Magnetospheres of the Outer Planets

Synchrotron Measurements of Jupiter's Inner Radiation Belts

M. J. Klein[1], S. J. Bolton[1], S. Gulkis[1],
M. A. Janssen[1], S. M. Levin[1] and R.Thorne[2]

[1]Jet Propulsion Laboratory, California Institute of Technology
[2]Dept. of Atmospheric Sciences, UCLA

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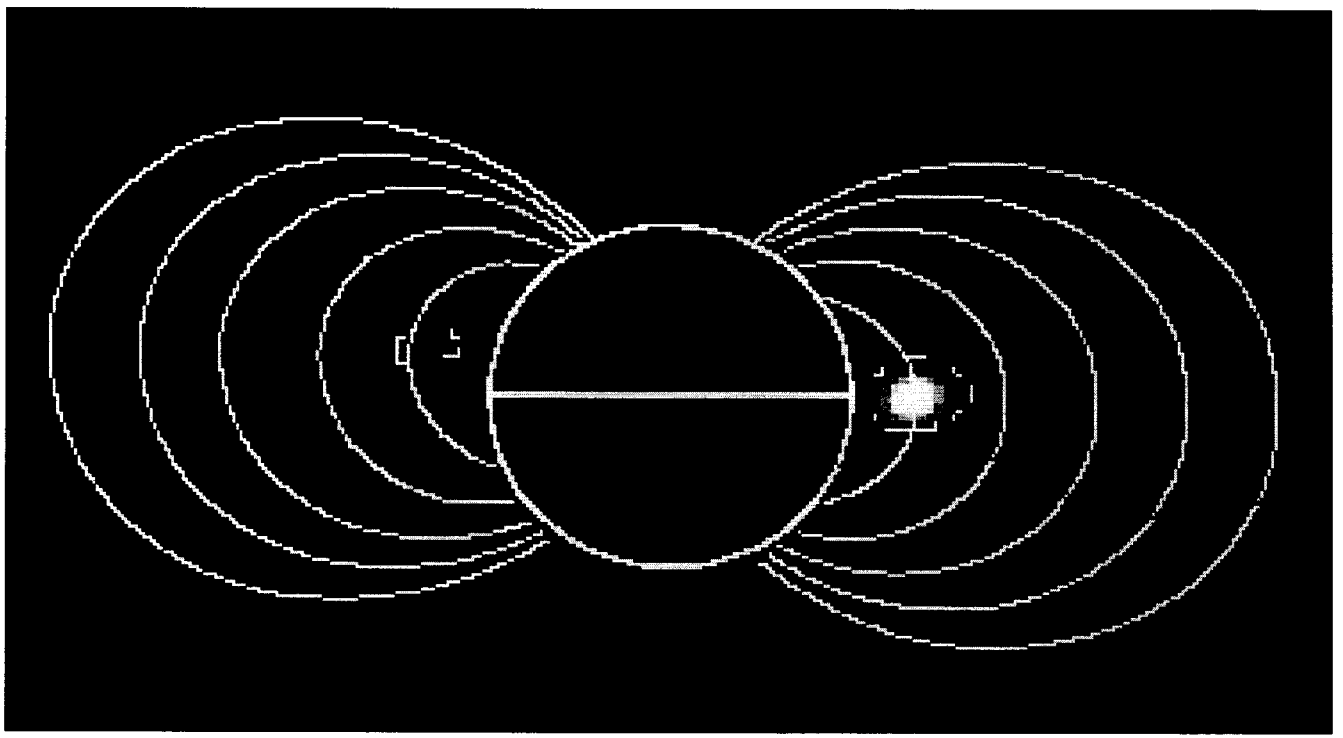
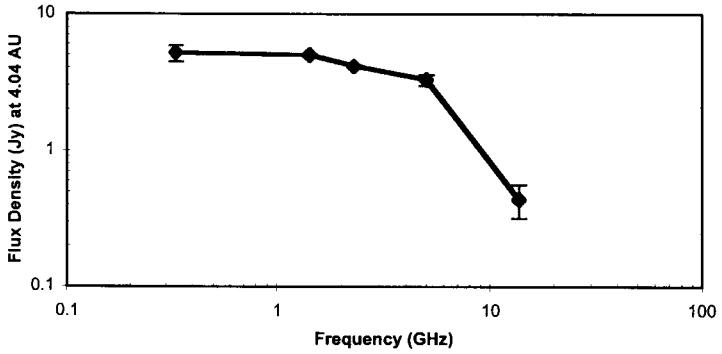
Jovian Synchrotron Radio Emission

Synchrotron emission depends on magnetic field geometry and particle energy, pitch angle and spatial distributions. Therefore, observations of Jovian synchrotron radio emission contribute to our understanding of the planet's inner radiation belts (6-1.3 Rj).

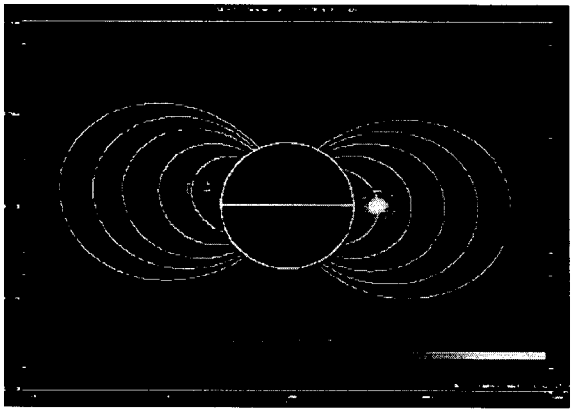


Jovian Synchrotron Radio Emission

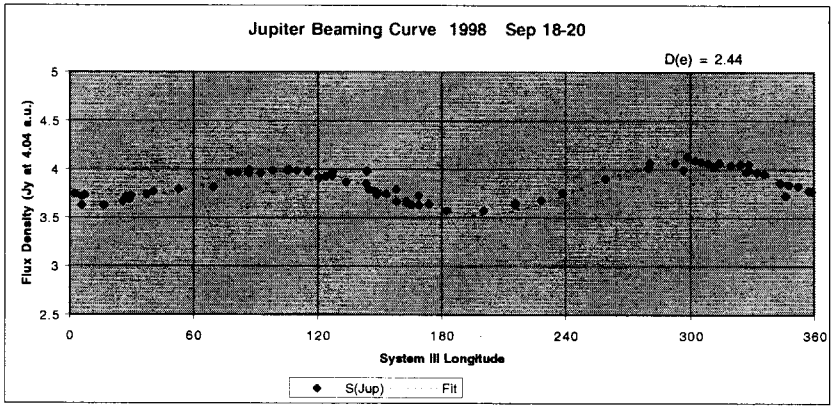
Examples of Earth-based observations that help constrain synchrotron emission models



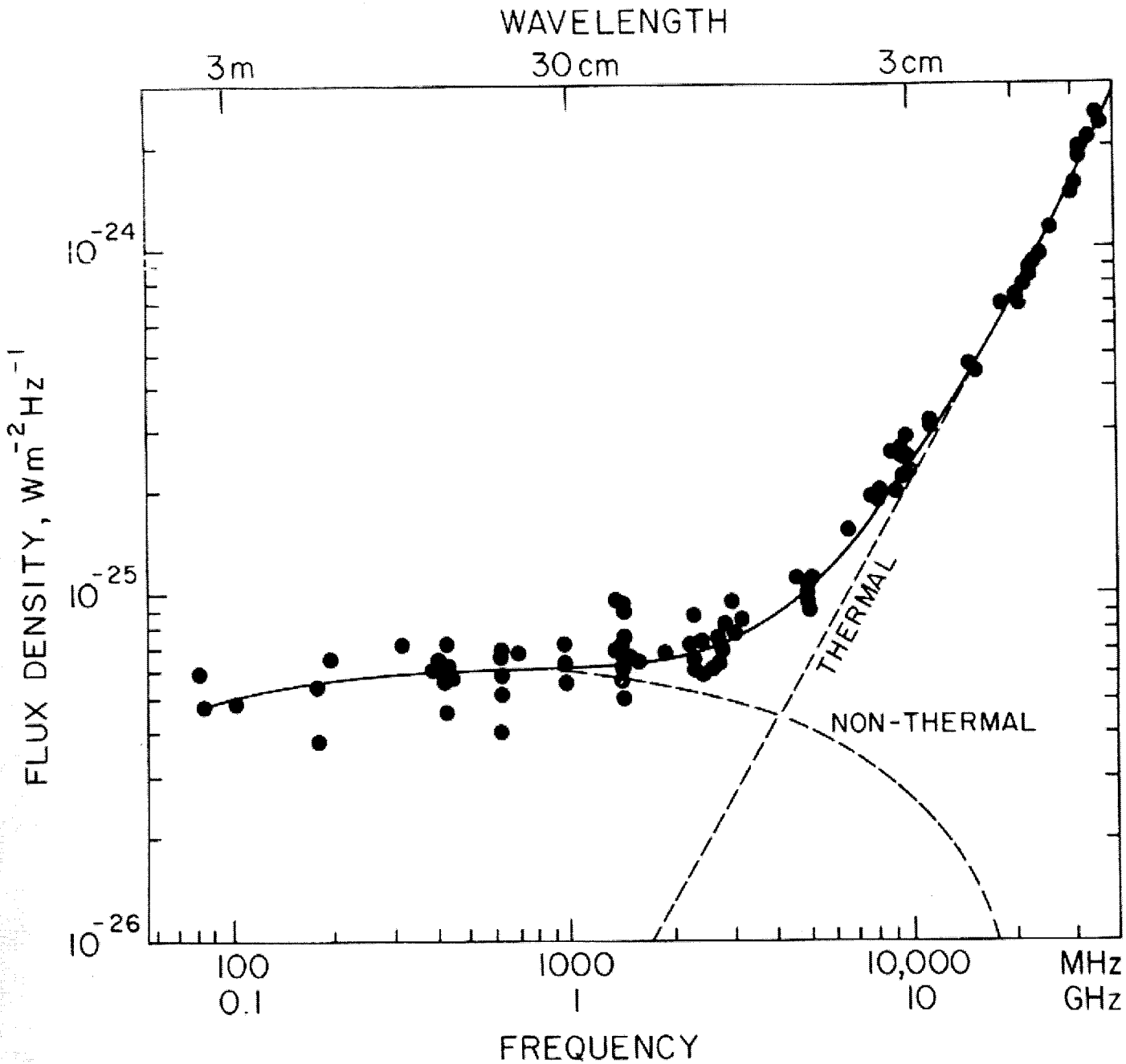
Flux density spectrum (~600 cm to ~2 cm)
Single Aperture and Interferometers



Radio maps (Total flux and polarized flux)
Interferometers & Cassini

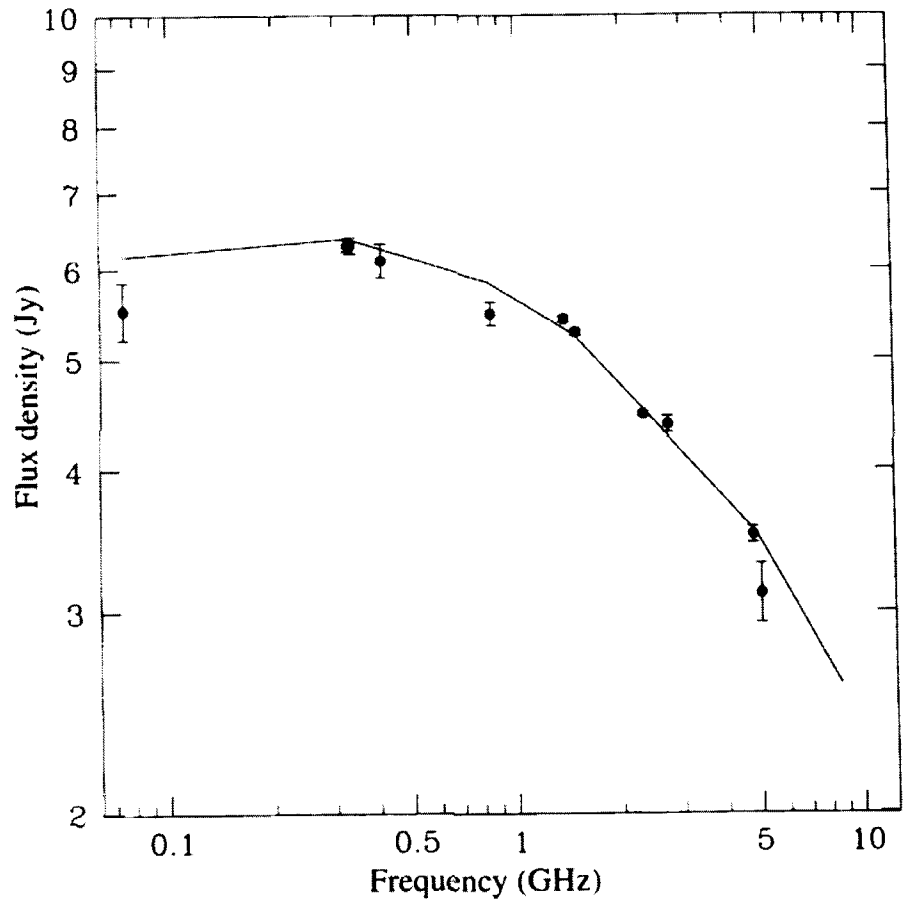


Rotation "Beaming Curves" (Total flux and polarized flux)
Single Aperture and Interferometers


WAVELENGTH
3m
30cm
3cm
10^{-24}
10^{-25}
10^{-26}
FLUX DENSITY, $Wm^{-2}Hz^{-1}$
THERMAL
NON-THERMAL
100
0.1
1000
1
10,000
10
MHz
GHz
FREQUENCY

Synchrotron Radio Emission Spectrum

- Synchrotron flux very difficult to measure above 5 GHz ($\lambda < 6$ cm)
- Cassini flyby presented a unique opportunity to map synchrotron emission at short wavelengths (~2.2 cm)
- Peak synchrotron emission at 2.2 cm wavelength corresponds to extremely high energy electrons (~40 MeV).



Flux density spectrum (~600 cm to ~3 cm)

Components of the Jupiter Synchrotron Campaign
(January 2001)

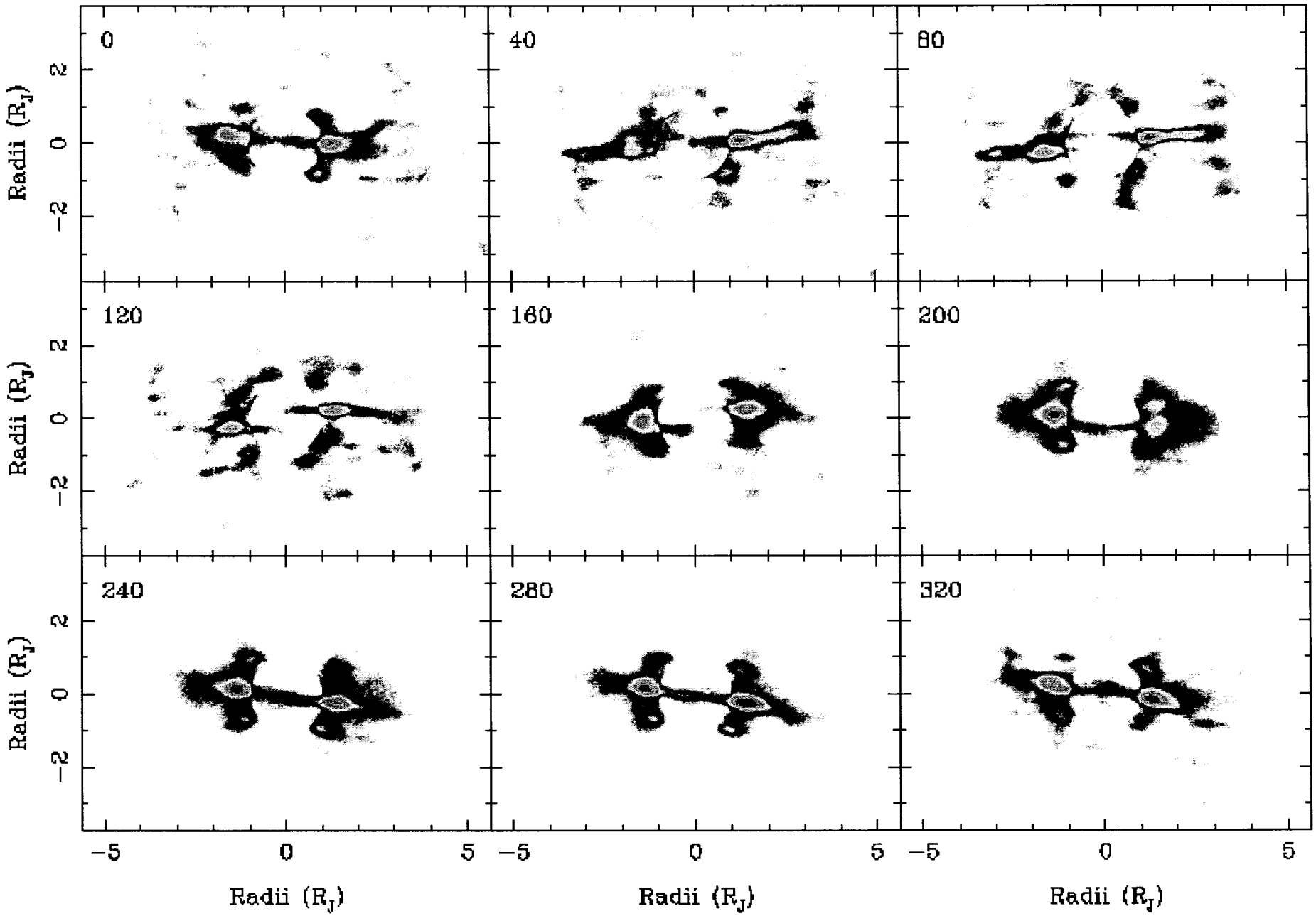
Using the Cassini Radar instrument operating in radiometer mode the synchrotron emission was easily separated from the atmospheric thermal emission by both its spatial distribution and polarization characteristics.

Simultaneous observations were carried out by the VLA operating at 20 and 90 cm.

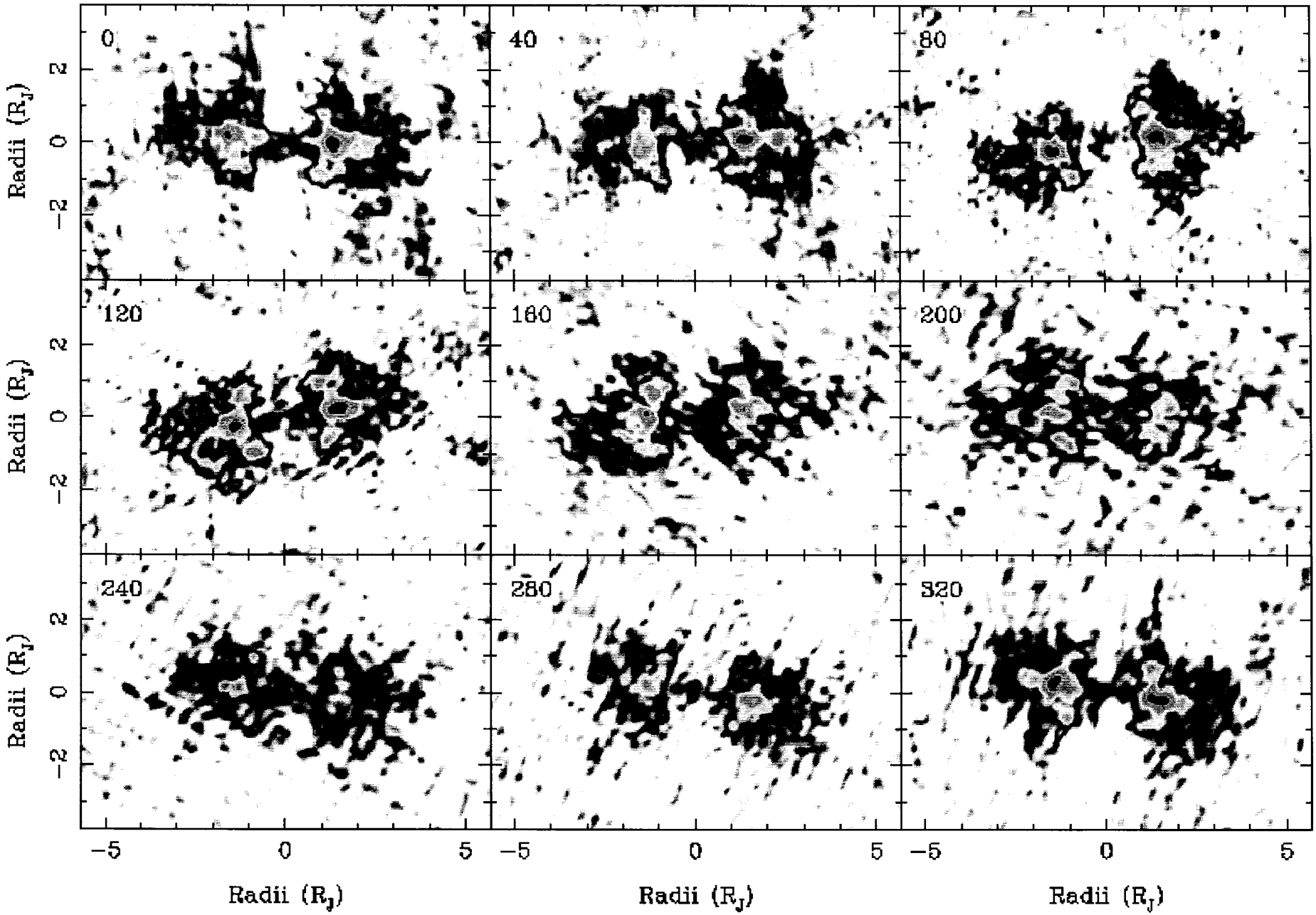
The DSN and Goldstone Apple-Valley Radio Telescope (GAVRT) project carried out a monitoring program at 3 wavelengths (13, 3.5 and 2.2 cm).

The GAVRT project involves middle and high school students observing, calibrating and reducing the data (supported by JPL scientists).

VLA 20 cm data



VLA 90 cm data



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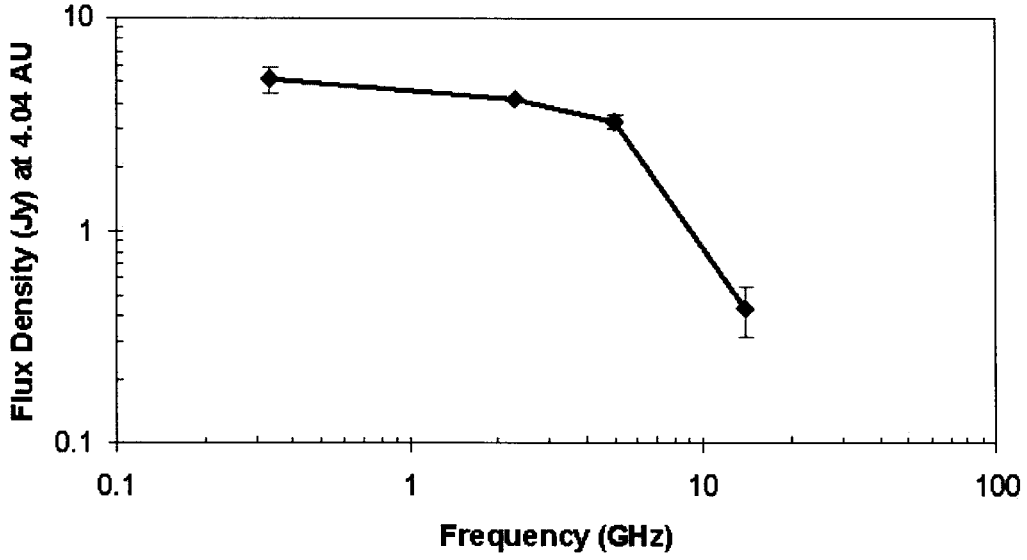
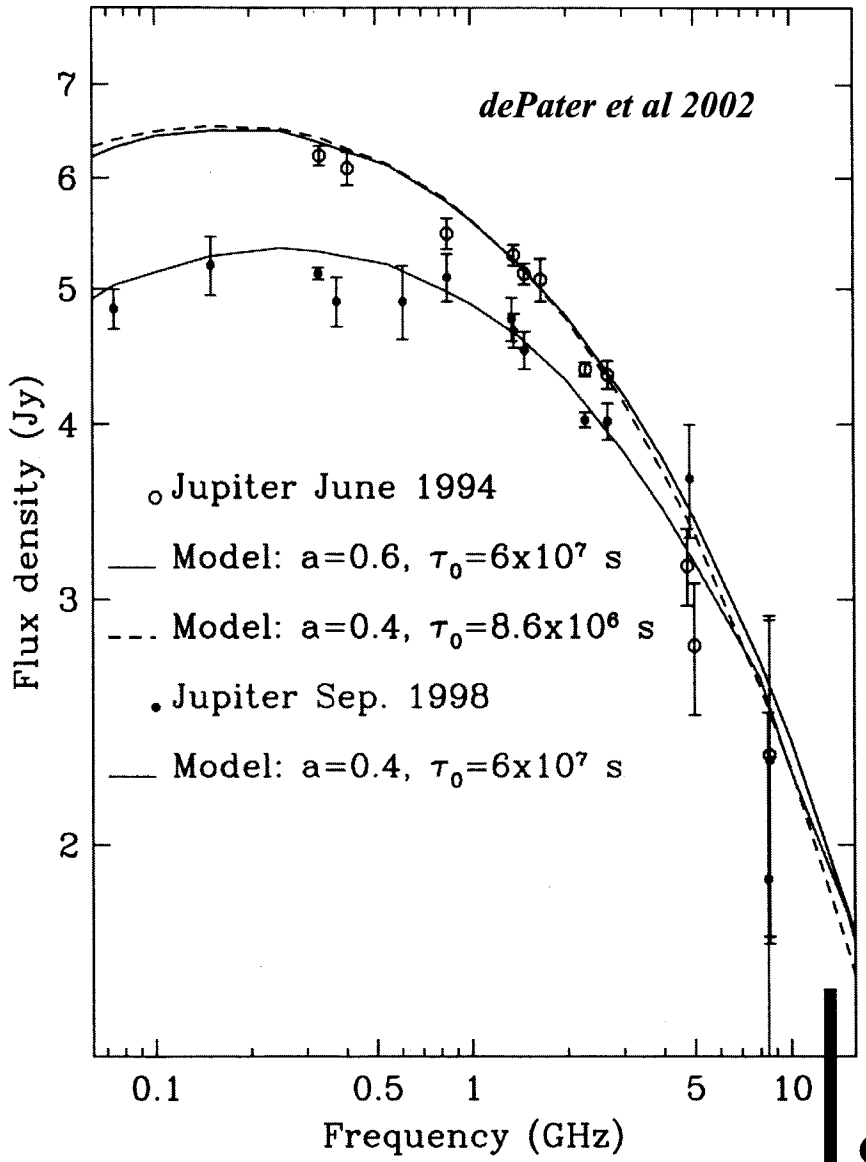
Synchrotron radio emission spectrum



$f_c \sim BE^2$

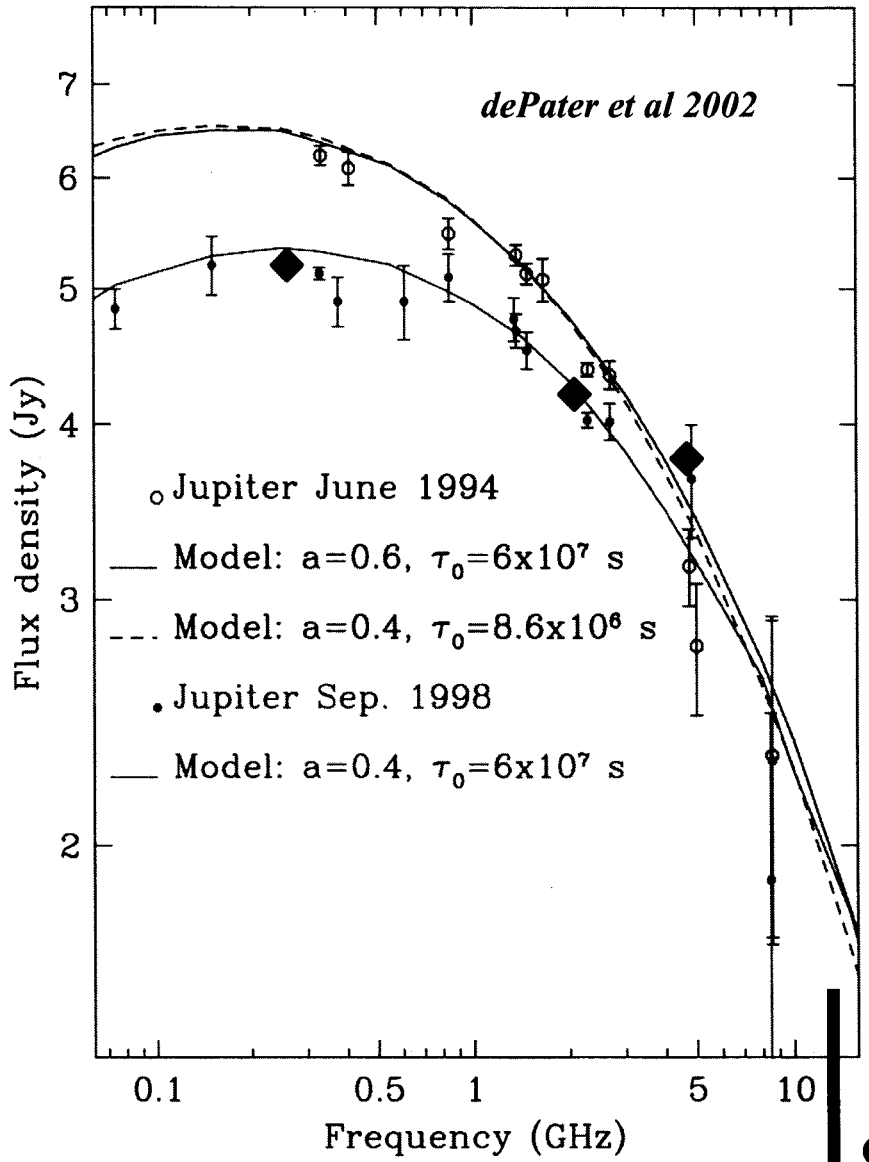
- In the presence of Jupiter's magnetic field, a combination of spatial and energy distributions is needed to model the observed synchrotron spectrum.
- Steep spectral slope above 8 GHz implies fewer high energy electrons close to the planet.

Jupiter's Synchrotron Radio Emission Spectrum at two epochs



- Flux value at 2.2 cm is only ~25 % of expected value
- 1994 and 1998 data suggest microwave spectrum is time-variable
- What was the spectrum at time of 2.2 cm Cassini observation in Jan 2002 ?

Cassini Map @ 2.2 cm
S = 0.44 Jy (+/- .15)



Jupiter's Synchrotron Radio Emission Spectrum at two epochs

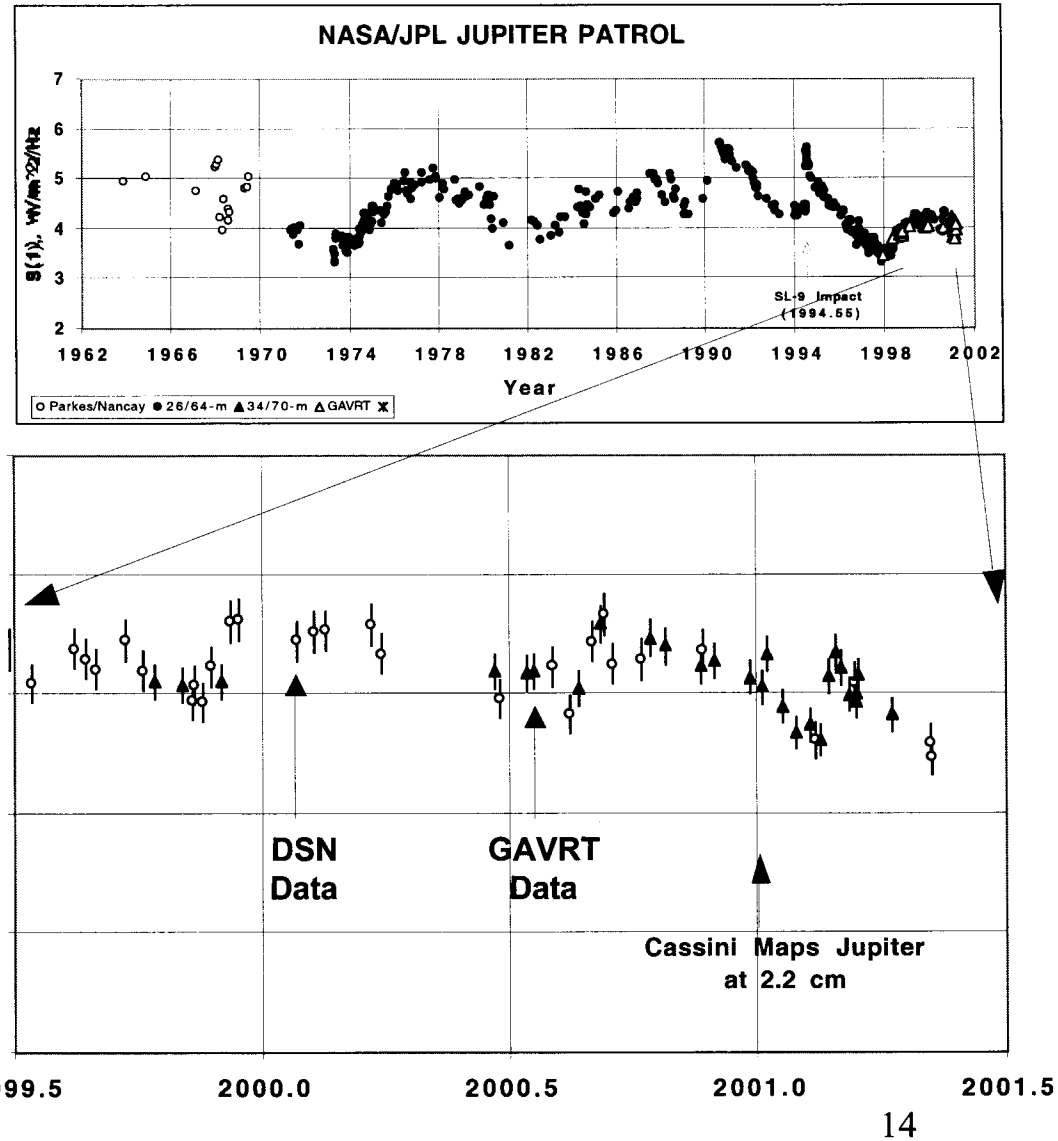
- Flux densities in January 2001 were consistent with the spectrum in 1998.
- Synchrotron spectrum is softer than expected at frequencies above 8 GHz.

Cassini Map @ 2.2 cm
S = 0.44 Jy (+/- .15)

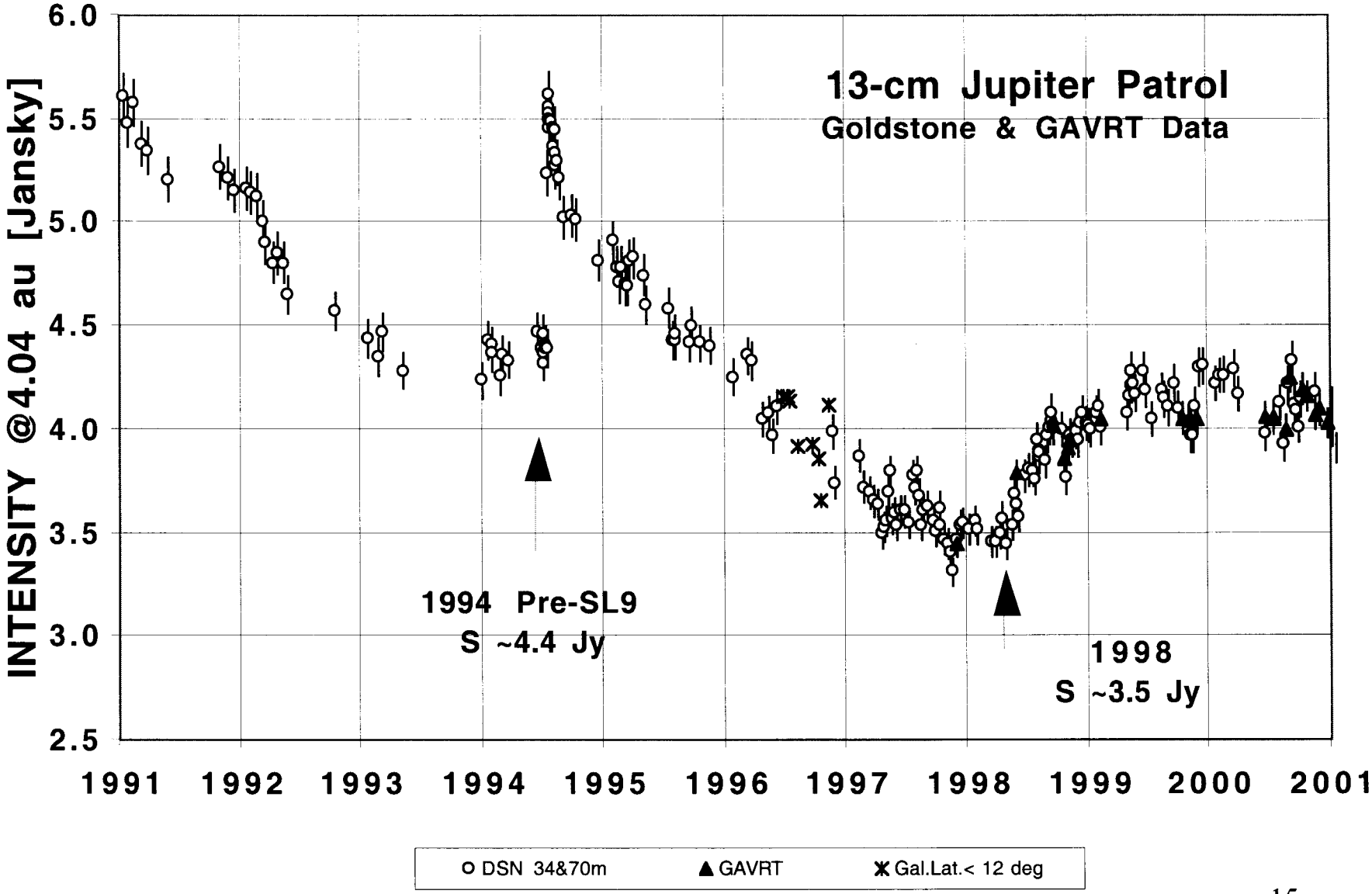
CASSINI-JUPITER MICROWAVE OBSERVING CAMPAIGN

GAVRT-DSN Results:

- Jupiter's Synchrotron Emission at λ13-cm Varies ~10% During Flyby
- Cause of variation is unknown
- Time-variable data will be compared with radiation belt data take *in situ* by Cassini and Galileo spacecraft
- Paper published in *Nature* (Special Issue on Cassini Flyby)

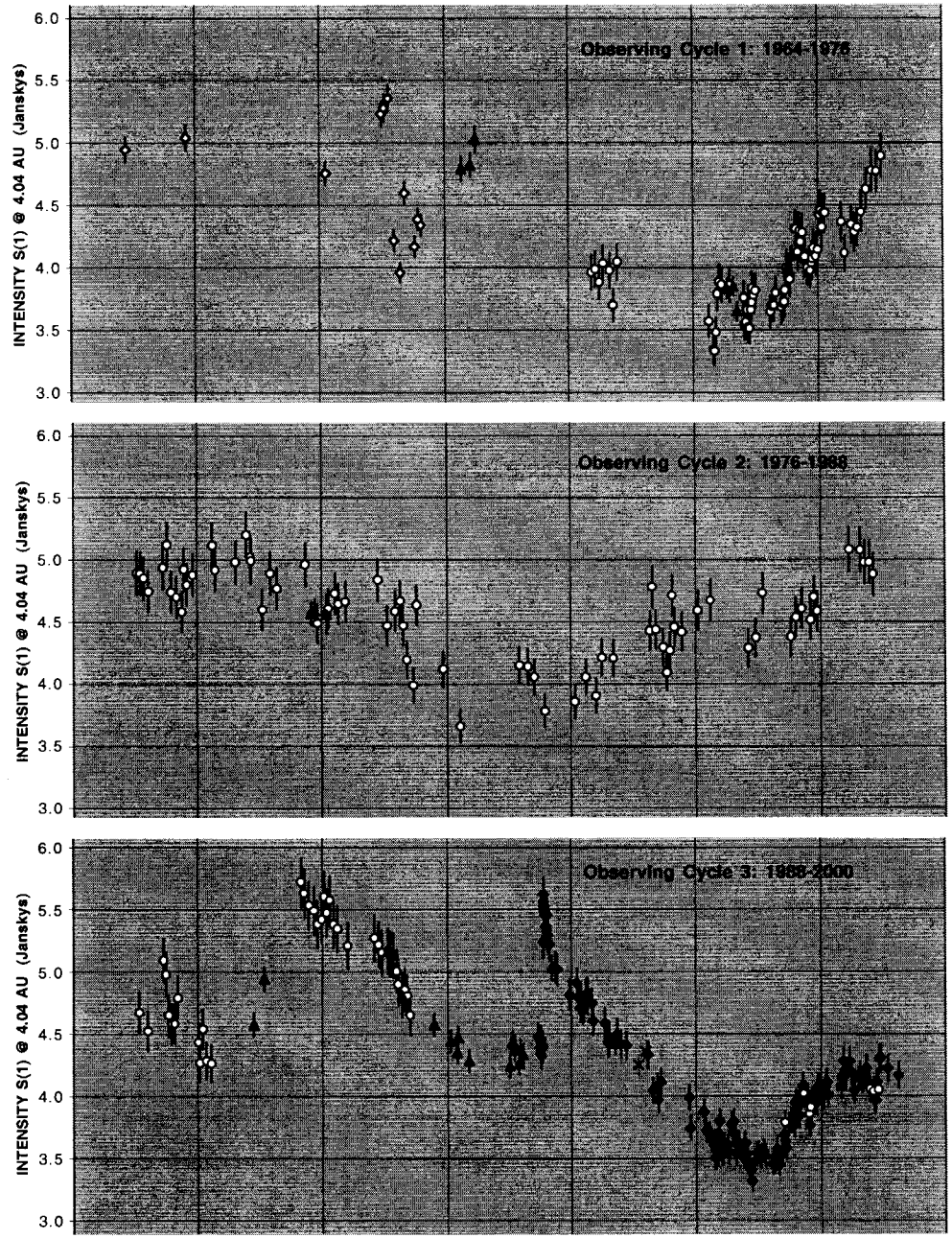


Temporal Variations of Intensity



Variations of Intensity with $\mathbf{D_e}$

- Geometric viewing angle ($\mathbf{D_e}$) cycles from -3 to +3 degrees during Jupiter's 12-yr orbit
- Observations over consecutive Jovian orbits show very different signatures (…even without SL-9)
- Intensity variations are likely to be functions of both time and $\mathbf{D_e}$ but they are NOT dominated by $\mathbf{D_e}$

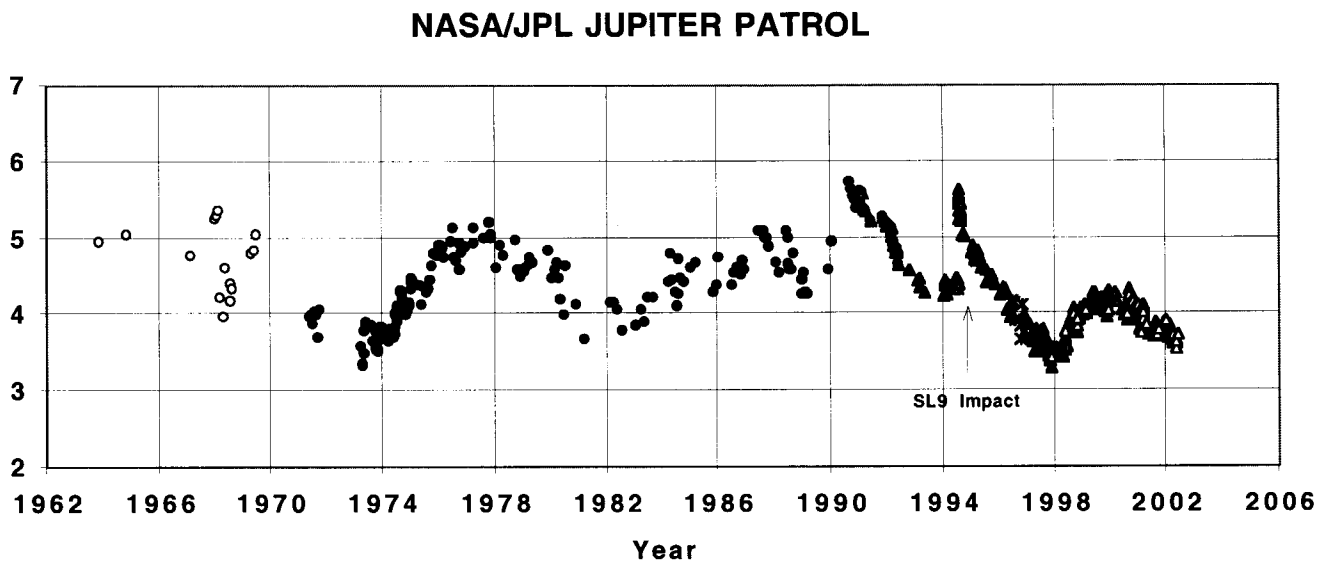


NASA DSN Jupiter Patrol @ 2.3 GHz

Time Variations -I

Observations exhibit time variations on time-scales from days, to years.

- Long-term (~ months) variations appear to be correlated with solar wind parameters, with lag times of 1-2 years
- Short-term (~ days) variations are probably real, but have yet to be explained.



Time Variations -II

Fragment impacts of Comet SL9 in July 1994 produced dramatic changes in Jovian synchrotron radio emission

- Dozens of papers have been published
- Interpretations are complicated by the following:
  - SL9 Impacts occurred at magnetic latitudes connected with the equatorial electrons
  - Relaxation time of synchrotron emission intensity following impacts are confused by "natural" time variations

- SL-9 Observations provide a rich data base that will be a valuable resource to test synchrotron emission models as they evolve.

Synchrotron Maps

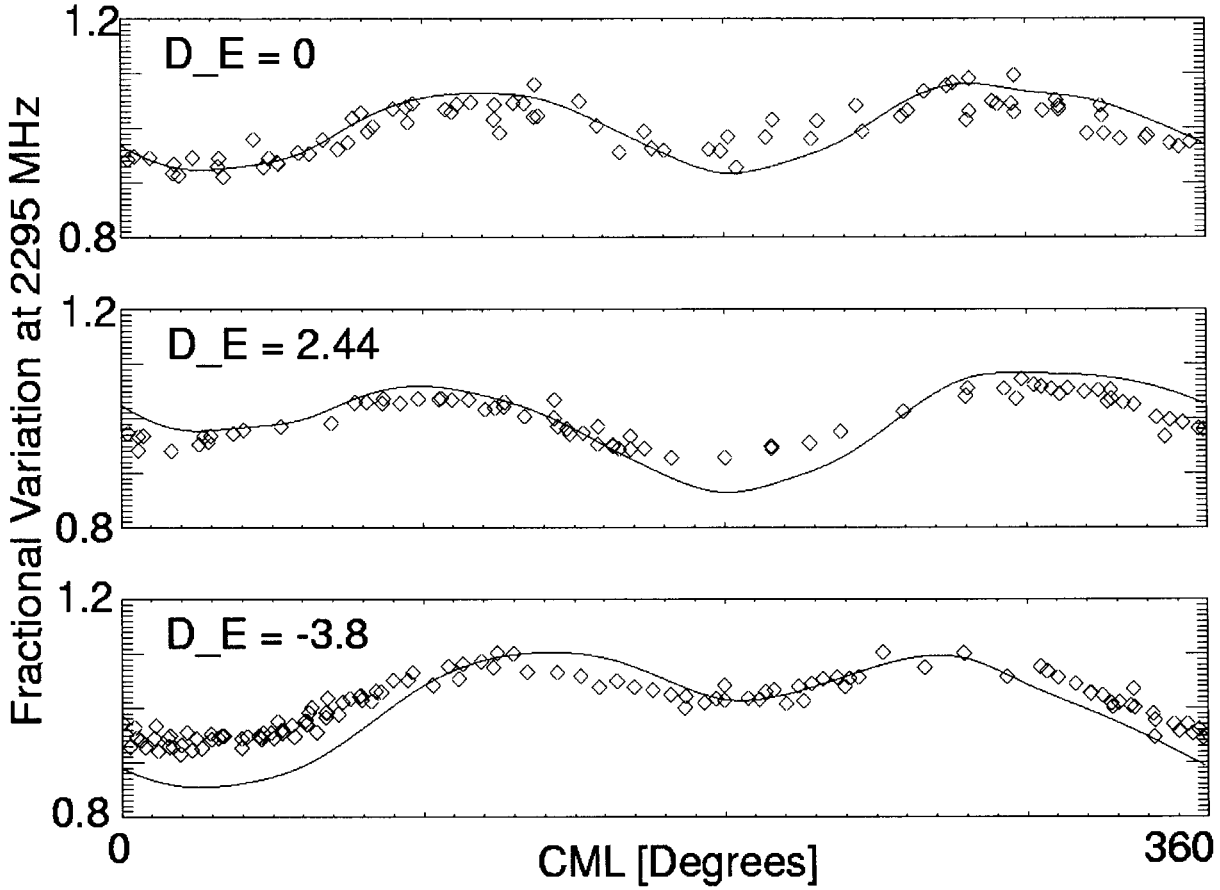
Map results depend upon combinations of pitch angle distribution, spatial distribution, energy distribution, magnetic field and viewing geometry.

Modeling in forward direction "works"

- Given input parameters, able to calculate synchrotron emission

Next step is to invert the process

- Find the set of parameters that produce the correct maps at multiple wavelengths and polarizations
- Must be consistent with *in situ* data



Because synchrotron emission is highly beamed, a longitudinally symmetric "pancake" of equatorial electrons, with the proper width, is sufficient to explain the beaming curve. The magnetic equator determines the shape of the beaming curve, and the degree of anisotropy determines the amount of variation. Using a set of input parameters adjusted to match (only) the map at 1400 MHz, the modeled beaming curve at 2295 MHz mimics the observations reasonably well.

Summary-1

- Microwave spectrum is being used to constrain energy distribution of radiating electrons
  - Cassini observations of 2.2cm synchrotron emission anchor the high end of the relativistic electron population in Jupiter's inner radiation belts. ***There are more electrons at energies below 20 MeV and less electrons above 20 MeV.***
  - Time variations of spectrum are being used to test models for electron energy gain and loss processes

- Microwave maps are used to model spatial distributions of the radiating electrons
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Summary-2

- Rotation Beaming Curves are used in conjunction with maps to model distribution of energetic electrons
  - Beaming curves from single aperture radio telescopes are able to "fill in" long time gaps between VLA mapping sessions
  - Because steady state beaming curves are explained by magnetic field and viewing angle (De), they constrain anisotropy of equatorial electrons

- Time variation observations are building a data base to test models for electron energy gain and loss processes, e.g.,
  - Influence of solar wind and/or satellite interactions
  - Other?

Future work is necessary to develop a comprehensive 3-D radiation belt model that is consistent with all observations and with theory.