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Potential for Solar System Science with the ngVLA: the Giant Planets

Thematic Areas:
- Planetary Systems
- Star and Planet Formation
- Formation and Evolution of Compact Objects
- Cosmology and Fundamental Physics
- Stars and Stellar Evolution
- Resolved Stellar Populations and their Environments
- Galaxy Evolution
- Multi-Messenger Astronomy and Astrophysics

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Abstract: Radio wavelength observations of solar system bodies are a powerful method of probing the deep atmospheres of the giant planets, its rings, and magnetospheres. The ngVLA will enable the highest sensitivity and resolution observations of this kind, with the potential to revolutionize our understanding of these bodies.
1 Introduction

Composition of a body is a key parameter for planetary formation models. Observations at radio wavelengths provide unique information as they probe regions inaccessible by nearly all other remote sensing techniques and wavelengths. For example, at radio wavelengths one can probe depths up to many tens of bars in atmospheres of the giant planets, and their magnetic fields can be probed through emissions by electrons in such fields. In order to extract the most information, high spatial and high spectral resolution is essential, as well as sensitivity to large scale structure. Since the atmospheres of our giant planets are highly time variable (rotation of the body itself, winds, storms) excellent sensitivity and imaging characteristics on short timescales (minutes or less) is highly desirable. These are attributes being planned for the ngVLA.

Observations of the giant planets in the frequency range of the ngVLA (1–116 GHz) are sensitive to both thermal and non-thermal emissions. These emissions are received simultaneously, and can be distinguished from each other by examination of their different spatial, polarization, time (e.g., for lightning), and spectral characteristics. Given the sensitivity and resolution of the ngVLA, detailed maps of both of these types of emissions will be possible. Below we highlight recent VLA results on Jupiter, and discuss how these will be improved with the ngVLA. We refer to reader for more details to the review “Potential for Solar System Science with the ngVLA” by de Pater et al. (2018).

2 Giant Planet Deep Atmospheres

Understanding the coupling of gas abundances, temperature, and dynamics of the deep atmospheres of the giant planets is vital to our understanding of these planets as a whole, and to our understanding of extrasolar giant planets.

The atmospheres of the giant planets all emit thermal (blackbody) radiation. At radio wavelengths sources of opacity are collision induced absorption (CIA) by hydrogen, and absorption by NH$_3$, H$_2$S, PH$_3$, and H$_2$O gases (opacity by clouds can probably be ignored; de Pater et al., 2019). For near-solar composition atmospheres most of the atmospheric opacity has been attributed to ammonia gas, which has a broad absorption band near 22 GHz. Indeed, for Jupiter and Saturn NH$_3$ gas indeed dominates, but not for Uranus and Neptune. The S/N ratio on these planets appears to be considerably enhanced above the solar value, and spectra can be modeled well by including opacity from H$_2$S gas, and selectively increase the H$_2$S abundance considerably (factors of $\sim$ 10 and 30 for Uranus and Neptune, resp.) (e.g., de Pater & Mitchell, 1993, and references therein).

The thermal emission from all four giant planets has been imaged with the VLA. To construct high signal-to-noise images, one needs to be integrated over several hours, resulting in maps that are smeared in longitude and only reveal brightness variations in latitude. In order to discern longitudinal structures on radio maps, such as the Great Red Spot (GRS) on Jupiter, Sault et al. (2004) developed an algorithm to essentially take out a planet’s rotation. This algorithm has recently been applied to data of all planets obtained with the VLA after its upgrade. Below we highlight results on Jupiter.

A longitude-smeared image of Jupiter is shown in Fig. 1a. This composite multi-wavelength radio image of Jupiter reveals numerous bright bands across the disk. These bands are roughly
Figure 1: a) Radio image of Jupiter constructed from VLA data taken between December 2013 and May 2014 at three wavelengths: 2 cm in blue, 3.5 cm in gold, and 6 cm in red. A uniform disk had been subtracted to better show the fine banded structure on the planet. The pink glow surrounding the planet is synchrotron radiation produced by spiraling electrons trapped in Jupiter’s magnetic field. This image is averaged from several 10-hr observing sessions, so any longitudinal structure is smeared by the planet’s rotation. (de Pater et al., 2016). b) Longitude-resolved map of Jupiter at a wavelength of 2 cm (Ku band, 12-18 GHz), from panel a). As in panel a), bright features indicate a high brightness temperature, or low NH$_3$ abundance, so deeper warmer layers are probed. Much finescale structure can be discerned. The Great Red Spot (GRS) and Oval BA are indicated, as well as hot spots (yellow arrows), ammonia plumes (red), small vortices (cyan), and tiny ammonia plumes (orange). (Adapted from de Pater et al., 2019)

co-located with the brown belts seen at visible wavelengths. A longitude-resolved map is shown in panel b. The image shows an incredible amount of detailed structure, including the GRS and Oval BA, but also numerous small vortices, hot spots and plumes. The observed variations have been attributed to spatial variations in NH$_3$ gas, caused by a combination of atmospheric dynamics and condensation at higher altitudes (de Pater et al., 2016). Spectra of zones and belts from the longitude-smeared images, and spectra of individual features on the longitude-resolved maps have been used together with radiative transfer calculations to determine the altitude distribution of ammonia gas at these locations. These calculations show that ammonia gas is brought up from the deep atmosphere to the cloud condensation levels in the Equatorial Zone (EZ), and in particular in the large plumes (red arrows in Fig. 1b), and that the dry air is descending in the hot spots and North Equatorial Belt down to 20 bar or deeper. The hot spots coincide with hot spots seen at a wavelength of 5 $\mu$m; the plumes have been hypothesized to form the counterpart of the equatorial Rossby wave (de Pater et al., 2016) theorized to produce the 5 $\mu$m hot spots (e.g. Showman & Dowling, 2000).

3 Giant Planet Ring Systems

Images of Saturn’s microwave emission reveal, in addition to the planet itself, its rings. Using data from the upgraded VLA, Fig. 2 shows the rings and planet in exquisite detail. The planet itself is visible through its thermal emission, and displays zones and belts as on Jupiter. The emission from the planet’s rings is dominated by Saturn’s thermal radiation reflected off the ring particles. Only a small fraction of the radiation at centimeter wavelengths is thermal emission from the rings themselves. Water ice comprises the bulk of Saturn’s rings, yet it is the small
fraction of non-icy material that is key in revealing clues about the system’s origin and age. Using the Monte Carlo Simrings package (Dunn et al., 2002) to fit multi-wavelength (0.7–13 cm) VLA and 2-cm Cassini/RADAR data of the rings, Zhang et al. (2017; 2019) show that the non-icy fraction of the rings varies from 0.1–0.5% in the B ring, to 1–2% in the C ring, and that the particles overall are quite porous (75%-90%, depending on location in the rings). They further showed that there is a band in the middle C ring where the intrinsic thermal emission is almost constant with wavelength, and which has an anomalously high non-icy material fraction (6–11%). This has been interpreted by the presence of large particles, composed of rocky cores covered by porous, icy mantles. Assuming that the non-icy fraction is due to continuous impacts by micrometeorites, the rings have been estimated to be no older than 200 Myr, while the middle C ring might have been hit by a rocky Centaur 10–20 Myr ago.

4 Giant Planet Stratospheres

Several molecules are prevalent in the stratospheres of the giant planets, such as hydrocarbons $C_mH_n$ (formed e.g., via photochemistry from methane gas), $H_2O$, CO and HCN (resulting from infalling materials, and/or brought up from the deep atmosphere). The distribution and line profiles of these species will help distinguish between species (or fractions thereof) brought up from the deep atmospheres versus those brought in from the outside. The data can also be used to derive the wind profiles as a function of latitude and depth. Prominent emission lines of CO and HCN were detected on Neptune in the early 1990s (Marten et al., 1993), with abundances $\sim$ 1000 times higher than predicted from thermochemical models. While HCN cannot have been brought up as such from Neptune’s deep interior (it would condense), it is still unclear whether a fraction of the CO in Neptune’s stratosphere is brought up from below, or if all of it has an external origin. Since the production of CO in Neptune’s interior depends on the water abundance ($CH_4 + H_2O \rightarrow CO + H_2$) and the vertical mixing rate, an accurate measurement of CO constrains the water abundance in the planet’s interior. The CO 1-0 line is the most sensitive to a potential internal source through accurate measurements of the wings of the line, which are seen in absorption (originates in the troposphere), in contrast to the
emission line at its center (originating in the stratosphere). One of the challenges is to observe the entire line, which is several GHz wide, with a narrow emission peak $\lesssim 10$ MHz.

5 Jupiter’s Synchrotron Radiation

Synchrotron radiation has only been detected from Jupiter. It is emitted by high energy ($\sim 1$–100 MeV) electrons trapped in the planet’s radiation belts. The synchrotron emission morphology and intensity is changing over time due to the planet’s rotation, as well as in response to impacts (e.g., the impact of comet Shoemaker-Levy 9; de Pater et al., 1995), changes in the solar wind ram pressure, and any other phenomena (internal or external to the magnetosphere) that induce changes in the energetic electron distribution in Jupiter’s magnetosphere.

Jupiter’s synchrotron radiation has been imaged at frequencies between 74 MHz and 22 GHz (de Pater et al, 2003; de Pater & Dunn, 2003), usually in all 4 Stokes parameters to better constrain the models (e.g., magnetic field geometry). Because the radio emission is optically thin and Jupiter rotates in 10 h, one can use tomographic techniques to map the 3D radio emissivity. The shape of Jupiter’s radio spectrum is determined by the intrinsic spectrum of the synchrotron radiating electrons, the spatial distribution of the electrons and Jupiter’s magnetic field. Time variability in the radio spectrum most likely reflects a change in either the spatial or intrinsic energy distribution of the electrons. With the ngVLA we may begin investigating the cause of such variability through its imaging capabilities at high angular resolution at different wavelengths (quasi)-simultaneously, while at the same time being sensitive to short spacings. Synchrotron radiation has not been detected from any of the other giant planets; a sensitive search might reveal such radiation, or put stringent constraints on such emissions.

6 Potential of the ngVLA

To highlight the capabilities of the ngVLA, we have constructed a toy model of a planet with typical features: banded structure indicating zonal features, and gaussian features such as (cold) plumes and (warm) hotspots. We used Neptune as a sample case and superimposed structure on the planet. The features are constructed to be smallest at the limb with increasing size and spacing towards the center of the planet. The results are shown in Figure 3. Our toy model (panel a) is shown after subtraction of a limb-darkened disk (disk-averaged brightness temperature $\sim 120$ K); it is populated with both bright and dark bands and spots, that have a contrast of $\sim 1\%$ of the background, or 1-2K. Panel b) shows the toy model as it would be seen using the A configuration for the VLA. Panel c) shows the structure imaged with the full array, where features that are $1\mathrm{K}$ in magnitude and about $0.01\,$arcsec in size can be distinguished. The banded structure can be seen across all simulations, where the VLA substantially smears the bands and cannot pick up the fine-scale structure at the limb. Only the ngVLA is able to pick up a substantial number of the small point sources, including features as small as $0.01\,$arcsecs. This can be generalized to resolving structures down to a size of order $< 10\,$km/au, and with that an order of magnitude better than the VLA and Juno in the case of Jupiter. In terms of sensitivity, the large collecting area of the ngVLA results in the lowest RMS in the beam, as seen by the lack of structure off the disk.
Figure 3: a) A toy model of Neptune after subtraction of a limb-darkened disk. Note the positive (bright) and negative (dark) stripes in the southern hemisphere and spots near the center, and extending up into the northern hemisphere up to \( \sim 1/4 \) of a radius from the northern limb, outlined by the white disk. The brightness temperature of the various features is of order 1-2 K. The beam size is shown as a white oval in the bottom left of each simulation. b) Toy model as seen with the VLA in its most extended (A) configuration. c) Toy model as seen using the fully extended ngVLA array. (simulations by Moeckel & Tollefson)

7 Conclusions

- **Giant Planet Atmospheres:** To determine the composition and unravel the dynamics in planetary atmospheres we need to map the 3D distribution of gases in the troposphere (e.g., \( \text{NH}_3 \), \( \text{H}_2\text{S} \), perhaps \( \text{H}_2\text{O} \)) through mapping at continuum wavelengths across the entire ngVLA band at high spatial resolution (\( \sim 0.01'' \)), and by mapping the stratosphere of the planets in particular molecular line transitions (e.g., CO, HCN, \( \text{H}_2\text{O} \)) at high spatial and spectral resolution (\( \sim 0.01'' \) and \( \sim 100 \text{ kHz} \)) to spectrally resolve the emission core of the lines and spatially the limb of the planets.
- **Giant Planet Synchrotron Radiation:** We distinguish two goals: 1) Map the 3D distribution of Jupiter’s synchrotron radiation from 0.3-30 GHz. 2) Search for synchrotron radiation from the other giant planets. Measurements of all four Stokes parameters are key to interpret the data in terms of magnetic field geometry and electron (spatial + energy) distributions.
- **Planetary Rings:** High precision maps of rings at high spatial resolution and at different frequencies (2-100 GHz) are needed to determine the thermal and scattered (planet) light emission from the rings, which provides information on e.g., the particle size distribution and composition of rings. The mass fraction of non-icy material in Saturn’s rings provides an estimate of the age of the ring system. Polarization will help interpret the data.
References