Investigating a Possible Spectral Signature of the Wind-ISM Interaction Region of α Tau

Brian E. Wood

JILA, University of Colorado, Boulder, CO 80309-0440

Graham M. Harper

Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309-0389

Hans-Reinhard Müller

Bartol Research Institute, University of Delaware, Newark, DE 19716

Gary P. Zank

Institute of Geophysics and Planetary Physics, University of California at Riverside, 1432 Geology, Riverside, CA 92521

Abstract.

Ultraviolet spectra from the GHRS instrument on board the Hubble Space Telescope reveal the presence of a mysterious absorption feature in the Mg II h & k lines of the nearby (d = 20.0 pc) K5 III star α Tau. The narrow absorption looks like an interstellar absorption feature but it is in the wrong location based on our knowledge of the local ISM flow vector. Since the absorption is close to the rest frame of the star, it has been interpreted as being from the interaction region between α Tau’s massive, cool wind and the interstellar medium, i.e., α Tau’s “astrosphere”. We compute hydrodynamic models of the α Tau astrosphere in order to see if the models can reproduce the Mg II absorption feature. These models do predict that stellar wind material heated, decelerated, and compressed after passing through a termination shock a few thousand AU from the star should produce a Mg II absorption feature with about the right width at roughly the right velocity. However, our first models underestimate the Mg II column density by an order of magnitude. A much larger parameter search is necessary to see whether the observed Mg II absorption can be reproduced by acceptable changes to the adopted stellar wind and ISM properties.

1Also at IGPP, University of California at Riverside, 1432 Geology, Riverside, CA 92521
Figure 1. HST/GHRS Mg II k line spectrum of α Tau, plotted on a heliocentric velocity scale, with the rest frame of the star indicated by the vertical dashed line. Broad absorption from α Tau’s wind dominates the central part of the profile. The narrow absorption feature shaded in green is the absorption that is presumed to be from the wind/ISM interaction region.

1. The Mysterious Mg II Absorption Feature

Figure 1 shows the Mg II k line from α Tau (K5 III) observed by the Goddard High Resolution Spectrograph (GHRS) on board the Hubble Space Telescope (HST) on 1994 April 8, first studied by Robinson et al. (1998). The center of the stellar line profile is dominated by very broad absorption from the massive, cool wind of the red giant star. However, near the rest frame of the star there is a much narrower absorption feature, which is also seen in the Mg II h line. The narrow absorption looks very much like interstellar absorption, and the strength of the absorption in the k and h lines has the expected 2 to 1 ratio of the oscillator absorption strengths, but Robinson et al. (1998) noted that the location of the absorption makes an interstellar origin very unlikely.

The flow vector of the Local Interstellar Cloud (LIC) from Lallement et al. (1995) suggests that LIC absorption should be at +25.5 km s$^{-1}$, which is within the saturated core of the wind absorption in Figure 1, and is therefore undetectable. Interstellar absorption components other than that of the LIC are occasionally seen for stars as nearby as α Tau ($d = 20.0$ pc), but they are generally close to the expected LIC velocity. Redfield & Linsky’s (2002) survey
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Table 1. Model Input Parameters

| #  | Stellar Wind Parameters at 1 AU | ISM Parameters |
|----|--------------------------------|----------------|
|    | \( n_\text{w}(\text{H} \ I) \) \text{(cm}^{-3}\text{)} | \( n_\infty(\text{H} \ I) \) \text{(cm}^{-3}\text{)} | \( T_\infty \) \text{(K)} | \( T_\text{w} \) \text{(K)} | \( V_\infty \) \text{(km s}^{-1}\text{)} | \( V_\text{w} \) \text{(km s}^{-1}\text{)} | \( \theta \) \text{(deg)} |
| 1  | \( 3 \times 10^4 \) | \( 5 \times 10^4 \) | 27 | 7500 | 0 | \( 4 \times 10^{-3} \) | 34 | \( 5 \times 10^5 \) | 149 |
| 2  | \( 3 \times 10^5 \) | \( 5 \times 10^4 \) | 27 | 7500 | 0 | \( 4 \times 10^{-3} \) | 34 | \( 5 \times 10^5 \) | 149 |
| 3  | \( 3 \times 10^4 \) | \( 5 \times 10^3 \) | 27 | 7500 | 0 | \( 4 \times 10^{-3} \) | 44 | \( 5 \times 10^5 \) | 170 |

of ISM absorption features within 100 pc demonstrates just how discrepant the location of the α Tau absorption feature is, if it is interstellar.

Noting the absorption feature’s location near the stellar rest frame, Robinson et al. (1998) proposed that the absorption is instead from the interaction region between α Tau’s wind and the ISM. The absorption would therefore be somewhat analogous to the H I Ly\( \alpha \) absorption detected from the interaction regions between the winds of solar-like stars and the local ISM (Linsky & Wood 1996; Wood et al. 2000, 2001, 2002; Müller et al. 2001). This “astrospheric” (analogous with “heliospheric”) absorption has proved to be a very useful diagnostic for the wind properties of solar-like stars (Wood et al. 2002).

2. Modeling the α Tau Atmosphere

We modeled the α Tau wind/ISM interaction region in order to see whether α Tau’s astrosphere can indeed account for the narrow Mg II absorption feature. Table 1 lists the ISM parameters and stellar wind properties at 1 AU from the star that are assumed in the initial astrospheric model (Model 1). The stellar wind parameters are estimated from an analysis of the Mg II wind absorption profile (e.g., Harper et al. 1995; Robinson et al. 1998), which suggests a mass loss rate of \( 1.0 \times 10^{-11} \text{M}_\odot \text{yr}^{-1} \), a result also consistent with an upper limit derived from VLA radio data. However, significant uncertainties exist for all the wind parameters in Table 1 and in Model 2 we compute a model with a significantly higher mass loss rate by increasing the assumed wind densities, \( n_\text{w}(\text{H} \ I) \) and \( n_\text{w}(\text{H}^+) \), by a factor of 10.

Unlike the Sun and other coronal stars with detected astrospheric absorption (e.g., Wood et al. 2002), α Tau probably lies in the hot ISM rather than the warm, neutral ISM. This conclusion is based on observations that show that in the direction of α Tau (\( l = 181^\circ, b = -20^\circ \)) H I column densities do not increase much with distance once the line of sight is \( > 5 \text{ pc} \) from the Sun, meaning that beyond \( \sim 5 \text{ pc} \) the ISM is hot and ionized and therefore contains no H I (Piskunov et al. 1997; Redfield & Linsky 2000, 2001). Such hot material fills most of the Local Bubble and is believed to account for much of the soft X-ray background (Sfeir et al. 1999).

The exact temperature of the hot ISM within the Local Bubble is not precisely known, but it is believed to be \( \sim 10^6 \text{ K} \). In our models, we assume \( T_\infty = 5 \times 10^5 \text{ K} \) (see Table 1), and we assume a proton density such that the pressure is about the same as that known to exist for the ISM around the Sun. Although the flow vector for the LIC is well known, and it is also known
that other warm neutral clouds near the Sun must have similar vectors, it is uncertain whether the LIC vector will apply to the hot ISM material within the Local Bubble. Nevertheless, for Models 1 and 2 we have assumed the LIC vector in deriving the ISM flow velocity seen by the star ($V_\infty = 34 \text{ km s}^{-1}$).

For Model 3, we assume that the hot ISM is at rest in the Local Standard of Rest (LSR). The Local Bubble was presumably created by a series of supernova explosions (Maíz-Apellániz 2001; Berghöfer & Breitschwerdt 2002). Since the hot stars that produce supernovae generally have low proper motions relative to the LSR, the assumption that the hot ISM within the Local Bubble is at rest in the LSR is a plausible one. Based on this assumption, the ISM flow velocity seen by the star increases to $V_\infty = 44 \text{ km s}^{-1}$. Assuming the LIC vector, the line of sight from the star toward the Sun is $\theta = 149^\circ$ from the upwind direction of the ISM flow seen by $\alpha$ Tau (see last column of Table 1), which means we are looking at the downwind part of the $\alpha$ Tau astrosphere. This is even more true with the LSR assumption, where $\theta = 170^\circ$, only $10^\circ$ from directly downwind.

In modeling $\alpha$ Tau’s astrosphere, we use the same hydrodynamic codes used to model the heliosphere and solar-like astrospheres (Pauls et al. 1995; Zank et al. 1996; Wood et al. 2000, 2002; Müller et al. 2001). We initially tried to use the “four-fluid” code of Zank et al. (1996), where the wind/ISM interaction is represented as the interaction between one plasma fluid and three separate neutral H fluids. However, we had trouble getting this code to converge, so we switched to a simpler “two-fluid” code like that of Pauls et al. (1995), where the neutrals are only described by a single fluid component. Based on this code, Figure 2 shows density distributions, temperature distributions, and flow patterns for the protons and H atoms for Model 1.

The astrospheric structure of $\alpha$ Tau is in many respects similar to that of the heliosphere (see, e.g., Zank et al. 1996). The stellar wind expands radially until it reaches a termination shock (TS), the roughly circular boundary seen about 1000 AU from the star in Figure 2. At the TS, the stellar wind is heated, compressed, and decelerated. The stellar wind cools adiabatically while expanding outwards, but we do not allow it to cool below 3 K (the cosmic background radiation temperature). Beyond the TS there is a parabolic-shaped boundary visible in Figure 2 separating the plasma flows of the stellar wind and ISM, the “astropause” (analogous to “heliopause”), which extends beyond the field of view in the downwind direction (to the left). There is no bow shock beyond the astropause in the upwind direction (to the right in Figure 2) like there is for the heliopause since the ISM flow is not supersonic.

3. Comparing the Data with Model Predictions

Figure 3 shows traces of H I density, temperature, and velocity for the line of sight from the star toward the Sun based on the three models listed in Table 1. We assume that the Mg II temperature and velocity are identical to those of H I, and we compute the Mg II density from the H I density assuming solar Mg abundances (Anders & Grevesse 1989) and assuming that Mg II is the dominant ionization state of Mg. We can then compute the predicted astrospheric Mg II absorption for all the models.
Figure 2. Hydrodynamic model of the α Tau astrosphere for Model 1, where the upper panels are the proton and H I temperature and the bottom panels are the proton and H I density, respectively. Streamlines are shown in the upper panels. The distance scale is in AU.

Figure 3. Traces of H I density, temperature, and velocity along the line of sight from α Tau toward the Sun for Model 1 (green lines), Model 2 (red lines), and Model 3 (blue lines).
We find that the Mg II column densities predicted by the models are too low by an order of magnitude. Figure 4 shows the predicted absorption if we arbitrarily increase the Mg II opacity by a factor of 10 for the models. Despite the order of magnitude underestimate of the Mg II column by these initial models, they do predict the presence of an absorption feature of about the right width at roughly the location of the observed absorption that has been proposed to be astrospheric. Therefore, the astrospheric interpretation of the absorption still shows promise. In this interpretation, the material responsible for the absorption is the heated, compressed, and decelerated stellar wind material outside the termination shock (TS), about $1500 - 4500$ AU from the star for Model 1, $6000 - 15,000$ AU for Model 2, and $1500 - 15,000$ AU for Model 3 (see Fig. 3).

Note that if we were observing the upwind portion of the atmosphere (i.e., $\theta < 90^\circ$), the path through the heated post-TS material would be much shorter and the astrospheric absorption would be much weaker (see Fig. 2). The downwind orientation of our line of sight through the $\alpha$ Tau atmosphere may be the main reason we see the astrospheric absorption for $\alpha$ Tau but not (so far) for other red giants. One mystery we cannot yet explain is why the astrospheric absorption seen in Mg II is not also seen in the O I $\lambda$1302 and C II $\lambda$1335 lines.
observed by HST. These lines have profiles very similar to the Mg II line in Figure 1, but without the narrow absorption feature that we believe is astrospheric (Robinson et al. 1998).

The model that appears to work best so far is Model 3, which predicts a greater amount of absorption thanks to the more downwind line of sight suggested by the assumption of the LSR for the ISM vector (see §2). The predicted absorption of all models in Figure 4 is blueshifted from its observed position by about $5 - 10 \text{ km s}^{-1}$, meaning that the models are predicting too little deceleration at the TS. Increasing the deceleration would lead to higher densities outside the TS, thereby also helping to correct the problem of underpredicting the Mg II opacity. Unfortunately, the Model 2 experiment shows that simply increasing the stellar wind density does not help much. Further experimentation with varying other model parameters listed in Table 1 is necessary to see if a model can be found that will increase both the deceleration at the TS and the total Mg II column density to the required extent to match the data. If ultimately successful, we can then see what constraints the observed absorption can place on the properties of the stellar wind and surrounding ISM.

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