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On the effects of stellar winds on exoplanetary magnetospheres

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Abstract. The habitable zone is the range of orbital distances from a host star in which an exoplanet would have a surface temperature suitable for maintaining liquid water. This makes the orbital distance of exoplanets an important variable when searching for extra-solar Earth analogues. However, the orbital distance is not the only important factor determining whether an exoplanet is potentially suitable for life. The ability of an exoplanet to retain an atmosphere is also vital since it helps regulate surface temperatures. One mechanism by which a planetary atmosphere can be lost is erosion due to a strong stellar wind from the host star. The presence of a magnetosphere can help to shield a planetary atmosphere from this process. Using a simple stellar wind model, we present the impact that stellar winds might have on magnetospheric sizes of exoplanets. This is done with the aim of further constraining the parameter space in which we look for extra-solar Earth analogues.

Keywords. stars: activity, chromospheres, Magnetic fields, mass loss, planetary systems, winds

1. Introduction

The first exoplanets were found nearly two decades ago. Since then, the attention has switched from simply looking for exoplanets to characterising them and their potential to host life. As far as we know, all life requires liquid water to survive. This means that any potentially habitable exoplanet will require an Earth-like surface temperature. Since it is unfeasable to measure the surface temperature of every exoplanet we find, we need an observable signature instead to act as a proxy – the habitable zone (Kasting *et al.* 1993). The habitable zone is the set of orbital radii in which it is thought liquid water could exist on the surface of a planet. It is calculated by considering the amount of flux incident on the planet from its host star. Stars which are more massive, and hence more luminous, will have habitable zones which lie further out. This is the most commenly used measure of exoplanetary habitability and quite often the only measure used.

However, it is important to consider other aspects which can affect the potential habitability of a planet. One such factor is the presence of an atmosphere. Indeed, the calculation of the habitable zone assumes this since atmospheres regulate surface temperatures.

If the host star has sufficiently strong stellar winds, the atmosphere can be eroded away. In the Earth's case, this has not happened due to our magnetosphere which diverts the wind around the Earth, shielding us from its erosive effects.

In general, it is the size of the magnetosphere which determines whether it can adequately protect the planet. This is in turn determined by the pressure balance of the system. Three external pressures – the stellar magnetic pressure, the ram pressure of the wind and the ambient thermal plasma pressure – balance the magnetic pressure associated with the planetary magnetosphere. It turns out that the thermal plasma pressure is negligable compared to the other two external pressures, Additionally, the stellar magnetic pressure falls off, with distance from the star, much quicker than the ram pressure meaning the ram pressure dominates for solar type stars. The size of the magnetosphere is therefore determined solely by pressure balance between the ram pressure and the planetary magnetic pressure. It should be noted that the stellar magnetic pressure cannot be ignored for M dwarfs, where the habitable zone lies much closer to the star (Vidotto *et al.* 2013).

This raises two potential problems. Firstly, it is not entirely clear what size of magnetosphere constitutes "adequate" protection. We will assume that exoplanet require at least an Earth-sized magnetosphere since we are searching for Earth-analogues. Secondly, in the absesnce of any direct exoplanetary magnetic field measuresments to date, we need some other observational signiture that might indicate the presence of a sufficiently sized magnetosphere which will be the focus of this work. It should be noted that methods to indirectly detect magnetospheres on planets outside of our solar system have been proposed (Vidotto *et al.* 2010, Llama *et al.* 2011, Llama *et al.* 2013).

2. Model

For this work, we shall use a sample of stars collected by the Bcool collaboration. This is an international collection of scientists studying magnetic activity in cool stars. The stars have effective tempertatres between 5000–6000K and masses between 0.5-1.5$M_\odot$ and for each star, the Bcool collaboration has measured the chormospheric activity. It is unknown whether these stars are planet hosting but for this study we will assume they are. We place a hypothetical Earth-like exoplanet, with all the characteristics of Earth, around each star and calculate the ram pressure exerted on the planetary magentosphere to determine its size.

To calculate the ram pressure, we use two wind models. The first is based on the wind model of Parker (1958) which is steady, isotropic and isothermal. Solving the momentum equation gives a velocity profile of the wind as a fuction of the distance. Then, using an empirically determined relation from (Mamajek *et al.* 2008), we find X-ray luminosities from the stellar chromospheric activity. We use this as a proxy for the emission measure from which the density at the stellar surface, or equivalently the base of the wind, can be determined. Combining the base density and velocity profile, we can derive a density profile for the wind by assuming mass conservation. Finally a ram pressure profile can be found by combining the veloctiy and density profiles. For this model, five inputs are required - stellar mass, radius, luminosity, chromospheric activity and wind temperature. The first four are observationally determined in the sample but the final one input is observationally unconstrained. We set the wind temperature to 1.3MK so that the the Sun/Earth system is calibrated correctly within our model.

The second wind model is the model of mass loss presented by Cranmer & Saar (2011). This is a more sophisticated model which we use as a check for the more simplistic model outlined above. It differs from the Parker type wind in that both thermal and wave

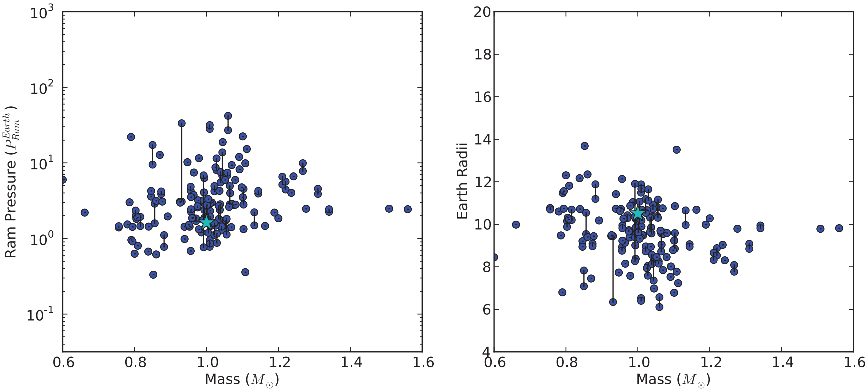

Figure 1. Each hypothetical exoplanet is placed in the habitable zone of its host star. The ram pressure, in units of ram pressure exerted on Earth from the Sun, is calculated using the Parker model of wind (left). The corresponding magnetospheric size for each exoplanet, in units of Earth radii, is also calculated (right). The Earth/Sun case is plotted using the star symbol.

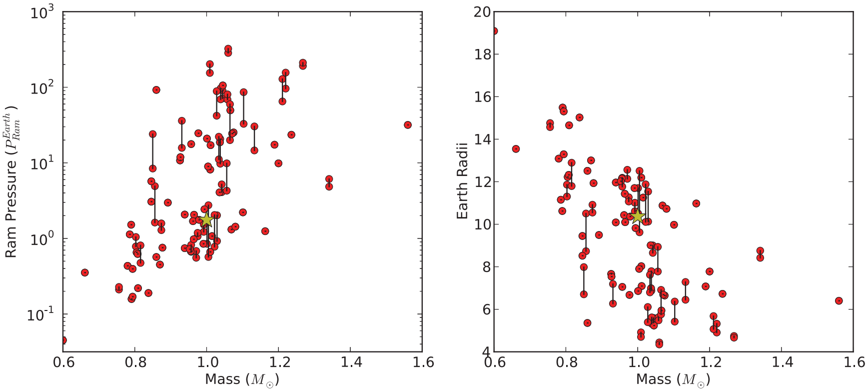

Figure 2. Ram pressures and magnetospheric size are calculated as in Fig 1 but with the Cranmer & Saar model of mass loss.

driving mechanisms are considered when calculating the total mass loss rate from the star. This model also requires five inputs – stellar mass, radius, luminosity, metallicity and rotation period which can all be observationally contrained.

3. Results

To begin with, we placed each hypothetical planet into the habitable zone of its host star. Figure 1 shows the ram pressure exerted on each planet and the corresponding magnetosphere size in Earth radii. A star symbol is used to denote the Earth/Sun system. By placing the planets within the habitable zone, we have forced them to have an Earth-like surface temperature. The figure clearly shows that only a fraction of the planets have at least an Earth-sized magnetosphere or bigger (those with magnetosphere's bigger than roughly $11R_E$). Figure 2 shows the same results but under the Cranmer & Saar model of mass loss. The results of the two models broadly agree with each other with some slight scatter in the results.

Next, we approach the problem from the opposite direction. Figure 3 shows the orbital distance each planet would need to orbit at in order to maintain an Earth-sized magnetosphere for both of the wind models. In this scenario, we have enforced the Earth-sized

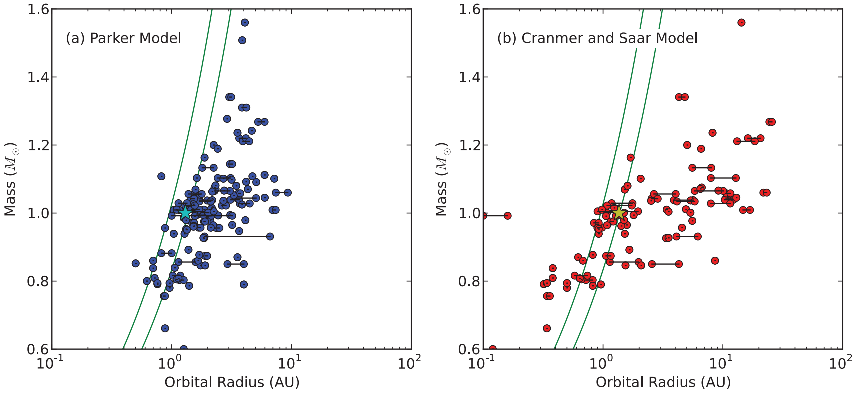

Figure 3. The distance each planet would need to orbit at in order to maintain an Earth-sized magnetosphere for both wind models. The habitable zone has been outlined in green. All symbols are as Fig 1.

magnetosphere condition and find out which of the planets can fulfull the Earth-like surface temperature condition. Again, the two models broadly agree with each other. Also, these results show that only a fraction of the planets can fulfill both of the requirements we outlined before, in agreement with the results from Figures 1 and 2.

4. Implications

The results presented suggest that only a fraction of exoplanets around solar-types can simultaneously fulfill the requirements of an Earth-like surface temperature and an Earth-sized magnetosphere. Additionally, they show that it's the stars with weaker winds which are more likely to host planets able to fulfill both requirements. Observationally, the Parker model indicates that we should look for planets around stars with low chromospheric activity to find such planets. The Cranmer & Saar model show indiates we should look around stars with longer rotation periods which, again, corresponds to lower activity. All of these reulsts point to the importance of characterising the host star when assessing exoplanetary habitabilty rather than focusing only on the orbital distance of the planet.

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