Stellar Coronal and Wind Models: Impact on Exoplanets

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Abstract Surface magnetism is believed to be the main driver of coronal heating and stellar wind acceleration. Coronae are believed to be formed by plasma confined in closed magnetic coronal loops of the stars, with winds mainly originating in open magnetic field line regions. In this Chapter, we review some basic properties of stellar coronae and winds and present some existing models. In the last part of this Chapter, we discuss the effects of coronal winds on exoplanets.

Introduction

About 90% of the currently known exoplanets orbit around low-mass stars. These stars ($0.1 \lesssim M_*/M_\odot \lesssim 1.3$), while in the main-sequence phase, have convective interiors that vary in extension as a function of the stellar mass. Below $\sim 0.4 M_\odot$, these stars are fully convective. Above this mass threshold, there is an appearance of a radiative core, whose size is larger for more massive stars. In turn, the convective part of the star is limited to the outer layers and becomes progressively smaller as one goes towards more massive stars. At $\sim 1.3 M_\odot$, the outer convective envelope is already very small.

As convection is one of the key ingredients in the generation of magnetic fields, main-sequence low-mass stars have . This magnetism gives rise to a multitude of phenomena, from small and localised features (spots, active regions, prominences) to large-scale ones (global magnetism, coronal holes, helmet streamers).

Surface magnetism is also believed to be the main driver of coronal heating and stellar wind acceleration. However, at present, there is no consensus of the basic physical mechanisms involved in these processes. Even for the Sun, heating of the solar corona and acceleration of the solar wind are still currently being debated, with possible scenarios relating to propagation and dissipation of waves and turbulence.
in open magnetic flux tubes and/or reconnection between open and closed magnetic flux tubes (Cranmer 2009).

In this Chapter, we start by reviewing basic properties of stellar coronae and winds. We then present a review of some existing models. The last part of this Chapter is dedicated to the impact of coronal winds on exoplanets.

Observationally-derived properties of stellar coronae

Low-mass stars harbour hot coronae with average temperatures on the order of \(10^6 – 10^7 \text{ K}\) (Guedel 2004; Telleschi et al. 2005; Johnstone and Guedel 2015). The hot stellar coronae are detected in X-ray wavelengths (e.g. Pizzolato et al. 2003; Guedel 2004; Telleschi et al. 2005; Maggio et al. 2011; Wright et al. 2011; Scandariato et al. 2013; Pillitteri et al. 2014; Johnstone and Guedel 2015), during both quiescent and flaring states. Coronae are believed to be formed by plasma confined in closed magnetic coronal loops of the stars. An indication that coronae have indeed their origins in stellar magnetism comes from the observed correlation between X-ray emission and stellar magnetic fields (Pevtsov et al. 2003; Vidotto et al. 2014a). In this Section, we highlight a few observed properties of stellar coronae. An interested reader will find comprehensive reviews of X-ray in, e.g., Guedel (2004); Guedel and Naze (2009); Testa et al. (2015).

X-ray coronae and stellar rotation: Earlier studies have shown the connection between and chromospheric activity (Kraft 1967). Similarly, X-ray emission has also been recognised to correlate with stellar rotation, with the exception of fast-rotating stars (e.g. Pallavicini et al. 1981; Pizzolato et al. 2003; Jeffries et al. 2011; Wright et al. 2011; Reiners et al. 2014). For this reason, the activity-rotation relation is usually divided into two parts. Fast-rotating stars have X-ray emission that is roughly independent of rotation. They are in the so called saturated regime. These stars have X-ray luminosities that account for about 0.1% of their bolometric luminosities. For slower rotators, in the unsaturated regime, X-ray luminosities increases with rotation rate \(\Omega_\star\) as (Reiners et al. 2014)

\[
L_x \propto \Omega_\star^{2.01\pm0.05}.
\]

The rotation rate at which stars transition from unsaturated to saturated regimes corresponds to (Johnstone and Guedel 2015)

\[
\frac{\Omega_{\star, \text{saturated}}}{\Omega_\odot} \simeq 13.53 \left(\frac{M_\star}{M_\odot}\right)^{1.08},
\]

where \(\Omega_\odot = 2.67 \times 10^{-6} \text{ rad s}^{-1}\). The saturation threshold is mass-dependent, with lower-mass stars transitioning from the saturated to the unsaturated regime at lower rotation rates. As rotation decreases with the square-root of the age of stars (Sku-
stars in the lowest-mass range (e.g., M dwarfs) remain saturated even at relatively old ages (note also that these stars have longer lifetimes).

Another observed link between rotation and X-ray emission is seen in X-ray lightcurves. Because X-ray emission arises in closed magnetic coronal loops and since the distribution of closed/open magnetic field line regions at the surface of the star is inhomogeneous, stars can also show rotational modulations in X-ray (Hussain et al. [2005, 2007]).

X-ray coronae and temperatures It has also been shown that stars with hot coro-
nae have high X-ray emission (e.g., Telleschi et al. [2005]). For low-mass main-
sequence stars, there is a tight relation between X-ray flux $F_x$ and average $T_c$ (John-
stone and Guedel [2015])

$$F_x = 0.9 \left( \frac{T_c}{10^6 \text{ K}} \right)^{3.8} \text{ erg cm}^{-2} \text{ s}^{-1}. \quad (3)$$

This empirical relation is useful for estimating the average coronal temperature of stars, once $F_x$ is known. $F_x$ can either be determined observationally or by using the rotation-activity relation (e.g., Equation 1). As we will see in this Chapter, the temperature is an unknown in the models. Models that relate the temperature of the wind to the temperature of the corona can benefit from the empirical relation (3).

X-ray coronae and magnetism The link between coronae and magnetism has long been identified. For this reason, X-ray emission is often used as a proxy for stellar magnetism. One way to validate this is by confronting observed values of X-ray luminosities/fluxes with observations of stellar magnetism.

Two methods are mostly used to measure stellar magnetism. The Zeeman-induced line broadening of unpolarised light (Stokes I), or Zeeman broadening (ZB) technique (e.g., Solanki [1994], Saar [1996], Johns-Krull et al. [1999], Johns-Krull [2007], Saar [2001], Reiners et al. [2009]), yields estimates of the average of the total unsigned surface field strength $\langle |B_I| \rangle$ (small- and large-scale structures). This technique does not provide information of the topology of the field. The $\psi$ technique (Stokes V), on the other hand, is able to reconstruct the intensity and topology of the stellar magnetic field (e.g., Donati and Brown [1997], Donati and Landstreet [2009], Morin et al. [2013]), but cannot reconstruct the small-scale field component, which is missed within the resolution element of the reconstructed ZDI maps (Johnstone et al. [2010], Arzoumanian et al. [2011], Lang et al. [2014]). As a consequence, the ZDI magnetic maps are limited to measuring large-scale magnetic field.

Pevtsov et al. [2003] found that the X-ray luminosities are related to the unsigned magnetic fluxes $\Phi_I$ measured by the ZB technique

$$L_x \propto \Phi_I^{1.3 \pm 0.05}, \quad (4)$$

where

$$\Phi_I = \langle |B_I| \rangle 4\pi R^2.$$
To derive this relation, Pevtsov et al. (2003) considered magnetic field observations of the Sun (X-ray bright points, active regions, quiet Sun and integrated solar disk) and pre- and main-sequence stars. This empirical relation can be seen in Figure 1, spanning about 12 orders of magnitude in magnetic flux.

Similarly, Vidotto et al. (2014a) found that 

\[ L_x \propto \Phi V^{0.913 \pm 0.054} \]

where 

\[ \Phi_V = \langle \mid B_V \mid \rangle 4\pi R^2 \]

is the unsigned magnetic flux as derived from the technique (i.e., only contains the large-scale component of the stellar magnetic field). To be consistent with the method from Pevtsov et al. (2003), the relation above considers both main-sequence stars and pre-main sequence (accreting) stars. The slope found by Vidotto et al. (2014a) is consistent to the nearly linear trend found by Pevtsov et al. (2003).

Figure 1 shows that the pre-main sequence stars (open circles) are under-luminous as compared to the empirical fit (solid line). When considering only the sample of 16 G, K and M dwarf stars (i.e., no solar data nor accreting PMS stars), Pevtsov et al. (2003) found that 

\[ L_x^{(\text{dwarfs})} \propto \Phi I^{0.98 \pm 0.19} \]

and the relation derived from ZDI data yields 

\[ L_x^{(\text{dwarfs})} \propto \Phi V^{1.80 \pm 0.20} \]

(based on a larger sample of 61 dwarf stars). This is shown in Figure 1b. Given the larger errors in the exponents of the fits, both relations are consistent to each other within 3\( \sigma \). Still, this is a topic worth of future investigation. For example, finding a different power law for \( \Phi_V \) and \( \Phi_I \) might clarify on how the small-scale and large-scale field structures contribute to X-ray emission.

**Observationally-derived properties of stellar winds**

Low-mass stars undergo mass loss through winds during their entire lives. Contrary to the Sun, in which the solar wind can be probed in situ, the existence of winds around low-mass stars is known indirectly, e.g., from the observed rotational evolution of stars (e.g., Bouvier et al. 2014). Measuring the wind \( \dot{M} \) of cool, low-mass stars is challenging, as these winds are rarefied and difficult to be directly detected.

Attempts to measure low mass star’s winds have been done through radio observations of their free-free thermal emission at radio wavelengths (e.g., van den Oord and Doyle 1997; Gaidos et al. 2000; Villadsen et al. 2014) and through X-ray observations of the emission generated when ionised wind particles exchange charges. The data provided in Figure 1 are from: Donati et al. (1999, 2003, 2008a,b, 2010a,b, 2011a,b,c, 2012, 2013); Marsden et al. (2006, 2011); Catala et al. (2007); Morin et al. (2008a,b, 2010); Petit et al. (2008, 2009); Hussain et al. (2009); Fares et al. (2009, 2010, 2012, 2013); Morgensthalter et al. (2011, 2012); Waite et al. (2011, 2013, 2015, 2017); do Nascimento et al. (2016); Folsom et al. (2016) and from Petit et al. in prep.
with neutral atoms of the interstellar medium (Wargelin and Drake 2002). Other attempts involve the observations of coronal radio flares (Lim and White 1996) or the accretion of wind material from a cool low-mass star to a white dwarf in binary systems (Debes 2006; Parsons et al. 2012). So far, the indirect method proposed by Wood et al. (2001), which involves reconstruction of stellar Lyman-α line (see below), has been the most successful one, enabling estimates of  for about a dozen dwarf stars. To illustrate the challenging aspects of measuring , we show in Table 1 tentative measurements of  of the closest star to us, namely Proxima Centauri. Recently, the interest in understanding Proxima Centauri has increased due to the discovery of a terrestrial type planet orbiting in its habitable zone (Anglada-Escudé et al. 2016).

Table 1 Characteristics of Proxima Centauri and its wind.

| Physical property | Value | Reference |
|-------------------|-------|-----------|
| mass \( (M_\odot) \) | 0.123 | a         |
| radius \( (R_\odot) \) | 0.141 | b,c       |
| rotation period (days) | \( \sim 83 \) | c         |
| \( F_\alpha \) \( (10^6 \text{erg cm}^{-2}\text{s}^{-1}) \) | \( \sim 1.2 \) | d         |
| \( T_\odot \) \( (10^6 \text{K}) \) | 2.7 | e         |
| spectral type | M5.5 | f         |
| total magnetic flux (G) | 600 | g         |
| \( M(M_\odot = 2 \times 10^{-14} \text{M}_\odot \text{yr}^{-1}) \) | \( < 350 \) | h         |
| \... | \( < 14 \) | i         |
| \... | 0.2 | f         |

a: Ribas et al. (2016); b: Demory et al. (2009); c: Anglada-Escudé et al. (2016); d: Wood (2004); e: Güdel et al. (2004); f: Wood et al. (2001); g: Reiners and Basri (2008); h: Lim et al. (1996); i: Wargelin and Drake (2002).
Wood et al.’s method explains the excess absorption observed in the blue wing of the Lyman-α line as caused by the hydrogen wall that forms during the interaction between the stellar wind and the interstellar medium. Wood et al. (2002, 2005) found a relation between the mass-loss rate per unit surface area \( \dot{M}/4\pi R_\star^2 \propto F_x^{1.34} \) and the for low-mass stars

\[
\dot{M}/4\pi R_\star^2 \propto F_x^{1.34}.
\]

As X-ray emission is related to rotation and rotation can be related to stellar ages, Equation (6) implies that younger stars have higher \( \dot{M} \) than older ones. Also, Equation (6) is only valid for \( F_x \lesssim 10^6 \text{ erg cm}^{-2} \text{s}^{-1} \) or ages \( \gtrsim 600 \text{ Myr} \). Figure 2 compiles the mass-loss rates derived by Wood (2004); Wood et al. (2014).

The break in the \( \dot{M} - F_x \) relation found by Wood et al. (2005) for active stars with \( F_x \gtrsim 10^6 \text{ erg cm}^{-2} \text{s}^{-1} \) has been suggested to be caused by the topology of that would inhibit the wind generation. Vidotto et al. (2016) analysed this hypothesis with a sub-sample of stars observed by Wood et al that also had observationally-derived large-scale magnetic fields with ZDI. These authors did not find any particular evidence that the magnetic field characteristics
show an abrupt change at the wind dividing line (WDL, at $F_x \sim 10^6$ erg cm$^{-2}$s$^{-1}$).
In general, solar-type stars to the right of the WDL (namely ξ Boo A and π$^1$ UMa) have higher fractional toroidal fields (blueish points in Fig. 2), but no break or sharp transition was found.

Very active stars, in particular, show variability in their properties on timescales on the order of a few years and can, for example, jump between states with highly toroidal fields and mostly poloidal fields (Petit et al. 2009, Morgenthaler et al. 2012, Jeffers et al. 2014, Boro Saikia et al. 2015). If magnetic fields are to affect stellar winds, significant scatter in the points to the right of the WDL are to be expected.

**Models of stellar coronal winds**

Studies of the solar wind have provided insights into the winds of low-mass stars. However, as there is still no consensus of the basic physical mechanisms involved in the acceleration of the solar wind (Cranmer 2009), this uncertainty also propagates to models of stellar winds. They are believed to be magnetically-driven, in which coupling between stellar magnetism and convection transports free magnetic energy, which in turn is converted into thermal energy in the upper atmosphere of stars (Matsumoto and Suzuki 2014), giving rise to a hot corona (illustrated in Figure 3 for the solar atmosphere). The scale height of X-ray emitting stellar corona is likely to vary with the properties of the star (Jardine 2004, Guedel 2004). A possible scenario to convert magnetic into thermal energy involves the dissipation of waves and turbulence (e.g., Holzer et al. 1983, Cranmer 2008, Cranmer and Saar 2011, Suzuki et al. 2013, Matsumoto and Suzuki 2014). In addition to depositing energy, waves also transfer momentum to the wind, accelerating it (e.g., Vidotto and Jatenco-Pereira 2006). In general, two modelling approaches are used in the study of the hot coronal winds of low-mass stars. We describe them next.

**Self-consistent heating/acceleration mechanism** The first approach involves a more rigorous computation of the wave energy and momentum transfer, i.e., the computations are done from “first principles” (e.g., Hollweg 1973, Holzer et al. 1983, Hartmann and MacGregor 1980, Jatenco-Pereira and Opher 1989, Vidotto and Jatenco-Pereira 2006, Falceta-Gonçalves et al. 2006, Cranmer 2008, Cranmer and Saar 2011, Suzuki et al. 2013). In these models, the increase in temperature from the colder photosphere to the hotter corona arises naturally in the solution of the equations as does the wind acceleration. Most of the models that treat the acceleration starting from the photosphere have been limited to analytical, one- and two-dimensional solutions, as, depending on the level of details of the physics involved in the wind acceleration/heating mechanism, models can become computationally intensive. In particular, a challenging numerical aspect is the large density contrast between the photosphere and the rarefied corona (e.g., Matsumoto and Suzuki 2012). Additionally, models are usually restricted to the inner-most part of the wind and they usually adopt simple topologies for the stellar magnetic field.
Global wind models The second approach adopts a simplified energy equation, usually assuming the wind is described by a polytropic equation of state. In the latter, the thermal pressure $p_{th}$ is related to density $n$ as $p_{th} \propto n^\gamma$, where $\gamma$ is known as the . In these models, the computation often starts at the point where the temperature has already reached coronal values $\sim 10^6$ K (e.g., Mestel 1968; Pneuman and Kopp 1971; Tsinganos and Low 1989; Washimi and Shibata 1993; Keppens and Goedbloed 2000; Lima et al. 2001; Matt and Pudritz 2005; Matt et al. 2012; Vidotto et al. 2009b, a, 2010b; Cohen et al. 2009, 2010; Pinto et al. 2011; Johnstone et al. 2015a, b; Réville et al. 2015; Lüftinger et al. 2015). This approach ignores the physical reason of what led temperatures to increase from photospheric to coronal values. On the other hand, equations are simpler, allowing us to perform three-dimensional numerical simulations of “global” stellar winds, i.e., extending out to large distances from the star (Vidotto et al. 2009b, a, 2010b, 2012, 2014b, 2015; Cohen et al. 2009, 2010; Jardine et al. 2013; Llama et al. 2013; Strugarek et al. 2015; Nicholson et al. 2016).

More recently, there have been efforts in developing a hybrid approach that combines the two approaches described above to study . In these hybrid models, a phenomenological approach of the (solar-based) wave heating mechanism is implemented in three-dimensional simulations of solar/stellar winds, starting from the upper chromosphere (van der Holst et al. 2010, 2014; Sokolov et al. 2013; Garrafò et al. 2015; Alvarado-Gómez et al. 2016). These models present a step forward in the modelling of winds of low-mass stars, as they, for example, do not need to impose a polytropic index to mimic energy deposition in the wind. However, there are still some parameters that need to be imposed a priori, such as the energy flux of
waves at the inner boundary and its dissipation length scale, as discussed in Sokolov et al. (2013). In the case of the solar wind, these free parameters can be constrained from observations (Sokolov et al. 2013; van der Holst et al. 2014).

One of the advantages of global wind models is that the numerical grid can extend out to large distances, allowing us to characterise the conditions around exoplanets (Vidotto et al. 2009a, 2010b, 2012, 2015; Cohen et al. 2011a, b; Llama et al. 2013; Nicholson et al. 2016; Vidotto and Donati 2017). The characterisation of the stellar wind (i.e., the ) is important to quantify the wind (magnetic and particles) effects on exoplanets, as we will discuss later. The global wind models can also incorporate more complex magnetic field topologies, including those derived from observations of (ZDI maps). The magnetic maps are imposed as boundary conditions at the stellar wind base. The magnetic field lines are then extrapolated into the computational domain (e.g., corona, astrosphere), initially assuming the field is in its lowest energy state (i.e., a potential field). With the interaction of the stellar wind particles, the magnetic field becomes stressed. The self-consistent interaction between magnetic field lines and stellar wind particles are let to evolve, until a relaxed solution is found (for more details, see e.g., Vidotto et al. 2014b). The left panel of Figure 4 illustrates the solution of the stellar wind model of the planet-hosting star HD 189733, computed using the observationally-derived ZDI magnetic map from Fares et al. (2010). Colour-coded is the total wind pressure (thermal, magnetic and ram pressures) relative to the solar wind pressure at the Earth’s orbit. The right panel of Figure 4 shows, in the background, the X-ray emission of the hot, quiescent corona of the star due to thermal free-free radiation (Llama et al. 2013). Coronal comes mainly from flaring magnetic loops with different sizes. As the small-scale magnetic structure is not resolved in ZDI observations, the X-ray emission computed in Llama et al. (2013) captures only the quiescent corona and, as such, provide a lower limit for the emis- sion. Overlaid to the X-ray image in Figure 4 is the velocity of the stellar wind at the position of the orbit of HD 189733b (indicated in the left panel by the black circumference).

**Stellar wind effects on exoplanets**

The majority of exoplanets known nowadays orbit stars at considerably close distances. These close orbits are not represented in our solar system. The giant exoplanets at close-in orbits are also known as hot-Jupiters. The system presented in Figure 4 and studied by Llama et al. (2013), for instance, hosts a hot-Jupiter, namely HD 189733b. The solid black line shown in the left panel of Figure 4 represents its orbital radius, at about $8.7\ R_\odot$. From the values of the stellar wind pressure at the orbital position of this exoplanet, we see that the environment surrounding hot-Jupiters have considerably different physical conditions than those around the solar system planets. densities, magnetic field intensities, temperatures, and pressures all decay with distance, albeit with different dependencies (see also Vidotto et al. 2015). This means that the interactions between winds or stellar magnetic field lines
are strongest for close-in planets. Despite the fact that stellar winds are still accelerating and therefore have usually low velocities at the position of close-in exoplanets, the orbital velocities of these planets are large due to the $1/\sqrt{r}$-dependence of Keplerian velocities. can, therefore, have supersonic orbital velocities in the azimuthal direction (Vidotto et al. 2010a). This means that the relative velocity of the close-in planet through the wind of its host star can be as large as that of the solar wind impacting on the Earth’s magnetosphere. The main difference between these two scenarios is the direction of the velocity vector, which has a large azimuthal (radial) component in the former (latter) case.

Because of the large stellar wind densities at the position of, the relative motion of the planet through the wind of the star results in large ram pressures. This, for example, can give rise to the formation of bow shocks surrounding exoplanets (Vidotto et al. 2010a, 2011a; Llama et al. 2013; Bisikalo et al. 2013). In a recent numerical study, Matsakos et al. (2013) showed that other structures, such as cometary-type tails, and inspiraling accretion streams, can also appear as a result of the interactions between stellar winds and planetary magnetic fields/outflows (see also Lai et al. 2010; Li et al. 2010; Bourrier and Lecavelier des Etangs 2013; Bourrier et al. 2016).

One consequence of the large pressure of the stellar wind environment around exoplanets is that it can constrain the sizes of planetary magnetospheres. The standoff distance between the planetary surface and the magnetopause is set by pressure balance. At the planet–stellar wind interaction zone, pressure balance between the stellar wind (left-hand side) and planetary magnetosphere (right-hand side) can be
written as
\[ \rho \Delta u^2 + p_{th} + \frac{B_{r,orb}^2}{8\pi} \simeq \frac{B_{p,M}^2}{8\pi}, \tag{7} \]
where \( \rho, p_{th} \) and \( B_{r,orb} \) are the density, thermal pressure and magnetic field strength of the stellar wind at the position of the planetary orbit, \( \Delta u \) is the relative velocity of the planet through the wind of the host-star and \( B_{p,M} \) is the planetary magnetic field intensity at a distance \( r_M \) from the planet centre. Eq. (7) neglects the planetary thermal pressure component on the right side. Because of the exponential decay of planetary densities, at the height of a few planetary radii, thermal pressure is usually negligible compared to the planetary magnetic pressure. We further take the to be dipolar, such that \( B_{p,M} = B_{p,eq}(R_p/r_M)^{3/2} \), where \( R_p \) is the planetary radius and \( B_{p,eq} \) its surface magnetic field at the equator (i.e., half the value of the intensity at the magnetic pole). For a planetary dipolar axis aligned with the rotation axis of the star, the magnetospheric size of the planet is given by
\[ \frac{r_M}{R_p} = \left[ \frac{B_{p,eq}^2}{8\pi(\rho \Delta u^2 + p_{th}) + B_{r,orb}^2} \right]^{1/6}. \tag{8} \]

Therefore, a large stellar wind pressure (ram, thermal and/or magnetic, shown in the denominator of Equation 8) acts to reduce the size of for a given planetary magnetisation (see also, e.g., Ip et al. 2004; Zieger et al. 2006; Lovelace et al. 2008; Lanza 2009; Vidotto et al. 2009a, 2010b, 2012, 2011b; Sterenborg et al. 2011; Khodachenko et al. 2012; Buzasi 2013). This can have important effects on the habitability of exoplanets, including terrestrial type planets orbiting inside the habitable zones of their host stars (Grießmeier et al. 2005, 2009; Khodachenko et al. 2007; Lammer et al. 2007; Vidotto et al. 2011b,c; Zendejas et al. 2010; Vidotto et al. 2013; See et al. 2014; Ribas et al. 2016). The magnetosphere acts to deflect the stellar wind particles, preventing its direct interaction with planetary atmospheres and, therefore, atmospheric erosion. If the is too small, part of the atmosphere of the planet becomes exposed to the interaction with stellar wind particles. Lammer et al. (2007) suggested that, for a magnetosphere to protect the atmosphere of planets, planets are required to have magnetospheric sizes of \( \gtrsim 2 R_p \).

**Effects on potentially habitable planets around M dwarf stars**

Due to a combination of a that is closer to the star and the technologies currently adopted in exoplanet searches, have been the prime targets for detecting terrestrial planets in the potentially life-bearing region around the star. dM stars, however, can have significantly high magnetic fields, in particular, when they are young, fast rotating and, thus, active (Donati et al. 2008a, Morin et al. 2008b, 2010, Reiners et al. 2009). For example, the late dM star WX UMa, have large-scale magnetic fields of up to 4 kG (Morin et al. 2010), significantly larger than the large-scale
solar magnetism of several G (Vidotto 2016). With time, the magnetic field intensity of dM stars decay (Vidotto et al. 2014a). However, dM stars are known to remain active over long timescales (on the order of Gyr, West et al. 2008). This implies that the environment surrounding exoplanets that orbit dM stars should remain highly magnetised for long periods of time.

Vidotto et al. (2013) studied the effects of the high magnetisation of dM stars in setting the sizes of the magnetospheres of (hypothetical) Earth-like planets orbiting in their habitable zones. Using a sample of 15 dM stars with measured surface magnetic fields and assuming planets to have a similar terrestrial magnetisation, they showed that these hypothetical Earths would have magnetospheres that extend as low as \(1.7 R_p\) and at most up to \(6 R_p\) \((11.7 R_p)\), for planets orbiting in the inner (outer) edge of the habitable zone. The magnetospheric size of Proxima b (orbiting around a M5.5V star, see Table 1) has been estimated to extend up to about \(1.3 \text{ to } 7 R_p\) \((\text{Ribas et al. 2016})\). For comparison, the Earth’s magnetosphere is located at \(r_M \approx 10 – 15 R_E\) (Bagenal 1992), showing that Earth-like planets with similar terrestrial magnetisation orbiting active dM stars present smaller than that of the Earth. If exoplanets lack a protective magnetic shield, this potentially implies that these planets can lose a significant fraction of their atmospheres (Zuluaga et al. 2013).

**Effects on potentially habitable planets orbiting young stars**

Sun-like stars are observed to emit larger X-ray and extreme ultra-violet (EUV) fluxes at a younger age (e.g. Guinan et al. 2003; Ribas et al. 2005, 2010). The large stellar irradiation can heat the outer atmospheres of exoplanets that become more extended and more susceptible to evaporation (e.g. Lammer et al. 2003; Baraffe et al. 2004; Sanz-Forcada et al. 2011). Planets can receive an enhanced flux of energetic photons if they are orbiting at close distances to their stars and/or if they are orbiting around young and more active stars.

In addition to larger X-ray and EUV fluxes, young and more active stars also harbour more intense magnetic fields and winds with larger \(\dot{M}\). Relation (6), between \(\dot{M}\) and \(F_x\), has important consequences, for example, for the evolution of the young solar System. Extrapolations using Eq. (6) suggest that the 700 Myr-Sun would have had \(\dot{M}\) that is \(~100\) times larger than the current solar mass-loss rate \(\dot{M}_\odot = 2 \times 10^{14} M_\odot \text{ yr}^{-1}\) (Wood et al. 2005). This could explain the loss of the Martian atmosphere as due to erosion caused by the stronger wind of the young Sun (Wood 2004).

Through modelling of the wind of the solar twin \(\kappa\) Ceti, do Nascimento et al. (2016) computed the magnetospheric size of the \(\kappa\) Ceti is believed to be a good representation of our Sun at an age of about 400 – 600 Myr, roughly the time that life started emerging on our planet. To calculate the magnetospheric size of the (hypothetical) Earth-twin, we make use of Equation (8). For a similar present-day magnetisation of the Earth, do Nascimento et al. (2016) estimated the size of the
magnetosphere of the to be about $5 R_p$. Contrary to Mars, which does not host a significant magnetic field and therefore no appreciable magnetosphere, the relatively large size of the early Earth’s magnetosphere may have been the reason that prevented the volatile losses from Earth and created conditions to support life.

**Final remarks**

In this Chapter, we presented one aspect of how stars can affect their surrounding planets. We concentrated on the effects that stellar winds might have on exoplanets. We only presented case studies in which the exoplanet hosts a protective magnetic field, which prevents a direct interaction between the stellar wind and the planetary outer atmosphere. Non-magnetised exoplanets are believed to undergo significant atmospheric erosion in short timescales. However, exoplanetary magnetic fields have not yet been directly observed and so far have only been elusively probed (e.g. Shkolnik et al. 2008, Vidotto et al. 2010a, Kislyakova et al. 2014). Due to the diversity of stellar and exoplanetary properties, of the architectures of exoplanetary systems and the complex nature of stellar wind–planet interaction, progress in this field is likely to come through different angles. This is another example of how exoplanetary studies are becoming more multi-disciplinary, where important physical insights can only be gained from efforts arising from different areas of Astrophysics, such as stellar, solar, and planetary Physics, and astrobiology.

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