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OPTICAL SPECTROSCOPY OF THE DUSTY K5 V STAR HD 98800

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ABSTRACT

High-resolution CCD spectra of the red region of the dusty K5 V star HD 98800, which may contain a protoplanetary disk, have been obtained at Kitt Peak National Observatory. The spectra verify the dwarf spectral type and show rotationally broadened photospheric lines, Hα emission, and a very strong Li I λ6707 absorption line, all of which confirm the star as a very young object. The overall spectrum of HD 98800 closely resembles that of the young, chromospherically active, single BY Dra star HD 82558 (=LQ Hya). The measured Li I equivalent width of 0.39 Å implies an abundance log N(Li) = 2.2 and suggests an age <10 Myr. HD 98800 should be photometrically variable with a probable rotation period of 5–10 days. The high level of chromospheric activity suggests HD 98800 may be detectable as an X-ray and radio source.

Subject headings: circumstellar matter — stars: activity — stars: late-type

1. INTRODUCTION

Both Skinner, Barlow, & Justtanont (1992) and Zuckerman & Becklin (1993) have drawn attention to the remarkable K5 V star HD 98800 (SAO 179815), which has an infrared excess and an apparent circumstellar disk (Walker & Wolstencroft 1988). HD 98800 thus joins objects such as Vega and Beta Pictoris (Aumann et al. 1984; Aumann 1985) where protoplanetary disks are believed to exist. However, HD 98800 stands apart from the other "Vega-excess" stars by virtue of its much later spectral type and the very high proportion (~10%; Zuckerman & Becklin 1993) of its bolometric luminosity that is emitted in the infrared.

Given the peculiar nature of HD 98800 and the limited amount of optical data that have heretofore been published, we obtained spectroscopic observations to confirm its spectral type and implied youth. We present data that show HD 98800 to be an extremely young and chromospherically active K5 V star, with Hα emission, rotationally broadened photospheric lines, and an extremely strong Li I λ6707 absorption line. All these spectral characteristics indicate HD 98800 is a very young system, with an implied age of <10 Myr.

2. OBSERVATIONS

High-dispersion spectroscopic observations of three different wavelength regions were obtained in 1993 April at the Kitt Peak National Observatory with the coudé feed telescope, coudé spectrograph, and a Texas Instruments CCD. The observations have a resolution of 0.2 Å, cover a wavelength range of 80 Å, and are centered at 6430 Å, 6565 Å, and 6695 Å, to confirm the spectral type, examine the nature of the Hα line, and determine the lithium abundance, respectively. The spectra have signal-to-noise ratios of about 100.

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3. BASIC PROPERTIES

The multiplicity of this system complicates the determination of its basic properties. HD 98800 is a close visual binary (not resolved on the spectrograph slit), ADS 8141, whose components have a V magnitude difference of about 0.4 mag (Heintz 1990). The visual observations listed in the Washington Double Star Catalog (Worley & Douglass 1993) cover 80 yr and show significant orbital motion, although a period is not known. One of the visual components has been found to be a spectroscopic binary with a period of 265 days (Latham 1993).

The spectrum has been classified as K5 V (Upgren et al. 1972) and K4 V (Houk & Smith-Moore 1988). Recently, Gregorio-Hetem et al. (1992) observed HD 98800 in a search for T Tauri stars based on the *IRAS* Point Source Catalog (PSC). They obtained several photometric and spectroscopic observations of it and called it a weak-lined T Tauri star.

Our spectrum of HD 98800 in the 6430 Å region was compared with spectra of HD 156026 (K5 V; Houk 1982) and HR 5568 (K4 V; Keenan & McNeil 1989). In this wavelength region there are several luminosity-sensitive and temperature-sensitive line ratios for F, G, and K stars (Strassmeier & Fekel 1990) that are used along with the general appearance of the spectrum to classify HD 98800. The fit with a rotationally broadened spectrum of HD 156026, particularly in the line wings, was slightly better than that of HR 5568, although the line wings of HD 98800 are broader than those of either comparison star. A fit with HR 8832 (K3 V; Keenan & McNeil 1989) was not nearly as good while an M0 V star has a distinctly different-looking spectrum. The combined spectrum in the 6430 Å wavelength region appears quite normal, with no evidence of veiling or line weakening, and is entirely consistent with K5 V or slightly later type, in agreement with the previously noted spectral classifications. Confirming the spectral type is particularly important because lithium-rich post–main-sequence stars have been found (Brown et al. 1989; Fekel & Balachandran 1993).

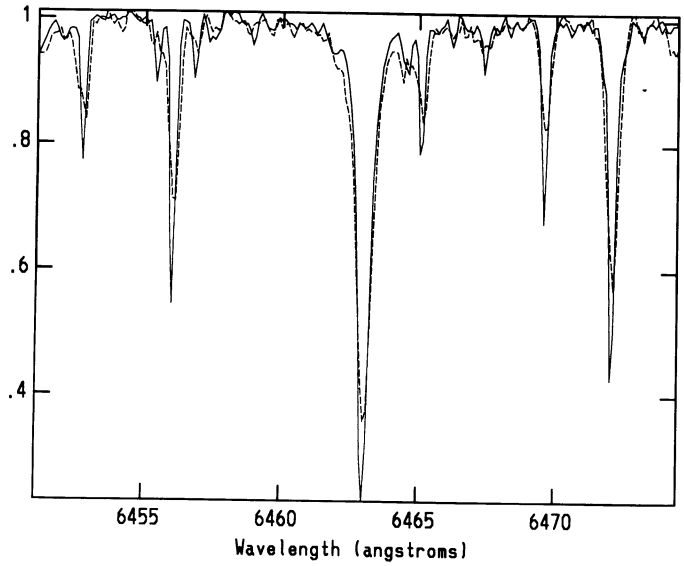

FIG. 1.—Photospheric absorption features in the spectrum of HR 5568 (K5 V; *solid line*) are compared with the corresponding lines in HD 98800 (*dashed line*). Note the shallower line cores and broader line wings in the spectrum of HD 98800, indicating a broadening of 11 km s^{-1}. The ordinate for this and the following figures is intensity, normalized to continuum.

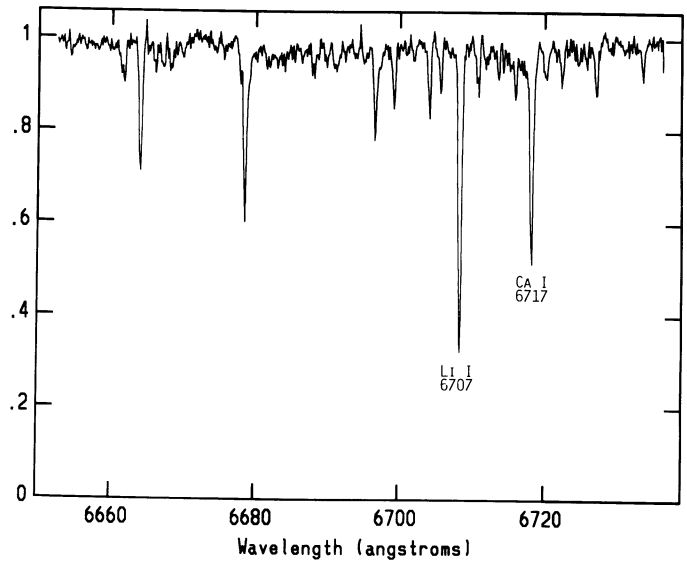

FIG. 2.—The Li I λ6707 region in the spectrum of HD 98800

The small magnitude difference of the visual binary (Heintz 1990) indicates that the two brightest components of this triple system, the primary of the spectroscopic binary and the visual companion, probably differ from the combined spectral type by only a couple of subclasses at most.

The photospheric absorption features in the spectrum of HD 98800 appear to be rotationally broadened (Fig. 1). We determine a $v \sin i$ value of 11 ± 1 km s^{-1} (internal precision) from the full width at half-maximum of several lines in the 6430 Å region. This width was converted into a rotational velocity with an empirical relation (Fekel, Moffett, & Henry 1986b), and a macroturbulence of 2 km s^{-1} was assumed. Rotational velocities for the two spectral type reference stars were determined to be 2 km s^{-1} or less for HR 5568 and 2.5 km s^{-1} or less for HD 156026. As the radial velocity of the spectroscopic binary changes, the width and depth of the combined line profiles (visual component plus SB primary) should also change. Although all the absorption features appear single, the average radial velocity of 7.4 km s^{-1} from our three observations differs by more than 5 km s^{-1} from the center-of-mass velocity found for the spectroscopic binary component (Latham 1993). Thus, in our observations the lines of the visual companion and the spectroscopic binary are almost certainly offset from each other resulting in a significant portion of the observed line broadening. Hence our $v \sin i$ value is an upper limit, and the actual $v \sin i$ value may be significantly less.

The Li I line is very strong in the spectrum of HD 98800 (Fig. 2). The equivalent width (EW) of the lithium feature at 6707.8 Å was determined by a Gaussian fit to the line and resulted in an EW of 0.41 Å. This value is somewhat larger than that found by Gregorio-Hetem et al. (1992). In late-type stars the lithium line is blended with an Fe I line at 6707.44 Å. From Pallavicini, Randich, & Giampapa (1992) we estimate the EW of the Fe I line to be 0.02 Å, and the resultant EW of the lithium line alone is 0.39 Å.

The Hα line was also observed by Gregorio-Hetem et al. (1992). Our spectrum of Hα is similar to theirs in that the line has a narrow, very weak absorption core indicating that the usually strong absorption line is extensively filled in by emission (Fig. 3). The line also has emission slightly above the continuum on either side of the absorption core, in contrast to the profile illustrated by Gregorio-Hetem et al., where the emission above continuum is present only on the short wavelength side.

4. DISCUSSION

The presence of Hα emission (or even a partial filling of the absorption feature) in a K-dwarf is a well-known indicator of chromospheric activity (see Thatcher & Robinson 1993 and references therein); stars of this type are usually called BY Draconis stars (Bopp & Fekel 1977). Although many BY Dra

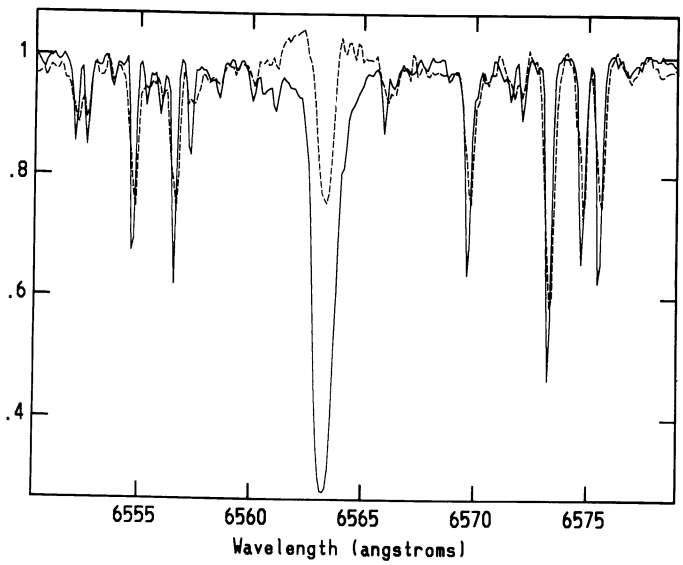

FIG. 3.—The Hα region of HD 98800 (*dashed line*) compared with that of HR 5568 (*solid line*) showing the filled Hα absorption line with weak blue and red emission components.

TABLE 1

SOME YOUNG K-TYPE ACTIVE CHROMOSPHERE STARS

Name	Sp.	V	Hα Emission	Binary Class	$v \sin i$ (km s^{-1})	EW (Li I) (mÅ)
HD 36705	K0 Ve	6.8v	Present	Visual	75	320
HD 82558	K2 Ve	7.8v	Filled	Single	25	230
HD 98800	K5 Ve	9.08	Filled/weak	Visual, SB	11:	390
FK Ser	K5e	9.5:	Strong	Visual	...	600

stars are spectroscopic binaries with orbital periods less than 6 days, a few show no velocity variations at the 1 km s^{-1} level, and are single stars (or visual pairs). Bopp & Fekel concluded that a close companion is a *sufficient*, but not a *necessary*, condition for the occurrence of enhanced chromospheric activity. Relatively rapid rotation, with v(equator) > 5 km s^{-1} is now viewed as the cause of the enhanced level of activity in the BY Dra stars. In this scenario, short-period systems interact tidally and thus rotate synchronously, with equatorial velocities >5 km s^{-1}. This drives chromospheric activity and Hα emission. On the other hand, single BY Dra stars, or those in widely separated (non–tidally interacting) binaries should be relatively young objects that have not been fully rotationally braked, such as HD 82558 (=LQ Hya; Fekel et al. 1986a) or HD 36705 (Collier Cameron et al. 1988). HD 98800 falls into this latter category.

The properties of some young K-type active chromosphere stars are compared in Table 1. HD 98800 closely resembles the active, single (K2 V star HD 82558, though the Li I line is nearly a factor of 2 stronger in the later type star, approaching the equivalent width seen in FK Ser, a K5 star classified as "post–T Tauri" by Herbig (1973).

We emphasize that the determination of the properties of HD 98800 depends on assumptions that are complicated by its apparent pre–main-sequence nature and its multiplicity. Nevertheless, because of the system's potential importance, we examine the evolutionary state of the system. Zuckerman & Becklin (1993) determined a single blackbody temperature of 4100 K for HD 98800. The effective temperature scale adopted by Popper (1980) and Cayrel de Strobel's (1992) analysis of HD 156026 suggest that the effective temperature of a K5 V star is 200–400 K hotter. Despite these differences we use the effective temperature of Zuckerman & Becklin (1993) along with the calibration of Padgett (1990) to determine a Li abundance of log N(Li) = 2.2, noting that a hotter temperature results in an even larger abundance. This value of 2.2 is about 0.6 dex below the values found by Padgett for late-type pre–main-sequence stars in the Taurus-Auriga clouds where Kenyon et al. (1990) estimate the T Tauri stars to have an age of 1 Myr, and far above (by at least a factor of 10) the Li abundances for stars of this spectral type in the Pleiades (Soderblom et al. 1993a) where the age is taken to be 70 Myr (Soderblom et al. 1993b). The implication, of course, is that the age of HD 98800 is between that of the Taurus-Auriga cloud complex and the Pleiades.

Another rough quantitative age estimate for HD 98800 is possible using the theoretical results on Li depletion and angular momentum loss given by Pinsonneault, Kawaler, & Demarque (1990). Figure 2*a* of Pinsonneault et al. suggests a mass of about 0.7 $M_\odot$ for an assumed temperature of 4100 K (using a higher temperature would increase the mass to perhaps 0.8 $M_\odot$). From their Figure 1 the observed depletion factor of 10 from the primordial Li abundance implies an age of about 10 Myr. Age estimates from their nonrotating models are rendered less certain by the blending and sin i problems associated with our v sin i determination. Those models (their Fig. 2*b*) predict a rotational velocity of 30 km s^{-1} (certainly ruled out by our results) for an age of 10 Myr and about 5 km s^{-1} for 1 Myr. All these lines of argument suggest an age for HD 98800 of <10 Myr.

The presumed young age of HD 98800 places it over 1 mag above the ZAMS for the assumed effective temperature. From Figure 2 of Pinsonneault et al., a mass of 0.7 $M_\odot$ at an age of about 10 Myr has log $(L/L_\odot) = -0.6$ and results in M_V = 6.87. This leads to a distance of about 34 pc.

Using a center-of-mass velocity of +12.8 km s^{-1} (Latham 1993), our estimated distance, and SAO Catalog values for the proper motions, we find space velocity components (U, V, W) = −8, −18, −1 km s^{-1}, respectively, in a right-handed coordinate system (Johnson & Soderblom 1987). The resulting space velocity is 19 km s^{-1}. We are unable to unambiguously associate these velocity components with any nearby region of star formation. Gregorio-Hetem et al. (1992) note that HD 98800 is within 10° of TW Hya, an isolated T Tauri star (de la Reza et al. 1989). Perhaps HD 98800 is a remnant of a small association that produced TW Hya and several other T Tauri stars (Gregorio-Hetem et al. 1992).

The chromospherically active nature of HD 98800 allows predictions about its photometric behavior and its detection at other wavelengths to be made. HD 98800 will display photometric variability with an amplitude of at least 0.1 mag in V, as is characteristic of other BY Dra stars (the observed amplitude *may* be affected by the presence of binary companions with different levels of activity). These variations are produced by cool starspots on the rotating star. Such light variability may already be evident since Zuckerman & Becklin (1993) report a recent V measurement of 9.13 while Gregorio-Hetem et al. (1992) found V = 8.89. A v sin i value of 11 km s^{-1} for HD 98800 would constrain the photometric (rotation) period to be ≤4.5 days, assuming a radius near solar. However, the profile blending suggests that the rotational period may be significantly longer. If v sin i is as low as 5 km s^{-1}, the rotation period is ≤10 days.

HD 98800 may be detectable as a radio and X-ray source. Gudel (1992) observed 12 active main-sequence K stars with the VLA and detected 7 at 3.6 cm, including HD 36705 and 82558. HD 98800 should be searched for such emission, which may be variable due to flares. Active-chromosphere stars possess hot coronae, making them detectable as X-ray sources (Dempsey et al. 1993). HD 36705 and 82558 have X-ray luminosities log L_X = 30.4 and 29.1 ergs s^{-1}, respectively (Gudel 1992). HD 98800 may have a comparable X-ray luminosity, though it does not appear in the *ROSAT* EUV Bright Source Catalog (Pounds et al. 1993). Finally, noting the striking spec-

troscopic similarities between HD 82558 and HD 98800, we suggest that the former star be observed in the infrared for the presence of a Vega-like excess. HD 82558 is not in the *IRAS* Point Source Catalog, but Johnson (1986) notes that it is in a poorly scanned area, and its absence from the PSC is not unexpected.

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