The Long and the Short of it: Timescales for Stellar Activity

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Abstract. Stellar activity varies on a range of timescales, from the long-term decrease due to stellar spindown, through the shorter timescales of magnetic cycles and the rapid fluctuations of flares and coronal mass ejections. All of these are influenced by the mass of the star. This governs the nature of the dynamo that generates magnetic field in the stellar interior and determines the observed large-scale magnetic structure. Stellar mass also governs the processes (such as differential rotation) that transport flux across stellar surfaces and drive coronal evolution and dynamics. In this review I will discuss recent progress in these areas and consider the impact that stellar activity on all these timescales may have on exoplanetary systems.

1. Introduction

Stellar activity varies on a range of time scales, from the long timescale of stellar evolution, through the shorter variations of stellar cycles, to the rapid energy release seen in flares and mass ejections. On the longest timescales, stars spin down as they age and their activity decays as a result. Rather like people, stars, when they are young, are more dynamic - they are certainly more active and rotate faster. Unlike people however, stars tend to lose mass as they age. More importantly, they lose angular momentum. Thus an active and dynamic youth is replaced by a more sedate middle age, characterised by slow rotation and more predictable behaviour.

1.1 The long timescale of angular momentum loss

Stars achieve this transformation by losing angular momentum in a hot, magnetically-channeled wind (Weber & Davis 1967). Angular momentum is removed at a rate given by

$$-\dot{J} = \frac{8\pi}{3\mu_0}\frac{\Omega}{u_A}(B_0 r_\star^2)^2$$

and therefore depends on the stellar angular velocity Ω, the Alfvén speed u_A, and magnetic flux $B_0 r_\star^2$ threading the surface. If the wind is thermally driven, then the Alfvén speed can be replaced by the sound speed. If we further assume a linear dynamo, such that $B \propto \Omega$, then we can recover the Skumanich braking law (Skumanich 1972). Of course the original formulation of this expression was based on only 3 data points, and we can do much better nowadays. Studies of rotation rates of stars in young open clusters (Irwin et al. 2011a) show a very characteristic behaviour as a function of time. Initially the stellar rotation rate is held constant by the presence of a disk, but once the disk is dissipated, the star spins up as it contracts. This generates an increasingly strong magnetic field, and hence an increasingly powerful wind that carries away angular momentum and spins the star down.

Over the timescale of this spin down, however, planets may form and evolve around the star. In order to see this timescale in context, we can look at what was happening in the solar system while the Sun was evolving in this way.

1.2 Solar system evolution

In the earliest phases, from 1 to 10 My, the gas giants formed (see Fig. .1). These planets therefore formed when the Sun was at its most active. The rocky planets formed later, sometime before around 100 My. Some time later, two catastrophic events happened in the solar system. The first was that Mars, being a small planet that cooled quickly, lost its internal convection and hence its magnetic field (Acuña et al. 2001). Planetary magnetic fields protect the atmosphere of the planet from the impact of the solar wind, and Mars lost its atmosphere not very long after this (Kulikov et al. 2007). The second catastrophic event was the Late Heavy Bombardment that showered to the inner solar system with impacts.

The very earliest evidence that we have the presence of the Earth's magnetic field comes from measurements taken in very ancient rocks (Tarduno et al. 2010). We don't know at what point the Earth began generating a magnetic field that could protect its atmosphere, but this is the earliest measurement that we have. It was still some time yet however before the Earth developed an oxygen rich atmosphere that signified the presence of life.

This brief history of the solar system emphasises how many different processes were taking place in the newly forming planets, while the Sun was steadily becoming less active. Had the Sun been a lower mass star, however, its rotational evolution would have been much slower, and therefore it would have maintained a high level of activity for much longer, posing a greater threat to any planets that might form around it (Khodachenko et al. 2007).

1.3 The expanding waistlines of exoplanetary magnetospheres

We can investigate the impact of stellar activity on planets by using some simple but transparent stellar wind models. See et al (2014, submitted) have recently used both a thermal model (Parker 1958) and one due to Cranmer & Saar that is rather more sophisticated, but which can still be run on a laptop, without the need of high-performance computing (Cran-

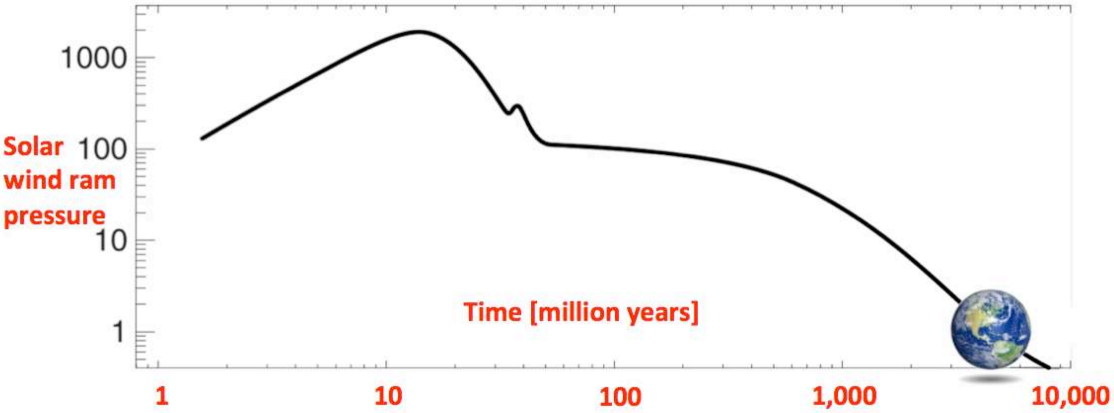

Figure .1: Ram pressure of the solar wind (scaled to the present-day value) as a function of time (adapted from Holzwarth & Jardine 2007).

mer & Saar 2011). They determined, for an Earth-like planet placed in the habitable zone of a star, what the size of the planet's magnetosphere would be. Using the scaling between chromospheric activity and age, they demonstrated the expansion of planetary magnetospheres with age. They found that most solar-like stars have magnetospheres whose sizes lie within the historical range expected for the Earth. This is in contrast to what is expected for M dwarfs, and suggests that for these low mass stars, planets simply have to wait a long time before the star has spun down sufficiently to allow the planet to maintain an Earth-sized magnetosphere (Vidotto et al. 2013, 2014).

1.4 Testing our assumptions about stellar dynamos

We are now in a position to test some of the assumptions that went into the Skumanich model. Using average values of the large-scale magnetic field determined from Zeeman Doppler imaging, Vidotto et al. (2014) have demonstrated that these observed magnetic fields follow a linear dynamo law. Interestingly, the technique of Zeemen broadening, which is sensitive to both the large and small scale fields, shows the same scaling. This may suggest that both the large and small scales of stellar magnetic fields share the same dynamo mechanism. A plot of the observed X-ray luminosity of these stars as a function of Rossby number and average field strength (see Fig. .2), shows a tight correlation at low luminosities and a broad plateau at high luminosities. The X-ray luminosity scales nearly linearly with the magnetic flux, as found by Pevtsov et al. (2003) from Zeeman broadening measurements.

1.5 Taking the shorter view of activity timescales

On shorter timescales still, magnetic activity can vary because of the stellar cycle. One very well studied example is Tau Boo for which a full magnetic reversal has been observed (Donati et al. 2008; Fares et al. 2009). An MHD wind model based on the observed magnetic field shows that the mass loss rate and X-ray flux vary little through the cycle, but the angular momentum loss rate varies by a factor of two (Vidotto et al. 2012). In the case of Tau Boo, the orbiting planet is tidally locked, such that its orbital period is the same as the stellar rotation period, and hence the planet always orbits over the same longitude of the star. In

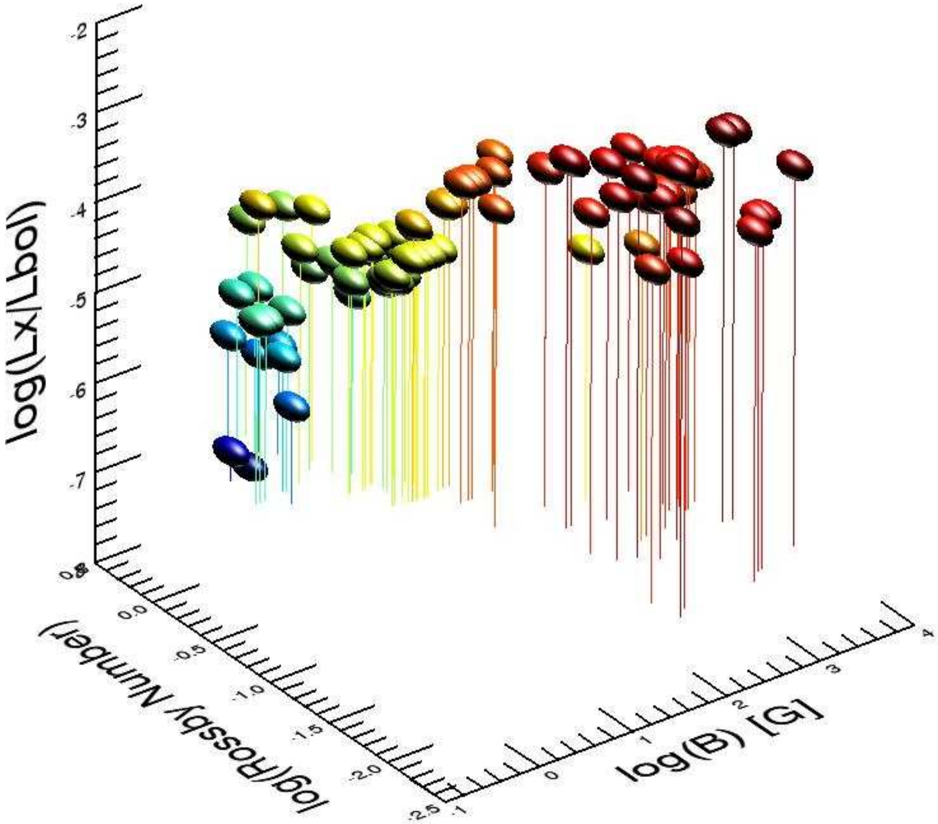

Figure .2: X-ray luminosity as a function of Rossby number and the average value of the large-scale magnetic field (based on Vidotto et al, 2014).

contrast, the orbiting planet in the HD 189733 system has an orbital period that is faster than the stellar rotation period, and hence the planet moves through different parts of the stellar wind and corona as it orbits. As a result, the bowshock formed when the stellar wind impacts on the exoplanetary magnetosphere is expected to vary both in geometry and strength throughout the planetary orbit (Llama et al. 2013). As shown by Llama et al, this may lead to a UV transit whose depth and shape and can change from one observation to the next (Ben-Jaffel & Ballester 2013; Bourrier et al. 2013; Bourrier & Lecavelier des Etangs 2013).

1.6 Flares and coronal mass ejections

Rapid changes in stellar magnetic activity are seen through X-ray and white light flares, and hence also possibly (although much more difficult to observe) coronal mass ejections. The timescale for these processes is influenced by the surface drivers, i.e. the processes that transport magnetic flux. These include diffusion, meridional flow, and differential rotation. In the case of the Sun, the most rapid timescale is the differential rotation. We now know that differential rotation varies with stellar mass, such that low mass stars, which have deep convective zones, rotate almost as solid bodies. Stars more massive than the Sun, which have shallower convective zones, show a higher differential rotation (Reiners 2006). In order to explore how this variation in differential rotation might influence the timescales for coronal activity, we have performed a simple experiment (Gibb et al. 2014, in press). We consider a single bipole evolving in response to surface transport processes. Using a magnetofictional approach, we determine the time taken to form a flux rope, and thereafter, the time for that flux rope to be ejected. We find that the formation time scales as the geometric mean of the timescales for diffusion and differential rotation, such that

$$\tau_{form} \simeq \sqrt{\tau_{Diffrot}\tau_{Diffusion}}.$$

This reflects the two processes that dominate this phase of evolution. The lifetime on the other hand, scales simply as the timescale for differential rotation, such that

$$\tau_{life} \simeq \tau_{Diffrot}.$$

This suggests that stars more massive than the Sun, whose differential rotation is more rapid than the solar value, might have rapidly-evolving coronae. This raises the interesting question: on these stars is there is time for prominences to form, and hence for coronal mass ejections to enhance the winds of the stars in the same way as we see on the Sun?

1.7 The hidden face of stellar activity

While these coronal mass ejections may be very important from the point of view of habitability of exoplanets, and the erosion of exoplanetary atmospheres, they are extremely difficult to observe. We do not, for example, know if all stars share the same relationship between the energy in coronal mass ejections and the energy in flares that we see on the Sun. Aarnio et al. (2012, 2013) use the solar scaling to estimate the angular momentum that might be carried away in these mass ejections on young stars. They suggest that this process may have a significant contribution after about 1 million years. In a related piece of work, Drake et al. (2013) use the solar scaling to estimate the energy carried away in coronal mass ejections in very active stars. They show that such a scaling would predict an unfeasibly large energy content, and hence suggest that the solar scaling breaks down for very active stars. Certainly, estimates of mass loss rates from a range of stars, using the enhanced absorption in the hydrogen wall of stellar astrospheres, suggests that the most X-ray bright stars do not have correspondingly powerful winds (Wood et al. 2002).

It seems that for some time yet, the question of the many timescales for standard activity will continue to challenge us.

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Moira Jardine shows the way with stellar activity timescales.