The solar wind in time

Jeffrey L. Linsky[1], Brian E. Wood[2] and Seth Redfield[3]

[1] JILA, University of Colorado and NIST,
Boulder, Colorado 80309-0440, USA
email: `jlinsky@jilau1.colorado.edu`

[2] Naval Research Laboratory, Space Science Division,
Washington, DC 20375, USA
email: `brian.wood@nrl.navy.mil`

[3] Astronomy Department, Wesleyan University, Middletown, CT 06459, USA
email: `sredfield@wesleyan.edu`

Abstract. We describe our method for measuring mass loss rates of F–M main sequence stars with high-resolution Lyman-α line profiles. Our diagnostic is the extra absorption on the blue side the interstellar hydrogen absorption produced by neutral hydrogen gas in the hydrogen walls of stars. For stars with low X-ray fluxes, the correlation of observed mass loss rate with X-ray surface flux and age predicts the solar wind mass flux between 700 Myr and the present.

Keywords. ISM:lines and bands, ISM:magnetic fields, solar wind, stars:winds, Sun: UV radiation, ultraviolet:ISM

---

1. Why mass loss rates are needed for the Sun and cool dwarf stars

Ultraviolet spectroscopy is an important tool for measuring mass loss rates ($\dot{M}$) of massive stars, late-type giants, and premain sequence stars when $\dot{M} > 10^{-10}$ $M_\odot yr^{-1}$. By comparison, the solar mass loss rate measured by space experiments is far smaller, about 2×10^{-14} $M_\odot yr^{-1}$. Until 10 years ago, there were no measured values of $\dot{M}$ for main sequence stars cooler than about spectral type A because there were no spectral or other diagnostics capable of measuring $\dot{M}$ far smaller than 10^{-10} $M_\odot yr^{-1}$.

While mass loss rates similar to the Sun do not significantly reduce a star's mass and thus nuclear evolution during its lifetime (see below), accurate measurements of $\dot{M}$ are needed for many reasons: (1) the torque exerted by even weak stellar winds reduces the stellar rotation rate and thus the magnetic dynamo and stellar activity, (2) knowledge of $\dot{M}(t)$ for the young Sun is important for understanding the evolution of the atmospheres of solar system planets like Mars that have lost their magnetic fields, and (3) the discovery of exoplanets close to their host stars highlights the need to predict the properties of stellar winds that impact the atmospheres of these exoplanets. Since we cannot measure $\dot{M}_\odot$ back in time, it is critical to find a reliable diagnostic to measure $\dot{M}$ for solar-mass stars with a range of ages and coronal properties in order to scale to the young Sun. Unfortunately, theoretical estimates of $\dot{M}$ are controversial, an empirical relationship between $\dot{M}$ and X-ray flux was not previously known, and no space probe will enter an astrosphere to directly measure $\dot{M}$ for a very long time.

2. The Lyman-α diagnostic for stellar mass loss rates

Baranov & Malama (1995) showed that charge exchange processes between solar wind protons and neutral hydrogen atoms in the local interstellar medium (ISM) produce a population of heated, decelerated hydrogen atoms concentrated in the interstellar upwind
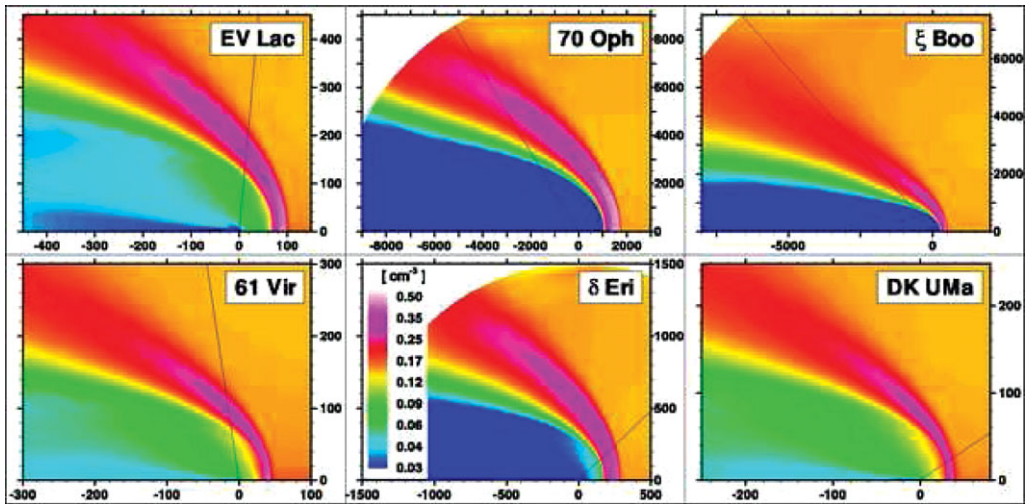
Figure 1. Theoretical models including charge exchange processes of the neutral hydrogen distribution around six stars. Units for the x and y axes are Astronomical Units, and the stars are moving to the right compared to the local ISM. High densities (red color, in the online version of this paper) indicate the location of hydrogen walls. Solid lines show the line of sight to the Earth (Wood *et al.* 2005).

direction, the so-called "hydrogen wall". These calculations and those in subsequent models of Zank *et al.* (1996), Izmodenov *et al.* (1999), and Müller *et al.* (2001) allowed Wood *et al.* (2001) to compute $\dot{M}$ for α Cen. They showed that along the line of sight to the star, the stellar Lyman-α line contains three absorption components due to interstellar hydrogen, the solar hydrogen wall, and the stellar hydrogen wall. The decelerated hydrogen atoms in the solar hydrogen wall produce absorption on the red side of interstellar absorption. Hydrogen atoms in stellar hydrogen walls are decelerated relative to the ISM as seen by the star and thus blue-shifted relative to the interstellar absorption as seen from the Earth.

Figure 1 shows maps of neutral hydrogen density computed for 6 stars studied by Wood *et al.* (2005). These models show the presence of hydrogen walls around the stars. Figure 2 shows the Lyman-α profiles for these stars observed with the *Space Telescope Imaging Spectrograph* on the *Hubble Space Telescope*. Also included are the interstellar hydrogen absorption profiles predicted from the observed deuterium Lyman-α interstellar absorption and additional astrosphere absorption based on models with a range of $\dot{M}$ values relative to the solar value. These models assume that the stellar wind speed is 400 km s^{-1}, but $\dot{M}$ scales roughly linearly with the wind speed.

The effect of increasing stellar mass loss rate is to increase the absorption on the blue side of the interstellar absorption. The theoretical Lyman-α profiles, which have been convolved with the instrumental profile, show good agreement with the observed profiles at a best fit value of $\dot{M}$ with about a factor of 2 uncertainty.

Figure 3 (left) shows the values of $\dot{M}$ obtained for 12 stars studied by Wood *et al.* (2005) and the Sun compared with the X-ray surface fluxes (F_X), obtained at different times than the $\dot{M}$ measurements. Since X-ray emission is variable, there should be some scatter in any correlation of such non-simulataneous data. Nevertheless, there appears to be a correlation of $\dot{M}$ per cm^2 of stellar surface with F_X over two orders of magnitude in $\dot{M}$ with the Sun consistent with the trend. The power-law fit to these data is
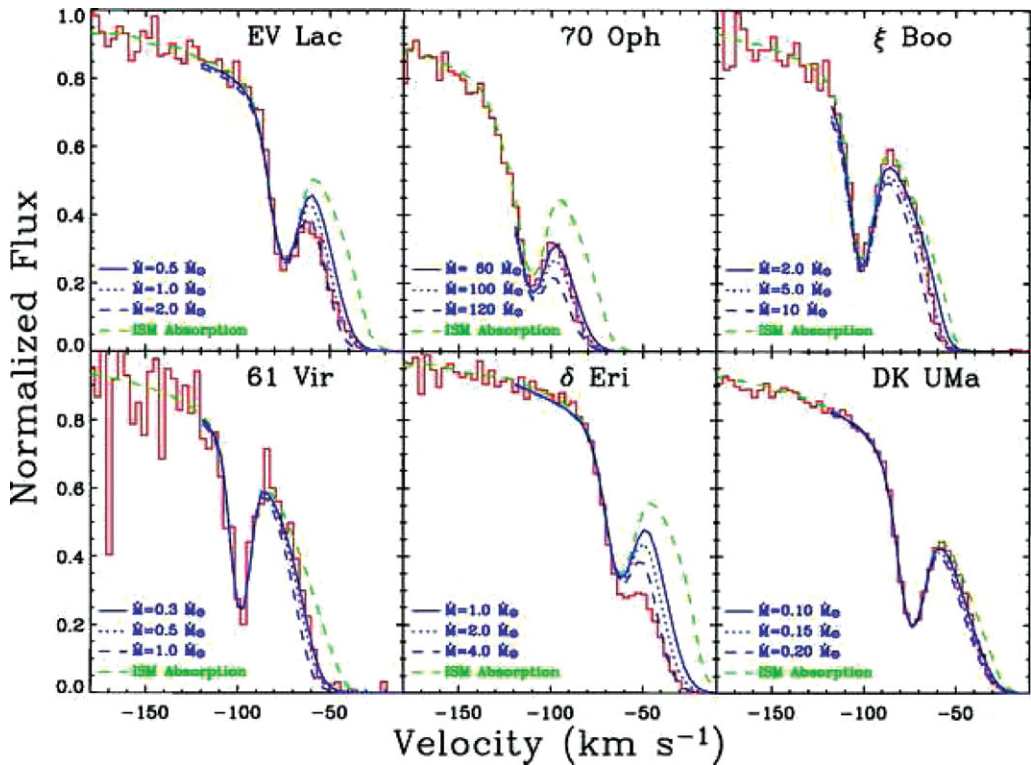
Figure 2. Observed Lyman-α profiles (red histograms) are compared to models with no mass loss (green (in the online version) dashed line marked ISM absorption) and models with different mass loss rates compared to the solar value (Wood *et al.* 2005). For a color figure, see the online version of the paper.

$$\dot{M} \propto F_X^{1.34 \pm 0.18}. \tag{2.1}$$

For $F_X > 8 \times 10^5$ erg cm^{-2} s^{-1}, the fit is no longer valid as all of the data points lie at lower values than predicted by an extrapolation of the fit. Why do the more active stars violate the fit shown by the less active stars?

Before we apply the $\dot{M}$-F_X relation to estimating the properties of the solar wind in time, it is important to understand the limitations of this relation. We have already mentioned that the mass loss and X-ray data are not simulataneous and that we have assumed that all of these stars have outflow velocities of 400 km s^{-1} similar to the quiet Sun. Also, the relation is based on data for stars with a range of spectral types (G2 V to K5 V), and some are binaries. Two of the more active stars are M dwarfs, but one is a G8 V star (ξ Boo). Clearly $\dot{M}$ values are needed for more stars to confirm the $\dot{M}$-F_X relation for the less active stars and to determine whether the more active stars are inconsistent because they are more active or because they are M dwarfs. Nevertheless, eight G and K-type stars fit the relation within a factor of two despite the uncertainties, and we assume the relation to be valid as a working hypothesis. We have two approved *HST/STIS* programs to observe eight more stars and there may be other observed targets to fill in the diagram and test our conclusions.

Ayres (1997) found a relation between X-ray surface flux and age (t) for solar-type dwarf stars, $F_X \propto t^{-1.74 \pm 0.34}$. Combining this relation with the $\dot{M}$-F_X relation leads to
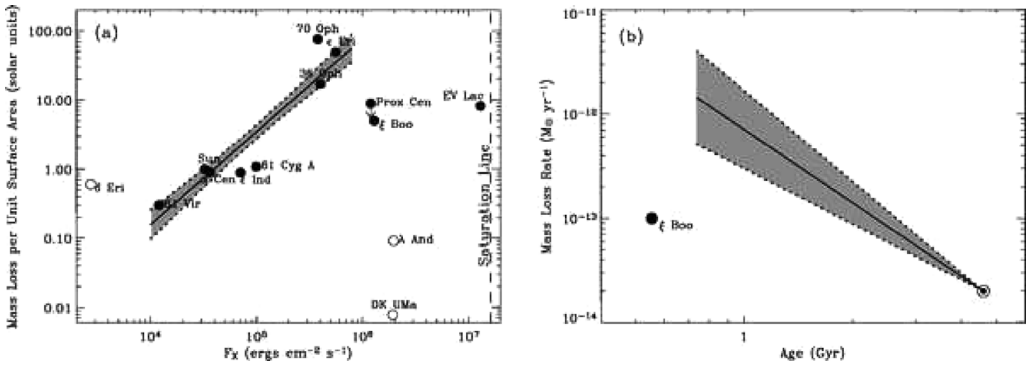
Figure 3. Left: Observed mass loss rates per cm^2 of stellar surface are compared to X-ray surface fluxes. Filed circles are for main sequence stars and unfilled circles are for subgiants and giants. The solid and dashed lines are for Eq. 2.1 and its uncertainty. Right: solar mass loss rate from 700 Myr to the present computed from Eq. 2.2 (Wood *et al.* 2005).

$$\dot{M} \propto t^{-2.33 \pm 0.55}. \tag{2.2}$$

This relation shown in the right hand side of Fig. 3 provides an estimate of $\dot{M}_\odot$ back to an age of 700 Myr when F_X would have been larger than the upper limit of the $\dot{M}$-F_X relation. This age is slightly larger than the age of the Hyades. The total mass loss for the Sun between 700 Myr and the present is 0.001 $M_\odot$ with an uncertainty of a factor of 10 (Wood *et al.* 2002). If $\dot{M}$ remained at 1.5×10^{-12} ($\pm$ a factor of 3) $M_\odot$ yr^{-1} over the Sun's early life on the main sequence ($0 \leqslant t \leqslant 700$ Myr), then the additional mass loss would be 0.001 $M_\odot$ ($\pm$ a factor of 3). This amount of mass loss would not have modified the Sun's evolution, but the amount of mass loss before 700 Myr is uncertain.

Can theoretical models for stars with solar-type magnetic field topologies explain the $\dot{M}$-F_X relation? Cranmer & Saar (2011) find that Alfvén wave-driven winds predict a factor of 30 increase in $\dot{M}$ for a solar mass star as the rotation period decreases from 25 to six days, consistent with the increase in $\dot{M}$ predicted by the $\dot{M}$-F_X relation.

Why is the $\dot{M}$-F_X relation not valid for the more active stars? A likely explanation is that the magnetic topology of rapidly rotating stars which have strong X-ray emission is different from that of slowly rotating stars. Zeeman-Dopler imaging studies show that rapidly rotating dwarf stars with mass greater than 0.5 M$_\odot$ have strong torroidal fields, and low mass stars often have strong poloidal fields (Donati & Lanstreet 2009). The maximum F_X for which Eq. 2.1 is valid corresponds to a rotation period of six days for a solar-mass star. Zeeman-Dopler images of such stars show large polar spots surrounded by torroidal magnetic fields. Theoretical models for stars with different magnetic topologies are needed to understand why the $\dot{M}$-F_X relation is not valid for these stars. We note that the solar wind mass flux is nearly the same in coronal holes and equatorial regions despite the difference in magnetic field topology (Phillips 1995).

References

Ayres, T. R. 1997, *J. Geophys. Res.*, 102, 1641
Baranov, V. B. & Malama, Y. G. 1995, *J. Geophys. Res.*, 100, 14755
Cranmer, S. R. & Saar, S. H. 2011, *ApJ*, 741, 54
Donati, J.-F. & Landstreet, J. D. 2009, *ARAA*, 47, 333
Izmodenov, V. V., Lallement, R., & Malama, Y. G. 1999, *A&A*, 342, L13

Müller, H.-R., Zank, G. P., & Wood, B. E. 2001, *ApJ*, 551, 495

Phillips, J. L. 1995, *Science*, 268, 1030

Wood, B. E., Linsky, J. L., Müller, H.-R., & Zank, G. P. 2001, *ApJ* Letters, 547, L49

Wood, B. E., Müller, H.-R., Zank, G. P., & Linsky, J. L. 2005, *ApJ*, 574, 412

Wood, B. E., Müller, H.-R., Zank, G. P., Linsky, J. L., & Redfield, S. 2005, *ApJ* Letters, 628, L143

Zank, G. P., Pauls, H. L., Williams, L. L., & Hall, D. T. 1996, *J. Geophys. Res.*, 101, 21,639

Discussion

DIBYENDU NANDI: We know that there is a strong power law relationship between magnetic flux and X-ray flux. Given that you find a connection between X-ray flux and stellar wind, perhaps this relationship can be utilized to infer the magnetic history of the Sun?

JEFFREY LINSKY: Yes, we will look for a correlation of the unsigned average magnetic flux with the mass loss rate and then the magnetic field history of the Sun.

JANET LUHMANN: Have you thought about the possible effect of a solar maximum type solar wind that is structured and bursty, rather than steady, laminar and uniform? Is your thinking affected by new IBEX results?

JEFFREY LINSKY: We find that the mass loss rate declines to a plateau when the X-ray surface flux becomes greater that 10^6 erg cm^{-2} s^{-1}, which corresponds to a stellar rotation rate of about 7 days for a solar mass star. At this rotation rate the stellar magnetic field is probably more dipole-like than for the Sun. We have not considered bursty and inhomogeneous flows.

We look forward to IBEX measurements of the speed of in-flowing helium atoms from the interstellar medium. This will tell us whether the heliosphere is located inside the Local Interstellar Cloud (LIC) or in a transition region between the LIC and another cloud. The answer to this question will determine the outer boundary condition of the solar wind.