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Star-Planet Interactions in the Radio Domain: Prospect for Their Detection

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Abstract All possible types of interaction of a magnetized plasma flow with an obstacle (magnetized or not) are considered, and those susceptible to produce a radio signature are identified. The role of the sub-Alfvénic or super-Alfvénic character of the flow is discussed. Known examples in the solar system are given, as well as extrapolations to star-planet plasma interactions. The dissipated power and the fraction that goes into radio waves are evaluated in the frame of the radio-magnetic scaling law, the theoretical bases and validity of which are discussed in the light of recent works. Then it is shown how radio signatures can be interpreted, in the frame of the cyclotron-maser theory (developed for explaining the generation of solar system planetary auroral and satellite-induced radio emissions), for deducing many physical parameters of the system studied, including the planetary or stellar magnetic field. Prospects for the detection of such radio signatures with new generation low-frequency radiotelescopes are then outlined.

Introduction

Stars interact in many ways with their planets in orbit: through gravitation that constrains the orbit and, at short range – i.e. for close in exoplanets – causes tidal effects of each body upon the other (Cuntz et al 2000) ; through stellar light – especially at short wavelengths – that ionizes the planet’s upper atmosphere (e.g. Encrenaz et al 2004); and through plasma and magnetic fields. Here we are mainly interested with the latter, that may lead to the generation of intense radio emissions. We use the generic name “plasma interaction” for interactions involving plasma flows and magnetic fields.

Plasma flow – obstacle interactions

Various types of plasma interactions are observed in our solar system, involving the solar wind and magnetized or unmagnetized planets, as well as magnetized planets and their satellites. A coherent frame for sorting these various interactions is the general frame of flow – obstacle interactions (Zarka 2007). The former is of course a flow of plasma, that can be strongly or weakly magnetized (the hypothetical case of a completely unmagnetized flow is not interesting for us because no radio signature is expected). The latter is a conductive or insulating body, with or without an atmosphere, and possessing or not an

intrinsic magnetic field (Lepping 1986).

Magnetized obstacle

When the obstacle is magnetized, its interaction with the magnetized flow is likely to occur through magnetic reconnection at their interface (where both magnetic field amplitudes are comparable but their orientations different), leading to energy release in the form of plasma waves and particle acceleration susceptible to produce radio waves. The location in the system where radio emission may occur depends on the region of space accessible to the accelerated electrons along magnetic field lines. This in turn depends on the Mach number ($M=V_{\text{flow}}/V_{\text{sound}}$) and especially the Alfvénic Mach number ($M_A=V_{\text{flow}}/V_{\text{Alfvén}}$) of the flow in the obstacle's frame, that will define the topology of the interaction (Alfvén waves carry magnetic perturbations and associated electric currents along magnetic field lines).

When the flow is super-Alfvénic ($M_A>1$), a bow shock forms upstream of the obstacle that slows down and heats the flow, making it become sub-Alfvénic ($M_A<1$) before it hits the obstacle and flows around it. This shock somewhat “disconnects” the obstacle from the source of the flow and thus prevents most of the waves, particles and energy to travel back to this source. Accelerated electrons will rather focus toward the magnetic poles of the obstacle, where they collectively acquire non-Maxwellian distributions susceptible to produce intense radio waves. This is what happens in the auroral regions of the magnetospheres of magnetized planets in the solar wind (the large scale cavities carved in the solar wind by planetary magnetic fields (Bagenal 2001; Encrenaz et al 2004)), and it should also result from the interaction of stellar winds with magnetized exoplanets, if they are in the super-Alfvénic region of the wind.

When the flow is sub-Alfvénic the perturbations of magnetic field lines (Alfvén waves) excited by reconnection at the flow-obstacle interface can propagate along magnetic field lines toward the source of the flow as well as toward the magnetic poles of the obstacle. These Alfvén waves propagate in two “wings” symmetrically oriented relative to the direction of the flow in the plane that contains the flow velocity \mathbf{V}_{flow} and magnetic field \mathbf{B}_{flow} . Currents are carried by these wings, that may also lead to electron acceleration to keV energy or more. The angle between these Alfvén wings and the flow is defined by the ratio between V_A along magnetic field lines and V_{flow} across them. In the limit where $V_A \gg V_{\text{flow}}$, Alfvén wings are simply the magnetic flux tube connecting the obstacle to the source of the flow.

If the flow is itself strongly magnetized, the conditions (accelerated electron distributions, plasma density and magnetic field amplitude) at the footprints of the perturbed field lines can be favourable for the production of radio emission. In the solar system, this does not happen in the solar wind, which is weakly magnetized and super-Alfvénic at all planetary orbits, but it does happen in the interaction of the magnetized satellite Ganymede with the rotating magnetic field of its parent planet Jupiter (Kivelson et al 2004), that leads to magnetic reconnection, electron acceleration and radio emission generation near the footprints in Jupiter's ionosphere of the Ganymede flux tube (and also marginally near Ganymede). A similar interaction should exist between magnetized hot jupiters, orbiting close enough to their parent star to be in the region where the wind is still sub-Alfvénic. If

the magnetic field amplitude at the stellar surface is ≥ 30 -100 times that of the Sun, radio emission should be produced not only in the exoplanet's auroral regions, but also near the footprints on the stellar surface of the magnetic field lines connecting the hot jupiter and the star.

Note that while both ends of Ganymede's flux tube are connected to Jupiter's ionosphere, at most one Alfvén wing of a hot jupiter may travel upstream to the stellar surface (Preusse 2006).

A particular case of the interaction between an exoplanet and a strongly magnetized wind concerns planets orbiting pulsars. Pulsar winds (beyond the light cylinder) are expected to be relativistic, so that both Alfvén wings of a planetary obstacle are carried away by the flow, independent of the magnetization of the obstacle. It has been proposed that the plasma conditions in these wings are favourable to radio emission generation, and that relativistic focussing of the produced emission can explain the elusive Fast Radio Bursts detected at cosmological distances (Mottez and Zarka 2014). This also applies when the obstacle in the pulsar wind is not magnetized, but only conductive (see below).

Unmagnetized obstacle

When the obstacle is not magnetized its interaction with the plasma flow will again depend on the flow magnetization and Alfvén Mach number, and on the obstacle's conductivity.

In the weakly magnetized super-Alfvénic solar wind, conductive obstacles will develop an induced magnetosphere via the (temporary) pile-up of the wind's magnetic field on the obstacle's nose, caused by the slow large-scale perpendicular diffusion of plasma across magnetic fields. Conductivity is high in the ionospheres of Venus, Mars, Titan or comets close to the Sun, and possibly in the interior for metallic asteroids. Similar induced magnetospheres are expected to exist for unmagnetized exoplanets orbiting within a weakly magnetized super-Alfvénic stellar wind. The absence of a large scale magnetic field of the obstacle prevents the focussing of accelerated electrons toward auroral regions and thus causes the absence of any intense radio emission for these systems.

When the flow is sub-Alfvénic, Alfvén wings similar to those described above develop in the flow past the obstacle. The difference with the previous case is that the Alfvénic perturbations are not caused by magnetic reconnection but by the deviation of the flow (and its embedded magnetic field) by the conductive obstacle. Because they are only driven by the relative motion between the obstacle and the flow, these Alfvén wings are said to result from an "Unipolar Inductor" (UI) interaction (the theory was initially developed for artificial satellites in the ionosphere (Drell et al 1965)). The first and most famous example of a natural UI interaction is that of Io with the strong rotating Jovian magnetic field (Neubauer 1980), that is now known to apply also to the Europa-Jupiter interaction. The conductivity of the obstacle is ensured by the existence of a volcanic atmosphere (and thus an ionosphere) around Io, and a subsurface ocean at Europa. Electrons accelerated in the Alfvén wings follow Jovian magnetic field lines down to the Jovian ionosphere. Above the northern and southern magnetic footprints of these two Galilean moons, the plasma conditions are favourable for the production of intense radio emission (Bigg 1964; Louis et

al 2017). Similar interactions may exist between some satellites of Saturn and the planet's magnetic field, but because Saturn's magnetic field is much weaker than Jupiter's, the UI energy budget (see below) is not expected to give rise to strong satellite-induced radio emissions at Saturn, and indeed none has been observed until now.

Unipolar induction is expected to take place in star-planet systems when the stellar wind is sub-Alfvénic (which should be the case for many hot jupiters) and the planet unmagnetized. If the star is weakly (Sun-like) magnetized, then no radio emission is expected similar to the Saturn-satellite case. If the star is strongly magnetized (≥ 30 -100 times the Sun), then the star-planet system is a giant analogue of the Io-Jupiter (or Europa-Jupiter) system and strong radio emission is expected to be generated near one or both footprints of the magnetic flux tube connecting the exoplanet to the stellar surface.

Willes and Wu (2004, 2005) studied the particular case of terrestrial planets in close orbits around magnetic white dwarf stars, acting as a unipolar inductor, and generating radio emission with large flux densities. These systems could be remnants of main sequence stars with a planet that has survived the stellar expansion phase and has settled again on a stable orbit.

As mentioned above, the case of a conductive obstacle (planet, asteroid, dwarf companion) orbiting in a pulsar wind is the relativistic analogue of the Io-Jupiter interaction, for which Mottez and Heyvaerts (2011) have shown that although close to c , V_{flow} is still likely to be lower than V_A , thus the interaction is expected to be a UI one.

It is tempting to extend the above conclusions to the case of a strongly magnetized super-Alfvénic stellar wind flowing past an unmagnetized planet: in that case, the UI interaction produces an induced magnetosphere, the envelope of which (the magnetopause) can be considered as the limiting case of the planet's Alfvén wings in a super-Alfvénic flow. It is remarkable that the transition between a super-Alfvénic and a sub-Alfvénic flow has been actually observed at Earth (Chané et al 2015). In the super-Alfvénic case, the accelerated electrons cannot focus toward the planet's auroral regions and they are not expected either to propagate upstream to the distant stellar surface, but it is not excluded that a mechanism similar to the one proposed by Mottez and Zarka (2014) takes place, i.e. an instability might develop along the magnetopause and produce radio emissions. This is speculative though, as no example of such an interaction exists in our solar system.

Finally, let us remind that when the obstacle is not only unmagnetized but also insulating, it only absorbs the flow that impacts it, creating a plasma cavity in its wake, that is progressively refilled due to charged particle motion along the magnetic field lines permeating the flow. This is the case for the Earth's Moon (and probably also some rocky asteroids) in the solar wind. No bow shock nor any radio emission is produced in that configuration.

Table 1 expands and generalizes the Table 1 from Zarka (2007), attempting to list all flow – obstacle interactions described above in a synthetic way, extrapolate them to star – planet interactions and predict their radio signatures.

Table 1 Possible types of flow-obstacle interactions, examples, radio signatures, and extrapolation to star-planet plasma interactions.

Flow $ \mathbf{B} ^a$	Flow M_A^b	Obsta- -cle	Known examples in the Solar system (mechanism) <i>Expected Star-Planet interaction (mechanism)</i>	Observed CMI ^c radio signature <i>Expected CMI radio signature</i>
$ \mathbf{B} \downarrow$	\uparrow	B	Solar wind – planet: Mercury, Earth, Jupiter, Saturn, Uranus, Neptune → magnetospheres (reconnection) <i>Stellar wind – Magnetized exoplanet (reconnection)</i>	From planet’s aurora (Earth, Jupiter, Saturn, Uranus, Neptune) <i>From exoplanet’s aurora</i>
$ \mathbf{B} \downarrow$	\downarrow	B	- <i>Stellar wind – Magnetized hot Jupiter (reconnection)</i>	- <i>From exoplanet’s aurora</i>
$ \mathbf{B} \downarrow$	\uparrow	No B	Solar wind – conductive obstacle: Venus, Mars, Titan, Asteroids [metallic], Comets [close to the Sun] (induced magnetosphere) Solar wind – insulating obstacle: Moon, Asteroids [rocky] (flow absorption, no shock, wake) <i>Stellar wind – Unmagnetized exoplanet (induced magnetosphere)</i>	- - -
$ \mathbf{B} \downarrow$	\downarrow	No B	Saturn – satellites (AW/UI) ^d <i>Stellar wind – Unmagnetized hot Jupiter (AW/UI)</i>	- -
$ \mathbf{B} \uparrow$	\uparrow	B	- <i>Magnetized star – Magnetized exoplanet (reconnection)</i>	- <i>From exoplanet’s aurora</i>
$ \mathbf{B} \uparrow$	\downarrow	B	Jupiter – Ganymede (reconnection) <i>Magnetized star – Magnetized hot Jupiter (reconnection)</i> <i>Pulsar – planet (reconnection)</i>	At Ganymede flux tube footprints <i>From exoplanet’s aurora and/or at star-planet flux tube footprints</i> <i>In Alfvén wing → Fast Radio Bursts ?</i>
$ \mathbf{B} \uparrow$	\uparrow	No B	- <i>Magnetized star – Unmagnetized exoplanet (AW/UI → induced magnetosphere)</i>	- <i>Along magnetopause ?</i>
$ \mathbf{B} \uparrow$	\downarrow	No B	Jupiter – Io, Europa (AW/UI) <i>Magnetized star – Unmagnetized hot Jupiter (AW/UI)</i> <i>Pulsar – planet (AW/UI)</i>	At Io and Europa - flux tube footprints <i>At star-planet flux tube footprints</i> <i>In Alfvén wing → Fast Radio Bursts ?</i>
No B		B	Particle precipitations into cusp (low energy)	-
No B		No B	Plasma wake	-

^a Flow magnetic field $|\mathbf{B}|$: \uparrow =strong, \downarrow =weak (the solar wind is weakly magnetized). ^b M_A : \uparrow =super-Alfvénic, \downarrow =sub-Alfvénic. ^c Cyclotron Maser Instability. ^d AW = Alfvén Wings, UI = Unipolar Inductor.

Dissipated power

Zarka (2007) proposed that the electromagnetic power P_d dissipated in all known flow-obstacle interactions can be expressed as:

$$P_d = \varepsilon (V_{\text{flow}} B_{\perp}^2 / \mu_0) \pi R_{\text{obs}}^2 \quad (1)$$

with B_{\perp} the flow's magnetic field component perpendicular to the flow direction in the obstacle's frame. Equation (1) is thus simply the fraction ε of the Poynting flux (or magnetic energy flux) $V_{\text{flow}} B_{\perp}^2 / \mu_0$ convected on the obstacle of cross-section πR_{obs}^2 . This expression, and the variation as a function of the distance to the Sun of B_{\perp} in the frame of a planet in Keplerian orbit, allowed Zarka et al (2001) and Zarka (2007) to identify a corridor at ~ 0.17 AU where the flow and the magnetic field are nearly aligned with each other and thus no or very little Poynting flux is generated in the interaction. This corridor should exist in all stellar winds near 0.1 – 0.3 AU (Saur et al 2013).

Theoretical considerations suggest that the efficiency of the dissipation ε is comprised between M_A (in the sub-Alfvénic case) and 1 (Zarka et al 2001; Zarka 2007). Measured efficiencies for the Earth's magnetosphere and satellite-Jupiter interactions are $\varepsilon = 0.2 \pm 0.1$. Electromagnetic signatures of flow-obstacle interactions cannot exceed a small fraction of P_d , estimated to 5-25% in the UV and 1-5% in the radio domain (see below and Zarka 2007). As a consequence, observed signatures can help to put constraints on the power dissipated in an interaction.

Zarka (2006, 2007) noted for example that in the case of HD 179949, the system for which the first optical evidence of a star-planet interaction was detected by Shkolnik et al (2003, 2004), the demands put on the dissipated power by the energetics of the optical signature suggests a stellar magnetic field 30–100 times stronger than the solar one, a wind strength much larger than the Sun's, an obstacle size much larger than πR_J^2 (extended magnetosphere or exo-ionosphere), or a combination of these factors. This conclusion is supported by Saur et al (2013), who computed analytically the magnetic energy fluxes dissipated in sub-Alfvénic interactions. These authors reach consistent – albeit more detailed – conclusions as those drawn from equation (1), with dissipated energy fluxes $\geq 10^{19}$ W in star – planet interactions (to be compared with $\sim 10^{12}$ W per hemisphere in the Io-Jupiter case). These conclusions must be compared to the measurement of the stellar magnetic field by Fares et al (2012) giving a value of a few Gauss.

The topology of sub-Alfvénic star – planet magnetic interactions has been studied via MHD simulation, focussing on close-in exoplanets (Ip et al 2004 ; Strugarek et al 2014, 2015). For the super-Alfvénic case, dissipated magnetic energy fluxes have been computed for the solar wind – Mercury interaction by Varela et al (2016) in order to make predictions on radio emissions from Mercury.

Radio signatures

From Table 1 it appears clearly that the existence of a strong magnetic field in the flow, the

obstacle or both, together with that of accelerated electrons, lead to the generation of intense radio emission from the system. This is systematically verified in the solar system. This can be understood considering that the most efficient and ubiquitous mechanism for generating magnetospheric (auroral and satellite-planet) radio emissions is the Cyclotron Maser Instability (CMI – Zarka 1998). The CMI is a wave-particle instability that directly converts the perpendicular energy of electrons gyrating in a large-scale magnetic field into electromagnetic (radio) energy (Wu and Lee 1979). It has been demonstrated that up to a few percent of the electrons’ energy can be converted into radio waves, if three conditions are met: the presence of a strong magnetic field, of accelerated electrons with keV (or tens of keV) energies, and a relatively depleted and strongly magnetized plasma at the source (quantified by $f_{pe}/f_{ce} \ll 1$, with f_{pe} the plasma frequency and f_{ce} the electron cyclotron frequency in the source). CMI radio emission is strongly circularly polarized, very anisotropic, and produced at frequencies $f \sim f_{ce}$ in the source. As f_{ce} varies continuously along magnetic field lines, a broadband continuum emission is expected (below a few tens of MHz for Jupiter’s radio emissions, and ≤ 1 MHz for other planetary radio emissions in the solar system (Zarka 1998)). The CMI is by far the most efficient radio emission mechanism, and it dominates all other emissions (beam-plasma instabilities and others) when the conditions at the source are met. This is why the auroral radio emissions of solar system planets – especially that of Jupiter – are as bright as Solar radio bursts (that are mostly not produced by the CMI due to $f_{pe}/f_{ce} > 1$ in the solar corona except at specific locations, e.g. at footprints of strong magnetic loops – Morosan et al 2016).

Energetics of radio signatures

In order to predict emitted radio powers or flux densities, it is necessary to estimate the fraction of the dissipated power that goes into electron acceleration. This was first done via comparison, in the solar system, of emitted radio powers to electromagnetic power involved in the corresponding flow-obstacle interactions (Zarka et al 2001; Zarka 2007). It was found that in all cases the emitted radio power P_r follows the relation:

$$P_r = \beta (V_{\text{flow}} B_{\perp}^2 / \mu_0) \pi R_{\text{obs}}^2 = \beta P_d / \varepsilon \quad (2)$$

with an efficiency factor $\beta = 2 \cdot 10^{-3}$. Taking the conservative values $\beta = 2 \times 10^{-3}$ and $\varepsilon = 0.2$, this implies that a large fraction of the dissipated energy goes into electron acceleration, and $\sim 1\%$ of the electrons’ energy then goes into radio waves (this number 1% is the canonical value used in all theoretical predictions). This radio-magnetic scaling law was found to apply to all solar system auroral or satellite-Jupiter radio emissions. It is illustrated in Fig. 1.

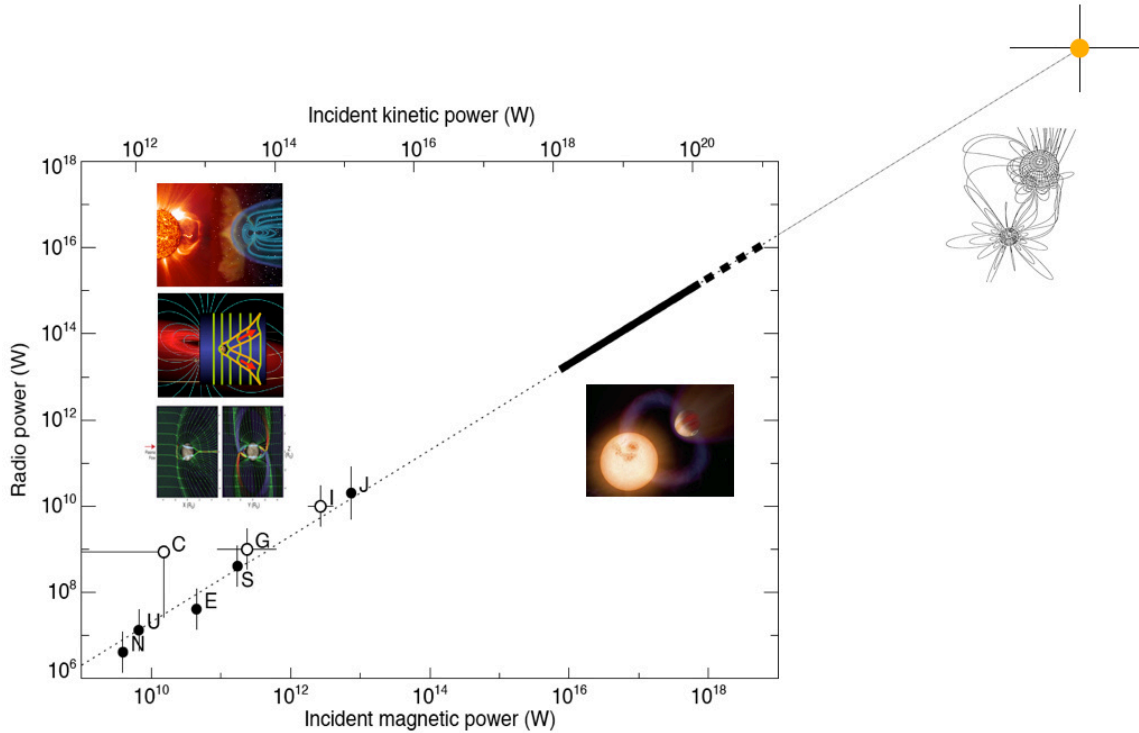


Fig. 1 Radio-magnetic scaling law relating magnetospheric (E,J,S,U,N = Earth, Jupiter, Saturn, Uranus and Neptune) and satellite-induced (I,G,C = Io, Ganymede, Callisto) radio power to incident Poynting flux of the plasma flow on the obstacle. Dashed line has slope 1, emphasizing the proportionality between ordinates and abscissae, with a coefficient 2×10^{-3} . The thick bar extrapolates to hot Jupiters the magnetospheric interaction (solid) and satellite-planet electrodynamic interactions (dashed). The orange dot illustrates the case of the RS CVn magnetic binary V711 Tauri discussed in the text. Inset sketch the types of interaction (solar wind-magnetosphere, Jupiter-Io, Jupiter-Ganymede).

Several theoretical works attempted to explore the causes and efficiency of the conversion of the incident magnetic energy flux into the energy of accelerated electrons. Jardine and Cameron (2008) proposed that runaway electrons are accelerated by the electric field resulting from magnetic reconnection at the flow-obstacle interaction, but this does not seem to be a significant process for generating solar system radio emissions. Nichols (2011) and Nichols and Milan (2016) studied the magnetosphere-ionosphere coupling in Jupiter-like and Earth-like magnetospheres. Magnetosphere-ionosphere coupling can be qualitatively understood as a limiting case of flow-obstacle interaction where the obstacle is the inertia of the plasma that resists displacement along with planetary magnetic field lines. As a consequence, magnetic field-aligned-currents arise to communicate the torque between the magnetosphere and the ionosphere. These currents are generally larger than that which can be carried by unaccelerated magnetospheric electrons, so that field-aligned potential drops appear, that cause electron acceleration to keV energies, and ultimately radio emissions. These processes are suspected to play a role in the generation of radio emission from cool dwarf stars, via the coupling of the stellar magnetic field with its plasma environment (Hallinan et al 2015).

For Jupiter-like, rotation driven dynamics, Nichols (2011) found that the radio output can reach 10^{16} W for fast rotating magnetospheres of strongly magnetized planets orbiting at a few AU from their parent star, with a strong stellar X-UV luminosity being a favourable factor maximising the magnetosphere-ionosphere coupling. For Earth-like, convection driven dynamics (magnetospheric convection results from dayside and nightside reconnections between the planetary magnetic field and the solar wind one), Nichols and Milan (2016) found that the radio output can reach 10^{15} W for close in exoplanets, somewhat smaller than that predicted by the radio-magnetic scaling law due to possible saturation of the convection that prevents to dissipate the full available incident Poynting flux.

To test the extrapolation of the radio-magnetic scaling law toward high Poynting fluxes and high radio powers, Zarka (2010) analysed the literature on radio emission from magnetized binary stars. They found that for the RS CVn stellar system V711 Tauri, measured radio flux densities (0.1-1 Jy - Budding 1998; Richards et al 2003) and distance (29 pc), and estimated magnetic fields (10–30 G at the interaction region) and bandwidth (≥ 8 GHz) allow to estimate that $10^{-4} \leq \beta \leq 10^{-2}$ (see the detailed calculation in (Mottez and Zarka 2014)). This good agreement with the solar system value of β ($\sim 2 \times 10^{-3}$) suggests that the radio-magnetic scaling law holds – at least approximately – for 10 orders of magnitude above the range of solar system planets.

Interpreting radio signatures

CMI radio emissions are expected to occur in the spectral range below a few tens of MHz, unless exoplanets much more strongly magnetized than Jupiter exist. For close in exoplanets, that are probably spin-orbit locked, the relatively long rotation period (equal to the orbital period) may lead to a decay of the planetary dynamo and thus of the magnetic field (Sanchez-Lavega 2004; Reiners and Christensen 2010). But some of the star-planet interactions described in Table 1 may lead to radio emissions at star-planet flux tube footprints, i.e. at cyclotron frequencies governed by the stellar magnetic field. These emissions might reach hundreds of MHz or more.

At these frequencies, the angular resolution of a few milli-arcseconds that would be necessary to separate the radio emission of an exoplanet from that of its parent star will not be available in the foreseeable future. Emission will thus be detected in dynamic spectra, i.e. measurements of the intensity and polarization as a function of time and frequency. With these data, discrimination between the stellar (coronal) and exoplanetary or exoplanet-induced CMI radio emissions can be done via the presence of circular polarization and the modulation at the exoplanet's orbital period.

As the CMI theory provides today a well-understood, quantitative framework for understanding radio emissions properties, the measurement of the radio intensity and polarization as a function of time and frequency will provide powerful diagnostics of the plasma environments and processes at work in star-planet interactions. Simulations by (Hess and Zarka 2011), well tested on Jupiter's radio emissions (Hess et al 2008), have shown that such measurements will give access to the type of interaction at work (exoplanet's auroral emission or exoplanet-induced emission in the stellar field), its

energetics, the exoplanet's magnetic field intensity and tilt (if emission comes from the exoplanet's magnetosphere), the planetary rotation and revolution periods (effectively testing tidal spin-orbit synchronization), and the orbit inclination (resolving the ambiguity on the planet's mass). Fig. 2 illustrates how these parameters can be deduced from the observed dynamic spectra. Temporal modulations different from the planetary rotation and orbital periods could additionally reveal the presence of moons or the signature of the stellar wind activity. Most of these parameters, especially those concerning the exoplanet's magnetic field and thus its interior structure, are very difficult or impossible to determine by other means than radio measurements.

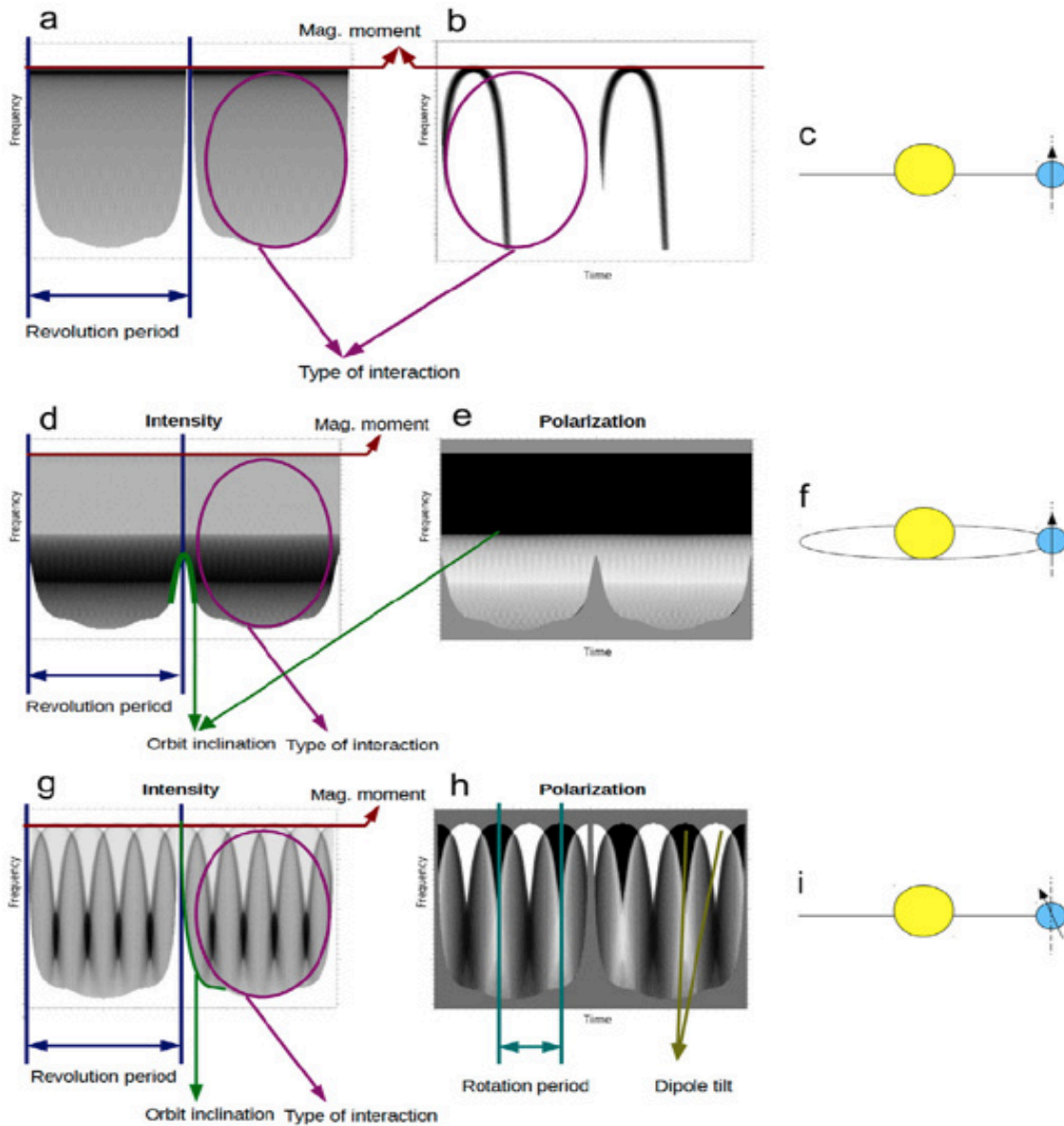


Fig. 2 Simulated dynamic spectra in intensity (a,b,d,g) and circular polarization (e,h) and associated parameters of the system that can be determined: (a,b,c) exoplanetary magnetic field aligned with the rotation axis and 0° orbit inclination, for emission (a) of a full exoplanet's auroral oval and (b)

an auroral active sector fixed in local time. (d,e,f) aligned exoplanetary magnetic field and 15° orbit inclination, for emission of a full auroral oval. (g,h,i) exoplanetary magnetic field tilted by 15° and 0° orbit inclination, for emission of a full auroral oval. From (Hess and Zarka 2011).

It can be noted that the existence of an exoplanet's magnetosphere is an essential ingredient in favour of the possibility to develop life: it ensures shielding of the planet's atmosphere and surface, preventing O_3 destruction by cosmic rays bombardment as well as atmospheric erosion by the stellar wind or CMEs; it also limits atmospheric escape, as ionized material following dipolar field lines returns to the atmosphere (Grießmeier et al 2004, 2005). Radio detection may eventually evolve as an independent discovery tool, complementary to radial velocities or transit measurements because it is more adapted to finding planets (giant or terrestrial) around and interacting with active, magnetic or variable stars.

Conclusion

Star-planet plasma interactions are expected to be common and diverse examples of flow-obstacle interactions. The proposed radio-magnetic scaling law summarized by equations (1) and (2) is likely to be an approximation, and various works suggest that deviations of one order of magnitude (up to two in extreme cases) are expected (Nichols 2011; Nichols and Milan 2016; Saur et al 2013). Conversely, the recent detection and study of the energetics of the Ganymede-Jupiter radio emission is fully compatible with this scaling law (Zarka et al 2017). And at least one case of magnetized binary stars interaction suggests that the scaling law still applies over ≥ 10 orders of magnitude above the range of solar system planets, and can thus be used for predicting radio flux densities from exoplanets and star-planet interacting systems. As a result, radio emissions up to 10^{5-6} times more intense than Jupiter's may exist, especially in hot Jupiter systems. Even if hot Jupiters are weakly or not magnetized due to slow sidereal rotation, the possibility of an interaction with a strongly magnetized parent star via Alfvén waves (Alfvén Wings or UI interaction) offers serious perspectives for radio detection, at frequencies up to hundreds of MHz, larger than those expected for magnetospheric emissions (\leq tens of MHz). Clearly the measurement of stellar magnetic fields via Zeeman Doppler spectropolarimetry (e.g. Donati et al 2006) is a crucial information for selecting candidates for radio emission.

Radio emissions 10^{3-4} times stronger than Jupiter's should be detectable at stellar distances (pc to tens of pc) with existing large low-frequency radiotelescopes (UTR-2 in Ukraine, LOFAR in Europe, NenuFAR in France), and SKA will make detection possible for emissions 10^{1-2} times stronger than Jupiter's (Zarka et al 2015). SKA will perform large surveys, and the observing parameters adapted to the radio detection of exoplanets and star-planet interactions are also adapted to the study of stellar coronal bursts or CMI emission from cool stars.

Based on the spatial in-situ exploration of planetary magnetospheres in our solar system, a reliable interpretation frame is ready (Hess and Zarka 2011), waiting for the first unambiguous detection, that has not occurred yet although tentative detections have been made (see Zarka et al 2015 and references therein). Unless most interacting star-exoplanet

systems are on the (very) low side of the radio-magnetic scaling law, radio detections should occur in the coming years. Those will open the new field of comparative exomagnetospheric physics and allow to probe flow-obstacle interactions in various regimes and over a large range of parameters (star-planet distance, stellar magnetic field and wind strength, stellar X-UV flux, planetary magnetic field, rotation, orbit inclination...). Measured radio fluxes should allow us to infer the energy dissipation involved in the corresponding star-planet interactions, and thus to confirm or refine the radio-magnetic scaling law.

Cross-references

The following chapters in the handbook are closely related to the present one.

- | | |
|--|-----------------------------|
| • Magnetic environment of the planets | Michel Blanc |
| • Radio observations as an exoplanet discovery method | Joseph Lazio |
| • Signatures of star-planet interactions | Evgenya Shkolnik + Joe Lama |
| • Magnetic fields in planet hosting stars | Claire Moutou |
| • The impact of stellar activity on the detection and characterization of exoplanets | Andrew Collier Cameron |
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One may also look at:

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| • <i>Planet and Star Interactions: Introduction</i> | <i>Antonino F. Lanza</i> |
| • <i>Radio emission from ultracool dwarfs</i> | <i>Peter K.G. Williams</i> |
| • <i>Stellar coronal and wind models: impact on exoplanets</i> | <i>Aline Vidotto</i> |

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