ACCRETION AND OH PHOTODISSOCIATION AT A NEARBY T TAURI SYSTEM
IN THE β PICTORIS MOVING GROUP

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ABSTRACT

We present spectra of an M-type, binary star system (LDS 5606) that belongs to the nearby ∼20 Myr old β Pictoris moving group. Both stars are very dusty; the dustier member displays optical emission lines from eight elements indicative of ongoing mass accretion. The spectra of both stars contain oxygen forbidden line emission at 6302 and 5579 Å, consistent with a recent model of far ultraviolet photodissociation of OH molecules in a circumstellar disk. These are the oldest dwarf stars presently known to display such a phenomenon. The spectral energy distribution of the dustier star indicates substantial quantities of dust as hot as 900 K, and its fractional infrared luminosity (LIR/Lbol) is almost as large as that of the main sequence record holder, V488 Per. The LDS 5606 binary joins a remarkable group of very dusty, old, T Tauri stars that belong to widely separated multiple systems.

1. INTRODUCTION

Beginning in the late 1990s, astronomers have identified numerous youthful stars near Earth (see reviews by Zuckerman & Song 2004; Torres et al. 2008; Malo et al. 2013; Gagne et al. 2014). Some of these stars belong to associations comprised of members that are moving, more or less, together through space. The principal tool for identification of such stars less massive than mid F-type has been the ROSAT all-sky X-ray survey (RASS). Recently it was realized that many late-type dwarf stars with excess ultraviolet emission in the Galaxy Evolution Explorer (GALEX) sky survey (Martín et al. 2005) are both young and within ∼100 pc of Earth (Rodriguez et al. 2011, 2013; Shkolnik et al. 2011). Indeed, in comparison with the RASS, the GALEX survey provides a more sensitive means for identification of youthful M-type stars.

As part of an ongoing survey of GALEX UV-excess stars, Rodriguez et al. (2014) identified an unusual binary star, LDS 5606, that they show is a likely member of the nearby β Pictoris moving group. Following previous designations in the literature, we designate the west and east members of the binary as LDS 5606A and LDS 5606B, respectively, with a projected separation on the sky of 26′. At a distance of 65 pc (Rodriguez et al. 2014), this corresponds to ∼1700 AU. The age of the β Pic stars has been deduced via placement on evolutionary tracks (Zuckerman et al. 2001), kinematic traceback (Ortega et al. 2002), and lithium depletion (Binks & Jeffries 2014, and references therein); these ages range from 12 to 21 Myr. At present, lithium depletion ages for youthful stars seem to be very much in favor. Thus we adopt a β Pic moving group age of 20 Myr.

At an age as old as 20 Myr, both the dust and the gas that orbit the two LDS 5606 stars display unusual properties. Rodriguez et al. (2014) note that for a binary star system of this age and older the presence of detectable dust in orbit about both members is very unusual. Rodriguez et al. establish that both members of LDS 5606 are of spectral type ∼M5. We know of no (published) evidence for the presence of orbiting gas around late-type dwarf stars with ages ≥20 Myr, but a few such dusty main sequence stars of spectral types G and A are orbited by substantial masses of gas. The gas has been detected optically, in the far-infrared, and at millimeter wavelengths; the following paragraph presents a brief overview.

The optical Ca H and K lines are seen toward two members of the β Pictoris moving group, β Pic itself and HD 172555 (Kiefer et al. 2014, and references therein). Such gas is usually interpreted in a model of falling evaporating bodies and the mass of gas implied in such a model is far smaller than the mass of gas implied by detection of the [O I] 63 μm line or by rotational emission from the CO molecule. With the Herschel Space Observatory the 63 μm [O I] line has been detected in emission toward HD 172555 (Riviere-Marichalar et al. 2012) and the 158 μm [C I] line toward β Pic (Cataldi et al. 2014). CO rotational emission has been seen toward V4046 Sgr (Rodriguez et al. 2010), 49 Cet (Zuckerman & Song 2012), HD 21997 (Kospal et al. 2013), and β Pic (Dent et al. 2014) with ages in the range 20–40 Myr. V4046 Sgr—a member of the β Pic moving group (Torres et al. 2008)—shows evidence for accretion (Stempels & Gahm 2004), but not of hot dust (Hutchinson et al. 1990; Jensen & Mathieu 1997; Rosenfeld et al. 2013). Because V4046 Sgr is a 2.4 day binary system, the accretion is likely to be driven by complex gas dynamics induced by the close binarity (de Val-Borro et al. 2011; Sytov et al. 2011; Donati et al. 2011). HD 21997 and 49 Cet show only cold dust and no evidence for accretion.

The oldest stars—not in a close binary and not yet evolved beyond the main sequence—previously known to be undergoing gas accretion reside in the 8 Myr old TW Association, for example, TWA 30AB (Looper et al. 2010a, 2010b) and TW Hya itself (Kastner et al. 2002; Curran et al. 2011). As shown in Section 4, the dustier (west) star of the LDS 5606 binary is definitely accreting material from a surrounding disk. Also present in the spectra of both members of the binary are forbidden lines of neutral oxygen at vacuum wavelengths of 6302 and 5579 Å. As we describe in Section 4.4, these lines are plausibly an outcome of photodissociation by far-ultraviolet radiation from the Sun.
photons of OH molecules located in disks that orbit each star. Such spectral features are unprecedented in dwarf stars of age 20 Myr (or older).

2. OBSERVATIONS

The spectra discussed in the present paper were obtained primarily with the HIRES echelle spectrometer (Vogt et al. 1994) on the Keck I telescope at Mauna Kea Observatory in Hawaii. Spectra were obtained during observing runs in 2013 October and November. The red cross disperser was combined with a 1′15 slit and the wavelength range between 4370 and 9000 Å was covered with a resolution of ∼40,000. HIRES employs three CCDs with spectral gaps between them and between some orders as listed in Table 9. Spectra were reduced using the IRAF and MAKEE software packages. Representative spectra appear in Figures 1–6. All wavelengths given in this paper are in vacuum. A ThAr lamp and velocity standards HIP 26689, HIP 47690, and HIP 117473 (Nidever et al. 2002) were used to determine heliocentric radial velocities.

Given their nearly identical JHK magnitudes in the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), their excess emission at UV and IR wavelengths, strong veiling in the western (A) star, and the large errors in optical magnitudes listed in VizieR, neither component of the binary star can be convincingly designated as the (brighter) primary. LDS 5606A was observed on 2013 October 17 and November 16 (UT). The echelle grating settings were not the same in October and November so the wavelength coverage differed at the extreme wavelengths and also in the gaps listed in Table 9. This is why some of the transitions listed in Tables 1 and 2 for LDS 5606A have only a single entry. Clouds were present during both nights and hampered the integrations (which were terminated early). Integration times were 1900 and 1713 s on October 17 and November 16, respectively.

The eastern component, (B), was observed on 2013 October 21 (UT). Some thin clouds were present on this night. The integration time was 2300 s. HIRES results for LDS 5606B are presented in Tables 3 and 4.

In Tables 1–4, equivalent widths (EWs) and line center wavelengths were obtained by fitting lines with Voigt profiles using the IRAF function splot. In a very few cases the lines have irregular shapes and the Voigt fits are quite poor. In such cases EWs were measured by summing the area either above (for emission lines) or below (for absorption lines) the continuum level. Examples are the He i emission line at 4389 Å and the questionable Sc i absorption line at 4739 Å as measured on 2013 October 17 in LDS 5606A. Line FWHMs intensity, discussed in Section 4, are obtained by fitting Gaussian profiles.

We used Voigt profiles in order to capture the full EW of a line. It was obvious for some of the strong lines with good signal-to-noise ratio (S/N) that a Gaussian fit missed energy in the linewings and thus would underestimate the EW. However at half-power both the Gaussian and the Lorentzian components of the Voigt profile contribute to the FWHM in a Voigt fit. This is unnecessarily complex for our needs; the Gaussian FWHM dominates and is sufficient for inter-comparison of linewidths (as per Section 4).

In Sections 3 and 4 we also utilize data obtained on 2013 December 3 (UT) with the UVES spectrograph (Dekker et al. 2000) on the Very Large Telescope (VLT). Details are given in Rodriguez et al. (2014); for the present paper, we note that...
spectra were obtained from 3760 to 5000 Å, from 5700 to 7500 Å, and from 7660 to 9460 Å with a 2′′ slit and a spectral resolution ∼20,000. The integration time was only 900 s per star so that the S/N in the UVES spectra is inferior to that of HIRES. Tables 5 and 6 and Figures 6–8 present some UVES results. For lines in the blue the UVES measured continuum level is so faint that EW measurements have large uncertainties. Fortunately, as part of the UVES pipeline, appropriate
calibrations were taken on December 3 so that the blue portion of the two UVES spectra were flux calibrated. Thus, Table 5 lists emission line flux densities rather than EW. At longer wavelengths, Table 6 presents some measured EW from the UVES spectra.

In 2013 September and November both members of the binary star were observed with the APEX telescope (Güsten et al. 2006) at the $J = 3 \rightarrow 2$ rotational transition of CO with spectral resolution 0.53 km s$^{-1}$ per channel. Water vapor columns ranged between 0.3 and 4.2 mm. A total of 248.8 minutes were spent on LDS 5606A and 140.7 minutes on LDS 5606B. The summed spectra for the A (western) star had an rms in antenna temperature (per 0.53 km s$^{-1}$ channel) of 7.17 mK and for the B (eastern) star 5.47 mK.
3. RESULTS

Much basic information about LDS 5606A and 5606B is given in Table 1 of Rodriguez et al. (2014), for example, their spectral types (M5), distance from Earth (∼65 pc), and radial velocities. A full discussion of the radial velocities can be found in Section 2 of that paper.

Following Vican & Schneider (2014), spectral energy distributions (SEDs) were created with a fully automated fitting technique that uses theoretical models from Hauschildt et al. (1999) to predict stellar photospheric fluxes. The SEDs were generated using available photometry from Hipparcos, Tycho-2, 2MASS, and ALLWISE (Wright et al. 2014). Stellar radii and effective temperatures are treated as free parameters to fit
The observed fluxes (B, V, J, H, and K) with a χ² minimization method.

The SEDs for the two stars are shown in Figures 9–11. Their fractional infrared luminosities (L_IR/L_Bol, 11.9% and 6.5%) are among the largest known for any dwarf star with age >10 Myr. More than half of the infrared luminosity of LDS 5606A is carried by dust particles with temperatures ~900 K. Excepting much more modest quantities of hot dust seen interferometrically at K-band by Absil et al. (2013) around some much older, earlier type (A–K) stars, this is the hottest
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Table 4
HIRES Measured Absorption Lines in LDS 5606B

| Vacuum Wavelength (Å) | Ion | EW (mÅ) |
|----------------------|-----|---------|
| 4413.474            | Cr i | 294     |
| 4417.708            | V i  | 128     |
| 4436.924            | Ca i | 374     |
| 4458.680            | Ti i | 125     |
| 4460.980            | Cr i | 120     |
| 4461.400            | Fe i | 196     |
| 4595.410            | V i  | 237     |
| 4608.622            | Sr i | 802     |
| 5298.165            | Cr i | 166     |
| 5299.751            | Cr i | 172     |
| 5329.521            | Fe i | 500     |
| 5342.509            | Fe i | 146     |
| 5347.288            | Cr i | 224     |
| 5349.799            | Cr i | 225     |
| 5350.953            | Ca i | 148     |
| 5372.983            | Fe i | 216     |
| 5396.176            | Mn i | 213     |
| 5398.628            | Fe i | 313     |
| 5407.277            | Fe i | 224     |
| 5411.276            | Cr i | 177     |
| 5427.745            | Ti i (?)| 86     |
| 5431.206            | Fe i | 230     |
| 5434.056            | Mn i | 178     |
| 5590.301            | Ca i | 147     |
| 5591.666            | Ca i | 170     |
| 5596.015            | Ca i | 101     |
| 5689.783            | Na i | 145     |
| 6104.412            | Ca i | 111     |
| 6123.912            | Ca i | 275     |
| 6163.878            | Ca i | 114     |
| 6440.855            | Ca i | 162     |
| 6464.353            | Ca i | 226     |
| 6473.450            | Ca i | 127(?)  |
| 6709.640            | Li i | 501     |
| 7701.093            | K i  | 1360    |
| 7802.414            | Rb i | 355     |
| 7949.789            | Rb i | 268     |
| 8049.830            | Fe i | 215     |
| 8077.370            | Fe i | 158     |

Notes. Rest wavelength for λ 4608.622 Sr i line is from http://physics.nist.gov/PhysRefData/ASD/lines_form.html.

a Possible contribution from Mn i at wavelength 4458.800 Å.

b Possible contribution from Fe i at 6464.512 Å.

dust ever seen at a dwarf star of age >10 Myr. Previous to the measurements of LDS 5606A, the hottest dust measured at a dwarf star far from interstellar molecular clouds and with properties similar to the dust at LDS 5606A is ~800 K at the ~60 Myr old K-type star V488 Per (see Section 4.6.2 and Zuckerman et al. 2012).

As indicated in Table 1, emission lines from at least eight elements are seen in the spectrum of LDS 5606A. For most lines the identification of the carrier seems secure; where the carrier is less certain we have added a (?) after what appears to be the most plausible ion. Many marginal (low S/N, ~5) emission features appear in the spectra. Future, deeper, integrations will clarify the reality of such features and may well add additional elements in emission.

Comparison of the two epochs of observation of LDS 5606A with each other and with the one epoch observation of LDS 5606B indicates the following.

1. The numerous and strong permitted emission lines at the western (A) star combined with the large FWHM intensity of the Hα line indicate an accretion flow (see Section 4). The weaker and fewer emission lines at the eastern (B)
Figure 9. SED of LDS 5606A. The solid black curve is a fit of a Hauschildt et al. (1999) photospheric model (see Vican & Schneider 2014 for details) plus blackbodies with temperatures of 215 and 900 K. The blackbodies are indicated with dashed curves and the model photosphere with a dotted line. The two green points at visual wavelengths are B and V from the GSC 2.3.2. The three green near-IR points are from 2MASS and the four blue points are from ALLWISE. Errors in the flux densities of the two shorter wavelength ALLWISE data points are smaller than the size of the blue points. Tau is equal to \( \frac{L_{\text{IR}}}{L_{\text{bol}}} \). Tau of the 900 K component is about 7.2% and of the 215 K component about 4.7%. (A color version of this figure is available in the online journal.)

Figure 10. SED of LDS 5606B with a blackbody fit (dashed curve) of 220 K to the infrared excess emission, otherwise the same as Figure 9. (A color version of this figure is available in the online journal.)

star can probably be accounted for by some combination of an active chromosphere and accretion. The difference in emission line intensities between the two stars is nicely illustrated in the broadband UVES spectra in Figure 3 in Rodriguez et al. (2014).

2. The presence of 900 K dust (Figure 9) near LDS 5606A is consistent with the ongoing accretion implied by the optical emission lines. If blackbodies, then these dust particles lie only \( \sim \)0.01 AU from LDS 5606A—similar to the semimajor axes of some Kepler discovered planets, and just where one might expect to find lots of dust if 20 Myr old planetary embryos of such close-in planets are colliding with each other (e.g., Hansen & Murray 2013).

3. The EW of the permitted emission lines from LDS 5606A were typically about 18% stronger on October 17 than on November 16 (Table 1). H\( \alpha \) is a notable exception, being substantially stronger on November 16. No overall change is evident in the average absorption line EWs between the two epochs.

4. To determine the veiling in the optical spectra of the two stars we compared the EW of their absorption lines with those of a star of similar spectral type but with no evidence for excess IR emission and much weaker emission lines (see Section 4.1). The conclusion is that LDS 5606A is heavily veiled and LDS 5606B modestly so (Table 7).

5. [O\( \text{I} \)] lines at 6302 and 5579 Å at both stars (Figure 6) indicate the presence of relatively low-density atomic gas; we attribute the [O\( \text{I} \)] to far ultraviolet photodissociation of OH molecules located in circumstellar disks (Section 4.4).

4. DISCUSSION

4.1. Veiling

The presence of overlying (excess) optical continuum emission at classical T Tauri stars is referred to as veiling. In the popular magnetospheric model, this emission can be generated by dissipation of energy of infalling gas in a postshock region at the base of a magnetic funnel at the stellar surface (Bertout 1989; Beristain et al. 2001, and references therein). The shocked region is also a plausible strong source of ionizing radiation.
Stars. For example in a sample of ~40 UV-bright late-type stars observed with HIRES (L. Vican et al., in preparation), only one shows emission lines beyond those from H, He, the NaI doublet near 5900 Å, and the Ca II IR triplet. Of note at LDS 5606A is the strong high excitation Paschen α line of ionized helium at 4687 Å, indicative of the existence of a region either of high temperature or close proximity to a source of ionizing radiation (Section 4.3). This line is not present in the spectra of young non-accreting stars (L. Vican et al., in preparation).

The situation regarding accretion at LDS 5606B is more ambiguous. We base our analysis on the discussion in White & Basri (2003) who consider three different indicators for accretion; these are veiling, Hα EW, and the 10% width of the Hα line. According to Section 3.3 in White & Basri, veiling of a star’s optical continuum is evidence for accretion and LDS 54606B is veiled (Section 4.1 and Table 7). According to White & Basri’s Section 4.2, an M5-type T Tauri star is “classical,” i.e., accreting, if its Hα EW is $\geq 20$ Å, which is true for LDS 5606B at least some of the time, but not always (see Table 2 in Rodriguez et al. 2014). On the other hand, the third accretion indicator, the Hα 10% width in LDS 5606B is only $\sim 135$ km s$^{-1}$ (Figure 12) which places the star squarely in the region of weak-line (non-accreting) stars according to the discussion in White & Basri.

Thus, LDS 5606B appears to pass the first and maybe the second of these three tests for accretion, but fails the third, thus placing it in a region of “phase space” not occupied by any of the much younger T Tauri stars investigated by White & Basri (2003). The referee suggests that these data might be reconciled if accretion at LDS 5606B is sporadic in nature.

An additional indicator that LDS 5606B actively accretes at least some of the time is its unusually strong near-UV flux measured by GALEX. As noted by Rodriguez et al. (2014), the near-UV emission from LDS 5606B was so strong that it fell outside of the standard region in color–color space occupied by candidate young late-type stars as defined in Rodriguez et al. (2013), a situation reminiscent of the actively-accreting young star TW Hya (Rodriguez et al. 2011).

### 4.3. $H\alpha$ and $He\beta$ Emission Lines

As noted in Section 4.2, the EW and 10% width of the Hα emission lines in the LDS 5606 stars can be used to deduce mass accretion rates. Out beyond the 10% width, the extent of the extreme velocities of H and He emission lines can be used to better understand physical conditions in the various mass flows near T Tauri stars, as discussed in the following paragraphs. We therefore consider the full velocity extent (FVE) of lines in LDS 5606. Our definition of FVE is that velocity at which the line wings appear to merge with the continuum. Because we are interested only in comparing FVEs among various transitions and stars—where the FVE differences among the transitions and stars are substantial (see below)—for the purposes of the present paper, FVE need not be defined too precisely.

The FVE of the Hα and $He\beta$ lines in LDS 5606A are much greater than the corresponding lines in LDS 5606B (Figure 1). For Hα, the FVE is $\sim 870$ km s$^{-1}$ in the A-component compared to $\sim 550$ km s$^{-1}$ in B. At $He\beta$ the difference between the two stars is greater; the FVE in A is $\sim 1370$ km s$^{-1}$, while for B the FVE is $\sim 550$ km s$^{-1}$.

Muzerolle et al. (2001) attribute broad Hα line wings to Stark broadening of energy levels of H atoms that are participating in the funneled flow of material onto a T Tauri star in the magnetospheric model. In contrast, Beristain et al. (2001)
propose that in some T Tauri stars He emission at velocity offsets more than 200 km s\(^{-1}\) from the stellar velocity is generated in a hot wind. They suggest that a choice can be made between these two models for high-velocity gas by measurement of asymmetry, if any, in the red and blue high velocity wings; a modest red asymmetry would favor the infall model and a blue asymmetry the outflow model. However, no convincing asymmetry is present in either the He\(\alpha\) or He\(\beta\) line wings in LDS 5606A. The infall model rather than the existence of a substantial, rapidly outflowing, wind is consistent with the generally modest FWHM of the emission lines in LDS 5606A. The broadest FWHM of any line is He\(\alpha\) at 138 km s\(^{-1}\) followed by He\(\beta\) at 123 km s\(^{-1}\). The broadest helium lines have FWHM \(\sim 50\) km s\(^{-1}\), but more typically \(\sim 25\) km s\(^{-1}\), while for heavier elements emission FWHM are typically 20 km s\(^{-1}\) or less. In classical T Tauri stars rapid outflow is characterized by much broader emission lines (Beristain et al. 2001).

Table 1 lists seven detected transitions of He\(\iota\) and one of He\(\iota\)I in LDS 5606A.\(^3\) Because of the high energies of the He energy levels, their excitation is generally attributed to photoionization and subsequent recombination and cascade rather than collisional excitation which would require very high gas temperatures. In the magnetospheric model the accretion shock at the stellar surface is deemed to be the principal source of ionizing photons. Beristain et al. (2001) decompose the He lines from classical T Tauri stars into two kinematic components, narrow and broad (\(\sim 50\) and \(\sim 200\) km s\(^{-1}\), respectively; see their Table 1). The narrow component arises in conjunction with postshock gas at the magnetospheric footprint while the broad component arises preferentially in a hot outflowing wind. The relatively narrow linewidths mentioned in the preceding paragraph in combination with the predominance of permitted emission lines rather than forbidden lines (see Sections 4.4 and 4.6.1) indicate that the spectrum of LDS 5606A is dominated by the narrow component. Thus, in the following we compare helium line ratios in LDS 5606A with those arising from the narrow component in classical T Tauri stars as analyzed by Beristain et al. (2001).

Beristain et al. (2001) focus their attention on the ratio of the intensity of the 5878 Å line of ortho-He to that of the 6680 Å line of para-He. The ratios of these intensities have been worked out for nebular (H\(\iota\)II region) conditions ranging from pure capture and cascade in the low-density limit to much higher densities where collisions dominate (see discussion and references in Beristain et al.). Like Beristain et al., our HIRES spectra are not flux calibrated so, like them, we use the ratio of EWs of the two lines. Over the modest 800 Å separation of the two lines, the combination of photospheric and nebular continuum at LDS 5606A is probably not much different from unity.

The 5878/6680 EW ratio is 4.7 (Table 1), consistent with densities \(\sim 10,000\) cm\(^{-3}\) and temperatures \(\sim 20,000\) K (Smits 1991) where collisional excitation of the metastable triplet and singlet 2\(S\) states can compete with radiative processes. According to the calculations by Smits (1991), a ratio of 4.7 is near the maximum achievable at any nebular density. The ratio of 4.7 is larger than those quoted by Beristain et al. (2001) for the narrow helium line component in 24 classical T Tauri stars and implies densities in the emitting region at LDS 5606A smaller than those in younger T Tauri stars. For the 4473/4714 ratio we measure an EW ratio of 9.8, in agreement with the nebular model prediction of 9.8 (Smits 1991).

Turning to a joint consideration of the seven lines of He\(\iota\) and the 4687 Å line of He\(\iota\)II in LDS 5606A, their kinematic properties are consistent with origin in postshock gas near the base of the accretion flows in the magnetospheric model. In Table 8 we compare the stellar velocity as deduced from strong photospheric absorption lines with the redshifts of the neutral and ionized He emission lines. A progression of He\(\iota\) moderately redshifted relative to the photosphere, to He\(\iota\)II redshifted relative to He\(\iota\)—as measured in LDS 5606A, see Notes to Table 8—is consistent with association of helium emission lines and the accretion shock (Beristain et al. 2001). The larger FWHM of the 4687 Å He\(\iota\)II line (51 km s\(^{-1}\)), relative to the average FWHM of the seven He\(\iota\) lines (28.4 \(\pm\) 9.2 km s\(^{-1}\)), is also anticipated in the magnetospheric model; the He\(\iota\)II line would be formed closer to the accretion shock, where gas velocities, ionizing flux, and temperature are all relatively larger. (These FWHM are from Gaussian fits to the emission lines. The shape and width of the 4389 He\(\iota\) line are anomalous and there may be contamination from other elements. If this line is removed from the calculation then the FWHM of the other six He\(\iota\) lines is 25.2 \(\pm\) 4.0 km s\(^{-1}\).) Thus the relative He linewidths and radial velocities are consistent with expectations of the magnetospheric shock model.

In the case where the helium lines result entirely from recombination and cascade, then the 4473/4687 intensity ratio would equal 0.04\((N[He\(\iota\)]/N[He\(\iota\)II]) (Osterbrock 1974). The measured EW ratio from Table 1 is 3.6. The near coincidence in wavelength between the Ly\(\alpha\) transition in hydrogen and the Balmer \(\beta\) \((n = 4\to 2)\) transition in He\(\iota\) provides a mechanism to

\(^3\) Three additional transitions of He\(\iota\), at vacuum wavelengths of 4438.8, 5049.1, and 7283.3 Å, are covered in the HIRES spectra, but none are detected. An He\(\iota\) transition at 7067.1 Å falls in a hole in the HIRES coverage (see Table 9), but is detected in the UVES spectrum of LDS 5606A (Table 6).

### Table 8

| Ion      | Wavelength (Å) | Redshift (Å) | Redshift (km s\(^{-1}\)) |
|----------|----------------|--------------|---------------------------|
| Fe\(\iota\) | 4935          | 0.254        | 15.4                      |
| Mn\(\iota\) | 5396          | 0.269        | 15                        |
| Mn\(\iota\) | 5434          | 0.244        | 13.5                      |
| Ca\(\iota\) | 6441          | 0.285        | 13.3                      |
| Li\(\iota\) | 6464          | 0.30         | 14                        |
| Ca\(\iota\) | 7328          | 0.346        | 14                        |
| Fe\(\iota\) | 8050          | 0.38         | 14                        |
| Fe\(\iota\) | 8077          | 0.39         | 14.5                      |
| He\(\iota\) | 4389          | 0.33         | 23                        |
| He\(\iota\) | 4473          | 0.33         | 22                        |
| He\(\iota\) | 4714          | 0.36         | 23                        |
| He\(\iota\) | 4923          | 0.33         | 20                        |
| He\(\iota\) | 5017          | 0.29         | 17                        |
| He\(\iota\) | 5877          | 0.43         | 22                        |
| He\(\iota\) | 6680          | 0.44         | 20                        |
| He\(\iota\) | 6867          | 0.49         | 31                        |
| [O\(\iota\)] | 5579          | 0.31         | 16.6                      |
| [O\(\iota\)] | 6302          | 0.29         | 14                        |

**Notes.** The mean of the heliocentric velocities of the nine photospheric absorption lines (from elements not helium or oxygen) is 14.5 \(\pm\) 0.4 km s\(^{-1}\). The mean velocity of the seven emission lines from He\(\iota\) is 21 \(\pm\) 0.9 km s\(^{-1}\). The velocity of the one emission line from He\(\iota\)II is 31 km s\(^{-1}\). The mean velocity of the two forbidden oxygen emission lines is 15.3 km s\(^{-1}\).
increase the population of the He+n = 4 level, thus enhancing the intensity of the 4687 line. Hence, the 4473/4687 ratio provides only a lower limit on the He II to He III number ratio.

4.4. [O I] Lines

Tables 1, 3, and 6 and Figure 6 include the [O I] electric quadrupole transition at 5579 Å and the magnetic dipole transition at 6302 Å. In gaseous nebulae the former line, sometimes referred to as an “auroral” transition, is between the singlet S and singlet D term of the ground configuration. The 6302 Å line, a “nebular” transition in gaseous nebulae, is between the singlet D and the ground state triplet P2 term. There also is a magnetic dipole transition at 6365.5 Å from the singlet D to the triplet P1 term with Einstein A-value 1/3 that of the 6302 Å transition. The 6365.5 Å line is not detected in the HIRES spectra; the EW upper limit is ~120 mÅ in both members of LDS 5606.

Forbidden line emission at classical T Tauri stars can come in two flavors, a high-velocity, strongly blueshifted component that comes from collimated outflowing jets and a low-velocity component with, at most, a modest blueshift. The 5579 Å line often accompanies the low-velocity component, but is never associated with the high-velocity one (Gorti et al. 2011). Various models to explain the origin of low-velocity [O I] emission at classical T Tauri stars have been proposed (Gorti et al. 2011; Rigliaco et al. 2013 and references therein). In the following we consider the HIRES [O I] measurements in the context of the OH photodissociation model proposed in these two papers. According to this model, stellar far-UV photons reach the surface of an orbiting molecular disk where they photodissociate both H2O and OH molecules, resulting in O atoms in the 1D and 1S states. These atoms then decay via the 6302 and 5579 Å transitions. Since [O I] emission is present at both members of LDS 5606 and because forbidden line radiation is quenched at high densities (such as might characterize the region where the 900 K dust is located around LDS 5606A), it seems reasonable to presume that the [O I] lines are associated with the 200 K dust component that likely is located ~0.34 AU from each star (see Section 4.5).

An absolute minimum requirement for this model to work is that the far-UV luminosity be sufficient to produce the observed [O I] luminosity. To account for a given 6302 Å [O I] luminosity, Rigliaco et al. (2013) estimate that the far-UV flux must be at least 20 times the [O I] flux and find (their Equation (3)) that the average ratio of far-UV to [O I] luminosity in their sample of T Tauri stars is ~2300 times this lower limit. For LDS 5606A we use the [O I] EW given in Table 1 and a (rather uncertain) R-band magnitude of 15.2 (see entries in VizieR) for the continuum to obtain the [O I] luminosity. The combination of the GALEX far-UV and near-UV channels from 1344 to 2616 Å (the photodissociation wavelength of OH)—yields a far-UV luminosity that is ~550 times the [O I] luminosity. The effective far-UV luminosity for OH photodissociation by Lyα photons could be an order of magnitude larger than the α effective far-UV luminosity for OH photodissociation by Lyα T Tauri stars given in Rigliaco et al. (2013). Because the HIRES is at the low end of the range (1–8) of ratios for classical T Tauri stars listed in Table 4 of Rigliaco et al. (2013). For the 6302 Å line in LDS 5606A, with a Gaussian fit, we measure 14.3 km s−1 and for the 5579 Å line 8.4 km s−1; these linewidths have been corrected for instrumental broadening. The stars in Table 4 of Rigliaco et al. that best match the lack of blueshift and small width of the [O I] lines in LDS 5606A are TW Hya and DR Tau whose orbiting disks have small (7') and moderate (37') inclination angles, respectively, with respect to the line of sight. Perhaps the disk at LDS 5606A also has a small inclination angle so that we are observing it nearly face-on. The contrast between the emission line patterns seen in LDS 5606A and TWA 30 (described in Section 4.6.1), would be consistent with a near face-on disk at LDS 5606A. The apparent correlation between FWHM and inclination angle in the entries in Table 4 of Rigliaco et al. (2013) suggest that disk inclination is a significant factor contributing to the relative [O I] linewidths seen among classical T Tauri stars.

4.5. Dust and Gas Abundances

In this section we estimate a minimum mass of dust around each member of LDS 5606 by assuming thin shells of small particles at distances from the stars set by their SEDs (Figures 9 and 10). For LDS 5606A the 900 K and 215 K dust particles absorb 7.2% and 4.7% of the starlight, respectively. For blackbody particles the 215 K dust is about 18 times farther from the star than the 900 K dust, so the minimum total mass of the cooler particles is about 300 times that of the hotter. Thus, the calculations to follow pertain to the ~220 K dust at both LDS 5606A and B and we refer to the star simply as LDS 5606.

We first estimate how far from LDS 5606 ~220 K blackbody dust particles would lie. The effective temperature and luminosity of LDS 5606 are about 2880 K and 0.012 L⊙ (Rodriguez et al. 2014). Then the radius of LDS 5606 is ~0.44 R⊙. The orbital semi-major axes (Rd)HB of blackbody particles is given by

\[ (R_d)_{HB} = (R_\ast/2)(T_\ast/T_d)^{3/2}, \]

where \( R_\ast \) and \( T_\ast \) are the radius and effective temperature of the central star and \( T_d \) is the particle temperature at \( (R_d)_{HB} \). With the above \( T_\ast \) and \( R_\ast \) for LDS 5606 and 220 K dust particles, then \( (R_d)_{HB} = 0.17 \) AU.

Figure 9 in Rodriguez & Zuckerman (2012) indicates that for thermally emitting dust particles seen at debris disks, the true particulate semi-major axis, \( R_d \), is typically about twice \( (R_d)_{HB} \), or for LDS 5606, ~0.34 AU.

A minimum dust mass can be estimated by assuming that the entire infrared luminosity is due to absorption of starlight by grains of radius a equal to \( \lambda_{peak} \) divided by \( 2\pi \), where \( \lambda_{peak} \) is the wavelength at peak stellar emission. For LDS 5606, \( \lambda_{peak} \)
is about one micron and thus a is \( \sim 0.2 \, \mu m \). At this optimum size, particles absorb starlight approximately as blackbodies; if a is substantially larger or smaller, then particle opacity per unit mass will be smaller.

The minimum dust mass \( (M_{\text{min}}) \) required to account for the luminosity of 220 K dust particles is

\[
M_{\text{min}} = \frac{16\pi}{3}\tau\rho(a)(R_\oplus)^2, 
\]

where \( \rho \) is the density of an individual grain (e.g., Chen & Jura 2001) and \( \tau = L_{\text{ir}}/L_{\text{bol}} \) is the infrared luminosity. With \( \rho = 2.5 \, \text{g} \, \text{cm}^{-3} \), \( M_{\text{min}} \sim 10^{21} \, \text{g} \). By comparison, the mass of the largest asteroid, Ceres, is \( 10^{24} \, \text{g} \).

There is no evidence for dust colder than 200 K and indeed such dust may not exist since it often does not for young stars that are members of wide binary systems (e.g., HD 15407; Melis et al. 2010). Therefore, we first estimate whether it would be possible for APEX to have detected optical thick \( J = 3-2 \) CO emission from a region around LDS 5606 with radius 0.34 AU. That is, we assume coexisting gas and dust at a common temperature of 220 K. A face-on disk of radius 0.34 AU at 65 pc will subtend a diameter of 0.01 to be compared to the APEX beam diameter of 17". The beam averaged CO brightness temperature would then be \( \sim 0.1 \, \text{mK} \), far smaller than the measured rms values of 7.2 and 5.5 mK for the western and eastern stars (see Section 2). Thus, the regions around the two stars that are known to contain dust would be invisible to APEX even if CO \( J = 3-2 \) emission is optically thick.

Optimistically, one might assume a dust extent at LDS 5606 analogous to that of the young K8-type star TW Hya. The bolometric luminosity of TW Hya, 53 pc from Earth, is \( \sim 0.26 \, \text{L}_\odot \) (Ducourant et al. 2014). The radius of the CO emission region at TW Hya is \( \sim 5" \) (Rosenfeld et al. 2012). Scaling by the relative parallaxes and bolometric luminosities, one could thus anticipate a CO emission region at LDS 5606 of radius \( \sim 0.8" \), and a CO brightness temperature smaller by a factor of \((0.8/5.0)^2 \) than that at TW Hya. The peak CO \( J = 3-2 \) flux density at TW Hya measured with APEX is \( \sim 30 \, \text{Jy} \) (J. Kastner 2014, private communication). With a conversion factor of 41 Jy K\(^{-1}\), the TW Hya CO \( 3-2 \) brightness temperature is 0.7 K, yielding a potential measured CO temperature of \( \sim 20 \, \text{mK} \) at LDS 5606; this is about three times the rms given in the previous paragraph. Thus, about all we can say at this point is that if a disk at LDS 5606 exists far beyond the region that contains 220 K dust, then the LDS 5606 disk is not much richer in CO than is the one that orbits TW Hya.

### 4.6. Comparison of LDS 5606 with other Young, Dusty, Nearby Stars

In the present section, we consider some young dusty stars that display some important similarities and differences with LDS 5606.

#### 4.6.1. TWA 30

The visual binary star TWA 30 (Looper et al. 2010a, 2010b) bears some striking similarities and differences in comparison to LDS 5606. Both systems are composed of stars of similar spectral types (\( \sim M5 \)) and with large projected separations in the plane of the sky, \( \sim 1700 \, \text{AU} \) for LDS 5606 and \( \sim 3400 \, \text{AU} \) for TWA 30. TWA 30 is a member of the \( \sim 8 \, \text{Myr old TW Hydrae Association} \) while LDS 5606 is a member of the \( \sim 20 \, \text{Myr old} \) Pictoris moving group. Unlike LDS 5606A, neither TWA 30A nor 30B appear in the GALEX catalog.

The optical-infrared SEDs of the less dusty of the two stars in each system are remarkably similar. TWA 30A has 210 K dust with an infrared luminosity \( \tau = 2.4\% \) (Schneider et al. 2012), while the dust at LDS 5606B has a temperature of 220 K and \( \tau = 6.3\% \) (Figure 10). The dust emission at TWA 30B can be decomposed into two components of 190 and 660 K (Schneider et al. 2012; Looper et al. 2010a), similar to our dust temperature decomposition at LDS 5606A of 215 and 900 K (Figure 9). The principal difference in the SEDs of TWA 30B and LDS 5606A is that the optical light in the former is largely extinguished by the nearly edge-on dust disk (Looper et al. 2010a; Schneider et al. 2012).

The optical spectra of TWA 30A and 30B and of LDS 5606A contain many emission lines, but only a few lines are common to the TWA stars and LDS 5606A. The spectra of both TWA stars are dominated by forbidden emission lines whereas permitted emission lines characterize the LDS 5606A spectrum. The only forbidden lines in the LDS 5606A spectrum are the two [O\,I] lines discussed in Section 4.4; their FWHM \( \sim 10 \, \text{km} \, \text{s}^{-1} \), are much narrower than the [O\,I] 6302 Å lines in both TWA 30A and 30B (\( \sim 100 \, \text{km} \, \text{s}^{-1} \)). TWA 30A displays very weak He\,I 5877 Å emission and TWA 30B displays no optical He line emission at all, in contrast to the many and strong helium lines in LDS 5606A.

Looper et al. (2010a, 2010b) interpret the TWA 30 spectra as due to a disk seen edge-on in the case of TWA 30B and nearly edge-on in the case of TWA 30A. The many and broad forbidden lines in the optical spectra of both stars are produced in strong outflows nearly in the plane of the sky. The edge-on disks obscure the regions near the base of the accretion flows, regions that are responsible for the strong permitted lines expected in the magnetospheric model and seen in many T Tauri stars. By contrast, as mentioned in Section 4.4, the orientation of the dusty disk at LDS 5606A is more likely to be nearly face-on than edge-on. This enables the optical helium and hydrogen lines to be seen. In addition, the general absence of forbidden line emission indicates that any outflow at LDS 5606A is much weaker than at the TWA 30 stars. As discussed in Section 4.4, the two oxygen forbidden lines detected in both LDS 5606 stars are likely formed by photodissociation of OH in its circumstellar disk and probably not in an outflow.

The relative X-ray properties of TWA 30 and LDS 5606 are considered in Section 3.3 of Rodriguez et al. (2014).

#### 4.6.2. V488 Per

V488 Per is a K-type member of the 60 Myr old \( \alpha \) Persei cluster. It is surrounded by a dusty disk with infrared SED similar to that of LDS 5606A (Zuckerman et al. 2012). The dust at V488 Per can be decomposed into components of temperatures 120 and 820 K with \( \tau = 16\% \). These values are similar to those of LDS 5606A, 215 and 900 K and \( \tau = 11.9\% \) (Figure 9). Along with LDS 5606B, with \( \tau = 6.3\% \) (Figure 10), these three stars have the largest fractional infrared luminosities of any known dwarf stars with ages \( > 10 \, \text{Myr} \). V488 Per is probably a member of a wide triple system (B. Zuckerman, in preparation).

Unlike LDS 5606A, and notwithstanding the 820 K dust, the optical spectrum of V488 Per is quite bland. The He line EW—measured from a high-quality HIRES spectrum obtained on UT 1997 December 12 by Dr. I. N. Reid and available from the Keck Observatory Archive—is 280 mA in absorption. The spectrum covers the range between 6340 and 8725 Å; the only emission lines to be seen are the self-reversed cores of the Ca IR triplet. Thus, the physical conditions near the two stars are quite
different. Zuckerman et al. (2012) suggest that the hot dust seen at V488 Per is a result of a collision of two planetary embryos.

The SEDs out to 22 μm at TWA 30B, V488 Per, and LDS 5606A can all be decomposed into two distinct temperature dust components, one quite hot and the other of moderate temperature. The SEDs at wavelengths longer than ∼ 5606 Å can all be decomposed into two distinct temperature components—one quite hot (700–900 K) and the other cooler (100–200 K)—as if the dust is divided by planets forming in a region with temperature similar to Earth in orbit around all three stars.

4.6.3. V4046 Sgr

V4046 Sgr is a 2.4 day period binary composed of two K-type stars. Like LDS 5606, it is a member of the β Pic moving group (Torres et al. 2008). The SED shows no evidence for dust hotter than about 200 K (Hutchinson et al. 1990; Jensen & Mathieu 1997; Rosenfeld et al. 2013). Nonetheless, with the UVES echelle spectrometer on the VLT, Stempels & Gahm (2004) detected strong emission lines from the Balmer series of hydrogen up to at least H16 and also the Ca II H- and K-lines, as well as weak emission lines of He I at 5877 Å and of [O I] at 6302 Å. They deduced the presence of a weak veiling continuum that contributes about one-third of the total observed flux between 3500 and 4000 Å, decreasing to about 10% of the total flux between 6000 and 6700 Å. Thus, some accretion appears to be ongoing, but because of complex dynamics induced by the close binary (de Val-Borro et al. 2011; Sytov et al. 2011; Donati et al. 2011), it is hard to compare this system with LDS 5606A.

5. CONCLUSIONS

We have identified an unusual low-mass binary star, LDS 5606, that Rodriguez et al. (2014) classify as a member of the β Pictoris moving group. The western member of the system (LDS 5606A) is still actively accreting material from an orbiting dusty disk ∼ 20 Myr after its central star began to form—this is more than twice as old as the oldest low mass stars previously known with measurable accretion signatures. These include both members of the 8 Myr old binary star TWA 30 (Looper et al. 2010a, 2010b) that appear both remarkably similar to and yet different from LDS 5606A.

All four members of these two wide-separation binary stars are among the most infrared luminous dwarf stars (in the sense of large LIR/L* currently known in astronomy. LDS 5606 thus can be added to a remarkable collection of nearby “old” and very dusty T Tauri type and more massive stars that are members of wide (of order 1000–10,000 AU) multiple star systems. In addition to LDS 5606 and TWA 30, these include TW Hya, Hen 3-600, HD 98800, HD 15407, V4046 Sgr, HR 4796, T Cha (Kastner et al. 2012), and probably V488 Per. The infrared SED of individual members of at least three of these systems (LDS 5606A, TWA 30B and V488 Per) can be fit with dust at two distinct temperatures—one quite hot (700–900 K) and the other cooler (100–200 K)—as if the dust is divided by planets forming in a region with temperature similar to that of Earth.

In their Conclusion section, Kastner et al. (2012) speculate about timescales for planet formation in hierarchical multiple systems and whether the presence of a wide binary or tertiary companion can have profound effects on planet building processes in close proximity to one or multiple members of such systems. The ensemble of such old systems now known may be sufficiently large that calculations of Kozai-driven evolution might be revealing.

APPENDIX

As noted in Section 2, the HIRES wavelength coverage is not continuous over the entire range of wavelengths discussed in this paper. Thus, some transitions—notably the Na I doublet near 8190 Å—fall in holes in our coverage and their absence in Tables 1–4 should not be taken to indicate that they are not present in the spectra of LDS 5606 (they clearly are present in the UVES spectra, Table 6). Table 9 summarizes the HIRES wavelength coverage during the three nights of observation of our program.

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