THE "MONOCHROMATIC DENSITY DIAGNOSTIC" TECHNIQUE: FIRST DETECTION OF MULTIPLE DENSITY COMPONENTS IN THE CHROMOSPHERE OF \( \alpha \) TAURI

P. G. Judge

High Altitude Observatory, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000
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ABSTRACT

Emission line profiles of the red giant \( \alpha \) Tau, obtained by Carpenter et al. (1991) using the echelle and medium dispersion gratings of the Goddard High Resolution Spectrograph, are re-examined. Ratios of monochromatic flux densities of lines of the \( C \) II \( 2s^22p^2P^o \rightarrow 2s2p^2^4P \) multiplet near 2325 Å, well-known diagnostics of electron densities in the chromospheres of cool evolved stars, change systematically with relative wavelength across the line profiles. With the justifiable assumption that these lines are optically thin, this implies that the electron density varies systematically across the line profiles. This is the first time that traditional electron density diagnostic line ratios have been successfully applied to monochromatic line flux densities in cool stars.

The \( C \) II data are examined together with lines of \( CO \) II and \( Si \) II also observed by Carpenter et al. (1991) to infer (1) possible causes of the apparent net downflow in \( C \) II lines, and (2) other basic properties of the gas flows in the chromosphere of \( \alpha \) Tau. These conclusions are based upon emission measure analysis as well as electron density determinations.

This work clearly demonstrates the power of very high signal-to-noise, high-resolution spectra in the UV. The monochromatic density diagnostic technique holds promise as a powerful tool for studying flows in a variety of astrophysical objects, including the Sun. The paper concludes with a compilation of ions from the boron and aluminum sequences for which this technique can be expected to produce valuable results using astronomical data from the GHRS and solar data from instruments on SOHO.

Subject headings: line: profiles — stars: chromospheres — stars: individual (\( \alpha \) Tauri) — ultraviolet: stars

1. INTRODUCTION

The first high quality chromospheric spectra obtained with the Goddard High Resolution Spectrograph on the Hubble Space Telescope revealed, not surprisingly, serious shortcomings in our understanding of stellar chromospheres (Carpenter et al. 1991). Profiles of optically thin lines formed below 10^4 K showed enormous “turbulent” line widths approaching 3 times the sound speed, profiles which (for the first time) were found to be decidedly non-Gaussian in shape, and peculiar redshifts of lines of \( C \) II relative to those of other chromospheric lines. Even the most basic features of these new observations have defied explanation, in spite of detailed theoretical modeling efforts (Judge & Cuntz 1993).

In this paper, I analyze the properties of the GHRS data reported by Carpenter et al. (1991) in more detail than before. I argue that important new clues to the gas dynamics in the chromosphere of \( \alpha \) Tau can be found by a simple study of monochromatic flux densities instead of frequency-integrated quantities. This study is made possible owing to the high spectral resolution of the GHRS coupled with the outstanding signal-to-noise properties of the spectra.

2. OBSERVATIONAL DATA

Carpenter et al. (1991) obtained echelle data of \( \alpha \) Tau between 2319 and 2332 Å, a region including the \( C \) II inter-system multiplet \( 2s^22p^2P^o \rightarrow 2s2p^2^4P \). Line wavelengths and definitions of ratios \( R_1 \) through \( R_3 \) are given in Table 1. The density-sensitive ratios \( R_1 \), \( R_2 \), and \( R_3 \) are as defined by Stencel et al. (1981). Below 2000 Å I give wavelengths in vacuum, above 2000 Å in air. The reader should refer to Carpenter et al. (1991) for details of the data acquisition and reduction. These data have a spectral resolution of \( 66 \Delta \lambda \approx 80,000 \). Medium-resolution data \( (66 \Delta \lambda \approx 20,000) \) were also obtained between 2320 and 2368 Å. Both data sets included data obtained through the large (LSA) and small (SSA) science apertures.

Here, I focus upon SSA data of the five lines of the \( C \) II multiplet and lines of \( CO \) II 12330.354 \( (a^5F_2 \rightarrow z^5D_2^o) \) and \( Si \) II 12350.170 \( (3s^23p^2P_{3/2} \rightarrow 3s3p^2^4P_{1/2}) \). The \( Si \) II data are from the SSA medium resolution spectra. These lines were chosen because they are not self-reversed or blended, they are expected to be optically thin throughout most of the chromosphere (see §3.1), and they have high quality line profiles. Other lines also present in the GHRS data (especially of \( Fe \) II) are either very weak, blended or are self-reversed indicating high optical depths. Such lines require an analysis beyond the scope of this paper.

3. ANALYSIS

3.1. Chromospheric Optical Depths of the Lines under Study

Below, important conclusions will be drawn based on comparisons between the \( C \) II line profiles and profiles of the \( C0 \) II 12330.354 line, assuming both are optically thin so that the observed profiles reflect gas motions and not the effects of radiative transfer. Hence, it is important to check that the lines do not have high optical depths in the chromosphere of \( \alpha \) Tau.

Judge & Jordan (1991) determined “mean” chromospheric optical depths of lines of \( Fe \) II from line ratios sensitive to the mean number of photon scatterings. They found a line center optical depth \( \tau_0 \) of \( \sim 10^6 \) for the 12599.397 line of \( Fe \) II from line ratios of \( Fe \) II lines. Using oscillator strengths from Fuhr,
TABLE 1
RATIOS OF LINES IN THE 2s2p\(^2\)\(^{4}P\) – 2s\(^{2}\)2p\(^1\)\(^{3}P\) MULTIPLET OF C II

<table>
<thead>
<tr>
<th>TRANSITIONS</th>
<th>WAVELENGTHS</th>
<th>DIAGNOSTIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(J_a \rightarrow J_i)</td>
<td>(J_a \rightarrow J_i)</td>
<td>(\lambda) (Å)</td>
</tr>
<tr>
<td>(R_1) (\rightarrow) ((\pm 4))</td>
<td>((\pm 4))</td>
<td>2325.398/2238.122</td>
</tr>
<tr>
<td>(R_2) (\rightarrow) ((\pm 4))</td>
<td>((\pm 4))</td>
<td>2325.398/2236.930</td>
</tr>
<tr>
<td>(R_3) (\rightarrow) ((\pm 4))</td>
<td>((\pm 4))</td>
<td>2324.689/2236.930</td>
</tr>
<tr>
<td>(R_4) (\rightarrow) ((\pm 4))</td>
<td>((\pm 4))</td>
<td>2262.930/2232.350</td>
</tr>
<tr>
<td>(R_5) (\rightarrow) ((\pm 4))</td>
<td>((\pm 4))</td>
<td>2328.122/2324.689</td>
</tr>
</tbody>
</table>

Martin, & Wiese (1988), relative abundances and partition functions from Allen (1973), by further assuming Fe II and Co II are the predominant ionization fractions in the chromosphere, and adopting a chromospheric electron temperature near 7000 K (Judge 1986a). I find \(\tau_{p}(\text{Co II})\) \(\lambda2330.354\) \(\sim 2\). At such low depths, little line broadening by multiple scattering and no deep self-reversals may be expected.

Similarly, using oscillator strengths from Fang et al. (1993) (C II]) and Calamai, Smith, & Bergeson (1993) (Si II]), and logarithmic abundances of 8.67, 7.53, 7.63 for C, Fe, and Si (on a scale where \(H = 12\)) from Judge (1986a), we find line center optical depths of 0.09 and 0.26 for the C II \(\lambda2324.398\) and Si II \(\lambda2350.170\) lines, respectively.

The optically thin assumption therefore seems to be valid for the lines of interest. This is also confirmed by detailed transfer calculations (§ 3.4). Judge (1986a) showed that the C II] and Si II] lines are excited by collisions with electrons. Carpenter et al. (1991) argue that the Co II line is excited by fluorescence by the Fe II/ Si II] blend near 2344.3 Å, owing to the weakness of other members of the Co II multiplet with different upper levels. This difference does not influence the present analysis since the source of excitation of the Co II line is irrelevant.

3.2. Electron Densities

The relative intensities of the transitions \(2s2p\(^2\)\(^{4}P\)_J \rightarrow 2s\(^{2}\)2p\(^{1}\)\(^{3}P\)_J\) in the boron-like ions have long been recognized as diagnostics of electron densities in plasmas in which the lines are optically thin (e.g., Vernazza & Mason 1978). Stencel et al. (1981) used \(IUE\) data of these transitions in C II to estimate mean electron densities in cool evolved stars, and much work has been done since then to determine electron densities in such objects (e.g., Judge et al. 1994).

In previous work, authors have integrated the observed flux densities (either directly or using parametric fits) over the entire line profile to derive a single electron density for each line ratio. While this made sense for unresolved line profiles (e.g., in chromospheric lines from \(IUE\) data where \(\lambda\)/\(\Delta\lambda\) \(\sim 12,000\), and the width of the stellar line is of this order or less, e.g., Judge 1986a), the new GHRS observations provided a dataset for which the observed line profile is fully resolved by the instrument, and the thermal width of the line is much smaller than the observed width (Carpenter et al. 1991). Thus, these data offer us the opportunity to look for density variations across the line profile.

Figure 1 shows the observed profiles of the components of the usual density-sensitive line ratios \(R_1\), \(R_2\), and \(R_3\) (Table 1), the ratios \(R_1\), \(R_2\), and \(R_3\) themselves and the deduced electron density from each ratio, plotted as a function of wavelength (expressed as a Doppler shift from line center). The zero point of the velocity scale is that of the stellar photosphere, and the maximum likely error is \(\sim 1\) km s\(^{-1}\) (Carpenter et al. 1991). To determine electron densities \(N_e\) from the observed line profile ratios requires several assumptions:

1. The effects of blended lines and background continuum are negligible, or they can be estimated.
2. The monochromatic flux densities have sufficiently high signal-to-noise ratios that meaningful data can be derived from this analysis.
3. All the atomic data and usual assumptions concerning the theoretical calculations of line emissivities are valid (these have been presented in detail by Judge et al. 1994). Our atomic data are from Blum & Pradhan (1992) (collision strengths) and Lennon et al. (1985), except that the oscillator strengths were modified using the measured lifetimes of Fang et al. (1993). Judge et al. (1994) show that these calculations are very similar to those of Lennon et al. (1985).
4. The emitting plasma is optically thin in the C II] lines.
5. The relative wavelength scale of the spectrograph is accurate enough to derive accurate ratios of lines as a function of wavelength.
6. The effects of hyperfine structure can be taken into account. These are discussed in § 3.4.

The GHRS data satisfy points 2 and 5. I performed several tests to determine the influence of point 1 and have found that the basic conclusions remain unaffected. First, I removed known line blends by using profiles of other lines in the echelle spectrum as templates. Ratios \(R_3\) and \(R_4\) are strongly affected by the blend of \(\lambda2326.930\) with emission from the (opacity-broadened) wings of the strong Fe II line at 2327.397 Å. Figure 2 shows the subtraction of this Fe II line from the C II] line, assuming that the observed flux density at the affected wavelengths is the linear sum of the flux densities of the C II] and Fe II lines, and that \(\lambda2327.397\) has an identical profile to Fe II \(\lambda2331.307\) (these lines fortuitously have very similar optical depths, using oscillator strengths of R. L. Kurucz 1988, private communication, or Fuhr et al. 1988). The regions which I have estimated to be influenced by the Fe II line are flagged with crosses. Secondly, I have subtracted realistic values of constant background flux density from the observed profiles. These greatly influence the far wings of the lines (Doppler shifts greater than 20 km s\(^{-1}\) from the line center), but the analysis of the profiles near the line cores remains unaffected.

The remainder of the paper is based on the "best attempt" to remove blends from the data, shown in Figure 1. Lines of Fe II \(\lambda2327.397\), Si II] \(\lambda2328.510\), and Co II \(\lambda2324.317\) were removed from the raw spectrum using the template lines Fe II \(\lambda2332.798\), Co II \(\lambda2330.358\), and Co II \(\lambda2330.358\), respectively. No "background continuum" was subtracted from these data since regions away from lines in the spectra (e.g., near 2324 or 2329 Å) have essentially zero flux.

Points (1) and (2) may be checked empirically. The multiplet \(2s2p\(^2\)\(^{4}P\)_J \rightarrow 2s\(^{2}\)2p\(^1\)\(^{3}P\)_J\) has two sets of lines each sharing a common upper level (\(J = 3/2\) and \(J = 1/2\)). Ratios of the emissivities of these lines are not sensitive to electron density or temperature. They can depart from the atomic branching ratios only by multiple scattering of photons (probably unimportant, see §§ 3.1 and 3.4), or by rapid changes in the gas thermodynamical properties on timescales smaller than the radiative decay rates of the upper levels (Feldman 1992). These ratios \(R_4\) and \(R_5\) are listed in Table 1 and plotted in Figure 1. Ratio \(R_4\) contains the very weak line at 2323.500 Å, and it is
therefore very noisy. Ratio $R_3$ demonstrates that, at least in the line cores (Doppler shift in the range $-15$ to $+25$ km s$^{-1}$), the GHRS data provide line ratios reliable to within $\pm 5\%$. If this level of uncertainty exists in ratios $R_1$, $R_2$, and $R_3$, it translates to relative uncertainties in the logarithm of the electron density $N_e$ of $\sim 0.03$. Since the total observed variation in $R_1$ approaches a factor of 2, and since $R_2$ and $R_3$ show the same behavior in electron densities as $R_1$ (at wavelengths unaffected by the Fe $\Pi$ line), I conclude that the observed changes in monochromatic line ratios $R_1$, $R_2$, and $R_3$ are real, and are stellar in origin. This conclusion is strengthened by the fact that the medium resolution data show very similar behavior.

Henceforth I assume that these changes are caused by changes in the chromospheric electron density between gas moving at different projected velocities. I will also use the density determinations from ratio $R_4$ since ratios $R_2$ and $R_3$ agree with this to within reasonable uncertainties and since they are undetermined at Doppler velocities influenced by the strong Fe $\Pi$ line. Figure 1 shows that the electron densities $N_e$ increase systematically across the line profiles, from $\sim 5 \times 10^8$ cm$^{-3}$ in upflowing gas at $-15$ km s$^{-1}$, to $\sim 2 \times 10^9$ cm$^{-3}$ in the downflowing gas at $+25$ km s$^{-1}$.

G. Harper (1993, private communication) has pointed out that although one can derive meaningful different densities from monochromatic flux density ratios, this does not mean that there is a one-to-one mapping of density onto Doppler velocity shift. In fact, he argued that line ratios similar to those shown in Figure 1 can be matched by as little as two density components, moving at $\pm 4$ km s$^{-1}$ and with an assumed “microturbulence” (the most probable speed in a Maxwelian distribution) of $11$ km s$^{-1}$. (This value is the maximum line width permitted by the observed C $\Pi$ and Si $\Pi$ profiles with the assumption of two components). Therefore, we can strictly say only that a minimum of two density components is needed to account for the observed line ratios, although a distribution of electron densities with Doppler velocity must be present in the stellar chromosphere. The point is that more than one density component is needed to fit the data.

3.3. Emission Measures

In analogous fashion to the case where integrated quantities of line profiles are used, emission measures can be derived for monochromatic line flux densities (or intensities) to derive additional information on the gas dynamics. In standard notation (e.g., Jordan & Brown 1981), the frequency-integrated flux density of a line between levels $j$ and $i$, which is optically thin in a slab of thickness $\Delta Z$ cm is

$$F = \frac{1}{2} \frac{hc}{\lambda_{ji}} \int_{\Delta Z} N_j(z) A_{ji} dz \quad (1)$$

where $N_j$ (cm$^{-3}$) is the population of the upper level $j$ of the transition. Following standard emission measure analysis, I express $N_j$ as

$$N_j = \frac{N_{j \to i}}{N_{i \to j}} \frac{N_{i \to j}}{N_{j \to i}} \frac{N_e}{N_{H^+}} \frac{N_{H^+}}{N_e} \frac{N_N}{N_{H^+}} \quad (2)$$

where $N_{i \to j}, N_{j \to i}$, and $N_{H^+}$ are the number densities of the ion, the element, and hydrogen nuclei, respectively. The population
Fig. 2.—Fully resolved line profiles, ratios of line profiles and deduced electron densities plotted as a function of wavelength from line center, expressed in Doppler units of km s$^{-1}$. The unit of flux density (as observed at the Earth) is $10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$. Ratios $R_1$, $R_2$, and $R_3$ are sensitive to the electron density $N_e$, but ratios $R_4$ and $R_5$ are not (Table 1). Ratio $R_4$ is constant to within $\pm 5\%$ between $-15$ and $+25$ km s$^{-1}$. This indicates the expected level of uncertainties present in ratios $R_1$, $R_2$, and $R_3$ data, and it implies relative uncertainties in $\log_10(N_e)$ derived of $\sim 0.03$. The “+” symbol flags data which are affected by the Fe ii blend (see text). The shaded areas plotted on the abscissa show regions of the line profiles where the signal-to-noise ratios are too small to derive meaningful information, or where the corrections for blends are large.

Ratios are computed from solutions to the atomic rate equations (with accompanying assumptions) and then equation (1) is inverted to determine the emission measure $E_m$ (units cm$^{-3}$) which represents the amount of material needed to account for the observed flux density $F$:

$$ E_m = \int_{\Delta z} N_e N_H \, dz \propto \left[ F \left( \frac{N_f}{N_{\text{ion}} N_e N_H} \right)^2 \right], $$

where the constant of proportionality contains known atomic parameters and the stellar angular diameter (I have used 20.5 milliarcseconds, Judge & Jordan 1991). Here I define the same quantity except that $F$ is replaced by $dF/d\nu$, where $\nu_0$ is the Doppler shift from line center in km s$^{-1}$, so that the differentiated emission measure $E'_m$ is now in units of cm$^{-8}$ (km s$^{-1}$)$^{-1}$:

$$ E'_m \propto \left[ \frac{dF/d\nu}{(N_{\text{ion}} N_e N_H)^2} \right]. $$

Figure 3 shows $E'_m$ plotted for three lines: C iii $\lambda 2325.398$, Si ii $\lambda 2350.170$, and Co ii $\lambda 2330.358$. These were computed using the atomic data described above. The densities used in calculating the emission measures were taken from the ratio $R_1$ shown in Figure 1, and the emission measures were computed at a fixed temperature $T_e = 7000$ K. For the Co ii line, excited by fluorescence, meaningful absolute emission measures cannot be derived. However, the Co ii line profile serves as a check on the distribution of emitting material as a function of Doppler shift velocity derived from the Si ii line (from medium-resolution data), whose radiative decay rates are small enough that some photons might be collisionally destroyed. (The Co ii line has an Einstein $A$-coefficient $A_f = 1.3 \times 10^8$ s$^{-1}$, compared with $4400$ s$^{-1}$ for Si ii and $51$ s$^{-1}$ for C vii.) All values of $E'_m$ were computed assuming an electron temperature $T_e \sim 7000$ K. They all scale as $E'_m \propto \exp \left[ -8.8/(T_e/7000) \right]$. In all cases the atomic calculations assumed that $N_{\text{ion}}/N_e = 1$.

The left panel of Figure 3 clearly shows that the derived emission measures differ for the C ii line compared with the
very similar Si ii] and Co ii lines. Therefore, something in the assumptions made in computing the emission measures is incorrect since $E_m$ must be independent of the line used to derive it. Furthermore, the figure clearly demonstrates that the redward asymmetry of the C ii] line profile (Carpenter et al. 1991) cannot be explained by changes in $N_e$ across the line profiles, since the emission measures of C ii] computed taking full account of this effect differ radically from those of Co ii and Si ii]. Some other thermodynamical parameter determining the derived emission measures must control the difference seen between these groups of lines. Possible scenarios are discussed below.

3.4. Model Calculations

Detailed radiative transfer calculations were made using the program MULTI (Carlsson 1986), in the model chromosphere of Kelch et al. (1978). These calculations were made (1) to check estimates of optical depths in the lines under study and (2) to provide a source of synthetic spectra for the C ii] lines.

Calculations for C ii] and Si ii] were performed as described by Judge, Carpenter, & Harper (1991) using the atomic data cited above. The calculations indicate that the lines are indeed optically thin in regions where the atmosphere is excited. The usefulness of this assertion is, however, limited because the chromospheric model clearly fails to describe the gas dynamics as inferred from the lines under study (compare Fig. 4 with Fig. 1). More fruitful is the use of the calculated line profiles as synthetic spectra for input to the procedures described above. Figure 4 shows the same analysis applied to the computed line profiles as was applied to the observed profiles (Fig. 1). The background continua were removed from the line profiles. Regions of the profiles containing significant line emission extend only to $\pm 20$ km s$^{-1}$ (the maximum

"microturbulence" [most probable speed] in the model is just 10 km s$^{-1}$, so our discussion is limited to regions within $\pm 20$ km s$^{-1}$ of line center. The figure shows that: (1) the line ratios which should be constant ($R_4$ and $R_5$), are indeed constant, and they have the correct branching ratios, (2) as expected, the lines are symmetric about line center (the chromospheric model is in hydrostatic equilibrium), (3) therefore the derived electron densities are symmetric with regard to Doppler velocity, (4) the derived electron densities vary with wavelength from line center.

Points (2) and (3) are in stark contrast to the observed data, and they therefore add further credence to the inferences drawn from the GHRS data. Point (4) is particularly interesting. Contribution functions for the C ii] lines show that near line centers (Doppler speeds less than say 5 km s$^{-1}$), the lines are formed in the middle of the chromosphere with electron densities typically near $5 \times 10^8$ cm$^{-3}$. Further in the line wings, the largest contributions come from higher in the model chromosphere where the microturbulence is higher and the electron density is lower ($\sim 3 \times 10^8$ cm$^{-3}$). I conclude that the monochromatic density diagnostic technique, when applied to the synthetic spectra, has succeeded in finding a correlation between electron density and projected velocity of the chromospheric gas.

I performed additional calculations to determine the magnitude of effects due to isotope shifts on the observed profiles. Morton (1991) lists the isotope shift for $^{12}$C of the C ii] inter-system multiplet $2s^22p^2P \rightarrow 2s2p^2P$ as $-0.042$ Å relative to the lines in $^{12}$C. (Morton argues that the isotope shift is the largest hyperfine structure effect for these UV lines). Denoting the abundance ratio $^{13}$C/$^{12}$C as $a$, the computed flux densities at a given wavelength consist of $1/(1 + 1/a)$ times the flux density from $^{12}$C and $1/(1 + a)$ times the flux density from $^{13}$C, the latter being blueshifted by $-0.042$ Å. Smith & Lambert
Fig. 4.—Identical figure to Fig. 2 using line profiles from the computations described in the text. The flux densities have been plotted as they would be observed at the Earth, and the unit is again 10^{-13} ergs cm^{-2} s^{-1} A^{-1}. The “noise” arises from linear interpolation used to put the line profiles on the same (Doppler) wavelength grid.

(1985) give $a = 10$ for a Tau, and $a \sim 90$ for the Sun. C II] lines in a Tau therefore represent a case where the effects of isotope shifts are expected to be large: the shift in wavelength is relatively large and the abundances of the most abundant isotopes differ by only a factor of 10. In spite of this, the calculations show that these effects are negligible, because the shift (corresponding to $-5.4$ km s^{-1}) lies within one Doppler width of the line center. Significant effects do not occur until the isotope shift moves outside of the Doppler core of the line. This situation is unlikely to occur in astrophysical sources owing to the large Doppler line widths.

4. DISCUSSION

What does the discovery of different electron densities and emission measures as a function of Doppler shift really mean? Firstly, it can be firmly stated that, on average, the downflowing gas-emitting C II] line photons is physically separated from the upflowing gas. This is because, if the gas were part of the same structure in which very turbulent plasma existed at the same density, the observed line ratios would not change across the line profiles. This is, in fact, the first undeniable empirical evidence that the chromospheric fluid motions leading to line broadening have components which are “macroscopic” in scale and not “microscopic” (the distinction being that there are physically separate packets of emitting gas on the star with different electron densities).

Secondly, as noted above, the different emission measures derived for the C II] and the Si II] (and Co II] lines imply that one (or more) of the assumptions made in computing these emission measures is incorrect. Equation (4) shows that the emergent monochromatic flux density for a given line depends on the product of the actual emission measure $E_m$ and the factors

$$\frac{N_j}{N_{\text{ion}j}} \frac{N_k}{N_{\text{ion}k}} \frac{N_E}{N_{\text{ion}E}} \frac{N_H}{N_{\text{ion}H}}$$

I now ask which of these factors is the most likely source of the difference between the C II] and Si II] lines:

1. Abundance changes ($N_j/N_{\text{ion}j}$). The observations could be explained if the relative abundance of carbon were lower by factors of 2-3 in the blueshifted gas compared with the redshifted gas. Given the current lively discussion of solar abundances (e.g., Meyer 1993) and the separation of elements by first ionization potential (“FIP”), such a scenario is not impossible, but it seems unlikely.
2. Changes in the ionization fractions $N_{\text{ion}}/N_e$. The observations could equally well be explained if the ratio $N_{\text{C}II}/N_{\text{C}}$ were substantially lower in the upflowing gas than in the downflowing gas, relative to the Si and C ions.

3. Changes in the atomic excitation cannot account for the observed monochromatic line flux densities through the remaining term $N_{\text{Si}/(N_{\text{ion}} N_{\text{C}})}$, since the excitation energies of the upper levels of the transitions considered differ by less than 0.03 eV for the C II] and Si II] lines, and relative differences between the emission measures caused by different temperatures through the dependence of collisional excitation rates on $T_e$ cannot account for the observed relative emission measures. As noted above, the dependence of this term on $N_e$ and the observed behavior of $N_{\text{Si}}$ in fact works in the wrong direction to explain the discrepancy.

The most appealing explanation appears to be point (2). This scenario is worthy of a more detailed study, since Si and C are "low-FIP" elements (ionization potentials 8.15 and 7.86 eV, respectively, Allen 1973), but C is a "high-FIP" element (11.26 eV). Previous work (Judge 1986b) found that the ionization of most neutral elements in the chromospheres of giant stars is dominated by photoionization, and that for "low-FIP" elements the dominant ion is singly ionized, but for "high-FIP" elements the ionization balance is less clear cut and detailed calculations are needed. Judge & Cuntz (1993) found that, in their dynamical calculations of the chromosphere of z Tau, the C II/C I ratio is greater than unity on average only at heights above the middle of the chromosphere. Also, since the C II] emission measure lies close to that of Si II] near Doppler shifts of $\pm 20$ km s$^{-1}$, but that it is much lower at lower velocities, this suggests that perhaps $N_{\text{Si}II}/N_{\text{Si}} \sim 1$ throughout the chromosphere, but that $N_{\text{C}II}/N_{\text{C}}$ approaches unity only in the downflowing material. This material is also substantially denser, which implies that the photoionization rate must be much stronger in these regions. If this explanation is correct, then blueshifted lines of C I are predicted (Carpenter et al. 1991).

Thirdly, we can combine the density determinations and emission measures to consider the column density of emitting material as a function of Doppler shift across the lines (right-hand panel of Fig. 3). This shows that the product of the column density of Si II ions and $\exp(-hc/2kT_e)$ is higher in the upflowing gas. Below, I suggest that $T_e$ is higher in the downflowing gas than the upflowing gas, which means that the Si II column density itself must be higher in the upflowing regions. If $N(\text{Si II})/N(\text{Si}) \sim 1$ as suggested by ionization balance calculations, then the gas column density must be higher in the upflowing material. These inferences are summarized in Table 2.

Fourthly, because the chromosphere is a region in which hydrogen is only partially ionized, important thermodynamical properties (enthalpy fluxes, energy densities) needed for studies of gas dynamics unfortunately cannot be determined from these data.

The cause of the higher electron densities in the downflowing plasma also cannot be determined from these data. One simple scenario exists given the present analysis (see Table 2): Perhaps the downflowing plasma has a slightly higher electron temperature (but lower column density) than the upflowing plasma which leads to higher electron densities through a combination of collisional excitation to the $n = 2$ level of hydrogen followed by photoionization in the Balmer continuum. This may also account for the higher intensity of C II] emission lines in the downflowing plasma if the ionization fraction $N_{\text{C}II}/N_{\text{C}I}$ were to be higher in the downflowing plasma.

Finally, I note that a comparison of these conclusions with the computed data of Judge & Cuntz (1993) reveals that the computations fail again to account for fundamental properties of the observed line profiles. The time-averaged line profiles of Judge & Cuntz (1993), when treated in the same manner as the GHR data, show increased electron densities in the blue wings of the line profiles.

5. CONCLUSIONS AND FUTURE WORK

The "monochromatic density diagnostic" technique has been successfully applied for the first time to GHR data of z Tau with interesting consequences. This technique is promising as a refinement of a well-established technique for deriving empirical properties of optically thin plasmas in a wide variety of astrophysical objects, provided that high resolution, high signal-to-noise data become available.

Table 3 lists the strongest lines of the density-sensitive multiplets of abundant elements of the boron and aluminum sequences. The boron and aluminum sequences were chosen only since the line ratios depend very weakly on other unknown quantities (e.g., temperature) and the emissivities of levels of the $2s2p^2 3P$ term are often dominated by collisional excitation from the ground term. Other isoelectronic sequences also deserve attention. The table also lists approximate line widths (most probable speeds) for thermal ($\xi_p$) and nonthermal motions observed in the Sun ($\xi_\odot$) and scaled (using observations listed in the footnote) to lower gravity evolved giant and supergiant stars ($\xi_G$ and $\xi_\odot$) showing larger nonthermal line-broadening velocities. The table assumes that all lines are formed under conditions where photoionization can be neglected (i.e., under "coronal" conditions). All entries with $\xi_p \leq \xi_{\text{obs}}$ are potential candidates for this technique, since then thermal broadening does not dominate the line widths.
This does not mean that ions with $\xi_T \geq \xi_{\text{sub}}$ should not be studied—indeed this technique might serve to provide independent checks on the temperature of formation of various ions, and thus provide further clues to the nature of the outer atmospheres of the Sun and stars.

A study of the table shows that the future is promising for significant advances using the GHSR on the Hubble Space Telescope for astronomical sources (e.g., the Capella system which has already been observed; Linsky, Wood, & Brown 1993), and using the SUMER and perhaps even the CDS instruments on the SOHO spacecraft for solar studies. Earlier solar spectra are mostly not useful, since they do not have adequate signal-to-noise ratios (e.g., photographic data from HRTS or SKYLAB). Some data from the UVSP on 3MM in the O IV lines might warrant a re-examination (e.g., Hayes & Shine 1987). Stellar observations of special interest should include re-observations of the C II region of $\alpha$ Tau with the GHSR, to attempt to determine the variation of chromospheric properties with time as a function of Doppler shift. One should also observe lines of C I (notably $\lambda$1993 which is optically thin in the chromosphere) and other ions (S I, O I) to determine the validity of the scenario proposed here to account for the observed shifts of the C II] lines relative to Si II] and Co II. Future applications should also include studies of the enigmatic "transition region downflows" seen on the Sun and stars (Brekke 1993, and references therein).

The atmospheric properties derived in this work provide very stringent constraints on models of the gas dynamics in the chromosphere and wind of $\alpha$ Tau. It remains to be seen if refined one-dimensional wave heated models of the type envisioned by Judge & Cuntz (1993) are consistent with these conclusions, or whether very different flow patterns involving perhaps granulation, supergranulation, or other three-dimensional flows must be invoked. Such work is in progress.

Finally, I note that GHSR data of $\alpha$ Ori (spectral type M2 Ib) and $\gamma$ Cru (M3 III) (K. G. Carpenter 1993, private communication) also show significant changes in the density sensitive C II] line ratios across the line profiles. Analysis of these spectra is underway.

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