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[1] Planetary radio astronomy mostly concerns plasma phenomena at low frequencies (i.e., below a few hundred MHz). The low frequency limit for ground-based observations of these phenomena is given by the Earth's ionosphere, which limits ground based radio observations to frequencies ≥10 MHz. We give an overview and update on the status of a few representative ground-based radio arrays that have been used for planetary studies within the frequency range 10–200 MHz, and we discuss their potential for the four types of planetary radio emissions that can be observed within this frequency range: (1) synchrotron emission from Jupiter's radiation belts, (2) radio bursts caused by solar system planetary lightning, (3) Jupiter's magnetospheric emission, and (4) magnetospheric radio emission from extrasolar planets, for which we also give an update to previous predictive studies. Comparing the four emission modes with the characteristics of existing ground-based radio arrays, we show that the Low Frequency Array (LOFAR) has the potential to bring considerable advances to those four fields of planetary radio science.

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1. Introduction

[2] When low-frequency (22.2 MHz) radio emission from Jupiter was first detected [*Burke and Franklin*, 1955], the existence of planetary radio emission came as surprise. Today we know that not only Jupiter, but also other planets of the solar system are sources of intense radio waves. Over the past decades, observations have been performed with both ground-based radio telescopes and with satellite missions. For the low-frequency range (between 10 and a few hundred MHz), four main emission mechanisms have been identified [*Zarka*, 2002, 2005]:

[3] 1. Jupiter's radiation belts are the source of synchrotron emission. This radiation has been imaged in the decimeter range, but high spatial resolution imaging below 200 MHz, preferably in combination with spectral studies, remains to be done. Large radio arrays can address this question, allowing to study the population of high energy electrons in Jupiter's inner radiation belts.

[4] 2. Short, broad-band radio bursts are associated with lightning in Saturn's atmosphere. While this has for a long time only been observable from spacecraft at short distances, the study of Saturn lightning recently became possible using large groundbased instruments [*Grießmeier et al.*, 2010, 2011; *Zakharenko et al.*, 2011]. Lightning emission from Uranus, Venus, from Martian dust clouds, and from Neptune are currently unobservable from the ground, but some of them may become accessible [*Zarka et al.*, 2004].

[5] 3. Jupiter's magnetosphere is a strong, yet variable source of intense decametric radio emission (≤40 MHz). The radiation is generated by the interaction of the magnetosphere with the solar wind and with the Galilean satellites (primarily Io). While spectral studies have been carried out by ground- and space-based instruments, low frequencies imaging remains to be done. Imaging with a resolution of 1–2″ at 30–40 MHz is possible with a radio array with baselines of 1000 km.

[6] 4. With Jupiter's decametric emissions being as intense as solar ones, it is tempting to search for analogue nonthermal coherent emissions from the magnetosphere of exoplanets. However, only emissions at least 10^3 – 10^4 times more intense than those of Jupiter have a chance of being detected at stellar distances. The best candidates for intense radio emission are likely to be planets around young and active stars. Both planets in very close orbits and more distant, rapidly rotating planets with strong internal plasma sources seem to be promising targets. Radio arrays with a huge collecting area are required to search for this faint emission.

[7] The aim of this article is to give an overview over these four emission mechanisms and to describe the potential for their observation using large ground-based radio arrays. This work is organized as follows: In section 2 we describe and give an update on the status of various large arrays used for observations of planetary radio emission. We will present the Ukrainian T-shaped Radio telescope (section 2.1), the Nançay Decameter Array (section 2.2), the Very Large Array (section 2.3), the Westerbork Synthesis Radio Telescope (section 2.4), the Giant Metrewave Radio

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Table 1. Telescope Characteristics, Adapted and Updated From *Zarka* [2005][a]

Instrument	Reference[b]	Array Description	Frequency (MHz)	Aperture Efficiency (%)	Effective Collecting Area (m^2)	Polarization	Angular Resolution
UTR-2 (Ukrainian T-shaped Radio telescope)	1, 2, 3	2040 dipoles	8–40	∼100	∼150000	1 linear	0.4°
NDA (Nançay Decameter Array)	4, 5	2 × 72 helical spiral antennae	10–120	∼100	2 × 4000	2 circular	6° × 12°
VLA (Very Large Array)[c]	6	27 dishes (25 m diameter)	73.8	∼15	2000	2	25″
WSRT (Westerbork Synthesis Radio Telescope)[d]	7	14 dishes (25 m diameter)	110–180	∼30	1500	2	160–104″
GMRT (Giant Metrewave Radio Telescope)	8	30 dishes (45 m diameter)	153	∼65	30000	2	20″
LOFAR (low band) (LOw Frequency ARray)	9, 10	48 stations (48/96 dipoles each)	15–80	∼100	100000–14000	2	5–0.9″
LOFAR (high band) (LOw Frequency ARray)	9, 10	48 stations (48/96 × 16 dipoles each)	110–240	∼100	70000–20000	2	0.6–0.3″

[a]In particular, the effective collecting area of this table takes into account the aperture efficiency (see table). For dish telescopes which do not intercept 100% of the incident energy, the aperture efficiency represents the ratio between the geometrical area and the effective collecting area. For dense arrays of dipoles, this factor equals unity.
[b]References: 1, *Braude et al.* [1978]; 2, *Abranin et al.* [2001]; 3, *Ryabov et al.* [2010]; 4, *Boischot et al.* [1980]; 5, *Lecacheux et al.* [2004]; 6, *Kassim et al.* [2007]; 7, *Karuppusamy et al.* [2011]; 8, *Swarup et al.* [1991]; 9, *de Vos et al.* [2009]; 10, *Nijboer and Pandey-Pommier* [2009].
[c]Since the upgrade of the VLA (the EVLA project), the low frequencies (74 and 330 MHz) are no longer available. A new low frequency system is planned.
[d]The WSRT LFFE receivers, covering 110–180 MHz, have been decommissioned and are no longer available.

Telescope (section 2.5), and the Low Frequency Array (section 2.6). In section 3 we describe the scientific targets and goals that can be achieved with these instruments. We discuss the synchrotron radiation from radiation belts (section 3.1), the study of radio emission associated with planetary lightning in the solar system (section 3.2), the radio emission generated in Jupiter's magnetosphere (section 3.3) and the search for radio emission from extrasolar planets (section 3.4). The latter section comprises a short introduction (section 3.4.1), a review of recent studies (section 3.4.2) and an update of exoplanetary radio predictions (section 3.4.3). Section 4 closes with some concluding remarks.

2. Large Radio Arrays

[8] In the past, a certain number of radio telescopes have been used for planetary observations. Because the Earth's ionosphere is not transparent to low frequency radio waves, emissions below 10 MHz can only be detected from space. Other advantages and disadvantages (of technical and observational nature) of ground-based observations when compared to measurements by spacecraft are discussed by *Grießmeier et al.* [2011]. In this work, we focus on ground-based observations in the frequency range between 10 MHz and 200 MHz.

[9] In this section, we give an update on the status of a few representative instruments that fall in this category and that were used for planetary studies. The main characteristics of these instruments (together with useful references) are shown and compared in Table 1.

2.1. The Ukrainian T-Shaped Radio Telescope (UTR-2)

[10] The Ukrainian T-shaped Radio telescope, Mark 2 (UTR-2) is the world's largest low frequency radio telescope. First observations were taken in 1970, and since 1972 it has been operating regularly [*Braude et al.*, 1978]. Since that time, the backend has undergone a series of considerable upgrades [e.g., *Abranin et al.*, 2001; *Ryabov et al.*, 2010].

[11] The UTR-2 has been used for observations of lightning on Saturn (see section 3.2), for observations of Jupiter's magnetospheric radio emission (see section 3.3), and for the search for radio emission from extrasolar planets (see section 3.4).

2.2. The Nançay Decameter Array (NDA)

[12] The Nançay Decameter Array (NDA) has been developed from 1975–78. Since January 1978, it is continuously monitoring Jupiter [*Boischot et al.*, 1980]. Today, besides solar observations, one of the main purposes of the instrument is to continuously monitor Jupiter's magnetospheric radio emission (see section 3.3) at decametre wavelengths. The NDA has a "routine mode", which is fully automated. It does, however, also have high resolution and full polarization modes for dedicated observations.

[13] Besides routine and non-routine observations of Jupiter (section 3.3), the NDA has also been used in searches for Saturn lightning (see section 3.2).

2.3. The Very Large Array (VLA)

[14] Although the Very Large Array (VLA) is mostly known for its observation in the GHz range, a receiver capable of observing around a central frequency of 73.8 MHz and a bandwidth of 1.6 MHz was installed in 1998 [*Kassim et al.*, 2007]. This receiver has been used in observations of Jupiter's synchrotron radiation (see section 3.1) and for the search of radio emission from extrasolar planets (see section 3.4).

[15] Over the past years, the VLA has been upgraded to the "EVLA" (Expanded Very Large Array). During this conversion, the low frequency capabilities were removed in 2009, and observations below 1 GHz are currently not possible with the VLA. However, there are plans to add new broad-band (∼50–500 MHz), low-noise EVLA "Low Band" receivers by 2012 [*Kassim*, 2010]. In comparison to the previous system, these will feature an improved sensitivity, a lower receiver noise temperature, and a much wider instantaneous bandwidth (∼20 MHz at 74 MHz and ∼200 MHz at 330 MHz, compared to the previously available bandwidths

of 1.5 MHz and 40 MHz), thus greatly enhancing the low frequency capability of the VLA.

2.4. The Westerbork Synthesis Radio Telescope (WSRT)

[16] At the end of 2004, a new suite of receivers, the Low Frequency Front Ends (LFFEs) has been installed and taken into operation at the fourteen telescopes of the Westerbork Synthesis Radio Telescope (WSRT) [*van der Marel et al.*, 2005]. The LFFEs covered the frequency range 110–180 MHz with an instantaneous bandwidth of 20 MHz. The LFFEs were used to observe lightning on Saturn (see section 3.2).

[17] In summer 2010, the WSRT LFFE receivers have been decommissioned and are no longer available. While the WSRT henceforth focusses on higher frequencies, the same observatory hosts LOFAR (see section 2.6), which offers much more extensive capabilities in the same frequency band.

2.5. The Giant Metrewave Radio Telescope (GMRT)

[18] The Giant Metrewave Radio Telescope (GMRT) has been constructed near Pune in India. Regular science operation started in 2002. Currently, five frequency bands are offered: 1420, 610, 327, 233 and 153 MHz, with a maximum bandwidth of 16 MHz [*Swarup et al.*, 1991]. Of these, the 153 MHz band is the most interesting for planetary studies, but a 50 MHz receiver system for the GMRT is currently under development [*Udaya Shankar et al.*, 2009].

[19] The GMRT has been used in observations of Jupiter's synchrotron radiation (see section 3.1) and for the search of radio emission from extrasolar planets (see section 3.4).

2.6. The Low Frequency Array (LOFAR)

[20] The LOw Frequency ARray (LOFAR) is both an international collaboration and a distributed network of radio sensors. While most stations are located in the Netherlands, further antennae are located in the United Kingdom, in Germany, Sweden and in France. Because on this distributed approach, the main complexity of LOFAR does not lie in the receivers, but in the hierarchical organization of a large number of antennae (almost 50,000) and in the analysis of the incoming data in a large computing facility.

[21] Table 1 shows that LOFAR will be 10 to 100 times more sensitive than most instruments in its frequency range. Due to its international stations, it will achieve sub-arcsecond resolution, which is 10 to 100 times better than the resolution of existing low-frequency instruments.

[22] The construction and rollout of LOFAR are almost terminated. Observations have begun [e.g., *Stappers et al.*, 2011], and the telescope was inaugurated in June 2010. At the same time, software development is ongoing. The different observation modes are gradually made available, and the data format to be used by LOFAR are being defined. While LOFAR is still being commissioned, it is already clear that it has a huge potential for a large number of fields within astronomy. Section 3 will show that this applies also to the field of planetary radio emissions.

[23] Already now, LOFAR has been used for test observations of Jupiter's magnetospheric radio emission (see section 3.3) and for observations of lightning on Saturn (see section 3.2). The future observing plan [*Braun et al.*, 2007] does also include observations of Jupiter's synchrotron radiation (see section 3.1) and the search of radio emission from extrasolar planets (see section 3.4).

3. Planetary Radio Emission Detectable From the Ground

3.1. Synchrotron Radiation

[24] The synchrotron radio emission from Jupiter's radiation belts (a non-thermal, incoherent radiation) spans a wide frequency range. It has been studied at frequencies between 74 MHz and 22 GHz (mostly at frequencies above 300 MHz) by a large number of radio telescopes, including the Australia Telescope Compact Array (ATCA), the WSRT, the GMRT and the VLA [e.g., *de Pater and Butler*, 2003a, 2003b; *de Pater et al.*, 2003; *Santos-Costa et al.*, 2009]. The emission is generated by relativistic electrons gyrating around magnetic field lines in Jupiter's inner radiation belt (<5 Jovian radii). Different frequency ranges allow to probe electron populations of different energies [see, e.g., *de Pater*, 2004]. In particular, the low frequency component of interest to this work is generated by particles of lower energies. Both images as well as spectral studies have contributed to our current understanding of Jupiter's radiation belt. With tomographic techniques, it has also been possible to reconstruct the three dimensional structure of the emission region [*Leblanc et al.*, 1997; *Sault et al.*, 1997]. Jupiter's synchrotron emission (i.e., the flux density and the spectral shape) has been found to be variable on timescales ranging from days to years [e.g., *de Pater et al.*, 2003; *Santos-Costa et al.*, 2009]. The origin of this variability is not fully understood.

[25] As far as low-frequency radio observations (<200 MHz) are concerned, Jupiter's radiation belts have so far only been observed by the VLA at 74 MHz [*de Pater and Butler*, 2003a, 2003b; *de Pater et al.*, 2003]. It was found that the variability of the emission was larger than in other frequency ranges. For this reason, low frequency radio observations provide a good means to retrieve information on the physical processes that operate in Jupiter's inner radiation belts. In particular, high spatial resolution imaging of the sources of such emission (and their time variability with planetary rotation and solar wind fluctuations) at frequencies below 300 MHz would prove useful, but remain to be done. With an angular diameter of less than 1′, Jupiter cannot be well resolved with the VLA at low frequencies (cf. Table 1). In order to investigate the cause of the variability of Jupiter's radiation belt, simultaneous images and spectral observations are required over a broad frequency range. This will allow to study possible correlations between changes in total intensity, spectral index, and the spatial brightness distribution and spectral shape [*de Pater et al.*, 2003]. LOFAR is well adapted for this task: It can provide high angular resolution at low frequencies (cf. Table 1 and section 2.6), a broad frequency coverage and it will allow precise spectral studies.

[26] The low-frequency radio component corresponds to electrons at low energies (a few keV to MeV), which is currently relatively unknown. LOFAR will address this question, allowing the study of the origin, transport, scattering (by plasma waves), and loss (through synchrotron

emission or by interaction with dust) of those particles in Jupiter's inner radiation belts [*de Pater*, 2004].

[27] No synchrotron emission has been detected from Saturn (probably due to the absorption of energetic particles in the planetary rings). Also, bursts of energetic electrons have been observed by the Mariner 10 mission in the magnetosphere of Mercury. These might cause bursts of synchrotron emission (although there was no radio instrument on Mariner 10 to confirm this). A deep search for weak synchrotron radiation from these planets will also be attempted by LOFAR.

3.2. Radio Emission From Solar System Planetary Lightning

[28] Not long after the beginning of radio observations, it was found that terrestrial lighting generates a high frequency radio signal. Later, satellite observations showed that this phenomenon is not limited to our own planet, but takes place also for other planets in the solar system. However, the limited reach and lifetime of satellite missions meant that the amount of available data was rather limited until recently: HF (high-frequency) radio emission caused by planetary lightning was clearly observed for Saturn (by Voyager 1 and 2 in 1980–1981 [see *Warwick et al.*, 1981]), and at Uranus (by Voyager 2 in 1986 [see *Zarka and Pedersen*, 1986]). These events were soon suggested to be caused by lightning activity [*Burns et al.*, 1983; *Kaiser et al.*, 1983; *Zarka and Pedersen*, 1983]. This has been confirmed by subsequent radio observations, by the comparison to optical images of storm clouds and by imaging of single cloud flashes [*Dyudina et al.*, 2010]. Saturn lightning observations, including spacecraft observations, are summarized e.g. by *Fischer et al.* [2011].

[29] The flux densities of Saturn lightning varies from event to event and from one planetary rotation to another. *Zarka et al.* [2004] estimate the flux density that can be expected at Earth. They find that a good fraction of the events should reach at least 10 Jy at 20 MHz. Sometimes, even flux densities of up to 1000 Jy are reached. At higher frequencies, however, the flux density probably decreases as f^{-1} or f^{-2}, making their observation more difficult. Due to these low flux levels and due to its low occurrence rate, Saturn lightning emission has only recently become detectable for ground-based telescopes. With the development of modern and powerful receivers and with the Cassini spacecraft in Saturn's orbit as a trigger for the observation, lightning radio emission was finally unambiguously detected at the giant Ukrainian radio telescope UTR-2 [*Grießmeier et al.*, 2010, 2011; *Zakharenko et al.*, 2011]. Saturn lightning was also recently observed by the WSRT and by LOFAR [*Grießmeier et al.*, 2010, 2011].

[30] *Zarka et al.* [2004, 2008] summarize and compare known lightning emission from solar system planets to the detection threshold of the NDA, UTR-2, and LOFAR. They show that LOFAR will not only be able to detect Saturn lightning, but it will also allow imaging. Saturn has an angular size of approximately 17″, while LOFAR can achive an angular resolution of 1–2″ using the long baselines to its international station (cf. Table 1 and section 2.6). Observations with LOFAR can be used to measure the spectrum over a wide frequency band (15–240 MHz), which could increase the range of frequencies with observed Saturn lightning activity by a factor up to 6. This will allow direct determination of the dependence of the spectral slope on frequency, and comparison to terrestrial lightning. The spectrum is expected to steepen at higher frequencies, but with the current spectral coverage this is not observable. It is, however, likely that this happens somewhere in the frequency range accessible by LOFAR.

[31] The stroke duration of Saturn lightning bursts is still unknown, but could be extremely short. The stroke time scales could be as low as 1 μs, while the terrestrial value is $\sim$70 μs [*Farrell et al.*, 2007]. This stroke duration is an important parameter required to estimate the discharge energy, which is uncertain by many orders of magnitude [*Farrell et al.*, 2007]. High time resolution profiles of Saturn lightning (up to 5 microseconds in standard mode for LOFAR, and finer resolution when using the transient buffer boards) will be able to solve this open question.

[32] In addition to the lightning discharge timescales and its energy budget, monitoring of planetary lightning (which will, at least in the case of Saturn, be combined with optical observations of storm clouds) will allow the study of of electrification processes, atmospheric dynamics and composition, geographical and seasonal variations, and will allow a comparison with the corresponding processes on Earth.

[33] According to *Zarka et al.* [2004], Uranus lightning will probably also be detectable with LOFAR, although the larger distance will lead to a lower signal-to-noise ratio and to more limited imaging capability (the angular size of Uranus is only 3″). Neptune is not likely to be detected due to the large distance. Similarly, the upper limit for lightning radio emission from Venus is below the detection threshold of LOFAR. Nonetheless, it has been suggested to use one of LOFAR's multiple beams to monitor these planets to search for potential rare and intense events. Finally, lightning on Jupiter and Titan will be undetectable from the Earth: For Jupiter, lightning is known to exist from optical images, but HF radio emission has not been detected by any instrument (including the Voyagers, Galileo and Cassini). Two different explanations for this discrepancy have been suggested [*Zarka et al.*, 2004], but both explain the lack of HF radiation by an emission frequency below Jupiter's ionospheric cutoff. For Titan, lightning is probably very rare, if it exists at all [*Fischer and Gurnett*, 2011].

3.3. Magnetospheric Radio Emission

[34] Jupiter's magnetosphere emits intense decameter radio waves. From the ground, they are detectable in the range 10 to 40 MHz [e.g., *Zarka*, 1998]. The generation mechanism has been identified as the cyclotron-maser instability [see, e.g., *Wu and Lee*, 1979], a non-thermal, coherent emission mechanism whose characteristics fulfill all the observed radiation properties [*Zarka*, 1998; *Treumann*, 2006].

[35] Prerequisites for the cyclotron-maser instability are strongly magnetized, depleted regions where the electron cyclotron frequency greatly exceeds the electron plasma frequency, i.e., $f_{c,e} \gg f_{p,e}$, energetic electrons (i.e., energies of the order of keV) and an anisotropy in the electron distribution function (e.g. a distribution with a positive gradient in the velocity perpendicular to the magnetic field.)

[36] In the case of Jupiter, the electrons are accelerated by magnetospheric processes taking place at the magnetopause

nose, in the magnetotail, or in the vicinity of the satellite Io which interacts with the Jovian magnetic field [*Zarka*, 1998]. In particular, the interaction of Io with Jupiter's planetary magnetic field is thought to lead to Alfvén wings, in which particles are accelerated to keV energies by potential jumps [e.g., *Hess et al.*, 2007]. These energetic electrons precipitate in the auroral regions as well as near the magnetic footprints of Io. The mirror effect reflects part of the particles, leading to an electron velocity distribution unstable with respect to the cyclotron maser instability. The corresponding radio emission is excited close to the local electron cyclotron frequency $f_{c,e}$, and the broad range of observed frequencies ($\Delta f \sim f$) is a direct consequence of the large difference of local $f_{c,e}$ between the inner and the outer magnetosphere. Because of Io's role in the particle acceleration, the decameter emission is strongly modulated by Jupiter's rotation and by the orbital position of Io (and marginally Ganymede [*Hospodarsky et al.*, 2001]). Finally, owing to the emission mechanism, the radio emission is circularly or elliptically polarized [*Zarka*, 1998].

[37] Many spectral studies have been carried out using ground- and space-based instruments, but imaging at decameter frequencies remains to be done. *Zarka* [2004] has investigated the possibilities that a large radio interferometer such as LOFAR would offer and shows that a wealth of fundamental information could be obtained on Jupiter's high-latitude/mild energy (keV) electrons. In particular, the international baselines of LOFAR will allow radio imaging of these decameter emissions with arcsecond angular resolution (cf. Table 1 and section 2.6), while Jupiter has an angular size of approximately 30–50″. Such images will give access to detailed information on Jupiter's magnetic field, the radio emission process itself, the electrodynamic interaction between Jupiter and Io, electric fields between Jupiter and Io [*Hess et al.*, 2007, 2009], and the electron distribution in the Io plasma torus. Details about the scientific benefit of imaging observations of Jupiter's DAM emission can be found in the work of *Zarka* [2004].

[38] First test observations of Jupiter have already been performed with a LOFAR prototype station ITS [*Nigl et al.*, 2007], with the first LOFAR test station having the final station design (station CS-1) and with a number of regular LOFAR stations (including both Dutch and International stations). More observations with the full array will follow soon.

3.4. Radio Emission From Extrasolar Planets

3.4.1. The Emission Mechanism

[39] Similarly to Jupiter's magnetospheric radio emission described in the previous section, all magnetized planets of the solar system emit radio waves from their magnetospheres [e.g., *Zarka*, 1998]. The emission is caused by a Cyclotron Maser Instability, which leads to radio waves with a frequency close to the local gyrofrequency. Thus, the maximum emission frequency $f^{\max}$ is given by

$$f^{\max} = \frac{eB_{\mathrm{P}}^{\max}}{2\pi m_{\mathrm{e}}}, \qquad (1)$$

where m_{e} and e are the electron mass and charge, and $B_{\mathrm{P}}^{\max}$ is the maximum magnetic field strength close to the polar cloud tops. Because the other planets of the solar system have magnetic field strengths much lower than Jupiter, their maximum emission frequency is below the terrestrial ionospheric cutoff ($\sim$10 MHz), which makes their emission unobservable from the ground. This is even true for the Earth's auroral kilometric radiation, which can usually only be observed using satellites.

[40] For a certain class of extrasolar planets (the so-called "Hot Jupiters"), an analogous, but much more intense radio emission is expected. When either the planet or the star has a sufficiently strong magnetic field, equation (1) shows that the maximum emission frequency is above the terrestrial ionospheric cutoff, and the emission is potentially observable from the ground.

3.4.2. Recent Studies

[41] In the last few years, the field of exoplanetary radio emission has become an active field of research, with a number of both theoretical studies and observation attempts. The theoretical studies are important not only because they indicate that the anticipated radio flux is strong enough to allow ground-based detection, but they also serve to guide the observation programs and select the most promising targets. A few recent results should be mentioned here:

[42] 1. At least in most cases, exoplanetary radio emission is expected to exceed the emission of the planetary host star [*Zarka*, 1997; *Grießmeier et al.*, 2005].

[43] 2. Because the stellar wind parameters strongly depend on the stellar age, the expected radio flux is a function of the age of the exoplanetary host star [*Stevens*, 2005; *Grießmeier et al.*, 2005]. The radio flux of a planet around a young star may be orders of magnitude higher than for a planet in an older system.

[44] 3. For the same reason, the uncertainty on the estimated radio flux at Earth is dominated by the uncertainty in the stellar age [*Grießmeier et al.*, 2007a], which is usually considerable.

[45] 4. For a small, but nonzero number of planets the plasma frequency in the stellar wind is expected to be of the same order of magnitude as the maximum emission frequency. In these cases, escape of the radio emission from its source toward the observer may not be possible [*Grießmeier et al.*, 2007b].

[46] 5. Even a purely planetary signal will be partially modulated by the stellar rotation period [*Fares et al.*, 2010]. This will complicate the discrimination between a stellar and a planetary radio signal.

[47] 6. Not only planets hosted by main sequence stars are interesting targets. More "exotic" environments have been studied, including terrestrial planets around white dwarfs [*Willes and Wu*, 2005], planets around evolved cool stars [*Ignace et al.*, 2010], and planets around T Tauri stars [*Vidotto et al.*, 2010]. Interstellar rogue planets (i.e., planets not bound to a star) were studied by *Vanhamäki* [2011].

[48] 7. For the emission to be detectable from the ground, either a magnetized planet is required, or a strongly magnetized star [*Zarka et al.*, 2001; *Zarka*, 2007; *Grießmeier et al.*, 2007b].

[49] 8. The planetary magnetic moment is an ill-constrained, yet important quantity for estimating exoplanetary radio flux. Different theoretical arguments have led to two main approaches: *Farrell et al.* [1999] and *Grießmeier et al.* [2004] assume the planetary magnetic moment can be calculated by a force balance, and find a planetary magnetic

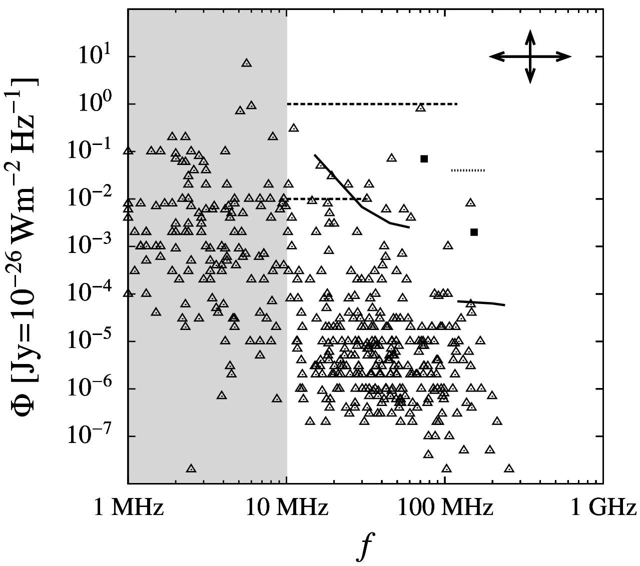

Figure 1. Maximum emission frequency and expected radio flux for known extrasolar planets for a *rotation-dependent* planetary magnetic field (adapted and updated from *Grießmeier et al.* [2007b]). Open triangles, predictions for planets. For comparison, the approximate sensitivity of the arrays described in the text is shown (for 1 h of integration time and a bandwidth of 4 MHz, or an equivalent combination): the upgraded UTR-2 (lower dashed line), the NDA (upper dashed line), the VLA (upper solid square), the WSRT (fine dotted line), the GMRT (lower solid square), LOFAR (two dash-dotted lines, one for the low band and one for the high band antenna). Frequencies below 10 MHz are not observable from the ground (ionospheric cutoff).

field which depends on the planetary rotation rate. On the other hand, *Reiners and Christensen* [2010] assume the planetary magnetic moment to be primarily driven 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. Planetary radio observations may be one way to discriminate between these models.

[50] 9. Most models favor close-in planets, especially "Hot Jupiters" [see, e.g., *Zarka*, 2007; *Grießmeier et al.*, 2007b]. However, rapidly rotating planets with strong internal plasma sources can also produce radio emission at detectable levels at orbital distances of several AU from their host star [*Nichols*, 2011].

[51] 10. *Hess and Zarka* [2011] recently performed simulations to study how physical information on the star-planet system can be extracted from radio observations. In particular, they show that the interaction mode (i.e., exoplanet-induced stellar emission versus planetary radio emission) and the orbital inclination can be obtained through repeated radio observations.

[52] In addition to those theoretical studies, a number of observation attempts were carried out. Maybe surprisingly, the first attempts at observation of exoplanetary radio emission go back at least to *Yantis et al.* [1977]. At the beginning, such observations were necessarily unguided ones, as exoplanets had not yet been discovered. Later observation campaigns concentrated on known exoplanetary systems. While up to now no detection has been achieved, studies are ongoing or planned at the VLA, GMRT, with UTR-2 and with LOFAR.

3.4.3. Radio Predictions

[53] The first predictive studies [e.g., *Zarka et al.*, 1997; *Farrell et al.*, 1999] concentrated on only a few exoplanets. Comparative studies of expected exoplanetary radio emission from a large number of planets were performed by *Lazio et al.* [2004], who compared expected radio fluxes of 118 planets (i.e., those known as of 2003, July 1) and by *Grießmeier et al.* [2007b], who examined 197 exoplanets (i.e., those known as of 2007, January 13). As the number of planetary detections has continued to grow rapidly over the last four years, it is worth while to update these predictions.

[54] In this section, we update and extend the analysis of *Grießmeier et al.* [2007b], including all currently known extrasolar planets (i.e., 547 planets as of 2011, April 28, taken from http://exoplanet.eu/). The results are shown in Figure 1. Rather than showing three different models separately (as was done by *Grießmeier et al.* [2007b]), we combine the results of the *magnetic energy* model, the *kinetic energy* model and the *CME* model in one graph, showing the maximum radio flux that can be expected from each planet (denoted by open triangles). The typical uncertainties within these models (approximately one order of magnitude for the flux density, and a factor of 2–3 for the maximum emission frequency [see *Grießmeier et al.*, 2007a]) are indicated by the arrows in the upper right corner. For comparison, we show the expected sensitivity of different detectors (for 1 hour integration and 4 MHz bandwidth, or any equivalent combination): The upgraded UTR-2 is represented by the lower dashed line, the NDA is shown by the upper dashed line, the VLA corresponds to the upper solid square, the WSRT is shown as a fine dotted line, the GMRT is indicated by the lower solid square, and two solid lines are used for the low band and high band of LOFAR, respectively. For a given instrument, a planet is observable if it is located either above the instrument's symbol or above and to its right. Figure 1 shows that up to eight of the currently known planets should be observable by the upgraded UTR-2. For LOFAR, the number of potential targets is approximately twelve. Considering the uncertainties of the estimate, these numbers should not be taken literally, but should be seen as an indicator that while observation seem feasible, the observed targets must be selected carefully. It can be seen that the maximum emission frequency of many planets lies below the ionospheric cutoff frequency, making ground-based observation of these planets impossible. Interestingly, the number of potential targets has approximately increased by the same ratio as the number of known planets when compared to *Grießmeier et al.* [2007b]. This may indicate that more good targets can be expected to join this list in the future.

[55] It has been mentioned above that the planetary magnetic field plays an important role, especially for the maximum emission frequency. In particular, close-in exoplanets, which receive the highest amount of energy by their host star and are thus believed to have the strongest radio emission, are tidally locked [*Grießmeier et al.*, 2007b]. For Figure 1, the corresponding slow planetary rotation was assumed to lead to a small planetary magnetic moment, and thus a

low maximum emission frequency (in many cases below 10 MHz, and thus unobservable). If however, as *Reiners and Christensen* [2010] suggest, planetary rotation has little influence on the planetary magnetic field then a different picture arises: Close-in planets still have a high radio flux density, but their emission frequency is higher, bringing it above the threshold of ground-based detectability. As shown in Figure 2, this leads to a considerably higher number of potentially observable planets (over 20 for both UTR-2 and LOFAR). Note, however, that we do not account for the age-dependence of the planetary magnetic moment considered by *Reiners and Christensen* [2010].

[56] The different approaches of Figures 1 and 2 are also reflected in Table 2, which shows the best candidates for ground-based radio observations of exoplanets. The second and third column contain the maximum emission frequency and the maximum expected radio flux density at Earth for the case of a rotation-independent planetary magnetic moment. Columns four and five contain the same numbers for the case where the planetary magnetic moment strongly depends on the planetary rotation. The table is sorted by decreasing values in column three. When the maximum emission frequency lies below 10 MHz, the numbers are shown in brackets, as an Earth-based observation is not possible. It can be seen that the model without rotational influence systematically has a considerable higher emission frequency f_c, but that the flux Φ is slightly reduced. This results from the fact that f_c and Φ have a very different dependency on the planetary magnetic moment $\mathcal{M}$: In a simple approximation [e.g., *Grießmeier et al.*, 2005, equations (9) and (12)], one finds $\Phi \propto \mathcal{M}^{-1/3}$, whereas $f_c \propto \mathcal{M}$. All good candidates being close-in planets, they are all tidally locked and rotate slowly, which explains the large differences between both models. In particular, the rotation-dependent model leads to emission frequencies below ionospheric cutoff in many cases (also can be seen in Figure 1), leading to

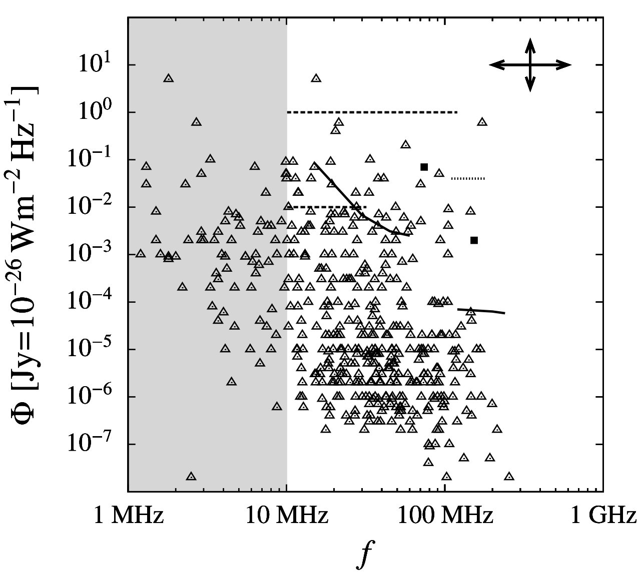

Figure 2. Maximum emission frequency and expected radio flux for known extrasolar planets for a *rotation-independent* planetary magnetic field. All lines and symbols are as defined in Figure 1.

Table 2. Expected Radio Emission Frequencies and Flux Densities for Exoplanetary Observations[a]

Planet	f_c^{norot} (MHz)	Φ_{max}^{norot} (mJy)	f_c^{rot} (MHz)	Φ_{max}^{rot} (mJy)
HD 41004 B b	170	610	70	820
HD 189733 b	21	560	(6.0)	(860)
tau Boo b	57	180	11	300
WASP-12 b	(3.3)	(99)	(1.6)	(130)
HD 73256 b	34	98	(8.2)	(160)
HD 63454 b	10	95	(2.3)	(150)
51 Peg b	11	93	(1.9)	(170)
HD 179949 b	19	90	(4.1)	(150)
ups And b	15	74	(2.5)	(140)
HD 46375 b	(6.3)	(69)	(1.4)	(113)
WASP-18 b	92	55	46	69
HD 75289 b	10	52	(2.0)	(89)
HD 209458 b	(2.9)	(51)	(0.6)	(88)
HD 212301 b	10	51	(2.8)	(77)
HD 20782 b	38	44	(0.2)	(270)
HD 102195 b	11	38	(2.0)	(68)

[a]Column 1, planet name; column 2, expected maximum emission frequency (case with no influence of planetary rotation); column 3, maximum expected radio flux density at Earth (case with no influence of planetary rotation); column 4, expected maximum emission frequency (case of strong influence of planetary rotation); column 5, maximum expected radio flux density at Earth (case of strong influence of planetary rotation); numbers in parentheses, emission frequency is below ionospheric cutoff (emission not observable); see text for details.

the more favorable results in the rotation-independent model.

[57] This question can also be inverted: planetary radio observations may be one way to discriminate between these models of planetary magnetic fields. The best test cases are planets which have radio emission above 10 MHz in one of the models, but not in the other. According to Table 2, good candidates for this test include HD 189733 b and HD 73256 b. However, as all numbers are to some extent model-dependent, caution is advised, and conclusions should not be based on one or two planets only.

[58] In addition to the information about the planetary magnetic field, direct radio detection of exoplanets could also yield information about their rotation periods [*Farrell et al.*, 1999], about their stellar wind environments, including stellar coronal mass ejections [*Grießmeier et al.*, 2007b], and on their orbital inclinations [*Hess and Zarka*, 2011].

4. Conclusions

[59] Planetary radio science is a field that traditionally uses both ground-based and space-based instruments. With the recent improvement of existing telescopes and with the development of new ground-based radio arrays, ground-based observations will continue to contribute to planetary radio studies. These instruments can be expected to contribute to the study of all four types of planetary radio emissions that can be observed between 10 and a few hundred MHz, namely synchrotron emission, radio bursts from lightning discharges, magnetospheric radio emission from Jupiter and its (expected) counterpart from extrasolar planets. In particular, LOFAR has the potential to bring considerable advances to the field of planetary radio science.

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