EWASS Special Session 4 (2017): Star-planet interactions
Edited by Emeline Bolmont & Sergi Blanco-Cuaresma
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Auroral radio emission from low-mass stars

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Abstract

It is now a well-established fact that also very low mass stars harbor planetary systems. These stars represent the large majority of our nearby stars but, despite their proximity, their low optical luminosity makes it difficult to apply the usual methods for exoplanet search. An effective probe for the environment of these stars is the auroral radio emission. This kind of emission is well understood for those stars whose magnetic field can be approximated as a dipole. In these cases the radio emission has a peculiar signature in time and in polarization. The presence of a planet nearby the star triggers or perturbs this emission leading to a predictable modulation. We present the case study of the ultra-cool dwarf TVLM 513-46546, for which we take advantage of VLA observations at 4.9 and 8.4 GHz. We reproduce the cyclic circularly-polarized pulses of the star using a 3D model of the auroral radio emission from the stellar magnetosphere. To take into account the possible deviation from the dipolar symmetry, the model simulates a magnetosphere shaped like an offset-dipole. To reproduce the timing and pattern of the observed pulses we explored the space of parameters controlling the auroral beaming pattern and the magnetosphere geometry. Our model explains the observed anomalies of the radio emission at 8.4 GHz as a possible interaction of the star with an external body, like in the case of the interaction between Jupiter and Io.

1 Introduction

Low-mass stars are becoming a very promising target for exoplanet search and many planetary systems have been found around red and brown dwarfs. These discoveries are going to be crucial for the entire exoplanet science because these stars represent the large majority of nearby stars and, since they are characterized by a very long life, there is plenty of time for favorable life conditions to develop. In particular, planetary systems have been successfully detected around the so-called ultra-cool dwarf stars, stars with an effective temperature below 2700 K. A recent remarkable example is the discovery of seven planets around Trappist-1 (M8; Gillon *et al.* 2017).

One of the main difficulties when studying this class of stars is that they are intrinsically faint, since their temperature is usually less than 3000 K and their radius is typically around 0.1 $R_\odot$. This makes it difficult to apply the usual methods for planet search, like transits and radial velocities, which benefit from bright stars. Furthermore, in general, each method for exoplanet search supplies only partial information on the planetary systems, so the introduction of other complementary methods can be extremely important. In this scenario, a great help can be provided by radio observations. In fact, the star-planet magnetic interaction is responsible for a characteristic radio emission that can be observed with current and future radio observatories.

The first observations of radio emission from planets concerned our solar system. Radio emission at very low frequency (from tens of kilohertz to tens of megahertz) and variable in time has been detected from all the magnetized bodies of the solar system (Zarka, 2014). Many different mechanisms concur to explain this emission. The one that gives rise to the most intense emission is usually the so-called cyclotron maser instability. This phenomenon takes place when the magnetosphere of the planet is perturbed, for example by the solar wind. In this case, electrons can be accelerated in the magneto-tail, mainly because of magnetic reconnection, and migrate toward the magnetic poles following the field lines in spiral trajectories. Once in proximity of the star they can be reflected by magnetic mirroring and emit at about the local cyclotron frequency (Melrose & Dulk, 1982). Beside the accelerated electrons interacting with the magnetic field, this phenomenon requires that the electron energy distribution is inverted. This inversion can be developed in several ways, like pitch angle anisotropy and horseshoe distribution (Wu & Lee 1979; Winglee & Pritchett 1986). The emission generated by this phenomenon is usually referred to as the auroral radio emission (ARE), since it originates close to the magnetic poles. The typical frequency of the ARE is proportional to the local magnetic field, so planets with more intense magnetic fields are characterized by a radio emission at higher frequencies. The ARE is a coherent emission, characterized by a circular polarization, time variability and strong directivity.

It is reasonable to suppose that the ARE can take place also in magnetized exoplanets. However such a kind of detection is hard because the expected flux density is predicted to be ~ 1 μJy even for nearby planetary systems and the typical frequencies are below 100 MHz (Zarka, 2007), a band where current instrument cannot reach the necessary sensitivity. Despite that, observing campaigns have been conducted with LOFAR and a great improvement is expected once SKA-LOW becomes operative. But there is another way to exploit the ARE to detect and characterize exoplanets, since the ARE can be observed not only in planets but also in stars. Here the ARE is caused by the interaction of the stellar magne-

Table 1: Stellar parameters of TVLM 513-46546 (Leto *et al.*, 2017).

Stellar radius	0.103 $R_\odot$
Rotation period	1.96 h
Rotation axis inclination	70°
Polar magnetic field intensity	3 kG

tosphere with the stellar wind or with orbiting planets that act as inductors. The advantage of study the stellar ARE is that, being stellar magnetic fields more intense than planetary ones, the ARE can be observed at higher frequencies. And in fact, the ARE have been already observed in magnetic chemically peculiar (MCP; e.g. Trigilio *et al.* 2000) and in ultra-cool dwarf (UCD; e.g. Berger 2002) stars. The fundamental emission mechanism is the same as for the solar system planets.

The ARE is therefore a powerful tool for studying planetary systems, both searching directly for planetary ARE or looking for planetary signature in stellar ARE. In this case we expect in fact a typical predictable modulation in stellar ARE. The radio flux densities expected and the relative frequencies for this phenomenon strongly depend on the magnetic field intensity and on the distance between the star and the planets. So estimates can vary greatly from ~ 1 μJy to ~ 10 mJy. The phenomenon would be observable at frequencies up to few GHz, a range more easily to observe.

In the following sections we present some interesting results that we obtained about the star-planet magnetic interaction in the case of the UCD star TVLM 513-46546 (Leto *et al.*, 2017). In particular, in Section 2 we recall the past observations and we use the model presented in Leto *et al.* (2016) to reproduce the radio emission. In Section 3 we discuss the possible presence of a close-in planet around it. Summary and conclusions are reported in Section 4.

2 Radio emission of TVLM 513-46546

TVLM 513-46546 is a well-known radio-emitting UCD star, with spectral type M8.5. Located at about 10 pc from us it is a fast rotator, being characterized by a very short rotation period of less than 2 hours (Wolszczan & Route, 2014). Other important parameters are reported in Table 1.

In 2006 the star was observed with the Very Large Array at 4.9 ad 8.4 GHz for a total amount of 19.5 hours, covering for each frequency about five rotational periods (Hallinan *et al.*, 2007). The data taken at this epoch are extremely useful for our analysis because the star passed through a stable active phase, showing radio pulses at every rotation period. In Figure 1 we report the Stokes-V light curves at the two observed frequencies. Starting from these observations, we re-analyzed the data to reproduce the observed light curve (both in Stokes I and V) and understand its peculiarities.

To achieve this goal we took advantage of the emission model that we developed for MCP stars (Leto *et al.*, 2016), which was able to succesfully reproduce the main observing features of the ARE pulses of the MCP star CU Vir (Trigilio *et al.*, 2008, 2011). MCP stars are a unique laboratory to study the ARE since they present a very stable radio emission modulated only by geometrical effects. The ARE is in fact strongly directive and the time variability of the radio emission can be simply explained with a lighthouse effect (oblique rotator model; Babcock 1949). Though MCP stars are somehow very different from UCDs, being hot late B or A stars, both classes are characterized by a similar large-scale dipolar magnetic field topology and the same geometrical consideration can be applied. To model the radio emission of TVLM 513-46546 we simulated about 25 000 light curves varying the geometrical parameters as the tilt angle between the rotation and magnetic axes, the beaming angle, the deflection angle (intrinsic to the elementary emission mechanism or due to refraction) and the dimension of the magnetosphere (Figure 2). The main result was that there is not a set of parameters that simultaneously reproduces the light curves at the two observed frequencies.

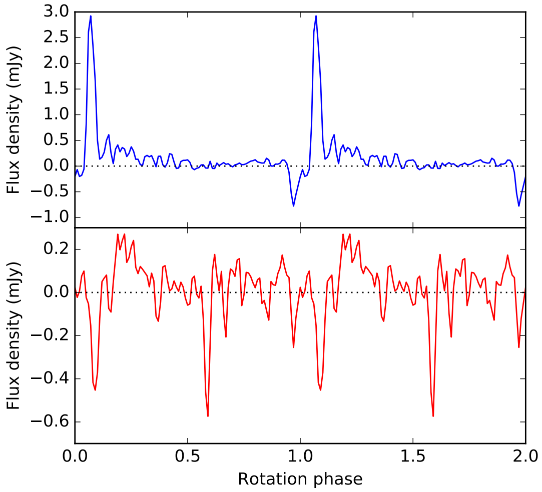

Figure 1: phase-folded Stokes-V flux density at 4.9 (bottom panel) and 8.4 GHz (top panel). Two complete stellar rotations are shown.

The next step was therefore to refine the model of the stellar magnetosphere. For fast-rotating fully convective low-mass stars 3D magnetohydrodynamic models suggest that the magnetic-field topology can be described as a large-scale dipolar field and a small scale toroidal field (Yadav *et al.*, 2015; Morin *et al.*, 2010). To take into account this more complicated topology we simulated an off-axis dipolar magnetic field by allowing a shift of the magnetic dipole along all the three axes. Such a kind of approximation was widely used to reproduce complex magnetic fields of some hot magnetic stars (Oksala *et al.*, 2012, 2015).

Even with this more complicated model we were not able to find a common geometry reproducing both the light curves. The first anomaly is that the peak emission shows a phase lag between the two frequencies. This however can be easily explained with the deflection of the emission due to refraction (e.g. Trigilio *et al.* 2008). The second anomaly is that the pulses at 4.9 GHz show only left-hand circular polarization, while the pulses 8.4 GHz show both left- and right-hand. This suggests that the radio emission at the two observed frequencies takes place in two different auroral cavities, one corresponding to a large-scale dipolar field (4.9-GHz pulses) and the other to a small-scale toroidal field (8.4-GHz pulses). The third anomaly is that if we suppose that the emission at the two frequencies originates from different magnetic field

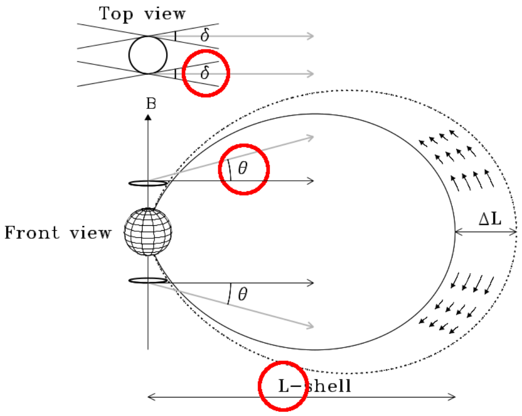

Figure 2: magnetosphere parameters varied in the simulation, δ is the beaming angle, θ is the deflection angle (due to refraction), L is related to the dimension of the magnetosphere. The other parameter is the tilt angle between the rotation and magnetic axes, not shown in this picture. (Adapted from Leto *et al.* 2017)

geometries, we can fully reproduce the light curve at 4.9 GHz but only partially that at 8.4 GHz.

3 A planet to explain light curve anomalies

The main feature of the light curve that cannot be explained by our model is the fact that the emission at 8.4 GHz is characterized by only one doubly-peaked pulse per stellar rotation (one peak is left-hand circularly polarized, one is right-hand), and not two as expected (see Figure 1). The simplest way to reproduce this behavior is to suppose that the 8.4-GHz emission is constrained within the magnetic flux tube crossing an external body. This scenario is very similar to the Jupiter-Io interaction, where the radio emission associated with Io originates from the magnetic flux tube crossing the satellite. This scenario has been already proposed to explain the emission of other UCD stars like LSR J1835+3259 (Hallinan *et al.*, 2015).

In the case of TVLM 513-46546 the 8.4-GHz emission is triggered by a close-in planet, whenever it is crossed by the stellar flux tube and excites it, with the ARE characterized only by one pulse per stellar rotation. In fact, because of its directivity, we can observe only the ARE related the magnetic flux tube lying on the plane of the sky (Figure 3). The emission at 8.4 GHz takes place at lower magnetic latitudes with respect to the 4.9-GHz emission, which takes place in a different auroral cavity as stated in the previous section. The revolution period of the planet has a measurable effect on the stellar ARE, which would show a peculiar temporal evolution of the ARE light curve. Therefore to check if a planet could really explain the radio light curve of TVLM 513-46546 and constrain its orbital period, we simulated the radio emission observable with several star-planet configurations, varying the orbital distance of the planet and the extension in longitude of the excited emission.

What we found is that the model predicts a seasonal periodicity of the ARE by supposing the presence of a planet that orbits around the star at a distance of about 5 stellar radii (Figure 4). This is in accord with the ARE pulses at 8.4 GHz that were measured for at least 5 consecutive stellar rotations. If the planet is moved farther from the star, from about 10 stellar radii on, the ARE pulses periodicity cannot be reproduced any more. A possible planet placed more than 24 stellar radii away from the star had been already excluded as the possible cause of the particular timing of the observed ARE by Kuznetsov *et al.* (2012).

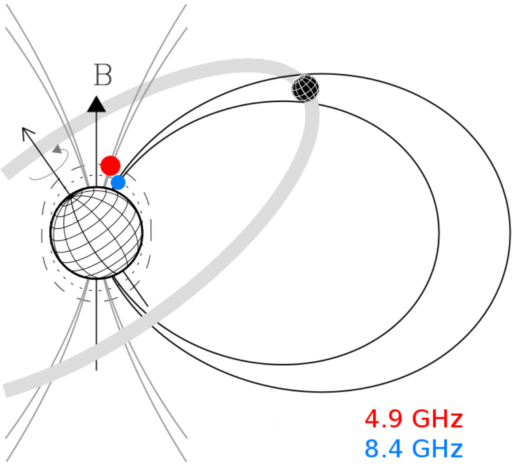

Figure 3: when the planet (in black) is crossed by a stellar magnetic flux tube (field lines in black), the planet triggers (by supplying electrons and shocking the magnetosphere) the ARE on the star at 8.4 GHz (blue spot). Since the ARE is strongly directive it can be observed only when the excited magnetic flux tube lies, as in figure, on the plane of the sky. (Adapted from Leto *et al.* 2017)

4 Summary and conclusions

In this paper and in the related paper by Leto *et al.* (2017), we discussed the scenario of the auroral radio emission originating from very low-mass stars, the so-called ultra-cool dwarfs, applying an emission model originally designed for MCP stars. In particular we took as test probe the radio emission from the UCD TVLM 513-46546.

We showed that the observed light curve of this star shows several anomalies with respect to the standard expectation for a star with an overall dipolar magnetic field. Part of these anomalies can be explained by supposing a more complicated geometry with a large-scale dipolar field and a small-scale toroidal field. A fully comprehension of the light curve could however be achieved by supposing the presence of a close-in planet, located at about 5 stellar radii from the star.

Will the presence of this planet be confirmed, it will be an extraordinary evidence that the study of the temporal evolution of the auroral radio emission, generated by the star-planet magnetic interaction, can be used as a new effective method for searching and characterizing exoplanets. Furthermore, this kind of observations are going to benefit soon from the advent of the new-generation radio instruments, like SKA, which will permit a huge step forward in this field.

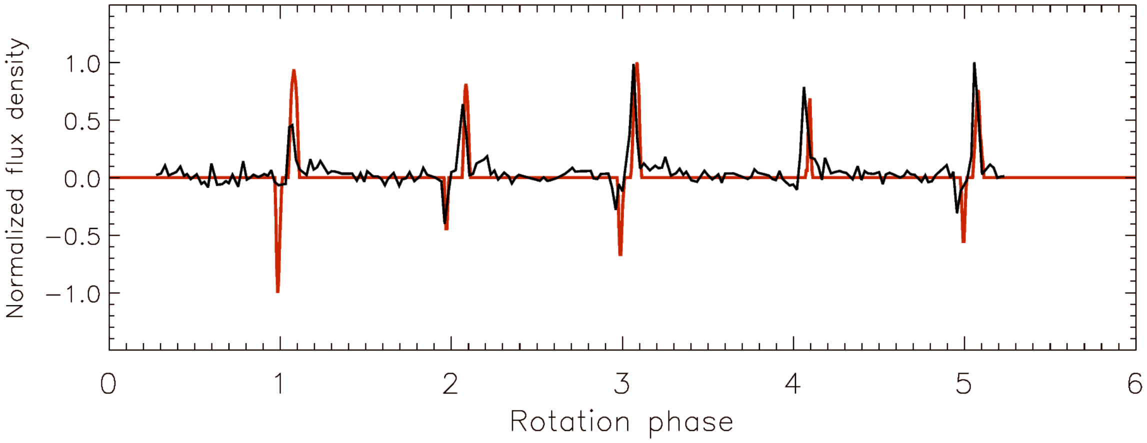

Figure 4: comparison between the phase-folded Stokes-V observed data at 8.4 GHz (black line) and the simulated lightcurve (red line) after the introduction of the planet in the model. The flux density of both the observed and simulated data is normalized to the maximum peak. It is possible to appreciate how the model output agrees with the data, in particular in reproducing the single doubly-peaked curve per stellar rotation.

Acknowledgments

This paper includes archived data obtained through the Karl G. Jansky Very Large Array Online Data Archive (https://archive.nrao.edu/archive/advquery.jsp), operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.. This research used the SIMBAD data base, operated at CDS, Strasbourg, France.

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