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OBSERVATIONAL ESTIMATES FOR THE MASS-LOSS RATES OF α CENTAURI AND PROXIMA CENTAURI USING *HUBBLE SPACE TELESCOPE* Lyα SPECTRA[1]

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ABSTRACT

We study H I Lyα absorption observed by the *Hubble Space Telescope* toward the nearby binary system α Centauri (G2 V + K0 V) and its distant companion star Proxima Centauri (M5.5 Ve). Absorption from heliospheric H I heated by the solar wind/interstellar medium interaction is observed toward both α Cen and Proxima Cen. Absorption from analogous "astrospheric" material surrounding the stars is detected toward α Cen but not Proxima Cen. The nondetection of astrospheric absorption toward Proxima Cen suggests that the stellar wind of Proxima Cen must be significantly weaker than that of the α Cen system. We compute several hydrodynamic models of the astrospheres assuming different mass-loss rates in order to predict astrospheric Lyα absorption for comparison with the observations. The model that best matches the α Cen data has a mass-loss rate of $\dot{M} = 2\ \dot{M}_{\odot}$, and the models suggest an upper limit of $\dot{M} \leq 0.2\ \dot{M}_{\odot}$ for Proxima Cen. Finally, we note that the heliospheric absorption observed toward Proxima Cen in 2000 May is identical to the heliospheric absorption observed toward α Cen in 1995 May, implying that the structure of the outer heliosphere does not change significantly during the solar activity cycle.

Subject headings: hydrodynamics — stars: individual (α Centauri, Proxima Centauri) — stars: winds, outflows — ultraviolet: ISM — ultraviolet: stars

1. INTRODUCTION

Coronal winds analogous to the solar wind have proved to be very difficult to detect around cool main-sequence stars like the Sun. This is not surprising given the low density of the solar wind, corresponding to a mass-loss rate of only about $\dot{M}_{\odot} = 2 \times 10^{-14}\ M_{\odot}\ \mathrm{yr}^{-1}$, and the fact that the wind is fully ionized. These properties mean that such winds cannot be detected spectroscopically like the massive winds of hot stars and evolved cool stars.

Ionized winds would be expected to produce radio emission, and searches for this emission have provided upper limits for the mass-loss rates of many solar-like stars. However, these upper limits are typically 3 or more orders of magnitude higher than the solar mass-loss rate (Brown et al. 1990; Drake, Simon, & Brown 1993; Lim, White, & Slee 1996b; Gaidos, Güdel, & Blake 2000). There have been some claims of high mass-loss rates detected for a few very active stars using observations at millimeter wavelengths and studies of UV absorption features (Mullan et al. 1989, 1992). However, these interpretations of the data remain highly controversial (Lim, White, & Cully 1996a; Lim & White 1996). There are theoretical arguments for large mass-loss rates from active stars (Coleman & Worden 1976; Mullan et al. 1992), but Lim & White (1996) argue that massive ionized winds would completely absorb the coronal radio emission that is commonly observed from these stars.

Fortunately, a new method for indirectly detecting winds around cool main-sequence stars has recently become available, using spectroscopic observations of stellar Lyα lines made by the *Hubble Space Telescope* (*HST*). Models of the interaction between the solar wind and the local interstellar medium (LISM) predict that charge exchange processes should create a population of heated neutral hydrogen gas throughout the heliosphere (Baranov & Malama 1995; Zank et al. 1996; Zank 1999b; Müller, Zank, & Lipatov 2000). This material produces a detectable absorption signature in the Lyα lines of many nearby stars (Gayley et al. 1997; Izmodenov, Lallement, & Malama 1999; Wood, Müller, & Zank 2000b). However, not only is heliospheric absorption detected in the data, but analogous "astrospheric" absorption from material surrounding the star is also observed in some cases.

Astrospheric Lyα absorption has by now been detected for seven nearby coronal stars, although some of the detections are tentative (Wood, Alexander, & Linsky 1996; Dring et al. 1997; Gayley et al. 1997; Wood & Linsky 1998; Wood, Linsky, & Zank 2000a). This absorption can only be present if a stellar wind is present and if the star is surrounded by interstellar medium (ISM) material that is at least partially neutral. A larger stellar mass-loss rate will result in a larger astrosphere and more Lyα absorption. Müller, Zank, & Wood (2001) use this fact to estimate mass-loss rates for two stars (ϵ Ind and λ And) based on the amount of observed astrospheric absorption. In this Letter, we perform a similar analysis to estimate the mass-loss rate of the α Centauri binary system (G2 V + K0 V), which has also been observed to have detectable astrospheric Lyα absorption (Linsky & Wood 1996; Gayley et al. 1997).

In addition, we present new *HST* Lyα observations of α Cen's distant companion star Proxima Centauri (M5.5 Ve), which can be compared directly with the α Cen data to search for differences in astrospheric absorption that would indicate differences in stellar wind properties. Unlike the two α Cen stars, which will share the same astrosphere since their orbit has a semimajor axis of only 24 AU (Pourbaix, Neuforge-Verheecke, & Noels 1999), Proxima Cen will have an astrosphere all to itself. Proxima Cen is about 12,000 AU from α Cen, based on its 2°.2 separation on the sky and its closer distance of 1.295 pc compared with 1.347 pc for α Cen (Perryman et al. 1997). Thus, while the LISM and heliospheric

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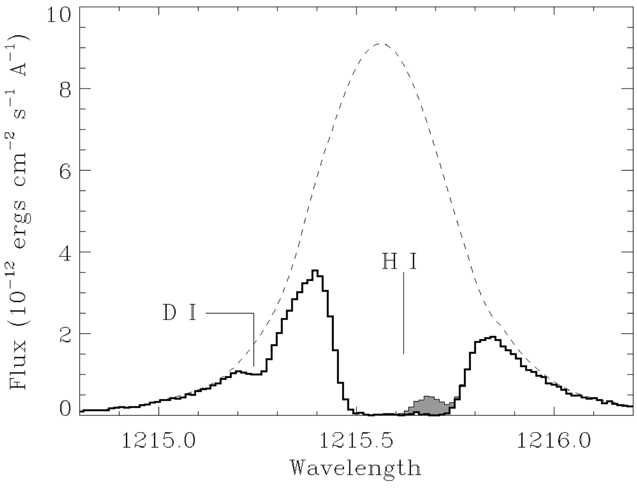

FIG. 1.—The *HST*/STIS spectrum of the Lyα line of Proxima Cen before and after removal of the geocoronal absorption (*shaded region*). The centroids of the H I and D I absorption are indicated. The dashed line is the intrinsic stellar emission line assumed in the analysis.

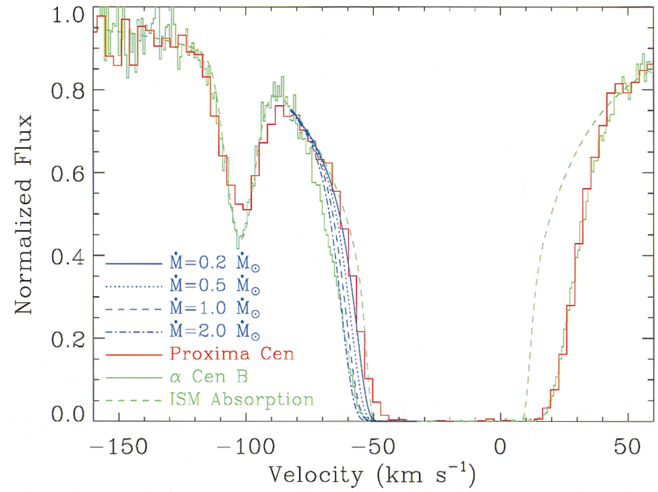

FIG. 2.—Comparison between the Lyα spectra of α Cen B (*green histogram*) and Proxima Cen (*red histogram*). The inferred ISM absorption is shown as a green dashed line. The α Cen/Proxima Cen data agree well on the red side of the H I absorption, but on the blue side the Proxima Cen data do not show 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 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 for the mass-loss rate of Proxima Cen.

absorption should be identical toward α Cen and Proxima Cen, the astrospheric absorption should be different.

2. COMPARING THE Lyα LINES OF α CEN AND PROXIMA CEN

Proxima Cen was observed on 2000 May 8 with the Space Telescope Imaging Spectrograph (STIS) instrument on *HST* (Woodgate et al. 1998). We observed the 1150–1720 Å spectral range through the $0''.2 \times 0''.2$ aperture with the moderate-resolution E140M grating. The total exposure time of the E140M spectrum was 20,580 s. The data were reduced in interactive data language (IDL) using the STIS team's CALSTIS software package (Lindler 1999). The reduction includes assignment of wavelengths using calibration spectra obtained during the course of the observations, and a correction for scattered light is performed using the ECHELLE_SCAT routine in the CALSTIS package. The resulting Lyα spectrum is displayed in Figure 1. The stellar emission is contaminated by narrow, weak deuterium (D I) absorption and very broad, saturated hydrogen (H I) absorption. A geocoronal emission feature is apparent at 1215.69 Å, which is removed from the data by fitting a Gaussian to the feature and then subtracting the Gaussian (see Fig. 1).

Both members of the α Cen binary system were observed in 1995 May with the Goddard High Resolution Spectrograph instrument that preceded STIS on board *HST*. The observations included high-resolution spectra of the Lyα line, which were analyzed by Linsky & Wood (1996). The α Cen B spectrum is shown in Figure 2, where we have normalized the fluxes using the assumed stellar emission profile. Since a precise LISM H I column density could not be derived for the α Cen line of sight, Linsky & Wood (1996) actually presented two possible stellar profiles. We use the one that results in a derived deuterium-to-hydrogen ratio of $D/H = 1.5 \times 10^{-5}$, the value that Linsky (1998) finds to be consistent with very nearby ISM material along many lines of sight. The LISM H I column density derived from the α Cen B data using this profile is $\log N_{\rm H\,I} = 17.60$.

We use this column density to estimate the stellar emission-line profile for Proxima Cen (see Fig. 1) using the following procedure. By assuming this column density, we can compute a wavelength-dependent opacity profile for the H I absorption, τ_λ. The stellar profile outside the saturated core of the H I absorption is then derived simply by extrapolating upward from the data, multiplying the spectrum by $\exp(\tau_\lambda)$. We then interpolate the profile over the saturated H I absorption core.

The green dashed line in Figure 2 shows the LISM absorption toward α Cen, based on a fit in which the H I absorption is forced to have a central velocity and Doppler-broadening parameter consistent with D I and other LISM absorption lines (Linsky & Wood 1996). Excess H I absorption is apparent on both sides of the LISM absorption. Gayley et al. (1997) used hydrodynamic models of the heliosphere to show that heliospheric H I could account for the excess absorption on the red side of the line but not the blue-side excess. The redshift of the heliospheric absorption relative to the LISM is due to the deceleration of interstellar material as it crosses the bow shock. The blue-side excess is presumably due to analogous astrospheric material surrounding the star, which is seen as blue-shifted rather than redshifted because we are observing the material from outside the astrosphere rather than inside (Gayley et al. 1997).

The observed Proxima Cen fluxes are normalized to the stellar profile shown in Figure 1, and the result is plotted in Figure 2 for comparison with the α Cen B data. We shifted the Proxima Cen spectrum by 2 km s^{-1} to force its D I absorption feature to line up with that of the α Cen spectrum. The Proxima Cen data have a lower spectral resolution than the α Cen B data, which explains why the D I line is broader and not as deep. The amount of observed D I absorption toward the two stars is essentially identical, as one would expect.

The Lyα absorption profiles of Proxima Cen and α Cen agree very well on the red side of the line, implying that the heliospheric absorption responsible for the aforementioned red-side excess is identical toward both stars. We would not expect to see any spatial variations in heliospheric absorption between two stars so nearby in the sky, but the data were taken 5 years apart and the heliosphere could have conceivably changed in the interim. The 1995 α Cen data were taken close to the minimum of the Sun's activity cycle, while the 2000 Proxima Cen data were taken close to solar maximum. Apparently, the structure of the outer heliosphere does not vary significantly during the solar activity cycle. This result is consistent with the theoretical predictions of Zank (1999a), whose time-dependent heliospheric models predict little variability for global H I properties in the outer heliosphere despite the fact that the solar wind ram pressure near Earth varies by about a factor of 2 during the solar activity cycle (Lazarus & McNutt 1990; Richardson 1997).

Unlike the red side of the Lyα line, the Lyα absorption profiles of α Cen and Proxima Cen do *not* agree well on the blue side of the line. The blue side of the Proxima Cen Lyα absorption agrees well with the estimated ISM absorption, which means that there is no detectable astrospheric absorption toward Proxima Cen, in contrast to α Cen. Note that the blue-side excess absorption seen toward α Cen and other stars has been interpreted as being due to astrospheres primarily because the properties of the absorption are consistent with theoretical expectations for astrospheric absorption. The difference in absorption between Proxima Cen and α Cen seen in Figure 2 represents the strongest *purely empirical* evidence that the blue-side excess absorption observed toward α Cen is indeed due to circumstellar material surrounding α Cen, which does not extend as far away as Proxima Cen. *This provides particularly strong evidence for the astrospheric interpretation of the excess absorption.* Differences in stellar wind properties must be responsible for the difference in astrospheric absorption. In particular, the significantly lower astrospheric H I column density of Proxima Cen suggests a much smaller astrosphere, which in turn suggests that Proxima Cen's wind is much weaker than that of α Cen.

3. ESTIMATING MASS-LOSS RATES

In an attempt to estimate mass-loss rates for α Cen and Proxima Cen, we compute a series of hydrodynamic models of the astrospheres assuming different loss rates (see Fig. 3). These models are extrapolated from a heliospheric model that correctly predicts the amount of heliospheric absorption for various lines of sight (see Wood et al. 2000b). We assume the same input parameters for the astrospheric models, with the following exceptions. Instead of an ISM temperature of 8000 K appropriate for the Local Interstellar Cloud (LIC) around the Sun, we assume a temperature of 5650 K for the ISM surrounding α Cen/Proxima Cen since these stars are not in the LIC but are in the cooler "G cloud" (Linsky & Wood 1996; Wood et al. 2000a). Based on the G cloud flow vector (Lallement & Bertin 1992) and the known stellar space motion of the α Cen/Proxima Cen system, we find that the stars experience a slightly slower ISM wind speed than the Sun: 25 km s^{-1} compared with 26 km s^{-1} for the Sun. This slight difference in ISM flow velocity is also taken into account.

The "baseline" heliospheric model that we are extrapolating from assumes a proton density for the wind of $n(\mathrm{H}^+) = 5.0$ cm^{-3} at 1 AU from the Sun. In our astrospheric models, we experiment with different stellar mass-loss rates by changing $n(\mathrm{H}^+)$. Figure 3 shows the H I density distribution for four models with mass-loss rates of 0.2, 0.5, 1.0, and 2.0 $\dot{M}_\odot$, illustrating how the size of the astrosphere increases with increasing mass loss. The H I density enhancement shown in red is the "hydrogen wall" between the bow shock and the "astropause" (analogous to the "heliopause"), which will be responsible for most of the astrospheric absorption for the line of sight toward the Sun (79° from the upwind direction).

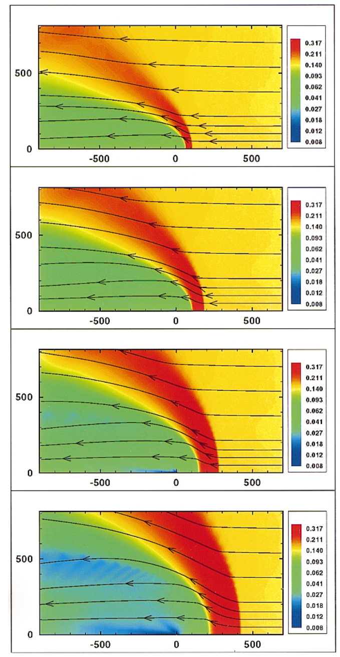

FIG. 3.—Distribution of H I density predicted by hydrodynamic models of the α Cen/Proxima Cen astrospheres, assuming stellar mass-loss rates of (*from top to bottom*) 0.2, 0.5, 1.0, and 2.0 $\dot{M}_\odot$. The distance scale is in astronomical units. Streamlines show the H I flow pattern.

The models provide tracings of H I temperature, density, and projected flow velocity along the line of sight toward the Sun from which we can compute the astrospheric Lyα absorption predicted by each model. The predicted absorption of the four models is shown in Figure 2. The 2.0 $\dot{M}_\odot$ model reproduces the α Cen data well. This is a very sensible result because the two α Cen stars individually have coronae with solar-like temperatures and X-ray luminosities (Hünsch et al. 1999) but collectively have about twice the surface area of the Sun, assuming radii of 1.20 and 0.90 $R_\odot$ for α Cen A and α Cen B, respectively (Pourbaix et al. 1999). The 0.2 $\dot{M}_\odot$ model is the only model that does not produce too much absorption to be consistent with the Proxima Cen data, and therefore it represents an upper limit for Proxima Cen's mass-loss rate ($\dot{M} \leq 0.2\ \dot{M}_\odot$). Despite this low value, Proxima Cen's mass loss per unit surface area could still be as much as 8 times larger than the Sun since Proxima Cen's radius of 0.16 $R_\odot$ (Panagi & Mathioudakis 1993) implies a surface area about 40 times smaller than that of the Sun.

We should point out that our mass-loss estimates may contain sizable systematic errors since our technique of applying solar wind models with rescaled densities to stellar winds relies on significant assumptions about the applicability of these models to other stars. For example, we assume that the stellar winds have the same velocity as the solar wind at 1 AU ($v = 400$ km s^{-1}). To first order, the size of an astrosphere and the column density of astrospheric absorption should scale with the square root of the wind ram pressure P_{wind} (Wood & Linsky 1998). Since $P_{\mathrm{wind}} \propto \dot{M}v$, our mass-loss estimates will vary inversely with the assumed wind speed. For the α Cen stars, a wind velocity equivalent to that of the Sun is clearly the best assumption since these stars and their coronae (where the winds are accelerated) are very solar-like. However, Proxima Cen's corona has a significantly higher temperature and X-ray surface flux than the Sun (Hünsch et al. 1999), so its wind velocity is more likely to be different.

The low mass-loss rate that we find for Proxima Cen is not surprising in the sense that Proxima Cen is much smaller and dimmer than the α Cen stars and the Sun. However, like many M dwarf stars, it has a surprisingly active corona that produces large flares, and it has a quiescent X-ray luminosity about equal to that of the Sun and α Cen (Hünsch et al. 1999). Since the winds of cool main-sequence stars are accelerated in the corona, one might therefore expect that Proxima Cen's wind might be as strong or stronger than that of α Cen and the Sun. Indeed, it has been proposed that the large flares on active M dwarfs like Proxima Cen should induce very large mass-loss rates (Coleman & Worden 1976; Mullan et al. 1992). Our observations suggest that this is not the case. However, general conclusions about the mass-loss rates of active M dwarfs should await observations of additional active M stars, especially since Proxima Cen's activity level is quite modest compared with many M dwarfs.

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