Measuring Stellar Mass Loss Rates at the Femto Level (10^{-15} $M_\odot$ yr^{-1})

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Stellar mass loss is important for stellar evolution and the chemical enrichment of the interstellar medium from which new generations of stars are formed. Three important diagnostic techniques have been employed: the study of blue-shifted absoption features (used by Deutsch (1956) to measure the mass loss rate from the M5 giant α Her), free-free continuum emission in the radio region, and continuum and molecular line emission in the infrared. These techniques can measure mass loss rates in the range 10^{-5} to 10^{-10} solar masses per year ($M_\odot$ yr^{-1}) for hot stars, late-type giants and supergiants, and pre-main sequence stars.

By comparison, the solar mass loss rate of 2×10^{-14} $M_\odot$ yr^{-1} is more than 4 orders of magnitude below the sensitivity limits of the three commonly used techniques. Since other main sequence and subgiant stars should also lose mass, a new technique is needed to measure it. While small mass loss rates may not effect the evolution of the stellar core, they are critically important for controlling the angular momentum evolution of a star and for understanding the evolution of planetary atmospheres, and thus whether or not life can form on planets around other stars. Is it possible to extend the sensitivity of mass loss rate measurements by 4 orders of magnitude? The high spectral resolution, well characterized instrumental profiles, and excellent wavelength scales of the GHRS and STIS instruments make this seemingly impossible task feasible.

One might guess that the most opaque spectral line in the universe, the Lyman-α line of hydrogen, could contain a very weak signal indicating stellar mass loss. Typically GHRS and STIS spectra of nearby main sequence stars show a Lyman-α emission line formed in the stellar chromosphere, a broad interstellar hydrogen absorption component located near line center, and a narrow unsaturated interstellar deuterium absorption line displaced by -82 km s^{-1} from the interstellar hydrogen absorption line. A careful analysis of this complex line from some nearby stars reveals the subtle features indicating stellar mass loss.

Figure 1 shows the Lyman-α line profile of α Cen B (K1 V) and its distant companion Proxima Cen (M5.5 Ve) observed by STIS. One can predict the shape of the interstellar hydrogen absorption feature from the interstellar deuterium and metal lines formed at the same temperature as hydrogen. The predicted interstellar hydrogen absorption (the dashed line in Figure 1) is narrower than the observed absorption, indicating that additional hydrogen absorption is present on both the red and blue sides of the interstellar absorption. What is the cause of this additional absorption?

The key to understanding the extra absorption is to understand the interaction of inflowing partially ionized interstellar gas with the outflowing ionized solar (or stellar) wind. This interaction defines the large scale structure of our heliosphere, and for other stars their "astrosphere". The heliospheric interaction has been modelled by Baranov & Malama (1993), Zank et al. (1996), and others. They find that charge exchange reactions between protons and hydrogen atoms lead to a concentration of hot hydrogen, the so-called "hydrogen wall," located at roughly 200 AU in the upwind direction where the two gas flows interact. The effect is to produce extra absorption in the Lyα line 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 of the interstellar gas flow 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 STIS and GHRS spectra of nearby stars for many lines of sight. 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 observe a stellar hydrogen wall from the outside, the additional Lyα absorption will be blueshifted relative to the interstellar absorption rather than redshifted. This is the observable quantity for measuring mass loss from solar-like stars.

Comparison of the STIS Lyα profiles for Proxima Cen and α Cen B (see Figure 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 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 rates. Wood et al. (2002) have modelled the astrospheric absorption for eight stars. Figure 2 shows a comparison of theoretical models with the blue side of the observed Lyα absorption for the lines of sight to six of these stars.

Since the winds of cool dwarf stars originate in coronae, we expect and indeed find that the measured mass loss rates (per unit stellar surface area) are correlated with the X-ray surface fluxes derived from *ROSAT* PSPC data. As stars age, their rotation rates decrease due to magnetic braking and the X-ray fluxes decrease. There are many empirical relations describing this evolution of stellar activity. We adopt the empirical relations of

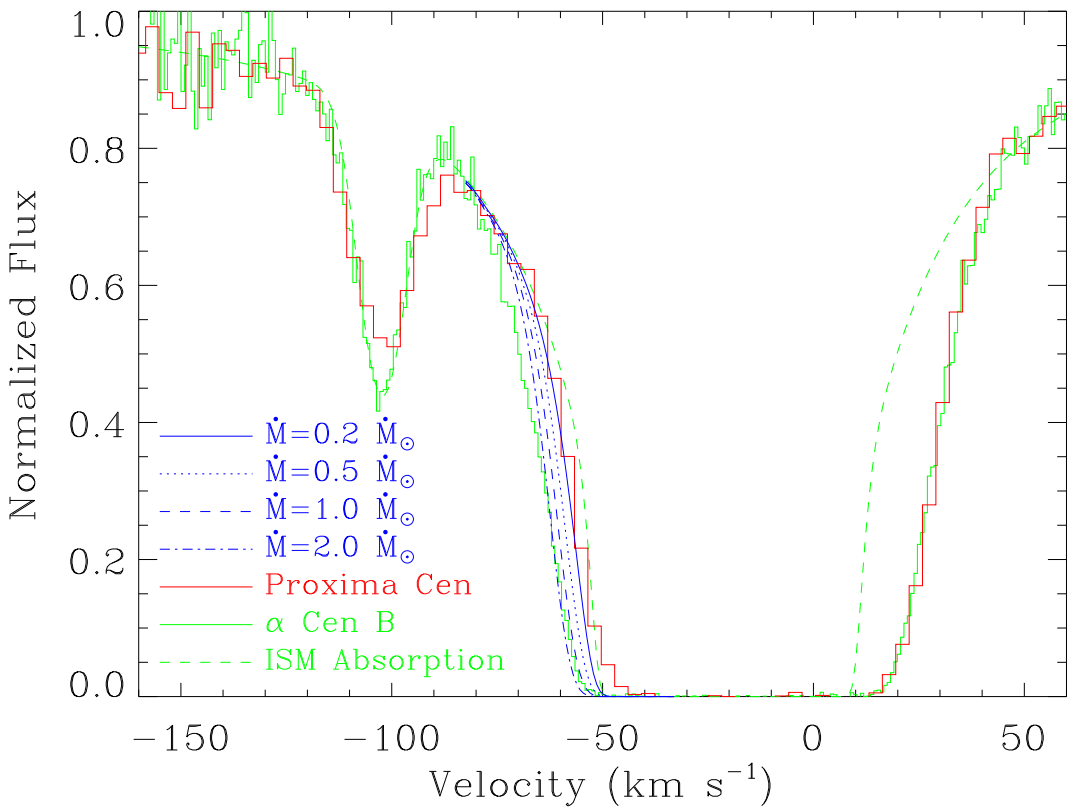

Fig. 1.— Comparison between the Lyα spectra of α Cen B (green histogram) and Proxima Cen (red histogram). The inferred ISM absorption is shown as a green dashed line. The α Cen/Proxima Cen data agree well on the red side of the H I absorption, but on the blue side the Proxima Cen data do not show the excess Lyα absorption seen toward α Cen B (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 $\dot{M}_\odot$ model fits the α Cen spectrum reasonably well, and the 0.2 $\dot{M}_\odot$ model represents an upper limit of 4×10^{-15} $M_\odot$ yr^{-1} for the mass-loss rate of Proxima Cen.

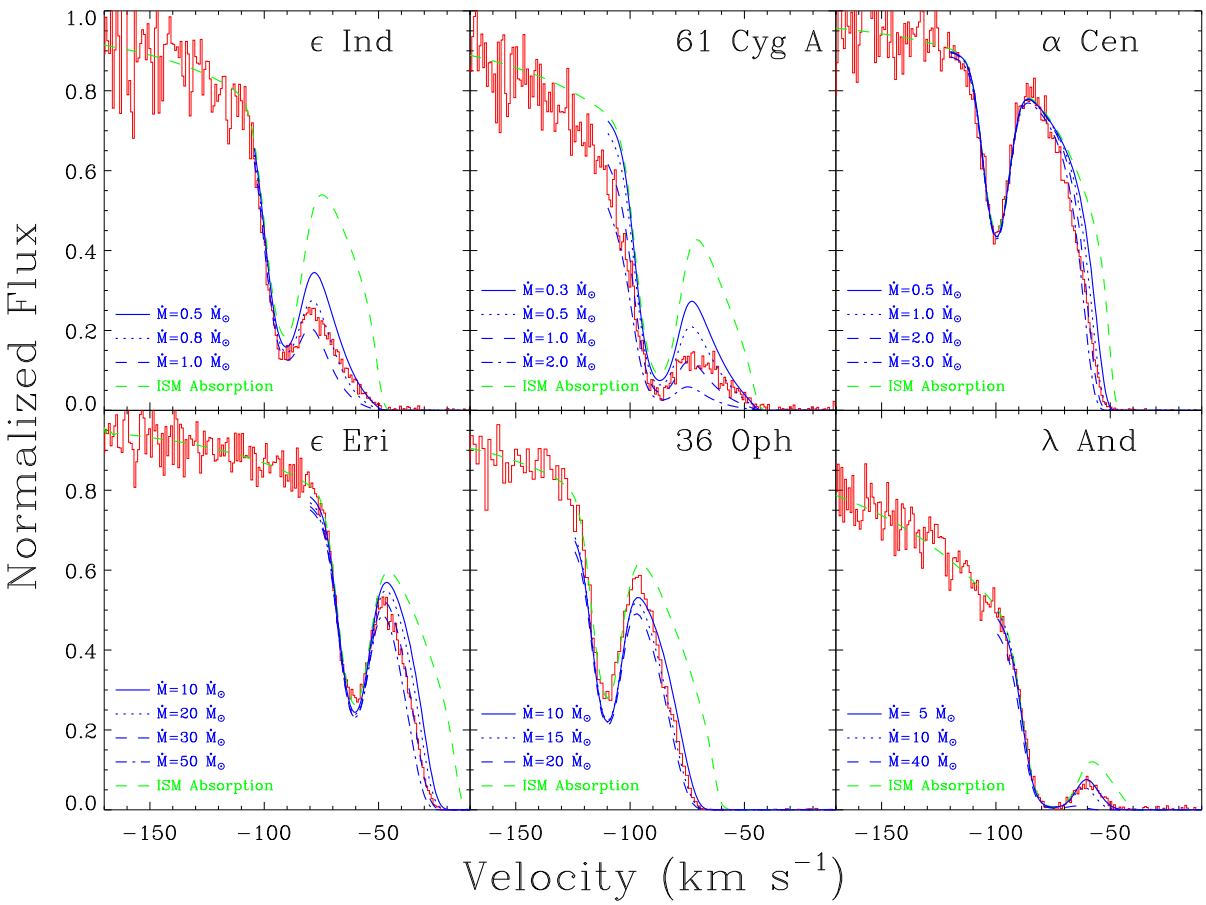

Fig. 2.— Closeups of the blue side of the H I Lyα absorption lines for six stars with detected astrospheric absorption, plotted on a heliocentric velocity scale. Narrow D I ISM absorption is visible in all the spectra just blueward of the saturated H I absorption. Green dashed lines indicate the interstellar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

Ayres (1997), combine them with our empirical mass loss/activity relation, and find a simple relation between mass loss rate and stellar age, $\dot{M} \propto t^{-2.00\pm0.52}$. This relation, plotted in Figure 3, predicts that the mass loss rate of the young Sun ($t \approx 10^8$ years) was 200–10,000 times larger than at present. The cumulative mass loss from age 10^8 years to the present is $\leq 0.03 M_\odot$.

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.

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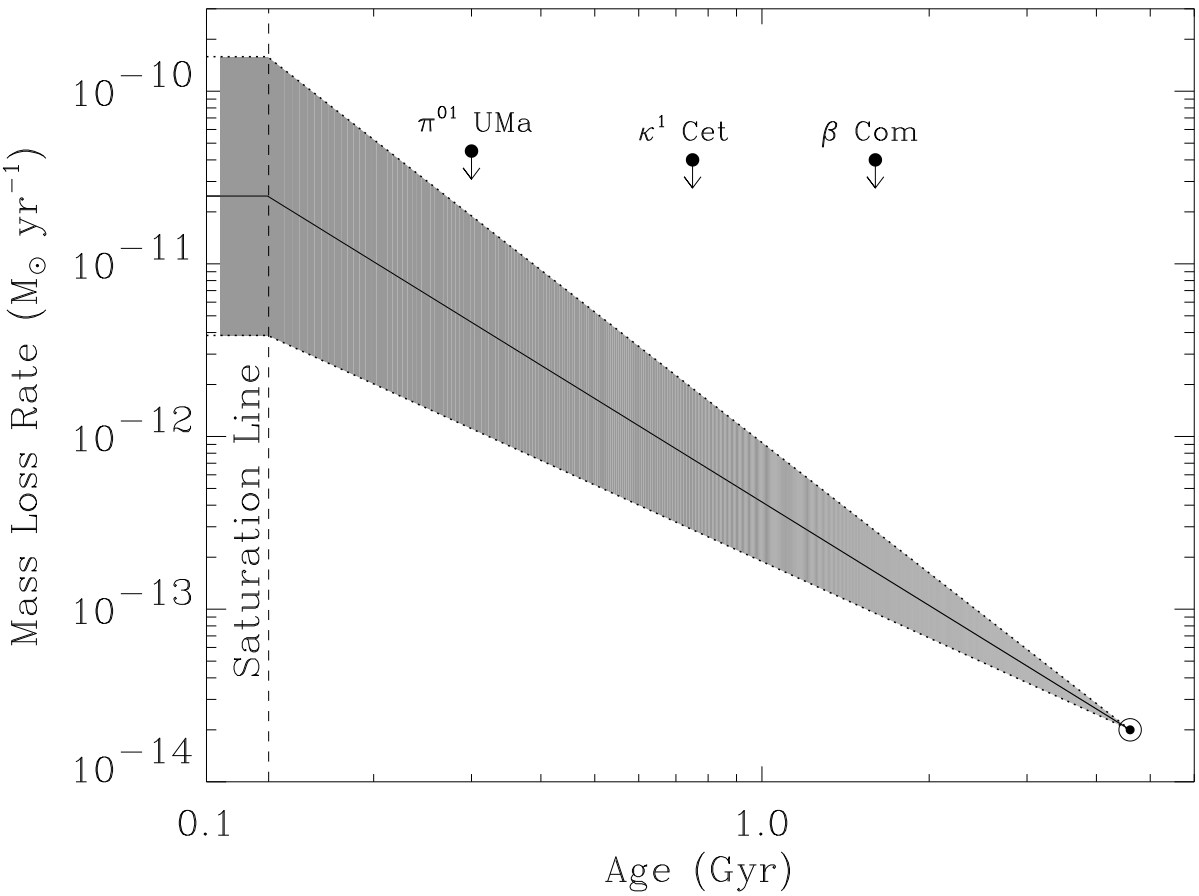

Fig. 3.— The mass loss history of the Sun. The upper limits are based on radio nondetections of three solar-like stars (Gaidos et al. 2000).

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