

RADIO DETECTION OF EXTRASOLAR PLANETS: PRESENT AND FUTURE PROSPECTS

T. J. W. Lazio* and W. M. Farrell†

Abstract

The five “magnetic” planets in the solar system (Earth and the four gas giants) emit at radio frequencies because solar-wind powered electron currents deposit energy in their magnetic polar regions. We summarize predictions of the radio emission from the known extrasolar planets and initial detection efforts. Most of the known extrasolar planets should emit in the frequency range 10–1000 MHz and, under favorable circumstances, some may have flux densities above 0.1 Jy. The current limits set by observations with the Very Large Array (VLA) and the Giant Metrewave Radio Telescope (GMRT) are consistent with but generally do not provide strong constraints on the predictions. Future radio telescopes, such as the Long Wavelength Array (LWA), the Mileura Widefield Array (MWA), Low Frequency Array (LOFAR) and the Square Kilometer Array (SKA), should be able to detect the known extrasolar planets or place austere limits on their radio emission. Planets with masses much lower than those in the current census will probably radiate below 10 MHz and will require a space-based array.

1 Introduction

The past few years have been an exciting time as extrasolar planets have been demonstrated to be widespread and multiple planetary systems have been found. The current census now numbers more than 150 extrasolar planets, in nearly as many planetary systems [Schneider, 2005].

The vast majority of these extrasolar planets have been detected via the reflex motion of the host star. As the existing census shows, this method has proven to be wildly successful. Nonetheless, the reflex motion of the star is a measure of the planet’s gravitational influence and is necessarily an *indirect* detection of the planet. Combined with the mass

* Naval Research Laboratory, 4555 Overlook Ave. SW, Washington, DC 20375-5351, USA

† NASA Goddard Space Flight Center, Greenbelt, MD, USA

function's dependence on the inclination angle ($\sin i$), the only property of the planet that one can infer is a minimum mass.

Detection of reflected, absorbed, or emitted radiation from a planet provides complementary information, and likely a more complete characterization of the planet. The prototype of such a direct detection is the sodium absorption from the atmosphere of the planet orbiting HD 209458 [Charbonneau et al., 2002], with the *Spitzer* observations of the thermal infrared emission from the planets orbiting TrES-1 and HD 209458 being spectacular, recent examples of direct planetary detections [Charbonneau et al., 2005; Deming et al., 2005]. Detection of radio emission from extrasolar planets would provide constraints on quantities such as their rotation rates and compositions.

The Earth and gas giants of our solar system are “magnetic planets,” containing internal dynamo currents that generate planetary-scale magnetic fields. The dynamo currents themselves arise from the rapid rotation of conducting fluids—liquid iron in the case of the Earth, probably metallic hydrogen in Jupiter and Saturn, and probably a salty ocean in Uranus and Neptune. In turn, these planetary magnetic fields are immersed in the solar wind. Via a coupling between the solar wind and the planetary magnetic fields, these magnetic planets produce radio emission.

By analogy to solar system planets, there have been a number of suggestions and searches for natural radio emission from extrasolar planets. Some of the extrasolar planets may indeed be magnetic planets. Shkolnik et al. [2003] have detected a modulation in Ca II lines from HD 179949 with a periodicity which is that of its orbiting planet. They infer a magnetic interaction between the star and planet, though there is no constraint on the magnetic field strength of the planet.

Detection of radio emission from an extrasolar planet could indicate the polar magnetic field strength at the planet, just as the 40 MHz cutoff of Jovian decametric bursts provided an estimate of the Jovian magnetic field strength 20 yr prior to *in situ* observations. The presence of a magnetic field also provides a rough measure of the composition of the planet, insofar as it requires the planet's interior to have a conducting fluid. Combined with an estimate of the planet's mass, one could deduce the composition of the fluid by analogy to the solar system planets.

The periodic nature of the radio emission is used to define the rotation periods of all of the gas giant planets in the solar system. As the magnetic field is presumed to be tied to the interior of a planet, it provides a more accurate measure of the planet's rotation rate than atmospheric phenomena such as clouds, which will be difficult to discern for extrasolar planets in any case.

Finally, there have been a number of suggestions that the extent to which cosmic rays are or are not deflected by a planetary-scale magnetic field may influence a planet's “habitability” [e.g., Wdowczyk and Wolfendale, 1977]. A magnetic field aids in the retention of a terrestrial planet's atmosphere [Shizgal and Arkos, 1996; Mitchell et al., 2001; Lundin et al., 2004]; may influence its albedo by reducing the density of nucleation sites at which clouds can form [Svensmark, 2000]; and may protect any organisms on the planet's surface from disruption of genetic material. While the current census is unlikely to contain any habitable planets, potentially habitable planets are likely to be discovered in the future.

The known extrasolar planets provide a valuable test bed with which to probe the “*universality*” of the radio emission process. Determining the extent to which magnetic fields can be estimated for extrasolar planets is crucial, particularly if magnetic fields play a role in habitability.

2 Magnetic Fields and Planetary Radio Emission

Various authors [Farrell et al., 1999; Zarka et al., 2001; Lazio et al., 2004; Sánchez-Lavega, 2004; Stevens, 2005] have described how one can make quantitative predictions about the radio emission from extrasolar planets. We summarize the salient points.

All of the solar system’s magnetic planets contain radio-wavelength electron cyclotron masers. The electron cyclotron maser emission arises from energetic (keV) electrons propagating along magnetic field lines into active auroral regions [Gurnett, 1974; Wu and Lee, 1979]. The source of the electron acceleration is ultimately the coupling between the incident solar wind and the planet’s magnetic field, which energizes the plasma.

Specific details of the cyclotron masers vary among the planets, depending upon factors such as the planet’s magnetic field topology and atmospheric density. Nonetheless, an empirical relation (the “radiometric Bode’s law”) appears to exist between the median emitted radio power P_{rad} , the incident solar wind power P_{sw} , and the planet’s magnetic field strength [Desch and Barrow, 1984; Desch and Kaiser, 1984; Desch and Rucker, 1985; Barrow et al., 1986; Rucker, 1987; Desch, 1988; Millon and Goertz, 1988],

$$P_{\text{rad}} = \epsilon P_{\text{sw}}^x. \quad (1)$$

Here $\epsilon \sim 10^{-3}$ – 10^{-6} is the efficiency at which the solar wind power is converted to emitted radio power and $x \approx 1$. The large range on ϵ depends upon whether one considers the kinetic or magnetic energy carried by the incident stellar wind. For reference, the auroral radio power of the Earth is of order 10^8 W while it can exceed 10^{10} W for Jupiter.

The incident solar wind power depends upon the ram pressure of the solar wind and the cross-sectional area presented by the magnetosphere. In general, the magnetopause has a dynamic configuration determined by the incident solar wind pressure [as shown vividly by Cassini observations at Saturn, Gurnett et al., 2005]. However, the average cross-sectional area depends upon the planetary magnetic field strength, which can be estimated either from scaling laws involving the mass, radius, and rotation rate, following modern versions of the so-called Blackett’s Law [Blackett, 1947], or from models of giant planet structure and magnetic field generation [Sánchez-Lavega, 2004].

The electron cyclotron emission maser can be sustained only if the local cyclotron frequency (which depends upon the magnetic field strength) is above the local plasma frequency. Using a similar set of arguments, one can predict the characteristic frequency at which this emission should occur.

Figure 1 presents the expected flux densities vs. the emission frequency in a graphical form [Lazio et al., 2004]. These estimates depend upon measured quantities—the planet’s

mass and distance from its star—and parameters that can be estimated reasonably—the rotation rate can be assumed to be of order 10 hr and the planetary radius can be taken to be roughly that of Jupiter. Importantly for the prospects of detection, the predicted radio power is a *median* value. The cyclotron maser is an exponential amplifier; modest changes in solar wind density or velocity or both (e.g., a factor of a few) have been observed to change planetary radio emissions by large factors [> 100 , Gallagher and D’Angelo, 1981]. Although the median value of an extrasolar planet’s radio emission might not be detectable, enhanced (“burst”) levels may be. Anticipating the discussion in §3, we follow the convention of Farrell et al. [1999] and increase the median flux densities by a factor of 100 in order to account for such variability.

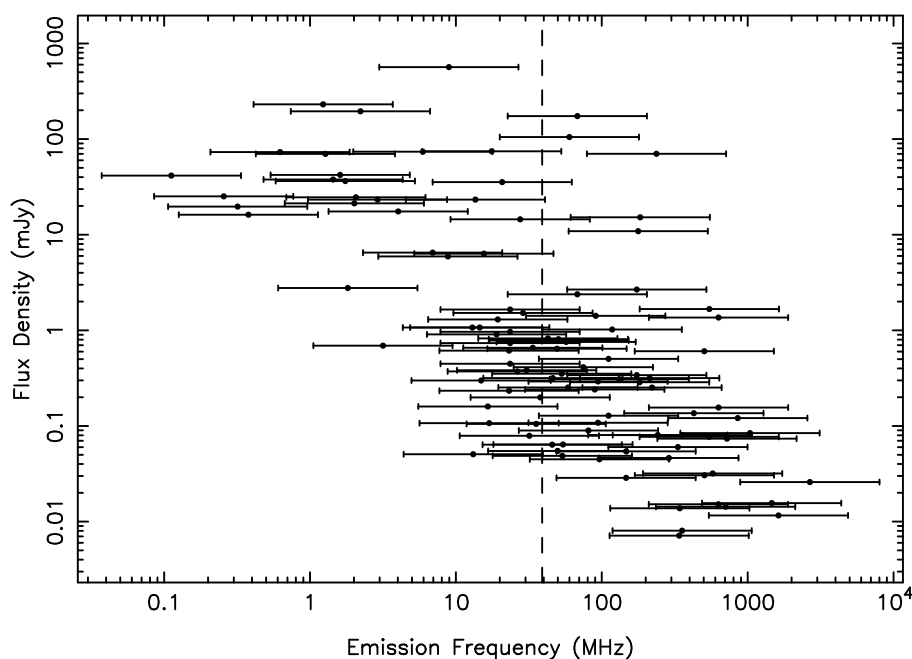


Figure 1: The predicted “burst” flux densities for 106 known extrasolar planets vs. the characteristic emission frequency based on the radiometric Bode’s Law and Blackett’s Law [from Lazio et al., 2004]. The horizontal bars indicate the assumed ranges for the emission frequencies, allowing for variations in the estimated planetary magnetic moments. The expected burst flux densities are obtained by assuming that increases of roughly a factor of 100 can be obtained by larger stellar wind loading of the planet’s magnetosphere. The vertical dashed line indicates the approximate cutoff frequency for Jupiter.

The trend in Figure 1 of increasing emission frequency and decreasing flux density reflects two effects. First, the lower envelope reflects a selection effect. A low flux density and small emission frequency results from a low-mass planet in a large orbit. These planets cannot be detected with current technology. Second, the upper envelope reflects the well-known deficit of planets with both large masses and small semi-major axes. Even if high-mass planets with close orbits did exist, however, they probably would be tidally locked. The rotation rate also determines the strength of the magnetic field, so tidally-locked planets may not produce intense cyclotron masers, though Zarka et al. [2001] have suggested that such “hot Jupiters” may radiate efficiently by the conversion of stellar magnetic pressure (which is large close to the star) into electromotive forces.

3 Radio Emission: Present and Future Observations

There have been a number of attempts to detect radio emission from extrasolar planets, including some before any extrasolar planets were known [Yantis et al., 1977; Winglee et al., 1986]. Extrasolar planets should not emit strongly much above 1000 MHz (Figure 1) because their magnetic moments are not large enough, thus, efforts to detect their radio emission must focus on the low-frequency capabilities of current (or future) telescopes. Searches to date have been at frequencies from 74 to 1400 MHz, with (1σ) sensitivities roughly between 100 mJy to below 1 mJy, with the higher sensitivities obtained at the higher frequencies [Bastian et al., 2000; Farrell et al., 2003; Farrell et al., 2004; Lazio et al., 2004]. Figure 2 illustrates typical results.

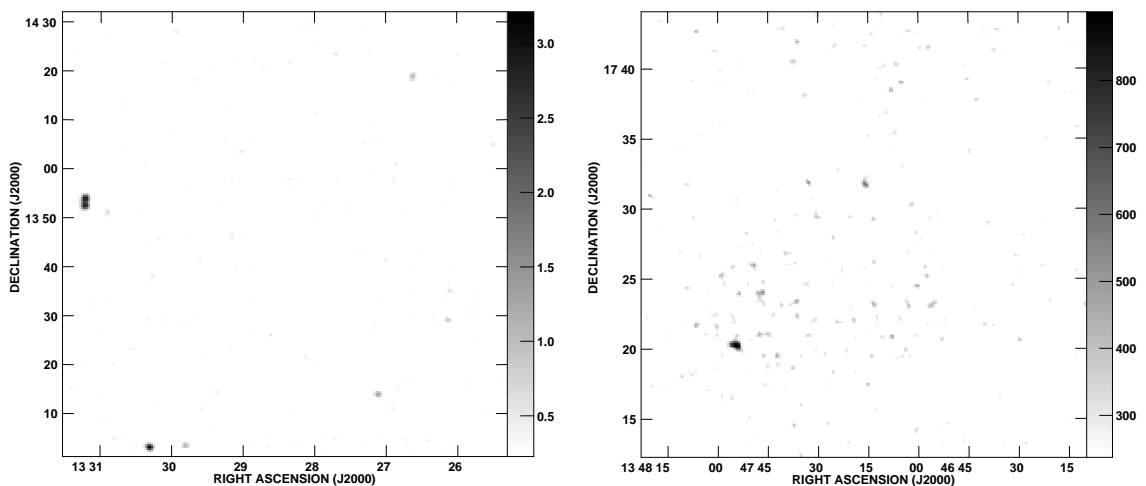


Figure 2: Typical images resulting from searches for radio emission from extrasolar planets. *Left:* The field around 70 Vir at 74 MHz [Lazio et al., 2004]. The grey scale flux range is linear between 0.24 (2σ) and 3.2 Jy beam⁻¹. The source at the extreme left is NVSS J1330+1303, likely to be an extragalactic radio source. *Right:* The field around τ Boo at 74 MHz [Farrell et al., 2004]. The grey scale flux range is linear between 0.24 (2σ) and 0.9 Jy beam⁻¹. The source in the lower right is NVSS J1347+1720, likely to be an extragalactic radio source.

In a few cases, the limits on radio emission approach or are below predicted values. Bastian et al. [2000] place an upper limit of 0.03 mJy at 1400 MHz for the planet orbiting HD 114762, though, this object is now thought to be a brown dwarf. Farrell et al. [2004] have a 1σ sensitivity around 100 mJy for observations of the planet orbiting τ Boo (Figure 2). Predictions on the *median* flux density of this planet range from a few milliJanskys to approximately 250 mJy [Lazio et al., 2004; Stevens, 2005]. Thus, the 3σ limit on the radio emission from this planet is comparable to the upper range of the predictions. However, flux density estimates also typically assume isotropic emission whereas the actual emission is most likely beamed (e.g., for Jupiter, the solid angle of the emission is roughly π). Beaming implies that the effective radiated power is higher (making detection more likely) but also that one has to be within the (unknown) beam of the emission to detect it (making detection less likely).

While these experiments have begun to place limits on the radio emission, they suffer

from a significant bias. With current radio telescopes, high sensitivities are obtained by long integrations. If the radio emission from extrasolar planets is “bursty,” then the signal-to-noise ratio, rather than increasing by the standard \sqrt{t} factor, also depends upon the duty cycle of the emission, which could be quite small.

Also, most observations of extrasolar planets have been obtained only for a single epoch, though this is beginning to change. For example, for the planet orbiting τ Boo, we have obtained observations at 3 epochs [Lazio and Farrell, 2005, in preparation]. Clearly the goal is to detect the radio emission, but even non-detections can provide useful information. This is particularly the case if the estimated flux density is above a telescope’s sensitivity, as the estimates of Stevens [2005] suggests for some planets. Farrell et al. [2003, 2004] have already discussed in a qualitative manner how a non-detection can be used to infer properties of the stellar wind or planetary magnetic field.

We are developing a likelihood method in which the probability P for obtaining M non-detections is cast in terms of the probability of detecting the planet in an individual trial p . This individual trial probability obviously depends upon the telescope sensitivity and the radiated power from the planet, which in turn depends upon various planetary parameters, such as its mass, distance, rotation rate, and the solid angle into which the planet radiates. Hence, the multi-epoch limits on the flux density of the planet can constrain, in a quantitative manner, the various unknown planetary parameters.

Future radio telescopes with low-frequency capabilities and much greater sensitivities than the current generation include the Long Wavelength Array (LWA), the Low Frequency Array (LOFAR), the Mileura Widefield Array (MWA), and the Square Kilometer Array (SKA). The LWA is being designed to operate in the frequency range 20–80 MHz, the MWA is being designed for the range 80–300 MHz, and LOFAR is expected to operate in the range 30–240 MHz. These telescopes are planned to be stations of phased dipoles, which are then combined interferometrically, and all are entering the prototype phase, with an initial station either deployed or soon to be deployed. About one-third of the current census of planets is expected to emit in the frequency range accessible to the LWA and, because of its expanded frequency coverage, about two-thirds of the census for LOFAR. The sensitivities of these telescopes will be direction-dependent, due to the effect on the system temperature from the Galactic synchrotron emission. For directions away from the Galactic plane, the design goals specify sensitivities (15-min. integration, 4-MHz bandwidth) around a few milliJanskys at the lower frequencies and improving to around 1 mJy at the higher frequencies. There are a number of candidates with the most promising perhaps being τ Boo, Gl 876, and Gl 86 as these three objects may be detectable even in the absence of any flux density increase due to stellar wind variability.

The SKA is a next-generation radio telescope that is expected to operate above 150 MHz, but with a goal of operating as low as 60 MHz. Its current design goals specify a sensitivity of approximately 1 μ Jy in a 15-min. integration. The SKA should be capable of detecting the radio emissions from the most massive extrasolar planets, without relying upon bursts to enhance the emission levels, and a substantial fraction of the current census if their stellar wind variability produces significant flux density enhancements.

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