EVIDENCE OF PLANETESIMAL INFALL ONTO THE VERY YOUNG HERBIG Be STAR LkHα 234

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ABSTRACT
We report here the first evidence of planetesimal infall onto the very young Herbig Be star LkHα 234. These results are based on observations acquired over 31 days using spectroscopy of the sodium D lines, the He i 5876 Å line, and hydrogen Hα lines. We find redshifted absorption components (RACs) with velocities up to 200 km s⁻¹ and very mild blueshifted emission components (BECs) up to 100 km s⁻¹ in the Na i lines. No correlation is observed between the appearance of the Na i RACs and BECs and the Hα and He i line variability, which suggests that these (Na i RACs and BECs) are formed in a process unrelated to the circumstellar gas accretion. We interpret the Na i RACs as evidence for an infalling evaporating body, greater than 100 km in diameter, which is able to survive at distances between 2.0 and 0.1 AU from the star. The dramatic appearance of the sodium RACs and mild BECs is readily explained by the dynamics of this infalling body, making LkHα 234 the youngest (age ~ 0.1 Myr) system with evidence for the presence of planetesimals.

Subject headings: circumstellar matter — stars: formation — stars: individual (LkHα 234) — stars: pre–main-sequence

1. INTRODUCTION

LkHα 234 (m_i = 11.9 mag) is a star embedded in a nebula associated with the NGC 7129 star-forming region and is at a distance of about 1250 pc. This is one of the youngest known Herbig Be objects and has an age of ~0.1 million years and spectral type of B5 (Fuente et al. 2001). Herbig Ae/Be stars are intermediate-mass (2–10 M⊙) pre–main-sequence stars (Herbig 1960). A number of Herbig Ae stars have been found to possess circumstellar disks and show both photometric and spectroscopic variability (Herbst & Shevchenko 1999). LkHα 234, although much hotter and more massive, also exhibits these properties (Fuente et al. 2001; Herbst & Shevchenko 1999; Polomski et al. 2002). The star shows photometric variability of 1.5 mag in the V band and is known to possess a circumstellar disk with the disk mass to stellar mass ratio (M_d/M_*) ≤ 0.02. A detailed description of LkHα 234 and its circumstellar region can be found in Fuente et al. (2001 and references therein).

Spectroscopic variations in metallic lines (like Na i, Ca ii, etc.) in young A-type stars like β Pictoris (20–100 million years) are often interpreted as the signature of star-grazing comets or falling evaporating bodies with sizes of tens of kilometers (Grinin et al. 1996; Smith & Terrile 1984; Thebault & Beust 2001). The only Herbig Be star where grazing cometary transient events have been inferred so far is HD 100546 (Viera, Pogodin, & Franco 1999). However, HD 100546 is much older (≥10 Myr) and cooler (spectral type ~B9) compared to LkHα 234. High-resolution spectroscopic monitoring of very young (0.1–1 Myr) Herbig Be stars are scanty and uncharted.

Here we report dramatic variations in the spectroscopic lines of Na i 5890 Å (D2) and 5896 Å (D1), He i 5876 Å, and Hα of LkHα 234 over a period of 31 days during 2003 October–November. The observations consist of high-resolution spectra (R = 30,000) from the Hobby-Eberly Telescope (HET) using the High Resolution Spectrograph (HRS). Section 2 describes the observations, in § 3 we discuss the results, and § 4 gives the conclusion.

1 Based on observations from the 9.2 m Hobby-Eberly Telescope.

2. OBSERVATIONS

We have obtained high signal-to-noise ratio and high-resolution spectra (R = 30,000, ~0.2 Å) of LkHα 234 covering the He i 5876 Å line, the Na i D2 and D1 lines, and the Balmer Hα line at 6563 Å. The observations were taken with the 9.2 m HET (Ramsey et al. 1998) using its HRS (Tull 1998). The echelle spectral orders were optimized to cover the wavelength range between 5700 and 6750 Å. This allowed the spectral lines of interest to be recorded by the “blue” CCD of the spectrograph that has a fewer number of bad pixels than the “red” CCD. The results consist of five data sets over a time period of 31 days. The observation dates were 2003 October 7, 13, 23, and 27 and 2003 November 8. On each night of observation, three 10 minute exposures on LkHα 234 were taken, which were combined to get high signal-to-noise ratio (S/N = 70–100). All data were reduced using standard IRAF routines under ECHELLE tasks. Every spectrum was bias subtracted and flat-fielded. Spectral calibrations were done using thorium-argon lamp spectra taken either immediately before or after the observations. We found that the wavelength calibration is accurate up to 0.05 Å.

Hα (6563 Å), He i 5876 Å, and Na i D2 and D1 spectral lines are shown in Figures 1 and 2, respectively, and the dates of observations are noted alongside the spectra. The x-axis is in terms of relative velocity (in units of kilometers per second) with respect to the center of the lines in the stellar rest frame, and the y-axis shows line intensities normalized with respect to the stellar continuum. In Figure 2, the zero of the relative velocity scale is with respect to the stellar rest frame of the sodium D2 line.

3. RESULTS AND DISCUSSION

3.1. Gaseous Accretion

We illustrate in Figure 1 the variability in Hα and He i lines. These are seen as stellar photospheric absorption lines in the spectra observed on 2003 October 7. However, in all the following days of observations the Hα appeared to be in emission consisting of two components, the redshifted emission component (REC) and the blueshifted emission component (BEC).
The Hα equivalent width varied from +3 Å (on October 7) to −50 Å (October 13) in just 6 days, and it continued to rise up to −100 Å (October 27) before it decayed to −74 Å (November 8). The relative velocity between the REC and BEC varied between 150 and 225 km s\(^{-1}\), with the REC stronger than the BEC by a factor of 2.5–3.5.

The spectra obtained on 2003 October 7 do not show any sign of emission or activity in Hα or He i. This observation shows the star in a quiescent state, with neither accretion nor stellar wind affecting the absorption-line profile. The variations in the Hα line are found to correlate with the variations in the Hα. Whenever the Hα BEC and REC are strong, the Hα either fills up owing to mild emission or shows a very large absorption width (almost 1.7 times the photospheric line width). The line width varied from 150 to 260 km s\(^{-1}\). A B5 star does not have sufficient energetic photons to ionize He i (Jaschek & Jaschek 1995), so the filling up of the Hα ionization line owing to mild emission is an indicator of accretion phenomena (de Winter et al. 1999). We find the disk luminosity to be about 1% of the stellar luminosity (L = \(10^{3} L_{\odot}\)) with a maximum disk temperature of \(\sim 21,000\) K, if we consider an accretion rate of \(10^{-7} M_{\odot}\) yr\(^{-1}\) (Natta, Grinin, & Mannings 2000a).

Therefore, the double-peak Hα (REC and BEC) profiles and the He i mild emission are because of orbiting accreting gas onto the star as well as outflow of circumstellar gas (the BEC in Hα is due to accretion heat). However, when the accretion luminosity is not strong enough to produce enough ionizing photons, the Hα line appears as a very broad absorption feature. The broad absorption feature is the effect of the combination of the stellar photospheric line and various unresolved circumstellar gas components corresponding to the REC and BEC of Hα.

The effects of gaseous accretion are probably also seen on the nebular emission lines. We found a correlation between the total equivalent width in Hα and the peak nebular emission in Hα and Na i. Figures 1 and 2 show that the nebular Hα and Na i lines were of minimal intensity (\(\sim 1.06\) above the continuum) on October 7. The same lines are strongest (Hα \(\sim 7.9\) on the blue wing of the REC, and Na i D2 line \(\sim 3.0\)) on October 27, when the Hα equivalent width is maximum (−100 Å). We plan to model the impact of the episodic accretion on the nebula using a photoionizing code (e.g., the CLOUDY code), which will be published along with the entire spectra of LkHα 234 elsewhere in the near future.

### 3.2. Planetesimal Infall

Figure 2 shows the variability in the Na i D2 and D1 lines. Redshifted absorption components (RACs) were observed in the Na i lines on only one night (2003 October 13) with a maximum redshifted velocity of 200 km s\(^{-1}\). The RACs associated with both Na i lines are of similar depth (for redshifts \(\leq 100\) km s\(^{-1}\)), which is an indicator of saturation (unshielded Na i column density \(= 10^{13} \text{ cm}^{-2}\); de Winter et al. 1999). However, the maximum depth of these components is about 30% of the stellar continuum, implying partial coverage of the stellar photosphere. In addition to Na i RACs, very mild BECs (60–100 km s\(^{-1}\) and 1.05–1.07 above the continuum) are also seen on the October 13 spectra. The variations in He i and Hα are observed even when no Na i RACs and BECs are seen (see Figs. 1 and 2). Thus, the appearance and disappearance of the Na i RACs and BECs are uncorrelated with the variations in Hα and He i line profiles. We conclude that we witnessed a transient phenomenon on 2003 October 13 whose effects lasted a few days at most.
From the Keplerian dynamics of an infalling object (Beust, Karmann, & Lagrange 2001), the most redshifted Na absorption component velocity (200 km s$^{-1}$) should correspond to a distance of 0.1 AU from the star. At this distance, both the number of ionizing photons and intensity of the stellar wind will be too high for any unshaded Na to survive (Sorelli, Grinin, & Natta 1996). Their calculations using photoionizing codes under local thermodynamical equilibrium (LTE) and non-LTE show that only a solid body like a comet or asteroid can approach a hot star this close before it disintegrates and evaporates. Furthermore, theoretical model calculations for stars up to B9 show that the size of solid bodies that are able to survive up to a distance of 0.1 AU should be at least 100 km in diameter (Beust et al. 2001). The mild Na BEC could then be part of the falling evaporating body being blown away by the stellar wind or radiation pressure. However, this would also mean that the falling solid body may have a high eccentric orbit so that the blown away material is not projected against the stellar surface. Our Na RAC and BEC observations are consistent with such an object dissociating between 2 and 0.1 AU from the B5 star LkHα 234.

In many Herbig Ae stars, variations in Na RACs and BACs usually correlate with Hα and He i variations (de Winter et al. 1999; Grinin et al. 1996). Such Na i variations are now thought to be generated by magnetohydrodynamic funneling of neutral gas onto the star rather than solid body infall (Beust et al. 2001; Mora et al. 2002; Natta, Grinin, & Tambovtseva 2000b). No such correlation is present in the current LkHα 234 data set. Of particular significance is the observation on 2003 October 27, when the REC and BEC of Hα are the strongest. The absence of any Na i RAC and BEC in this observation is a strong argument against the Na i line variations being caused by neutral matter funneled onto the star by magnetic fields. The variability of Hα and He i in LkHα 234 are due to episodic gas accretion, while the observed variation in the Na i lines is a transient event that exhibits the dynamical signature of a body (≥100 km in diameter) falling onto the star. It is worth mentioning here that recent studies on meteors from cometary origin by Trigo-Rodríguez, Llorca, & Fabregat (2004) have shown greater sodium abundances than those expected for interplanetary dust particles and chondritic meteorites, and Potter, Killen, & Morgan (2002) have detected a comet-like sodium tail from planet Mercury. Also, the presence of a sodium tail in comets was discovered (Cremone et al. 1997). Thus, an infalling solid body of asteroid size and deficient in H can produce the observed Na i RAC and BEC and no correlation with the H and He i lines.

The dusty circumstellar disk of the young star LkHα 234 could be a newly formed protoplanetary disk consisting of solid bodies of different sizes (Fuente et al. 2001). Theoretical models of the formation of planetary bodies in circumstellar disks around a 1 M$\odot$ star show that planetesimals of sizes of up to a few hundred kilometers can quickly form within the first 10$^4$ yr and the typical cumulative number of such bodies can be 10$^5$–10$^6$ between 0.5 and 1.5 AU from the star (Lissauer 1993; Weidenschilling et al. 1997). While such numbers are not known for B-type stars, LkHα 234 (age ∼ 0.1 Myr) may have a high frequency of infall events (Grady et al. 2000).

4. CONCLUSION

We have presented here high-resolution spectroscopic monitoring of the Herbig Be star LkHα 234 in the Na i (D2 and D1), He i (5876 Å), and Hα lines. We found no correlations between the Na i and the He i and Hα line variability in the five data sets over a period of 31 days (2003 October 7 to 2003 November 8), although we do find a correlation between He i and Hα. Thus, the origin of variation in the Na i line (RAC up to 200 km s$^{-1}$ and BEC up to 100 km s$^{-1}$) seen only on 2003 October 13) is different from those of Hα and He i. While the Hα and He i line variations are due to episodic gaseous accretion, the Na i RACs indicate a dramatic transient event of solid body infall onto the star and the BECs the blown away parts of the solid body not projected against the stellar surface. Considering the Keplerian dynamics and the harsh environment of a B5 star, we estimate that a solid body of size ≥100 km broke up and integrated at a distance between 0.1 and 2.0 AU from the star. This makes LkHα 234 the youngest system (<0.1 Myr) with evidence for protoplanetary bodies of asteroidal size. We plan to pursue further spectroscopic monitoring of the star with the HET to determine the frequency of such events and further understand the complicated dynamics of this very young circumstellar environment.

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REFERENCES

Beust, H., Karmann, C., & Lagrange, A. M. 2001, A&A, 366, 945
Cremone, G., et al. 1997, ApJ, 490, L199
de Winter, D., Grady, C. A., van den Ancker, M. E., Pérez, M. R., & Eiroa, C. 1999, A&A, 343, 137
Fuente, A., Neri, R., Martín-Pintado, J., Bachiller, R., Rodríguez-Franco, A., & Palla, F. 2001, A&A, 366, 873
Grady, C. A., Sitko, M. L., Russell, R. W., Lynch, D. K., Hanner, M. S., Pérez, M. R., Bjorkman, K. S., & de Winter, D. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 559
Grinin, V. P., Kozlova, O. V., The, P. S., & Rostopchina, A. N. 1996, A&A, 309, 474
Herbig, G. H. 1960, ApJS, 4, 337
Herbst, W., & Shevchenko, V. S. 1999, AJ, 118, 1043
Jaschek, C., & Jaschek, M. 1995, The Behavior of Chemical Elements in Stars (Cambridge: Cambridge Univ. Press)
Lissauer, J. J. 1993, AR&AA, 31, 129
Mora, A., et al. 2002, A&A, 393, 259
Natta, A., Grinin, V. P., & Mannings, V. 2000a, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 613
Natta, A., Grinin, V. P., & Mannings, V. 2000b, ApJ, 542, 421
Polomski, E. F., Teleseco, C. M., Piñar, R., & Schulz, B. 2002, AJ, 124, 2207
Potter, A. E., Killen, R. M., & Morgan, T. H. 2002, Meteoritics Planet. Sci., 37, 1165
Ramsey, L. W., et al. 1998, Proc. SPIE, 3352, 34
Smith, B., & Terrile, R. 1984, Science, 226, 1421
Sorelli, C., Grinin, V. P., & Natta, A. 1996, A&A, 309, 155
Thebault, P., & Beust, H. 2001, A&A, 376, 621

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Trigo-Rodríguez, J. M., Llorca, J., & Fabregat, J. 2004, MNRAS, 348, 802
Tull, R. G. 1998, Proc. SPIE, 3355, 387
Viera, S. L. A., Pogodin, M. A., & Franco, G. A. P. 1999, A&A, 345, 559
Weidenschilling, S. J., Spaute, D., Davis, D. R., Marzari, F., & Ohtsuki, K. 1997, Icarus, 128, 429