# Detecting and Characterizing Extrasolar Planets via Magnetospheric Emissions

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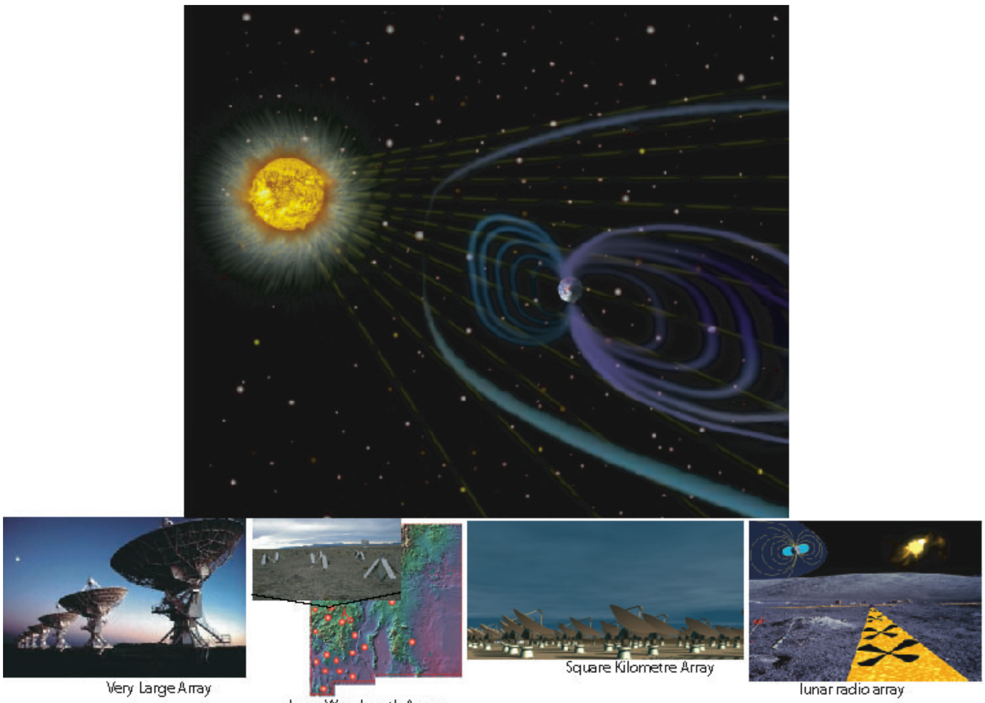
## EXECUTIVE SUMMARY

All of the solar system giant planets and Earth produce radio wavelength emissions as a result of an interaction between their magnetic fields and the solar wind. In the case of the Earth, its magnetic field may contribute to its habitability by protecting its atmosphere from solar wind erosion and by preventing energetic particles from reaching its surface. Indirect evidence for at least some extrasolar giant planets also having magnetic fields is the modulation of calcium emission lines of their host stars. If magnetic fields are a generic property of giant planets, then extrasolar giant planets should emit at radio wavelengths. In the case of terrestrial-mass planets, if magnetized, they should also emit at radio wavelengths, and detecting this radiation may be a means of assessing their habitability. Existing radio wavelength observations place limits comparable to the flux densities expected from the strongest emissions. Future radio wavelength facilities will offer more than one order of magnitude improvement.



Very Large Array

Long Wavelength Array

Square Kilometre Array

lunar radio array

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## 1. Planetary Magnetospheric Emissions

The Earth and gas giants of our solar system are described commonly as "magnetic planets" because they contain internal dynamo currents that generate planetary-scale magnetic fields. These magnetic fields are immersed in the solar wind, a high-speed magnetized plasma. The solar wind deforms a planetary magnetic field, compressing the field on the front side and elongating it on the back, forming a "tear-dropped"–shaped magnetosphere aligned with the solar wind flow. The magnetopause forms the boundary between the magnetosphere, in which the planet's magnetic field is dominant, and the solar wind. The stellar wind incident on the magnetopause is an energy source to the planetary magnetosphere.

All of the solar system's magnetic planets generate electron cyclotron masers within their magnetospheres via a coupling between it and the incident solar wind. The magnetosphere-solar wind interaction produces energetic (keV) electrons that then propagate along magnetic field lines into auroral regions, where an electron cyclotron maser is produced.

Specific details of the cyclotron maser emission vary from planet to planet, depending upon such secondary effects as the planet's magnetic field topology. Nonetheless, applicable to all of the magnetic planets is a macroscopic relation relating the incident solar wind power $P_{\mathrm{sw}}$, the planet's magnetic field strength, and the median radio luminosity $L_{\mathrm{rad}}$ (Figure 1). Various investigators (Desch & Barrow, 1984; Desch & Kaiser, 1984; Desch & Rucker, 1985; Barrow et al., 1986; Rucker, 1987; Desch, 1988; Millon & Goertz, 1988) find

$$L_{\mathrm{rad}} = \epsilon P_{\mathrm{sw}}^{x}, \qquad (1)$$

with $\epsilon$ the efficiency at which the solar wind power is converted to radio luminosity, and $x \approx 1$. The value for $\epsilon$ depends on whether one considers the magnetic energy or kinetic energy, respectively, carried by the stellar wind. The strong solar wind dependence is apparent in Figure 1, as the luminosity of the Earth is larger than that of either Uranus or Neptune, even though their magnetic field are 10–50 times stronger than that of the Earth.

The incident solar wind power depends upon the ram pressure of the solar wind and the cross-sectional area of the magnetosphere. In general, the magnetopause has a dynamic configuration determined by the instantaneous solar wind flow, but the average cross-sectional area depends upon the strength of the planet's magnetic field, which can be estimated from various planetary (Figure 1).

The electron cyclotron maser occurs at a characteristic emission frequency (or wavelength) determined by the cyclotron frequency in the magnetic polar region, which in turn depends upon the planet's magnetic moment or magnetic field strength. Using a similar set of arguments (Figure 1), one can predict this characteristic frequency.

These scaling relations are not only descriptive but also *predictive*. Before *Voyager 2* reached both Uranus and Neptune, their luminosities were predicted (Desch & Kaiser, 1984; Desch, 1988; Millon & Goertz, 1988). For both planets, the predictions were in excellent agreement with the measurements.

Indirect evidence for extrasolar planetary magnetic fields is found in modulations of the Ca II H and K lines of the stars HD 179949 and $\upsilon$ And—modulations in phase with planetary orbital periods (Shkolnik et al., 2005). In addition, while the Ca II lines of $\tau$ Boo do not vary, Catala et al. (2007) find an apparently complex magnetic field topology for the star itself, consistent with a possible interaction with the planet's magnetic field.

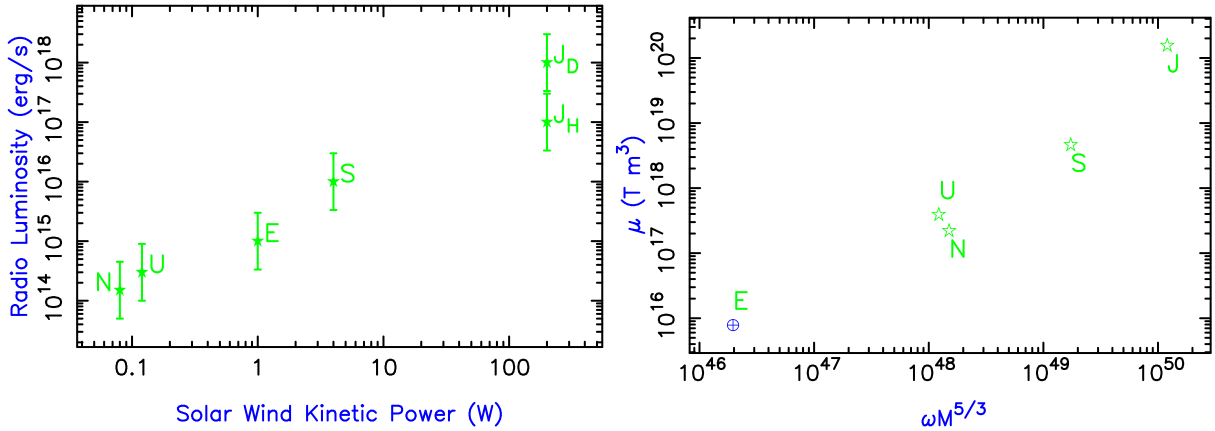


Fig. 1.— *(Left) The coupling between planetary magnetospheric emissions and the incident solar wind kinetic energy. Plotted are the luminosities for the five magnetic planets; for Jupiter, both its hectometric and decametric emissions are shown (from Zarka et al., 2001). A similar relation exists for the magnetic energy contained in the solar wind. (Right) The magnetic moment or surface magnetic field strength as a function of the quantity $\omega M^{5/3}$, where $\omega$ is the rotation rate of the planet and $M$ is its mass. This quantity was determined empirically by Blackett (1947). Modern versions exist, including attempts to "derive" the appropriate scaling, but they typically differ only slightly in the value of the exponents for $\omega$ and $M$.*

These solar system scaling laws enable quantitative predictions for an extrasolar planet's radio emission (Zarka et al., 1997; Farrell et al., 1999; Zarka et al., 2001; Lazio et al., 2004; Stevens, 2005; Zarka, 2006, 2007). In the case of a known planet, these estimates depend either upon measured parameters—the planet's mass and orbital semi-major axis—or upon parameters that can be estimated reasonably—the rotation rate can be assumed to be of order 10 hr. Combined with the distance of the star from the Sun, one can predict the planet's flux density. Figure 2 illustrates a recent set of predictions for extrasolar planets. In the case of stars not yet known to have planetary companions, any radio limits can be inverted to obtain constraints on the presence of planets.

Implicit in some of the early predictions (and Figure 2) is that the stellar winds of other stars are comparable to the solar wind. From measurements of the sizes of astropauses (i.e., the boundary between the stellar wind and the local interstellar medium), Wood et al. (2002, 2005) find the mass loss rate as a function of age, $\dot{M} \propto t^x$, with $x \approx -2$. Thus, the stellar wind around a 1 Gyr old star may be 25 times as intense as the solar wind.

Accordingly, planets around young or "adolescent" stars are likely to have stronger cyclotron maser emissions than the planets in our solar system. Young stars are often not observed in radial velocity surveys because the high stellar activity levels (which are in turn related to their stellar wind strengths) make it problematic to isolate a planetary signal. Thus, a blind survey for magnetospheric emissions presents a search methodology that could mitigate a selection bias in the current extrasolar planet census. If iron-rich "super-Earths" exist, they may also have sufficiently strong magnetic fields to power radio emissions detectable over interstellar distances.

As a specific illustration of the effect of stronger stellar winds, early predictions for the flux density of the planet orbiting $\tau$ Boo were of order 1–3 mJy at wavelengths

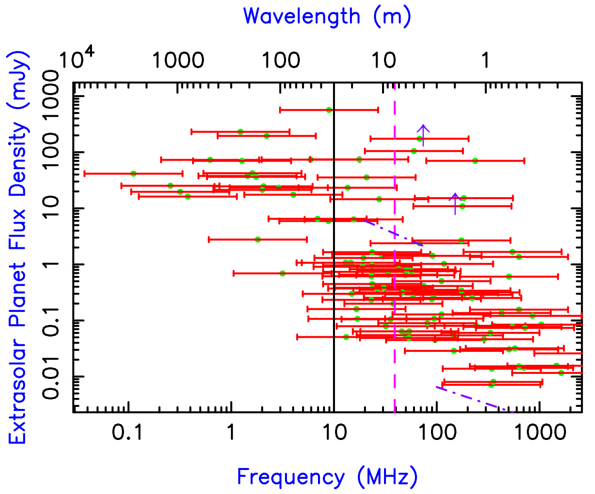


Fig. 2.— *Predicted flux densities for extrasolar planets based on empirical solar system scaling laws (Lazio et al., 2004). Horizontal bars indicate the ranges for the emission frequencies, allowing for statistical variations in planetary magnetic moments. Sensitivities for the 74-MHz VLA and the 151-MHz GMRT are shown as arrows (§3.1). The expected sensitivity of the LWA (SKA) is the upper (lower) sloped line (§3.2); for clarity, LOFAR is not shown, though its sensitivity should be similar to that of the LWA. The dashed vertical line indicates the approximate cutoff frequency for Jupiter. The solid vertical line indicates the approximate ionospheric cutoff; ground-based observations are not possible to the left of this line.*

around 10 meters (Farrell et al., 1999; Lazio et al., 2004). More recent estimates, that attempt to take into account the likely stellar wind strength of $\tau$ Boo, predict flux densities of order 60–300 mJy. The former prediction (1–3 mJy) is below the sensitivity of current instrumentation; the latter is not.

## 2. Magnetic Fields and Planetary Characterization

The dynamo currents generating the planetary magnetic field arise from the rapid rotation of a conducting fluid in the planet's interior. Consequently, magnetic fields can provide a variety of information about the planet, some of which can be difficult to determine reliably by other means.

For the solar system planets, the composition of the conducting fluid ranges from liquid iron in the Earth to probably metallic hydrogen in Jupiter and Saturn to probably a salty ocean in Uranus and Neptune. The high-frequency cutoff of Jovian emissions ($\simeq$ 40 MHz) allowed an estimate for the strength of the Jovian magnetic field 20 yr prior to *in situ* observations. Likewise, radio detection of the magnetic field of an extrasolar planet would provide an indication of the planet's internal composition, insofar as it would require the planet to have a partially conducting interior. Combined with an estimate of the planet's mass, one could deduce the composition of the fluid by analogy to the solar system planets.

Planetary rotation not only appears necessary to generate the magnetic field, but it can also impose a periodic modulation on the radio emission. As the magnetic field is presumed to be tied to the interior of the planet, it provides a more accurate measure of the planet's rotation rate than atmospheric phenomena such as clouds. For instance, the rotation period of Neptune was determined initially by observations of differentially rotating cloud tops but then was redefined after detection of its radio emission (Lecacheux et al., 1993).

In addition to being modulated by its rotation, Jupiter's radio emission is affected strongly by the presence of its satellite Io, and more weakly by Callisto and Ganyemede. As the Jovian magnetic field sweeps over a moon, a potential is established across the moon by its $\mathbf{v} \times \mathbf{B}$ motion in the strong Jovian magnetic field. This potential drives currents along the magnetic field lines connecting the moon to the Jovian polar regions, where the currents modulate the radio emission. Modulations of planetary radio emission may thus also reveal the presence of a satellite.

Finally, there have been a number of suggestions that a planetary-scale magnetic field may influence the habitability of a planet. All of them rely on the magnetic fields deflecting cosmic rays, high-energy charged particles (e.g., Wdowczyk & Wolfendale, 1977; Griessmeier et al., 2005).

**Atmospheric retention** A common and simple means of estimating whether a planet can retain its atmosphere over geological time is to compare the thermal velocity of atmospheric molecules with the planet's escape velocity. If the thermal velocity is a substantial fraction of the escape velocity, the planet will lose its atmosphere.

For a planet immersed in a stellar wind, *nonthermal* atmospheric loss mechanisms can be important (Shizgal & Arkos, 1996). These are varied (sputtering, mass loading), but all result from the typical stellar wind particle having a *supra-thermal* velocity relative to the planet's atmosphere. If directly exposed to a stellar wind, a planet's atmosphere can erode more quickly than a thermal-only estimate would suggest. While this effect is unlikely to be important for the known extrasolar giant planets, it is thought to have been important for the Martian atmosphere (Mitchell et al., 2001; Lundin et al., 2004).

**Planetary albedo** Cosmic rays can induce nucleation in water-vapor–saturated air and stimulate cloud formation. Larger cosmic ray fluxes can produce more cloud cover and an increased albedo. This effect has already been seen for Galactic cosmic rays (Svensmark, 2000), but stellar wind particles may be an important secondary effect.

**Genetic impact** If the cosmic ray flux at the surface of an otherwise habitable planet is too large, it could cause severe cellular damage and disruption of genetic material to any life on its surface or frustrate its origin altogether.

## 3. Observational Prospects

The magnetospheric emissions of the solar system planets motivated searches for analogous emissions prior to the discovery of extrasolar planets (Yantis et al., 1977; Winglee et al., 1986). The two significant changes in the past decade have been the discovery of extrasolar planets and the initiation of projects to construct sensitive long-wavelength telescopes. (See also Zarka et al. 1997.)

### 3.1. Current Ground-based Facilities

The scaling relations developed from solar system planets predict that the relevant frequencies are below 1000 MHz ($\lambda > 30$ cm). The two premier instruments in this range are the Very Large Array (VLA), with its 74 MHz system, and the Giant Metrewave Radio Telescope (GMRT), with its 150 MHz system. Notably, the 74-MHz VLA observes at a frequency that is within a factor of two of the highest frequency Jovian emissions (40 MHz or 7.5 m wavelength). There have been a handful of searches at both telescopes, targeting known extrasolar planets.

Perhaps the most effort has been directed toward the planet orbiting $\tau$ Boo (Bastian et al., 2000; Farrell et al., 2003; Lazio & Farrell, 2007), as various authors predict that its flux density is comparable to or greater than what can be obtained in a modest duration (few hours) observation (Farrell et al., 1999; Lazio et al., 2004; Stevens, 2005). Lazio

& Farrell (2007) have obtained multi-epoch observations, as magnetospheric emissions are expected to be "bursty" and the predicted flux densities are just comparable to the current sensitivity limits. A single observation might occur at an inopportune time when the stellar wind flux was below average. The observational limits now constrain this planet's luminosity to be less than $10^{23}$ erg s$^{-1}$, unless its radiation is highly beamed into a solid angle $\Omega \ll 1$, which would be much smaller than that for any of the solar system planets. Presuming that the radiation is not highly beamed, this luminosity limit is lower than some, but not all, recent predictions. Although higher sensitivity observations are likely required, the non-detection may also be hinting that the magnetic fields, and internal compositions, of extrasolar planets are as varied as the planets themselves.

**3.2. Future Ground-based Facilities** There are a number of long-wavelength telescopes, in various stages of development, which will have sensitivities potentially as much as two orders of magnitude better than current facilities (Figure 2). For some facilities, searching for the radio emission from extrasolar planets is recognized explicitly as part of the science case.

In the initial construction phases are the Long Wavelength Array (LWA, in New Mexico) and the Low Frequency Array (LOFAR, in the Netherlands). The LWA will operate in the 20–80 MHz band (3.75–15 m wavelength); LOFAR will operate in the 30–80 MHz and 110–240 MHz bands (1.25–2.7 m wavelength). Both instruments cover the frequency range expected for emission from Jovian-mass to several Jovian mass planets.

The Square Kilometer Array (SKA) is a next-generation telescope that is expected to operate above 100 MHz. Located either in Australia or South Africa, its design goals are such that it should be easily capable of detecting the radio emissions from the most massive extrasolar planets.

**3.3. Future Space Facilities** A significant constraint to all ground-based facilities is the Earth's ionosphere. While the value changes with time (e.g., day vs. night), the ionosphere generally is opaque below about 10 MHz ($\lambda > 30$ m). Jupiter produces the most intense and highest frequency emissions of the solar system planets, but even these cut off above 40 MHz. The Earth's magnetosphere emits auroral kilometric radiation (AKR) below 1 MHz. Thus, the detection of AKR from extrasolar terrestrial-mass planets—and assessments of their habitability (§2)—can only be accomplished from space.

The most promising location for a telescope designed to detect AKR from extrasolar terrestrial-mass planets is the far side of the Moon. Not only is the far side always shielded from the Earth, for half of the Moon's orbit, an array on the far side would be shielded from solar radio emissions as well.

Proposals for a lunar radio telescope predate the Apollo missions (North American Aviation, 1966; Greiner, 1967). NASA plans a return to the Moon in the next decade ($\sim$ 2018), while ESA, the aerospace company EADS, and various European institutes have been investigating the deployment of a lunar radio array. It is unlikely that a lunar far-side array could be constructed on this time frame, as prototype arrays would need to be constructed first. Lazio et al. (2007) have described the science case and a strawman plan for how a series of ever more capable lunar radio telescopes could be deployed.

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