THE LINE PROFILE VARIABILITY OF SU AURIGAE

CHRISTOPHER M. JOHNS AND GIBOR BASRI
Astronomy Department, University of California, Berkeley, CA 94720
Received 1994 June 20; accepted 1995 February 27

ABSTRACT

We analyze approximately 100 echelle spectra of the T Tauri star SU Aur. The photospheric lines appear unveiled and show little variability. We find evidence for periodic intensity variations in the blue wing of Hβ between $-170 < v < -110$ km s$^{-1}$ from line center with a period of approximately 3 days, the rotation period of the star. Both the period and velocity are the same as previously reported for Hα in SU Aur. Furthermore, evidence for unsteady accretion is found in the presence of a variable red displaced absorption feature with a velocity of $v \sim +100$ km s$^{-1}$ in Hβ. This feature is also periodic at 3 days (unlike in Hα). Several spectra indicate simultaneous mass inflow and outflow. The Ca II infrared and He i 5876 lines show modest variability and imply that the structure of the chromosphere on SU Aur is very different than solar plage regions. Variations of the Ca II lines and the He i line are well correlated with each other but only poorly correlated with Balmer line variability.

We use spherically symmetric radiative transfer codes to calculate the line profiles for SU Aur. The equations of statistical equilibrium are solved using the general purpose program CLOUDY. By simultaneously fitting the Balmer lines in SU Aur, we determine to what extent these lines can be produced in a spherically symmetric wind and constrain the parameters of this wind. We find that large turbulent velocities are required at the base of such a wind, where the bulk of the emission is produced. The steady absorption feature seen at $v \approx -50$ km s$^{-1}$ must form in the outer portions of the stellar wind, implying a terminal velocity of the wind much below the stellar escape velocity. The mass-loss rate is determined to be about $4.5 \times 10^{-9}$ $M_\odot$ yr$^{-1}$.

Subject headings: line: profiles — stars: individual (SU Aurigiae) — stars: pre-main-sequence

1. INTRODUCTION

T Tauri stars (TTSs) are now generally believed to represent young solar-mass stars that have only recently formed. They offer the exciting possibility that in looking at these objects we are seeing replayed not only the early history of our Sun as a star, but perhaps the entire solar system as well. Of particular interest in the study of TTSs is the goal of discovering how they rid themselves of the circumstellar material associated with star formation. Winds and disks appear to play a pivotal role in the evolution of angular momentum in these systems. Material accreting onto the star through a disk would rapidly spin the star up to breakup speeds, yet TTSs are observed to be relatively slow rotators (Hartmann & Stauffer 1989). TTS winds seem to be one agent that carries away this excess angular momentum which allows the star to accrete material. Furthermore, winds from TTSs and younger embedded sources may be the driving mechanism of bipolar molecular outflows. Taking into account the neutral component of the winds, Natta & Giovanardi (1991) have shown that the momentum and energy flux in TTS winds is comparable to that in observed outflows.

In addition to the wind, the disk may have an active role in regulating the stellar rotation. Edwards et al. (1993) find that classical TTSs (CTTSs) (stars with disks) appear to occupy a narrow range of rotation periods, whereas the naked TTSs (NTTSs) which lack disks have a variety of rotation periods. The disk must be coupled to the star in some way, probably via magnetic fields, for such regulation to occur (Camenzind 1990; Königl 1991). Further exposition of the nature of TTS winds may provide clues as to the role of winds and outflows in the star formation process; it may even be that the onset of a wind determines the mass of a protostar (Shu, Adams, & Lizano 1987).

T Tau has been known to be a variable star for over a century. Ever since the pioneering studies of Joy (1945, 1949) and Herbig (1962) it has been known that TTSs in general are quite variable. This variability manifests itself in broadband continuum variability as well as in variations of emission-line strengths and shapes. The initial studies of TTS emission line variability merely noted the existence of line shape changes and tried to correlate equivalent width changes with photometric variability. Joy (1945) and later studies (e.g., Cohen & Schwartz 1976) found that at least for some of the strong-emission-line TTSs a positive correlation exists between line equivalent width and continuum flux. On the other hand, studies of weak-emission TTSs find an anticorrelation (see, e.g., Herbst, Holtzman, & Phelps 1982). Still other studies have found dramatic emission line changes with no continuum change and vice versa (see, e.g., Bertout et al. 1977). Most of these early studies only focused on emission-line equivalent widths, primarily because spectra were obtained only with low-to-moderate resolution. Later studies at higher spectral resolution have demonstrated that the emission-line profiles are also variable. For example, Mundt & Giampapa (1982) noted profile variability on timescales as short as 10 minutes for Hβ observed in RW Aur. They interpreted these observations in terms of strong flares or possibly variable accretion. Mundt (1984), in a broader survey of TTSs at high-resolution, noted that several stars showed variations in Hα, Ca II H and K, and Na D. For a few stars such as DR Tau, there exist some very constant blueshifted absorption features.

1 Based on observations obtained at the Lick Observatory, run by the University of California.
2 Now at McDonald Observatory, University of Texas, Austin, TX 78712-1083.
in the generally variable Na D lines, which Mundt argued indicated a formation region for the absorption component at a large distance from the star in a strong stellar wind.

Basri (1987) argued early on that the stellar magnetic field should play a large role in the star-disk interaction, and Bertout, Basri, & Bouvier (1988) interpreted periodic behavior in DF Tau as being due to magnetically controlled accretion. Guenther & Hessman (1993) studied the spectroscopic variability of DR Tau at modest resolution. They found variations in the veiling on timescales of hours to days which, combined with the inverse P Cygni profiles seen in many of the lines, led them to conclude that magnetically controlled accretion is occurring in DR Tau. In a recent photometric study of DR Tau, Kenyon et al. (1994) also found evidence for a direct relationship between optical and IR variations. Edwards et al. (1994) saw direct evidence for redshifted absorption components in many of the TTSs in their sample and argued that they could arise in magnetospheric accretion flows. Hartmann, Hewett, & Calvet (1994) have made a detailed modeling study relevant to this explanation and found that magnetospheric accretion flows can produce lines with or without redshifted absorption, depending on the thermalization properties of the flow. Petrov & Vilhu (1991) have made repeated observations of the TTS RY Tau at high resolution. By studying the extremes of the Hz line shape, they propose that the emission lines form both in a spherically symmetric wind and in the boundary layer of an accretion disk which abuts the stellar surface.

As indicated above, it is generally believed that a strong wind component is present in all CTTs. Mass-loss estimates by various authors put the mass-loss rate at about $10^{-8}$ to $10^{-7}$ $M_{\odot}$ yr$^{-1}$ (see Kuhn 1964, 1966; Kuan 1975; Edwards et al. 1987; Natta & Giovanardi 1990). DeCampli (1981) showed that thermally driven winds similar to the solar wind could not drive these high mass-loss rates but that Alvén wave-driven winds could power mass-loss rates up to a few $10^{-8} M_{\odot}$ yr$^{-1}$. Hartmann, Edwards, & Avrett (1982) independently reached the same conclusion. Hartmann et al. (1990) calculated line profiles for spherically symmetric Alvén wave-driven winds, and Calvet, Hartmann, & Hewett (1992) calculated line profiles for winds originating from a disk star boundary. While these models have met with some success, they have had trouble reproducing the typical observed line profiles in TTSs.

Since these are steady state models, they make no predictions as to the variability that might be observed in line profiles. In the case of the Alvén wave model originating on the stellar surface, if the field is not axially symmetric over the surface of the star, we might expect periodic modulations of the profile with the period of stellar rotation. Shu et al. (1988) proposed a model of mass loss based on a centrifugally driven wind, dubbed the X-celerator mechanism. The model requires that the equatorial regions of the star are rotating at breakup; hence, a natural period for this system is the Keplerian orbital period at the stellar surface, which is 11 hr for typical TTS parameters. Basri & Bertout (1989) suggested that a similar mechanism may work farther out in the accretion disk (where every point is rotating at breakup), and Shu et al. (1994) have indeed shown that a modified version of the X-celerator mechanism can work at larger radii where stellar field lines truncate an accretion disk. The natural period for this modified version of the X-celerator is the rotation period of the star as a whole. Lines formed in magnetospheric accretion flows (Hartmann et al. 1994) which are controlled by the stellar field might also show periodicity at the stellar rotation period, especially in accretion diagnostics such as redshifted absorption components.

Grinin & Mitskevich (1991) and Mitskevich, Natta, & Grinin (1993, henceforth MNG) have developed models of stochastic winds for TTSs. These models posit a clumpy nature to the TTS winds and provide a natural source of variability. As such, these models represent the first theoretical attempt to account for emission-line variability seen in TTSs and make some predictions concerning the level of variability across lines such as Hz. These predictions can be tested only by compiling many repeated observations for several TTSs.

Over the past several years we have been compiling synoptic observations of several TTSs. M. Giampapa has also been collecting repeated observations of the TTS SU Aur using the McMath telescope of the National Solar Observatory, and we combined data on this star in Giampapa et al. (1993, henceforth GBJI). In GBJI only the variations of the Hz line profile in SU Aur were discussed, since no data on other lines were gathered with the McMath telescope. GBJI found strong periodicity in a wind signature in Hz with the same period as the stellar rotation period. This was interpreted as evidence for the wind being directly influenced by the star, probably via magnetic fields. This argues against the pure disk wind hypothesis for TTSs. Here we discuss the profile variations of all the lines observed at Lick Observatory, with particular emphasis on Hz, Hβ, and the Ca II IR triplet. In § 2 we discuss the observations themselves, § 3 describes the analysis of the Hβ line profile variations and compares them with previous results for Hz, § 4 describes the variations seen in Ca II, H, and the photospheric lines, § 5 describes efforts to model the Balmer lines with a spherically symmetric wind code, and a discussion of the results appears in § 6.

2. OBSERVATIONS

Table 1 gives a log of the observations of SU Aur taken at Lick Observatory. All observations were made with the Hamilton Echelle Spectrometer (Vogt 1987) coupled either to a T1 800 × 800 CCD or a FORD 2048 × 2048 CCD. The resolution of the spectrograph is λ/Δλ = 48,000. The spectrometer was fed with either the 3 m Shane reflector or the 0.6 m could auxiliary telescope (CAT). Exposure times varied and are listed in Table 1. Most exposures contain Hz in the format. Owing to the relatively small size of the T1 CCD, it is difficult to include Hβ and all three members of the Ca II IR triplet in a single exposure; therefore, not all these lines appear in each exposure. At some times a red setting was used to acquire Hz and the Ca II IR triplet, and a separate blue setting was used to observe higher Balmer lines and Ca II K. Table 1 indicates in which setting each exposure was taken. Table 2 lists these settings, the CCD used in the setting, and a number of the potentially interesting lines covered in the setting. The FORD chip is able record the spectrum from about 3000 Å to 9000 Å without any gaps. The quantum efficiency of the FORD chip is approximately half that of the T1 chip (Misch 1991).

Owing to the effects of varying exposure times, weather, and the difference in efficiency between the chips, there is a range in the signal-to-noise ratio (S/N) of the spectra. Hz profiles can be reliably extracted from all the observations presented here. Hβ profiles can be extracted from most of the exposures which contain the line in the format. The 1R triplet line and other weak absorption features such as Li 6707 Å can be reliably extracted from all the 3 m spectra and some of the CAT
### Table 1: Observations

<table>
<thead>
<tr>
<th>UT Date</th>
<th>Julian Date</th>
<th>Telescope</th>
<th>Exposure Time (s)</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986 Oct 22, 13:12</td>
<td>2,446,726.05</td>
<td>3 m</td>
<td>1500</td>
<td>1</td>
</tr>
<tr>
<td>1986 Oct 23, 6:55</td>
<td>2,446,726.79</td>
<td>3 m</td>
<td>2000</td>
<td>2</td>
</tr>
<tr>
<td>1986 Nov 12, 10:04</td>
<td>2,446,746.92</td>
<td>3 m</td>
<td>900</td>
<td>1</td>
</tr>
<tr>
<td>1986 Nov 12, 13:51</td>
<td>2,446,747.08</td>
<td>3 m</td>
<td>3600</td>
<td>2</td>
</tr>
<tr>
<td>1986 Nov 13, 6:25</td>
<td>2,446,747.77</td>
<td>3 m</td>
<td>2700</td>
<td>1</td>
</tr>
<tr>
<td>1986 Nov 13, 8:08</td>
<td>2,446,747.84</td>
<td>3 m</td>
<td>4000</td>
<td>2</td>
</tr>
<tr>
<td>1986 Dec 21, 5:02</td>
<td>2,446,785.71</td>
<td>3 m</td>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>1986 Dec 21, 9:53</td>
<td>2,446,785.91</td>
<td>3 m</td>
<td>2000</td>
<td>2</td>
</tr>
<tr>
<td>1986 Dec 21, 12:14</td>
<td>2,446,786.01</td>
<td>3 m</td>
<td>1500</td>
<td>1</td>
</tr>
<tr>
<td>1986 Dec 22, 4:19</td>
<td>2,446,786.68</td>
<td>3 m</td>
<td>2000</td>
<td>1</td>
</tr>
<tr>
<td>1986 Dec 22, 13:14</td>
<td>2,446,787.76</td>
<td>3 m</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1987 Oct 11, 7:12</td>
<td>2,447,079.80</td>
<td>3 m</td>
<td>900</td>
<td>1</td>
</tr>
<tr>
<td>1987 Oct 11, 13:08</td>
<td>2,447,080.05</td>
<td>3 m</td>
<td>2200</td>
<td>2</td>
</tr>
<tr>
<td>1987 Oct 12, 12:00</td>
<td>2,447,081.00</td>
<td>3 m</td>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>1987 Nov 7, 8:10</td>
<td>2,447,106.84</td>
<td>3 m</td>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>1987 Dec 13, 7:26</td>
<td>2,447,142.81</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1987 Dec 14, 5:17</td>
<td>2,447,143.72</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1987 Dec 17, 12:14</td>
<td>2,447,147.01</td>
<td>CAT</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1987 Dec 18, 9:50</td>
<td>2,447,147.91</td>
<td>CAT</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1987 Dec 21, 9:07</td>
<td>2,447,150.88</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1988 Jan 6, 10:19</td>
<td>2,447,166.93</td>
<td>CAT</td>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>1988 Jan 7, 7:41</td>
<td>2,447,167.82</td>
<td>CAT</td>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>1988 Jan 12, 4:05</td>
<td>2,447,172.67</td>
<td>CAT</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1988 Jan 13, 8:53</td>
<td>2,447,173.87</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1988 Jan 14, 4:05</td>
<td>2,447,194.67</td>
<td>CAT</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1988 Jan 16, 5:31</td>
<td>2,447,196.73</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1988 Jan 19, 8:53</td>
<td>2,447,197.87</td>
<td>CAT</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1988 Jan 23, 4:48</td>
<td>2,447,183.70</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1988 Jan 24, 3:07</td>
<td>2,447,184.63</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1988 Jan 25, 4:34</td>
<td>2,447,185.69</td>
<td>CAT</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 4, 9:36</td>
<td>2,447,195.90</td>
<td>3 m</td>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>1988 Feb 8, 3:50</td>
<td>2,447,199.66</td>
<td>CAT</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 9, 5:16</td>
<td>2,447,200.72</td>
<td>CAT</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 10, 4:05</td>
<td>2,447,201.67</td>
<td>CAT</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 12, 4:48</td>
<td>2,447,202.77</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 12, 12:48</td>
<td>2,447,203.70</td>
<td>CAT</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 13, 4:19</td>
<td>2,447,204.68</td>
<td>CAT</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 13, 7:12</td>
<td>2,447,204.80</td>
<td>CAT</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 14, 3:36</td>
<td>2,447,205.65</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 14, 6:58</td>
<td>2,447,206.79</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 15, 3:36</td>
<td>2,447,206.65</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 15, 4:34</td>
<td>2,447,206.69</td>
<td>CAT</td>
<td>3000</td>
<td>4</td>
</tr>
<tr>
<td>1988 Feb 15, 5:46</td>
<td>2,447,206.74</td>
<td>CAT</td>
<td>3300</td>
<td>4</td>
</tr>
<tr>
<td>1988 Feb 15, 6:43</td>
<td>2,447,206.78</td>
<td>CAT</td>
<td>3000</td>
<td>4</td>
</tr>
<tr>
<td>1988 Feb 15, 7:41</td>
<td>2,447,206.82</td>
<td>CAT</td>
<td>3000</td>
<td>4</td>
</tr>
<tr>
<td>1988 Feb 15, 8:38</td>
<td>2,447,206.86</td>
<td>CAT</td>
<td>2884</td>
<td>4</td>
</tr>
<tr>
<td>1988 Feb 16, 3:07</td>
<td>2,447,207.63</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 16, 6:12</td>
<td>2,447,207.90</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 17, 3:22</td>
<td>2,447,208.64</td>
<td>CAT</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 17, 6:14</td>
<td>2,447,208.76</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 18, 4:05</td>
<td>2,447,209.67</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
<tr>
<td>1988 Feb 19, 9:02</td>
<td>2,447,210.71</td>
<td>CAT</td>
<td>3000</td>
<td>3</td>
</tr>
</tbody>
</table>

---

spectra, though with much less success from the CAT data taken with the FORS chip. As it turns out, the evidence suggests these features do not vary; therefore, we lose relatively little information for the purposes of this study. The spectra are reduced in a standard way described by Basri, Wilcots, & Stout (1989). Wavelength calibration is performed by observing a thorium-argon arc lamp and performing a two-dimensional solution to the thorium lines. A radial velocity correction, using a radial velocity of $+16$ km s$^{-1}$ (Herbig & Bell 1988), and barycentric velocity corrections are applied. All the data shown here are in the stellar rest frame.

In Figure 1 we plot the pairs of Hα and Hβ profiles for which we have both from the same night and which have reasonable S/N in Hβ. Approximately half of the Hα profiles observed for this project appear in GBJI. The Hβ line profiles have had the profile of a G2 spectral standard which has been rotationally broadened by 68.5 km s$^{-1}$ (the $v\sin i$ of SU Aur, Bouvier et al. 1986) subtracted from the observed profile. There are other photospheric features in the same spectral order which contains Hβ. These features easily subtract out, indicating that the veiling in SU Aur is negligible, which is consistent with the value of $0.0 \pm 0.1$ found by Basri & Batalha (1990). By far, the largest variability is seen in the Balmer lines. The Ca ii IR triplet shows some variations, as does Li 6707 Å to a more
limited extent, while strong photospheric lines such as Mg I show no variation at all. The lines in Figure 1 look relatively weak compared with most CTTSs. Since SU Aur is a G2 star (Cohen & Kuhi 1979) with a luminosity of 13.1 $L_\odot$ (Cohen, Emerson, & Beichman 1989), the flux in these lines is actually comparable to other classical TTSSs. For future reference we note that with a spectral type of G2 and a luminosity of 13.1 $L_\odot$, SU Aur has a radius of 3.6 $R_\odot$. Cohen et al. (1989) have used models of stars plus accretion disk to determine the mass of SU Aur from its placement in the H-R diagram and find $M = 2.25 M_\odot$.

3. H$\beta$ Profile Variations

3.1. Parameterization of the Line Profiles

It is apparent from Figure 1 that both the H$\alpha$ and H$\beta$ line profiles show considerable variations. GBJI describe the parameterization of the H$\alpha$ profile in terms of a flat-top component with from one to five Gaussians superposed on it, depending on the complexity of the line profile. The flat-top component was motivated by the general flat-topped appearance of many of the line profiles and is physically motivated by the fact that optically thin stellar winds have a general flat-top appearance (Mihalas 1978). In § 5 we show that large, variable turbulent velocities can also produce generally flat-top-shaped profiles, so the assumption of an optically thin envelope is not required. This was hinted at by GBJI, who had trouble interpreting the behavior of different components of the H$\alpha$ line profile variability with a fast, optically thin wind.

For H$\beta$ we follow the same general procedure of line parameterization to aid in comparisons with the H$\alpha$ line profile. Because the S/N of our H$\beta$ line profiles is lower than in H$\alpha$ and the flat top is not very pronounced in most of the H$\beta$ profiles, we could not allow all the freedom GBJI allowed in the flat-top component without producing many nonsensical fits. Therefore, we elected to constrain the flat-top component to be perfectly flat (whereas GBJI allowed for asymmetry in the flat top) and require the flat top to be centered at zero velocity instead of allowed to float. The parameters of the flat top are then its height, width, and Gaussian wing width. Superposed on this are from one to four Gaussians, depending on the complexity of the line profile. A gradient search algorithm (Bevington 1969) is used to find the best-fitting parameterization of each line profile. An example of a H$\beta$ profile and its parameterized fit is shown in Figure 2.

In Figure 2 we label various components of the line profile which are often repeated. Component A is the main absorption feature which appears in most of the H$\beta$ profiles and appeared in all but two of the H$\alpha$ profiles. Component B is referred to as the central emission feature which is a dominant component in the H$\alpha$ line profile, but less so in H$\beta$. GBJI suggested that this component in H$\alpha$ might arise in a stellar chromosphere; however, its weakness in H$\beta$ suggests otherwise since Calvet, Basri, & Kuhi (1984) showed that the source functions of the two lines cannot be too different in deep chromosphere TTS models. Component C is a redshifted absorption component which sometimes appeared in H$\alpha$ and appears quite regularly in H$\beta$. Component D is a blueshifted absorption feature which appears in both Balmer lines.

In Table 3 we list these features, the number of times they appear, and the mean and standard deviation of their positions and widths as derived from the fits. Only observations which contain both Balmer lines are included in this table. Some features are apparent more often in one line or the other. In these cases the values in brackets under the line where the feature appears most represent the average calculated from only the profiles where the feature appears in the other line.

<table>
<thead>
<tr>
<th>Component*</th>
<th>H$\alpha$ Mean</th>
<th>H$\alpha$ $\sigma^b$</th>
<th>H$\beta$ Mean</th>
<th>H$\beta$ $\sigma^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat-top: 78 (67), Height</td>
<td>480.5 [482.3]</td>
<td>35.3 [35.6]</td>
<td>380.9</td>
<td>100.0</td>
</tr>
<tr>
<td>Width</td>
<td>0.70 [0.70]</td>
<td>0.29 [0.29]</td>
<td>0.14</td>
<td>0.10</td>
</tr>
<tr>
<td>Main Absorption (77, 55), Velocity</td>
<td>-41.5 [-44.3]</td>
<td>15.6 [13.8]</td>
<td>-44.9</td>
<td>17.3</td>
</tr>
<tr>
<td>FWHM</td>
<td>64.9 [67.5]</td>
<td>24.9 [25.4]</td>
<td>53.0</td>
<td>21.0</td>
</tr>
<tr>
<td>Blue Absorption (48, 21), Velocity</td>
<td>-143.2 [-134.0]</td>
<td>25.5 [24.1]</td>
<td>98.6</td>
<td>17.5</td>
</tr>
<tr>
<td>FWHM</td>
<td>86.1 [94.7]</td>
<td>36.7 [34.8]</td>
<td>75.0</td>
<td>31.5</td>
</tr>
<tr>
<td>Red Absorption (26, 55), Velocity</td>
<td>115.2</td>
<td>31.9</td>
<td>100.7 [100.8]</td>
<td>21.9 [12.0]</td>
</tr>
<tr>
<td>FWHM</td>
<td>80.7</td>
<td>39.6</td>
<td>127.3 [115.3]</td>
<td>37.4 [27.2]</td>
</tr>
</tbody>
</table>

Notes.—Brackets here indicate values for one line determined from the same nights used to calculate the quantity for the other line.

* Numbers given in parentheses are the number of occurrences in H$\alpha$ and H$\beta$, respectively.

a For velocities and widths, units are kilometers per second; for flat-top height, units are relative intensity in continuum units.
Fig. 1a

Fig. 1a—(a)-(e) The Hα and Hβ line profiles for nights on which both lines were observed. The Hα profiles are the dotted lines and the Hβ profiles are shown with the solid line. The Hβ line profiles have had a rotationally broadened G2 V standard star subtracted from them to better show the excess emissions and absorptions present.
The statistics on the flat-top component show that the Hα line profile is 100 km s$^{-1}$ wider on average than the Hβ line profile. At first this may not appear significant since the standard deviation of the Hβ profile is so large. However, there are a number of very low widths in the Hβ profiles, which brings down the mean somewhat and greatly increases the standard deviation. In order to test the significance of this difference we performed a multivariate Student's t-test (Press et al. 1986) on the two distributions of flat-top widths. This calculation estimates that the difference in the two means is significant at well above the 99.9% confidence limit. However, this is just a statistical statement on the distributions of determined flat-top components. Since the average height of the Hβ flat top is only 3σ above the average noise level in the spectra, it is obvious that the Hβ flat top is not well detected, and hence the true width of the feature is probably larger than the measured values. Therefore, we cautiously conclude that Hα may be broader than Hβ.

Two other curious observations from Table 3 which deserve some note concern the velocities of the blueshifted and redshifted absorption features. The table shows that the velocity of the redshifted feature seen in Hα is greater than that in Hβ. For infalling material, if we assume that the formation region of this feature in Hβ is closer to the star than in Hα owing to the difference in their optical depths, then we might draw the conclusion that the material is decelerating as it approaches the star. It should be kept in mind that the central emission component seen in Hα is very strong but is almost completely absent in Hβ, as can be seen in Figure 1. This feature can crowd the redshifted feature in Hα and make the resulting intensity profile appear as if the absorption has a larger redshift. This suggests that the apparent velocity difference in this feature may not be real.

There is also an apparent velocity difference in the blueshifted absorption feature. This feature is blueshifted enough relative to the central emission feature that it should be very little of the above-mentioned problem. We conclude that the blueshifted feature does appear at higher velocity in Hα than in Hβ. Assuming that the Hα feature forms farther from the star owing to its higher optical depth, this indicates that this material is accelerating as it moves away from the star.

Bertout, Basri, & Bouvier (1988) argued that the bulk of the Balmer line emission arises in a magnetically dominated region adjacent to the source of the boundary layer emission, and Hartmann et al. (1994) more specifically propose that this emission arises in a magnetospheric accretion flow. Both sets of investigators argue that an overlying optically thin wind is primarily responsible for only the blueshifted absorption components seen in these lines. Assuming the Balmer lines can be parameterized as described above, we can test the hypothesis that the main absorption feature (component A—blueshifted to $-45$ km s$^{-1}$ in Hα and Hβ) arises in optically thin gas which contributes little or no emission of its own. The profile parameterization allows us to estimate the emission level, $I_{o}$, in the absence of any absorption, and we can measure the resulting residual intensity, $I$, after the absorption occurs. Assuming the material is primarily absorbing, these are related by $I = I_{o} e^{-\tau}$, from which the optical depth can be estimated. Calculating the average value of $\tau$ for both lines we find $\tau_{H\alpha}/\tau_{H\beta} = 4.78$. If our assumptions are correct, this ratio should equal the ratio of the $\lambda$ values for these lines, since they share a common lower level (ignoring stimulated emission, which is proper, since we are assuming that the wind contributes little or no emission in the first place). The ratio $(\lambda_{H\alpha}/\lambda_{H\beta}) = 7.25$, so the lines do not form in an optically thin region (wind) with negligible emission. This conclusion is subject to our being right about the shape of the underlying emission.

3.2. Time Series Analysis

GBJ1 contains a detailed discussion of time series analysis of the Hα line profile in SU Aur. We refer the reader to that discussion, as we will show the results of a similar analysis for Hβ and only new results for Hα. One of the most striking results in the analysis of Hα was the discovery of periodic intensity variations in one wing of the line profile centered on a blueshifted absorption feature visible in the profile. Figure 7 of GBJ1 showed the power spectra at each position in the line profile as a surface plot. This plot was made by normalizing the power spectra at each position in the line profile by the variance of the entire Hα profile. R. Donahue & J. Horne (private communication) have pointed out that this is an overly conservative way to estimate the power spectra. So long as each pixel in velocity (wavelength) position in the line profile is wider than the resolution of the spectrograph, each velocity position can then be treated as an independent time series for the purpose of estimating the power spectra. Therefore, the power spectra at each velocity position can be normalized by the variance of the profile intensity in only that velocity position as a function of time. Figure 3 shows a gray-scale map of the entire power spectra of the Hα time series observed in 1988 February with this new normalization. As discussed in GBJ1, this time is the longest nightly series of observations of SU Aur and the only one really appropriate for finding periods near the rotation period of $\sim 3$ days determined from photometric monitoring of SU Aur (see Herbst et al. 1987; Bouvier et al. 1993). The previously observed peak centered near $-150$ km s$^{-1}$ and 3 days is still plainly visible, and following the prescription given in GBJ1 has a total false alarm probability of $10^{-21}$.

In addition to the previously reported peak, there are other fairly strong peaks, of which one is potentially significant. A peak appears at $v = -80$ km s$^{-1}$ with a period near 7.7 days. This feature is much narrower in velocity width than the peak found at 3 days. The period of the power spectrum peaks in adjacent velocity bins is not the same throughout this feature; however, given the uncertainty in period determination for the
time series we are sampling here, the peaks appear at the same period to within the errors of our period determination. Therefore, if we treat this as one feature, the total false alarm probability is $10^{-5}$. We regard this as a marginal detection because the total data span covered in the 1988 February run is only 1.8 periods, so we do not observe the complete repetition of the signal. Periodogram analysis of the rest of the data in the absence of the 1988 February run shows no evidence for the 7.7 day period; however, as discussed in GBII, this could result if the source of the periodicity does not maintain its phasing over long time intervals.

The peak in the power spectrum is confined to the blue wing of the main absorption feature where the profile intensity is affected by the velocity of the main absorption feature, its width and strength, as well as being affected by the high-velocity blueshifted absorption feature. With all these factors affecting the resulting intensity, it is difficult to say what is causing periodic modulation in this portion of the line profile. Furthermore, the 7.7 day peak fails to show up as strongly in other power spectrum estimation routines. For example, we have used the maximum entropy method of power spectrum estimation given by Press et al. (1986). Implementation of this method requires interpolation of our data onto a regularly spaced time grid of nightly observations. Unfortunately, this method gives no estimate of the significance of recovered peaks; however, the 3 day peak in the neighborhood of $v = -150$ km s$^{-1}$ appears quite strongly. At the same time there is no sign of the 7.7 day peak at $v = -80$ km s$^{-1}$ at the

Fig. 3.—The top panel shows the average Hα line profile from the 1988 February observing run. The bottom panel shows a gray-scale and contour plot of the periodogram calculated from the 1988 February run. The contours are shown at levels of 4, 6, and 8 in normalized power. Note the strong peak at $P \sim 3$ days on the blue side of the profile.

same order in the maximum entropy estimator. Use of higher order in the maximum entropy estimator which forces the method to recover smaller peaks does reveal the 7.7 day peak.

During the 1988 February run, Hβ was recorded on each exposure in addition to Hα. The power spectrum of the entire Hβ profile is shown in Figure 4. Note again the peak centered at $v = -150$ km s$^{-1}$ and a period of 3 days. This is the same as observed in Hα. The total false alarm probability for this feature is $10^{-20}$. This peak again occurs where a blueshifted absorption feature appears in the Hβ line profile, and it is confirming evidence for a rotationally modulated wind. In addition to this peak, there is power on the red side of the Hβ profile in the vicinity of the redshifted absorption feature seen in the upper panel of Figure 4. As with the $v = -80$ km s$^{-1}$ Hα feature, the adjacent velocity bin power spectra at $v \approx +120$ km s$^{-1}$ do not peak at exactly the same period, but they peak at periods within the error bars on the period determination. If we assume the peaks in adjacent velocity bins really represent the same period and calculate the total false alarm probability for the entire feature, we get $10^{-10}$. Additionally, both these peaks show up in other types of power spectrum estimators such as the maximum entropy method, which lends additional support to their reality. Since this peak occurs in a redshifted

Fig. 4.—The top panel shows the average Hβ line profile from the 1988 February observing run in the solid line (shown in the dashed line). A G2 V spectral standard has been subtracted from this profile to produce the residual shown in the solid line. The bottom panel shows a gray-scale and contour plot of the periodogram calculated from the 1988 February run. The contours are shown at levels of 2, 4, and 6 in normalized power. Note the peaks at $P \sim 3$ days on both the blue and red sides of the line.
absorption feature with the same period as the stellar rotation period (see GBJ1), we interpret this as evidence for rotationally modulated infall and outflow, we may then ask whether they are in phase or not? For this we use the profile fit parameters (described above for Hβ and in GBJ1 for Hα) to calculate the equivalent width of the two absorption components. Figure 5 shows these equivalent widths for the 2 week run in 1988 February. The Hβ equivalent width has been offset by 300 km s⁻¹ for clarity. Along with the data are the best-fit sine waves to the two time series. As can be seen from these fits, the two time series are approximately 180° ± 20° out of phase, indicating that the wind is strongest when the infall is weakest. As will be discussed further in § 6, we believe this observation can be easily explained by the Shu et al. (1994) magnetocentrifugal model if the stellar dipole magnetic field is misaligned with respect to the star-disk rotation axis.

Aside from potential periodic behavior in the Balmer line profiles, it is informative to see if the variations seen in Hβ are in general correlated with those in Hα. Figure 6 shows the linear correlation coefficient (r) between the Hα and Hβ line profiles in each velocity bin. This shows that over most of the line profiles, the Hz and Hβ variations are well correlated. However, the two profiles are uncorrelated near v ~ 30 km s⁻¹.

4. THE PHOTOSPHERIC AND Ca II LINES

4.1. Mg i and Li Lines

CCTTs often show variable veiling in their photospheric lines as a result of variable accretion onto the star. The strongest photospheric lines are the easiest in which to detect veiling as well as being the first lines which will show filling-in from the effects of an extended emitting/absorbing envelope around the star. The Mg i b triplet lines are very strong in G2 stars and are in the format of most of our spectra. In addition, we usually record the Li 6707 Å which is also a relatively strong line in TTSs owing to their youth. Figure 7 shows the Mg i b 5184 Å

FIG. 6.—The linear correlation coefficient (r) between the Hα and Hβ line profiles in each velocity bin. This shows that over most of the line profiles, the Hz and Hβ variations are well correlated. However, the two profiles are uncorrelated near v ~ 30 km s⁻¹.

FIG. 7.—The upper panel shows several Mg i 5183 Å profiles from nights which show strong Hα variability. The bottom panel shows the Li 6707 Å line from these same nights.
line and the Li line for several observations of SU Aur during which Hz and Hβ showed strong variability. These profiles all come from 3 m observations and have relatively high S/N. This figure merely illustrates that the photospheric lines of SU Aur are essentially nonvariable and are well fitted by the lines of the G2 standard star, which comes as no surprise since SU Aur is measured to have zero veiling (Basri & Batalha 1990). Comparing the Mg I line of SU Aur with a G2 spectral standard (the solar spectrum) indicates that the core of the line is filled in by SU Aur by 10%. In G2 stars the core of the Mg I line forms in the chromosphere. The slight filling in we observe could be due to veiling or enhanced chromospheric activity. Basri & Batalha (1990) measured zero veiling for this star (and, as mentioned in the previous section, we find zero veiling in the vicinity of the Hβ line), and, as discussed below, the Ca II and He I lines indicate enhanced chromospheric activity. We therefore conclude that the Mg I core is filled in by chromospheric activity; however, we caution that no allowances have been made for metallicity differences.

4.2. Na D Lines

Most of our CAT observations are severely contaminated in the Na D lines by sky glow from the low-pressure Na vapor lamps used in the city of San Jose. Spectra taken with the 3 m suffer much less contamination owing to the fact that the plate scale of the 3 m reduces the area of sky on the slit by a factor of 25 and also because exposure times tend to be shorter on the 3 m. Additionally, the 3 m spectra have higher S/N than the CAT spectra. Therefore, many of our 3 m spectra are suitable to do some comparisons of the Na D line profiles. The Na D profiles are dominated by the stellar absorption features and show very little variability. There may be some slight emission in the continuum near the Na D lines when comparing them to spectra of a G2 standard star, but owing to the presence of other moderately strong lines nearby which get quite broad due to the fast rotation of SU Aur, the interpretation is not clear and will not be discussed further. On a few nights such as 1988 February 15 when the Balmer lines show exceptionally strong blueshifted absorption, absorption appears in the blue wing of the Na D lines. The Na D absorption appears approximately 46 km s⁻¹ closer to rest velocity that the strong feature seen in Hz, possibly indicating that the material is accelerating outward.

In addition to the stellar component, there is a narrow interstellar component seen in spectra taken before 1992. Several spectra taken after that time appear to show two narrow interstellar medium (ISM) absorption lines. One line appears to be the same feature which was there earlier, and on several spectra there is an additional feature redshifted by approximately 20 km s⁻¹. Unfortunately, the portion of the profile where these ISM lines are seen is in just the region which gets contaminated by the night-sky lines; therefore, we can say that there are some spectra which show two ISM components, but we cannot rule out the possibility that both components are always there and one is just erased by the night-sky line. As a result, we just note the two components and hint at their variability and leave it to investigators with more suitable observing sites to explore the behavior of the ISM lines.

4.3. Ca II Infrared Lines

Both the He I 5876 Å line and the Ca II IR triplet lines appear in absorption in SU Aur. These lines are usually seen in emission in CTTS (Hamman & Persson 1992). These lines could in principle still be of circumstellar origin but appear in absorption merely because SU Aur is a G2 star and has a substantially higher effective temperature than most TTSs. The width of these lines indicate, however, that they may well be of stellar origin. The Ca II IR lines are very strong lines on G2 stars. In comparing the lines seen in SU Aur with a G2 standard star whose lines have been artificially rotationally broadened, it is apparent that the lines in SU Aur are filled-in relative to the standard but have the same width. We compare the IR lines to those observed in a solar plage spectrum (again rotationally broadened) and find that the Ca II lines of SU Aur are filled-in relative to plage (with the filling-in usually appearing symmetric), indicating that either SU Aur has a deep chromosphere (as in Calvet et al. 1984) or there is some nonstellar emission filling the line in. In seven out of a total of 42 observations of the IR lines with good S/N we observe slight emission (above the continuum) in the far wings of the line. The maximum extent of this emission is 200 km s⁻¹ and in six of the seven spectra is seen only on the blue side of the line profile (the one case of red emission is shown in Fig. 8, where it can be seen that the emission is stronger on the blue side of the lines). Overt emission is highly asymmetric, which can be explained by either occultation of the red side of the flow by the star or through absorption occurring on the red side. In the case of occultation we conclude that the emission is formed in a small extended region which is expanding away from the star. This could be associated with the heated region surrounding the accretion shock. If redshifted absorption is the cause, these lines may form predominantly in the accretion flow itself; however, at the time of the emission's strongest appearance (JD 2,448,635.76—shown in Fig. 8) there is no hint of redshifted absorption in either Balmer line, while the blueshifted absorption is quite strong.

There are real variations in the equivalent width of the Ca II lines which are summed up in Table 4. During six of the seven appearances of the wing emission component, the Hz flat-top component is stronger than its average value. Another similarity between SU Aur and other CTTSs is that the emission is strongest in the 8498 Å line which has the lowest oscillator strength. This behavior has been reported for CTTSs as a whole where it is thought there might be a rising source function in the inner part of the circumstellar envelope (Hamman & Persson 1992). GBJ interpreted the flat top as a good signa-

### Table 4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>He I 5876 Å</th>
<th>Ca II 8498 Å</th>
<th>Ca II 8542 Å</th>
<th>Ca II 8662 Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_{\text{min}} ) (Å)</td>
<td>0.30</td>
<td>0.58</td>
<td>1.66</td>
<td>1.46</td>
</tr>
<tr>
<td>( W_{\text{max}} ) (Å)</td>
<td>0.11</td>
<td>0.42</td>
<td>0.31</td>
<td>0.36</td>
</tr>
<tr>
<td>( W_{\text{range}} ) (Å)</td>
<td>0.16-0.54</td>
<td>0.44-1.07</td>
<td>1.04-2.13</td>
<td>0.75-1.94</td>
</tr>
<tr>
<td>( W_{\text{G1V}} ) (Å)</td>
<td>1.46</td>
<td>3.67</td>
<td>2.60</td>
<td></td>
</tr>
</tbody>
</table>
ture of the wind from SU Aur, so there is modest indication that the wing emission components and hence some of the filling-in of the IR lines comes from the extended envelope of SU Aur. However, such a connection is weak since a correlation analysis of the variations in Ca ii equivalent width compared to the Hα flat-top equivalent width implies a real correlation at only the 93% confidence level.

In the analysis of the Hα line profile of SU Aur, GBJI suggested that the central emission component of the Hα line might be of chromospheric origin. This proposal was largely driven by the fact that the width of the central emission component is very similar to the width of the Hα absorption line in a G2 V star rotationally broadened to the same $v \sin i$ as SU Aur. In that case we expect a correlation between the variations of this Hα feature with the equivalent width variations of the filled-in Ca ii lines. No such correlation exists, indicating that this component of the Hα profile may not arise in a strong stellar chromosphere. There have been a number of suggestions that UV bright spots result from material accreting along magnetic field lines which shocks when it strikes the stellar surface (Bertout, Basri, & Bouvier 1988; Simon, Vrba, & Herbst 1991; Hartmann et al. Calvet 1994; Kenyon et al. 1994). These bright spots, which are rotating with the stellar surface, are thought to produce the observed optical veiling and may also be the source of the narrow emission components observed in many TTSs (Bertout & Basri 1991; Hamman & Persson 1992). If such bright spots are responsible for filling-in either the Ca ii lines or for the central emission feature observed in Hα, a correlation is expected with the accretion rate onto the star.

Since the redshifted absorption feature seen in Hβ is so persistent, and line profile calculations by Hartmann et al. (1994) show such absorption features in magnetic accretion flows, we have used the equivalent width of this component of the Hβ line profile as a diagnostic of the accretion rate onto the star. No correlation is found between this feature and the equivalent width of the Ca ii lines or the central emission component of the Hα line profile. This leaves us with the curious conclusion that there is very little correlation between the Ca ii IR lines and the Balmer lines. This result is in contrast to Hamman & Persson’s (1992) finding that the luminosity of the narrow (and hence thought to be chromospheric) component of the Ca ii lines is well correlated with the luminosity of the Hα line when looking at several CTTSs at only one epoch, which is confirmed by Batalha et al. (1994). We find that the total equivalent width of Hα shows no correlation with the Ca ii line equivalent widths, and the best potential correlation is found by comparing only the flat-top component of the Hα profile with the Ca ii lines (see above). A possible explanation of this is that since Hamman & Persson (1992) were looking at many different CTTS’s, they find that the general level of all types of activity (chromospheric, accretion, and wind) do correlate well with one another, but in the case of SU Aur there is no simultaneous connection between the stellar chromosphere (as seen in Ca ii) and the region probed by Hα.

4.4. He i 5876 Å Line

We were surprised to find the He i 5876 Å line in absorption in SU Aur (Fig. 8) since it is not seen in G2 dwarf stars and usually appears in emission as a broad line in TTSs (see Ulrich & Wood 1981, for example). In addition to the 5876 Å line, we detect another member of this triplet, the 6678 Å line, in absorption in spectra taken with the 2048 × 2048 chip. We have only a few profiles of this line and will not discuss it further. The width of the He i 5876 Å line and its shape are consistent with a photospheric absorption line on a star rotating with the $v \sin i$ of SU Aur. Like the Ca ii lines, the He i 5876 Å line shows significant variation in its equivalent width, which is summarized in Table 4. He i 5876 Å absorption is a defining characteristic of solar plage regions (see, for example, Landman 1981) and has been detected on chromospherically active stars (Lambert & O'Brien 1983; Wolff & Heasley 1984). The formation of the D3 line is not completely understood in these stars. Initial work on the subject by Athay & Johnson (1960) showed that for collisional excitation to be the dominant factor, significant amounts of material must be at temperatures of 40,000 K to 50,000 K and a density of $N_e = 10^{11}$ cm$^{-3}$. Zirin (1975) proposed that coronal ionization ionizes He i and the resulting recombinations result in significant population of the lower D3 state in material at much lower temperatures. Work by Vernazza, Avrett, & Loeser (1973) and more recent calculations by Avrett, Fontenla, & Loeser (1993) indicate that the excitation of the triplet lines results from a combination of collisional excitation in transition region material at 20,000 K and from recombinations resulting from coronal ionization of chromospheric He i. They also note that the 10,830 Å line variations in coronal emission can have a larger effect on the resulting equivalent width of the line.
Regardless of the details of the $D_3$ line formation mechanism, observations indicate that the strength of the $5876$ Å absorption line is linearly correlated with the X-ray emission from active dwarf stars (Danks & Lambert 1985; Womack, Heasley, & Varsik 1985). Danks & Lambert (1985) found a linear correlation with a slope of unity between the equivalent width of the $D_3$ line and the X-ray luminosity from a sample of active dwarfs and argued that area coverage by active regions was the determining factor. The strongest stars in this study have a $D_3$ equivalent width of about 26.5 mA and log $(L_x)$ = 29.4. Inspection of Table 4 shows that SU Aur has an average $D_3$ equivalent width of 300 mA. Observations by Feigelson & DeCampli (1981) show that the X-ray luminosity of SU Aur is log $(L_x)$ = 30.48; therefore, the linear trend reported by Danks & Lambert (1985) seems to hold over an order of magnitude beyond their sample. However, we do not believe this can result from proportionally more of the surface of SU Aur being covered by solar-like plage as proposed by Danks & Lambert (1985), for two reasons. First, the equivalent width of the $D_3$ line seen in solar plage is 20–30 mA (Landman 1981), which would indicate that this is the most $D_3$ absorption a star covered by solar-like plage could have. Along a similar line, we discussed above that the Ca II IR lines of SU Aur are filled-in relative to a solar plage spectrum, again suggesting that if the entire surface of SU Aur were covered with solar-like plage, the Ca II lines could still not be explained.

We have argued that both the Ca II IR lines and the He I $5876$ Å line probe stellar activity (chromospheres); therefore, there should be a correlation between the equivalent widths of these lines. In Figure 9 we show the correlation between the $D_3$ line and the Ca II 8542 Å line. The correlation is fairly strong, but its sense is quite puzzling. The correlations found for active main-sequence dwarfs indicate that the strength of the $D_3$ absorption line increases with increasing activity, and similar studies (Linsky et al. 1979) indicate that the absorption strength of the Ca II lines should decrease with increasing activity as the lines become more filled-in. Thus, an inverse correlation is expected in a strong chromosphere, while Figure 9 shows a positive correlation. A positive correlation could result if SU Aur is at a stage where collisional excitation of the $D_3$ line dominates over the photoionization mechanism so that increases in activity actually increase the $D_3$ source function and cause the line to become filled in.

In Figure 8 we show two extreme cases for the Ca II and He I lines. From the Ca II line it is obvious that excess nonstellar emission is filling-in the line, and the He I line seems to show excess filling-in of its blue wing which may result from the same emitting material. As for the Ca II IR lines, we tried to correlate the variability of the He I $5876$ Å line with the Balmer line variability. Two marginal correlations were found. The best, with a false alarm probability of 1.1%, shows the equivalent width of He I inversely correlated with the equivalent width of the Hz flat-top feature. This supports our earlier conclusion regarding Ca II that some amount of wind emission could be filling in these lines and may also be filling in the He I lines. In the majority of CTTSs, the emission in the narrow components of the $5876$ Å positively correlates with the narrow emission components of the IR lines as well as with the Balmer lines (Batalha et al. 1994). The second, more marginal correlation with a false alarm probability of 2.4% shows a positive correlation with the equivalent width of the redshifted absorption feature seen in the Hβ line profile. If the $D_3$ line is filled in by wind emission, this might be explained by the mass loss and mass accretion being out of phase as described in the time series analysis of the Balmer lines.

5. BALMER LINE PROFILE MODELS

5.1. Previous Work and Motivation

Modeling of TTS line profiles has been carried out by a number of investigators (see Bertout 1984a; Appenzeller & Mundt 1989; Basri & Bertout 1993 for reviews). While we do not intend to discuss all the previous work in the field, some remarks on the need for continued modeling are presented here along with the motivation for the modeling effort discussed below. When considering the shape of the Balmer line profiles of SU Aur, we readily discover that the geometry and physical conditions of the emitting region is far from obvious. Particularly difficult is the formation region of the main absorption feature at a velocity of $v = -40$ km s$^{-1}$. GBJ discuss possible formation regions for this feature and the resulting variations seen in the line profile each scenario might produce. While no definite conclusion was reached, they suggested that this component was formed relatively close to the star before the wind has been completely accelerated. This region is in turn viewed through the fast, optically thin portions of the wind which surround the star. Under more careful examination of all our data, it is apparent that this hypothesis needs modification. It could not hold if the higher velocity material is optically thick, because then the material responsible for the main absorption feature must be exterior to absorb light at all. In the optically thin case for the high-velocity emission, the amount of light added at each velocity is the same (for a flat-topped emission profile). The core intensity of the main absorption feature must therefore be equal to or greater than the level of flat-top emission above the continuum. A good example of a profile which violates this is on JD 2,447,202.72 in Figure 1. Fully one-third of our observed Hz profiles conflict with this expectation.

Therefore, some or all of the material responsible for the main absorption feature must be exterior to the bulk of the emitting material in the wind to absorb some of the wind photons. However, this material must also be along our line of sight to the star, since in almost every observation the main

![Figure 9](image-url)
Absorption feature appears below the stellar continuum, implying stellar photons are being absorbed as well. The conclusion that the main absorption feature forms in an optically thick outer region of the wind is most dramatically illustrated by a set of eight line profiles collected over 7 days in 1992 September which we show in Figure 10. This figure shows these profiles plotted on top of one another, illustrating the substantial variability in all parts of the line profile except the main absorption feature, which stays at exactly the same level. The behavior of this feature is not always this constant, but this time series clearly indicates that the formation region for this feature must be fairly removed from and exterior to the rest of the emitting region.

Given that the main absorbing material must be somewhat removed from the star, its velocity becomes a problem. The feature appears on average at a velocity of \(-40 \text{ km s}^{-1}\) and is relatively narrow compared to typical P Cygni-type line profiles, indicating that there is a discrete (not very turbulent) column of material moving at this velocity. However, this velocity is also below the local escape velocity out to a distance of \(150 R_* (2.5 \text{ AU})\), which means either that the material later returns to the star in a fountain-type flow (recall the evidence for accretion in the Balmer line profiles) or that the material is moving much slower than ballistically. Of course the material could be in a hydrodynamic flow which pushes it at this low velocity after it becomes invisible in H\(\alpha\) until it reaches escape. However, since we see strong emission at higher velocity, either the velocity profile of the wind includes a very rapid acceleration up to \(\approx 300 \text{ km s}^{-1}\) followed by a fairly rapid deceleration to \(40 \text{ km s}^{-1}\), or there is some other broadening agent in the line formation region. The three most obvious possibilities are large turbulent velocities, an accretion component to the flow, or a substantial rotational component to the flow.

As pointed out by Holzer, Fla, & Leer (1983), it is very difficult to construct hydrodynamic flows whose terminal velocity is much below the escape velocity off the surface of the star. Hartmann & MacGregor (1980) were able to use Alfvén winds to drive the winds off cool giants to terminal velocities approximately one-half the escape velocity; however, the velocity structure of these winds was still basically increasing with radius, and models of Alfvén driven winds from TTSs produce winds with relatively high terminal velocities (Decampli 1981; Hartmann, Edwards, & Avrett 1982). Najita (1992) has shown that the velocity structure of an X-celerator wind (a centrifugally driven wind) increases with radius out to the Alfvén radius, where the material decouples from the stellar field and then coasts out into the ISM. Therefore, these winds are basically monotonically increasing in velocity. For a very narrow range of stellar field strengths, the Alfvén radius is close enough to the star that the wind material is accelerated to above escape velocity but then decelerates as it moves out. This is a limited set of solutions to the centrifugally driven wind but may be applicable to SU Aur.

On the other hand, there is a family of solutions to the Parker wind problem with just this property of deceleration at large radii. These solutions require the wind to be moving subsonically at all radii, which means that for TTS winds with temperatures between 6000–20,000 K (as found by Natta, Giovannardi, & Palla 1988 and Hartmann et al. 1990) the expansion velocity cannot be greater than \(\approx 20 \text{ km s}^{-1}\). This is much too small compared to the observed line profiles (see discussion in next section). Thus, this family of winds can be ruled out. It should be apparent that the formation region of this feature is quite puzzling.

As pointed out above, if we wish to avoid winds with nonmonotonic velocity fields, some other broadening agent must be present to produce the high-velocity emission seen in the Balmer lines of SU Aur. Turbulence is one such agent. In models of Alfvén winds from TTSs, Decampli (1981) and Hartmann et al. (1982) suggest that turbulent broadening might be very important in TTS winds, and Hartmann et al. (1990) showed that only strong turbulent broadening in the optically thick regions of the wind will result in emission blueward of the absorption reversal in the line profiles. The absorption reversals shown by Hartmann et al. (1990) are much too broad and highly blueshifted relative to those seen in SU Aur, primarily because the authors stick to a limited range of models dictated by the theory of Hartmann et al. (1982), which accelerates up to fairly high velocity and maintains high turbulent velocities throughout most of the wind.

Also mentioned above is the possibility that the high velocity emission arises in an accretion flow. Model profiles for lines formed in magnetospheric accretion flows have been worked out initially by Calvet et al. (1992) and more completely by Hartmann et al. (1994), and these authors suggest that most, if not all, of the emission in TTS lines is produced in such flows. While these models have been successful at reproducing several of the features of TTS line profiles, especially the high Balmer lines which often show redshifted absorption (EDWARDS et al. 1993), the Balmer profiles shown in Hartmann et al. (1994) do not look very much like the profiles of SU Aur. In their favor (using the appropriate high inclination case) the models produce a narrow central emission component. Even allowing for the lack of blue absorption features (produced outside the modeled region), the tendency for the red wing to be depressed compared to the blue is vaguely supported by the flat-top asymmetry deduced by GBII. The free-fall velocity to SU Aur is \(\approx 490 \text{ km s}^{-1}\) and might seem to provide a natural explanation for the width of the observed line profiles. However, examination of the magnetospheric accretion models casts some doubt on their ability to explain the full width of the observed lines. The stellar parameters used by Hartmann et al. (1994) result in a free-fall velocity of \(~436 \text{ km s}^{-1}\); however, none of their calculated profiles produce significant blueshifted emission beyond \(-200 \text{ km s}^{-1}\), even in the H\(\alpha\) line. This is
most likely due to a combination of the material not quite falling from infinity, occultation by the star, and velocity projections as the material follows the stellar field lines. Thus, the magnetospheric models as shown produce blue emission out to a velocity of \( \sim 0.46V_\text{eq} \), where \( V_\text{eq} \) is the free-fall velocity. For SU Aur, we then expect these models to produce blue emission out to only \( \sim 240 \text{ km s}^{-1} \), yet emission is seen beyond \( \sim 300 \text{ km s}^{-1} \) in most spectra. These numbers cast some doubt on the ability of magnetospheric accretion flows to account for the highest velocity emission seen in SU Aur purely by themselves.

The models also suffer some difficulties in explaining some of the general properties of TTS line profiles as well as the Balmer lines of SU Aur. Basri (1987, 1990) and Bertout & Basri (1991) have stressed the symmetry of the profile wings, especially at Hz, but many of the higher Balmer lines of CTTSs also show highly symmetric line profile wings. Models such as the magnetospheric accretion flow which contain a velocity structure such that the highest velocities are reached closest to the star will inevitably produce asymmetric wings due to occultation of the far side of the flow by the star. Indeed, all the profiles shown in Hartmann et al. (1994) (including Hz) have asymmetric wings, particularly for the high inclinations we know are appropriate to SU Aur. There are also a number of low-inclination CTTSs shown in Edwards et al. (1994) that display pronounced emission redward of the redshifted absorption feature, which is not found in the magnetospheric accretion models.

One of the recurring themes in TTS research is the presence of winds around these stars, indicated by the blueshifted absorption seen in SU Aur and other TTS line profiles. The only model calculations of line profiles for CTTS winds have been performed by Kuhi (1964), Hartmann et al. (1990) and Calvet et al. (1992). Kuhi (1964) assumed a fully ionized wind for his calculations despite no known source for the ionizing flux required. Hartmann et al. (1990) and Calvet et al. (1992) performed proper calculations of the line source functions and optical depths primarily in the context of temperature, velocity, and turbulent structures dictated by the Alfvén wave–driven wind model of Hartmann & MacGregor (1980). While many of the properties of spherical winds have been elucidated by these authors, full exploration of temperature, velocity, and turbulent laws has not been performed to see what types of winds might reproduce the observed line profiles independent of a fully developed theory of the wind generation mechanism. Since these authors have abandoned winds in favor of the magnetospheric accretion models of Calvet & Hartmann (1992) and Hartmann et al. (1994), we have elected to explore more fully the range of temperature, velocity, and turbulence laws required in a spherically symmetric wind to reproduce the average Balmer line profiles of SU Aur.

We therefore turn our attention to calculating line profiles for various wind models to try and constrain the formation region of these lines. In this paper we will restrict our attention to spherically symmetric models in an effort to determine how much of the observed line profiles can be accounted for in this very simple geometry. We recognize that our calculations are rather schematic; they are only intended to point the way to more physical models.

5.2. Ad Hoc Models

Our first effort involves a purely ad hoc procedure to determine what types of optical depth and source function scales in more or less traditional wind models produce the actual average Hz and Hβ line profiles we observe. For this we specify the velocity, turbulent velocity, optical depth, and source function as functions of radius in a spherically symmetric wind and calculate the resulting line profile. The line profiles were calculated from

\[
I(v) = 2\pi \int_{\rho_1}^{\rho_2} I(v, p)p\, dp ,
\]

(1)

where \( p \) is the impact parameter and

\[
I(v, p) = \int_{z_1}^{z_2} S(r)e^{-\tau(v, r)}\, dz .
\]

(2)

Here, \( S \) is the source function for the given line; \( z = (r^2 - p^2)^{1/2} \) is the distance along the line of sight; and the starting point of the integration is \( z_1 = -\infty \) for \( p > R_\star \) and \( z_1 = (R_\star^2 - p^2)^{1/2} \) for \( p \leq R_\star \). We have written a FORTRAN code to compute these equations typically using about 200 grid points on the line of sight over approximately 100 impact parameters. These numbers vary depending on the complexity of the model and the minimum turbulence used, with higher turbulence requiring fewer points. The number of grid points is determined to be the value at which increasing beyond makes less than a 5% change in the resulting profile at any wavelength.

Since according to many investigations (e.g., Mundt 1984; Hartmann et al. 1990; GBJ) the turbulence in TTS envelopes is likely to be high, we have approximated the local line profile as a Gaussian:

\[
\phi(v) = \frac{1}{\Delta V_F \sqrt{2\pi}} e^{-(1/2)(v - v_0)/(\Delta V_F)^2} ,
\]

(3)

where \( \Delta V_F \) is the turbulent width of the line and \( v \) is a function of radius. The intensity emitted by the surface of the star must be accounted for along impact parameters which strike the star. In the simplest case, a flat continuum could be assigned to the star (as in Wagenblast, Bertout, & Batian 1983), which is a good approximation if the stellar profile is unimportant relative to the resulting emission profile. This is not the case for SU Aur. The average emission equivalent width of Hz is approximately 5 Å and G2 standard stars have an absorption equivalent width of approximately 4 Å in Hz; therefore, the stellar component could contribute substantially to the line shape, especially if some or all of the emitting envelope is optically thin. Therefore, for impact parameters striking the stellar surface, we set \( I_\star \) equal to the line profile of a G2 spectral standard span up to the same \( v \) sin \( i \) (68.5 km s\(^{-1}\)) as SU Aur. Of course, the stellar chromospheric profile of SU Aur could be different than our standard star, but this will only affect the lowest velocity portions of the line profile.

Another complication for the case of SU Aur is its extremely rapid rotation. If the wind is made to rotate (perhaps because it is controlled by magnetic field lines attached to the star) the spherical symmetry is broken due to the different Doppler shifts induced on one side of the star relative to the other. In an effort to keep things simple in the initial exploration of wind models, we do not allow the wind to rotate, thus allowing use of the above equations. It is also possible the envelope is not rotating rapidly even though the star is. The rotation definitely makes a considerable difference in the shape of the stellar line profile, which we argued above can substantially influence the final line profile.

Our procedure is to find a run of source function, optical depth, velocity, and turbulence which provides a good match.
to the Hα line profile. Stimulated emission is then ignored to calculate the optical depth scale for Hβ,

$$\frac{\tau_{\text{H\beta}}}{\tau_{\text{H\alpha}}} = \frac{B_{2,4}}{B_{2,3}} = 0.138,$$

(4)

which is then used with the same velocity and turbulence scale to find the proper Hβ source function to match the observed line profile. With the two source function and optical depth scales determined, the relative populations of the n = 2, 3 and 4 levels are calculated, and we can start to put constraints on the structure of a physical wind which may be responsible for these profiles. There are always very real concerns regarding the uniqueness of such a model. Exploration of such ad hoc models is intended to give a feeling for the type of wind structures capable of producing the observed line profiles but is not intended to prove those structures actually exist. This information will be carried over into the construction of more physical models in the next section; however, we feel such an ad hoc procedure is justified because the profiles from more physical models of the circumstellar envelope do not adequately reproduce the observed line profiles of TTSs (see Calvet et al. 1992).

As described above, the data argue that the main absorption feature forms in a slowly moving region exterior to that which produces the broad flat-topped emission. This emission region could be either a fast, optically thick, constant velocity wind, or it could be a region dominated by high turbulence with very modest wind velocities. The speed of the absorbing material is well below escape velocity anywhere near the star, and we must then decide if it should be at large distances from the star (like MNG). Here excitation of Balmer lines is a problem; MNG rely on ad hoc heating to solve it. Since in the MNG picture the absorption features arise in discrete blobs moving ballistically far from the star, these features should not always appear at the same velocity at different observing epochs. Indeed, we see some variability in the velocity position of this feature. However, on subsequent nights in a single observing epoch we should see the feature accelerate as it moves out of the star's potential well. This is not so clearly seen.

In 1988 February we have 14 nights of data on this feature. On the first night the velocity of the feature was $-51 \pm 2$ km s$^{-1}$, determined from a paraboloid fit to the absorption core. The last observation of this epoch was taken 14.03 days later. Using equation (13) of MNG for the velocity law of this feature, the absorption should appear at $v = -46$ km s$^{-1}$ at the end of this epoch. Fitting the absorption core to a parabola gives a velocity of $-55 \pm 2$ km s$^{-1}$ for the last night's observation. The change is not even in the right direction. Furthermore, the velocity behavior of this feature throughout this time period does not show a smooth, continuous deceleration but instead shows initially an erratic behavior followed by a smooth acceleration over a period of about 5 days.

One might worry that we are observing more than one blob along our line of sight to the star. However, multiple blobs would appear as discrete absorption features if separated enough in radius (and hence velocity) from the star. This is not observed, but even if multiple blobs appear as a single absorption component, they should all be smoothly decelerating in the outer portions of the MNG wind. Another worry is that new blobs appearing at nearby velocities may make the absorption feature appear at more negative velocities. This might affect the apparent strength of the absorption feature and would certainly make the feature appear broader. The strength of the absorption feature shows no correlation with its velocity, and its width actually appears to decrease over most of this observing epoch. Since the velocity behavior of the main absorption feature does not provide evidence for its formation far away from the star in ballistic blobs, we explore models with the feature forming closer to the star, around 10 $R_\star$ away. This implies reliance on some (unspecified) hydrodynamic process to move the material out of the potential well of the star or letting it fall back in.

Figure 11 shows the average Hα and Hβ line profiles of SU Aur along with model profiles for an ad hoc model with the main absorption feature formed in a thick shell between 8–10 $R_\star$. Here we are trying to just match the shape of the flat-top, main absorption feature and central emission seen in Hα and the corresponding features in Hβ. The parameters of the wind model are illustrated in Figure 12. The central emission component in Hα in this model is produced by the same thick shell of material which is responsible for the main absorption feature. Since this emission component is almost completely absent in Hβ, the Hβ source function in the shell must be reduced by a factor of approximately 100 relative to Hα, whereas the Hβ source function in the fast wind portion is reduced by only a factor of 2 relative to the Hα source function. Such a large reduction in the source function of the central emission feature again argues for the necessity of a non-chromospheric origin for this feature. In the average Hα profile there is additional absorption in the blue wing which results from the periodic appearance of a blueshifted absorption

![Graph](image-url)
feature. The average $H\beta$ profile shows redshifted absorption also arising from a periodic component described in § 3. Because these two components are periodic, they violate the spherical symmetry assumed here and are not modeled.

5.3. Non-LTE Models Using CLOUDY

The ad hoc models described in the last section give us a framework within which to work, but we can test this framework only by constructing more physical models of a possible wind around SU Aur. Since there is no satisfactory theory of the heating of TTS winds, we let the temperature be a free parameter in our modeling. Given the temperature in the wind, the question then becomes the solution of the statistical equilibrium equations for the level populations of hydrogen at each radius in the wind in order to set the optical depths and source functions in the Balmer lines. In general, this is a very difficult problem since the level populations depend on the radiation field which in turn depends on the level populations. The problem is particularly bad for a stellar wind because the geometry is no longer plane parallel, and widely separated regions can influence each other depending on the velocity gradients present and the resulting Doppler shifts of line photons. There exist a number of general codes to attack this problem. We have elected initially to use the rather approximate non-LTE code CLOUDY developed by Ferland (1993) to aid in these calculations. Since we do not really know the basic physical paradigm of the emitting envelope, it is desirable to incorporate the basic physical processes occurring in the envelope while keeping the computation time short to allow many models to be calculated. Hartmann et al. (1994) make the point that very useful information about the shapes of line profiles can be determined from model calculations using only a two-level atom to determine source functions. CLOUDY is very user friendly, and most models can be computed in under 3 minutes with a Sun Sparcstation SLC, making it an excellent choice for this purpose.

CLOUDY assumes spherical symmetry and uses the Sobolev approximation to formulate local escape probabilities in order to handle the radiation field. Below we will show that low-velocity winds with large turbulence at their base provide good matches to the observed Balmer line profiles. Such winds violate the formal Sobolev approximation; however, Bertout (1984b) asserts that using the Sobolev approximation to calculate source functions and optical depths, followed by a proper integration of the line transfer equation to calculate the profile shapes, results in only small errors in the shape of the resulting profiles. We have made modifications to the basic code to allow us to specify arbitrary velocities, turbulence, and temperatures as a function of radius in the wind. Once the optical depths and source functions are calculated for a given model, we again use equations (1)–(3) to generate the final line profile. In each model run we use a 5800 K blackbody with a luminosity equal to that of SU Aur for the central star. We have not included any extra component to represent the boundary layer because the measured veiling in SU Aur is less than 0.05 (Basri & Batalha 1990), and blackbody functions overestimate the UV emission of stars anyway. As noted before, SU Aur is a strong X-ray source, so we tested the effect of strong coronal emission on the resulting level populations produced by CLOUDY. In addition to the stellar continuum, we input an optically thin bremsstrahlung continuum specified with a temperature of $10^6$ K and a luminosity $L = 10^{30.48}$ ergs s$^{-1}$ to approximate the corona of SU Aur. This additional continuum made a negligible difference in resulting line profiles for specified wind models, so we do not include a coronal continua in the wind models of SU Aur.

Our goal then is to match the average $H\alpha$ and $H\beta$ line profiles shown in Figure 11 with a wind model with a structure similar to our ad hoc model (Fig. 12) but whose source function and optical depth scales are calculated in a physical way as described above. The wind is rapidly decelerated at a specified distance in order to produce the main absorption component at $v \sim -50$ km s$^{-1}$. The wind is spherically symmetric with a constant mass loss rate $M = 4\pi r^2 \rho v$. We have as free parameters the mass-loss rate and the velocity, temperature, and turbulent velocity at each radius in the wind. In an effort to keep the modeling simple and the number of free parameters low, we try to keep these parameters constant with radius and only change them as required to match specific features of the line profiles.

With this relatively simple prescription for wind models it is difficult to match the observed line profiles. As discussed in Hartmann et al. (1990) and Grinin & Mitskevich (1991) the main problem encountered is producing enough emission on the blue side of the line profile. Constant velocity, constant temperature models with temperatures in the 6000–20,000 K range (as found by Natta et al. 1988; Hartmann et al. 1990) produce line profiles that tend to have classical P Cygni shapes: strong absorption at the highest blue velocities. This results because, independent of the temperature of the wind (as
long as it is at least high enough to produce some emission), as the wind material moves farther from the star, the density drops so that collisions become unimportant. The higher hydrogen levels drain more rapidly than $n = 2$, resulting in appreciable optical depths in the outer regions of the wind with very low source functions. The result is blueshifted absorption.

We find the same behavior in all our CLOUDY models in which we try to reproduce the broad emission with a classical wind: too much blueshifted absorption. Thus, without some unknown physics, the wind structure of the ad hoc model shown in Figure 12 is impossible to produce. For SU Aur, we do note a fascinating but unexplained occurrence of very high velocity absorption is shown for JD 2446,746.92 in GBJ.

Hartmann et al. (1990) produce blueshifted emission by having large turbulent velocities close to the star where the source function in the wind is relatively high. This broadens the line considerably and produces emission blueward of the absorption. Because their models have fairly high turbulence throughout the wind, the absorption reversals they find are too broad, and the red wing of the profile is too smooth to match the profiles shown in Figure 11. Grinin & Mitskevich (1991) and MNG produce emission blueward of the absorption reversal by making the wind clumpy and decelerating beyond a few stellar radii. As discussed above, this model predicts behavior not observed in our data, and the model profiles calculated in MNG do not provide a good match for the profiles shown in Figure 11.

We find that the general shape of the Balmer lines of SU Aur can be matched with a wind which has very high turbulence at its base which drops off more rapidly than the Hartmann et al. (1990) models. In Figure 13 we again show the average observed Balmer line profiles along with model profiles. Figure 14 shows the parameters of the wind model. We require large turbulent velocities at the base of the wind to produce the blueshifted emission seen in the Balmer lines. The turbulence peaks at 120 km s$^{-1}$ at the stellar surface where the total hydrogen density is $\sim 3.2 \times 10^{13}$. Such turbulence is hypersonic and would be expected to produce strong shocks. If this region is permeated by a magnetic field, then shocks will not result until the Alfvén velocity is exceeded. This requires a field of $B = (4\pi\mu_0\rho)^{1/2} = 36$ G, assuming $v_\infty = 120$ km s$^{-1}$. Such fields in these regions are well within the expectation of theoretical models (Shu et al. 1994) and are well below the surface fields measured in NTTS by Basri, Marcy, & Valenti (1992). Therefore, it is likely that such large turbulent velocities are sub-Alfvénic and will not produce strong shocks.

As a result of such large turbulence, the velocity of the wind is not required to be very high. The mass-loss rate for this model is $\dot{M} = 4.5 \times 10^{-9} M_\odot$ yr$^{-1}$. Figure 14 shows the maximum velocity of only 60 km s$^{-1}$; at large radii where the density has dropped considerably, the velocity could become quite large and would make no observable consequence on the profile since the optical depth in the Balmer lines is too low. In any case, 60 km s$^{-1}$ is still more than twice the velocity attained in a Parker wind which asymptotically approaches zero velocity at 20,000 K and is approximately 5 times the

![Fig. 13](image1.png)

**Fig. 13.** The top panel shows the average Hα profile (solid line), a G2 V standard star (dotted line), and our best-fitting wind model computed with CLOUDY (dash-dotted line). The bottom panel shows the same for Hβ. The wind model is shown in Fig. 15.

![Fig. 14](image2.png)

**Fig. 14.** The wind model used to produce the profiles in Fig. 13. The top panel shows the temperature (solid line), the flow velocity (dashed line), and the turbulent velocity (dotted line). The bottom panel shows the density of hydrogen in the $n = 2$ level (solid line), the Hα source function (dashed line), and the Hβ source function (dotted line). Again the source functions are shown in units of the continuum at their respective wavelengths (see legend of Fig. 12).
maximum possible velocity in such a Parker wind with a temperature equal to the maximum in Figure 14. Thus, it still seems appropriate to ignore Parker type wind solutions which do not go through a sonic transition.

As mentioned above, uniqueness is a problem in this type of modeling, and these numbers are not intended to represent well-determined values. For instance, mass-loss rate and temperature effects can often play off against one another within certain limits. We have explored a variety of models and find that the mass-loss rate can range anywhere between $2.0 \times 10^{-9}$ and $8.3 \times 10^{-9} M_\odot$ yr$^{-1}$, producing equally good matches to the line profiles. Likewise, maximum temperatures in the wind can range from 8000 to 9000 K. Therefore, the model shown in Figure 14 is intended only to schematically represent the required parameters for matching the average profile of SU Aur. We note that our estimate for the mass-loss rate from SU Aur is substantially lower than the upper limit of $M < 6 \times 10^{-8} M_\odot$ yr$^{-1}$ found by Natta & Giovanardi (1991) in their analysis of Na i and IR hydrogen lines of SU Aur. Kuhu (1966) found a mass-loss rate of $M = 2.5 \times 10^{-8} M_\odot$ yr$^{-1}$ in an analysis of the Hx and Ca ii K line profiles; however, his analysis was based on the assumption that the emission envelope is completely photoionized (basically an H ii region). There is no known source for the requisite number of high-energy photons, and Natta et al. (1988) have shown that the emission envelopes of TTSs are largely neutral.

Another key part of the model which controls the depth of the main absorption feature is to have the wind cool rapidly. If the wind stays warm, conditions are such that the lower levels of the Balmer lines remain populated as the upper levels drain, resulting in relatively large optical depths and low source functions over an appreciable amount of the wind which then produces stronger absorption. By allowing the wind to cool rapidly, the upper levels still drain, but the $n = 2$ level also rapidly drains, producing smaller optical depth in the Balmer lines and keeping the absorption from being too strong. Ruden, Glassgold, & Shu (1990) demonstrate that adiabatic cooling resulting from the expansion of the wind is the most effective cooling process occurring in winds with the general parameters given in Figure 14, though the results of their calculations do not produce thermal structures which cool quite as rapidly as Figure 14. This may indicate that the geometry of the situation is different such that adiabatic cooling is even more effective.

Such a geometry is the X-celerator mechanism of Shu et al. (1988, 1994) in which the wind arises from a tiny region in the disk and then expands to fill nearly a spherical geometry. This would enhance the adiabatic cooling; however, the difference in the geometry and the inclusion of rotation (which is an integral part of this model) may also make large effects on the line profile shapes. Indeed, Calvet et al. (1992) have calculated line profiles for inner disk winds which mimic the geometry of the X-celerator. These models produce greater blueshifted emission than the spherical models (Hartmann et al. 1990) but again do not provide good matches to our observed line profiles, primarily because the turbulence falls off more slowly. It should be mentioned that since CLOUDY is a Sobolev code, it is leaky (especially as the optical depths become low), so the source functions found by CLOUDY are most likely lower than really would result from our physical conditions, producing stronger absorption for a given set of wind parameters than a proper code would produce. Therefore, the wind is probably not required to cool quite as rapidly as shown in Figure 14.

Finally, to produce the main absorption feature with its observed width the turbulence in the outer portion of the wind must be reduced by a factor of 5.5 relative to the base of the model. The falloff of the turbulence in Figure 14 is much more rapid than the Hartmann et al. (1990) models, which explains why the absorption features they find are much broader than that observed in SU Aur.

The model shown in Figure 14 does not match the blue wing of the Hx line or the redshifted absorption feature seen in the Hβ line profile. As described above, it is not intended to reproduce such features, which are probably formed in non-axisymmetric flows (and in Hβ's case in an accretion flow); our purpose here is to explore the possibilities of spherically symmetric winds. Even so, the model is not a perfect match to the observed profiles. Hx is matched fairly well, but the Hβ line profile is more problematic. The red side of the Hβ line profile cannot be reproduced with a spherically symmetric wind while simultaneously fitting the Hx profile. Clearly, an accretion component of the envelope is required. Hartmann et al. (1994) have calculated line profiles formed in magnetospheric accretion flows and found good matches for the higher Balmer lines in some TTSs, especially the ones which show redshifted absorption features. These models were calculated for more typical TTS parameters (M spectral type), and it would be very useful for a few such models to be calculated using hotter underlying stars. At this point one cannot strongly prefer either model based on the fits to actual profiles; it is certain in any case that both accretion and outflow are present.

While the spherical wind model does not provide a complete match to the average Balmer lines, it is still interesting to understand what aspects of the variability seen in Figure 1 can be accounted for in the model. Variations in the emission level of the broad wings can be reproduced by changing the density (mass-loss rate) and/or the temperature at the base of the wind. There are some cases (such as the first panel of Fig. 1) where the emission level in Hβ is much higher in the wings relative to Hx than what is seen in the averages. Lowering the mass-loss rate slightly while raising the temperature can produce this behavior in the two lines. As mentioned before, the depth of the main absorption feature is controlled largely by the temperature gradient just outside the maximum temperature region of the wind. The gradient and the maximum temperature both have strong effects on the level of the central emission component.

As an example, when the temperature falls more gradually than shown in Figure 14, the absorption gets deeper and the emission component becomes stronger. Lowering the maximum temperature in the wind strongly reduces the central emission component but has a relatively small effect on the depth of the absorption component. This model cannot reproduce profiles in which the blue wing is stronger than the red wing, examples of which can be found in Figure 1. Profiles with the red wing stronger can be reproduced by keeping the turbulence high as the wind accelerates. The source function begins to drop as the density drops, producing some absorption in the blue wing, but it is difficult to keep the main absorption feature properly narrow in such situations. Our experience is that a spherically symmetric wind model can reproduce much of the behavior seen in the Hx line profile of SU Aur but is very weak at reproducing the behavior of Hβ, which is dominated by the variations of the redshifted absorption feature which must be forming in an accretion flow. The presence of blueshifted absorption indicates that there must be a wind around SU Aur,
and we find that large velocities are required at the base of a spherically symmetric wind in order to produce the blueshifted emission observed in both Balmer lines.

6. DISCUSSION AND SUMMARY

We have analyzed an unprecedented collection of high-resolution spectra of the TTS SU Aur. SU Aur is a classical TTS since it has an appreciable IR excess, indicating the presence of a circumstellar disk (Bertout et al. 1988). The equivalent width of Hα is low, but this is due to the fact that SU Aur is a 13 L⊙ G2 star which produces a much brighter continuum than typical CTTSs.

Analysis of the profile variations in the Hβ line have revealed periodicity in two components of the profile, each with the rotation period of the star. The first is in a blueshifted absorption component which seems to be the same material responsible for the periodicity seen in Hα and reported in GBJI. This is evidence for a rotationally modulated outflow from SU Aur. The second component which shows periodicity (although at a reduced confidence level) is the redshifted absorption component which is a conspicuous feature in the Hβ line profile. No periodicity was detected on the red side of the Hα line profile in the long run of 1988 February, at which time the redshifted component of the Hα line profile was not visible. GBJI point out that at other times in the Hα line profile there is some hint of periodic behavior in this feature of the Hα line profile (see GBJI, Fig. 10 and discussion). We believe our current analysis of the Hβ and Hα line profiles simultaneously is evidence for rotationally modulated infall occurring at the same times as the rotationally modulated wind reported in GBJI. Analysis of the relative phase of the wind and accretion component reveals that they are approximately 180° out of phase. As a result of this analysis we favor a scenario illustrated in Figure 15 which has been adapted from the generalized magnetocentrifugally driven flow model of Shu et al. (1994), which we dub the "eggbeater" model.

In the eggbeater model a stellar dipole field truncates the accretion disk at a radius where the Keplerian angular velocity is equal to the stellar angular velocity. Because the disk is partially ionized, it sets up currents which try to cancel the stellar field in the disk, and the resulting magnetic field configuration is similar to that illustrated in Figure 15 (in Shu et al. 1994 the dipole and rotation axis are coincident, so the picture is slightly different). At the truncation point the ionized disk material loads onto either inner closer field lines which funnel flow onto the stellar surface, or the material loads onto outer (effectively) open field lines which drive a centrifugal wind flow. Neutral disk components are dragged along by the ions to fill these two flows (accretion and wind), which occur simultaneously.

In the (ideal) aligned dipole case the eggbeater model would not produce any rotational modulation since everything is assumed to be axisymmetric. Modulation could occur if the disk material is not axisymmetric at the truncation radii; however, the aligned model predicts variations of the wind and accretion to be in phase to within a small error due to the bending of the open field lines which carry the wind. The misaligned dipole pictured in Figure 15 both allows for rotational modulation of the wind and accretion flows and predicts that they should be 180° out of phase. For a system viewed nearly edge-on, if the observer is, say, to the right and above the disk in Figure 15, the resulting field configuration is such that it is easier to load material onto the visible wind flow and more difficult to load it onto the visible funnel flow relative to the aligned case. A half-rotation later the situation is reversed, and it is now easier to load material onto the visible accretion flow and more difficult to load the wind. Thus, such a model is able to account for rotationally modulated wind and accretion signatures, and it predicts the two to be exactly out of phase, which we find is true for the case of SU Aur. One flaw is that the modulation is not always readily apparent.

Reanalysis of the Hα profile indicates the possible existence of an additional periodic signature in the blue side of the main absorption feature. The derived period is about 8 days, and we do not have a data stream which contains two or more complete cycles. Periodogram analysis of the remainder of the data set does not reveal this periodicity, so we regard this a tentative detection and leave it to further investigation to be verified. If this periodicity is confirmed, it is difficult to see what would be the cause of it. If the winds of TTSs really arise in the disk as in the eggbeater, this may represent the timescale of some disk instability.

In addition to the Balmer lines, the Ca II IR lines and the He i 5876 Å line show variability, but at a much lower level. There is some indication of correlation between the Ca II lines and Hα, but nothing as clear as shown by Hamann & Persson (1992) for a sample of TTSs. The Ca II lines do appear well correlated with the He i 5876 Å line, but the equivalent widths of these absorption lines appear positively correlated, which is opposite to the relation expected from the behavior of active main-sequence dwarf stars. We suggest that this can be explained by the extended envelope around SU Aur (which is responsible for the Hα emission) having a small (compared to Hα) but significant optical depth in these lines, giving rise to an emission component (collisionally controlled). We then expect these lines to trace the same material and their variations to be correlated. Since it is quite rare to see these variations at veloci-
ties greater than the rotationally broadened photospheric lines, this material must be very close to the stellar surface, and the velocities of this region of the envelope cannot be too great.

We have constructed spherically symmetric wind models in an effort to explore to what extent such models can reproduce the observed Balmer line profiles of SU Aur. It is no surprise that such models cannot explain all the data we have collected. There are definitely accretion components seen in the Hβ line profile which our models do not even attempt to reproduce. In addition, there are some clearly nonaxisymmetric components (those responsible for the observed periodicity) which we cannot reproduce with such a model. However, we find that spherically symmetric wind models can nicely reproduce the average observed Hα line profile as well as aspects of the Hβ profile, but only given a high, fairly symmetric, velocity component at the base of a relatively slow moving wind.

These large velocities, which are not part of the bulk outflow, are required at the base of the wind. They are needed to produce the strong emission seen in the blue wing of Hα and must also be capable of producing symmetric wings in Hα. They must fall off fairly rapidly so as not to produce absorbing layers farther out which would reduce the wing emission, as well as to allow the narrowness of the main absorption feature near $v = -50 \text{ km s}^{-1}$. If there really is high turbulence at the base in a magnetized region, Alfvén waves will be launched into the envelope which in turn will generate further turbulence. A key question is then the damping length of these waves. As Hartmann et al. (1990) pointed out, the damping length of Alfvén waves is poorly understood, but with the rapid falloff of turbulence required to match our profiles, the damping length could not be more than $\sim 0.1 R_*$. We have spoken of the high base velocity component as turbulence, and it would be not at all surprising if flows in the eggbeater had a turbulent component to them (there is plenty of available energy). It is also true that some other flow pattern, such as rotation, which produces symmetric emission components could be present. Further, the redshifted accretion component in the Hβ line indicates that accretion flows are definitely present, and the profiles calculated by Hartmann et al. (1994) have some of the attributes required. Their asymmetries are not entirely consistent with the observations (indeed, any flow which has its highest velocities closest to the star will produce such asymmetries due to occultation by the star), so accretion cannot be the only source of the high velocities. Very likely there is a combination of turbulence, accretion, and rotation. Our main point is that the emission width and strength of the lines does not arise primarily in the wind.

We find that it is very important to fit more than one line simultaneously to constrain the densities and temperature in the line formation region. Many models can reproduce the Hα profile, but they have different effects on Hβ. Cooler, denser winds provide a better match with a mass-loss rate of $\sim 5 \times 10^{-9} M_\odot \text{ yr}^{-1}$. This mass-loss rate is approximately an order of magnitude less than the mass accretion rate of $6 \times 10^{-8} M_\odot \text{ yr}^{-1}$ found by Bertout et al. (1988) in their analysis of the IR and UV continuum excesses in TTSs. It should be noted that Valenti, Basri, & Johns (1993) found that the mass accretion rates in TTSs determined from IR data are systematically higher by an order of magnitude than the accretion rates found by analyzing the optical excess in TTSs. They argue that the optical measurements are a better indicator of accretion onto the star, which would bring the previous mass accretion rate for SU Aur more into line with our mass-loss rate, indicating that the two are about equal. The X-celerator wind mechanism of Shu et al. (1988, 1994) estimates that the mass accretion rate onto the star should be just over twice the mass-loss rate in the wind, and Cabrit et al. (1990) have shown that the forbidden-line luminosity is proportional to the IR excess in CTTs, indicating a direct relation between mass loss and mass accretion. Given the uncertainties in the observational determination of these two quantities, SU Aur appears to be consistent with this expectation.

It should be reiterated that our models do not match all aspects of the line profiles and do not represent a complete model of the system. The red side of the Hβ line shows the largest discrepancies with the observations, suggesting that accretion plays a dominant role in the formation of this part of the profile. In addition, there is the $\sim -150 \text{ km s}^{-1}$ blueshifted feature which periodically appears in the line profile. This feature is not spherically symmetric and furthermore suggests the presence of gas moving at velocities much greater than the $\sim 60 \text{ km s}^{-1}$ wind we use to model the line profiles. Another aspect we have ignored is rotation in the wind. At the base of the wind this may be negligible, since the derived velocities are approximately twice the stellar rotation rate. If magnetic fields enforce corotation out to large radii, rotation will have a major impact on the line profiles.

It is interesting to consider the magnetocentrifugally driven flow of Shu et al. (1994) in this context, since it postulates the origin of the wind at the corotation point in the disk, which is about $3 R_*$ from the center of SU Aur. The rotation velocities there are approximately $190 \text{ km s}^{-1}$. Rotation generates double-peaked line profiles, so this region of the model may produce the broad wings of the observed line profiles. The central portion of the profile then results from the interplay of rotation and expansion velocities as the wind and accretion flows get launched. This model shows great promise to be the true physical paradigm for the TTS emission-line region; however, line profile calculations are urgently needed for this model to see if it can produce the types of profiles we observe. One important conclusion we present that holds true in both the eggbeater model and in the spherically symmetric wind models is the following: the width of the observed lines need not represent the velocity of the outflow in SU Aur.

Our analysis of the variations in the Hα and Hβ line profiles indicate that the eggbeater geometry shown in Figure 15 can explain the accretion and high-velocity wind diagnostics of SU Aur being 180° out of phase with one another. Though no line profiles from this model have been calculated, our modeling of a spherical wind around SU Aur indicates that the bulk of the emission and the width of that emission arise in a high-velocity zone very close to the star. In the eggbeater, this zone is probably near and inside the truncation point of the disk where both the wind and accretion flows originate, namely, in the stellar magnetosphere. Our models suggest that both the main absorption feature and the central emission component of the Balmer lines can arise in a slow wind exterior to this zone. As illustrated in Figure 10 and in the variance analysis of GBUI, the main absorption feature varies less and over a timescale longer than for the emission wings of the profile. We suggest that because the high-velocity zone is near the star and fairly compact, while the main absorption feature forms farther out in the wind away from the perturbing interactions of the stellar magnetic field and the active accretion disk. Our analysis provides clear support for the picture that the strong emission lines in CTTs are primarily diagnostic of the stellar magneto-
sphere and that the absorption components within them arise from bulk flows into or away from the star. The optical absorption components may not indicate the conditions in the wind where it is actually escaping the star.

We would like to thank Jeff A. Valenti, Joan Najita, and Frank Shu for many useful discussions and comments on this work. In addition, we would like to thank Anthony Misch, Jeff A. Valenti, Matthew Richter, and Frank Wilkin for their assistance in collecting the data presented here. Observations presented were collected at Lick Observatory, which is operated by the University of California. We thank the referee for comments which helped improve and clarify the presentation.

REFERENCES

Bevington, P. R. 1969, Data Reduction and Error Analysis for the Physical Sciences (New York: McGraw-Hill)
Camenzind, M. 1990, Reviews in Modern Astronomy, Vol. 3 (Berlin: Springer), 234
Cohen, M., & Schwartz, R. D. 1976, MNras, 174, 137
Ferland, G. J. 1993, Univ. of Kentucky Dept. of Phys. and Astron., Internal Rept.
Hartmann, L., & Stauffer, J. R. 1989, AJ, 97, 873
Mihalas, D. 1978, Stellar Atmospheres (2nd ed.; San Francisco: Freeman)

© American Astronomical Society • Provided by the NASA Astrophysics Data System