

DETECTION OF EXOMOONS THROUGH OBSERVATION OF RADIO EMISSIONS

J. P. NOYOLA, S. SATYAL, AND Z. E. MUSIELAK

The Department of Physics, University of Texas at Arlington, Arlington, TX 76019, USA;

joaquin.noyola@mavs.uta.edu, ssatyal@uta.edu, zmusielak@uta.edu

Received 2013 August 16; accepted 2014 June 19; published 2014 July 22

ABSTRACT

In the Jupiter–Io system, the moon’s motion produces currents along the field lines that connect it to Jupiter’s polar regions. The currents generate and modulate radio emissions along their paths via the electron–cyclotron maser instability. Based on this process, we suggest that such modulation of planetary radio emissions may reveal the presence of exomoons around giant planets in exoplanetary systems. A model explaining the modulation mechanism in the Jupiter–Io system is extrapolated and used to define criteria for exomoon detectability. A cautiously optimistic scenario of the possible detection of such exomoons around Epsilon Eridani b and Gliese 876 b is provided.

Key words: methods: analytical – planets and satellites: detection – planets and satellites: dynamical evolution and stability

Online-only material: color figure

1. INTRODUCTION

Since the discovery of the first confirmed extra-solar planet (exoplanet) around the pulsar PSR1257 + 12 by Wolszczan & Frail (1992), there has been great progress in detection techniques and instrumentation, resulting in hundreds of confirmed exoplanets¹ and thousands of exoplanet candidates identified by NASA’s *Kepler*² space telescope. Nonetheless, the current limits of observational techniques have not made it possible to confirm any exomoon detection.

Based on our knowledge of the solar system, one might expect exomoons to be present around some of the known exoplanets and several potential candidates have already been suggested. For example, the orbital stability criterion was used by Quarles et al. (2012) and Cuntz et al. (2013) to suggest the existence of exomoons in the Kepler 16 and HD 23079 planetary systems, respectively. Moreover, Kipping et al. (2009) suggested that exomoons may actually be discovered in the data already collected by the *Kepler* mission. Among the moons of our solar system, there is an interesting example of a planet–moon interaction observed in the Jupiter–Io system, where Io’s motion inside Jupiter’s magnetosphere induces radio emissions (Bigg 1964). The motion produces currents along the field lines that connect Io to the Jupiter’s polar regions, where the radio emissions are modulated by said currents (Acuna et al. 1981; Mauk et al. 2001).

In this study, we use Io-controlled decametric (Io-DAM) emissions as a basis to demonstrate how the presence of exomoons around giant exoplanets may be revealed by the same modulation mechanism. We determine the required physical conditions for such interaction, then assess the feasibility of our model by providing a cautiously optimistic scenario whereby exomoons could be found. Then, we use the available information on the proposed Square Kilometer Array (SKA)³ radio telescope as an example of what kinds of exomoons could be detected if such technologies were fully implemented. Furthermore, we apply our results to the two nearby exoplanetary systems,

Epsilon Eridani and Gliese 876, to show that finding exomoons using this system is not beyond the realm of possibility. Finally, we discuss future improvements to our model and how those improvements might change the results presented here.

There are several previous studies that are at least partially based on the Jupiter–Io system and in which the authors suggest detecting exoplanets by using exoplanetary radio emissions (Lazio et al. 2004 and references therein). However, those authors based their studies on the non-Io-controlled decametric Jovian emissions instead of the Io-DAM, which originate directly from interactions between Io and the Jovian magnetosphere. Moreover, Nichols (2011) studied the Jupiters magnetosphere–ionosphere coupling mechanism and hypothesized that this mechanism could produce enough radio power to be detectable from Earth. Both his study and ours are based on the unipolar inductor mechanism and the current source is Io’s plasma torus. However, the circuit made by the current in each case is fundamentally different. In our study, the circuit directly couples Io to Jupiters poles, whereas in Nichols’s study, the current bypasses Io and instead flows through magnetic field lines well beyond the moon.

As with the other studies mentioned above, Nichols’s mechanism requires a large stellar luminosity. Specifically, it requires large X-ray and EUV stellar irradiation of the exoplanets ionosphere to produce a large enough output power to make it detectable. Our detection method, as it is explained in this paper, does not have such a requirement and in fact favors low stellar irradiation scenarios. More importantly, even though Nichols emphasizes active moons as the sources of plasma, this might not be the case. Recent computational studies have shown that stellar irradiation alone can ionize the hydrogen-rich atmosphere of a Jovian exoplanet to levels that can match and even vastly exceed the amount of plasma in Io’s plasma torus (Trammell et al. 2014). In other words, Nichols’s mechanism cannot be used to detect exomoons, only exoplanets.

This paper is organized as follows. In Section 2, we present the basic theory on the Io–Jupiter system, the intensity of radio emissions, and the magnetic fields in giant planets. In Section 3, we present our results on the detectability scenario of exomoons, followed by discussion. In Section 4, we conclude with a brief overview of our results.

¹ <http://exoplanet.eu/catalog/>

² <http://kepler.nasa.gov/Mission/discoveries/candidates/>

³ <http://www.skatelescope.org/>

2. THEORY

2.1. The Io–Jupiter System

Io is an intensely volcanic moon orbiting inside Jupiter’s magnetosphere. The volcanic activity creates a light atmosphere of SO_2 around Io, which ionizes to create an ionosphere (Lopes & Spencer 2007). This ionosphere then injects ions into Jupiter’s magnetosphere to create a plasma torus, which orbits Jupiter’s magnetic equator at an angle of 9.6° from the rotational equator and co-rotates with the magnetic field at a speed of 74 km s^{-1} (Su 2009). Io orbits Jupiter at a linear speed of 17 km s^{-1} , so Jupiter’s magnetic field passes Io at a speed of 57 km s^{-1} . The speed difference gives rise to a unipolar inductor (Gri  meier et al. 2007), which induces a current across Io’s atmosphere of a few million amps. The current then accelerates the electrons that produce the characteristic radio emissions (Crary 1997). It must be noted that while volcanism is essential to the formation of a dense ionosphere around Io, such a process might not be required for larger moons, since moons like Titan are already large enough to sustain a thick atmosphere, which in turn can give rise to an ionosphere.

Furthermore, the interaction between Io and the plasma torus gives rise to Alfv  n waves (Belcher 1987). The precise mechanism by which Alfv  n waves interact with the torus is complex, and several analytical and numerical models have been proposed. In these models, Alfv  n waves produce electric fields parallel to Jupiter’s magnetic field lines, which then transport and accelerate electrons toward Jupiter’s magnetic poles (Su 2009; Saur et al. 1999; Crary 1997; Neubauer 1980 and references therein). The electrons traveling through the field lines create a cyclotron maser, which then emits radio waves whose existence in the Jupiter–Io system has been observationally verified (Crary 1997; Mauk et al. 2001).

Our studies of exoplanet–moon interactions are based on an extrapolation of both Io’s plasma environment and Jupiter’s magnetic field to different scenarios that could potentially be encountered in newly discovered planetary systems. We begin by finding an expression for the maximum intensity of the radio emissions, then proceed to address the magnetic field and plasma properties, and finally we analyze the dependence of the radio emissions on these parameters.

2.2. Intensity of Radio Emissions

Assuming a simple current distribution around Io and that the magnetic field lines are approximately perpendicular to the plasma velocity, Neubauer (1980) found that the maximum Joule dissipation of the system is given by

$$P_T = \frac{\pi R_{\text{Io}}^2 V_0^2 B_{\text{Io}}^2}{\mu_0 \sqrt{V_A^2 + V_0^2}}, \quad (1)$$

where R_{Io} is Io’s radius, B_{Io} is the magnetic field at Io’s position, V_0 is the plasma speed relative to Io, μ_0 is the permeability of free space, and V_A is the Alfv  n velocity. The Alfv  n velocity depends on the magnetic field, B_{Io} , and the plasma density, ρ_{Io} , through the relationship $V_A = B_{\text{Io}} / \sqrt{\mu_0 \rho_{\text{Io}}}$.

Since only a small fraction of the maximum Joule dissipation, P_T , is converted to radio waves, we will introduce the efficiency coefficient β_{Io} , which, based on previous studies, is $\approx 1\%$ for the Jupiter–Io system (Zarka et al. 2001). There is little information on the variability of this parameter, so we assume that other exoplanet–moon systems have similar efficiency coefficients.

Hence, the maximum radio emission intensity, P_{rad} , from these systems is given as

$$P_{\text{rad}} = \frac{\pi \beta_S R_S^2 V_0^2 B_S^2}{\mu_0 \sqrt{B_S^2 / (\mu_0 \rho_S) + V_0^2}}, \quad (2)$$

where the subscript “Io” was switched to “S” to denote that these variables now belong to a generic exomoon or “satellite.” The plasma speed, V_0 , is computed assuming it corotates with the planet’s magnetic field, as in the Jupiter–Io case. Explicitly, if the moon orbits at a distance of r_S from the planet, then $V_0 = \omega_P r_S = \sqrt{GM_P / r_S}$, where G is the gravitational constant, M_P is the planet’s mass, and ω_P is the planet’s angular velocity. The other parameters in Equation (2) are explored in later sections.

Equation (2) does not depend on the properties of the host star and therefore the exoplanet–moon system does not have to be close to its star (or even have a host star) to be detectable. In fact, exomoons around exoplanets with small orbits might be undetectable because stellar winds can also induce radio emissions, which increase with decreasing planetary semi-major axis (Zarka 1998). Furthermore, moon-induced radio emissions do not solely occur along the orbital plane, which means the system’s bodies do not have to orbit parallel to our line of sight.

The dependence of Equation (2) on R_S^2 clearly favors large exomoons. Although there has been no observational evidence, the possibility of detecting such exomoons is still plausible. Nevertheless, given that mass grows as the cube of the radius, the long-term stability of such systems can also be called into question; however, orbital stability analysis is beyond the scope of this study and it will not be discussed any further.

2.3. Magnetic Fields in Giant Planets

All the giant planets and several rocky bodies in the solar system have magnetic fields and extended magnetospheres, of which Jupiter’s is the largest. Consequently, one can expect exoplanets to have similar magnetic fields and extended magnetospheres. To model an exoplanet’s magnetic field, we begin by assuming that the field is mostly dipolar, as is the case for all magnetized bodies in the solar system, and that its angle of inclination with respect to the exoplanet’s axis of rotation is small enough to be neglected. If the exomoon orbits close to the rotational equator of the exoplanet, then the magnetic field affecting the exomoon at its location is given by $B_S = (\mu_0 / 4\pi)(m / r_S^3)$, where m is the exoplanet’s magnetic dipole moment.

To approximate the magnetic moment of an exoplanet, we adopt the approximation introduced by Durand-Manterola (2009) who found that the magnetic moment of a planetary body can be expressed as $m = 10^{-5}(\sigma M_P / T_P)^K$, where the exponent K is experimentally determined to be 1.10 ± 0.13 (we use 1.15 to better fit the giant planets), T_P is the planet’s rotation period, and σ is the conductivity of the liquid at its core, which is responsible for creating the magnetic field. In the case of giant planets, the liquid that creates their magnetic field is metallic hydrogen, which is estimated to have a conductivity of about $2 \pm 0.5 \times 10^5 \text{ S m}^{-1}$ (Shvets 2007). The expression for the magnetic field affecting the exomoon is thus

$$B_S = \frac{10^{-12}}{r_S^3} \left(\frac{M_P \sigma}{T_P} \right)^K. \quad (3)$$

It must be mentioned that there are other approximations that we could have chosen to calculate m , but we chose

Durand–Manterola’s formula because of its simplicity and because it can be at least partially justified using standard electrodynamics. If the exomoon is sufficiently large, it could also have its own magnetic field, but here we assume its effects to be negligible. However, based on the interaction between planets and the solar wind, we hypothesize that the exomoon’s magnetic field creates a bow shock where the exomoon’s magnetic field pressure equals the plasma torus pressure and its net effect is to increase the apparent cross-sectional area of the exomoon, thereby increasing the power of its radio emissions. This effect will be quantitatively discussed in later publications.

2.4. Other Parameters and Assumptions

The intensity of exomoon-induced radio emissions depends on many parameters, thus a thorough clarification of how each of these parameters are treated is crucial. A very important parameter in our calculation of a radio signal’s flux is T_P , but it is also very difficult to measure or predict. Therefore, it is typically assumed to be equal to Jupiter’s rotational period, T_J , or that the planet is tidally locked if it is closer than 0.1 AU to its host star (Lazio et al. 2004 and references therein). Since we mostly consider exoplanets with large orbits, we assume $T_P = T_J$ throughout the calculations.

The atmospheric plasma density of an exomoon (or exoplanet) is difficult to determine if the environmental properties of the body are not already known. Even though we cannot predict the plasma density of a hypothetical exomoon, we can find a reasonable estimate based on what we know about the solar system. The plasma density depends not only on the number of ions present, but also on the molecular weight of the ions that constitute it. For example, on Io, one can find O^+ , S^+ , SO^+ , etc., because Io’s atmosphere is made from the SO_2 emitted by its volcanoes (Su 2009). Io’s mean plasma density is $\sim 4.2 \times 10^4 \text{ amu cm}^{-3}$, or $\sim 7 \times 10^{-17} \text{ kg m}^{-3}$ (Kivelson 2004). Earth’s ion number density is typically on the order of 10^5 cm^{-3} , and the dominant ion is O^+ , which gives us a plasma density of $\sim 1.7 \times 10^6 \text{ amu cm}^{-3}$, or $\sim 2.7 \times 10^{-15} \text{ kg m}^{-3}$ (Schunk & Nagy 2009). Venus and Mars also have similar plasma densities to Earth, with O_2^+ and O^+ ions from CO_2 being the dominant species in their ionospheres (Schunk & Nagy 2009). Given the large variability of this parameter, we chose to work with three different values: 10^4 amu cm^{-3} , 10^5 amu cm^{-3} , and 10^6 amu cm^{-3} , which cover most of the range of plasma densities that can lead to a detectable exomoon with reasonable size (as explained in the next section). We can see the dependence of P_{rad} on the plasma density, ρ_S , by rearranging Equation (2) to get

$$P_{\text{rad}} = \frac{\pi \beta_S R_S^2 B_S^2 V_0}{\mu_0} \sqrt{\frac{\rho_S}{\rho_S + \frac{1}{\mu_0} \left(\frac{B_S}{V_0} \right)^2}}. \quad (4)$$

Equation (4) allows us to define a critical density $\rho_C = \mu_0^{-1} (B_S/V_0)^2$, which in turn allows us to characterize the three limiting cases:

$$P_- \equiv P_{\text{rad}}(\rho_S \ll \rho_C) = \pi \beta_S R_S^2 V_0^2 B_S \sqrt{\frac{\rho_S}{\mu_0}}, \quad (5)$$

$$P_C \equiv P_{\text{rad}}(\rho_S = \rho_C) = \frac{1}{\sqrt{2}} \pi \mu_0^{-1} \beta_S R_S^2 B_S^2 V_0, \quad (6)$$

$$P_+ \equiv P_{\text{rad}}(\rho_S \gg \rho_C) = \pi \mu_0^{-1} \beta_S R_S^2 B_S^2 V_0. \quad (7)$$

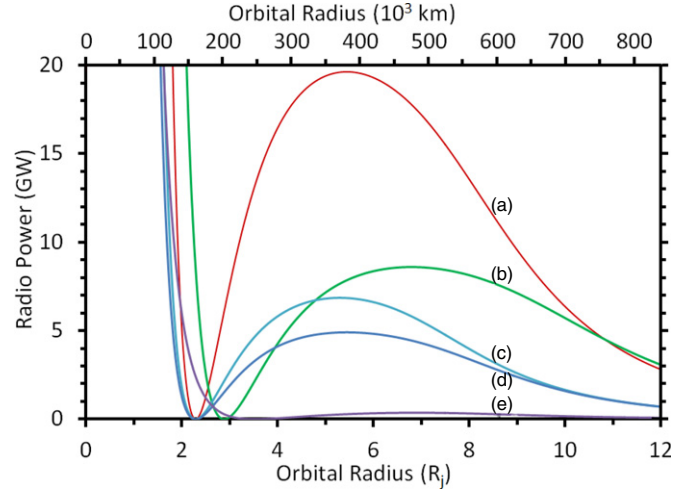


Figure 1. P_{rad} as a function of r_S , starting with values from the Jupiter–Io system and changing one parameter at a time. (a) $R_S = 2 R_{\text{Io}}$, (b) $M_P = 2 M_J$, (c) $\rho_S = 2 \rho_{\text{Io}}$, (d) all Jupiter–Io values, (e) $T_P = 2 T_J$. The node seen at the synchronous orbit occurs because $V_0 = 0$ at this orbital distance. (A color version of this figure is available in the online journal.)

The fact that $P_C = (1/\sqrt{2})P_+ \sim 71\%P_+$ tells us that the emitted radio power is much less dependent on ρ_S for plasma densities larger than ρ_C . Furthermore, since P_- decreases with decreasing ρ_S , then systems with higher plasma densities are more likely to be observable.

Regarding the orbital radius r_S , the only real physical constraint on the exomoon’s orbit is that it must be close enough to the exoplanet to be well inside the magnetosphere and gravitationally stable, but farther than the Roche limit to avoid structural instability. However, we can also make use of Equation (2) to find orbits that might favor radio emissions, since exomoons in these orbits are the most likely to be detected.

The function $P_{\text{rad}}(r_S)$ is plotted in Figure 1 for various parameter combinations. The purpose of Figure 1 is to demonstrate how changing a single parameter in P_{rad} affects its properties. Clearly, P_{rad} always has a single maximum in the orbits larger than the synchronous orbit. The only parameter that does not affect the orbital distance at which this maximum occurs is R_S ; however, ρ_S only affects the point’s position weakly and T_P is always held constant, so M_P is the dominant parameter when finding P_{rad} ’s maximum. The region around the maximum is also relatively flat; therefore, it seems reasonable to assume that an exomoon could be close to this maximum. In fact, Io and four Saturnian moons (including the large moon Enceladus) have orbits well within an area that would allow the moons to output at least 95% of the maximum predicted radio power. Therefore, we set r_S to be the value that gives the maximum radio power and rename it r_{Opt} from this point forward to avoid confusion. We avoid the treatment of orbits smaller than the synchronous orbit due to their proximity to the Roche limit.

It is noteworthy that the optimal orbital radius for each planetary mass needs to be found numerically, but it approximately follows a power law. For example, using $\rho_S = \rho_{\text{Io}}$ we get $r_{\text{Opt}} = 5.4 M_P^{0.32}$, where M_P and r_{Opt} are given in units of Jupiter’s mass and radius.

3. DETECTABILITY OF EXOMOONS

For a power source a distance d away from an observer, the incident flux is given by $S = P/(\Delta f \Omega d^2)$, where P is the

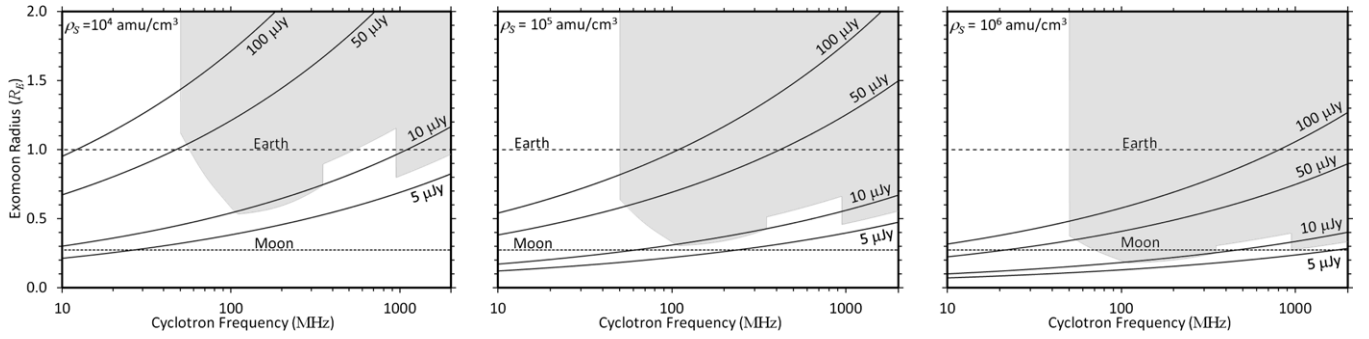


Figure 2. Curves of output flux, S , plotted in the R_S – f_C plane for several plasma densities. The radii of detectable exomoons that are 15 light years away are plotted as a function of the host exoplanet’s cyclotron frequency for several flux sensitivity values. From left to right, the panels show results for plasma densities of 10^4 , 10^5 , and 10^6 amu cm^{-3} . The shaded area corresponds to the potential detection capabilities of a fully implemented SKA telescope. $1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}$.

source’s output power, Δf is its bandwidth (usually taken to be half of the cyclotron frequency), and Ω is the solid angle through which the power is emitted by the source. In the case of the Io-DAM, the emission cone half angle ranges from 60° to 90° , with a wall thickness of 1.5 (Lopes & Spencer 2007; Queinnec et al. 2001), which gives a solid angle of ~ 0.14 – 0.16 sr. Assuming a system also emitting with a wide half angle and wall thickness of up to 2° gives $\Omega \sim 0.2$ sr. Taking P_{rad} to be source’s power, the incident flux becomes

$$S = \frac{2\pi\beta_S R_S^2 B_S^2 V_0}{\mu_0 f_C \Omega d^2} \sqrt{\frac{\rho_S}{\rho_S + \mu_0^{-1} (B_S/V_0)^2}}, \quad (8)$$

where f_C is the cyclotron frequency of the system.

The cyclotron frequency is calculated using $f_C = eB_{\text{pole}}/(2\pi m_e)$, where e is the electron charge, m_e is the electron mass, and we use the magnetic field strength at the poles of the exoplanet, B_{pole} , because that is where most of the radio emissions occur. At the poles of the planet, the magnetic field is twice as strong as it is at the equator. Hence, we can use Equation (3) to express the strength of the magnetic field at the poles as $B_{\text{pole}} = 2(r_{\text{opt}}/R_P)^3 B_S$, where R_P is the radius of the exoplanet. Under this assumption, the cyclotron frequency increases as M_P^K , thereby limiting the number of exoplanets that a telescope could successfully scan for exomoons. Nonetheless, there is still a wide range of frequencies within which an exomoon with radius $\leq 1R_E$ could be detected up to 15 light years away, if the plasma density ρ_S of the system is at least 10^4 amu cm^{-3} and if the telescope’s sensitivity is at least tens of μJy (see Figure 2). The proposed SKA telescope, if fully implemented, could even detect Mars-size moons ($\sim 0.532 R_E$)⁴ in this case, if present. The range of detection of SKA is shown as the shaded areas in Figure 2. Also, it must be noted that in reality these systems emit over a range of frequencies instead a single one, so the range of detectable systems is effectively larger than shown here. The calculation of the whole frequency band will be treated in future studies. Regarding R_P , a survey of currently known gas giants shows great variability in the value of this parameter. Nonetheless, for large planetary masses, R_P seems to converge to a value close to Jupiter’s radius, R_J . Furthermore, many authors (e.g., Zarka et al. (2001)) assume that $R_P = R_J$ unless the exoplanet’s radius is explicitly known. Thus we will also assume $R_P = R_J$ to be the general case.

Applying our results to the exoplanet Epsilon Eridani b ($1.55 M_J$, 10.5 light years away), we find that a telescope

with a flux sensitivity of $S \leq 50 \mu\text{Jy}$ around 49 MHz could detect exomoons with radius between $0.24 R_E$ for high ρ_S ($\sim 10^6 \text{ amu cm}^{-3}$) and $0.73 R_E$ for low ρ_S ($\sim 10^4 \text{ amu cm}^{-3}$). For comparison, the Moon is $\sim 0.273 R_E$. On another nearby exoplanet, Gliese 876 b ($2.28 M_J$, 15.29 light years away), a telescope with similar sensitivity around 93 MHz could detect an exomoon with a radius between 0.28 and $0.86 R_E$, depending on ρ_S . In both cases, a fairly large minimum radius is required for exomoons to be detectable unless there is a large amount of plasma present. In fact, Equation (8) tells us that to find an exomoon of radius 2500 km (similar to Mercury or Titan) orbiting Epsilon Eridani b, we would need a telescope with a flux sensitivity of $14 \mu\text{Jy}$ if ρ_S is low. Nevertheless, improvements to radio telescope technology and observational techniques could one day make it possible to reach these sensitivities.

4. CONCLUSIONS

The primary goal of this study was to find a set of conditions that would allow detection of an exomoon through the radio emissions it induces on its host exoplanet and to assess whether these conditions are attainable. The results presented in Section 3 show that such conditions can exist, hence confirming the possibility of exomoon detection using this method, and we showed what sensitivities observational facilities need have to detect said exomoons. An exomoon orbiting Epsilon Eridani b, with a radius as low as $0.24 R_E$, lies in the detectable range of telescopes with a sensitivity of $S \leq 50 \mu\text{Jy}$. However, detection of a Titan- or Mercury-size exomoon under low plasma conditions would require a telescope with a flux sensitivity of $\sim 14 \mu\text{Jy}$ or better.

The model presented here still requires several refinements, such as including the effects of magnetic exomoons, finding better constraints on T_P and ρ_S , and calculating a complete emission spectrum rather than a single cyclotron frequency. These improvements will be treated in later studies. Nonetheless, it is still our hope that the results presented here will give new insight to the observational community and stimulate searches for the modulation of exoplanetary radio emissions caused by the presence of exomoons.

We are grateful to the anonymous referee for useful comments and suggestions that have allowed us to significantly improve this manuscript. We also thank M. Cuntz for stimulating discussions and rendering his valuable comments. Our research on Alfvén waves in the exoplanet–exomoon environment was partially supported by NSF under grant No. AGS 1246074

⁴ Assuming 2 pol., 1 hr integration, and 16 MHz bandwidth.

(Z.E.M. and J.P.N.). Moreover, this work was also supported by the GAANN Fellowship (J.P.N.). Z.E.M. also acknowledges the support of this work by the Alexander von Humboldt Foundation and by the University of Texas at Arlington through its Faculty Development Program.

REFERENCES

- Acuna, M. H., Neubauer, F. H., & Ness, N. F. 1981, *JGR*, **86**, 8513
- Belcher, J. 1987, *Sci*, **238**, 170
- Bigg, E. K. 1964, *Natur*, **203**, 1008
- Crary, F. J. 1997, *JGR*, **102**, 37
- Cuntz, M., Quarles, B., Eberle, J., & Shukayr, A. 2013, *PASA*, **30**, e033
- Durand-Manterola, H. J. 2009, *P&SS*, **57**, 1405
- Grißmeier, J.-M., Zarka, P., & Spreuw, H. 2007, *A&A*, **475**, 359
- Kipping, D. M., Fossey, S. J., & Campanella, G. 2009, *MNRAS*, **400**, 398
- Kivelson, M. G. 2004, *Jupiter* (Cambridge: Cambridge Univ. Press), chapter 21
- Lazio, T. J., Farrell, W. M., Dietrick, J., et al. 2004, *ApJ*, **612**, 511
- Lopes, R. M., & Spencer, J. R. 2007, *Io After Galileo: A New View of Jupiter's Volcanic Moon* (Geophysical Sciences; Berlin: Springer)
- Mauk, B. H., Williams, D. J., & Eviatar, A. 2001, *JGR*, **106**, 26195
- Neubauer, F. M. 1980, *JGR*, **85**, 1171
- Nichols, J. D. 2011, *MNRAS*, **414**, 2125
- Quarles, B., Musielak, Z. E., & Cuntz, M. 2012, *ApJ*, **750**, 14
- Queinnec, J., & Zarka, P. 2001, *P&SS*, **49**, 365
- Saur, J., Neubauer, F. M., Strobel, D. F., & Summers, M. E. 1999, *JGR*, **104**, 25105
- Schunk, R., & Nagy, A. 2009, *Ionospheres: Physics, Plasma Physics, and Chemistry* (2nd ed.; Cambridge: Cambridge Univ. Press), 22
- Shvets, V. T. 2007, *PMM*, **103**, 330
- Su, Y. -J. 2009, in *IAU Symp. 259, Cosmic Magnetic Fields: From Planets, to Stars and Galaxies*, ed. K. G. Strassmeier, A. G. Kosovichev, & J. E. Beckman (Cambridge: Cambridge Univ. Press), 271
- Trammell, G. B., Li, Z.-Y., & Arras, P. 2014, *ApJ*, **788**, 161
- Wolszczan, A., & Frail, D. A. 1992, *Natur*, **355**, 145
- Zarka, P. 1998, *JGR*, **103**, 20159
- Zarka, P., Treumann, R. A., Ryabov, B. P., & Ryabov, V. B. 2001, *Ap&SS*, **277**, 293