Chapter 1
Radio Observations as an Extrasolar Planet Discovery and Characterization: Interior Structure and Habitability

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Abstract Detection of radio emission from Jupiter was identified quickly as being due to its planetary-scale magnetic field. Subsequent spacecraft investigations have revealed that many of the planets, and even some moons, either have or have had large-scale magnetic fields. In the case of the Earth, Jupiter, Saturn, Uranus, and Neptune, the their magnetic fields are generated by dynamo processes within these planets, and an interaction between the solar wind and their magnetic fields generates intense radio emission via the electron cyclotron maser instability. In the case of Jupiter, its magnetic field interacts with the moon Io to result in radio emission as well. Extrasolar planets reasonably may be expected to generate large-scale magnetic fields and to sustain an electron cyclotron maser instability. Not only may these radio emissions be a means for discovering extrasolar planets, because magnetic fields are tied to the properties of planetary interiors, radio emissions may be a remote sensing means of constraining extrasolar planetary properties that will be otherwise difficult to access. In the case of terrestrial planets, the presence or absence of a magnetic field may be an indicator for habitability. Since the first edition of the Handbook, there have been a number of advances, albeit there remain no unambigous detection of radio emission from extrasolar planets. New ground-based telescopes and new possibilities for space-based telescopes provide promise for the future.

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Introduction

While the planet Jupiter has been known since antiquity, the serendipitous discovery of its decametric wavelength ($\lambda \sim 10\,\mathrm{m}$, $\nu \sim 30\,\mathrm{MHz}$) radio emission (Burke & Franklin, 1955; Franklin & Burke, 1956) illustrates how planetary radio emissions could be used to detect (extrasolar) planets. Indeed, one of the developments since the first edition of the Handbook was published has been publications reporting possible extrasolar planetary analogs. (See "Observational Constraints for Extrasolar Planets" below.)

Jupiter's decametric radio emission is linked to its magnetic field (Carr & Gulkis, 1969, and references within), and, in the Solar System, the combination of decametric radio emissions, other remote sensing measurements, and *in situ* spacecraft measurements have established that the Earth, all of the giant planets, Mercury, and Jupiter's moon Ganymede contain internal dynamo currents that generate planetary-scale magnetic fields.

Since the detection of Jupiter's radio emission, Earth and the other three giant planets in the Solar System, Saturn, Uranus, and Neptune, all have been confirmed to emit at radio wavelengths via a similar process (Zarka, 1992): Immersed in the stellar wind of a host star, a planetary-scale magnetic field forms a magnetosphere that can extract energy from the stellar wind. Some of this energy then can be radiated via the electron cyclotron maser instability, likely at decametric wavelengths or longer. Notably, in the case of Uranus and Neptune, their luminosities were *predicted* before the Voyager 2 encounters (Desch & Kaiser, 1984; Desch, 1988; Millon & Goertz, 1988).

Even before the confirmation of extrasolar planets, extrapolation from the planetary radio emissions in the Solar System led multiple groups to attempt to detect analogous emissions, typically by targeting nearby stars in hopes that they would be orbited by one or more giant planets (Yantis et al., 1977; Winglee et al., 1986). Indeed, in vivid contrast to the case at other wavelengths, the star-planet ratio for radio emissions can be of order unity, and during its most intense radio bursts, Jupiter even can be *brighter* than the (quiet) Sun (viz. Figure 1.1).

Extrapolated to extrasolar planets, radio emissions provide not only a potential means for discovering or detecting planets, but they would provide a direct measure of an extrasolar planet's magnetic field, in turn placing constraints on the thermal state, composition, and dynamics of its interior—all of which will be difficult to determine by other means. In the case of a terrestrial planet, the detection of a magnetic field also may provide crucial information about the extent to which its surface is shielded from energetic particles and potentially habitable.

This chapter reviews how radio emissions could be used not only to discover extrasolar planets, but also how they might be used to study extrasolar planets, regardless of the means of discovery. Since the first version of the Handbook, there have been a number of developments in searches for magnetically-generated radio emission, potential magnetic field-moderated star-planet interactions, advances in theoretical understandings about planetary magnetic fields, and constraints on planetary magnetic fields from other techniques. Callingham et al. (2023a) provide

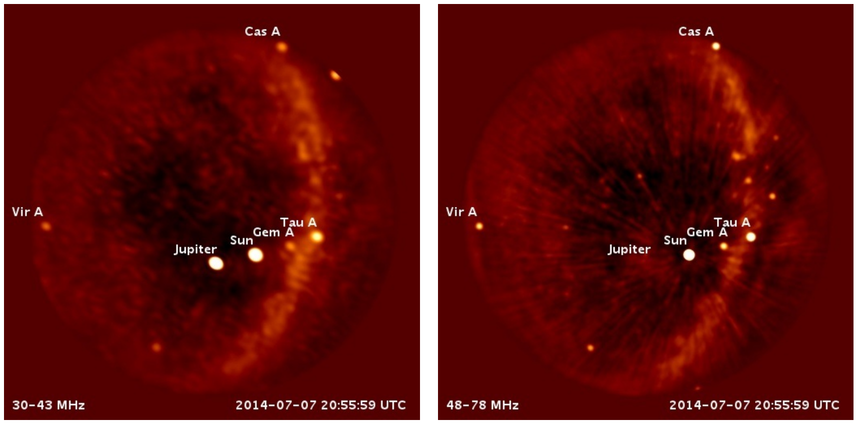

Fig. 1.1 Radio sky in the 30 MHz–43 MHz (*left*) and 47 MHz–78 MHz bands (*right*); zenith is at the center of the images. Strong sources are labeled, notably including Jupiter and the Sun. In the lower frequency image, Jupiter is of comparable brightness to the Sun, illustrating that the star-planet intensity ratio can be of order unity at radio wavelengths. In the higher frequency image, the absence of Jupiter is consistent with the exceptionally strong cutoff of cyclotron maser emission where the local plasma frequency exceeds the local cyclotron frequency within the planet's magnetosphere. (Images courtesy of M. Anderson)

a recent, complementary review of some of these topics, extending to cover radio emission from brown dwarfs and stars as well.

The structure of this chapter is the following. The next section, "Observational Constraints for Extrasolar Planets," presents a summary of efforts to date, focussing on recent results. The following four sections—"Planetary Magnetic Fields," "The Electron Cyclotron Maser Instability and (Extrasolar) Planetary Radio Emission," "Observational Considerations," and "Extensions to and Predictions for Extrasolar Planets"—are intended to be high-level summaries of fundamental aspects motivating observations at radio wavelengths. Some of material in these initial sections also is relevant for describing the radio emission from brown dwarfs, a topic discussed in brief in the final section. The following sections—"Planetary Magnetic Fields and Interiors," and "Planetary Magnetic Fields and Habitability"—present the implications of detection of magnetically-generated radio emission from planets. These sections have been revised substantially since the first version of this chapter to take into account the latest developments. A concluding section, "Future Steps," envisions likely progress in the next decade and beyond.

The focus of this chapter is on *electron cyclotron maser instability* (ECMI) emissions resulting from a stellar wind-planetary magnetosphere interaction. While planets, or at least Jupiter, can generate synchrotron emission that appears at decimeter and centimeter wavelengths, it is likely to remain well beyond detection capabilities in the near future. As an example, the centimeter-wavelength flux density of Jupiter is of order a few Janskys (e.g., Klein et al., 1989; de Pater et al., 2003). Scaled to a distance of even a few parsecs, the resulting flux density would be *sub-nanoJanskyy*, which is well beyond even the most optimistic expectations for next-generation centimeter-wavelength telescopes, such as the Phase 1 of the Square Kilometre Array (SKA1, cf. Cendes et al., 2022). Planets, or more likely proto-planets, likely also are to be detected at centimeter to millimeter wavelengths (e.g., Wolf, 2008; Pérez et al., 2016), with the the Very Large Array (VLA) or the Atacama Large Millimeter/submillimeter Array (ALMA), and there is increased potential of such studies with the next-generation Very Large Array (ngVLA). Clearly promising, but also poised for significant discoveries over the next few years, this chapter defers any discussion of radio emission at these wavelengths. Finally, this chapter does not consider the possibility of detecting artificial transmissions, though this approach may represent the ultimate in extrasolar planet discovery (Tarter, 2001).

Observational Constraints for Extrasolar Planets

Since the first edition of the Handbook, there have been a number of notable developments, including multiple claims of detections of extrasolar planets at radio wavelengths.

- Turner et al. (2021) reported a detection of radio emission from τ Boo b at a frequency near 25 MHz. From the earliest quantitative estimates for extrasolar planetary radio emission (Farrell et al., 1999; Lazio et al., 2004; Griessmeier et al., 2007b), this planet has been identified consistently as likely to have emissions both strong enough and at a high enough frequency to be detectable from the ground. However, a notable aspect of the reported radio emission was that it was relatively narrow band ($\Delta\nu/\nu \sim 0.3$), in contrast to the emission from Jupiter for which $\Delta\nu/\nu \approx 1$. Unfortunately, subsequent efforts to detect this emission from τ Boo b have not been successful (Turner et al., 2023).
- Substantial progress has been achieved in calibration of Low Frequency Array (LOFAR) observations at 50 MHz, with the result that the upper limits on the radio emissions from HD 80606b are at the level of a few millijanskys (de Gasperin, Lazio, & Knapp, 2020). As Jupiter emits up to approximately 35 MHz, this improved capability means that searches can be conducted at frequencies comparable to those at which Jupiter emits and with sensitivities consistent with what might be expected for nearby extrasolar planets. Unfortunately, HD 80606b itself is approximately 60 pc distant. Even the most optimistic projections for its radio emission suggest that it is likely an order of magnitude fainter than the current limits (de Gasperin, Lazio, & Knapp, 2020).
- There have been multiple reports of low-mass stars producing radio emission, including for the nearby M dwarf GJ 1151 (Vedantham et al., 2020), the flare star AD Leo (Zhang et al., 2023), and YZ Ceti (Pineda & Villadsen, 2023; Trigilio et al., 2023). For at least some of the stars, the radio emission is the result of the ECMI, notably AD Leo, and there have been multiple claims of magnetic star-planet interactions, including estimates of planetary magnetic field strengths (0.4 G in the case of YZ Ceti). However, in the case of GJ 1151, while Blanco-Pozo et al.

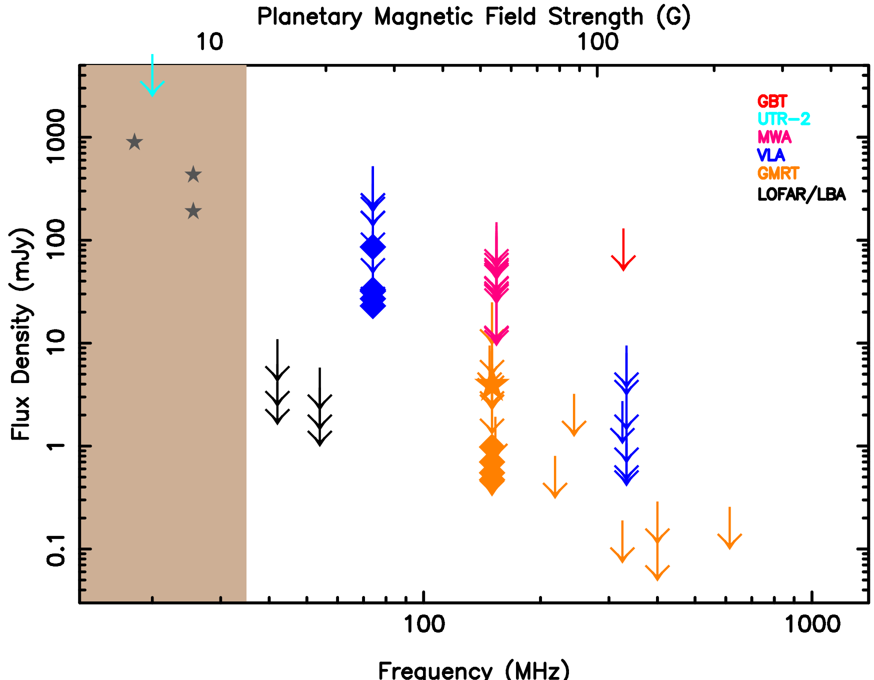

Fig. 1.2 Published upper limits for radio emissions from extrasolar planets, shown both as a function of radio frequency (bottom axis) and implied planetary magnetic field strength (top axis). Observations have been obtained by, and are color-coded for, the Ukranian T-shaped Radio Telescope (UTR-2), Green Bank Telescope (GBT), Murchison Widefield Array (MWA), Very Large Array (VLA), Giant Metrewave Radio Telescope (GMRT), and the Low Frequency Array/Low-Band Antennas (LOFAR/LBA). For clarity, the upper limits at 150 MHz on all extrasolar planets known at the time and in the footprint of the Tata Institute of Fundamental Research (TIFR)-GMRT Sky Survey (TGSS) are not shown (Sirothia et al., 2014), and only the ensemble analysis results of Ling et al. (2022) are shown. Solid diamonds show statistical limits on the average planetary radio emission from various samples of planets (Lazio et al., 2010a; Ling et al., 2022). The solid stars represent the tentative detection of HAT-P-11b at 150 MHz (Lecavelier des Etangs et al., 2013) and the unconfirmed detections of τ Boo b near 20 MHz (Turner et al., 2021, 2023). The shaded region shows the approximate frequency range for Jovian decametric emissions (cf. Figure 1.4). All of these observations have been from ground-based telescopes, emphasizing that future space-based observations likely will be needed to study lower-mass planets.

(2023) detected a planet orbiting GJ 1151, its mass is larger than that argued initially to be responsible for the radio emission from that system, and, in all cases, ambiguity remains about whether the star is emitting or the planet is emitting. Finally, as noted below, a unipolar induction mechanism can generate radio emissions, as in the Jupiter-Io system. As such, while the detection of radio emissions could provide evidence for the existence of a planet, in general, little information about its properties may result.

- There have been searches focussed on detecting the extrasolar planetary equivalent of Jupiter's emission that is driven by the interaction between its magnetosphere and its moon Io (Narang et al., 2023a,b).
- Multiple observations have been conducted of M dwarfs and brown dwarfs, including of TRAPPIST-1, which have shown that they can produce coherent radio emission in the absence of a planet or that the presence of planets does not lead necessarily to magnetic star-planet interactions generating radio emissions (Pineda et al., 2017; Llama et al., 2018; Pineda & Hallinan, 2018; Villadsen & Hallinan, 2019; Callingham et al., 2021b).

Figure 1.2 presents a graphical summary of most published limits on the radio emission from extrasolar planets (Zarka et al., 1997; Bastian et al., 2000; Lazio et al., 2004; George & Stevens, 2007; Lazio & Farrell, 2007; Lecavelier Des Etangs et al., 2009; Smith et al., 2009; Lazio et al., 2010a; Lecavelier Des Etangs et al., 2011; Lecavelier des Etangs et al., 2013; Hallinan et al., 2013; Sirothia et al., 2014; Murphy et al., 2015; de Gasperin, Lazio, & Knapp, 2020; Green & Madhusudhan, 2021; Ling et al., 2022; Narang et al., 2023a,b; Shiohira et al., 2023). Not shown are a few observations at frequencies above 1000 MHz and a few observations at frequencies around 20 MHz—limits above 1000 MHz are not shown as these are likely to be at too high of a frequency, and would require planetary magnetic field strengths larger than 500 G, while the published limits around 20 MHz are typically above the range of flux densities shown or do not have adequate information to assess or both. Based on a number of predictions that it is a promising target for detection, the most intensively studied planet to date is τ Boo b.

Several items deserve mention. First, it is apparent that most searches have been conducted at frequencies sufficiently high that Jupiter would not have been detected. Of all planets in the solar neighborhood, it is unlikely that Jupiter has the strongest magnetic field (cf. eqn. [1.1]). Nonetheless, at least some of the non-detections plausibly can be attributed to searching at frequencies that are too high.

Second, the trend of upper limits becoming less constraining at lower frequencies is real and represents limits on radio telescope sensitivities at these frequencies. A primary factor determining the telescope sensitivity is $A_{\mathrm{eff}}/T_{\mathrm{sys}}$, the ratio between the effective area of the telescope and the system temperature. For a given telescope (e.g., VLA or GMRT), the effective area A_{eff} is essentially fixed (by the number of antennas and the diameter of each antenna). At these frequencies, the dominant contribution to the system temperature T_{sys} is the sky temperature or the power contributed by the Milky Way Galaxy's synchrotron radiation. This temperature increases dramatically to lower frequencies, scaling approximately with frequency as $\nu^{-2.6}$ (Cane, 1979) Consequently, the limits become less constraining at lower frequencies. For a dipole-based array (see below), the effective area of the individual dipoles scales with frequency as approximately ν^{-2}, so that any limits that they place should be much more constant with frequency.

Third, the solid diamond at 74 MHz is the upper limit on the average planetary radio emission from planets orbiting nearby solar-type stars (Lazio et al., 2010a). It was constructed from a stacking analysis of the radio emission in the direction of stars within 40 pc. As such, it represents a limit on the combination of the average planetary radio luminosity and the fraction of solar-type stars hosting planets that radiate at 74 MHz.

Fourth, the solid star at 150 MHz is the tentative detection, on a single day, of radio emission from HAT-P-11b (Lecavelier des Etangs et al., 2013). If this measurement represents an actual detection, it implies that the magnetic field strength of HAT-P-11b is 50 G. However, equally sensitive observations on another day did not detect any radio emission. Thus, as even the authors acknowledge, some caution is warranted in concluding that this measurement represents the first discovery of extrasolar planetary radio emission.

Fifth, as noted above, any claim of detection of the radio emission from an extrasolar planet must address whether it the extrasolar planet or host star has been detected. In general, extrasolar planetary radio emission is expected to exceed the emission of the planetary host star (Zarka et al., 1997; Griessmeier et al., 2005a). Further approaches suggested to distinguish planetary from stellar radio emission have included whether the radio emission is modulated with the planet's orbital period (if known) or with a time scale characteristic of Solar System planetary rotational periods ($\approx$ 10 hr). However, Fares et al. (2010) note that even a purely planetary signal may be partially modulated by the stellar rotation period, which could complicate the discrimination between a stellar and a planetary radio signal.

Finally, nearly all, if not all, of these searches have targeted known extrasolar planets. Only recently, with blind surveys being conducted at LOFAR (e.g., Vedantham et al., 2020; Callingham et al., 2023b) would the discovery of new extrasolar planets be possible.

Planetary Magnetic Fields

There is a rich literature on the topic of the generation and sustainment of planetary magnetic fields, and a full review is beyond the scope of this chapter. Interested readers are encouraged to consult Christensen (2010), Stevenson (2010), and Schubert & Soderlund (2011) for extensive reviews and Christensen et al. (2009) for extension to extrasolar planets and dwarf stars; a W. M. Keck Institute for Space Studies Program on Planetary Magnetic Fields also considered both the state of knowledge of the field and observational manifestations of planetary magnetic fields, beyond likely radio detections (Lazio, Shkolnik, Hallinan, et al., 2016). Nonetheless, a brief consideration of planetary magnetic fields is essential for this chapter, both because they are a critical element for the generation of radio emission and because their presence may provide information on extrasolar planets (and Solar System planets?) that will be difficult to obtain through any other means.

Within the Solar System, a diversity of magnetic field configurations and amplitudes are observed. They are observed on planets, some small bodies, and some moons. Configurations range from predominantly dipolar to asymmetric but large-scale to probably residual crustal magnetism. Amplitudes range from more than

10 G in strength (Jupiter) to much weaker and even induced fields (e.g., Io, Europa, Callisto).

Of relevance to detection over interstellar distances, it is only the planets having magnetic fields with strengths of order 1 G and larger—Earth, Jupiter, Saturn, Uranus, and Neptune—that are capable of generating a planetary-scale magnetosphere (Figure 1.3) and therefore sufficiently strong radio emissions.

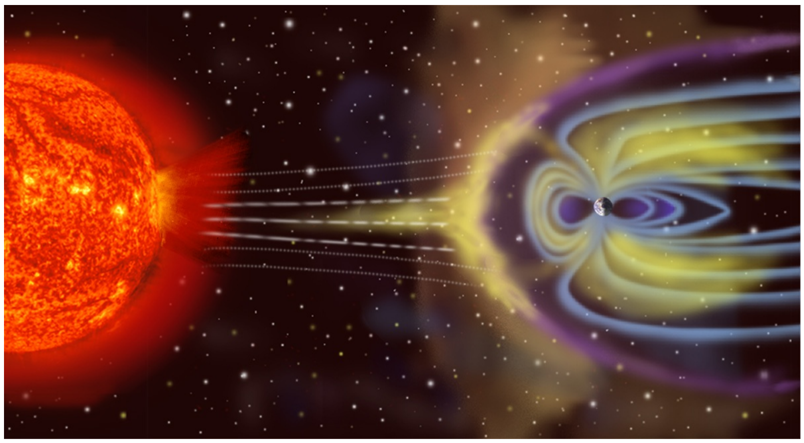

Fig. 1.3 Artist's impression of Earth's magnetosphere, which is produced by the interaction between the solar wind and Earth's magnetic field. The Earth's magnetic field is generated by internal dynamo currents, and the solar wind-magnetosphere interaction both shields the Earth's atmosphere and surface and produces intense radio emission from its polar region via the electron cyclotron maser instability. Similar processes occur at Jupiter, Saturn, Uranus, and Neptune, though the natures of their dynamos are different than that of Earth, and the resulting radio emissions should be detectable over interstellar distances. (Image credit: NASA)

It is nearly certain that the generation of these planetary-scale magnetic fields requires a dynamo process, in which kinetic energy in a conducting medium is converted into a magnetic field. The dynamo currents interior to a planet may arise from differential rotation, convection, compositional dynamics, or a combination of these processes. At the very least, it is clear that the conducting fluids within the different "magnetic planets" are different, with Earth containing liquid iron in its (outer) core, Jupiter and Saturn likely having metallic hydrogen, and Uranus and Neptune likely due to salty water under high pressure. The topic of planetary dynamos is revisited in the section "Planetary Magnetic Fields and Interiors" to discuss both how radio wavelength emissions might provide constraints on extrasolar planetary interiors and the potential diversity of planetary interiors.

The Electron Cyclotron Maser Instability and (Extrasolar) Planetary Radio Emission

All of the "radio active" planets in the Solar System (Earth, Jupiter, Saturn, Uranus, and Neptune) produce radio emission via the *electron cyclotron maser instability* (ECMI). This section provides an introduction to the conditions necessary to create the ECMI; Treumann (2006), Vorgul et al. (2011), and Baumjohann & Treumann (2022) provide extensive discussions of the ECMI.

A heuristic summary of the ECMI as applied to radio emission from planetary magnetospheres is to consider a (monoenergetic) beam of electrons traveling along magnetic field lines. The electrons will gyrate around the field lines, producing cyclotron radiation at the electron *cyclotron frequency* $\Omega_{\rm ce}$. (Ions also gyrate around magnetic field lines at a frequency $\Omega_{\rm ci}$, but the (much) larger mass of ions means that this frequency is sufficiently low that it is not relevant for this discussion.) If the local environment were a vacuum, this cyclotron radiation would escape to infinity, but any realistic magnetosphere has an ambient plasma. A plasma has a characteristic *plasma frequency* $\omega_{\rm pe}$, determined by the (local) plasma density, $\omega_{\rm pe} \propto \sqrt{n_e}$. In general, radiation with a frequency ν will neither propagate through nor escape from a region for which $\nu < \omega_{\rm pe}/2\pi$. The fact that the Solar System's "radio active" planets produce detectable ECMI emissions indicates that planetary magnetospheres reasonably can be expected to sustain conditions such that $\nu \sim \Omega_{ce} > \omega_{pe}/2\pi$.

Two effects can combine to enable the escape of cyclotron radiation from a planetary magnetosphere. First, in a low density environment, the plasma frequency can approach or even be less than that of the cyclotron frequency, $\omega_{\rm pe} \lesssim \Omega_{\rm ce}$. Second, the velocity of the electrons introduces a Doppler shift. If the electron velocity is high enough, the electron cyclotron radiation is shifted into resonance with radiation modes that can escape the planetary magnetosphere and the planet radiates in the radio.

In a realistic magnetosphere, the electrons will not be monoenergetic but will have some distributions of energies. If the electron energy distribution has more electrons with energies above the escaping cyclotron modes, the electrons will feed energy into the escaping cyclotron radiation modes, making the emission even more intense. By analogy to the inverted population states that can give rise to laser and maser emission, having an electron energy distribution that "stimulates" more intense radiation is termed a "maser instability," leading to the ECMI. In general, the ECMI requires an electron energy distribution with a supra-thermal, non-Maxwellian component—for a Maxwellian energy distribution always has more electrons at lower energies.

A more exact treatment would consider the dispersion relation of waves in a magnetized plasma, but essentially the same conclusions would be reached. A population of energized electrons traveling along magnetic field lines through a low plasma density environment can generate intense radio emissions via a resonance with the (Doppler shifted) electron cyclotron frequency.

Observational Considerations

Several observationally-relevant conclusions can be drawn, either from the heuristic approach described in the previous section or from a more exact treatment. First, ECMI planetary radio emission should be highly circularly polarized. This conclusion follows simply from the nature of cyclotron emission itself (producted by gyrations around magnetic field lines), and circularly polarized emission is the standard for planetary radio emissions in the Solar System. As few radio astronomical sources are circularly polarized, searching for circularly-polarized radio sources is a common technique for identifying candidate extrasolar planets (or stars) emitting via the ECMI (Callingham et al., 2023b).

Second, a planet will radiate up to a maximum (radio) frequency determined by the largest magnetic field strength within the region where the conditions for the ECMI can be sustained (Farrell et al., 1999). In practice, this region is typically near the magnetic polar regions, for which the maximum radiated frequency is then

$$\begin{aligned} \nu_{\max} &= \frac{e\mathscr{M}R_p^3}{2\pi m_e} = \frac{eB_{\mathrm{pole}}}{2\pi m_e}, \\ &\approx 2.8\,\mathrm{MHz}\left(\frac{B_{\mathrm{pole}}}{1\,\mathrm{G}}\right), \end{aligned} \tag{1.1}$$

where e is the charge on the electron, m_e is the mass of the electron, R_p is the radius of the planet, $\mathscr{M}$ is the magnetic moment of the planet at the surface or cloud tops (as distinct from the magnetic moment at the "surface" of the dynamo region), and B_{pole} is the magnetic field strength at the surface of the planet or cloud tops in the magnetic polar regions, which is assumed to be the relevant region for the ECMI radiation. Figure 1.1 provides an illustration of the exceptionally sharp nature of the frequency truncation of the ECMI.

Figure 1.4 shows the (average) radio spectra for the planets in the Solar System that sustain the ECMI (Zarka, 1992). Jupiter, with a polar magnetic field strength at the cloud tops of about 14 G, is clearly the most intense emitter, and the only Solar System planet detectable from the ground (Burke & Franklin, 1955; Franklin & Burke, 1956). With the other magnetic planets having much smaller magnetic moments—the Earth's polar magnetic field strength is only about 1 G—their maximum emission frequencies are below the terrestrial ionospheric cutoff (~ 10 MHz), which makes their emissions unobservable from the ground.

The third conclusion is that, all other things being equal, more intense emissions will be generated when more (supra-thermal) energetic particles are available. This conclusion follows from the need to have an electron energy distribution that can feed energy into the escaping radiation modes. With more energetic particles, or a more extreme supra-thermal distribution of energies, the ECMI can work more effectively. Extreme examples of solar wind control of the ECMI have been observed, including a factor of 100 increase in the power of the Earth's ECMI emissions from a factor of about 2 increase in solar wind velocity (Gallagher & D'Angelo, 1981)

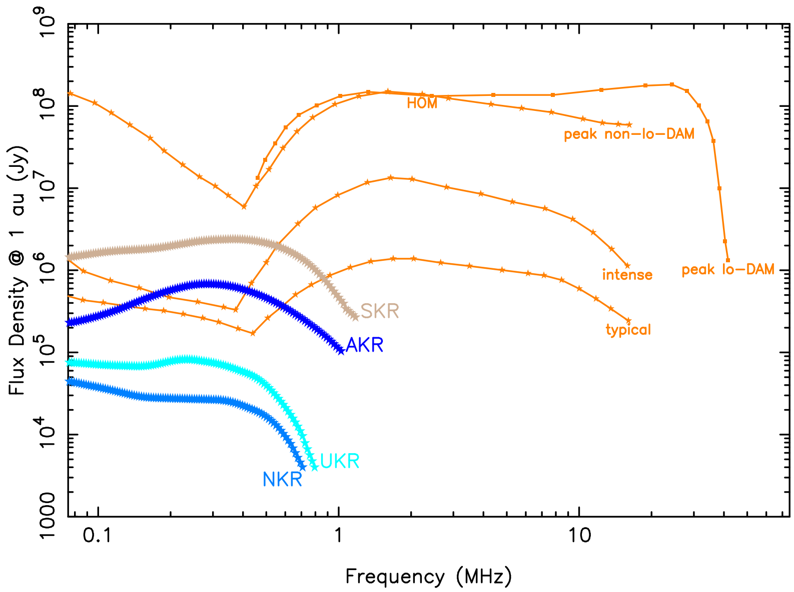

Fig. 1.4 Radio spectra for the Solar System planets, scaled to a distance of 1 au. For Jupiter, the hectometric emission (HOM), the decametric component linked to the moon Io (Io-DAM), and the decametric component not linked to Io (non-Io-DAM) are shown. The intensities vary depending upon solar wind and internal magnetospheric conditions, and "typical," "intense," and "peak" values are shown, with "peak" occurring approximately 1% of the time. For the other planets, there is only a single contribution to the radio emission, which are the Saturnian kilometric radiation (SKR), the Earth's auroral kilometric radiation (AKR), the Uranian kilometric radiation (UKR), and the Neptunian kilometric radiation (NKR). The Earth's AKR also is termed the terrestrial kilometric radiation (TKR). [Data courtesy of P. Zarka.]

and about a factor of 100 decrease in the power of Saturn's ECMI emissions when Saturn moved into the trailing region of Jupiter's magnetosphere (Desch, 1983).

A related aspect of Figure 1.4 concerns the nature of Jupiter's radio emissions. At higher frequencies ($\nu \gtrsim 10$ MHz), Jupiter's decametric radio emissions (DAM) are a combination of those related to the presence of its moon Io (so-called Io-DAM) and those not related to Io (non-Io-DAM, Gurnett et al., 2002; Hess et al., 2012; Louis et al., 2023). (There are weaker contributions from Europa and Ganymede as well.) A common misconception is that Jupiter's radio emission results solely by the presence of Io, and, by extension, a satellite is required for a Jovian-mass planet to generate radio emission.

It is beyond the scope of this chapter, but the presence of a planetary-scale magnetic field also may result in Ohmic dissipation occurring in the planet's atmosphere as it moves through the stellar wind of the host star. The Ohmic dissipation would represent a heat source, in addition to the stellar insolation, which could explain the inflated radii of some "hot Jupiters" (e.g., Batygin & Stevenson, 2010; Perna et al., 2010).

Extensions to and Predictions for Extrasolar Planets

Soon after the recognition that Solar System planets could be radio emitters, Fennelly & Matloff (1974), Gary & Gulkis (1974), Yantis et al. (1977), and Winglee et al. (1986) speculated about and conducted searches for analogous emission from extrasolar planets. If extrasolar planets host magnetic fields, it is reasonable to expect them to generate radio emission via the ECMI as well, though the challenges in detecting it are clear from simple considerations. At distances of at least 10^5 times larger than for Solar System planets (Figure 1.4), the flux densities of extrasolar planets should be lower by factors of at least 10^{10}, though there also may be mechanisms that would lead to (much) enhanced flux densities relative to what such simple considerations might predict.

The flux density of an extrasolar planet depends upon the source of available energy to the planetary magnetosphere. Five different input sources have been considered:

Stellar Wind Kinetic Energy The flux of protons of the host star's stellar wind incident on the planet's magnetosphere provides a power input proportional to ρv^2, for a stellar wind of density ρ and velocity v. This input energy source has been the most frequently considered one for extrasolar planets (Zarka et al., 1997; Farrell et al., 1999; Zarka et al., 2001; Lazio et al., 2004; Stevens, 2005; Griessmeier et al., 2005a; Griessmeier, 2007; Griessmeier et al., 2007a,b)

Stellar Wind Magnetic Energy The flux of magnetic energy, or the electromagnetic Poynting flux, from the interplanetary magnetic field incident on the planet's magnetosphere provides a power input proportional $B^2 v$, for an interplanetary magnetic field strength B embedded in the stellar wind (Zarka et al., 2001; Zarka, 2007; Griessmeier et al., 2007b; Jardine & Collier Cameron, 2008; Hess & Zarka, 2011).

Stellar Coronal Mass Ejections The kinetic energy of a stellar coronal mass ejection (CME) impacting a planetary magnetosphere provides power to the magnetosphere, in a manner akin to the "Stellar Wind Kinetic Energy" above. The distinction is that the kinetic energy of a CME is sufficiently large that the radio emission of the planet can be enhanced substantially relative to "normal" or quiet stellar conditions (Gallagher & D'Angelo, 1981; Griessmeier et al., 2005a; Griessmeier, 2007; Griessmeier et al., 2007a,b).

Internal Magnetospheric Plasma Sources Because Jupiter's magnetic field rotates faster than Io orbits, a particle flux exists in the magnetic flux tube linking Io to Jupiter, and the ECMI is operative producing intense decametric radio emission (Io-DAM, Figure 1.4); as noted above, weaker contributions are produced by the flux tube footprints linking Europa and Ganymede as well. This mechanism could result in strong radio emissions from a planet, even if it is sufficiently distant from its host star that the stellar wind pressure is relatively low. Further, Nichols (2011, 2012) showed a planet with corotation-dominated magnetosphere, such as that of Jupiter, orbiting a star with strong X-ray emission also could produce radio emission if there is enhanced coupling between planet's ionosphere, where the stellar X-ray photons deposit energy, and its magnetosphere.

Unipolar Interaction (Planet-Moon or Star-Planet) There could be equivalents of the Jupiter-Io system in which the interaction between a planet's magnetosphere and its moon, a so-called exomoon, generate radio emission (Noyola et al., 2014). Alternately, *star-planet* systems with magnetic interactions could produce radio emission in an analogous manner. In such a case, there would be a magnetic flux tube linking the planet and the star, and the ECMI would be operative in the *stellar* magnetosphere as the result of an orbiting planet, regardless of whether that planet has a magnetic field or not (Zarka et al., 2001; Zarka, 2006, 2007; Griessmeier et al., 2007a; Jardine & Collier Cameron, 2008; Hess & Zarka, 2011). While this method could reveal the existence of a planet, it is not clear that this mechanism would provide much insight into the planet itself.

Generally, these models predict that close-in planets, especially "hot Jupiters," should have more intense emissions, due to the higher stellar wind loading of the magnetosphere. Amplification factors could be of order 10^3, though, at very close distances, within the closed magnetosphere of the host star, the ECMI mechanism may saturate rather than continue to increase (Jardine & Collier Cameron, 2008).

A cautionary consideration regarding "hot Jupiters," however, is that they could be too close to their host stars for detectable radio emission to be produced. A star's stellar wind is a plasma, which has its own plasma frequency. If the stellar wind density near a "hot Jupiter" is too high, its plasma frequency may be higher than the cyclotron frequency of the planet's radio emission, and the planet's radio emission would not be able to escape nor be detected (Griessmeier et al., 2007b).

Further caution is required when applying simple scaling laws for radio emissions produced by stellar wind interactions. The solar wind-auroral radio emission connection may not be direct in large corotating magnetospheres. Earth's convection-driven magnetosphere is especially sensitive to solar wind pressure, and Earth's auroral kilometric radiation (AKR) can show a factor of 100 increase in power for a factor of about 2 increase in solar wind velocity (Gallagher & D'Angelo, 1981). However, Jovian aurora are driven by currents that form in the co-rotating outer magnetosphere (Nichols, 2011), where the solar wind may impose only a secondary controlling influence. There is a correlation of Jovian radio power with the solar wind, but it is not as evident as the AKR case (Gurnett et al., 2002).

As the stellar wind parameters strongly depend on the stellar age (Wood et al., 2001; Wood et al., 2002, 2005), for those mechanisms that depend upon energy input from the stellar wind, the age of the host star also must be incorporated into predictions (Stevens, 2005; Griessmeier et al., 2005a; Lazio et al., 2010a). The radio flux of a planet around a young star may be orders of magnitude higher than for a planet in an older system. Unfortunately, stellar ages are often poorly constrained, in turn often leading to significant ranges in the predicted planetary flux densities.

By the same token, if a planet is in an eccentric orbit, the effective stellar wind density and velocity at the planet's magnetosphere will vary over the course of the planet's orbit, in turn modulating the planet's emission (Griessmeier et al., 2007a).

In the most dramatic cases, the modulation of the planet's radio emission might approach a factor of 10^3 (Lazio et al., 2010b). However, if the planet's orbit is sufficiently eccentric, it may be carried into a region where the *stellar* wind plasma density is sufficiently high that the considerations above concerning "hot Jupiters" become relevant.

Regardless of the energy source powering the radio emission, the same constraints of equation (1.1) apply for extrasolar planets as for Solar System planets, namely, only those with sufficiently strong magnetic fields will generate radio emission at a high enough frequency to be detectable from the ground. Estimating this frequency for an extrasolar planet requires an estimate of the planetary magnetic moment, which is often ill-constrained. Two main approaches have been adopted. Farrell et al. (1999) and Griessmeier et al. (2007b) assume the planetary magnetic moment can be calculated by a force balance, and find a planetary magnetic field that depends on the planetary rotation rate. In contrast, Reiners & Christensen (2010) assume the planetary magnetic moment to be driven primarily by the energy flux from the planetary core. Thus, they find no dependence on the planetary rotation rate; however, they obtain stronger magnetic fields and more favorable observing conditions for young planets. Driscoll & Olson (2011) considered the specific case of terrestrial planets. They found that anomalously strong fields ($3\times$ larger than the most optimistic prediction) are required for emission at frequencies above the Earth's ionospheric cutoff; furthermore, the expected flux levels are very low.

Finally, in the interest of completeness, planets in more "exotic" environments have been considered as possible radio emitters. These environments include planets around pulsars (Mishra et al., 2023), terrestrial planets around white dwarfs (Willes & Wu, 2005), planets around evolved cool stars (Ignace et al., 2010; Fujii et al., 2015), planets around T Tauri stars (Vidotto et al., 2010), and even interstellar "rogue planets," i.e., planets not bound to a star (Vanhamäki, 2011). While there nature is not yet clear, Jupiter-Mass Binary Objects (JuMBOs) may be planets (Pearson & McCaughrean, 2023), and at least one such JuMBO has been detected at radio wavelengths (Rodriguez et al., 2024).

Planetary Magnetic Fields and Interiors

The detection and measurement of extrasolar planetary magnetic fields, whether in the context of discovering new extrasolar planets or observing known extrasolar planets, could provide constraints on the thermal states, compositions, and dynamics of extrasolar planetary interiors. The mass-radius diagram can provide some constraints for models of planetary interiors, but, because the same bulk density can be obtained by different admixtures of constituents (iron vs. silicates vs. volatiles), there are considerable degeneracies (e.g., Rogers & Seager, 2010; Spiegel et al., 2014; Lopez & Fortney, 2014; Schaefer et al., 2017). Further, even for a planet with a fixed bulk composition, its location on the mass-radius relation may change over time as the planet's thermal state evolves (Noack & Lasbleis, 2020). It may even be the case that the presence of a magnetic field may help determine a planet's location in the mass-radius relation by shielding its atmosphere from erosion (Owen & Adams, 2019). (See also the section below, "Planetary Magnetic Fields and Habitability.")

The most simple approach to imposing constraints on a planet's interior is that a planetary-scale magnetic field implies that there must be an electrically-conducting region within a planet. More sophisticated approaches include using the period of rotation determined from the magnetic field, or from radio emission linked to the magnetic field, as an input to interior structure models, as Hubbard et al. (1991) did for Neptune. There likely are rich opportunities to explore for using detections of extrasolar planetary magnetic fields to constrain the structure of planetary interiors (e.g., Yunsheng Tian & Stanley, 2013).

Emerging approaches to provide additional constraints on a planet's interior structure are to assume that the composition of the planet is similar to that of its host star, at least for the refractory elements (Dorn et al., 2015, 2017; Brugger et al., 2017; Schulze et al., 2021; Unterborn et al., 2023), or can be inferred from atmospheric abundances (e.g., Bloot et al., 2023; Guimond et al., 2023). The technique of linking the host star-planet compositions likely requires high-precision spectroscopic measurements of the host star in order to obtain sufficient constraints on a planet's composition (Wang et al., 2019). Moreover, there also are recent examples of planets that appear to have compositions discrepant, sometimes substantially so, from their host stars (e.g., Bean et al., 2023; Shi et al., 2023). There is even the possibility that a planet's composition may reflect not only how far from its host star that it formed (radial location within the protoplanetary disk), but also azimuthal variations or other variations (e.g., temperature) within the protoplanetary disk (Keyte et al., 2023; van Dishoeck et al., 2023). Nonetheless, there also may be opportunities to model the likelihood of a planet generating a magnetic field using its host star metallicity as an additional constraint.

The technique of inferring the interior composition from the atmospheric composition typically uses spectroscopic observations of a planet's atmosphere to infer the atmospheric (or envelope) composition. There is considerable interest in this technique with the advent of the *JWST*. This technique depends crucially on the extent to which the atmosphere or envelope is able to mix homogeneously with lower layers (such as a mantle in the case of a rocky planet). As discussed by (Bloot et al., 2023, and references within), even within the Solar System, the results of the Juno mission at Jupiter and the *Cassini* mission at Saturn provide cautionary notes about this approach.

Measurements of or constraints on the strengths of extrasolar planetary magnetic fields, even for a small number of extrasolar planets, would be valuable from two, complementary perspectives. First, the presence of a magnetic field requires the planet to support an internal dynamo, which in turn requires some internal region of the planet to support convection. Considering a planet with a given mass and radius, only a limited set of bulk compositions, thermal states, and internal pressure profiles may enable a dynamo region to persist (e.g., Yunsheng Tian & Stanley, 2013).

Second, detecting planetary magnetic fields may enable new insights about the planetary dynamo process itself. The wide variety of magnetic fields observed for Solar System planets results in data starvation for models and has confounded efforts to develop a comprehensive description of planetary dynamos. Having more examples of planetary magnetic fields on which to test models may provide better information on the planets in the Solar System, much like how the diverse nature of planetary systems have provided insights into the mechanisms by which planets form and evolve.

The constraints that a magnetic field measurement would provide depend upon the class of the planet.

Gas-Giant Planets

For gas-giant planets (i.e., Jupiter mass), the equation of state of hydrogen is known sufficiently well to be confident that it undergoes a transition to a metallic state in a gas-giant planet's interior (Hubbard et al., 2002; Helled et al., 2020). Further, Batygin (2018) argues that rotation rates of gas giants planets being well below their breakup velocities is consistent with magnetic braking of the planet due to its magnetic field being coupled to the (ionized) circumplanetary disk. Consequently, all gas-giant planets are expected to sustain planetary-scale magnetic fields, but there might be a wide range of magnetic field strengths. For instance, estimates for the polar magnetic field strength of HD 209458 b, achived with a variety of different (model-dependent) methods, have ranged over as much as two orders of magnitude (Sánchez-Lavega, 2004; Batygin & Stevenson, 2010; France et al., 2010; Ekenbäck et al., 2010; Khodachenko et al., 2021), from much smaller than that of Jupiter to much larger.

The *absence* of a magnetic field in a gas-giant planet would be the more consequential result.

Ice-Giant Planets

Based on the Voyager 2 measurements of the magnetic fields of Uranus and Neptune, the standard explanation is that the dynamo regions of ice-giant planets are in ionic layers, located at roughly 70% of the planetary radii (Stanley & Bloxham, 2004; Helled et al., 2011). These ionic layers would contain the dominant volatiles of ice giants—water, ammonia, methane, or some combination of all.

A wide variety of different internal compositions and structures have been explored. Yunsheng Tian & Stanley (2013) modeled the dynamo regions of planets with masses ranging from terrestrial mass to ice giants, with a focus on the geometry of the dynamo region, which could be characterized by the thickness of the dynamo region. They found that the thickness of the dynamo region varied, depending upon the mass, temperature, and composition. In turn, the thickness of the dynamo region produced substantially different magnetic field morphologies, with largely axial and dipolar magnetic fields resulting from thick dynamo regions and non-axisymmetric and multipolar magnetic fields resulting from thin dynamo regions.

The composition of the dynamo region of an ice giant may be more complex than can be inferred from a single spacecraft flyby (i.e., from the Voyager 2 results). Ravasio et al. (2021) demonstrated, using a sample at pressures and temperatures likely achieved in the interior of ice giants, that ammonia may undergo a phase transition to a plasma or metallic state. In this state, they found that ammonia could have an electrical conductivity up to an order of magnitude larger than that of water, and they concluded ice giant magnetic fields might be produced in the regions that are the most ammonia-rich. Similarly, (Oka et al., 2024) find that the electrical conductivity of water at the temperatures and pressures in the interior of an ice giant does not appear sufficient to sustain a dynamo. Finally, Nellis (2016, 2017) has argued that metallic hydrogen in the interfaces between the envelopes of Uranus and Neptune and their lower layers is responsible for generating their dynamos.

Observationally, there are two clear directions to pursue. Within the Solar System, a future Uranus Orbiter, such as that recommended by the *Origins, Worlds, and Life* (2022) report from the Planetary Science & Astrobiology Decadal Survey in the United States, could obtain a much higher fidelity characterization of the Uranian magnetic field. However, the Uranus Orbiter would provide measurements for only a single ice giant, and a potentially unrepresentative one. With both its high obliquity and low thermal flux, the extent to which Uranus' interior structure can be taken to be representative of all ice giants is yet to be determined.

A complementary approach is to obtain magnetic field measurements for even a modest sample of extrasolar ice giants. A testable hypothesis motivating such measurements could be that ice giants produce magnetic fields with a broad range of strengths, with Uranus and Neptune at the low end of this range. This broad range of magnetic field strengths could result from various origins or evolutions. For instance, ice giants forming at different distances from their host stars might have different bulk compositions, which could affect whether a water-rich or ammonia-rich internal layer generates the dynamo. Similarly, ice giants might produce a range of magnetic field topologies, ranging from the complex multi-polar topologies of Uranus and Neptune to more dipolar topologies characteristic of Jupiter and Earth. At a distance, dipolar toplogies would appear to have larger magnetic field strengths than multi-polar topologies.

Super Earths

Because the Solar System contains no sub-Neptunes nor super-Earths, there is an opportunity for discovery should magnetic fields be able to be measured for these classes of planets. Indeed, Coppari et al. (2021) have measured various properties of samples under the pressures and temperatures expected in the interiors of super-

Earths. They find that the higher temperatures and pressures in super-Earths, relative to terrestrial-mass planets, could result in different mineralogic properties, including lower viscosities. A potential consequence, they speculate, could be that super-Earths would have an increased “electromagnetic coupling between the core and the mantle, enhancing convection and heat transport out of the core and affecting the strength and expression of the magnetic field.”

Terrestrial-Mass Planets

The dynamos, if not interior structures, of terrestrial-mass planets can be expected to exhibit a large range. In the Solar System, Earth exhibits a strong, dipolar magnetic field, while Venus produces no (current) planetary magnetic field, even though the two planets are nearly “twins.”

Noack & Lasbleis (2020) have shown that variations in the relative fractions of silicates and iron within terrestrial-mass planets could produce substantially different temperature-pressure profiles. While they do not extend their analysis to modeling the generation of a dynamo, differences in the interior state reasonably can be expected to result in different magnetic field strengths, topologies, or both. Indeed, estimates of the Earth’s paleomagnetic field show variations (in the median) of approximately a factor of a few over the past 3500 Myr (e.g., Bono et al., 2022), suggesting that the dynamo evolved (substantially) over gelogic time as its interior properties evolved. Further, Ziegler & Stegman (2013) and Blanc et al. (2020) illustrate how the Earth’s dynamo may have shifted from its mantle to its core as its interior cooled and the inner core began to solidify (Figure 1.5). If the dynamo has evolved over geological time scales, the Earth’s radio emissions may have had considerably different intensities as well.

Observationally, there is considerable information on the magnetic fields of terrestrial-mass planets within the Solar System. Finding and characterizing terrestrial-mass planets will be a significant focus for the coming decades, as discussed in the *Pathways to Discovery* (2021) report from the recent Decadal Survey in Astronomy & Astrophysics conducted in the United States. Determining magnetic field strengths of terrestrial-mass planets not only may yield information about their interior structures, in a manner analogous to ice giants, but also be relevant for their habitability, as the next section discusses.

Planetary Magnetic Fields and Habitability

A challenging, yet intriguing, possibility is that the detection of extrasolar planetary magnetic fields may provide information about the potential habitability of terrestrial planets, or help explain why some terrestrial planets are not inhabited. As summarized in the *Exoplanet Science Strategy* (2018), a planetary magnetic field could

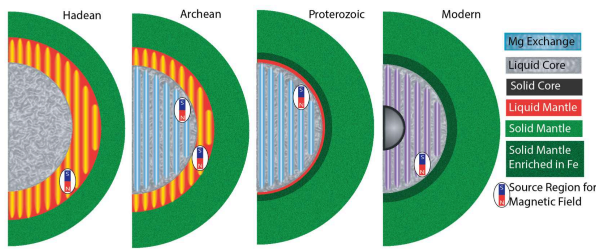

Fig. 1.5 Illustration of how the source region of the Earth's magnetic field may have changed as the Earth has cooled over geological time scales. The different source regions potentially would have generated magnetic fields of different strengths, with concomitant implications for the Earth's radio emissions. Similar processes may occur for other terrestrial-mass planets. (Credit: D. Stegman)

protect the (secondary) atmosphere (and potentially surface) of a terrestrial planet from cosmic rays and the effects of intense stellar flares and eruptions (coronal mass ejections, CMEs). (See also Shahar et al., 2019).

There is a rich literature regarding how a planet's magnetic field might protect its (secondary) atmosphere from erosion by its host star's stellar wind or its surface from the effects of high-energy particles or both (Grießmeier et al., 2004; Grießmeier et al., 2005b; Lammer et al., 2008; Grießmeier et al., 2009; Grießmeier et al., 2010; Driscoll & Bercovici, 2013; Grießmeier et al., 2015; Foley & Driscoll, 2016; Garcia-Sage et al., 2017; Owen & Adams, 2019). The essential concept is that, if a planet's magnetic field is sufficiently strong, and the kinetic and magnetic energies of the host star's stellar wind are not too strong, the energetic particles in the host star's stellar wind are deflected (by $\mathbf{v} \times \mathbf{B}$ forces) before they reach the planet's atmosphere. This concept has been extended to consider the possibility that, even if a planet itself is not habitable, its magnetosphere could contribute to protecting a moon, thereby contributing to the moon's habitability (Green et al., 2021).

This potential importance was identified in *Pathways to Discovery* (2021) by the Science Priority Question 2, "What are the Properties of Individual Planets and Which Processes Lead to Planetary Diversity?" with the secondary questions, Question 2b, "How Does a Planet's Interior Structure and Composition Connect to Its Surface and Atmosphere?" and Question 2d, "How Does a Planet's Interaction with

Its Host Star and Planetary System Influence Its Atmospheric Properties over All Time Scales?"

There have been efforts to assess the role of the Earth's magnetosphere in determining its habitability (Varela et al., 2023) and speculation that changes in the Earth's paleomagnetosphere may have contributed to substantial changes in the evolution of life (e.g., Meert et al., 2016). This expectation of atmospheric protection is has been extended to be included in models that attempt to assess or predict the likely habitability of extrasolar planets (Rodríguez-Mozos & Moya, 2017, 2019; McIntyre et al., 2019).

The possibility of a stellar wind eroding completely, or nearly so, a planet's atmosphere is particularly acute in the case of a planet orbiting an M dwarf, for two reasons. First, the lower stellar insolation means that the planet must orbit (much) closer to the star in order to be in the traditional habitable zone where the temperature is high enough that liquid water could exist on the planet's surface. Second, M dwarfs can have intense stellar wind activity. Notably, the closest potentially habitable planet may orbit Proxima Centauri b, emphasizing these concerns (Ribas et al., 2016; Garcia-Sage et al., 2017). Additionally, the extent to which a planet's atmosphere is exposed to high-energy particles, either from its host star or Galactic cosmic rays, may affect its chemistry (Grießmeier et al., 2016).

Dramatic evidence of the effects on a planetary atmosphere without magnetic shielding, and exposed to the effects of a stellar wind, were provided by Mars Atmosphere and Volatile Evolution (MAVEN) observations showing erosion of the Martian atmosphere when it was struck by a solar CME (Jakosky et al., 2015). However, a more nuanced view notes that the Earth's magnetosphere presents a larger obstacle in the solar wind as compared to the ionospheres of Venus or Mars, allowing for more interactions and greater rate of atmospheric loss Blackman & Tarduno (2018). Recent reviews, motivated by space physics observations within the Solar System, have emphasized that Earth has both a stronger magnetic field than either Venus or Mars and a *larger* atmospheric loss rate (Gronoff et al., 2020; Ramstad & Barabash, 2021); of particular note is Figure 5 of Ramstad & Barabash (2021). Even for a larger planet, interactions between its magnetosphere and the host's star stellar wind can inject energy into its atmosphere, at least inflating if, and potentially increasing its mass loss (Lanza, 2013).

A complication regarding the atmospheric shielding effects of a planetary magnetic field is that a magnetic field is only effective in shielding energetic charged particles. Other processes, such as photoevaporation from the host star's soft X-ray and UV emission or core-powered mass loss, also may contribute to atmospheric loss.

Future Steps

Since the first edition of the *Handbook of Exoplanets*, there have been a number of notable improvements in capabilities and new searches, albeit there remains no current, unambiguous detection of radio emission from an extrasolar planet (Figure 1.2). There are two, complementary avenues that hold promise for the future. New (ground-based) capability is emerging below 50 MHz, as exemplified by the observations of HD 80606 b (de Gasperin, Lazio, & Knapp, 2020), and the potential for future space-based missions is increasing.

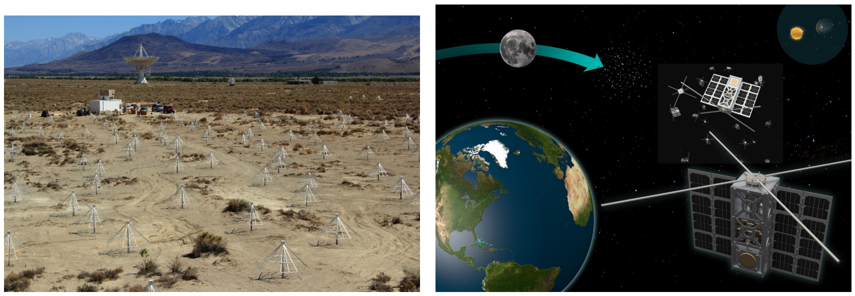

Fig. 1.6 (*Left*) Long Wavelength Array at Owens Valley Radio Observatory (LWA-OVRO), one of the new capabilities for searching for and observing the extrasolar planetary radio emission and a possible model for future space-based observations. The signals from all of the individual dipole antennas are transmitted to a central location for processing, producing an effective aperture equivalent to the approximate maximum separation between the antennas ($\approx$ 300 m). (In the background are other antennas at the Owens Valley Radio Observatory.) The low-band antennas of the Low Frequency Array (LOFAR/LBA) are more closely packed in individual "stations" or groups, but the stations are widely distributed across the Netherlands and Europe. (*Right*) Artist's impression of a possible future space-based radio telescope for observing radio emission from extrasolar planets. Space-based observations are likely to be required for detecting planets with magnetic fields weaker than about 10 G. This architecture is analogous to that of the LWA-OVRO and LOFAR/LBA, with each small spacecraft carrying a single dipole antenna. Signals from the individual spacecraft would be combined to form the synthetic aperture.

There are three primary (ground-based) telescopes enabling future searches and observations below 50 MHz, LOFAR, the Long Wavelength Array at the Owens Valley Radio Observatory (LWA-OVRO), and NenuFAR.

The Low Frequency Array LOFAR can observe from 10 MHz to 90 MHz (and at higher frequencies, van Haarlem et al., 2013). There is a plan to upgrade its low-band antennas (LBAs) in order to provide increased sensitivity (ASTRON Press Release, 2023), and there is an increasing emphasis on improving the calibration of the telescope at these low frequencies, which must contend with the Earth's ionosphere.

LWA-OVRO The Long Wavelength Array at the Owens Valley Radio Observatory (LWA-OVRO) can observe between about 20 MHz and 80 MHz (Figure 1.6). Building on the lessons from the first station of the LWA (LWA1, Taylor et al., 2012), the LWA-OVRO has enhanced imaging capabilities, which provide a higher sensitivity. The LWA-OVRO has been undergoing an expansion-upgrade project and, while still in its commissioning phase, initial observations are promising.

NenuFAR is a substantially enlarged station ("super station") of LOFAR-like antennas that can be used as part of LOFAR or as a stand-alone telescope (Zarka et al., 2020).

A crucial aspect for searching for radio emission from extrasolar planets is that both LOFAR and LWA-OVRO provide wide-field capabilities, enabling surveys of the sky to be conducted (e.g., Shimwell et al., 2017). Such surveys have resulted in the discovery of radio emission from low-mass stars, possibly indicative of star-planet interactions (Vedantham et al., 2020). Further, because planetary radio emission is expected to be weak, the most likely first detections will be of planets in the solar neighborhood. Their host stars are distributed widely on the sky, so a wide-field capability enables a radio telescope to monitor multiple stars simultaneously. Such long-term monitoring capability is particularly important given that there may be (likely are) geometric effects that result in planets illuminating the Earth only during specific phases of their orbits.

In this context, motivated in part by the Habitable Worlds Observatory (HWO) concept, over the next few years, a much more complete census of extrasolar planets in the solar neighborhood is expected (Mamajek & Stapelfeldt, 2023, e.g.,), from a variety of both ground- and space-based efforts. A possible consequence is that, within the volume for which it is likely that radio emissions could be detected, there will be few extrasolar planets discovered initially by their radio emissions because other techniques will discover them first. Conversely, this census of nearby extrasolar planets will provide specific targets for radio telescopes.

Finally, both LOFAR and LWA-OVRO are making considerable efforts to calibrate their polarization responses. As the electron cyclotron maser instability (ECMI) naturally produces circularly polarized radiation, and few other sources produce high levels of circular polarization, searches for circularly-polarized sources could be a particularly fruitful approach to discovering the radio emissions of extrasolar planets. Indeed, at least one such survey for circularly polarized sources is underway using LOFAR, the V-LoTSS (Callingham et al., 2023b).

While the focus of this chapter has been on the detection and study of extrasolar planets at radio wavelengths, a related aspect is any potential connection between gas-giant planets and brown dwarfs. Both are (degenerate) sub-stellar objects capable of generating large-scale magnetic fields, and scaling laws suggest that there should be a continuum of magnetic field strengths between planets and brown dwarfs (Christensen, 2010; Stevenson, 2010; Schubert & Soderlund, 2011; Christensen et al., 2009). Brown dwarfs have been detected at radio wavelengths (e.g., Berger et al., 2001; Route & Wolszczan, 2016; Lynch et al., 2016; Pineda & Villadsen, 2023; Rose et al., 2023), and, at least for some objects, their radio emissions have been confirmed to be due to an ECMI in their auroral regions (Hallinan et al., 2008; Kao et al., 2016, 2018). Further, the ultracool dwarf LSR J1835+3259, which may be either a brown dwarf or a low-mass star, supports radiation belts akin to those of Jupiter (Kao et al., 2023; Climent et al., 2023), providing additional support for the hypothesis that the generation of magnetic fields within brown dwarfs and giant planets likely share similarities. To date, though, brown dwarfs have been detected mostly at frequencies $\nu \gtrsim 5$ GHz, implying magnetic field strengths $B \gtrsim 1\,\mathrm{kG}$; efforts to detect them at lower frequencies largely have been unsuccessful (Jaeger et al., 2011; Burningham et al., 2016). Further study of brown dwarfs may provide clues to guide the discovery of radio emission from extrasolar planets.

This chapter also touches only lightly upon the larger topic of *extrasolar space weather* (Osten et al., 2018; Callingham et al., 2023a), though it clearly is linked to the radio emission of extrasolar planets.

It has been beyond the scope of this chapter, but the on-going Juno mission continues to provide insights about Jupiter's interior structure and its radio emissions (e.g., Louis et al., 2022, 2023), and will continue to do so until at least 2025 (NASA Press Release, 2021). Complementing the Juno science investigation, the Jupiter ICy moons Explorer (JUICE) is scheduled to arrive into the Jupiter system in 2031, where it also will study the Jovian interior and magnetosphere (Grasset et al., 2013). Ice giants may be among the most numerous of extrasolar planets, but there has never been a dedicated mission to either Uranus or Neptune, only a single fly-by of both planets by the Voyager 2 spacecraft. The recent *Origins, Worlds, and Life* (2022) Decadal Survey report in the United States recommends that a Uranus Orbiter & Probe mission be a future NASA Flagship mission, with the science motivation being in part to understand Uranus' interior and magnetosphere.

If the Solar System planets are any guide, Figure 1.4 emphasizes that observations must be able to be conducted below 10 MHz, i.e., the approximate plasma frequency of the Earth's ionosphere. The concept of a space-based radio telescope is not new (e.g., French et al., 1967), and there have been the initial demonstrations of the capability to conduct radio astronomical observations from space. The first Radio Astronomy Explorer (RAE-1) was in an Earth orbit and made the first measurements of the Galaxy's spectrum between 0.4 and 6.5 MHz (Alexander et al., 1969) while the second Radio Astronomy Explorer (RAE-2) was in a lunar orbit and observed between 25 kHz and 13 MHz (Alexander et al., 1975). Jupiter's radio emission was detected with both spacecraft (Desch & Carr, 1974; Kaiser, 1977). The Earth's AKR has been studied by simple space-based telescopes including a single-element interferometer consisting of the ISEE-1 and ISEE-2 spacecraft (Baumback et al., 1986) and a time-difference-of-arrival (TDOA) analysis with the Cluster spacecraft (Mutel et al., 2004).

There have been initial descriptions and proposals of concepts for radio astronomy arrays of small spacecraft, notably including the Astronomical Low Frequency Array (ALFA) mission concept (Jones et al., 2000), and "CubeSat"-based arrays (Banazadeh et al., 2013), for which the detection and study of extrasolar planets was either a part of the science mission or the prime science mission. Most of the attention for future space-based radio telescopes has been focussed on constellations of small spacecraft (Figure 1.6), which are straightforward analogies to how current radio telescopes in this frequency range are realized.

An initial realization of such a space-based radio telescope will be the Sun Radio Interferometer Space Experiment (Kasper et al., 2022, SunRISE,[]), an array of six CubeSats. The primary science focus for SunRISE is determining the locations of solar radio bursts, and, with only six antennas, it will not have the sensitivity to detect the radio emissions from extrasolar planets. However, as a pathfinder to future, larger constellations, it likely will provide valuable lessons.

Moreover, in a microgravity environment, it may be possible to contemplate much larger single apertures than is possible on the Earth. The two approaches have different strengths and weaknesses (Lazio, Shkolnik, Hallinan, et al., 2016)—a constellation of small spacecraft may generate infeasible data rates while there is little experience in constructing extremely large structures ($> 100\,\mathrm{m}$) in space.

Combined with new capabilities at low radio frequencies, the study of extrasolar planets at radio wavelengths remains a promising field.

Acknowledgements It is a pleasure to thank many colleagues for their discussions, speculations, and multiple explanations on the topic of (exo-)planetary radio emission, most notably B. Farrell, P. Zarka, J. Callingham, J. M. Griessmeier, G. Hallinan, E. Shkolnik, D. Stevenson, J. Turner, K. Weiler, and L. Henning and the students at Thomas Jefferson High School for Science & Technology. The author acknowledges the ideas and advice from the participants in the "Planetary Magnetic Fields: Planetary Interiors and Habitability" workshop organized by the W. M. Keck Institute for Space Studies. This research has made use of NASA's Astrophysics Data System. 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 this material is pre-decisional information and for planning and discussion only.

Cross-References

- Planetary Interiors, Magnetic Fields, and Habitability
- Future Exoplanet Research: Radio Detection and Characterization
- Star-Planet Interactions in the Radio Domain: Prospect for Their Detection
- Magnetic Environment of the Planets
- Radio Emission from Ultracool Dwarfs
- Pulsar Timing as an Exoplanet Discovery Method
- The Solar System as a Benchmark for Exoplanet Systems Interpretation
- Factors Affecting Exoplanet Habitability
- Interiors and Surfaces of Terrestrial Planets and Major Satellites
- Internal Structure of Giant and Icy Planets: Importance of Heavy Elements and Mixing

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