Chapter III:
SOLAR ATMOSPHERE AND SOLAR WIND

Aline Vidotto from Leiden University (The Netherlands) listening to questions after her talk on the evolution of the solar wind.

How has the solar wind evolved to become what it is today?

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Abstract. In this contribution, I briefly review the long-term evolution of the solar wind (its mass-loss rate), including the evolution of observed properties that are intimately linked to the solar wind (rotation, magnetism and activity). I also briefly discuss implications of the evolution of the solar wind on the evolving Earth. I argue that studying exoplanetary systems could open up new avenues for progress to be made in our understanding of the evolution of the solar wind.

Keywords. stars: mass loss, stars: winds, outflows, stars: evolution

1. Introduction

The Sun is the best studied star in the whole Universe: we can measure its properties with accuracy like no other star. However, all this information just tells us about how the Sun looks like now. Understanding how the winds of cool stars evolve is key to understand, for example, how has the solar wind and the solar system planets evolved during the past 4 billion years or what the implication of a strong wind is for young exoplanets.

To understand the past, and future, evolution of the Sun, including its wind, magnetism, activity, rotation, and irradiation, we rely on data of solar-like stars, in an effort to better place the Sun and the solar wind in a stellar context. Solar-like stars form a broad group of stars with spectral types from early M to late F ($0.4 \lesssim M/M_\odot \lesssim 1.3$) in the main sequence. These stars have in common a convective outer envelope, which is linked to the generation of magnetism, which ultimately drives their high-energy radiation and winds. In this contribution, I review the evolution of some key ingredients associated to stellar winds.

2. Evolution of mass-loss rates

Detecting winds of cool dwarf stars can be very tricky, as they are in general tenuous and more difficult to detect. By modelling the observed interaction between stellar winds and the interstellar medium (ISM) Wood et al. (2002) proposed a correlation between X-ray flux and mass-loss rate. He showed that stars that have higher X-ray fluxes in general have winds with higher mass-loss rates. In addition to the method proposed by Wood et al. (2002), other methods have also been proposed to detect winds of cool dwarfs. In Vidotto (2021), I reviewed some of the methods proposed so far – this is now summarised in Figure 1, while Figure 2 † shows a compilation of these results. Following

† The values used in this plot were compiled from the following works: Drake et al. (1993); Lim et al. (1996); Gaidos et al. (2000); Wood et al. (2001, 2002, 2005, 2014); Wood & Linsky (2010); Wood (2018); Wargelin & Drake (2002); Bourrier et al. (2013); Kislyakova et al. (2014);

How to detect winds of cool dwarfs?

Method	key requirement associated reference
Astrospheric Ly-α absorption	partially neutral ISM, ≤10 pc Wood 2004
Radio free-free emission	denser winds and/or radio flares Lim & White 1996; Güdel 1992
Using exoplanets as probes	needs evaporating planet Vidotto & Bourrier 2017
Prominences in Hα	needs fast rotation Jardine & Cameron 2019
Type II radio bursts CME-dominated	fast CME associated w/ flare Crosley & Osten 2018
Radio wave propagation	radio source (planet?) within wind Vidotto & Donati 2017
X-ray limits from stellar winds	hot coronal winds Lim & White 1996, Llama et al 2013
Charge-exchange induced X-ray	partially neutral ISM Wargelin & Drake 2001, 2002
Accretion onto white dwarfs	close binary Debes 2006

Figure 1. Table summarising (most of) the proposed methods to detect tenuous winds of cool dwarf stars (adapted from Vidotto 2021).

the suggestion from Wood et al. (2002), I present a fit for the solar-like stars (black line in Fig 2):

$$\frac{\dot{M}}{R_\star^2} = 10^{-2.75\pm0.68} \left[\frac{F_X}{\mathrm{erg\,cm^{-2}s^{-1}}}\right]^{0.66\pm0.12} \frac{2 \times 10^{-14} M_\odot/\mathrm{yr}}{R_\odot^2} \,. \tag{2.1}$$

In general, stars that have higher X-ray surface fluxes are younger (see Section 4). With age, stellar activity decreases. Therefore, the x-axis in Fig. 2 can also be interpreted as a roughly age indicator, whereby younger stars (which are more active and with faster rotation) are shown to the right while the older stars (which are less active and show slower rotation) are shown to the left of the plot. Using the relation from Guedel (2007), who found that $L_X \propto t^{-1.5\pm0.3}$ (for solar-like stars in the non-saturated regime) and Eq. (2.1), we have that

$$\dot{M} \propto \mathrm{age}^{-1.5\times0.66} \sim 1/\mathrm{age} \quad (\mathrm{roughly}) \,. \tag{2.2}$$

Therefore, the mass-loss rates of solar-like stars, in the non-saturated regime, should decrease with age.

3. Stellar magnetism evolution

Because winds of cool dwarf stars are magnetic in origin (similar to the solar wind), magnetic field measurements are one of the essential input quantities in models of stellar winds†. In particular, it is interesting to note that the (large-scale) topology of the magnetic field evolves during solar cycle (e.g., DeRosa et al. 2012; Vidotto et al. 2018), which affects the observed structure of the solar wind. For example, at minimum, when

Fichtinger et al. (2017); Vidotto & Bourrier (2017); Vidotto & Donati (2017); Jardine & Collier Cameron (2019); Finley et al. (2019); O Fionnagain et al. (2020).
† What makes solar-like stellar winds so effective at removing angular momentum is the stellar magnetic field (Weber & Davis 1967).
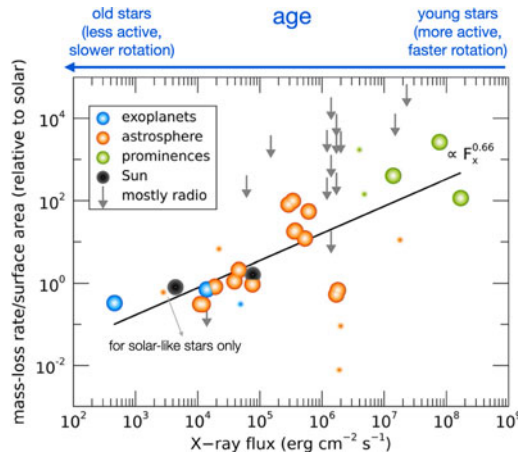
Figure 2. Relation between mass-loss rates and X-ray surface flux. Colour indicates the method used in the derivation of mass-loss rates (see panel on the left), with grey arrows indicating upper limits. The solid line is a power-law fit through the larger circles (Equation 2.1). The smaller symbols are either evolved stars or M dwarfs, which were not included in the fit and neither were the stars for which only upper limits exist (arrows). Figure from Vidotto (2021).

the solar large-scale field can be characterised by an aligned dipole, the solar wind velocity shows a bimodal structure, with fast streams coming from the polar regions, where the solar magnetic field has open field lines (McComas et al. 2008).

To measure surface magnetic fields, I highlight two different methods. (1) Zeeman-Doppler imaging (ZDI) maps the large scale field of the stellar surface, through an image reconstruction algorithm which uses as input time-series of spectropolarimetric data. (2) By measuring the broadening of magnetically sensitive lines, the Zeeman broadening technique derives the total field strength at the stellar surface.

While the former technique is able to reconstruct the topology of the magnetic field, it can only do so on the large-scale component. While the latter technique is able to derive the total field strength (including the ZDI-undetected small-scale component), it only obtains the unsigned field (i.e., no topology indicator). As a result the two techniques are highly complementary. In depth reviews of these techniques can be found in Donati & Landstreet (2009) and Reiners (2012).

While stellar magnetism has been expected to decrease with age, it was only by grouping a relatively large sample of magnetic field observations that we finally were able to quantitatively assess this decay (Vidotto et al. 2014). Figure 3 shows that the large scale field of solar-like stars decay with $\sim \mathrm{age}^{-0.6}$, which is a rather similar slope as the "Skumanich-law", whereby rotation is observed to decay with $\sim \mathrm{age}^{-0.5}$ (Skumanich 1972). Rotational evolution will be discussed next.

4. Evolution of stellar rotation and high-energy radiation

A key concept of winds of cool dwarf stars is that they carry away angular momentum. Therefore, during the main sequence, as a star ages, its rotational velocity decreases (spin down). On the other hand, rotation is observed to be linked with (magnetic) activity, therefore, as a star spins down, its activity also decreases. Hence, older stars are characterised by slower rotation and less intense activity. There is, thus, a feedback-loop between age, rotation and (magnetic) activity, which is mediated by the angular momentum carried away by stellar winds.
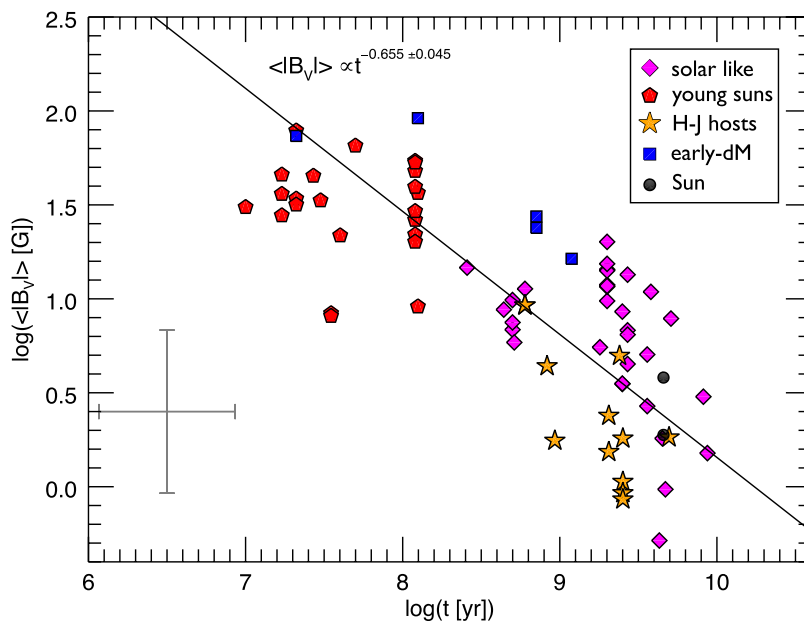
Figure 3. Evolution of the average large scale magnetic field of a sample of solar-like stars, as measured from the ZDI technique. The large scatter shown around the fit (black line) are attributed to variability of the stellar magnetic field (e.g., cycles) as well as a large uncertainty in determining stellar ages. Figure from Vidotto et al. (2014).

Activity is a broad term that is usually related to a number of processes. Activity can be identified in the form of spots (which can be probed through photometric monitoring). Activity can also be identified through spectroscopic lines formed in the chromosphere (e.g. CaII H&K). Alternatively, it can be linked to coronal diagnostic measurements, such as X-ray emission and high-energy radiation in general. Note that all these processes (spots, chromospheric and coronal emission) are magnetic in nature, albeit they are indirect measurements of magnetism. More directly, activity can be probed by measuring stellar magnetic fields (see previous section). As activity (in the broad term) decreases with age, each of these processes are also observed to decrease with age (albeit with different slopes).

In terms of rotation, there are several observational studies dedicated to mapping the evolution of surface rotation. To reduce the uncertainty in age measurements, stars in open clusters (which are coeval) have been frequently used to to measure how stellar rotation varies as a function of age (e.g. Irwin & Bouvier 2009). In recent years, thousands of measurements of rotation periods of low-mass stars have become available thanks to new telescopes, such as Kepler (e.g. McQuillan et al. 2014). In the main sequence, stellar winds brake the rotation of stars. Therefore, models that describe stellar rotational evolution usually parameterise the evolution of angular momentum loss through stellar winds, albeit in different scales of complexity. Examples of such models are: Kawaler (1988); Spada et al. (2011); Gallet & Bouvier (2013); Johnstone et al. (2015); Matt et al. (2015); Amard et al. (2019); Pezzotti et al. (2021).

Because high-energy radiation is linked to rotation, and high-energy radiation (in particular in the ultra-violet) is very hard to measure, in recent years, semi-empirical frameworks to model and predict the evolution of high-energy radiation have been developed (Tu et al. 2015; Johnstone et al. 2021; Pezzotti et al. 2021). In general terms, these

frameworks rely on models of stellar rotational evolution which are coupled to empirical relations between X-ray emission and rotation (e.g. Wright et al. 2011; Reiners et al. 2014) and to relations between UV radiation and X-ray emission (e.g. Sanz-Forcada et al. 2011; Johnstone et al. 2021). These semi-empirical frameworks provide a much needed input for models of (exo)planetary evolution, which I will discuss next.

5. Concluding remarks: effects of the evolving particle, magnetic and radiation environments of solar-like stars on (exo)planets

Understanding how the winds of cool stars evolves is key to understand wind effects on orbiting planets. A few open questions and related studies are listed below:

• *How have the solar system planets evolved during the past 4 billion years?* There are indications that Mars lost its atmosphere because of atmospheric erosion due to a stronger wind of the young sun (Kulikov et al. 2007). Earth, on the other hand, is believed to have retained its atmosphere because of its strong intrinsic magnetic field (Blackman & Tarduno 2018), in spite of the fact that its magnetosphere would have been smaller at earlier ages (Carolan et al. 2019).

• *What is the implication of a strong wind on atmospheric evaporation of close-in exoplanets?* The wind environment surrounding close-in exoplanets are harsher than the environment around planets orbiting far from their host stars (Vidotto et al. 2015). For unmagnetised planets, this could enhance their atmospheric evaporation (McCann et al. 2019; Hazra et al. 2022, but see also Vidotto & Cleary 2020; Carolan et al. 2020b). The interaction with a stellar wind can also shape the atmospheric material escaping from the planet (Bourrier & Lecavelier des Etangs 2013; Debrecht et al. 2019; Villarreal D'Angelo et al. 2021; Kubyshkina et al. 2022). Even if the effect of winds on erosion is not significant, it can substantially affect their observational signatures of atmospheric evaporation through spectroscopic transits (Carolan et al. 2020a,b).

• *How strong are the interactions between a close-in planet and the wind of its planet-hosting star?* There are different types of star-planet interactions (Vidotto 2020), including interactions that are mediated by the stellar wind, such as planetary auroral radio emission (Kavanagh et al. 2019; Turner et al. 2021) or planet-induced emission on the host star (Vedantham et al. 2020; Kavanagh et al. 2021). The strength of these interactions depend on the local (i.e., at the planet's orbit) conditions of the stellar wind, which are higher for planets orbiting closer to their host star. For this reason, star-planet interactions mediated by the wind particles and its magnetic fields are stronger in closer-in planets (Strugarek 2016).

• *Are stellar winds big "cosmic ray filters"?* Cosmic rays are ionised, high-energy particles that permeate the Galaxy (in which case they are known as galactic cosmic rays) or particles that originate in stellar flares or coronal mass ejections (in which case they are know as SEPs or stellar energetic particles). Once these particles are inside the stellar wind, the magnetised wind can modulate them both in momentum and spatial domains (what I refer above as giant cosmic ray filters). In essence, the wind can push cosmic rays out, as they are spatially advected, or can allow them in, as they diffuse into the system (e.g., Potgieter 2013). These processes depend on the properties of stellar winds, which evolve in time (Cohen et al. 2012; Rodgers-Lee et al. 2020, 2021a,b). Knowing whether cosmic rays have been more or less suppressed in the past† are important for chemical modelling of planetary atmospheres: cosmic rays can penetrate atmospheres, providing an extra source of atmospheric ionisation, driving the formation of prebiotic molecules, and dissociating molecules (e.g. Rimmer & Helling 2013; Atri 2017; Barth et al. 2021).

† Also around other planetary systems (e.g., Fraschetti et al. 2019; Herbst et al. 2020; Mesquita et al. 2021, 2022a,b).

The strength of some star-planet interactions (e.g., planetary auroral emission, the interplay between an evaporating atmosphere and the stellar wind, cosmic ray suppression) depends directly on the local and/or global characteristics of the stellar wind. Therefore, an interesting "by-product" of studying star-planet interactions, in particular interactions with the stellar wind, is that if such interactions can be observed, they can help characterise not only the planet but also the stellar wind of cool dwarf stars, which form the majority of planet hosts known nowadays.

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