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# Search for possible exomoons with the FAST telescope

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**Abstract** Our knowledge of the solar system encourages us to believe that we might expect exomoons to be present around some known exoplanets. With present hardware and existing optical astronomy methods, we do not expect to be able to find exomoons for at least 10 years, and even then, it will be a hard task to detect them. Using data from the Exoplanet Orbit Database (EOD) we find stars with Jovian exoplanets within 50 light years. Most of them will be fully accessible by the new radio telescope, the Five-hundred-meter Aperture Spherical radio Telescope (FAST), under construction which is now in the test phase. We suggest radio astronomy based methods to search for possible exomoons around two exoplanets.

**Key words:** exoplanets: general — exoplanets: radioastronomy — exomoons

## 1 INTRODUCTION

The discovery of 51 Pegasi b (Mayor & Queloz 1995), an exoplanet orbiting a Sun-like main sequence star, was only the first in a series of many exoplanets discovered thenceforth. Such progress has been made thanks to advanced detection techniques and instrumentation. Nowadays, the result is thousands of confirmed and potential exoplanets, with most of them having been identified by NASA's Kepler space telescope. Every prudent connoisseur of the solar system would expect the presence of exomoons close to known exoplanets. Planets and dwarf planets in the solar system are known to be orbited by 182 natural satellites. In our solar system, Jovian planets have the biggest collections of moons and we expect a similar situation for gas giant planets in extrasolar systems. Nonetheless, contemporary techniques for observation have not made a single detection of any exomoon so far.

One of the leading models describing planetary satellite formation is the actively supplied gaseous accretion disk model (Canup & Ward 2006). In this model, the final total mass of a satellite system, approximately $10^{-4}\,M_P$ ($M_P$ is the mass of the planet) is derived by balancing the supply of material to the satellite with what the satellite loses through orbital decay driven by the gas. Dust grains stick and grow to form satellitesimals within a circumplanetary disk. An alternative model is the solids enhanced minimum mass model (see e.g. Mosqueira & Estrada 2003). This model only qualitatively describes the expected mass ratios. Since this model does not give us the masses of satellites, we will only use the first model for our analysis of possible exomoons.

## 2 SELECTION OF DATA AND METHOD OF ANALYSIS

Many of the detected exoplanets are gas giants located in the habitable zone of their stars. These large planets cannot support life, but it is believed that some of their exomoons could be habitable. In our analysis, assuming that the scaling law (Canup & Ward 2006) observed in the solar system also applies for extrasolar super-Jupiters (Heller & Pudritz 2015b), we use planetary data from the Exoplanet Orbit Database catalog (Wright et al. 2011 and Han et al. 2014). We only select exoplanets closer than 50 light years, which have comparable mass or are more massive than Jupiter within declination limits of full sensitivity of the new radio telescope in China. Approximately half of these are hot or warm Jupiters. According to Heller & Pudritz (2015a), if these planets migrated into the stellar habitable zones from beyond a few AU, they could be orbited by large, water rich satellites. Liquid water on the surface is possible for sufficiently massive satellites.

Besides the telescopes described in Grießmeier et al. (2011) and Noyola (2015), an additional radio telescope is in the final phase of construction, the Five-hundred-meter Aperture Spherical radio Telescope (FAST) (Nan et al. 2011) and the latter SKA telescope. FAST is located in a great depression with a diameter of about 800 m at $25.647°$N and $106.856°$E, near the village of Dawodang, in Guizhou Province, China. FAST will be capable of covering the sky within $40°$ from the zenith with full sensitivity. A set of nine receivers covers a frequency range from 70 MHz to 3 GHz. It has an illuminated aperture of 300 m in diameter within the 500 m diameter reflector. FAST is an order of magnitude more sensitive than 100 m telescopes in Green Bank, West Virginia, USA and Effelsberg, Germany, and about two times more than the Giant Metrewave Radio Telescope (GMRT) in India.

The first direct detection of exoplanets will be tried in the meter wave band (van Leeuwen 2012). The quasi-periodicity of a planetary radio burst is tied to the spin of the planet, which is on the order of days. This time-modulation of radio signals augments the detectability of exoplanets by FAST. The idea of direct radio detection of exoplanets was first suggested by Lecacheux (1991). To search for exomoons, we count on interaction of the magnetic field of extrasolar planets with plasmas from exomoons (Zarka 2007). In the solar system, Jupiter's magnetosphere radiates intense decameter radio waves. From the Earth, these radio waves are detectable in the frequency range from 10 to 40 MHz (Zarka 1998). The generation mechanism is cyclotron-maser instability (Wu & Lee 1979). Selected exoplanets are presented in Table 1. Listed frequencies in Table 1 are the maximum values reported in Grießmeier et al. (2007).

In Table 2 we compare frequencies $f_{\rm mG}$ calculated by Grießmeier et al. (2007), with other models of extrasolar planet radio emission $f_{\rm mL}$ (Lazio et al. 2004) and $f_{\rm mR}$ (Reiners & Christensen 2010) and expected radio fluxes. Other radio telescopes with the most suitable frequency range are: super LOFAR extension (NenuFAR, 10–80 MHz) in France, 1–2 mJy in a 4 MHz bandwidth, GMRT (153 MHz) in India, 0.2 mJy/sqrt($t$/15 minutes) in a 4 MHz bandwidth, the Ukrainian T-shaped Radio telescope (UTR-2, 8–40 MHz) and Arecibo (47 MHz).

We can see that the selected planets in Table 1 orbit stars from M to F type. The closest planets are eps Eridani b at a distance of 3.22 pc and Gliese 876 b and c at 4.69 pc. Since these planets most likely were not formed at those distances, but have migrated from larger ones, possible exomoons could also be captured rocky planets. If possible exomoons in these systems were captured, they could survive for a long enough time in all the star systems listed in Table 1 (Barnes & O'Brien 2002). These captured satellites could be more massive than the ones that formed in the system (Porter & Grundy 2011 and Teachey et al. 2017). Because we are not aware of any theory which can predict such an event, we do not consider them. Even if 50 percent of planets are falsely detected (Santerne et al. 2016) we still have enough candidates. We will most likely have high mean plasma density between $\rho$S$\sim 10^6$ amu cm$^{-3}$ and $\rho$S$\sim 10^7$ amu cm$^{-3}$ due to the presence of some exomoons in a star's habitable zone and closer to the star (Schunk & Nagy 2009).

## 3 SOME OF THE CLOSEST EXOPLANETS WITH POSSIBLE EXOMOONS

All stars under consideration that are fully accessible by FAST are: eps Eridani, Gliese 876, Gliese 849, HD 62509, 55 Cancri, HD 147513, Upsilon And A, 47 UMa b, HIP 79431 and HD 176051, and these have long enough lifetimes to be listed in HabCat (Turnbull & Tarter 2003). If, as we can see in Table 1, these stars do not have exomoon emitters with frequency above 70 MHz, our next chance is the low-end Low-Frequency Array (LOFAR). At present, LOFAR has a frequency range of $10-240$ MHz, which is the best for exomoon and exoplanet detection. NenuFAR (10–80 MHz) has a frequency range in our region of interest. Sensitivity in this range is a few mJy. Let us check some of the closest planets from our list around stars eps Eridani, Gliese 876, Gliese 849, 55 Cancri and Upsilon And A.

Eps Eridani is an orange dwarf star located at a distance of 3.22 pc. Exoplanet Eps Eridani b is a prime target for attempts at future extrasolar planet direct imaging due to its proximity. Its mass was calculated to be $0.83\,M_{\odot}$. It was a target in previous measurements (George & Stevens 2008 and Noyola 2015) with GMRT. They did not find signs of exomoon radio activity. It is fully accessible with FAST. NenuFAR would be good for searching for radio emission from possible exomoons around this star.

Gliese 876 is a red dwarf star located 4.69 pc away. It has two large exoplanets, Gliese 876 b ($2.27\,M_{\odot}$) and Gliese 876 c ($0.7\,M_{\odot}$). Both planets lie in the habitable zone around the star. It is fully accessible with FAST and the GMRT, but maximum frequencies of the planets are below operational frequencies of these telescopes, which leaves only the NenuFAR telescope.

Gliese 849 is a red dwarf 9.1 pc away from the Sun. There is a large separation of planets in this system from the star. The orbital separation of Gliese 849 b (2.39 AU) amounts to an angular separation of $0.25''$. Due to the proximity, it provides a good chance for high-resolution imaging using adaptive optics. It is fully accessible with FAST and the GMRT. The maximum frequency of Gliese

849 b is 21.8 MHz, much below frequencies of these telescopes besides NenuFAR.

55 Cancri is a binary star 12.3 pc away from the Sun. The system consists of a yellow dwarf star 55 Cancri A, and a smaller red dwarf 55 Cancri B. The primary star, 55 Cancri A, is more enriched than the Sun in elements heavier than helium, with 186% the solar abundance of iron. It is classified as a rare "super metal-rich" (SMR) star (Marcy et al. 2002). It only has low emission from its chromosphere. The 55 Cancri A system has at least five planets. Exoplanet 55 Cancri b is a hot Jupiter with mass 0.95 $M_\mathrm{J}$. Due to the vicinity of the star, tidal forces would either eject exomoons from the orbit or destroy them, so it is not expected to have large ones (Barnes & O'Brien 2002). 55 Cancri d is orbiting at a distance of 5.74 AU and it has a mass of 3.878 $M_\mathrm{J}$. The maximum calculated frequency of 55 Cancri d is close to 70 MHz (Grießmeier et al. 2007). It is fully accessible with FAST and the GMRT.

Upsilon Andromedae is a binary system. The system consists of a yellow-white dwarf star $\upsilon$ And A, and of a red dwarf star $\upsilon$ And B, (Lowrance et al. 2002 and Santos et al. 2004). The declination of this system is $+41°24'19.6443''$ (van Leeuwen 2007). It is fully accessible with FAST and the GMRT. The separation between the stars is 750 AU (Lowrance et al. 2002). Radial-velocity measurements led to the detection of four planets around $\upsilon$ And A, and one of the planets, i.e., $\upsilon$ And A d, is found to be located within $\upsilon$ And A's habitable zone. The planet stays inside the extended zones of habitability at its apoapsis at 3.26 AU. Its periapsis is identified as 1.76 AU, a distance close to the inner limit of the general habitable zone. General and extended zones of habitability are in use as in Kasting et al. (1993) and subsequent works. The planets $\upsilon$ And A b, c, d and e have semimajor axes of 0.0592, 0.828, 2.51 and 5.25 AU respectively. The measured mass of planet $\upsilon$ And A d is 3.75 $M_\mathrm{J}$ (Ligi et al. 2012). The eccentricity of $\upsilon$ And A d is identified as 0.299 (Curiel et al. 2011), and its true mass has been estimated as 10.19 $M_\mathrm{J}$ (Barnes et al. 2011) and 10.25 $M_\mathrm{J}$ (McArthur et al. 2010). The mutual inclination between planets c and d is as large as 30° (Barnes et al. 2011). $\upsilon$ And A is the only multiplanetary system with astrometry measurements (Deitrick et al. 2015). The age of the star is about 3 Gyr (McArthur et al. 2010 and Takeda et al. 2007). The maximum calculated radio frequency of $\upsilon$ And A d is close to 70 MHz (Grießmeier et al. 2007), the lowest frequency range measurable with the receiver at FAST, similar to 55 Cancri d.

Gliese 86 A (13 G. Eridani) is an orange dwarf main-sequence star with a declination of $-50°49'25.4179''$ (van Leeuwen 2007), approximately 10.8 pc away in the southern constellation Eridanus. Its binary companion is Gliese 86 B, a white dwarf star. Exoplanet Gliese 86 Ab (Table 2) is the most promising candidate, but it lies out of the field of view of full sensitivity of all radio telescopes mentioned in this paper and it needs to wait for the SKA to begin operation. Gliese 86 A has lower metallicity than our Sun, unlike most stars with an exoplanet. The orbit of the planet is almost circular; it has an eccentricity of 0.05 and a period of 15.83 days. This planet's observed characteristics, combined with the double-star nature of this system, suggest that planetary systems are perhaps not formed in the standard agglomeration scheme.

We can see that the most suitable radio telescopes to search for the closest possible exomoons are NenuFAR and FAST, especially for two extrasolar planets 55

**Table 1** Possible Exomoons

| Planet name | Mass | Star type | Semi. axis | Dist. | Sat. mass | Dec | Freq. |
|---|---|---|---|---|---|---|---|
| | ($M_\mathrm{J}$) | | (AU) | (pc) | ($M_\oplus$) | | (MHz) |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| eps Eridani b | 1.55 | K2V | 3.4 | 3.22 | 0.049 | $-09°$ $27'29.7312''$ | 33.2 |
| Gliese 876 b | 2.27 | M4V | 0.2 | 4.69 | 0.072 | $-14°15'49.32''$ | 38.2 |
| Gliese 876 c | 0.7 | M4V | 0.13 | 4.69 | 0.022 | $-14°15'49.32''$ | 16.4 |
| Gliese 849 b | 0.91 | M3.5V | 2.39 | 9.1 | 0.0289 | $-4°38'26.62''$ | 21.8 |
| Gliese 849 c | 0.94 | M3.5V | 4.82 | 9.1 | 0.0298 | $-4°38'26.62''$ | |
| HD 62509 b | 2.9 | K0III | 1.64 | 10.3 | 0.092 | $+28°01'35''$ | 49.5 |
| 55 Cnc b | 0.8 | G8V | 0.11 | 12.3 | 0.025 | $+28°19'51''$ | 18.9 |
| 55 Cnc d | 3.878 | G8V | 5.74 | 12.3 | 0.123 | $+28°19'51''$ | 61.4 |
| HD 147513 b | 1.21 | G1VH-04 | 1.32 | 12.9 | 0.038 | $+39°11'34.7121''$ | 24.5 |
| ups And A b | 0.62 | F8V | 0.059 | 13.47 | 0.019 | $+41°24'19.6443''$ | 2.4 |
| ups And A c | 13.98 | F8V | 0.832 | 13.47 | 0.44 | $+41°24'19.6443''$ | 38.4 |
| ups And A d | 10.25 | F8V | 2.53 | 13.47 | 0.33 | $+41°24'19.6443''$ | 61.4 |
| ups And A e | 0.96 | F8V | 5.25 | 13.470 | 0.031 | $+41°24'19.6443''$ | |
| 47 UMa b | 2.5 | G1V | 2.1 | 14.06 | 0.079 | $+40°25'27.97''$ | 46.6 |
| HIP 79431 b | 2.00 | M3V | 0.36 | 14.4 | 0.064 | $-18°52'31.8''$ | 40 |
| HD 176051 b | 1.5 | F9V | 1.76 | 15 | 0.047 | $+32°54'5''$ | |

**Table 2** Possible Maximum Frequencies for Exomoons and Exoplanets

| Planet name | Star type | Semimajor | $f_\mathrm{mG}$ | R. flux | $f_\mathrm{mL}$ | R. flux | $f_\mathrm{mR}$ | R. flux |
|---|---|---|---|---|---|---|---|---|
| | $[M_\mathrm{J}]$ | Axis | [MHz] | [mJy] | [MHz] | [mJy] | [MHz] | [mJy] |
| eps Eridani b | K2V | 3.4 | 33.2 | 0 | 53 | 6.3 | 18.3 | 6 |
| Gliese 876 b | M4V | 0.2 | 38.2 | 6.3 | 66 | 3.1 | 68 | 160 |
| Gliese 876 c | M4V | 0.13 | 16.4 | 61.7 | 16 | 2.1 | 8.9 | 630 |
| Gliese 849 b | M3.5V | 2.39 | 21.8 | 0 | | | | |
| Gliese 849 c | M3.5V | 4.82 | | | | | | |
| HD 62509 b | K0III | 1.64 | 49.5 | 0 | 68 | 0.1 | | |
| Gliese 86 Ab | K1V | 0.11 | 61 | 3.8 | 113 | 43.8 | 237 | 63 |
| 55 Cnc b | G8V | 0.11 | 18.9 | 3 | | | 17.6 | 80 |
| 55 Cnc d | G8V | 5.74 | 61.4 | 0 | | | 242 | 0 |
| HD 147513 b | G1VH-04 | 1.32 | 24.5 | 2 | 43 | 4.1 | 23.5 | 0.2 |
| ups And A b | F8V | 0.059 | 2.4 | 178.5 | 27 | 41.8 | 2.2 | 200 |
| ups And A c | F8V | 0.832 | 38.4 | 0 | 84 | 2.8 | 68 | 2.5 |
| ups And A d | F8V | 2.53 | 61.4 | 0 | 163 | 0.1 | 213 | 0.3 |
| ups And A e | F8V | 5.25 | | | | | | |
| 47 UMa b | G1V | 2.1 | 46.6 | 0 | | | 111 | 0.5 |
| HIP 79431 b | M3V | 0.36 | 40 | 0 | | | | |
| HD 176051 b | F9V | 1.76 | | | | | | |

Cancri d and $\upsilon$ And A d, for which these facilities can be very useful. Both possible exomoons fulfill the requirement to be more massive than Mars (Heller & Pudritz 2015a). As we can see in Table 2, for other models of radio emission from extrasolar planets (Lazio et al. 2004 and Reiners & Christensen 2010) the second set of FAST receivers (Nan et al. 2011) is also suitable for these two extrasolar planets and plans for methods to search for exoplanets using radio astronomy (van Leeuwen 2012). To my best knowledge, I do not know of an exoplanet detection made by radio astronomy methods.

## 4 CONCLUSIONS

Since we shall not be able to find exomoons with existing optical astronomy methods for at least 10 years from now (Kipping 2014) and even then it will be a hard task to detect them (Hippke & Angerhausen 2015 and Heller et al. 2016), I suggest searching for exomoons around these planets with radio astronomy based methods (see Noyola et al. 2014 and Noyola 2015). The main problem could be that the distances to the exoplanets I am suggesting for investigation with the FAST telescope are greater than the ones selected in the first searches (George & Stevens 2008 and Noyola 2015). The closest planets are 55 Cancri d at 12.3 pc and $\upsilon$ And A d at a distance of 13.47 pc. At present such sensitivity can be expected only from NenuFAR (10–80 MHz) and the just finished radio telescope FAST.

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