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Winds of Late-type Dwarf Stars – Observational Constraints

Jeffrey L. Linsky and Brian E. Wood

JILA, University of Colorado and NIST, Boulder, CO, 80309-0440, USA

Hans-Reinhard Müller[1], Gary P. Zank

Institute of Geophysics and Planetary Physics, University of California at Riverside, Riverside, CA 92521, USA

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 and thus have little influence on a stellar atmosphere, 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, 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 8 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. Very active stars like Proxima Cen and λ And do not fit this trend.

1. Introduction

Although the solar wind mass flux depends somewhat on the magnetic structure from which it originates, the mean mass-loss rate of the Sun is about $2\times10^{-14}M_\odot$ yr^{-1} (Phillips et al. 1995). Other dwarf stars have high temperature coronae and thus should have winds, but until very recently 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. Ultraviolet emission lines formed in the chromospheres and transition regions of these stars typically show red shifts (e.g., Wood, Linsky, & Ayres 1997), indicating circulation patterns in which the downflows are brighter, but such data provide no

[1]Bartol Research Institute, University of Delaware, Newark, DE 19716, USA

spectroscopic evidence for net outflows. High resolution spectra of coronal emission lines like Fe XXI 1354Å observed by GHRS and STIS (e.g., Linsky et al. 1998) and the Fe XVIII 977Å line observed by FUSE (e.g., Young et al. 2001) 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) and 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," at the heliopause, which is located between the solar wind termination shock and the bow shock where the interstellar gas flow becomes subsonic. 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 outward 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. When we observe a stellar hydrogen wall from the outside, the additional Lyα absorption will be blueshifted relative to the interstellar absorption for the observed line of sight.

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

Comparison of the Lyα profiles for Proxima Cen and α Cen B (see Fig. 1) by Wood et al. (2001) provides an excellent example of heliospheric and astrospheric absorption. Since the two stars are less than 2° apart in the sky and only 1.3 pc distant, the interstellar absorption (measured with 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 sides of the Lyα absorption in the spectra of the two stars are 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 our estimates of the stellar mass loss rate.

We have now modelled the astrospheric absorption for the 8 stars listed in Table 1. Our paper describing this work in detail will appear in the 2002 July 20 issue of ApJ. Figure 2 shows a comparison of the blue side of the observed Lyα absorption for the lines of sight to six stars with theoretical models for different assumed mass loss rates relative to the Sun. The theoretical models take into

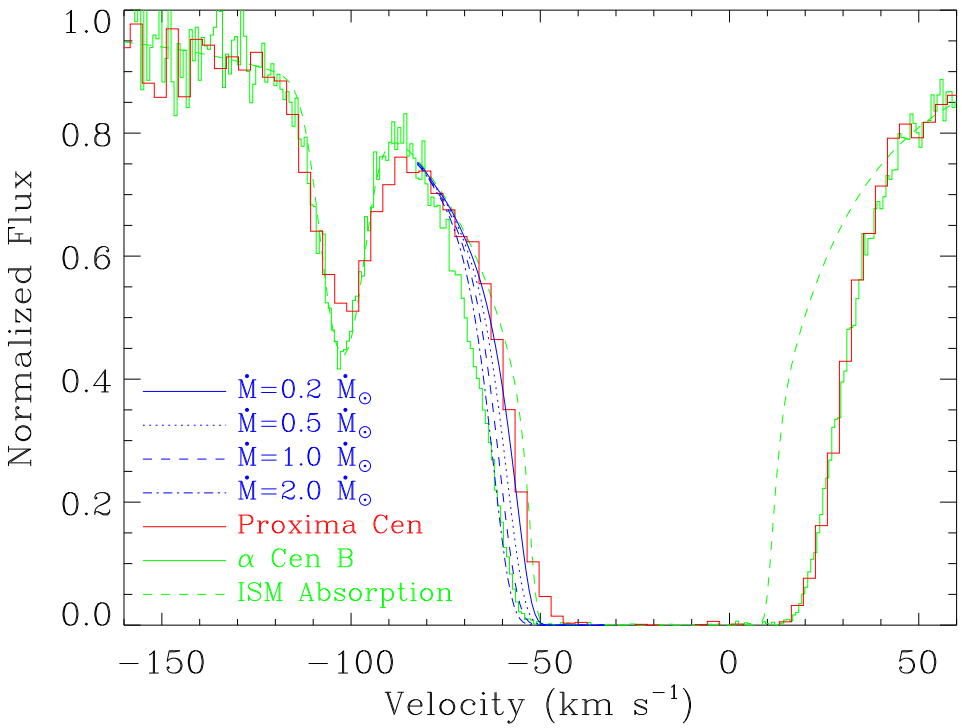

Figure 1. Comparison between the Lyα spectra of α Cen B (green histogram) and Proxima Cen (red histogram). The inferred ISM absorption is shown as a green dashed line. The α Cen/Proxima Cen data agree well on the red side of the H I absorption, but on the blue side the Proxima Cen data do not show the 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.

Table 1. Mass Loss Measurements

Star	Spectral Type	d (pc)	$V_{\rm ISM}$ (km s^{-1})	$\dot{M}$ ($\dot{M}_\odot$)	θ (deg)	log N(H I)	log L_x
α Cen	G2 V+K0 V	1.3	25	2	79	15.24	27.34
Prox Cen	M5.5 V	1.3	25	< 0.2	79	–	27.23
ϵ Eri	K1 V	3.2	27	30	76	15.82	28.32
61 Cyg A	K5 V	3.5	86	0.5	46	14.11	27.26
ϵ Ind	K5 V	3.6	68	0.5	64	14.25	27.18
40 Eri A[a]	K1 V	5.0	127	< 5	59	–	27.61
36 Oph	K1 V+K1 V	5.5	40	15	134	16.10	28.28
λ And[a]	G8 IV-III+	26	53	5	89	15.20	30.53

[a] Uncertain detection.

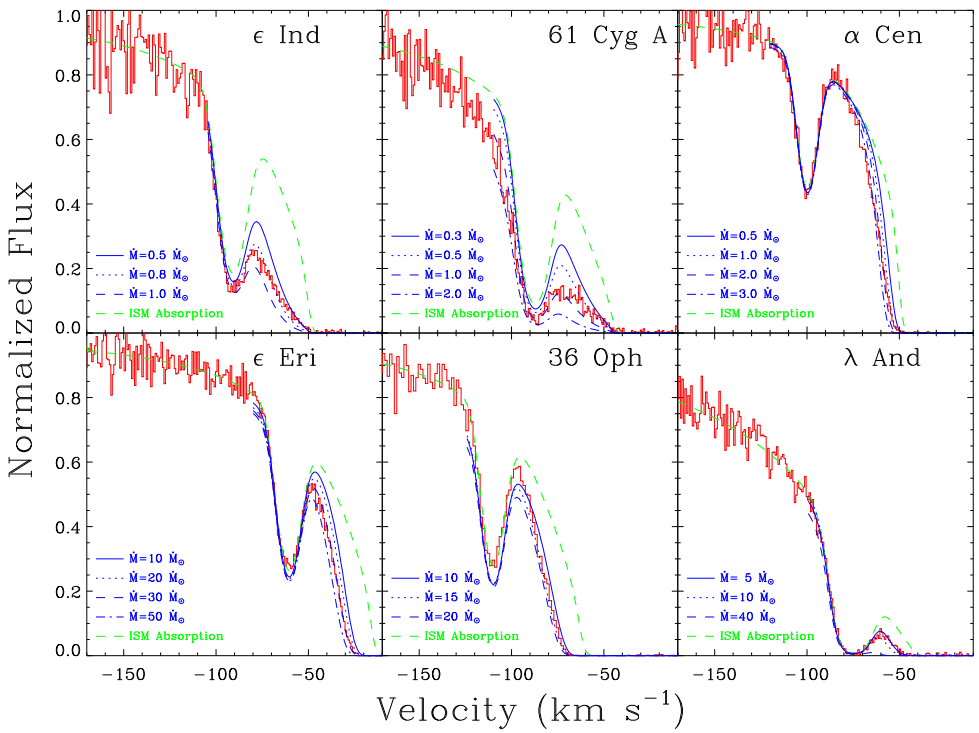

Figure 2. Closeups of the blue side of the H I Lyα absorption lines for all stars with detected astrospheric absorption, plotted on a heliocentric velocity scale. Narrow D I ISM absorption is visible in all the spectra just blueward of the saturated H I absorption. Green dashed lines indicate the interstellar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

account the interstellar wind velocity as seen by the star ($V_{\rm ISM}$) and the angle (θ) between the upwind direction and the line of sight to the star, which is in the range 46°–134° for these stars. N(H I) in Table 1 refers to the hydrogen column density of the astrosphere for the observed line of sight. 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 as the solar wind, except that the proton density is a free parameter to allow for different mass loss rates. Table 1 lists the best fit mass loss rates for the stars based on the results shown in Figure 2.

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

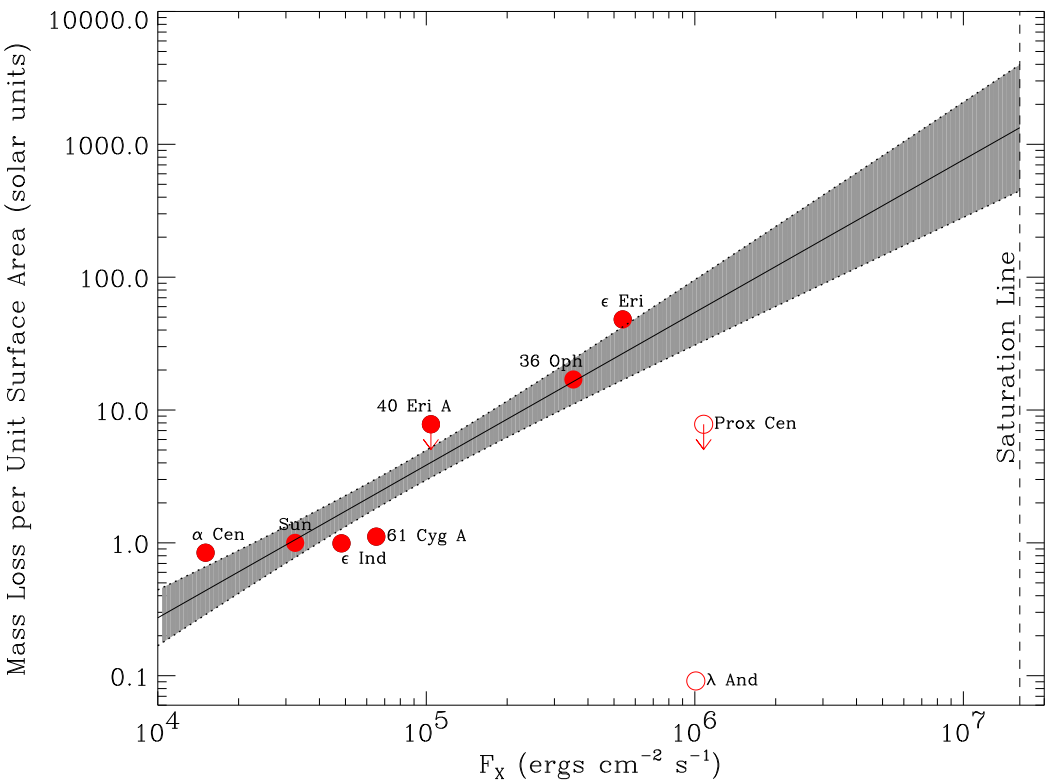

Figure 3. Measured mass loss rates (per unit surface area) plotted versus X-ray surface flux. A power law has been fitted to the solar-like GK dwarfs (filled circles), and the shaded region is the estimated uncertainty in the fit. Proxima Cen (M5.5 Ve) and λ And (G8 IV-III+M V) appear to be inconsistent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

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 decribing this evolution of stellar activity. We adopt the empirical relations of Ayres (1997), $V_{rot} \propto t^{-0.6\pm0.1}$, and $F_x \propto V_{rot}^{2.9\pm0.3}$. Combining these two equations with our mass-loss vs. F_x relation provides a relation between mass loss rate and stellar age, $\dot{M} \propto t^{-2.00\pm0.52}$. This result, 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 comulative mass loss from age 10^8 years to the present is $\leq 0.03 M_\odot$ (see Fig. 5).

While this new result should be checked by studies of other stars and by more sensitive radio measurements, it provides the first quantitative estimate of the solar wind flux that planets received during the early solar system. In particular, it 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)

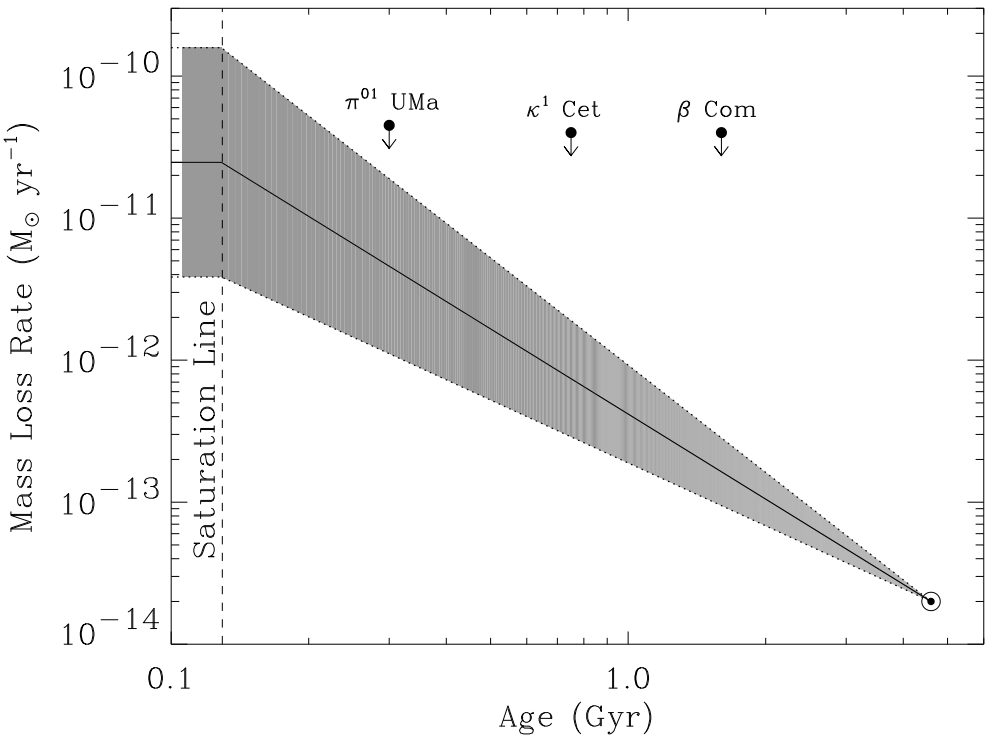

Figure 4. The mass loss history of the Sun suggested by the power law relation from Fig. 3. The upper limits are based on radio nondetections of three solar-like stars (Gaidos et al. 2000).

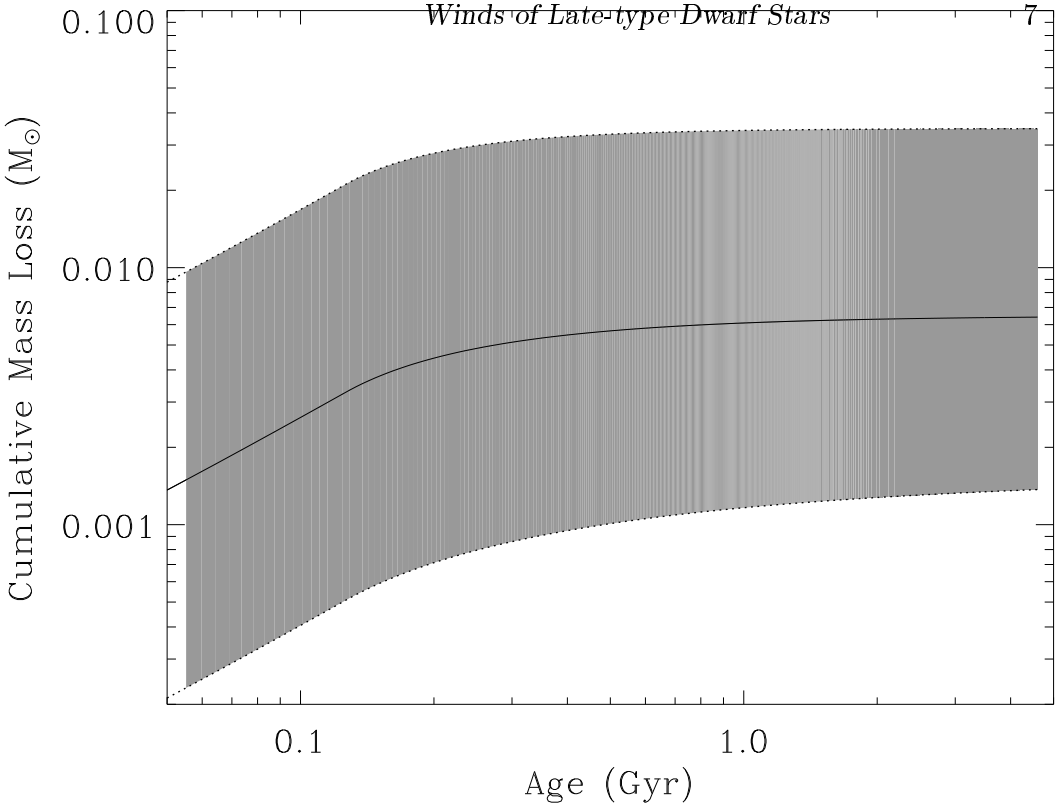

Figure 5. Cumulative mass loss for the Sun as a function of time, based on the mass loss history of the solar wind in Fig. 4.

whether solar wind erosion removed water and other molecules from the young Martian atmosphere.

4. Conclusions

- Analysis of the astrospheric absorption features seen in the Lyα lines toward nearby stars provides 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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