

# The Atmospheric Dynamics of $\alpha$ Tau (K5 III) – Clues to Understanding the Magnetic Dynamo in Late-Type Giant Stars

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**Abstract.** Using HST/GHRS, HST/STIS and FUSE archival data for  $\alpha$  Tau and the CHIANTI spectroscopic code, we have derived line shifts, volumetric emission measures, and plasma density estimates, and calculated filling factors for a number of UV lines forming between 10,000 K and 300,000 K in the outer atmosphere of this red giant star. The data suggest the presence of low-temperature extended regions and high-temperature compact regions, associated with magnetically open and closed structures in the stellar atmosphere, respectively. The signatures of UV lines from  $\alpha$  Tau can be consistently understood via a model of upward-traveling Alfvén waves in a gravitationally stratified atmosphere. These waves cause non-thermal broadening in UV lines due to unresolved wave motions and downward plasma motions in compact magnetic loops heated by resonant Alfvén wave heating.

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## OBJECTIVES OF THE PROGRAM

The primary objective of this program is to determine and use the properties of select UV emission lines in the spectrum of  $\alpha$  Tau to further our understanding of the structure and heating of the outer atmospheres of red giant stars and obtain clues as to the nature of their magnetic dynamos. For reference, the physical properties of  $\alpha$  Tau are given in Table 1.

**TABLE 1.** The physical properties of the Red Giant  $\alpha$  Tau

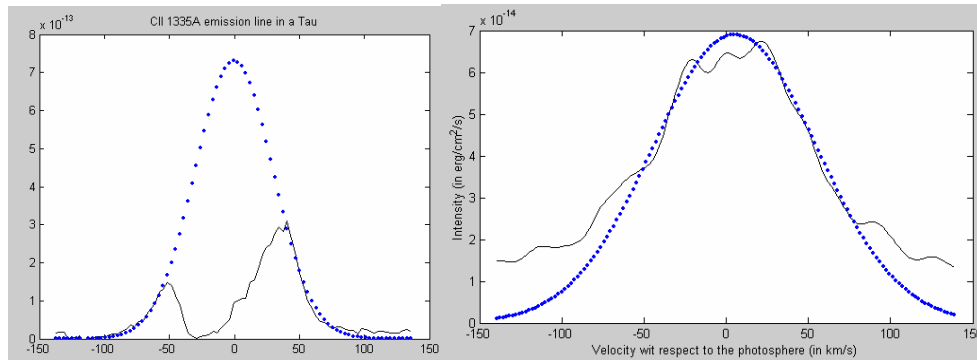
Parameter	Value
Spectral Type	K5 III
Distance (pc)	20
Radius (in solar radii)	44
Effective Temperature	3898 K
Mass (in solar masses)	1.3
Turbulence in the photosphere	5 km/s
Mean turbulent velocity at the wind base	24 km/s
Asymptotic Flow Speed	30 km/s

## UV EMISSION LINES IN RED GIANTS

Almost all late-type evolved giants show signatures of plasma at T of 10,000 - 300,000 K. We have compiled and analyzed data obtained with HST/GHRS, HST/STIS and FUSE on evolved late-type stars [1, 2, and 3] for this study. These data indicate that:

- UV emission lines are non-thermally broadened, up to as much as  $V \sim 120$  km/s
- UV emission lines are mostly red- shifted with respect to the photosphere
- The profiles of CII 1335, Si IV 1393, C III 977, OVI 1032 Å show that their non-thermal broadening increases with the temperature of UV emitting plasma

Sample UV emission line profiles from the  $\alpha$  Tau spectrum are shown in Figure 1 and the properties of a broad sample of lines are listed in Table 2.



**FIGURE 1.** A single Gaussian is sufficient to fit the profile of the CII  $\lambda$ 1335.70 line (left), as well as the CIII  $\lambda$ 977, but the OVI  $\lambda$ 1032 emission line (right) has extended wings signifying anisotropically distributed turbulence. The latter also provides signatures of plasma downflows in one or a few magnetic loops in the atmosphere of  $\alpha$  Tau, as indicated by the red-shifted emission lines and anisotropically distributed turbulence produced by a non-linear Alfvén wave at the Alfvén speed.

Emission Line	Log T	$V_{\text{shift}}$ (in km/s)	$D\lambda_{1/2}$ (in km/s)	Log (VEM)	Data Source
CII] 2325.5Å	4.1	$2 \pm 1$	$24 \pm 1$	54.7	[1]
SiII 2350.9 Å	4.3	$3 \pm 2$	$21 \pm 2$	54.0	[1]
C III 1908 Å	4.4	N/A	$\leq 25$	53.6	[3]
CII 1335 Å	4.6	$2 \pm 2$	$66 \pm 5.9$	51.5	[3]
CII 1334Å	4.8	$2 \pm 2$	$66 \pm 5.9$	51.3	[3]
CIII 977Å	4.85	$98 \pm 9$	$86 \pm 8$	49.9	[3]
NIII 991Å	4.9	$92.4 \pm 9$	$76 \pm 8$	50.4	[3]
OVI 1032Å	5.5	$5.3 \pm 5$	$121.6 \pm 10$	49.5	[3]
O VI 1037Å	5.5	$5.3 \pm 5$	$121.6 \pm 10$	49.5	[3]

## CLUES TO THE STRUCTURE AND HEATING OF THE OUTER ATMOSPHERES OF RED GIANTS: CII, CIII, & O VI LINES

Analysis of the UV lines from the CII ion indicates that:

- Opacity effects are not important in formation of the line profile
- CII 1335Å is well fit with a single Gaussian, while CII 2325Å requires 2
- The ratio of FWHM's of CII 1335Å/CII 2325Å  $\sim 3$
- $I(1335\text{Å})/I(2325\text{Å}) \sim 1.6 - 2$  indicates that 2325Å line forms at  $T \sim 10,000\text{K}$
- Filling factor for CII 1335Å is  $f \sim 3 \times 10^{-4}$

Analysis of the UV lines from the CIII ion indicates that:

- Opacity effects are not important in the formation of these line profiles
- CIII 977Å is well fit with a single Gaussian
- Ratio of the FWHM's of CIII 977Å/CIII 1908Å  $\sim 4$
- CIII 977Å and NIII 991 Å line shifts are 100 km/s, while the CIII 1908Å line does not show a shift  $> 10$  km/s
- $I(977\text{Å})/I(1908\text{Å}) \sim 1.375$  indicates that 2325Å line forms at  $T \sim 12,000\text{K}$
- 977Å/1176Å line ratio  $\Rightarrow N_e > 10^{10} \text{cm}^{-3}$  (technique from [4])
- Filling factor of CIII 977Å is  $f < 10^{-5}$

Analysis of the UV lines from the OVI ion indicates that

- Opacity effects are not important in the formation of 1032Å and 1038Å line
- OVI 1032Å, 1038Å is well fit with 2 Gaussians
- OVI 1032Å, 1038Å lines are unshifted and show  $> 100$  km/s non-thermal broadening

*This provides evidence for the existence of both low-T, high-f (open magnetic field) and high-T, low-f (magnetic loops) regions in the outer atmosphere of  $\alpha$  Tau.*

## ALFVEN WAVES IN THE ATMOSPHERES OF COOL GIANTS

### Heating by Alfven Waves

Our modeling [5] has shown that Alfven Waves (AW) can provide the required plasma heating in loops via resonant absorption and that the observed non-thermal broadening can be understood in terms of the amplitudes of unresolved wave motion at  $V \leq V_A$ . For weakly dissipated AWs, the amplitudes of wave motions increase with T, as measured (see Table 1). Magnetic loops serve as resonant cavities at  $P = 2L/V_A \sim 1$  day (consistent with [6]) with the absorption rate of waves [7] of  $E \sim BV_A P/L^3 \sim 4 \times 10^6$  erg/cm<sup>2</sup>/s. Cool condensations within a magnetic loop are formed due to radiatively driven thermal instability at  $T \sim 100,000\text{K}$ , at scales  $< 0.005 R_{\text{star}}$ . These cool condensations slide down along the magnetic field line at free-fall velocities  $V \sim 100$  km/s, consistent with the red-shift observed in CIII 977Å. This suggests no dependence of  $V_{\text{redshift}}$  on T, consistent with Table 1.

## The Source of Alfvén Waves in these Atmospheres

In our models, radial pulsations ignite sound waves, and therefore, a periodic variation of density along large-scale magnetic field lines in the atmosphere. The Alfvén waves with the half frequency of pulsation can be amplified in the atmosphere due to the swing wave-wave interaction [8] and have periods of a few days. This is consistent with the period of waves required by the resonant heating mechanism [7].

## CONCLUSIONS

A comparison of our models with observations of  $\alpha$  Tau and other red giant stars leads to the following results:

- Volume Emission Measures and line ratios of FUV lines suggests the presence of dense and compact regions in the atmosphere of  $\alpha$  Tau
- Red-shifted and non-thermally broadened UV lines can be explained in terms of AW induced heating and subsequent formation of radiatively driven condensations sliding down from the top of the loop
- The filling-factor ( $f$ ) of open structures is least 100 times greater than that of loop structures
- The energy density flux of AWs in the atmosphere derived from UV lines is consistent with calculated heating rates and the  $f$  of magnetic structures
- This is consistent with HD simulations of convective cells in giant stars [9]. The estimated magnetic flux in loops is  $(1-2) \times 10^{22}$  Maxwell

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