near Here

The flux densities assumed for each of the calibration sources are derived from precision measurements using the DSN radio telescopes at several frequencies and the radio astronomy calibration scales published by Baars et. al. 1977, Ott et. al. 1994. The 13.78 GHz flux densities for the mean epoch 2001.1 were assumed to be: 3C274 (30.36 Jy); 3C286 (3.52 Jy); NGC7027 (5.45 Jy); 3C123 (5.58 Jy): 3C405 (102.7 Jy). The disk temperature of Venus was assumed to be 578.6 K (Steffes et. al. 1990).

It is important to note that results reported here are preliminary because additional calibration work is continuing through the remainder of 2001. While this report contains nearly all of the GAVRT data, the average disk temperature and error estimate will be modified as additional information is gathered to reduce the systematic error "budget". Most notable of these will be the results of a new set of observations being carried out with the 34-m antenna to map the brightness distribution of 3C405 and 3C274 at 13.8 GHz using a "raster scan" technique developed by Richter and Rochblatt (1997). The spectral indices of several sources will also be updated with new results from the National Radio Astronomy Observatory (NRAO) and improved model calculations of the microwave spectrum of Venus (B. Butler, private communication) will be applied. The anticipated result of these and other updates will be to reduce the 7.3 K relative error and achieve an absolute error in the range of 2-to-4 percent.

3 Discussion and Conclusions

The Cassini-JMOC observations have revealed new information about the synchrotron radio emission from Jupiter's radiation belts close to the planet inside ~2.5 Rj. The space-based observations reported by Janssen et al (2001) produced the first high resolution map of the synchrotron emission from the radiation belts at short centimeter wavelengths. The total intensity derived by spatially integrating and then combining the two orthogonally polarized maps at 2.2 cm is only about one-sixth the intensity that was predicted from a computational model of the synchrotron radiation (Levin et. al., 2001) using an electron energy spectrum similar to the Divine Garrett (1983) model. The implications of these space-based results are discussed by Bolton et. al. (2001) and Janssen et. al. (2001).

The ground-based Cassini-JMOC observations at 2.2 cm (13.8 GHz) reported in this paper will be used to refine the calibration of the space-based measurements made with the passive microwave radiometer that was built into the Cassini Radar Instrument. Reducing systematic errors of the radiometer subsystem will improve the capability of the instrument to accurately map the 2.2 cm emission from the surface of Titan and the rings and atmosphere of Saturn. The Cassini radar experiment is designed to penetrate the clouds of Titan and image the surface. The passive radiometer data will provide additional information to identify the location, extent, and composition of surface features that the radar is likely to detect. To be effective the absolute calibration accuracy must be in the range 2-4 percent. The team is confident that this objective will be met with the combination of the Cassini-JMOC data and some additional calibration sequences that are being planned.

The ground-based Cassini-JMOC observations at all three DSN wavelengths and the two VLA wavelengths will be compared with results from the computational model of the synchrotron radiation (Levin et. al., 2001) to improve current knowledge of the relativistic electron population within the inner Jovian magnetosphere. The models will also be used to search for plausible causes of the temporal variations in the 13-cm radio emission that have been observed for three decades as well as the short-term dip in the 13-cm total intensity that was observed from ~20 January to ~20 February 2001. The team is especially interested in the 2001 event because it occurred during the Cassini-JMOC campaign, which offers the opportunity to compare the time variable data from the GAVRT and DSN observations with the particle and field data collected *in situ* by two spacecraft, Cassini and Galileo.

4 GAVRT Schools & Teachers on the Cassini-JMOC Team

The Cassini-JMOC could not have accomplished the ground-based observing objectives without the dedicated work of the GAVRT teachers and their students. The interest and enthusiasm of the GAVRT team was a driving force to complete multiple observing sessions each week throughout the campaign, and as it turned out, the repetitive observations were needed to detect the short-term dip in the 13-cm total intensity data. These important members of the Cassini-JMOC team and their schools are recognized here:

Ballard Junior High School	Huxley, IA	S. Barth, D. Williams
Barton Junior High School	Buda, TX	D. Keel
Brewton Middle School	Brewton, AL	C. Brown, D. Godwin
Brownstown Central	Brownstown, IN	R. Slaton
Camden Middle School	Camden, SC	K. Dozier
Carver High School	Columbus, GA	L. Richardson
Cherokee County High School	Centre, AL	M. Miller
Connect Middle School	Pueblo, CO	L. Hawkins
Don Benito Elementary	Pasadena, CA	L. Bush
East High School	Erie, PA	R. Fetzner
George County Middle School	Lucedale, MS	J. Mills, D. Wilson
Glendora High School	Glendora, CA	R. El Yousef
Harborside School	San Diego, CA	B. Arii
Lakes Middle School	Couer d'Alene, ID	C. Lind
Academy for Academic Excellence	Apple Valley, CA	K. Gay, M. Huffine, C. Hinojosa, D. MacLaren, D. Dorcey
Mesquite Elementary School	Apple Valley, CA	L. Smith
Mojave Mesa Elementary School	Apple Valley, CA	M. Deppe, M. Face
Oak Mountain Middle School	Birmingham, AL	A. Walker
Opelika Middle School	Opelika, AL	F. Seymore, M. Matin
Ramona Middle School	LaVerne, CA	M. Rodgers, D. Swinney M. Rasmussen, S. Massoudi
Redlands East Valley High School	Redlands, CA	J. Monaco
Sanford Middle School	Opelika, AL	F. Ware
St. Mary's School	Medford, OR	H. Bensel, J. Sokolowski
Strong Vincent High School	Erie, PA	D. Beard, C. Tattersail
Unversity Public School	Detroit, MI	R. Rohn
Vista Campana Middle School	Apple Valley, CA	L. Hoegerman

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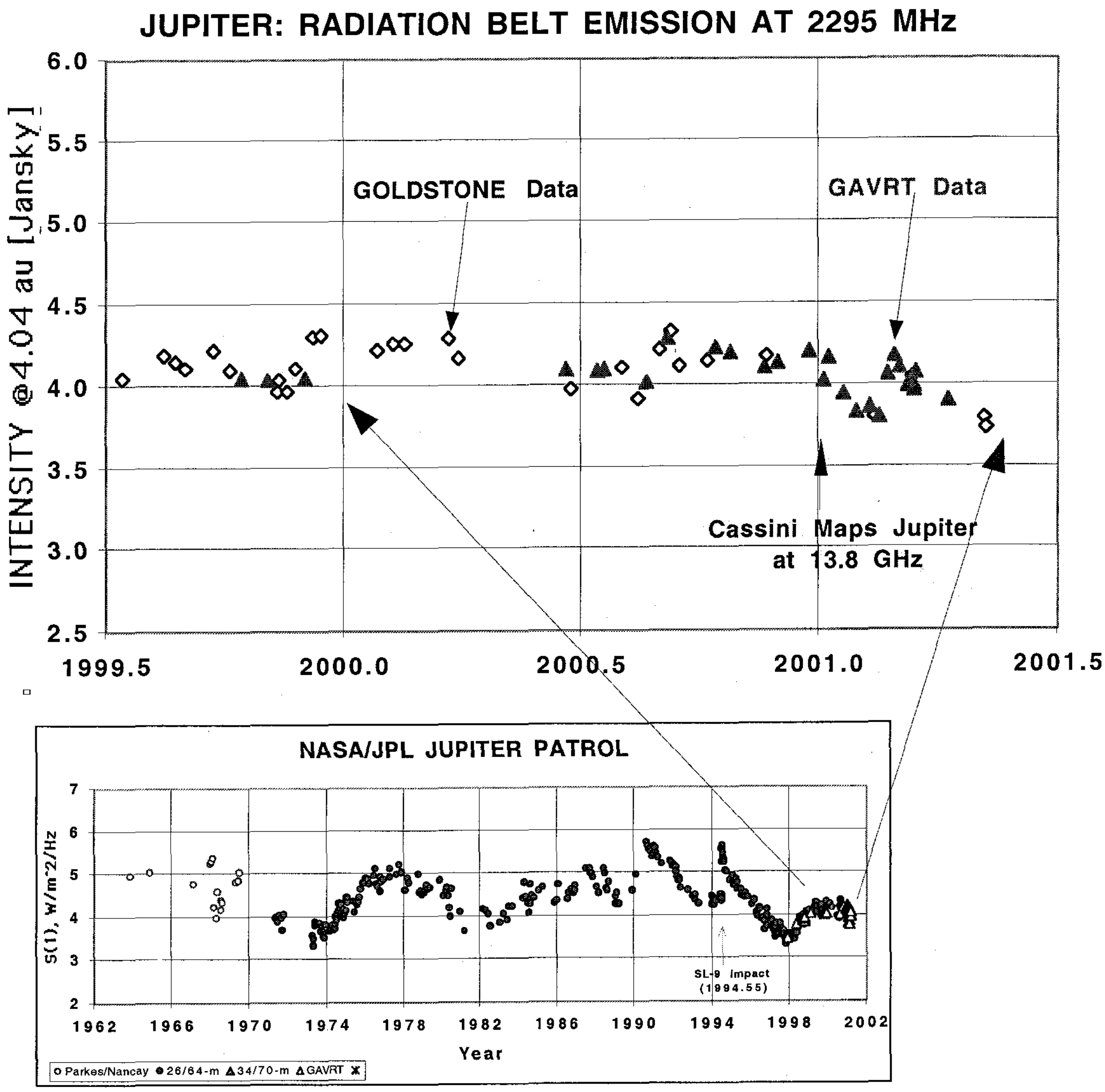
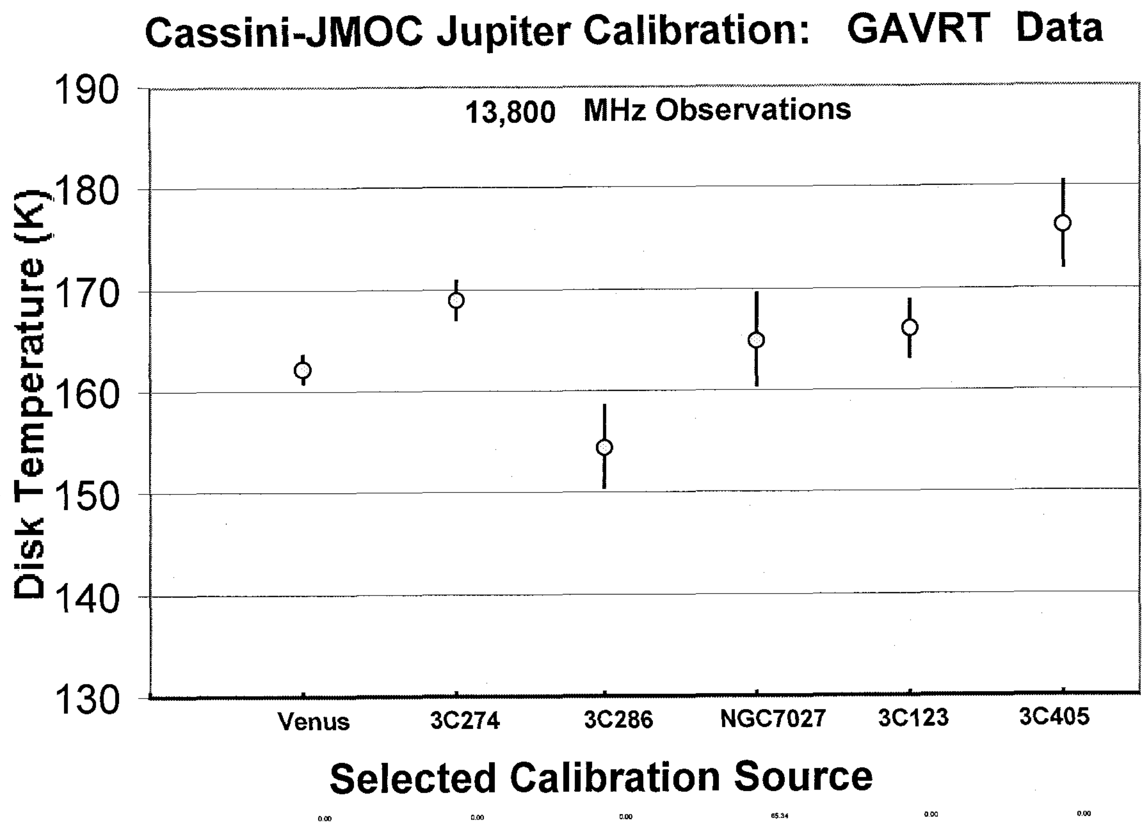

JUPITER: RADIATION BELT EMISSION AT 2295 MHz
INTENSITY @4.04 au [Jansky]
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
1999.5
2000.0
2000.5
2001.0
2001.5
GOLDSTONE Data
GAVRT Data
Cassini Maps Jupiter
at 13.8 GHz
NASA/JPL JUPITER PATROL
7
6
5
4
3
2
1962
1966
1970
1974
1978
1982
1986
1990
1994
1998
2002
Year
SL-9 Impact
(1994.55)
Parkes/Nancay
26/64-m
34/70-m
GAVRT


Cassini-JMOC Jupiter Calibration: GAVRT Data
13,800 MHz Observations
Disk Temperature (K)
190
180
170
160
150
140
130
Venus
3C274
3C286
NGC7027
3C123
3C405
Selected Calibration Source

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