The Winds of Solar-like Stars and Their Interactions with the ISM

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Abstract:
Models of the solar wind’s interaction with the local interstellar medium predict the existence of hot, decelerated neutral hydrogen gas just outside the heliopause. Lyman-\(\alpha\) absorption from this “hydrogen wall” has been detected in HST GHRS spectra. The recent detection of Lyman-\(\alpha\) absorption from stellar hydrogen walls allows us for the first time to study the solar-like winds of other stars. In this article, we summarize the hydrogen walls detected to date (some only tentatively). We then try to determine if the measured properties of the walls are consistent with theoretical expectations, and we assess the usefulness of the hydrogen wall properties for inferring properties of the stellar winds. Stellar wind pressures estimated from the hydrogen wall column densities appear to be correlated with stellar X-ray surface fluxes, \(F_X\), in a manner consistent with the relation \(P_{\text{wind}} \propto F_X^{-1/2}\), a relation that is also consistent with the variations of \(P_{\text{wind}}\) and \(F_X\) observed during the solar activity cycle. If this relation does in fact apply to solar-like stars in general, stellar wind pressures and mass loss rates are then predicted to increase with time, since \(F_X\) is known to decrease with stellar age.

1. Introduction

The interaction between the solar wind (SW) and the local interstellar medium (LISM) has been a subject of study for over four decades (see the review of Holzer 1989). This interaction determines the size of the heliosphere, which is the volume of space dominated by the SW. Models of the heliosphere generally predict the existence of three important discontinuities in the flows of the LISM and SW material, which are shown schematically in Figure 1. The termination shock is an oval-shaped boundary surrounding the Sun, where the supersonic SW is decelerated to subsonic speeds. Further out in the direction of the inflowing LISM material (i.e., the “upwind” direction) lies the bow shock, where the supersonic interstellar wind is decelerated to subsonic speeds. Finally, between these two shocks lies the heliopause, which separates the plasma flows of the solar and interstellar winds and defines the outer boundary of the heliosphere.

A problem that has always plagued studies of the heliosphere is the lack of observational constraints for the models. Properties of the SW and LISM

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Figure 1. A schematic illustration of how the solar wind (thin solid lines) interacts with the plasma component of the interstellar wind (dotted lines). The shaded area indicates the general location of a region of heated, compressed, and decelerated H\,i that has been referred to as a “hydrogen wall.” The heliopause, which roughly marks the inner edge of the hydrogen wall, is about 120 AU from the Sun in the upwind direction according to recent models of the heliosphere.

Particles in the solar system have been measured by Ulysses and the Voyager satellites, among others, but inferring properties of the heliosphere outside of the solar system from these data is difficult and somewhat model dependent. Fortunately, a promising new technique for studying the outer heliosphere has recently been discovered using data from the Hubble Space Telescope (HST). Analyses of the Lyman-α lines of α Cen A and B observed by the Goddard High Resolution Spectrograph (GHRS) onboard HST have revealed the presence of a wall of compressed and heated interstellar H\,i surrounding the Sun (Linsky & Wood 1996; Gayley et al. 1997). The existence of this “hydrogen wall” (or “H-wall” for short) is predicted by recent heliospheric models (Baranov & Malama 1995; Pauls, Zank, & Williams 1995). The general location of the H-wall is indicated in Figure 1, although the H-wall does not really have such a sharply delineated boundary.
Table 1. Compilation of Detected Stellar Hydrogen Walls

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectral Type</th>
<th>( d ) (pc)</th>
<th>( v ) (km s(^{-1}))</th>
<th>( \theta ) (deg)</th>
<th>( v_{HW} - v_{ISM} ) (km s(^{-1}))</th>
<th>( T_{HW} ) (10(^3) K)</th>
<th>( \log N_{HW} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>G2 V</td>
<td>...</td>
<td>25.6</td>
<td>52</td>
<td>( &gt; 2 )</td>
<td>29 ± 5</td>
<td>14.74 ± 0.24</td>
</tr>
<tr>
<td>( \varepsilon ) Eri</td>
<td>K1 V</td>
<td>3.3</td>
<td>25.9</td>
<td>77</td>
<td>(-12 ± 6)</td>
<td>28 ± 5</td>
<td>14.3 ± 0.2</td>
</tr>
<tr>
<td>( \alpha ) And</td>
<td>G8 IV–III+?</td>
<td>29</td>
<td>47.7</td>
<td>89</td>
<td>(-8 ± 3)</td>
<td>62 ± 18</td>
<td>14.8 ± 0.2</td>
</tr>
<tr>
<td>( \varepsilon ) Ind</td>
<td>K3 V</td>
<td>3.5</td>
<td>64.0</td>
<td>60</td>
<td>(-18 ± 6)</td>
<td>100 ± 20</td>
<td>14.2 ± 0.2</td>
</tr>
<tr>
<td>61 Cyg A</td>
<td>K5 V</td>
<td>3.5</td>
<td>85.0</td>
<td>46</td>
<td>(-21 ± 10)</td>
<td>180 ± 20</td>
<td>14.1 ± 0.2</td>
</tr>
<tr>
<td>40 Eri A</td>
<td>K1 V</td>
<td>4.8</td>
<td>123.2</td>
<td>58</td>
<td>(-20 ± 15)</td>
<td>360 ± 80</td>
<td>13.75 ± 0.20</td>
</tr>
</tbody>
</table>

In addition to the solar H-wall, GHRS data have also been used to at least tentatively detect H-walls around five other stars (Wood, Alexander, & Linsky 1996; Dring et al. 1997; Wood & Linsky 1998). The discovery of these structures represents the first detection, albeit indirect, of the solar-like winds of other stars. In Table 1, we summarize the measured properties of the H-walls detected to date. Listed in the table are the stars, their spectral types, their distances from the Sun (\( d \)), their velocities through the LISM (\( v \)), and the angle in the stellar rest frame between the upwind direction and the line of sight sampled by the GHRS observations (\( \theta \)). We also list the three parameters measured for the hydrogen walls: the H-wall temperature (\( T_{HW} \)), the H\(^{\text{I}} \) column density (\( N_{HW} \)), and the H-wall flow velocity (\( v_{HW} \)), which in Table 1 is listed relative to the line-of-sight ISM velocity (\( v_{ISM} \)).

2. How are Hydrogen Walls Detected?

The H\(^{\text{I}} \) column densities of the hydrogen walls are large enough to produce sufficient Lyman-\( \alpha \) absorption to be detectable in GHRS observations of stellar Lyman-\( \alpha \) lines. However, separating this absorption from the broad interstellar absorption is not easy, especially since one must also estimate the unknown shape of the intrinsic stellar emission line, much of which is obliterated by the ISM and H-wall absorption.

The 61 Cyg A and 40 Eri A fits of Wood & Linsky (1998) provide good examples of the uncertainties inherent in this kind of analysis. Figures 2a and 3a show that the Lyman-\( \alpha \) spectra of both stars can be fitted with just interstellar hydrogen and deuterium absorption lines, without any need for a hydrogen wall component. (For 40 Eri A, a very narrow geocoronal component is also included.)

However, in Figure 2a the assumed stellar Lyman-\( \alpha \) profile for 61 Cyg A has a very deep self-reversal that we believe is unlikely, based on previous experience with optically thick chromospheric lines such as Lyman-\( \alpha \) and Mg\(^{II}\) h & k. The only way to fit the data without assuming such a deep self-reversal is to add another absorption component to the analysis. This is done in Figure 2b, and the parameters of the additional component (dashed line) are consistent with those expected for a stellar H-wall. These expectations include a line velocity suggesting substantial deceleration from the line-of-sight ISM velocity, a very high temperature produced by shock heating, and a relatively low column density — too low to be detected in any line but H\(^{\text{I}} \) Lyman-\( \alpha \).

For the 40 Eri A fit in Figure 3a, there is nothing wrong with the assumed stellar Lyman-\( \alpha \) profile, but the interstellar deuterium-to-hydrogen ratio of this fit, \( D/H = (1.11 ± 0.09) \times 10^{-5} \), is inconsistent with all other measurements.
Figure 2. Two fits to the H1 and D1 absorption lines seen toward 61 Cyg A (at 1215.65 Å and 1215.3 Å, respectively). The thin solid lines are the assumed stellar Lyman-α profiles. In panel (a), only interstellar absorption is considered, while in panel (b) both an interstellar absorption component (dotted line) and a stellar H-wall absorption component (dashed line) are included. In both panels, the combination of all absorption components is shown as a thick solid line, which fits the data.

of very nearby interstellar material, which suggest D/H ≈ 1.5 × 10⁻⁵ (Linsky et al. 1997). The apparent detection of D/H variations in the ISM could be a very interesting and important result, but Figure 3b shows that the expected D/H ratio can be recovered simply by including a stellar H-wall component with reasonable parameters.

Because of the problems with the fits in Figures 2a and 3a mentioned above, we consider the fits presented in Figures 2b and 3b, the ones with stellar H-wall components, to be better interpretations of the data. Nevertheless, the detections of stellar H-wall absorption toward 61 Cyg A and 40 Eri A should still be considered to be tentative at this point.

3. Testing the Hydrogen Wall Measurements

In the previous section, we used the analysis of the 61 Cyg A and 40 Eri A data to illustrate the difficulties in positively detecting stellar H-wall absorption in Lyman-α spectra. However, the case for the presence of stellar H-wall absorp-
Figure 3. Two fits to the H\textsc{i} and D\textsc{i} absorption lines seen toward 40 Eri A (at 1215.75 Å and 1215.4 Å, respectively). The thin solid lines are the assumed stellar Lyman-\(\alpha\) profiles. In both fits, interstellar and geocoronal absorption components are included (dotted and dashed lines, respectively), but in panel (b) a stellar H-wall absorption component is added (dot-dashed line). In both panels, the combination of all absorption components is shown as a thick solid line, which fits the data.

...tion is stronger for the \(\epsilon\) Ind and \(\epsilon\) Eri data (see Wood et al. 1996 and Dring et al. 1997), and additional support for the H-wall detections is provided by comparing the data and the measured hydrogen wall parameters with theoretical expectations. Gayley et al. (1997) have made a direct comparison between the Lyman-\(\alpha\) absorption predicted by heliospheric models and the Lyman-\(\alpha\) spectra used by Linsky & Wood (1996) to detect the solar H-wall. Gayley et al. (1997) concluded that solar H-wall absorption was indeed present in the data and could be used to constrain the heliospheric models.

Stars traveling rapidly through the ISM should have hotter hydrogen walls than stars moving at slower speeds, due to greater shock heating. Inspection of columns 4 and 7 of Table 1 shows that the H-wall measurements are consistent with this prediction. A more quantitative comparison between the measured temperatures and theory is provided in Figure 4, where the measured H-wall temperatures (relative to the pre-shock local ISM temperature) are plotted versus the stellar velocity through the ISM. Also shown in the figure are predicted relations based on the hydromagnetic shock jump conditions. The jump rela-
Figure 4. We plot the ratio of the measured hydrogen wall temperature ($T_2$) to the interstellar temperature ($T_1 = 8000$ K) versus the stellar velocity through the LISM ($v_1$). The lines in the figure are theoretical predictions based on the hydromagnetic shock jump conditions. In the top (bottom) panel, the ratio of magnetic pressure to thermal pressure in the LISM is assumed to be $\alpha = 0$ ($\alpha = 2$). In each panel, theoretical curves are plotted for three assumed values of the hydrogen ionization fraction in the LISM ($x = 0.0$, $0.5$, and $1.0$).

...tions depend on two free parameters, the hydrogen ionization fraction in the local ISM ($x$) and the ratio of the magnetic pressure to thermal pressure in the ISM ($\alpha$), both of which are poorly constrained by observation. In general, the agreement between the data and the theoretical curves is quite good, especially for the $\alpha = 0$, $x = 0.5$ case.
4. Estimating Stellar Wind Ram Pressures from the H-Wall Measurements

In the upwind direction, the stellar wind ram pressure, $P_{\text{wind}}$, is balanced by the interstellar wind pressure at the termination shock (see Fig. 1). This interstellar wind pressure can be expressed as $P_{\text{ISM}} = \rho_{\text{ISM}} v^2$, where $\rho_{\text{ISM}}$ is the interstellar density and $v$ is the velocity of the star through the ISM. Since $P_{\text{wind}}(r)$ falls off as $1/r^2$, the distance to the termination shock is approximately

$$R_{\text{TS}}^2 = 0.88 \frac{P_{\text{wind}}(r)}{P_{\text{ISM}}} r^2,$$

where the 0.88 factor is meant to account for the reduction in pressure that occurs just outside the termination shock due to flows in that region (Parker 1963). We are interested in comparing wind pressures of stars with different radii (especially $\lambda$ And). In order to make for a more equitable comparison, we choose to evaluate $P_{\text{wind}}$ at the surfaces of the stars, so we will set the reference radius, $r$, to be equal to the stellar radius, $R$.

The termination shock distance is indicative of the size scale of the entire atmosphere, so the thickness of the hydrogen wall, $h_{\text{HW}}$, should be roughly proportional to $R_{\text{TS}}$. Since the H-wall column density is proportional to $h_{\text{HW}}$, $N_{\text{HW}} \propto h_{\text{HW}} \propto R_{\text{TS}}$. Thus, equation (1) can be turned into the following expression for the stellar wind pressure (at the stellar surface) relative to the solar wind pressure [$P_{\odot} \equiv P_{\text{wind}}(R_{\odot})$],

$$\frac{P_{\text{wind}}(R)}{P_{\odot}} = \left( \frac{N_{\text{HW}}}{N_{\odot}} \frac{v}{v_{\odot}} \frac{R_{\odot}}{R} \right)^2.$$

Values for $v$, $v_{\odot}$, $N_{\text{HW}}$, and $N_{\odot}$ are listed in columns 4 and 8 of Table 1. Assumed stellar radii are listed in Table 2, along with values of $P_{\text{wind}}(R)/P_{\odot}$ computed using equation (2). We also list X-ray surface fluxes for the stars ($F_{\chi}$) in the table, which are based on ROSAT PSPC data.

<table>
<thead>
<tr>
<th>Star</th>
<th>$R/R_{\odot}$</th>
<th>$\log F_{\chi}$</th>
<th>$P_{\text{wind}}(R)/P_{\odot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>1.0</td>
<td>4.21</td>
<td>1.00</td>
</tr>
<tr>
<td>$\epsilon$ Eri</td>
<td>0.8</td>
<td>5.86</td>
<td>0.22</td>
</tr>
<tr>
<td>$\lambda$ And</td>
<td>7.0</td>
<td>6.09</td>
<td>0.09</td>
</tr>
<tr>
<td>$\epsilon$ Ind</td>
<td>0.7</td>
<td>4.71</td>
<td>1.06</td>
</tr>
<tr>
<td>61 Cyg A</td>
<td>0.7</td>
<td>4.79</td>
<td>1.18</td>
</tr>
<tr>
<td>40 Eri A</td>
<td>0.8</td>
<td>5.01</td>
<td>0.38</td>
</tr>
</tbody>
</table>

It is difficult to predict how $P_{\text{wind}}$ might vary with $F_{\chi}$ based on our current limited understanding of solar/stellar winds. On one hand, magnetic fields play a vital role in many wind acceleration mechanisms, which suggests that $P_{\text{wind}}$ should increase with $F_{\chi}$. One the other hand, a more magnetically active star will have more closed field lines that inhibit stellar wind flow, suggesting that $P_{\text{wind}}$ should decrease with increasing $F_{\chi}$. The solar example demonstrates the
importance of this latter effect. During its 11-year activity cycle, the solar X-ray luminosity in the ROSAT PSPC bandpass varies by about a factor of 4 (Ayres 1997). However, while $F_X$ decreases by a factor of 4 from solar maximum to minimum, data from Voyager 2 shows that the solar wind ram pressure actually increases by a factor of 2, at least near the ecliptic plane (Lazarus & McNutt 1990). In Figure 5, we plot $\log P_{\text{wind}}(R)/P_\odot$ versus $\log F_X$. Two points are used to represent the Sun, one for solar minimum and one for solar maximum. These points are connected by a thick line, and the dashed line extends the relation to larger values of $F_X$. This $P_{\text{wind}} \propto F_X^{-1/2}$ relation is indeed consistent with our crude estimates of $P_{\text{wind}}(R)/P_\odot$ for the other stars.

Figure 5 raises the possibility of extrapolating the relationships between $F_X$ and solar wind properties seen during the solar activity cycle to other stars with larger $F_X$ values. It then becomes possible to study stellar winds simply
by measuring stellar X-ray fluxes. One can then, for example, estimate how mass loss varies with time for solar-like stars, since it is already known that $F_X$ decreases with time. In particular, $F_X \propto t^{-1.74}$ for solar-like stars (Ayres 1997). Thus, the $P_{\text{wind}} \propto F_X^{-1/2}$ relation predicts

$$P_{\text{wind}} \propto t^{0.87}.$$  \hspace{1cm} (3)

Since the solar mass loss rate ($\dot{M}$) also appears to be lower at solar maximum than at solar minimum, a similar time dependence would be predicted for $\dot{M}$. Relation (3) implies that wind pressure and mass loss increase with time, and that the solar wind should have been weaker in the past.

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