Searching for the Cause of Hybrid Star Activity

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Abstract:
UV spectra for a wide range of chromospheric diagnostics have been obtained for the non-coronal giant $\alpha$ Tau and the ‘hybrid’ star $\gamma$ Dra using the Goddard High Resolution Spectrograph. These stars have very similar spectral types and are very close to one another in mass, luminosity, size, effective temperature and gravity. A detailed comparison shows that the photosphere and chromosphere of the stars are very similar. The two stars show the same level of UV continuum emission and chromospheric turbulence and have Fe\textsc{ii} emission profiles which are nearly identical. The amount of transition region plasma, as measured by the C\textsc{iv} surface flux, is also nearly the same. The winds of these two stars, however, are significantly different. Preliminary models based on the O\textsc{i} (UV 2) and Mg\textsc{ii} (UV 1) profiles show that the wind for $\alpha$ Tau has a terminal velocity of $\sim$30 km s\textsuperscript{-1} and a much slower acceleration than the wind of $\gamma$ Dra, which has a terminal velocity of $\sim$ 65 km s\textsuperscript{-1}. However, despite the different wind properties, the mass loss rate from these two stars is very similar.

1. Introduction

Giant stars on the cool side of the Linsky-Haisch dividing line are normally classified as non-coronal or hybrid, depending upon whether or not they have hot plasma and a high speed wind (e.g., Hartmann et al. 1980). Since hybrids and non-coronal stars overlap in the HR diagram it is expected that properties other than effective temperature and luminosity are responsible for the differences in atmospheric characteristics. In this study we compare HST observations of the non-coronal star $\alpha$ Tau (Aldebran) and the hybrid star $\gamma$ Dra, both of which have a spectral classification of K5 III, in an effort to understand the nature of these physical properties.

2. Observations and Data Reduction

Observations were obtained using the Goddard High Resolution Spectrograph (GHRS) aboard the Hubble Space Telescope on 1994 April 08 and 1995 July 20 for $\alpha$ Tau and $\gamma$ Dra respectively. The data were taken using the medium resolution ($R=20,000$) gratings. To ensure the greatest accuracy in both profile shape and measured radial velocities, both stars were observed through the 0.25

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arcsec Small Science Aperture, which is matched to one resolution element on
the detector. A wavelength calibration exposure (referred to as a WAVECAL)
was also obtained prior to each observation to ensure the maximum wavelength
accuracy. These procedures produce an accuracy of better than 3 km s\(^{-1}\) in the
absolute wavelength scale.

The data were reduced using the CALHRS procedure, which combined the
sub-exposures, subtracted background, corrected the effects of vignetting and
applied the absolute flux and wavelength calibrations.

3. Comparing the Stars

3.1. Basic Properties of the Program Stars

A literature survey shows that \(\gamma\) Dra and \(\alpha\) Tau have very similar physical
properties, with \(\gamma\) Dra being slightly larger, hotter and more luminous than \(\alpha\)
Tau. There is also some indication that the gravity of \(\gamma\) Dra is larger than that
of \(\alpha\) Tau, suggesting that it is also more massive. In both cases the rotational
velocity (\(v \sin i\)) and photospheric turbulence are small. Finally, an examination
of the infrared colors (Engelke 1992) shows essentially no difference between the
two stars, implying that the circumstellar environment is similar.

3.2. A Comparison of the UV Continua

A measurable continuum was observed in all of the GHRS observations. This
continuum extends down to at least 1300 Å and had a count rate which was at
least 5 times larger than the measured background. The photospheric continuum
for a K5 III star will rapidly decrease in intensity below 2800 Å, so we expect that
the observed continuum emission arises in the lower chromosphere. In Figure 1
we compare the average flux in regions which were free of prominent absorption
or emission features. In this figure we have scaled the \(\gamma\) Dra fluxes by a factor
of 3.55, which is the ratio of the stars’ Johnson V magnitudes. The continua
for the two stars are seen to have comparable surface fluxes and spectral shape,
implying a similarity in the temperature structure of the lower chromosphere.

3.3. Character of the Fe II lines

The various Fe II emission lines probe the lower to middle chromosphere. The
close agreement in the profiles of the two stars shown in Figure 2 indicates the
similarity in the atmospheric structure in this region. In fact, the differences
seen between the two stars is smaller than the variations seen in the profiles of \(\alpha\)
Tau over a period of a few years (see Robinson, Carpenter, & Brown, 1998). The
stellar wind, which causes the profile asymmetry, is visible in only the strongest
of these lines. This suggests a relatively small mass loss rate for both stars.
Figure 1. A comparison of continuum fluxes seen in $\alpha$ Tau and $\gamma$ Dra. The $\gamma$ Dra fluxes have been scaled by the ratio of its $V$ magnitude to that of $\alpha$ Tau. The dotted line shows the expected photospheric flux from a K5 III star as calculated by Kurucz.

Figure 2. Comparing Fe II line profiles observed on $\alpha$ Tau in 1994 (solid line) with those seen from $\gamma$ Dra in 1996 (dotted). Numbers in brackets in the upper left hand corner represent the log of the relative optical depth of the lines. The $\gamma$ Dra fluxes have been scaled by the ratio of its $V$ magnitude to that of $\alpha$ Tau.
3.4. Chromospheric Turbulence

Because of their intrinsically narrow widths, the C II] (UV 0.01) intercombination lines are often used to measure chromospheric turbulence. Figure 3 shows the close agreement between the turbulence in α Tau and γ Dra. Modeling these profiles (see, e.g., Carpenter & Robinson 1997) shows that the turbulence has a most probable velocity of \( \sim 25 \text{ km s}^{-1} \) in both stars. The broad, non-Gaussian wings of the profiles also suggest that the turbulence is not isotropically distributed but is primarily directed either along or perpendicular to the radial direction, as suggested by Gray (1992) for cool stellar photospheres. This turbulence is large compared with the photospheric turbulence (about 2 km s\(^{-1}\)) and the local sound speed (about 10 km s\(^{-1}\)) and is probably related to the chromospheric heating.

![Figure 3. A comparison of profiles for several C II] intercombination lines observed in α Tau (solid) and γ Dra (dotted). The lines have been normalized so that the peak flux of the 2325.4 Å line matches.](image)

3.5. Hot Plasma

The C IV doublet near 1550 Å is formed at temperatures of \( \sim 10^5 \) K and is a common diagnostic of transition region plasma. While this hot plasma is expected from the hybrid star (Brown et al. 1995) it was a surprise to find it in α Tau (see Figure 4), especially at a surface flux level which is nearly the same as that seen in γ Dra. The C IV flux is similar to that seen in a variety of other relatively inactive K giant and supergiant stars (Ayres et al. 1997) and may represent a “basal” level possessed by all the stars in this spectral range. An analysis of these profiles shows that their formation region is essentially at rest with respect to the photosphere.
Note in Figure 4 that the C iv lines in α Tau are affected by several narrow absorption features. These lines have not yet been identified. However, aside from C iv there are no known spectral lines at these wavelengths which are formed at hot temperatures, suggesting that the hot plasma is embedded in much cooler gas. This cool, dense gas is also implied by the numerous narrow, fluorescent emission features in the α Tau spectrum which do not show up in γ Dra.

![Graph showing the C IV wavelength region in α Tau compared to γ Dra](image)

Figure 4. Comparing the C IV wavelength region in α Tau (a), observed in 1994, with that in γ Dra (b), observed in 1996.

4. Diagnosing the Stellar Wind

The cores of the O i (UV 2) and Mg ii (UV 1) resonance lines are formed high in the atmosphere and are prime diagnostics of the stellar wind. In Figure 5 we compare the O i profiles for each of the stars and include the strong Fe ii (λ2755) line for comparison. The Fe ii profiles are almost identical. However, the O i lines show dramatically different behaviors in the two stars. The acceleration in the wind of α Tau can be seen in the changing position of the central reversals for lines of progressively larger optical depth, which probe progressively greater heights in the atmosphere. Here the Fe ii λ2755 line has the smallest opacity while the O i λ1302 line has the largest. In contrast, the lines in γ Dra show a pronounced absorption on the blue wing of the lines and an enhancement in the core. This is a classic P Cygni effect in which an absorption feature occurs near the terminal velocity of the wing, while an enhancement near zero velocity results from photon scattering in a spherically symmetric atmosphere (see, e.g., Castor & Lamers 1979).
The differences in the winds are further illustrated in Figure 6, which compares sample O I and Mg II profiles for the two stars. Note the strong similarity in the red wings of the lines as well as the overlap in the blue wings at (negative) velocities greater than $-80$ km s$^{-1}$. This shows that the intrinsic profiles at the base of the wind are identical and that the differences in the cores result from mutilations within the wind.

To determine the basic properties of the wind we use the SEI radiative transfer code (Lamers et al. 1987) to empirically model the observed O I (UV 2) and Mg II (UV 1) profiles. The model assumes spherical symmetry and pure scattering of photons which are created in the stationary chromosphere at the base of the wind. For simplicity we assume a constant turbulence with height and an ionization fraction such that O I and Mg II are the dominant species. The wind velocity-height relation is parameterized using the relation:

$$
\frac{v(R)}{v_\infty} = \left(1 - \frac{R_*}{R}\right)^\beta
$$

(1)
where $v_\infty$ is the terminal velocity and $R_*$ is the stellar radius. The parameter $\beta$ specifies the wind acceleration.

The results of this modeling suggest that $\gamma$ Dra has a wind which has both a higher terminal velocity ($v_\infty \sim 65$ km s$^{-1}$) and greater acceleration ($\beta \sim 0.3$) than is the case for $\alpha$ Tau (which has $v_\infty \sim 30$ km s$^{-1}$ and $\beta \sim 1.5$). The detailed character of the wind is shown in Figure 7. It is interesting to note that despite the differences in the character of the wind the mass loss rate from the two stars is about the same, with a value of $\approx 10^{-11} M_\odot$ yr$^{-1}$.

5. Summary and Conclusions

A comparison of the properties of the non-coronal giant $\alpha$ Tau and the hybrid giant $\gamma$ Dra shows remarkable similarities. (a) The UV, optical and IR colors are almost identical. (b) The strengths and profiles of optically thin and marginally thick emission lines such as C II] and Fe II are the same. (c) The chromospheric turbulence and density are the same. (d) The surface flux of hot, transition region material is the same. About the only observed difference in the photosphere or chromosphere of the two stars is the existence of pockets of dense, cool material in $\alpha$ Tau which are responsible for the numerous fluorescent emission features in its spectrum. Despite these similarities, the wind properties of the two stars are quite different, with $\gamma$ Dra having a wind which accelerates more quickly and reaches a higher terminal velocity than in $\alpha$ Tau.
From this study we can therefore conclude that (a) there is probably no relation between the presence of hot, transition region plasma and the mass loss rate, terminal velocity or acceleration rate of the stellar wind for stars on the cool side of the Linsky-Haisch coronal dividing line and (b) the amount of chromospheric turbulence is not the characteristic which determines the properties of the stellar wind. Overall, however, we are left with the same question with which we started. Given the close similarity of $\alpha$ Tau and $\gamma$ Dra, what physical properties are responsible for the dramatically different winds in these two stars?

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References