Search for exoplanets and brown dwarfs with VLBI.

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ABSTRACT
The main aim of this work is to estimate possible radio GHz emission of extrasolar planets and brown dwarfs and to check if such radiation can be detected by Very Large Baseline Interferometers (VLBI). In the estimation we assume that the emission may originate in processes similar to those observed in the Jupiter system. The frequency of the radio emission that is produced in this system depends mostly on the magnetic field strength. Jupiter’s magnetic field (∼9 G on average) allows for radiation from kHz frequencies up to 40 MHz. This is well below the frequency range of VLBI. However, it was demonstrated that the magnetic field strength in massive and young object may be up to two orders of magnitude higher than for Jupiter, which is especially relevant for planets around short-lived A type stars. This should extend the range of the emission up to GHz frequencies. We calculated expected flux densities of radio emission for a variety of hypothetical young planetary systems. We analysed two different emission scenarios, and found that the radiation induced by moons (process similar to Jupiter-Io interactions) appears to be less efficient than the emission generated by a stellar wind on a planetary magnetosphere. We also estimated hypothetical emission of planets and brown dwarfs located around relatively young and massive main sequence A-type stars. Our results show that the emission produced by stellar winds could be detected by currently operating VLBI networks.

Key words: planets and satellites: detection – planets and satellites: magnetic fields – planets and satellites: physical evolution – planet–star interactions – planetary systems.

1 INTRODUCTION
The angular resolution of very large baseline radio interferometers like the Very Long Baseline Array (VLBA1) or the European VLBI Network (EVN2) can reach a few milliarcseconds (note that the resolution depends on the frequency of observations, see Fig. 1). This may give an opportunity for direct observations of extrasolar planets in nearby stellar systems. However, the main problem of detecting low mass companions in these systems is the frequency of the observations. All radio telescopes in such interferometric networks are parabolic antennas, designed to work efficiently at GHz frequencies (ν ≥ 1.2 GHz for the VLBA and ν ≥ 1.4 GHz for the EVN). On the other hand, observations of planets in the Solar system and especially observations of the Jupiter system show that the dominant radio emission extends there from kHz frequencies up to 40 MHz. If this emission range is typical for all massive extrasolar planets then their radiation could be likely detected only by a low frequency interferometers like the Low Frequency Array for Radio Astronomy (LOFAR3). If the emission extends up to a few hundred MHz. Then it should be possibly observed by the Giant Metrewave Radio Telescope (GMRT4). However, such interferometers have limited angular resolution due to significantly smaller baselines and relatively low frequency of observations, when compared to VLBI networks.

The theoretical models of the MHz radio emission from massive exoplanets were already investigated by several authors (e.g. Grießmeier et al. 2005, 2007; Reiners & Christensen 2010; Nichols 2011; Noyola et al. 2014), for a review see Grießmeier et al. (2011). It was demonstrated that in principle, it should be possible to detect such emission from at least a few objects (e.g., τ Boo b, Gl 86 b, GJ 3021 b, eps Eridani b, Gliese 876 b). However, despite many observational trials (e.g., Wingée et al. 1986; Bastian et al. 2000; George & Stevens 2007; Lazio & Farrell 2007; Lazio et al. 2008).

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The expected maximal separation between stars and planets estimated for different orbits and distances (curved lines). Horizontal lines with labels show the angular resolution of the main interferometric networks in the frequency range from 0.24 to 5 GHz. The angular resolutions are gathered from the specifications provided at the web pages of the projects.

2010; Lecavelier des Etangs et al. 2013) there is no confirmed detection that could be addressed as a radio emission of an exoplanet. Note, that recently Sirothia et al. (2014) found sources of radio emission towards four planetary systems. However, these tentative detections require further investigation because the emission may come from coincidental background sources.

In this work we explore higher frequency range to check if the radio emission from massive planets can be observed at GHz frequencies with the VLBA or the EVN interferometers. This frequency range was not well explored from the theoretical and the observational point of view (e.g., Grießmeier et al. 2006; Shiratori et al. 2006). On the other hand the radio interferometry in the GHz range provide very good angular resolution, and potentially can be very useful for the search of exoplanets. In Fig. 1 we compare the angular resolution of the main interferometric networks with the angular separation for different planetary systems, observed from different distances. The comparison shows that the angular resolution of the interferometers that work at GHz frequencies can be one or even two orders of magnitude better than the resolution of the instruments that operate in the MHz range. Note that according to the estimations presented in this paper we should not expect any emission around 5 GHz. Thus, the angular resolutions at 5 GHz in Fig. 1 are plotted just for comparison. If we focus at 1.4 GHz, possible planets could be resolved from the distance smaller than 10 pc for the orbital radius of about 0.05 au. However, there are only four interesting stars within the radius of 10 pc. Therefore, the reasonable distance between the star and the possible planet, that we consider here, is about 1 au.

Interferometers like EVN or VLBA provide also an excellent sensitivity. For example, after 2h of integration with the recording rate 1 Gb/s, the EVN is able to reach 3σ detection level for sources with fluxes \( \sim 35 \, \mu Jy \) at 1.4 GHz. In Table 1 we specify sensitivities for main VLBI networks at different frequencies and recording rates. Note that an increase of the recording rate extends the bandwidth (for example 1 → 2 Gb gives 128 → 256 MHz). The sensitivities presented in Table 1 are given per beam. However, for point like sources, which is the case of the radio emission expected from planets, these sensitivities are equivalent to values given in Jy.

The sensitivity of EVN at 1.4 GHz is three orders of magnitude better than the sensitivity of GMRT at 150 MHz for comparable integration time (e.g., Sirothia et al. 2014). The comparison of the sensitivities at different frequencies can be misleading. Especially if the observed spectra are steep (\( F \propto \nu^{-\alpha}, \alpha \gg 1 \)) or if such spectra contain an abrupt cut-off above some maximum MHz frequency. In general, the spectrum detectable at GHz frequencies should also be observed at MHz frequencies. However, if there is no significant increase of the MHz emission, this region of the spectrum can be problematic for observations, because of relatively low sensitivity of LOFAR or GMRT. This illustrates the potential of radio interferometers that contain big antennas and shows that the VLBI could potentially provide very important observations of exoplanets. However, the question is if we can expect any radio emission from exoplanets at the GHz frequencies?

The main motivation for the calculations presented in this work is the estimation of the magnetic field strength made by Reiners & Christensen (2010). They demonstrated that in young (age \( < 10^8 \) yr) and massive (from a few to several Jupiter masses) objects the magnetic fields strength may even excess 1 kG. This is two orders of magnitude larger than the value of polar dipole magnetic field strength of Jupiter \( \sim 11 \, G \) south pole , ~ 14 G north pole). The maximum frequency of the emitted radiation is simply the cyclotron frequency, that is directly proportional to the magnetic field strength. Therefore, the emission that is observed in the Jupiter system below 40 MHz, in younger systems could be generated at GHz frequencies. It should be also mentioned that the radio emission at GHz frequencies has been discovered already in ultra cool dwarfs of L, M spectral types (e.g., Berger & et al. 2001; Hallinan & et al. 2007; Hallinan et al. 2008; McLean et al. 2012) and also in a T6.5 spectral type brown dwarf J1047+21 (Route & Wolszczan 2012, 2013). The mechanism of such emission is probably similar to the radiation observed in the Jupiter system. This is a coherent emission powered by the electron cyclotron maser.
The emission observed from J1047+21 is sporadic and has a form of short burst (duration from tens to hundreds of seconds). Short spikes observed during the burst allows to constrain the size of the emitting region to \( \lesssim 0.4 R_\odot \). The independent estimation derived from the frequency drift during the burst, give the size in the range 0.3–1 \( R_\odot \). Nevertheless, the fact that the emission of J1047+21 was observed around 4.75 GHz indicates that the magnetic field strength in this particular object is \( B \approx 1.7 \, \text{kG} \). This value is similar to the strengths obtained for L–M type dwarfs. The magnetic field strength estimated in a case of ultracool dwarf TVLM 513-46546 (spectral type M9) was around 7 kG (Yu et al. 2011). The observational findings described above give additional motivation to check what exactly we can expect observing massive planets using the VLBI at GHz frequencies.

Among a few possible processes that can generate radio emission in the planetary systems (see for a review Grießmeier et al. 2011), we focus on two possible scenarios, that are well known from the Solar system. The first mechanism assumes an interaction between the stellar wind and the planetary magnetosphere. The power of the radio emission in such process is proportional to the kinetic energy flux of particles that are impacting on the planet magnetopause (e.g., Zarka et al. 1997; Farrell et al. 1999; Stevens 2005). Such process is responsible for the most of the Jupiter’s hectometric (HOM) emission. The second scenario assumes the existence of a moon around a planet. This mechanism similar to the process that generates the Io decametric (DAM) emission in the Jupiter system. The volcanic activity of Io fills the magnetosphere with matter (sulphur, oxygen) that is ionized and accelerated by electric currents inducted by Io. The currents are inducted because of the difference between the Jupiter’s rotation velocity and the Io’s orbital velocity (e.g., Nichols 2011, 2012; Noyola et al. 2014).

It must be mentioned that there is also a third important emission scenario. According to this scenario the radiation is produced by the interaction between the magnetic energy flux of the interplanetary magnetic field with the planetary magnetosphere (Zarka et al. 2001; Farrell et al. 2004; Grießmeier et al. 2007). In the Solar system it is impossible to distinguish which emission process dominates, this one or the dissipation of the wind kinetic energy. However, in this work we are going to focus on main sequence A-type stars, were the wind velocity, the key parameter for the first mentioned emission scenario is a few times higher than in the Solar system. On the other hand the third process depends strongly on the interplanetary magnetic field that is difficult to estimate or measure in the case of main sequence A-type stars. Some observational evidences (e.g. Lignières et al. 2009; Blazère et al. 2016) suggest that magnetic field of such stars is similar or less (\( B \lesssim 1 \, \text{G} \)) to the value observed for the quiet Sun. This may favour our first emission scenario over the third process discussed here. However, this requires further detailed investigation and is out of the scope of this paper.

The most important parameter for all emission scenarios discussed above is the magnetic field strength. There are several different models that describe how the magnetic field of planets and brown dwarfs can be generated (for a review see Christensen 2010). In the next section we describe the model selected for our calculations and discuss this particular choice. The description of first two mentioned above emission scenarios is given in Sections 3 and 4. In the Section 5 we compare fluxes expected from these scenarios, calculated for a wide range of ages and masses of hypothetical planetary systems. Finally, we focus on selected A-type main sequence stars, where planetary systems could possibly be observed due to their young age and strong magnetic fields. Note that recently Nielsen et al. (2013) reported results of the Gemini NICI Planet-Finding Campaign. They conducted direct imaging of 70 young B and A-type stars, searching for planets and brown dwarfs. As the result they identified two new low-mass companions to HD 1160 and HIP 79797 stars. They also investigated previously discovered planet \( \beta \) Pic b (Lagrange & et al. 2009), estimating their orbital parameters. They found for example the semi-major axis of this object to be in the range 8.2–48 au with 95% confidence (Nielsen & et al. 2014). On the other hand the radio interferometry may potentially provide significantly better angular resolution. According to the parameters plotted in our Fig. 1, at the distance of about 20 pc (distance to \( \beta \) Pic) radio interferometers should resolve planets with the orbital radius less than 1 au. Thus, the main motivation of this work is to estimate, if the radio interferometry at GHz frequencies can be useful for the search of exoplanets and brown dwarfs.

## 2 MAGNETIC FIELD ESTIMATION

The magnetic field observed on the surface of planets in the Solar system originates from the dynamo mechanism. The field is inducted by circulating electrical currents created inside a fluid interior of a planet. The circulation comes from the Coriolis force and the convecting flows supported by the internal heating. Therefore, the strength of the field may depends on many parameters. The most important of them are the density, the conductivity and the size of electrically conducting fluid core of the planet. Important are also the convected energy flux in the core and the rotation rate. Several simple but completely different relations were proposed to connect these mostly unknown parameters with observed values of the magnetic fields (e.g., Christensen 2010). Such relations are called dynamo scaling laws. The diversity of the proposed solutions is confusing, especially because all of them provide values of the magnetic field strength that are in a good agreement with the observations made in the Solar system. Therefore, it is difficult do decide which solution should be used, and especially which approach should be adopted for extrasolar planets.

In this work we decided to adopt the scaling law given by Reiners et al. (2009) and the approach proposed by Reiners & Christensen (2010), that was based on the work of Christensen et al. (2009). According to this scaling law the dynamo magnetic field strength at the surface of a planet is given by

\[
B_{\text{dyn}} = 4.8 \times 10^3 \left( \frac{M L^2}{R^8} \right)^{1/6} \text{Gauss},
\]

where mass \( (M) \), luminosity \( (L) \) and radius \( (R) \) of the planet are given in the solar values. We may derive the parameters required by the above formula from observations or from theoretical models. This illustrates advantage of this.
most of massive planets and brown dwarfs (Reiners & Basri 2008; Christensen et al. 2009). Finally, the dynamo scaling law described by equation (1) predict that the magnetic field strength in young massive planets and brown dwarfs may exceed 1 kG. This is of crucial importance for our calculations. It is necessary to reach this level of the magnetic strength in order to expect any emission at GHz frequencies. Therefore our results strongly depend on the selected scaling law. If this law is not accurate or cannot be used to some of object, then our predictions should be revised.

The dynamo magnetic field is related to the polar dipole magnetic field strength by a simple formula

\[ B_{\text{pol}} = B_{\text{dyn}} \left(1 - \frac{0.17}{M/M_J} \right)^3, \]

where \( M_J \) is the Jupiter mass. It is assumed here that the polar magnetic field strength is two times larger than the equatorial field strength. The parameters required in the first equation were obtained from the evolutionary models proposed by (Burrows et al. 1993, 1997). Those relatively old models confronted with the recent observations (Burrows et al. 2011) and calculations (Marleau & Cumming 2014) appears to be precise enough for our estimations.

In Fig. 2 we show the evolution of the main physical parameters \((R, L)\) and estimated magnetic field strength for objects with different masses. The upper panel in this figure demonstrates that above the age of about \(10^7\) yr, objects with different masses have similar radii \((\sim R_J)\). Therefore, this parameter is of less importance in the estimations, starting from this age. The middle panel demonstrates the evolution of the luminosity in comparison to the solar luminosity. This parameter depends on the mass but decreases in time, in different object, in a similar way. Note the discrepancy in luminosity of about four orders of magnitude for objects with different masses. In the lower panel we show estimated \(B_{\text{pol}}^2\) and the corresponding cyclotron frequency. The magnetic field strength from a few hundreds Gausses up to values above 1 kG should be expected only in relatively young giant planets \((age \lesssim 4 \times 10^7\) yr\). Whereas in brown dwarfs we can expect a strong magnetic field also in old objects \((age \gtrsim 10^8\) yr\). This means that the emission at GHz frequencies should be detectable in many brown dwarfs. This is already confirmed by the detection that we have quoted above.

3 INTERACTION WITH THE WIND

The main aim of this work is to provide simple estimations of the expected radio emission from different planetary system. Since most of physical parameters in such systems are usually unknown, we use as simple as possible description of the emission processes, where most of the parameters can be derived or extrapolated from the Solar system.

First, we analyse the interaction of a stellar wind with the planet magnetosphere. This process is similar in origin to the Jupiter’s HOM radiation. To calculate the total radiated power we adapted a simple formula derived by Grießmeier et al. (2005)

\[ P_I = \left( \frac{\mathcal{A}}{P_I} \right)^{2/3} \left( \frac{n}{n_{1\text{au}}} \right)^{2/3} \left( \frac{\nu}{\nu_{1\text{au}}} \right)^{7/3} \left( \frac{d}{d_1} \right)^{-4/3} P_I, \]

Figure 2. The evolution of radius and luminosity calculated for different masses of giant planets \((\lesssim 15M_J\), solid lines) and brown dwarfs \((\lesssim 80M_J\), dashed lines), according to the model by Burrows et al. (1993, 1997). The lower panel shows estimated value of polar dipole magnetic field strength and the corresponding cyclotron frequency. Jupiter’s magnetic field strength, that is about 2 G higher than the prediction of the model, is indicated by a dot. A typical range of frequencies used by the global interferometers is indicated by the shaded area.
where the magnetic moment is given by

$$\mathcal{M} = 4\pi \frac{B_{\text{pol}} R^3}{2 \mu_0}$$  \hspace{1cm} (4)$$

where \( n \) is the wind particle number density, \( v \) is the wind velocity and \( d \) is the planet to star distance. All these parameters are normalized by the Solar system values (. \( \mathcal{M}_J = 1.5 \times 10^{27} \text{ Am}^2, n_{\text{ion}} = 6.59 \times 10^6 \text{ m}^{-3}, v_{\text{lan}} = 425 \text{ km/s}, d_J = 5.2 \text{ au} \)). This formula depends on the assumed power of the emission in the Jupiter’s system \( P_J \). The average value of \( P_J \) is of about 3.1 \( \times 10^{27} \text{ W} \). However, the average power during high activity periods is \( P_J = 2.1 \times 10^{11} \text{ W} \) and the peak power may reach even \( P_J = 1.1 \times 10^{12} \text{ W} \) (Zarka et al. 2004). This gives the discrepancy reaching two orders of magnitude. In our estimations we use the average power during high activity periods. This means that we are expecting observations in a preferable conditions. Therefore, the estimated flux should be treated as the maximum possible value.

The crucial factors in equation (3) are the wind parameters. In principle the velocity and the density of wind can derive from an appropriate wind model. In the case of main sequence G, K, M type stars winds are mostly driven by gas pressure gradients in the corona (Parker 1958) and various additional acceleration processes (see for a review Echim et al. 2011). Parker’s wind model was used for example by Grießmeier et al. (2007) to predict low-frequency radio fluxes of known extrasolar planets.

Here, we are going to focus on main sequence A-type stars. Such object are much more luminous than G, K, M stars (by 1-2 orders of magnitude). Therefore, we assume that the winds of such stars are driven by the radiation pressure. The radiative force that accelerates the wind comes from the scattering on free electrons and interception of photons by ions of the atmospheric plasma. Ions in turn produce the observed spectral lines. Thus such winds are frequently called line-driven winds. First models of such winds were proposed by Lucy & Solomon (1970) and Castor et al. (1975), to explain mass loss rates in O-type stars. In last few decades the models were successively improved and today we may speak about a family of CAK models (after Castor, Abbott and Klein 1975). In should be mentioned that the CAK theory was successfully applied to O, B type stars (e.g., Vink et al. 2000; Kudritzki 2002; Puls et al. 2008) and A, F, G supergiants (e.g., Ahmad et al. 1997; Curé et al. 2011). There are only a few works that try to apply the CAK theory to main sequence A-type stars (e.g., Babel 1995; Bertin et al. 1995; Vick et al. 2010). This may be related to the fact that there are no direct observational measurements for mass loss rates in main sequence A-type stars. The upper limits derived from the observations (Brown et al. 1990; Lanz & Catala 1992) are 2-3 orders of magnitude above very few estimations (Bruhweiler et al. 1991; Bertin et al. 1995) we have for such stars.

According to the standard CAK theory the mass loss rate of a star can be approximated by

$$\dot{M}_{\text{CAK}} \approx \frac{L_\ast}{c_s} \left( \frac{Q \Gamma}{1 - \Gamma} \right)^{1/\alpha} ,$$

(e.g., Owoccki & ud-Doula 2004) where \( L_\ast \) is the star bolometric luminosity, \( \alpha \) is one from three so-called line force multiplier parameters (assumed here to be 0.5) and

$$\Gamma = \frac{a_\ast}{a_g} = \frac{\sigma_\ast L_\ast}{4\pi GM_*}$$

is the Eddington factor that relates the radiative acceleration by the scattering on free electrons (\( a_\ast \)) with the gravitational acceleration (\( a_g \)). Other parameters in the above formula are mass of a star \( M_* \), the electron scattering opacity \( \sigma_\ast = 0.325 \text{ cm}^2\text{g}^{-1} \), and the speed of light c. Note that the mass loss rate given by equation (5) was derived under assumption that the star was a point source at the origin. Improved implementations of the CAK theory (e.g., Friend & Abbott 1986; Pauldrach et al. 1986) takes into account the finite size of the star and the centrifugal force due to the star’s rotation. This reduces the mass loss rate by a factor

$$M \approx \frac{M_{\text{CAK}}}{(1 + \alpha)^{1/\alpha}}.$$  \hspace{1cm} (7)$$

Equation (5) contains also the dimensionless line strength parameter \( Q \) that replaced two other force multiplier parameters, referred in the CAK terminology as \( \alpha \) and \( \delta \) (e.g., Abbott 1982; Owoccki & ud-Doula 2004). The \( Q \) parameter depends on the star metallicity. In the case of O, B stars \( Q \approx 10^2 \), with the assumption that \( Z_* \approx 0.019 \) (Gayley 1995). However, this parametrization of \( Q \) used for A-type stars gives mass loss rates order of magnitude higher than expected values. We verified our calculations with the mass loss rates estimated for the Sirius A star. An early findings by Bertin et al. (1995) based on the observations of Mg II lines give for this object \( 2 \times 10^{-13} < \dot{M} < 1.5 \times 10^{-12} \text{ M}_\odot/\text{yr} \). However, more recent investigations suggest the mass loss rate in Sirius A should be of the order of \( 10^{-13} \text{ M}_\odot/\text{yr} \) or less. A higher mass loss rate \( (\sim 10^{-12} \text{ M}_\odot/\text{yr}) \) would not allow to reproduce observed surface abundance patterns for this star (Vick et al. 2010). Assuming \( Q = 1.5 \times 10^2 \), we obtained \( (2 \times 10^{-13} \text{ M}_\odot/\text{yr}) \) for Sirius A. This assumption is also in a good agreement with the mass loss rate estimated for \( \beta \text{ Pic} \) \( \dot{M} \approx 1.1 \times 10^{-14} \text{ M}_\odot/\text{yr} \) (Bruhweiler et al. 1991), where our calculation gives \( \dot{M} = 10^{-14} \text{ M}_\odot/\text{yr} \).

The CAK wind velocity law is given by

$$v_w(d) = v_{\text{esc}} \left( 1 - \frac{R_*}{d} \right)^{\frac{\beta}{\alpha}} ,$$

where \( R_* \) is the star radius, \( \beta \) describes the velocity profile and lies in the range \( 0.5 < \beta < 1 \). In the standard CAK theory (point–like star) \( \beta \approx 0.5 \). Improved CAK models suggest \( \beta \approx 0.8 \), the value that we used in this work. However, detailed value of \( \beta \) is not important for \( d \gg R_* \), when the wind velocity becomes equivalent to the terminal velocity, given by

$$v_{\text{esc}} \approx 2.25 \frac{\alpha}{1 - \alpha} v_{\text{esc}},$$

that is of the order of the effective escape velocity

$$v_{\text{esc}} = \sqrt{\frac{2GM_{\text{eff}}}{R_*}},$$

where the effective mass \( M_{\text{eff}} = M_\ast (1 - \Gamma) \) combines the radiative acceleration on electrons and the gravity. The wind velocity obtained from equation (8) must be transformed to the reference frame of the planet \( v = \sqrt{v_{\text{esc}}^2 + v_{\text{K}}^2} \), where \( v_{\text{K}} \) is the Keplerian velocity of the planet. However, this effect is
important only for planets at relatively tight orbits, where the Keplerian velocity is comparable to the wind velocity.

Having the mass-loss ratio and the wind velocity, we may easily obtain the particle number density using the mass continuity equation

$$M = 4\pi d^2 n(d)v(d)m_p,$$

where $m_p$ is the proton mass.

### 4 INTERACTION WITH A MOON

The second emission scenario assumes the existence of a moon around the planet. This is a mechanism similar to the Io-Jupiter interactions that produce the so-called Io-DAM emission. We follow here the approach proposed by Noyola et al. (2014), where the formula for the maximum Joule dissipation in the Jupiter system (Neubauer 1980) was used. According to this formula, the power of radio emission related to the planet–moon interaction is given by

$$P_2 = \beta \frac{\pi R_m^2 V^2 B_m^2}{\mu_0 \sqrt{\frac{\mu_0}{m_p} + V^2}},$$

where $R_m$ is the moon radius, $B_m$ is the planet magnetic field strength at the moon position, $V$ is the difference between the velocity of the planet magnetosphere at the moon position and the moon velocity

$$V = \omega d_m - \sqrt{\frac{GM}{d_m}},$$

where $\omega$ is the planet’s angular velocity and $M$ is the mass of the planet. This difference depends on the distance between the planet and the moon ($d_m$). At some point, the difference between the velocities reaches the maximum value. In the Jupiter–Io system this maximum point is located at about 5.5 Jupiter’s radii. Note that the Io’s orbit has radius slightly larger ($\sim 6R_J$). Since the radiated power is proportional to the square of $V$, the power radiated in the Jupiter–Io system is almost maximal. In our estimations we always assume the distance $d_m$ that gives the maximum value of $V$. This again means that we have chosen a preferable physical conditions. Therefore, the fluxes we calculate are maximal. The other important parameters in the equation (12) are the plasma density ($\rho$) and the efficiency of the emission process ($\beta$). The plasma density is an unknown, free parameter. We assume that the value of this parameter can be of the order of plasma density around Io ($\sim 7 \times 10^{-17}$ kg m$^{-3}$). We also assume that the efficiency is similar like in the Jupiter–Io system $\beta = 0.01$ ($\sim 1\%$). Another free parameter is the planet’s angular velocity. In principle the lower limit for this parameter can be established at the critical velocity. This is the velocity at which the dynamo process is saturated. However, in practice the critical velocity is very low and do not give a useful constrain (see the discussion in Reiners & Christensen 2010). On the other hand, the upper limit for the angular velocity is given by the maximum angular velocity allowed by the centrifugal stability $\omega_{\text{max}} = \sqrt{GM/R^2}$.

**Figure 3.** The expected flux densities of objects located at the distance of 25 pc, generated by the stellar wind (upper panel, according to Section 3) and the planet–moon interaction (lower panel, according to Section 4). The continuous lines show expected emission levels for different masses and ages. The dotted lines join the fluxes generated by object with the same mass at different ages. The masses are given in the Jupiter units. The continuous “U” like curve shows the frequency range (1.4 – 5 GHz) and the 3$\sigma$ detection threshold ($\sim 21 \mu$Jy) that may be reached after five hours of the EVN integration with 1GB recording rate (see also Table 1 for other interferometric networks and recording rates).

### 5 COMPARISON OF THE EMISSION SCENARIOS

The observed flux densities from both above discussed processes are calculated according to the formula

$$F = \frac{P_{1/2}}{\Omega D^2 V_{\text{cyc}}},$$

where $\Omega = 1.6$ sr is the solid angle of the emission beam (Zarka et al. 2004), $D$ is distance to the planetary system and $V_{\text{cyc}} = eB/(2\pi m_e)$ is the cyclotron frequency.

The results of our calculations are illustrated in Fig. 3. In the upper panel, we show the emission generated by the interaction between the stellar wind and the planet magnetosphere. To calculate this emission we assumed the density of the wind equal to the density in the Solar system $n = n_{\text{Sun}}$ and the wind velocity three times higher than in the Solar system $v = 3v_{\text{Sun}}$. Our analysis presented in the next section
Table 2. Planets and brown dwarfs discovered around main sequence A–type stars so far (after expoplanets.eu, Schneider et al. 2011). Note that only two first object are located at relatively small distance and therefore were selected for our detailed investigations. (1) – according to Meshkat et al. (2013) this is pre-main sequence star. (2) – spectral type derived by Grenier et al. (1999).

| Name       | \( M_\text{vis} \) | \( S_\text{min} \) | \( D \) | \( M_\text{wind} \) | Age (Gyr) | Spec. |
|------------|------------------|------------------|------|----------------|-----------|-------|
| \( \alpha \) PsA b | 3.0+0.6 | 115.0 | 7.7 | 1.92 | 440 | A4V |
| \( \beta \) Pic b | 7.0+0.8 | 9.04 | 19.44 | 1.8 | 21 | A6V |
| HR 8799 b | 7.0+0.8 | 68.0 | 39.4 | 1.56 | 60 | A5V |
| HR 8799 c | 10.0+3.0 | 42.9 | 39.4 | 1.56 | 60 | A5V |
| HR 8799 d | 10.0+3.0 | 27.0 | 39.4 | 1.56 | 60 | A5V |
| HR 8799 e | 9.0+4.0 | 14.5 | 39.4 | 1.56 | 60 | A5V |
| HD 95086 b | 5.0+2.0 | 61.5 | 90.4 | 1.6 | 17 | A8±1(1) |
| WASP-33 b | 2.1+0.1 | 0.026 | 116.0 | 1.495 | 40 | A5mA8F4(2) |
| HIP 73990 b | 21.0+30.0 | 20.0 | 125.0 | 1.72 | 15 | A9V |
| HIP 73990 c | 22.6+30.0 | 32.0 | 125.0 | 1.72 | 15 | A9V |
| HD 169142 b | 30.0+2.0 | 22.7 | 145.0 | 1.65 | 60 | A7V |

shows that such numbers appears to be an average values for the main sequence A–type stars, that we analyse in this work. Moreover, we assumed the planet to star distance to be \( d = 1\text{au} \) and we located our hypothetical planetary systems at the distance \( D = 25\text{pc} \). The first distance was assumed arbitrary, the second one is typical for the stars analysed in the next section. Note that the formulas that describe the emitted power and the observed flux density are simple power-law functions. Therefore one can easily recalculate our results for other distances \( (d, D) \). The first panel in Fig. 3 shows that the emission of almost all young system (age \( \lesssim 1\text{Gyr} \)) should be detected by the EVN after five hours of integration, if the level of this emission will remain constant. Note that such emission very likely will be variable with the periods of higher activity and possible outburst. It is difficult to predict exact character of such emission for extrasolar planets. Therefore, the effective time required for the detection can be significantly longer.

The hypothetical emission produced by the planet-moon interaction is demonstrated in the lower panel of Fig. 3. This emission in general appears to be significantly weaker than in the previously analysed case. The emission of a system similar to Jupiter-Io (with magnetic field \( > 1\text{kG} \)) cannot be detected by currently operating VLBI networks at GHz frequencies. Therefore, to estimate what we can expect from such emission scenario, we assumed significantly higher values of the main parameters \( (R_m = 3R_{\text{Io}}, \rho = 3\rho_{\text{Io}}, \omega = 5\omega_{\text{Io}}) \). However, even with this assumption the fluxes calculated for the distance of 25 pc are very small \( (F < 1\mu\text{Jy}) \). At smaller distance, for example 10 pc, the number of possible targets is reduced just to three stars, and the expected emission from such systems is below 10 \( \mu\text{Jy} \). Thus, below the sensitivity threshold of currently operating interferometers. Therefore, in our further investigations we will focus on the first emission scenario, where the radiation is produced by the interaction between the stellar wind and the planet magnetosphere.

Figure 4. Stellar wind parameters estimated for the sample of main sequence A–type stars analysed in this work. The upper panel shows mass loss rates, in the middle panel we plotted terminal velocities and the bottom panel shows wind particle densities normalized to the Sun wind particle density observed at the distance of 1\text{au}. 

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Parameters of stars selected for the calculations presented in Section 6. In the cases where the bolometric luminosity was not directly available, we give the effective temperature (in brackets), that we used to calculate the luminosity. References: 1) van Leeuwen (2007), 2) Chen et al. (2014), 3) Chen & et al. (2005), 4) Zorec & Royer (2012), 5) Gáspár et al. (2013), 6) Yoon et al. (2010), 7) Aumann et al. (2012), 8) Cote (1987), 9) Shulyak et al. (2014), 10) Nakajima & Morino (2012), 11) Su & et al. (2006), 12) Mamajek (2012), 13) Binks & Jeffries (2014), 14) Smith & Terrile (1984), 15) Absil & et al. (2013), 16) Morales & et al. (2009), 17) Galland et al. (2006), 18) da Silva et al. (2006), 19) Boyajian & et al. [A] (2012, A), 20) Ertel & et al. (2014), 21) Kochukhov & Baguña (2006), 22) Bruntt & et al. (2008), 23) van Belle & von Braun (2009), 24) van Belle & et al. (2006), 25) Plavchan et al. (2009), 26) Fitzpatrick & Massa (2005), 27) Shulyak et al. (2014), 28) Boyajian & et al. [B] (2012, B), 29) van Belle (2012), 30) Di Folco et al. (2004), 31) Wu et al. (2011), 32) Gray et al. (2006), 33) Gray et al. (2003), 34) Monnier & et al. (2007), 35) Paunzen & et al. (2002), 36) Montesinos et al. (2005), 37) Crifo et al. (1997), 38) Peterson & et al. (2006), 39) King et al. (2003), 40) Boeggaard et al. (1988), 41) Trilling & et al. (2007), 42) McDonald et al. (2012), 43) Plavchan et al. (2009).

### APPLICATION TO KNOWN STARS

The calculations presented in the previous section demonstrate that the strongest emission could be generated in the youngest systems as old as about a few hundreds Myr (Fig. 3), where the magnetic field strength may reach the highest values (Fig. 2). Therefore, looking for star candidates that may host young objects or possibly brown dwarfs we selected main sequence A-type stars located in the solar neighbourhood ($D<30$pc). What is important, these objects evolve relatively fast and usually leave the main sequence in less than 1 Gyr. Thus, possible planets around such stars should also be relatively young. Moreover, the main sequence A-type stars are more massive than the Sun (masses from 1.3 to $3M_\odot$). Statistical analyses of known planetary systems suggests that planets originate more frequently around massive stars (e.g., Johnson et al. 2007). The observed fraction of stars with giant planets is: 3.3% for M-type dwarfs, 8.5% for F, G, K type stars and 20% in the case of ‘retired’ A-type objects (Johnson et al. 2010). On the other hand there is a theoretical prediction that massive planets should originate more frequently around less massive stars (Kornet et al. 2006). However, this work is based on the core accretion theory that may have difficulties to explain the existence of giant planets relatively close to massive stars (Ribas et al. 2015). Moreover, there are only a few planets discovered around main sequence A-type stars, so far (see Table 2). However, this is related rather to difficulties in detection of such planetary system, where for example fast rotation of a star or less number of spectral lines rules out standard radial velocity measurements. From the planets listed in Table 2, one object (WASP-33 b – Collier Cameron & et al. 2010) was discovered by the observations of transits. The rest of these planets were detected by the direct imaging. This indicate significance of this technique, that may be even more important in the radio domain.

### Physical parameters of main sequence A-type stars selected for the calculations presented in this section are collected in Table 3. The errors for the most of the specified parameters are at level of a few percent, with the exception for the age. This parameter is the most difficult value

**Table 3** Parameters of stars selected for the calculations presented in Section 6. In the cases where the bolometric luminosity was not directly available, we give the effective temperature (in brackets), that we used to calculate the luminosity. References: 1) van Leeuwen (2007), 2) Chen et al. (2014), 3) Chen & et al. (2005), 4) Zorec & Royer (2012), 5) Gáspár et al. (2013), 6) Yoon et al. (2010), 7) Aumann et al. (2012), 8) Cote (1987), 9) Shulyak et al. (2014), 10) Nakajima & Morino (2012), 11) Su & et al. (2006), 12) Mamajek (2012), 13) Binks & Jeffries (2014), 14) Smith & Terrile (1984), 15) Absil & et al. (2013), 16) Morales & et al. (2009), 17) Galland et al. (2006), 18) da Silva et al. (2006), 19) Boyajian & et al. [A] (2012, A), 20) Ertel & et al. (2014), 21) Kochukhov & Baguña (2006), 22) Bruntt & et al. (2008), 23) van Belle & von Braun (2009), 24) van Belle & et al. (2006), 25) Plavchan et al. (2009), 26) Fitzpatrick & Massa (2005), 27) Shulyak et al. (2014), 28) Boyajian & et al. [B] (2012, B), 29) van Belle (2012), 30) Di Folco et al. (2004), 31) Wu et al. (2011), 32) Gray et al. (2006), 33) Gray et al. (2003), 34) Monnier & et al. (2007), 35) Paunzen & et al. (2002), 36) Montesinos et al. (2005), 37) Crifo et al. (1997), 38) Peterson & et al. (2006), 39) King et al. (2003), 40) Boeggaard et al. (1988), 41) Trilling & et al. (2007), 42) McDonald et al. (2012), 43) Plavchan et al. (2009).
for the estimation, especially in the case of main sequence stars, that for relatively long period of time radiate almost the same amount of energy. Thus, in many papers the errors of the estimated ages are not specified at all. From all collected informations we may conclude that the age of Vega (454 ± 13 Myr) is estimated with the best precision (better than 3%), whereas the age of η Ind (250 ± 200 Myr) has the highest uncertainty (80%).

More than half of the selected objects exhibit an excess in the infrared range. This may indicate that these stars are surrounded by debris discs, what increases a chance to find planets or brown dwarfs in such systems. Note that for three from the selected stars (α Lyr, β Pic, α PsA) debris discs were already directly observed (Holland & et al. 1998), and the massive Jovian planets were discovered inside the debris disk of α PsA (Kalas & et al. 2008) and β Pic (Lagrange & et al. 2009). Finally, our putative planetary systems are located at relatively small distances, what should help to detect possible radio emission.

The most important stellar wind parameters obtained for the selected stars are presented in Fig. 4. Expected mass-loss rates extends over two orders of magnitude. This is the result of differences in radii and luminosities of these stars. An average value of the mass loss rate \( \dot{M} \) is \( 8.6 \times 10^{-14} \, M_\odot/\text{yr} \) is a few times higher than the Sun mass loss rate \( \dot{M}_\odot \). \( \dot{M} \) for most of the stars lies in the range between \( 10^{-14} \) and \( 10^{-13} \, M_\odot/\text{yr} \), which is close to \( \dot{M}_\odot \). Estimated terminal velocities are in range 1100 – 1550 km/s. This is 2 to 4 times higher than the velocities observed in the Solar wind. Note that in the Solar wind there are two components, slower and heavier with the velocity around 425 km/s and the faster component with the velocity \( \sim 750 \) km/s. Expected wind particle densities for most of the stars are in the range \( 0.1 < n < 10 \) in comparison to the Sun wind particle density at the distance of 1 au. However, an average value of this parameter is similar to the value observed in the Solar system (\( n_{\text{1 au}} \approx 6.6 \times 10^9 \, \text{m}^{-3} \)).

In Fig. 5 we show possible radio emission that can be generated by the interaction between the stellar wind and objects orbiting around selected stars. To calculate expected maximal frequencies and fluxes we assumed that in each system there is an object with the mass \( M = 15 M_\odot \) located at the distance \( d = 1 \au \) from the star. For most of the selected stars the maximum frequency of the emission appears around 1 GHz and the expected flux lies in the range from 10 to 400 \( \mu \text{Jy} \).

Our calculations show that the strongest radio emission should be expected from hypothetical planetary system around Vega (α Lyr) and Fomalhaut (α PsA). These two stars are located at the distance \( \sim 7.7 \) pc. Thus, the observed flux density should be relatively high \( \sim 350 \mu \text{Jy} \). The maximum frequency of the radio emission in these systems may reach \( \sim 0.9 \) GHz. Note that Brown & et al. (1990) using VLA made observations of several A and F type stars at 4835 and 4885 MHz (50 MHz bandwidth). However, they obtained no detections, only upper limits were estimated. In the case of Fomalhaut the upper limit was set to \( F_{\text{lim}} \leq 100 \mu \text{Jy} \). As it was already mentioned Vega is surrounded by the debris disc (Holland & et al. 1998). The close neighbourhood of this star may contain also dust (Absil & et al. 2006). The direct imaging of the disc around Fomalhaut led to the detection of a planet (Kalas & et al. 2008). This planet is located at the distance of at least 100 au from the star (Kalas et al. 2013). Therefore, the emission produced by the stellar wind should be negligible. On the other hand, if there is a moon around this planet that through volcanic activity fills the planet magnetosphere with matter, then we may expect the radio emission from such system. However, as we already demonstrated this emission process is relatively weak at GHz frequencies. Thus, from the distance of almost 8 pc it would be difficult to detect such emission. Still, detection of a radio emission from a planet located tens of astronomical units from the star can indicate an existence of extrasolar moons.

The emission similar to that of Vega and Fomalhaut can also be expected from Altair (α Aql). This star is located at the distance \( \sim 5 \) pc. Therefore, the expected flux density is also relatively high \( \sim 280 \mu \text{Jy} \). However, this is quite old object (age \( \sim 700 \) Myr). Therefore, the magnetic field strength in this system may be too weak to produce sufficient emission at GHz frequencies (maximum emission frequency is expected to be around 760 MHz). According to Brown et al. (1990) the upper limit for the emission in this system is \( F_{\text{lim}} \leq 100 \mu \text{Jy} \). On the other hand this can be an interesting target for the low frequency interferometers (GMRT & LOFAR).

Another interesting star is β Pictoris. The planet discovered around this star (Lagrange & et al. 2009) is massive (4-11 \( M_\oplus \)) and located at relatively small distance to the star \( d \sim 1.5 \, \text{au} \) (Currie & et al. 2013). The system is also very young (age \( \sim 21 \) Myr), therefore it fulfills all the necessary conditions to be detected at the radio GHz frequencies. Unfortunately, the star is rather distant (\( D = 19.4 \) pc) and located at the Southern hemisphere (\( \delta \sim -51^\circ \)), beyond the operating range of the most sensitive interferometers (VLBA, EVN). Our calculations show that the flux density

\[
F_{\mu \text{Jy}} = \text{maximum frequency [GHz]}
\]
of the radio emission from the planet in this system should be at the level of about 30 $\mu$Jy above 3 GHz. Thus, this is an excellent target for the Square Kilometre Array\(^5\) in near future.

The most promising candidate for detection of the radio emission at GHz frequencies from massive exoplanet or a brown dwarf is Denebola ($\beta$ Leo). This star is young ($\sim$45 Myr) and located at relatively small distance ($\sim$11 pc). Therefore, a massive object ($M = 15 M_J$) in this system, located at the distance of 1 au should generate the flux around 166 $\mu$Jy at $\sim$ 2.9 GHz. It must be mentioned that the upper limit obtained by Brown et al. (1990) for this star is $F_{4.8 \, \text{GHz}} \leq 116 \mu\text{Jy}$. However, this does not exclude the possibility that planets are present around this star. Our calculations show that Denebola is the best candidate for search of possible planetary emission at GHz frequencies.

7 SUMMARY

We calculated possible radio GHz emission that may originate in extrasolar planetary systems. The key parameter for the frequency range and the power of such emission is the magnetic field strength. This parameter was obtained from the theoretical model that describes the evolution of massive planets and brown dwarfs. We analysed two emission scenarios that are observed in the Jupiter system. The first mechanism gives quite promising results. This emission could be detected from massive planets ($M \geq 10 M_J$) and brown dwarfs at the distances $\lesssim$ 30 pc. The less optimistic is the fact that the emission from planets is limited to young and massive objects and could be observed practically only at 1.4 GHz by global VLBI systems. Using these results we selected several young and massive A-type stars to calculate possible radio emission from planets and brown dwarfs around such objects. Our estimations demonstrated that in almost all cases the emission can be detected by VLBI.

The interaction between hypothetical moons and planets that may produce some radio emission appears to be less significant. In principle, the observations of such emission may give a direct evidence for an existence of extrasolar moons (Noyola et al. 2014). However, such a planet with the moon should be located at relatively large distance from the star (at least several au) to exclude possibility that the radio emission is dominated by the interaction of the star wind with the planet magnetosphere. Our calculations show that such detection can be very difficult with currently operating instruments.

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\(^5\) http://www.skatelescope.org/

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