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Microwave remote sensing of Jupiter's atmosphere from an orbiting spacecraft

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Abstract

Microwave remote sounding from a spacecraft flying by or in orbit around Jupiter offers new possibilities for retrieving important and presently poorly understood properties of its atmosphere. In particular, we show that precise measurements of relative brightness temperature as a function of off-nadir emission angles, combined with absolute brightness temperature measurements, can allow us to determine the global abundances of water and ammonia and study the dynamics and deep circulations of the atmosphere in the altitude range from the ammonia cloud region to depths greater than 30 bars in a manner which would not be achievable with ground-based telescopes.

Keywords: Jupiter, atmosphere; Abundances, interior; Radio observations; Radiative transfer

1. Introduction

Ground-based work to date, based mainly on high-resolution radio-wavelength observations made at the Very Large Array, has established a thermal spectrum for the integrated disk emission of Jupiter that shows the expected long-wavelength thermal signature of the deep atmosphere (e.g., Berge and Gulkis, 1976; de Pater et al., 2001; Gibson et al., 2004). However, as shown by de Pater et al. (2004), the integrated disk brightness temperature spectrum is difficult to interpret in terms of its deep composition, even if the measurement uncertainties were as low as one might optimistically expect to achieve with a large ground-based radio telescope (2–5%). Causes of this difficulty include accounting for the non-thermal synchrotron radiation that dominates the planet's emission at long wavelengths, uncertainties in atmospheric structure, cloud properties, and the absorption coefficients of water and ammonia under the conditions of high temperature and pressure encountered in the deep atmosphere.

2. Observation from an orbiting platform

Observation of Jupiter's long-wavelength atmospheric emission from an orbiting spacecraft offers many advantages over Earth-based observations. A spacecraft can fly inside the radiation belts, effectively avoiding the synchrotron emission that obscures the atmospheric thermal emission at longer wavelengths. An orbiting spacecraft allows observations with global coverage and high spatial resolution, made difficult from the VLA because of Jupiter's rotation and the need to perform rotational synthesis to image the planet. For example, Fig. 1 shows the nadir-viewing footprints afforded by an elliptical polar orbit with a perijove of 4500 km at the equator and a $20R_J$ apojove ($\sim$ 11-day period). This figure demonstrates that major dynamical features such as the belts,

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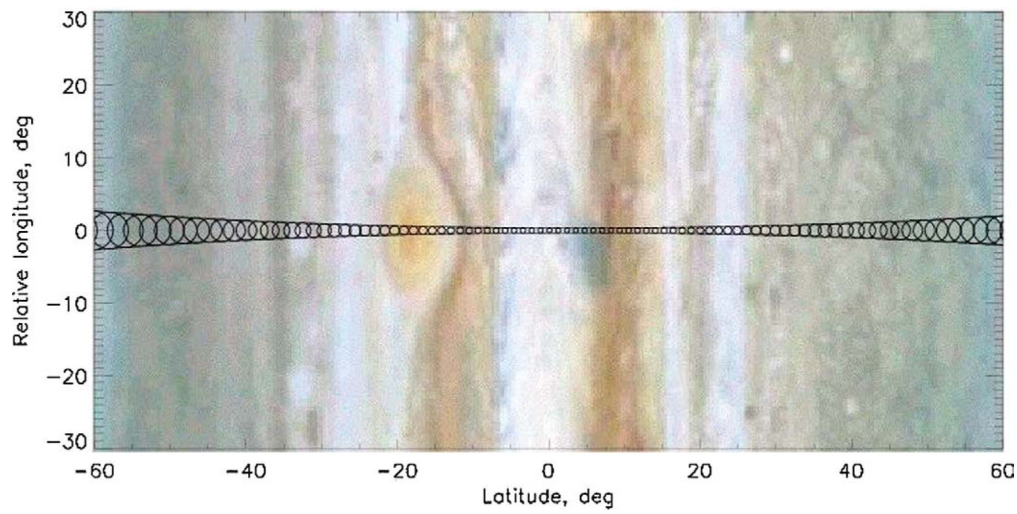

Fig. 1. Nadir footprints for a 10° beam from a nominal elliptical polar orbit (4500 km altitude at perijove, 11-day orbit). A spinning spacecraft is envisioned that scans each radiometer beam along the nadir track, so that each point is observed at a number of emission angles. The density of footprints is much greater than shown.

zones, red spot, and large ovals are readily resolved with the relatively large antenna beams practical at low frequencies from a spacecraft.

An immediate advantage over disk-averaged measurements is given by the ability to observe discrete points in the atmosphere along single lines of sight. The weighting functions and consequent spectral features are more sharply defined for this case than that for a disk average; e.g., by about 10% by our estimation. More importantly, by allowing the spacecraft to rotate so that the beams scan along the nadir track, each point can be viewed at many different emission angles. Absolute calibration at the 2% level or better is achievable in space-borne radiometers (e.g., Ruf et al., 1995; Keihm et al., 2000), comparable to or somewhat better than the ground-based approach. However, the relative brightness temperature, from point to point, or at different emission angles at the same point, can be measured with much higher precision. The ability to collect precise data on the emission angle and spatial dependence of the brightness temperature in combination with the spectrum determination offers an entirely new approach to the microwave sounding of Jupiter.

We estimate that a measurement precision of 0.1% is feasible for relative measurements taken with the same antenna and electronics at the same frequency over short time scales, after accounting for radiometer stability, beam uncertainties, residual synchrotron emission, and imperfect footprint overlap. Intrinsic radiometer noise is easily kept below 0.1% with 1-second signal averaging and modest (10 MHz) receiver bandwidths. Experience with the Cassini microwave radiometer has demonstrated that gain drifts can be maintained at better than this level for minutes to hours in a space environment with current technology (Janssen et al., 2001); further, state-of-the-art microwave noise sources used for gain calibration have demonstrated stability to this level over longer time scales (Tanner, 1998; Tanner and Riley, 2003).

We have investigated the effects of antenna pattern uncertainties and unaccounted emission entering through the sidelobes, including synchrotron emission from Jupiter's radiation belts, to see how these might compromise relative brightness temperature measurements. Within 10,000 km of Jupiter, state-of-the-art antenna design and beam pattern measurement allow the use of beams with $\sim 10°$ half-power widths to obtain relative brightnesses at the 0.1% level, to emission angles as large as 60°, and to at least 40° at much larger distances. Specifically we calculated that the antenna pattern must be known or controlled as follows: (1) main beamwidth to 2%, (2) sidelobes to 30° off-axis measured or suppressed to 30 dB below the central peak, and (3) sidelobes to 40° measured or suppressed to 40 dB. We revised a synchrotron emission model by Levin et al. (2001) to calculate synchrotron emission from the perspective of an orbiting spacecraft and determined that antenna backlobes must be kept below 55 dB at frequencies below 1 GHz to reduce the residual synchrotron contribution to the 0.1% level. Such requirements are within expected capabilities for horn antennas, patch-array and waveguide slot antennas (Rahmat–Samii, private communication, 2004).

Finally, the effect of horizontal variations in the atmosphere is minimized by observing the same locations at different emission angles. The nadir-viewing data can be averaged along-track to equalize the width of the footprint in latitude at off-nadir angles. The distance to the source increases at off-nadir angles, however, and the increased perspective of the longitudinal dimension (e.g., a factor of $\sqrt{3}$ at 60° emission angle) cannot be easily compensated for. On the other hand, the local horizontal variability is readily estimated from the nadir measurements and the consequent limb darkening uncertainty can be well bounded. Janssen et al. (1995) give a technique for estimating errors due to unequal beam footprints when the statistical properties of the measured quantity are known.