Modelling Exoplanetary Radio Emissions Using a Realistic Magnetic Field Geometry

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Abstract. To date, there have been no exoplanetary radio emission detections. Efforts at studying radio emission are necessarily confined to the solar system planets and numerical simulations. Radio emission models typically assume a stellar surface magnetic field strength and extrapolate this out to the planet in an isotropic manor. However, this ignores variations in the magnetic field strength and geometry. We explore how a realistic field geometry affects the radio emission one might expect from an exoplanet and the time dependent variations this can induce.

1. Introduction

The process of exoplanetary radio emission is an example of an interaction between an exoplanet and its host star. The stellar wind carries magnetic energy from the stellar magnetosphere into the planetary magnetosphere, in the form of a poynting flux, where it is deposited into the local plasma. The energised electrons will then radiate some of their excess energy away as radio emission. Therefore, to understand exoplanetary radio emission, there are three parts of the star-planet system that must be understood. These are the properties of the host star magnetic field, the interplanetary wind and the magnetic field of the exoplanet.

To date, no positive detections of radio emissions originating from planets outside of our solar system have been made. Studies of exoplanetary radio emission have therefore been largely theoretical in nature. The vast majority of these studies have treated the system as steady and isotropic, which ignores the variability that we see at the solar system planets (Lazio et al. 2004; Zarka 2007; Grießmeier et al. 2007; Jardine & Collier Cameron 2008). In these proceedings, I will focus on the stellar magnetic field aspect of the system and look at the timescales over which we could expect exoplanetary radio variability.

2. Magnetic modelling

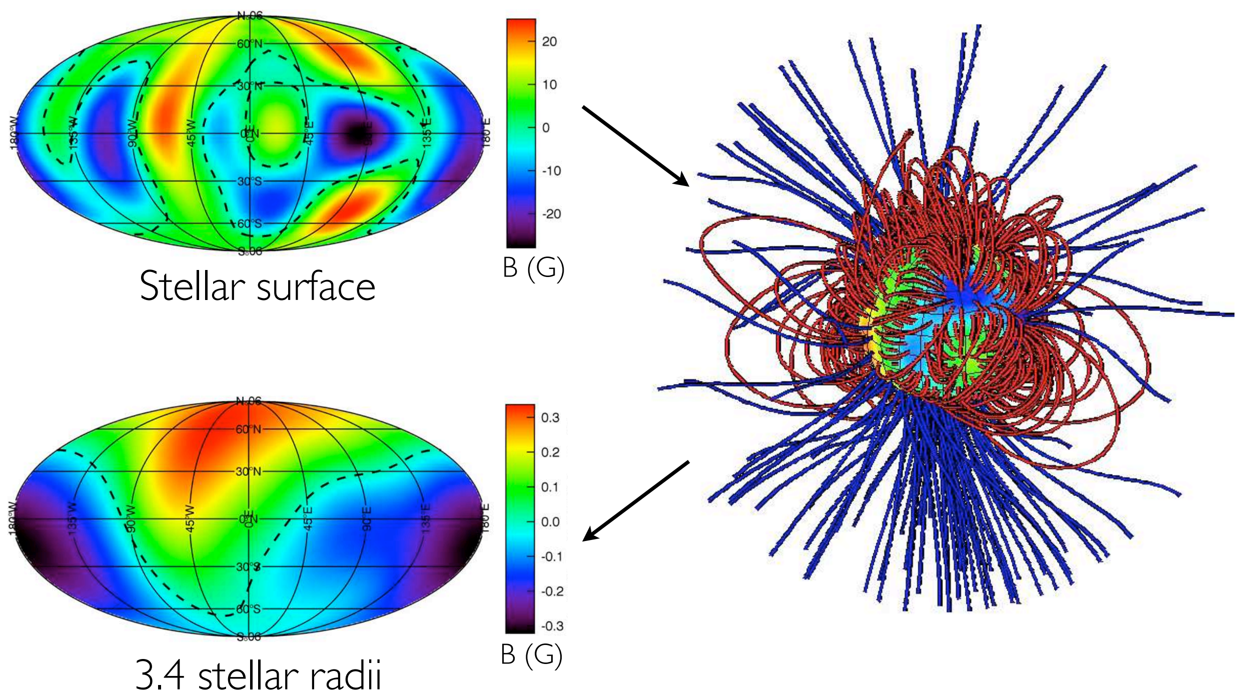

Figure .1: The magnetic structure of HD 189733 during June 2008. Top left: Magnetic map of the surface of HD 189733 obtained via Zeeman-Doppler Imaging. Dashed lines indicate polarity inversion lines. Right: A three dimensional field extrapolation using the potential field source surface model. Blue lines are open field lines, along which, the stellar wind flows. Red lines are closed field lines which hold hot coronal material. Bottom left: Magnetic map at the source surface of the star. The field here is predominantly dipolar since higher order modes decay more rapidly with height from the stellar surface.

Using the technique known as Zeeman-Doppler Imaging (ZDI) (Donati & Brown 1997), it is possible to reconstruct stellar magnetic field maps. An example of such a map, for the star HD 189733 during June 2008, is shown in the top left of figure .1. With ZDI maps as an inner boundary condition, it is possible to extrapolate the surface magnetic field upwards into the corona of the star using a potential field source surface (PFSS) (Altschuler & Newkirk 1969) model (right of figure .1). The PFSS model imposes that, at a distance from the stellar surface known as the source surface, the magnetic field lines must become purely radial. This mimics the action of the stellar wind which blows open closed field lines. The source surface is set to 3.4 stellar radii in our models. The magnetic field geometry at

Table .1: Parameters for the HD 189733 and τ Boo systems. All values referenced from Fares et al. (2013) with the exception of P_{syn} (calculated) and d, which is taken from Fares et al. (2010) for HD 189733 and from Grießmeier et al. (2007) for τ Boo.

Star	$M_\star$	$r_\star$	r_{orb}	P_{rot}	P_{orb}	P_{syn}	d
	$[M_\odot]$	$[r_\odot]$	[AU]	[days]	[days]	[days]	[pc]
HD 189773	0.82	0.76	0.031	12.5	2.22	2.70	19.3
τ Boo	1.34	1.42	0.048	3.31	3.31	∞	15.6

the source surface for HD 189733 can be seen in the bottom left figure .1. There is a lot of structure in the magnetic field at the surface of the star but by the source surface, the geometry is dominated by the dipole component of the field as higher order modes decay more quickly with height from the surface. Above the source surface, the structure of the magnetic field will not change since it is purely radial. We note that, in our simulations, the exoplanets orbit at a greater distance than the source surface.

As an exoplanet orbits through the stellar magnetic field structure, the local stellar magnetic field strength in the vicinity of the planet will vary. This changing poynting flux into the planetary magnetosphere will cause the radio emission to vary as well. Over many orbits, we would expect the planetary radio signal to vary periodically. Naively, one might expect the periodicity to be on the timescale of the orbital period. However, the stellar rotation must be accounted for. Therefore, the true timescale for periodicity would be the synodic period of the system.

3. Results

In this set of proceedings we focus on the HD 189733 and τ Boo systems. Parameters for these systems can be found in table .1. The orbital period of HD 189733b is shorter than the rotational period of its host star. As such, the synodic period of the system is not much longer than the planetary orbital period. On the other hand, τ Boo b is tidally locked to the rotation period of τ Boo leading to an infinitely long synodic period.

For HD 189733, we have access to two ZDI maps made a year apart (Fares et al. 2010). In figure .2 we show the magnetic field structure at the source surface of the star during each epoch (top row). Additionally, we show the corresponding, local stellar magnetic field strength along the orbit of the planet and the predicted planetary radio flux density we would receive at earth as a function of synodic phase (bottom row). The plots have been laid out such that the synodic phase matches the equatorial longitude of the source surface maps above.

We see that the predicted radio emission correlates strongly with the local stellar magnetic field as expected. During both epochs, there is a large degree of variability with the radio emission dropping to zero several times per synodic period. This occurs as the planet is passing over a polarity inversion line which is where we would expect the magnetic cusps to lie. Lastly, we also see that the magnetic field itself has evolved between the two sets of observations due to dynamo action.

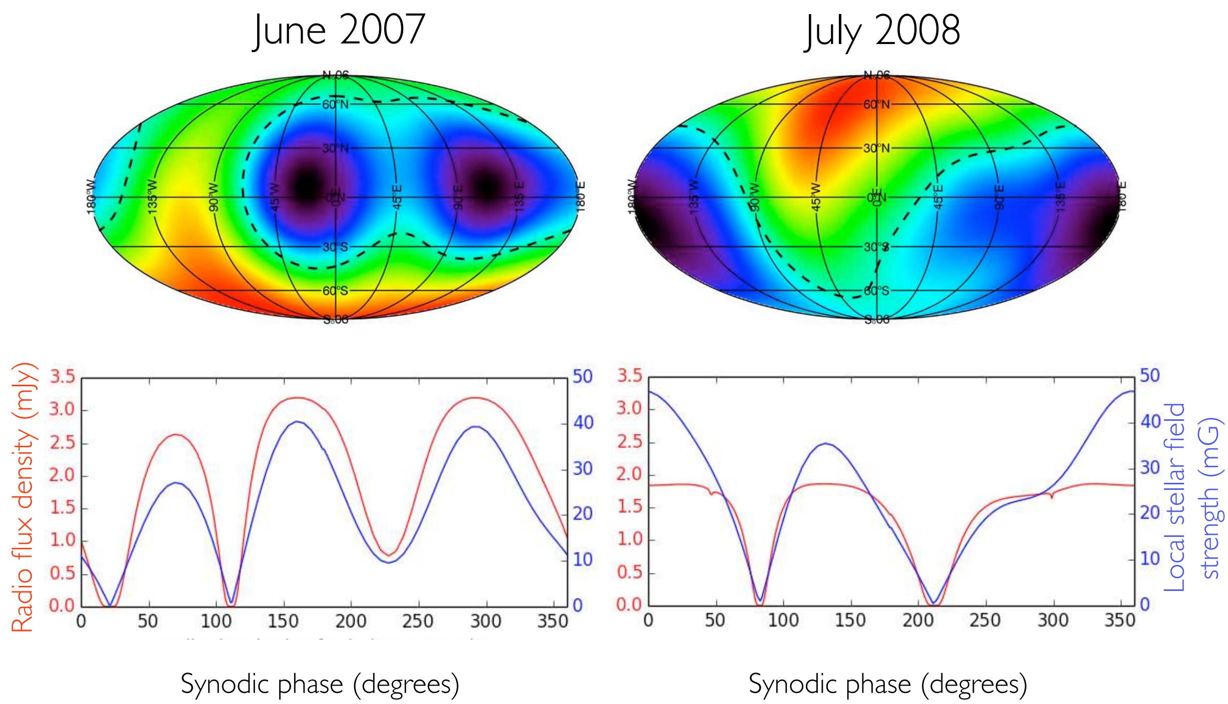

Figure .2: Top row: Magnetic field structure of HD 189733 at the source surface during June 2007 and July 2008. Bottom row: the local stellar magnetic field strength along the orbit of HD 189733 b (blue) and the predicted exoplanetary radio emission flux (red) as a function of synodic phase. The synodic phase plots are aligned with the stellar longitude at the equator of the magnetic maps above them.

For τ Boo, we have access to five ZDI maps across several years (Donati et al. 2008; Fares et al. 2009, 2013). In figure .3 we show the magnetic field structure at the source surface and the corresponding predicted radio emission curves are shown in figure .4. These curves show the same variability that was evident at HD 189733. However, since the system is tidally locked, the planet is orbiting over one fixed stellar longitude (at 180° on the plots in figure .4). As such, it is co-rotating with the stellar magnetosphere. Radio emission variability is still expected from τ Boo b which can be seen from the changing emission values between epochs, indicated with red points at 180° in figure .4. However, the cause of this variability is different. At HD 189733, we saw variability, on the order of days, due to planetary motion through a changing field structure. However, variability at τ Boo is caused by dynamo driven evolution of the stellar magnetic field itself and would have a timescale on the order of months. Dynamo driven variability is also seen at HD 189733 but is not the dominant source of variability there.

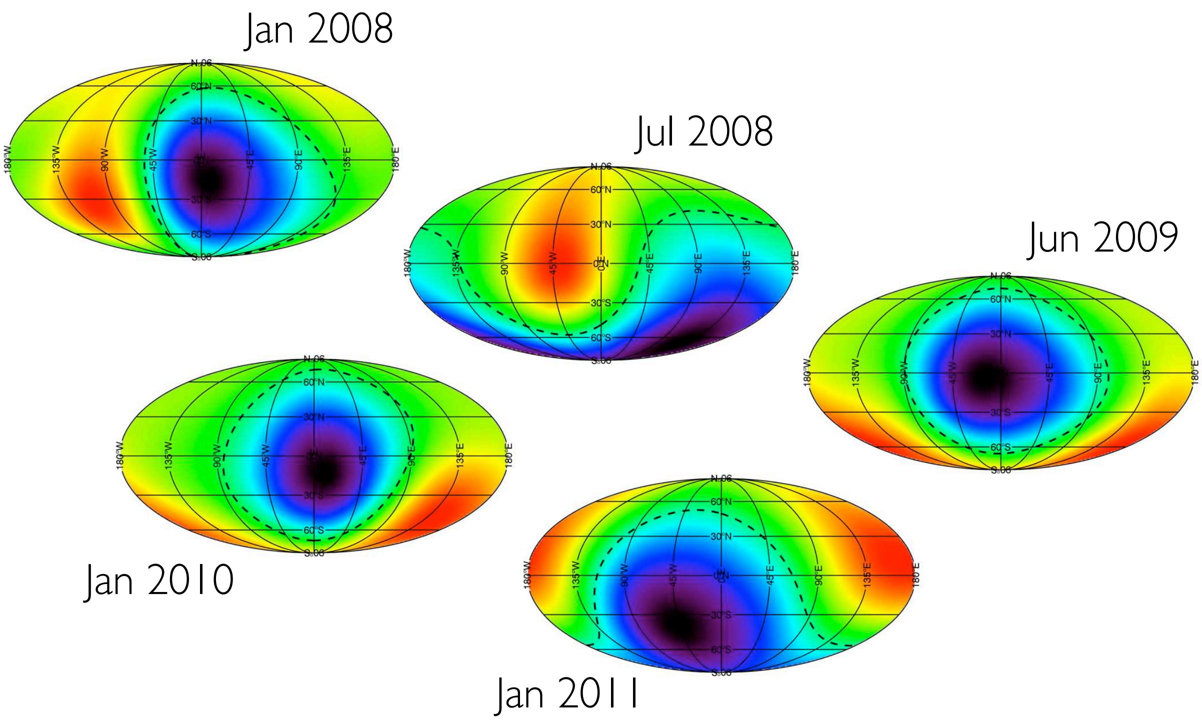

Figure .3: Magnetic field structure at the source surface of τ Boo during five different epochs. Predicted radio fluxes can be found in figure .4.

4. Conclusions

Exoplanetary radio emission is expected to be a strong function of the local stellar magnetic field strength in the vicinity of the planet. We have looked at how using a realistic stellar magnetic field geometry affects the variability of exoplanetary radio emission. We find that variability can occur on several timescales. The first is on the order of days as the planet orbits through the stellar magnetic field structure. The second is on the order of months as the stellar magnetic field itself evolves due to dynamo action.

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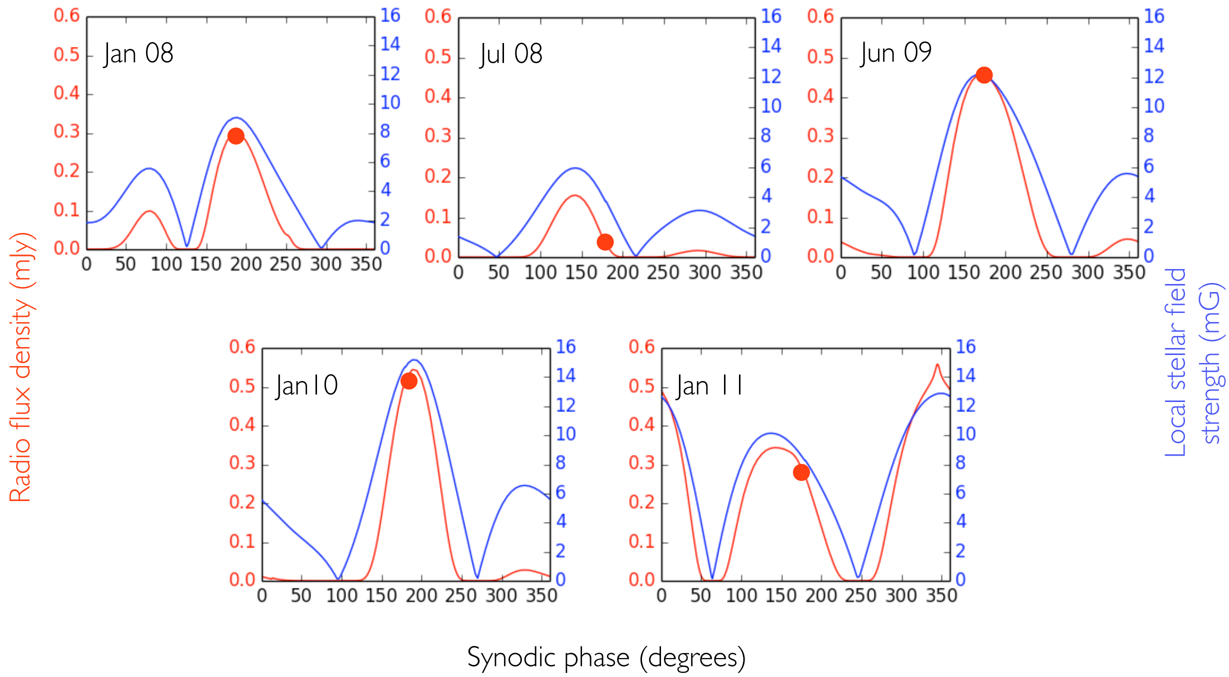

Figure .4: Local stellar magnetic field strength along the orbit of τ Boo (blue) and the predicted exoplanetary radio emission flux (red) as a function of synodic phase during five different epochs. The corresponding magnetic maps at the source surface can be found in figure .3.

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(L to R) Jake Turner, Raphaëlle Haywood, Neil Cooke, Joe Llama, Lil' Brown Dwarf, Victor See, Gordon Gibb watching sunset at the conference dinner.