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The Aging Solar Wind: a Break in Wind Evolution at Older Ages?

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Abstract. The current solar wind is well studied from remote observations and in situ measurements. However, we have very little information of the solar wind as it has evolved. We investigate the evolution of the solar wind by modeling the winds of solar analogues. By using X-ray temperatures as proxies for wind temperatures, we find that a break in behaviour occurs. At 2 Gyr there is a sharp decline in coronal temperatures, which results in a steep decay in mass loss rates for older stars. As the wind is responsible for stellar spin down, through angular momentum loss due to magnetised winds, our results suggest a decline in angular momentum loss for older stars. This agrees with recent observations which find anomalously high rotation rates in older stars. We also find that this evolution in the wind has adverse effects on the Earth's magnetosphere, with an Earth aged 100 Myr having a magnetosphere 3 Earth radii in size.

Keywords. Late-type stars; stars: winds, outflows; Sun: solar wind

1. Introduction

Winds are known to carry away mass and angular momentum from stars, causing them to spin down. These magnetised winds from solar analogues are assumed to be analogous to the aging solar wind. As these stars age, various properties evolve over time, such as rotation and magnetic activity. Magnetic stars tend to have more active winds, and as such, spin down faster as they lose angular momentum. van Saders *et al.* (2016) recently showed that a sample of more evolved stars, observed by Kepler, display unusually fast rotation rates. These do not agree with previously defined age-rotation relations (Skumanich 1972), and it is suggested that there is a weakening in magnetic braking of stars after rossby number ≈ 2.

The 'Sun in time' program considered the evolution of solar-type stars, examining properties such as X-ray flux (Güdel 2007), high energy flux (Ribas *et al.* 2005), magnetic activity (Guinan & Engle 2009). This provided inspiration to study stellar winds from solar analogues, and investigate how they evolve to what we see today from our Sun. Our sample is based off this study and shown in Table 1. We use a 1D stellar wind model (Parker 1958) to simulate the winds of solar analogues. We take X-ray derived coronal temperatures (Johnstone & Güdel 2015) and scale these down to find wind temperatures; an important input parameter for our model. The results presented in these proceedings are discussed in depth in Ó Fionnagáin & Vidotto (2018).

2. Break in wind behaviour

Recent works have suggested that there is a break in the rotation-activity behaviour of solar analogue stars at older ages. This includes a break in coronal temperature with

Table 1. Sample of stars used in the present study: This sample is largely similar to that used in The Sun In Time sample Güdel (2007). Values are mostly taken from Güdel (2007); Vidotto *et al.* (2014). The X-ray luminosity of the sun here is considered to be between activity maximum and minimum.

Star	M ($M_\odot$)	R ($R_\odot$)	P_{rot} (d)	Age (Gyr)	$log[L_X]$ (erg/s)	d (pc)
EK Dra	1.04	0.97	2.77	0.12	29.93	34.5
HN Peg	1.10	1.04	4.55	0.26	29.00	17.95
χ^1 Ori	1.03	1.05	4.83	0.5	28.99	186.0
π^1 UMa	1.00	1.00	5	0.5	28.97	14.36
BE Cet	1.09	1.00	12.4	0.6	29.13	20.9
κ^1 Cet	1.03	0.95	9.3	0.65	28.79	9.14
β Com	1.10	1.10	12.4	1.6	28.21	9.13
15 Sge	1.01	1.10	13.5	1.9	28.06	17.69
18 Sco	0.98	1.02	22.7	3.0	26.8	13.9
Sun	1.00	1.00	27.2	4.6	$\approx$27	1 AU
α Cen A	1.10	1.22	30	5.5	27.12	1.34
16 Cyg A	1.00	1.16	35	7.0	26.89	21.1

rotation for older stars, which we use to define our wind temperatures (Ó Fionnagáin & Vidotto 2018). There is also evidence for a break in magnetic energy in solar type stars after 2-3 Gyr, which can be seen in Vidotto *et al.* (2014) (Figure 2 within). Additionally, van Saders *et al.* (2016) found a break in angular momentum loss for stars older than $\sim$ 4 Gyr, Booth *et al.* (2017) found similar behaviour after $\sim$ 2 Gyr, with a steeper drop in X-ray luminosity from these stars. From our 1D hydrodynamical simulations of these solar type stars, we find that a steep decrease in mass loss rate has occurred for the Sun as it aged. Figure 1 shows that the mass loss rate of aging solar type stars breaks around 2 Gyr, leading to a steep decrease of $\dot{M} \propto t^{-3.89}$, compared to the relatively flat $\dot{M} \propto t^{-0.74}$ relation before 2 Gyr.

From our models we can derive the values of wind velocity, density and temperature at the vicinity of an Earth-like orbit. This allows us to calculate the ram pressure impinging on the Earth as it has aged. By equating the ram pressure and the magnetospheric pressure from Earth (Chapman & Ferraro 1930), we can calculate the magnetospheric standoff distance. We find that a young Earth orbiting a young Sun would have a significantly compressed magnetosphere, at an age of 100 Myr displaying a 3 R_E magnetosphere size.

3. Implications of an aging solar wind

The break in wind-age relation that we found has many consequences for the aging solar wind, affecting mass loss rates which indirectly affects angular momentum, planetary environments, Earth's magnetosphere and atmospheric loss:

• Older stars with lower-than-expected base wind temperatures will experience lower mass-loss rates from their winds (Figure 1). Since the wind is responsible for stellar spin down, through the loss of angular momentum in these magnetised winds, it is expected that this will also result in older stars exhibiting much faster rotation than expected from standard age-rotation relationships. This agrees well with asteroseismic observations presented by van Saders *et al.* (2016).

• Although the mass loss rates presented here result in a rapidly increase in mass loss rate in the past, it is not sufficient to account for the discrepancy in solar evolution

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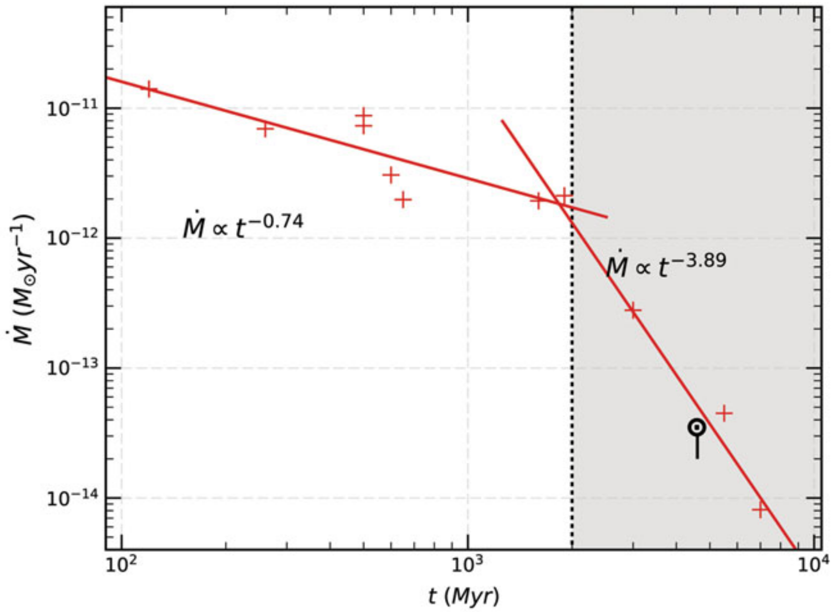

Figure 1. Calculated mass loss rates (*red crosses*) using our 1D wind model shown in this plot describe how the mass loss rate of the Sun would change as it ages. Included in our calculation is our estimation of the current solar mass loss rate ($\odot$) and the range of values calculated directly from observations (*black line*) (Wang 1998). Note the clear break into a rapidly declining mass loss rate regime (*grey shaded region*) at 2 Gyr.

models and evidence for liquid water on Earth in the past, also known as the faint young Sun problem (Feulner 2012). This is discussed further in Ó Fionnagáin & Vidotto (2018) in which we find a total mass loss since 100 Myr of $0.8\% M_\odot$.

• As these winds permeate and compose the interplanetary medium, they directly effect exoplanets. Our evolving winds from solar analogues can not only provide information on the environment surrounding exoplanets, but also on the environment around an evolving young Earth. We find that an Earth of 100 Myr possesses a magnetosphere of 3 Earth radii in size.

• We find that this decreased magnetosphere would cause the polar opening angle in the magnetosphere to increase in size dramatically. With closed field regions beginning at 55-60° latitude. This could possibly contribute to a significant boost in atmospheric loss.

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References

Booth, R. S., Poppenhaeger, K., Watson, C. A., Silva Aguirre, V. & Wolk, S. J., 2017, *Mon. Not. Royal Soc.*, 471, 1012
Chapman, S. & Ferraro, V. C. A., 1930, *Nature*, 126, 129
Feulner, G., 2012, *Reviews of Geophysics*, 50, RG2006
Güdel, M., 2007,*Living Reviews in Solar Physics*, 4, 3

https://doi.org/10.1017/S1743921317010134 Published online by Cambridge University Press

Guinan, E. F. & Engle, S. G., 2009, in Mamajek E. E., Soderblom D. R., Wyse R. F. G., eds, IAU Symposium Vol. 258, The Ages of Stars. pp 395–408 (arXiv:0903.4148), doi:10.1017/S1743921309032050

Johnstone, C. P. & Güdel, M., 2015, *A&A*, 578, A129

Ó Fionnagáin, D. & Vidotto, S. S., 2018, *Mon. Not. Royal Soc.*, 476, 2465

Parker, E. N., 1958, *Astrophysical Journal*, 128, 664

Ribas, I., Guinan, E. F., Güdel, M. & Audard, M., 2005, *Astrophysical Journal*, 622, 680

Skumanich, A., 1972, *Astrophysical Journal*, 171, 565

Vidotto, A. A., *et al.* 2014, *Mon. Not. Royal Soc.*, 441, 2361

Wang, Y.-M., 1998, in Donahue R. A., Bookbinder J. A., eds, Astronomical Society of the Pacific Conference Series Vol. 154, Cool Stars, Stellar Systems, and the Sun. p. 131

van Saders, J. L., Ceillier, T., Metcalfe, T. S., Silva Aguirre, V., Pinsonneault, M. H., García, R. A., Mathur, S. & Davies, G. R., 2016, *Nature*, 529, 181