URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Exoplanets and Radio Astronomy Beyond Earth

T. Joseph W. Lazio
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109 USA

Abstract

Jupiter's radio emission has been linked to its planetary-scale magnetic field, and spacecraft investigations have revealed that most planets, and some moons, have or had a global magnetic field. Generated by internal dynamos, magnetic fields are one of the few remote sensing means of constraining the properties of planetary interiors. For the Earth, its magnetic field has been speculated to be partially responsible for its habitability, and knowledge of an extrasolar planet's magnetic field may be necessary to assess its habitability. The radio emission from Jupiter and other solar system planets is produced by an electron cyclotron maser, and detections of extrasolar planetary electron cyclotron masers will enable measurements of extrasolar planetary magnetic fields. Key advances would include the ground-based detection of the radio emission from Jovian-mass planets and laying the technological foundations for space-based detections of the radio emissions from lower-mass planets.

1 Introduction

Even early explanations for Earth's magnetic field linked it to Earth's interior structure. After the discovery of Jupiter's radio emission [2, 9], it was determined that this radiation is due to Jupiter's magnetic field [3], which was then tied to the planet's interior structure. Remote sensing and *in situ* measurements have since shown that the Earth, Mercury, Ganymede, and the giant planets of the solar system all contain internal dynamos that generate planetary-scale fields; Mars and the Moon show residual magnetism indicative of past dynamos.

The stellar wind, a super- or transonic magnetized plasma, when incident on a planet's magnetosphere is an energy source to the magnetosphere. The radio emission from an electron cyclotron maser, resulting from this magnetosphere-solar wind interaction, has been detected from the Earth and all of the gas giants in the solar system. Detecting magnetospherically-generated radio emission from extrasolar planets provides a ready means to address a broad range of questions, two of which are

- What constraints can be placed on the interior structures and compositions of extrasolar planets? Internal dynamos arise from differential rotation, convection, compositional dynamics, or a combination of these processes. Knowledge of extrasolar planetary magnetic fields has the potential to constrain internal compositions and dynamics, which will be difficult to determine by other means.
- What characteristics of an extrasolar planet might contribute to it being habitable? A planet's magnetic field shields its atmosphere from its host star's stellar wind, which may be a factor in terrestrial planet habitability.

A combination of ground- and space-based telescopes will be required, with ground-based telescopes likely focusing on Jovian-mass planets and space-based telescopes likely focusing on ice giants and terrestrial planets.

This paper draws heavily on the W. M. Keck Institute for Space Studies report *Planetary Magnetic Fields: Planetary Interiors and Habitability* [12], and it incorporates topics discussed at the American Astronomical Society Topical Conference "Radio Exploration of Planetary Habitability."

2 Scientific Motivation

2.1 Planetary Interiors

The detection of even a single extrasolar planetary magnetic field could provide essential information on planetary interiors and dynamos. A limiting factor in understanding planetary dynamos is the small sample in the solar system [18, 17]. Just as the discoveries of hot Jupiters gave crucial

---

insights to the diversity of planets, the detection of extrasolar magnetic fields likely will improve our understanding of magnetic dynamos, including in our solar system.

Inferring planet compositions is an under-constrained inversion problem because planets with disparate compositions can have similar masses and radii. For instance, similar bulk densities could be obtained for a planet with a rock-ice interior and primordial H/He envelope or a water planet or a super-Earth with a H-rich outgassed atmosphere. Magnetic field measurements, providing information about interior structures and compositions, would complement measurements of upper atmosphere compositions obtained by spectroscopy.

The *absence* of magnetic fields in either ice giants or gas giant would challenge our understanding of their interiors. For ice giants, water is electrically conducting above a few thousand Kelvin [10], and detections of their magnetic fields would confirm their compositions as being substantially volatiles. Similarly, in Jovian planets with massive H/He envelopes, hydrogen is metallic above about 25 GPa [19], and they are expected to be convective at depth.

The presence of magnetic fields might be most informative for rocky planets, which are not guaranteed to have electrically conducting liquid iron cores. Partial solidification of the core may limit the range of planet masses that can sustain dynamos, and the extent to which an iron core solidifies is also sensitive to the presence of volatiles. Further, the energy budget for convection in Earth's core is marginal. Higher temperature ($>$ 1500 K), stronger tidal heating, higher concentrations of radioactive nuclei, the presence of a thick H/He envelope, or a stagnant lid tectonic regime could turn off convection (and a dynamo) in the core of an otherwise Earth-like planet. It is even possible that different mechanisms operating at different times have been responsible for generating the Earth's magnetic field [21]. The inference of convection via a magnetic field measurement would constrain the planet's thermal evolution and energy budget and may serve as an indirect indication of plate tectonics.

2.2 Planetary Habitability

Among the factors expected to affect habitability, the Exoplanet Science Strategy identified "[t]he presence and strength of a global-scale magnetic field, which depends on interior composition and thermal evolution ...." Further, "... the persistence of a secondary atmosphere over billion-year time scales requires low atmospheric loss rates, which in turn can be aided by the presence of a planetary magnetic field ...." Ideally, a large sample of planets, with a range of atmospheric compositions and magnetic field properties would be available to test the extent to which the presence of a magnetic field protects an atmosphere.

Table 1. Notional Requirements for Detecting Extrasolar Planetary Magnetic Fields

Parameter	Value	Rationale
Frequency	$\lesssim 50$ MHz	eqn. (1)
Sensitivity	$\lesssim 1$ mJy ($\lesssim 10^{29}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$)	Jupiter's flux density at ~ 10 pc
Polarization	Full	Electron cyclotron maser emission is circularly polarized.

Spacecraft observations confirm that the solar wind stagnates at the bow of a planet's magnetosphere, with the bulk of the plasma deflected around the magnetospheric cavity. As such, it seems plausible that a global field reduces a planet's atmospheric loss, in particular helping to retain the hydrogen and oxygen ions (i.e., water). Surprisingly, Venus, Earth, and Mars have similar present-day atmospheric losses, of order 10^{25} $\mathrm{O^+}$ $\mathrm{s^{-1}}$ from their polar regions [14].

3 Extrasolar Planetary Magnetic Fields

Electron cyclotron maser emission enables a direct measure of a planet's magnetic field (Figure 1). The emission occurs up to a characteristic frequency determined by the polar cyclotron frequency, which depends upon the planet's magnetic field B (in Gauss),

$$\nu_{\mathrm{ECM}} = 2.8\,\mathrm{MHz}\,B; \tag{1}$$

for Jupiter, $\nu_{\mathrm{ECM,J}} \approx 30\,\mathrm{MHz}$. Further, scaling laws exist, based on the solar system planets [20, 8, 4]. These relations are *predictive*, with the luminosities of Uranus and Neptune predicted before the Voyager 2 encounters [6, 5, 13].

The remainder of this paper focuses on a space-based detection of extrasolar planetary magnetic fields, and Table 1 presents a minimal set of requirements for such a future mission. I base my discussion on the Sun Radio Interferometer Space Experiment (SunRISE) [11], which is designed to observe solar radio bursts. SunRISE will be a synthetic aperture consisting of six small spacecraft (6U form factor, 10 cm × 20 cm × 30 cm), each carrying a dual-polarization dipole and collecting data at $\nu \leq$ 20 MHz. The constellation will have an altitude just above geosynchronous (GEO), with individual spacecraft orbits designed to produce an approximately 10 km-diameter synthetic aperture. SunRISE will not have the sensitivity to detect extrasolar planetary radio emission, but it meets the two other requirements of Table 1 and it would prove technologies for a future space-based telescope.

Over the next decade, I expect the following activities to occur in parallel:

- The Juno mission, and potentially subsequent outer planet missions, will improve our knowledge of the magnetic dynamos of the solar system's giant planets.
- Studies of the solar neighborhood will refine the target list of extrasolar planets for which magnetic field measurements would be possible and valuable.

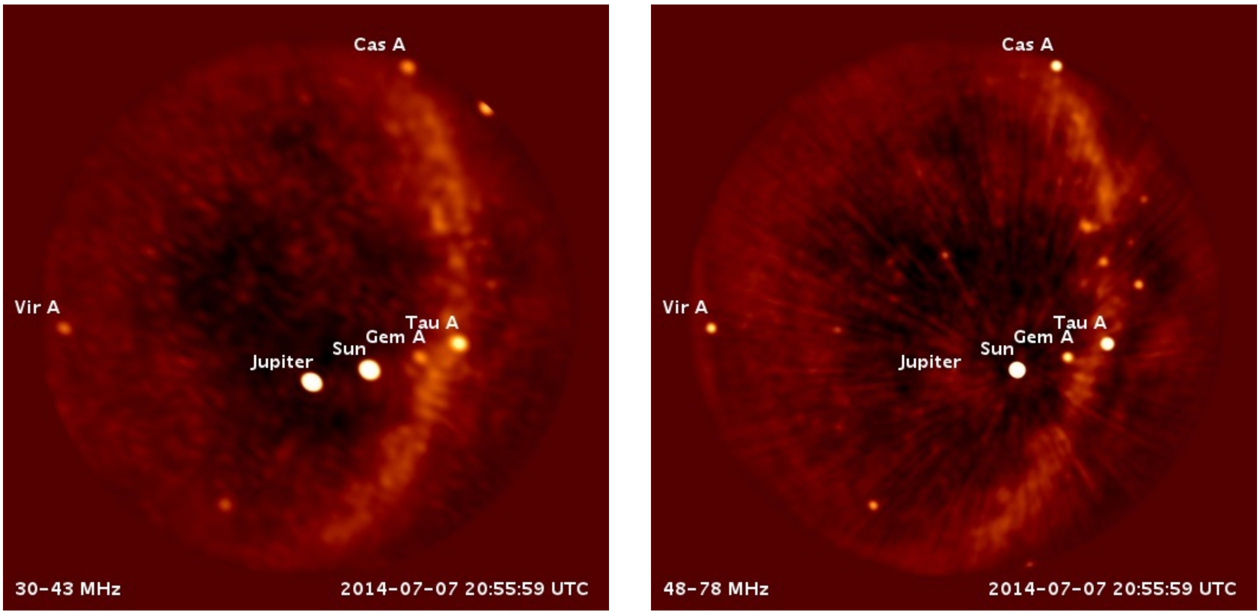

Figure 1. Jupiter as an extrasolar planet, as observed by the Owens Valley Radio Observatory-Long Wavelength Array at 30 MHz–43 MHz (*left*) and 47 MHz–78 MHz (*right*). Strong sources are labeled, notably including Jupiter and the Sun. Jupiter's absence in the higher frequency image is consistent with the cutoff frequency of its electron cyclotron maser emission. Ground-based telescopes have been making steady progress toward detecting analogous emissions from nearby giant planets; a space-based telescope would be required to study planets with weaker fields, such as might be expected for ice giants or terrestrial planets. (*Credit: M. Anderson)*

- Ground-based telescopes, e.g., the LWA, NenuFAR, and LOFAR, will improve upon the sensitivity and techniques for detecting extrasolar planetary magnetospheric emissions [e.g., 7], with a likely focus on giant planets, and potential surprises from ice giants if their fields are sufficiently strong. Surprises may result from observations at higher frequencies of younger planets, which may sustain higher field strengths.

Based on the number of antennas in the OVRO-LWA, NenuFAR, and LOFAR, I consider a mission concept of 100 spacecraft. There are considerable differences between 100-antenna arrays fixed to the (approximately) two-dimensional surface of the Earth and the six-dimensional phase space of a spacecraft constellation. I illustrate these differences by considering two likely technical challenges: **operations** and **data rates**, both of which were addressed partially in the 32-spacecraft RELIC concept [1].

Constellations with more than 100 spacecraft have been realized, most notably by the company Planet. However, these constellations are operated in Earth orbit, typically well separated in orbit and even on different orbital planes (orbital inclinations). In contrast, an extrasolar planetary radio mission concept, or a general low radio frequency astronomical mission concept, would have the spacecraft in a volume perhaps no more than 1000 km in radius, and potentially as small as 100 km.

The science community has realized constellations, including the four-spacecraft Magnetospheric Multiscale (MMS) mission, the seven-spacecraft Themis mission, and the four-spacecraft Cluster mission. These scientific constellations are not yet close to the scale required for extrasolar planetary radio emission studies, though, using an interferometric time-difference-of-arrival technique with the Cluster spacecraft, Mutel et al. [15, 16] determined the emission locations of the auroral kilometric radiation (AKR), i.e., Earth's electron cyclotron maser emission.

Collisions represent a potential operational difficulty for a radio astronomy constellation, being problematic not only because of immediate damage to the spacecraft involved but because any debris generated could affect other spacecraft. An uncertainty in a spacecraft's velocity of only 5 mm s^{-1} becomes a position uncertainty of approximately 3 km in a week. This position uncertainty is comparable to the scale of the SunRISE constellation ($\approx$ 10 km). For SunRISE, the orbits of the spacecraft are monitored on a weekly basis, and collision avoidance is a key factor limiting how long SunRISE can operate without ground communications.

An apparent "solution" would be a (local) mesh network that would enable each spacecraft to monitor its local environment and take action autonomously to avoid collisions. However, this "solution" has consequences. SunRISE carries three radios—one for the science data, one for reception of Global Navigation Satellite Service (GNSS) signals that are used for (ground-based) orbit determination, and one for telecommunications. If an additional radio needed to be added for realizing the mesh network, the available mass and volume might not be available within a 6U volume, increasing the cost of each spacecraft and of the overall mission. Further, a spacecraft would have to generate sufficient power to ensure that the mesh network could be maintained over sufficiently large distances that each spacecraft could identify other approaching spacecraft.

Turning to consider data rates, it is a simple exercise to show that, with a mere 1 MHz bandwidth (Nyquist sampled) and a modest 4-bit sampling depth, a single spacecraft would produce 16 Mbps. The full 100-spacecraft constellation would produce of order 1.6 Gbps.

For comparison, the entire SunRISE constellation has a data rate of order 2 Mbps, due to a combination of spectrum allocation regulations and a lack of space-qualified radios for small spacecraft at frequencies for which larger spectrum allocations exist ("near-Earth Ka band," ≈ 26 GHz). The NASA-Indian Space Research Organization (ISRO) Synthetic Aperture Radar (NISAR) mission will transmit a data rate of up to 4 Gbps, which can be sustained only by a combination of dual radios on a relatively large spacecraft and a low-Earth orbit (LEO) altitude of only 750 km (compared to SunRISE's altitude of nearly 40 000 km).

Acknowledgments

It is a pleasure and privilege to thank the many colleagues who have aided my understanding of planetary magnetic fields, planetary radio emissions, and the possibilities for (and challenges of) future space missions. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Some of the information in this paper is pre-decisional and for planning and discussion purposes only.

References

1 Belov, K., Branch, A., Broschart, S., et al. 2018, "A space-based decametric wavelength radio telescope concept," *Exp. Astron.*, **46**, pp. 241–284

2 Burke, B. F., and Franklin, K. L. 1955, "Observations of a Variable Radio Source Associated with the Planet Jupiter," *J. Geophys. Res.*, **60**, pp. 213–217

3 Carr, T. D., and Gulkis, S. 1969, "The Magnetosphere of Jupiter," *Ann. Rev. Astron. Astrophys.*, **7**, pp. 577–618

4 Christensen, U. R. 2010, "Dynamo Scaling Laws and Applications to the Planets," *Space Sci. Rev.*, **152**, pp. 565–590

5 Desch, M. D. 1988, "Neptune radio emission: Predictions based on planetary scaling laws," *Geophys. Res. Lett.*, **15**, pp. 114–117

6 Desch, M. D., and Kaiser, M. L. 1984, "Predictions for Uranus from a radiometric Bode's law," *Nature*, **310**, pp. 755–757

7 de Gasperin, F., Lazio, T. J. W., & Knapp, M. 2020, "Radio Observations of HD80606 Near Planetary Periastron: II. LOFAR Low Band Antenna Observations at 30–78 MHz," *Astron. & Astrophys.*, in press; arXiv:2011.05696

8 Farrell, W. M., Desch, M. D., and Zarka, P. 1999, "On the possibility of coherent cyclotron emission from extrasolar planets," *J. Geophys. Res.*, **104**, pp. 14025–14032

9 Franklin, K. L., and Burke, B. F. 1956, "Radio observations of Jupiter," *Astron. J.*, **61**, p. 177

10 French, M., Mattsson, T. R., Nettelmann, N., and Redmer, R. 2009, "Equation of state and phase diagram of water at ultrahigh pressures as in planetary interiors," *Phys. Rev. B*, **79**, 054107

11 Kasper, J., Lazio, J., Romero-Wolf, A., Lux, J., and Neilsen, T. 2020, "The Sun Radio Interferometer Space Experiment (SunRISE) Mission Concept," in *2020 IEEE Aerospace Conference*

12 Lazio, T. J. W., Shkolnik, E., Hallinan, G., et al. 2016, *Planetary Magnetic Fields: Planetary Interiors and Habitability* (Keck Institute for Space Studies: Pasadena, CA) doi: 10.26206/EDQW-D450

13 Millon, M. A., and Goertz, C. K. 1988, "Prediction of radio frequency power generation of Neptune's magnetosphere from generalized radiometric Bode's law," *Geophys. Res. Lett.*, **15**, pp. 111–113

14 Moore, T. E., and Khazanov, G. V. 2010, "Mechanisms of ionospheric mass escape," *J. Geophys. Res.: Space Physics*, **115**, A00J13

15 Mutel, R. L., Gurnett, D. A., Christopher, I. W., Pickett, J. S., and Schlax, M. 2003, "Locations of auroral kilometric radiation bursts inferred from multispacecraft wideband Cluster VLBI observations. 1: Description of technique and initial results," *J. Geophys. Res.*, **108**, 1398

16 Mutel, R. L., Gurnett, D. A., and Christopher, I. 2004, "Spatial and temporal properties of AKR burst emission derived from Cluster WBD VLBI studies," *Annales Geophys.*, **22**, 2625

17 Schubert, G., and Soderlund, K. M. 2011, "Planetary magnetic fields: Observations and models," *Phys. Earth Plan. Interiors*, **187**, pp. 92–108

18 Stevenson, D. J. 2010, "Planetary Magnetic Fields: Achievements and Prospects," *Space Sci. Rev.*, **152**, pp. 651–664

19 Wigner, E., and Huntington, H. B. 1935, "On the Possibility of a Metallic Modification of Hydrogen," *J. Chem. Phys.*, **3**, pp. 764–770

20 Zarka, P., Queinnec, J., Ryabov, B. P., et al. 1997, "Ground-Based High Sensitivity Radio Astronomy at Decameter Wavelengths," in *Planetary Radio Emissions IV*, eds. H. O. Rucker, S. J. Bauer, and A. Lecacheux (Austrian Academy of Sciences: Vienna) pp. 101–127, ISBN: 3700126913

21 Ziegler, L. B., and Stegman, D. R. 2013, "Implications of a long-lived basal magma ocean in generating Earth's ancient magnetic field," *Geochem. Geophy. Geosy.*, **14**, 4735