MEASUREMENTS OF THE WINDS OF SOLAR-LIKE STARS AND THEIR INFLUENCE ON EXTRASOLAR PLANETS

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ABSTRACT

Until recently there have been no reliable measurements of the mass loss rates for main sequence stars of spectral type F–M. Although such mass loss rates are generally presumed to be small as in the solar case, there has been no confirmation of this assumption. We report on a new method for measuring dwarf star mass loss rates using the observed absorption on the blue side of the interstellar Lyman-α absorption feature to study the star's astrosphere. Astrospheres, which are analogs of the heliosphere, are produced when the stellar wind interacts with the interstellar gas flow. Neutral hydrogen piles up at the astropause when the interstellar hydrogen atoms charge exchange with the stellar wind protons. This absorption is blue-shifted with respect to the interstellar medium flow. Astrosphere models constructed to be consistent with the absorption features of eight dwarf stars provide mass loss rates and show a dependence of mass loss rate per unit surface area on X-ray surface flux and thus stellar age. We infer a relation of mass loss rate with age for solar-like stars, and discuss its implications for planets around the Sun and stars.

Key words: Stars: Winds; Stars: Mass Loss; Exoplanets.

1. INTRODUCTION

The solar wind has a mean mass-loss rate of about $2\times10^{-14} M_{\odot}\,\mathrm{yr}^{-1}$. Other dwarf stars have high temperature coronae and thus should have winds, but there have been no measured mass-loss rates for any other main sequence star in the spectral range F–M. This is not surprising as all of the *in situ* techniques used to study the solar wind cannot be applied to other stars without sending a spacecraft there. High resolution spectra of coronal emission lines like Fe XXI 1354 Å observed by GHRS and STIS (e.g., Linsky et al. 1998) and the Fe XVIII 977 Å line observed by FUSE (e.g., Redfield et al. 2003) also show no evidence for outflows, presumably because most of the emission measure is from coronal plasma confined by strong magnetic fields, rather than from outflowing open field regions. Therefore, a very different new technique is needed to measure mass-loss rates from these stars.

2. MEASURING MASS LOSS RATES

Baranov & Malama (1993), Zank et al. (1996), and others have modelled the interaction of inflowing partially ionized interstellar gas with the outflowing ionized solar wind. They find that charge exchange reactions between protons and hydrogen atoms lead to a concentration of hot hydrogen, the so-called "hydrogen wall," near the heliopause. The effect is to produce absorption in the Lyα line with a broad profile that is redshifted relative to the centroid of the interstellar absorption for the line of sight to a star. Redshifts are predicted for nearly all angles relative to the upwind direction as the solar wind slows the charge-exchanged atoms in the upwind direction and accelerates them in the downwind direction.

Additional absorption on the red side of the interstellar Lyα line by the heliospheric hydrogen wall is now detected in many lines of sight to nearby stars. Stars with coronal winds like the Sun will have astrospheres (analogous to the heliosphere) if they are embedded in partially ionized interstellar gas. Since we are observing a stellar hydrogen wall from the outside, the additional Lyα absorption will be blueshifted relative to the interstellar absorption for this line of sight.

Astrospheric absorption on the blue side of the interstellar absorption feature was first identified for the lines of sight to ϵ Ind and λ And by Wood et al. (1996), but is now detected toward many stars (Wood et al., 2002).

The comparison of the Lyα profiles for Proxima Cen and α Cen B (see Figure 1) by Wood et al. (2001) provides an excellent example of heliospheric and as-

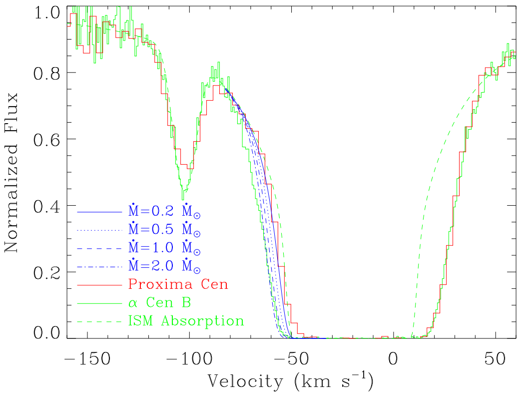

Figure 1. Comparison between the Lyα spectra of α Cen B (green histogram) and Proxima Cen (red histogram). The inferred ISM absorption is shown as a green dashed line. The α Cen/Proxima Cen data agree well on the red side of the H I absorption, but on the blue side the Proxima Cen data do not show the excess Lyα absorption seen toward α Cen (i.e., the astrospheric absorption). The blue lines show the blue-side excess Lyα absorption predicted by the four models of the α Cen/Proxima Cen astrospheres, assuming four different mass-loss rates. The 2.0 $M_\odot$ model fits the α Cen spectrum reasonably well, and the 0.2 $M_\odot$ model represents an upper limit for the mass-loss rate of Proxima Cen.

trospheric absorption. Since the two stars are less than 2° apart in the sky and only 1.3 pc distant, the interstellar absorption (predicted from the deuterium and metal lines) and the heliospheric hydrogen wall absorption (on the red side of the interstellar absorption) should be the same. Indeed, this is the case.

On the other hand, the blue side of the Lyα absorption in the spectra of the two stars is different. Since this part of the absorption is due only to the astrospheric hydrogen wall absorption, the stellar winds of the two stars must be different. Comparison of such observations with theoretical models lead to estimates of the stellar mass loss rate.

We have now modelled the astrospheric absorption for the eight stars listed in Table 1. Our paper describing this work in detail is Wood et al. (2002). Figure 2 shows a comparison of theoretical models with the blue side of the observed Lyα absorption for the lines of sight to six stars. (For a color version of Figure 2 see my website http://jilawww.colorado.edu/~jlinsky/.) The theoretical models take into account the interstellar wind velocity as seen by the star ($V_{\rm ISM}$) and the angle between the upwind direction and the line of sight to the star, which is in the range 46°–134° for these stars. The solar wind model assumes a velocity of 400 km s^{-1}, $T = 10^5$ K, and $n_p = 5$ cm^{-3} at 1 AU. The stellar wind models assume the same parameters, except that the proton density is a free parameter to allow different mass loss rates. Table 1 lists the best fit mass loss rates for the stars.

Table 1. Mass Loss Measurements.

Star	Spectral Type	d (pc)	$V_{\rm ISM}$ (km s^{-1})	$\dot{M}$ ($\dot{M}_\odot$)
α Cen	G2 V+K0 V	1.3	25	2
Prox Cen	M5.5 V	1.3	25	< 0.2
ϵ Eri	K1 V	3.2	27	30
61 Cyg A	K5 V	3.5	86	0.5
ϵ Ind	K5 V	3.6	68	0.5
40 Eri A[a]	K1 V	5.0	127	¡ 5
36 Oph	K1 V+K1 V	5.5	40	15
λ And[a]	G8 IV-III+	26	53	5

[a] Uncertain detection.

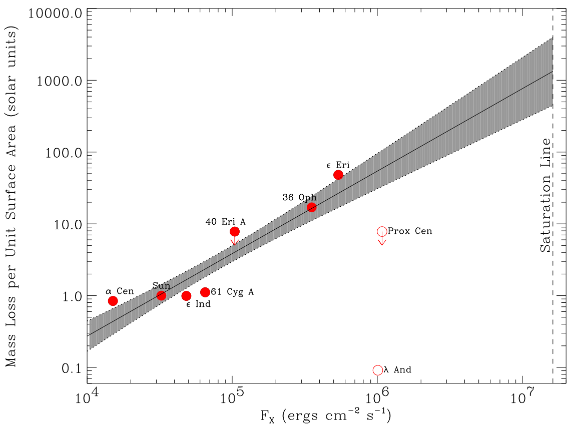

Figure 3. Measured mass loss rates (per unit surface area) plotted versus X-ray surface flux. A power law has been fitted to the solar-like GK dwarfs (filled circles), and the shaded region is the estimated uncertainty in the fit. Proxima Cen (M5.5 Ve) and λ And (G8 IV-III+M V) appear to be inconsistent with this relation. The saturation line represents the maximum F_X value observed from solar-like stars.

3. IMPLICATIONS OF THE MASS LOSS MEASUREMENTS

Since the winds of cool dwarf stars originate in coronae, we plot in Figure 3 the mass loss rates (per unit stellar surface area) vs. the X-ray surface fluxes derived from *ROSAT* PSPC data. For the seven G and K dwarfs there is a clear trend of higher mass loss rate with activity as measured by the X-ray surface flux. The power law fit to the data shown in Figure 3 is $\dot{M} \propto F_x^{1.15\pm0.20}$. The M dwarf (Proxima Cen) and RS CVn G giant (λ And) do not follow this trend.

As stars age, their rotation rates (V_{rot}) slow down due to magnetic braking and the X-ray fluxes decrease. There are many empirical relations describing this evolution of stellar activity. We adopt the

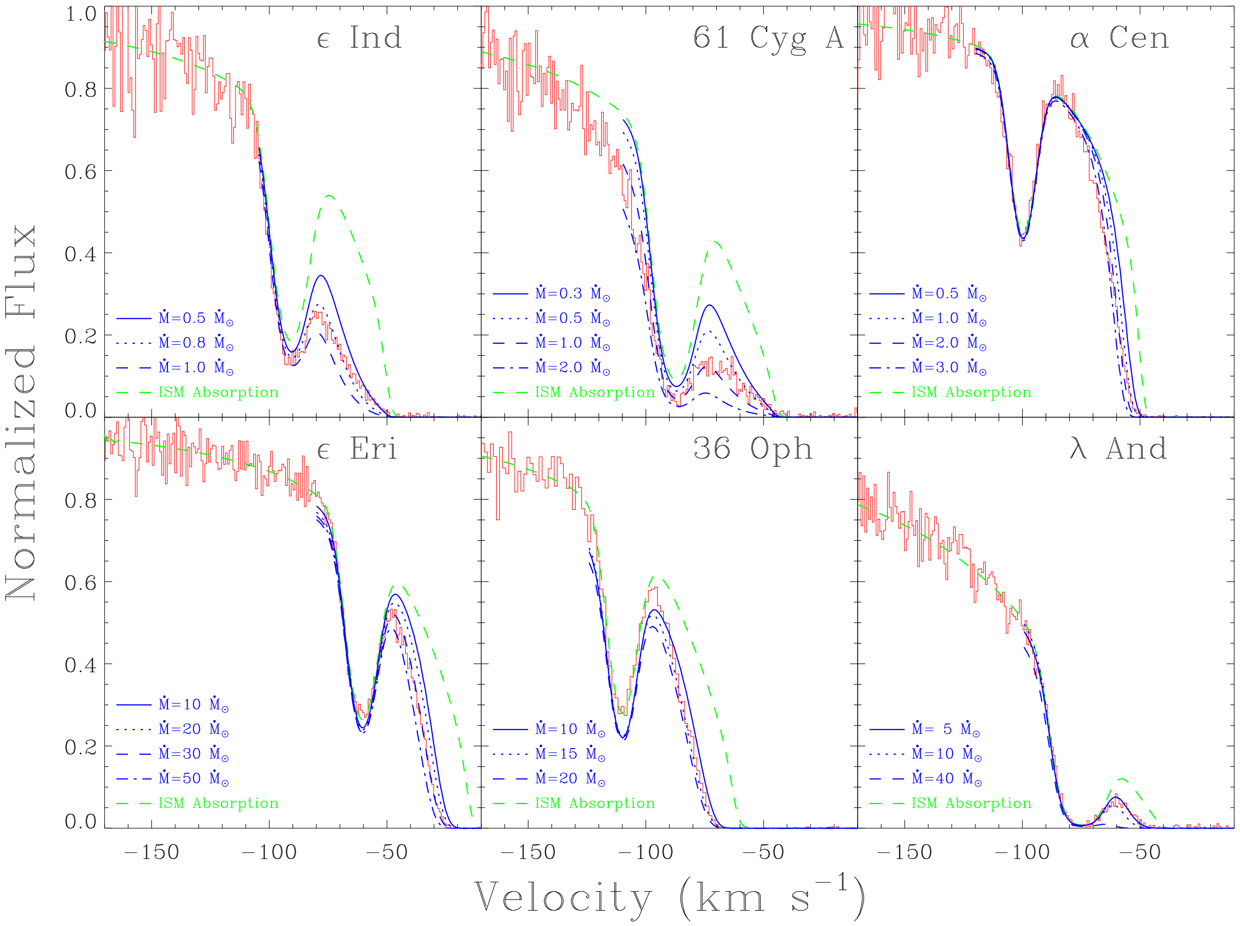

Figure 2. Closeups of the blue side of the H I Lyα absorption lines for all stars with detected astrospheric absorption, plotted on a heliocentric velocity scale. Narrow D I ISM absorption is visible in all the spectra just blueward of the saturated H I absorption. Green dashed lines indicate the interstellar absorption alone, and blue lines show the additional astrospheric absorption predicted by hydrodynamic models of astrospheres assuming various mass loss rates.

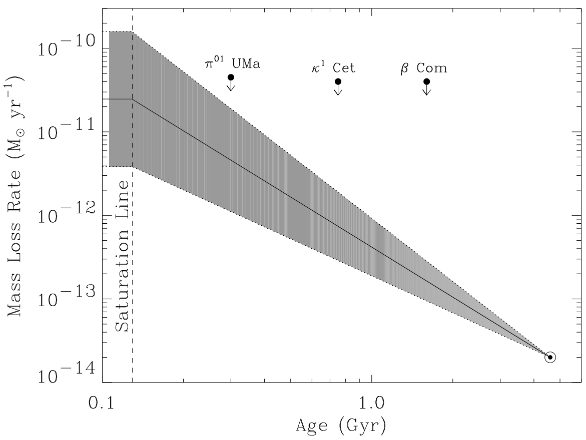

Figure 4. The mass loss history of the Sun suggested by the power law relation from Fig. 3. The upper limits are based on radio nondetections of three solar-like stars (Gaidos et al. 2000).

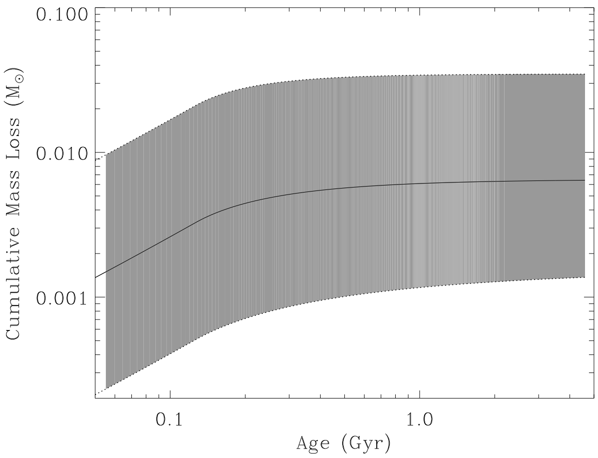

Figure 5. Cumulative mass loss for the Sun as a function of time, based on the mass loss history of the solar wind in Fig. 8.

empirical relations of Ayres (1997), $V_{rot} \propto t^{-0.6\pm0.1}$, and $F_x \propto V_{rot}^{2.9\pm0.3}$. Combining the three equations provides a relation between mass loss rate and stellar age, $\dot{M} \propto t^{-2.00\pm0.52}$. This relation, plotted in Figure 4, predicts that when the young Sun ($t \approx 10^8$ years) had saturated X-ray emission ($L_x/L_{bol} = 10^{-4}$), its mass loss rate was 200–10,000 times larger than at present. The cumulative mass loss from age 10^8 years to the present is $\leq 0.03 M_\odot$ (see Fig. 5).

4. INFLUENCE ON EXTRASOLAR PLANETS

This new result provides the first quantitative estimate of the solar wind flux that planets received during the early solar system. This is important for addressing such questions as (i) why the young Earth had running water when the Sun was 25% fainter than today, and (ii) whether solar wind erosion removed water and other molecules from the young Martian atmosphere.

Stellar winds can erode planetary atmospheres, and the higher mass-loss rates suggested for the young Sun and young stars with high X-ray fluxes would exacerbate these effects. Solar wind sputtering processes have been proposed to have important effects on the atmospheres of Venus and Titan, but the Martian atmosphere may be the most interesting case of solar wind erosion, since the history of the Martian atmosphere is linked to whether water, and perhaps life, once existed on the surface.

Unlike Earth, the Martian atmosphere is not currently protected from the solar wind by a strong magnetosphere. There is evidence that Mars once had a magnetic field, which disappeared at least 3.9 Gyr ago (Acuña et al., 1999). At that time, the Martian atmosphere would have been exposed to a solar wind about 40 times stronger than the current wind, which would have had a dramatic effect on its atmosphere. Mars appears to have had running water on its surface in the distant past and a thicker atmosphere that could have supported a climate consistent with surface water (e.g., Jakosky & Phillips 2001). Solar wind erosion is a leading candidate for the cause of Mars' present thin atmosphere and lack of surface water (e.g., Lundin 2001). Planets around other stars could have similar histories.

5. CONCLUSIONS

- Analyses of the astrospheric absorption features seen in the Lyα lines toward nearby stars provide the first quantitative measurements of mass loss rates for G and K dwarf stars.
- We find that the mass loss rates increase with activity, as measured by the X-ray surface flux, and thus with decreasing stellar age.
- The mass loss rate for the Sun at 10^8 years is predicted to be 200–10,000 times larger than at present and likely played a major role in the evolution of planetary atmospheres.

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