BIPOLAR JETS PRODUCED BY A SPECTROSCOPIC BINARY

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ABSTRACT

We present evidence that the spectroscopically identified bipolar jets of the pre-main sequence binary KH 15D ($P = 48.4$ d, $\epsilon \sim 0.6$, periastron separation $\sim 18\,R_A$, $M_A = 0.6\,M_\odot$, $M_B = 0.7\,M_\odot$) are a common product of the whole binary system, rather than being launched from either star individually. They may be launched from the innermost part of the circumbinary disk (CBD) or may result from the merging of two outflows driven by the individual stars. This evidence is based on high-resolution Hα and [O I]λ6300 line profiles obtained during eclipse phases of this nearly edge-on system. The occultation of star A (the only currently visible star) by the disk strongly suppresses the stellar Hα and continuum emission and allows one to study the faint redshifted and blueshifted emission components of the bipolar jets. The strongest evidence for jet production by the whole binary system comes from the observed radial velocity symmetry of the two jet components relative to the systemic velocity of the binary in combination with current accretion models from the CBD onto a binary system.

Key words: binaries: spectroscopic – circumstellar matter – ISM: jets and outflows – stars: individual (KH 15D) – stars: pre-main sequence

1. INTRODUCTION

The models proposed for driving jets and outflows from young stars can be roughly categorized as disk-driven outflows (e.g., Pudritz et al. 2007), X-winds (e.g., Shang et al. 2007), and stellar wind-driven flows (e.g., Matt & Pudritz 2008). In all of these models, the young star is surrounded by a circumstellar disk with an outer radius of about 10–100 AU and an inner radius of only a few stellar radii. So far it has not been investigated whether any of these models can be applied to a close binary system such as KH 15D, where the spectroscopic signature of a bipolar outflow has been found in the [O I]λ6300 line (Hamilton et al. 2003). A small-scale bipolar jet of $\sim$70 AU length in [S II]λ6731 is also known for the close 19 d T Tauri star (TTS) binary UZ Tau E (Hirth et al. 1997), and the [O I]λ6300 line profile of the 15.8 d TTS binary DQ Tau of Huerta et al. (2005) suggests that this system also drives an outflow. In this Letter, we discuss for the first time simple possible models for jet formation in close TTS binary systems and hope that our Letter will initiate detailed theoretical and observational studies of this challenging astrophysical problem.

In recent years, KH 15D (age $\sim$ 2 Myr, $d = 760$ pc) has been the subject of many detailed observational and theoretical studies (e.g., Winn et al. 2006; Herbst et al. 2008 and references therein). It first got attention for its unique photometric variability with deep and practically gray eclipses every 48.4 days that have become deeper and wider with each passing year (Hamilton et al. 2005; K. LeDuc et al. 2010, in preparation). As discussed in these references, the following model describes the available data. A nearly edge-on binary system is surrounded by a circumbinary disk (CBD) which is inclined to the binary plane by $\approx$10°–20° (Winn et al. 2004; Chiang & Murray-Clay 2004). For more than a decade the CBD has been totally occulting the orbit of star B and has been increasingly occulting that of star A. This is due to its precession on a $\sim$10³ yr timescale, which causes

the occulting edge to cover the orbit of the binary. During the epoch of observations discussed here, only eclipses of star A are observed, which result from the disappearance of this star behind the occulting edge. Without this sharp edge acting as a "natural coronagraph" it would have been practically impossible to trace in Hα or [O I] the much fainter emission from the outflowing gas analyzed here.

2. OBSERVATIONS

The high-resolution spectra analyzed here have been obtained during various observing runs with UVES at the VLT ($R \sim 50{,}000$, slit width 0″8–1″0) and with HIRES at Keck ($R \sim 70{,}000$, slit width 0″8). A full description of the data and their reduction will be given in C. M. Hamilton et al. (2010, in preparation). At the distance of KH 15D, 1″0 corresponds to 760 AU. The observing dates of the individual spectra are indicated in Figures 1 and 2. The continuum levels of all these spectra have been calibrated onto a common flux scale by using the Cousins *I*-band fluxes that were measured simultaneously (or nearly so) in our CCD imaging campaigns. One uncertainty in this procedure is the system's $R - I$ color, since *R*-band fluxes are requested for calibration of Hα and [O I]. The $R - I$ color was calculated on the basis of the 2002/2003 data set (Hamilton et al. 2005). In the spectra presented here, any uncertainty will most probably affect only the two spectra taken at minimum light (i.e., from 2001 December 14 and 2004 March 12) since only there is the $R - I$ versus *I* correlation unreliable.

3. JET PROPERTIES DERIVED FROM [O I]λ6300 AND Hα

It is now generally accepted that the forbidden emission lines (FELs) of TTSs are an important diagnostic for their outflows close to the star on scales of 20–40 AU (Hirth et al. 1997; Hartigan et al. 1995; Eislöffel et al. 2000). The most important line for these studies is the [O I]λ6300 line, which is
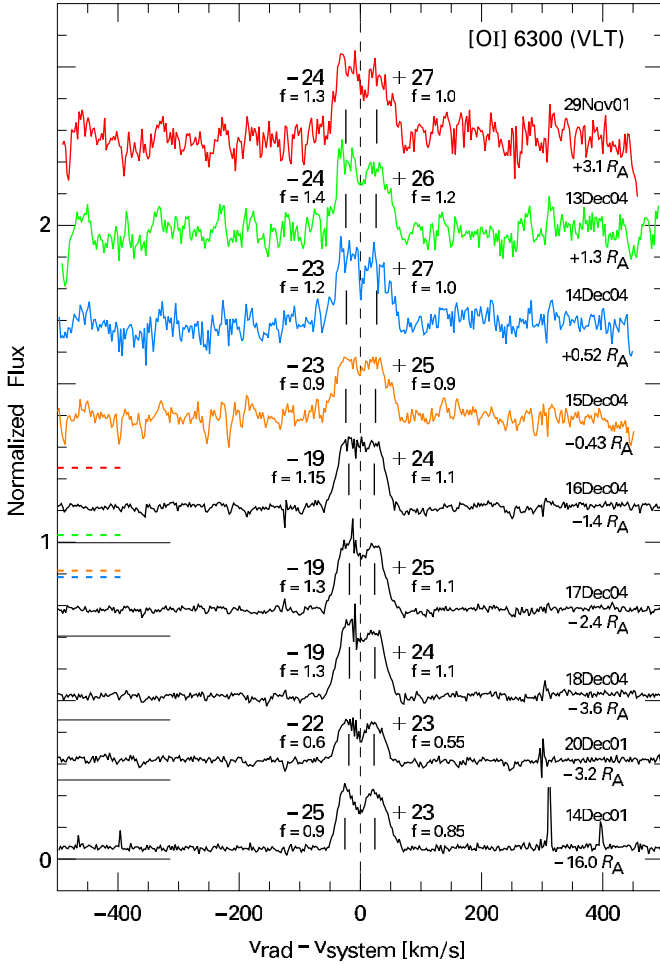
Figure 1. VLT [O I]λ6300 line profiles: the top four colored ones are taken out of eclipse (or at partial eclipse), while the five bottom ones are taken during eclipse. In order to minimize profile changes due to the stellar absorption spectrum, we have subtracted from the top four profiles a properly scaled and broadened spectrum of the K5 dwarf HD 36003. The number indicated on the right-hand side (below each profile) gives the distance between star A and the occulting edge in radii of star A (for details see Herbst et al. 2008). The zero flux levels of the profiles are indicated on the left-hand side (dashed colored lines for the four top profiles, black lines for the five bottom ones). The velocities of the jet components are indicated in km s^{-1} and are based on Gaussian component fitting. The given f-values indicate the relative fluxes of the jet components, with the top right-hand component set to $f = 1$.
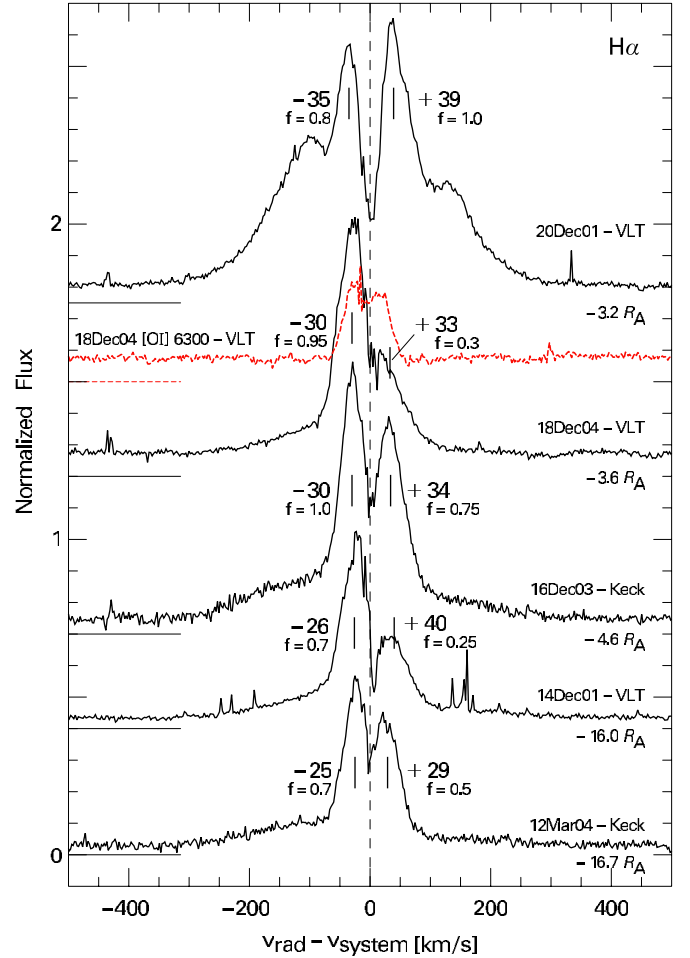
Figure 2. Sample of Hα line profiles obtained during eclipse at various observing runs at the VLT and KECK. The VLT [O I]λ6300 line profile from 2004 December 18 is shown for comparison (dotted red line). For details see the caption of Figure 1.

usually the strongest FEL in TTSs in the optical and therefore most easily observable. For KH 15D, the rather small measured out of eclipse W_λ([O I]λ6300) = 0.4–0.5 Å (which would be ∼0.2 Å if both stars would be unoccluted), compared to classical TTS (CTTS) jet sources, indicates a mass outflow rate that is ∼10 times smaller than in other CTTSs (e.g., Hartigan et al. 1995).

In principle, the Hα line is a much better diagnostic for investigating outflows on very small scales (e.g., 0.1–10 AU from the source) because it is not quenched above a certain electron density like FELs. Note that the critical density of the [O I]λ6300 line of ≈10^6 cm^{-3} is among the highest of all FELs observable in the red spectral region of TTSs. However, in most TTSs the very bright stellar (magnetospheric) Hα emission makes studies close to the star extremely difficult. For KH 15D, however the natural coronagraphic mask (see Section 1) strongly suppresses the stellar Hα emission and allows one to study the faint Hα emission from the outflow.

In Figure 1, we display all our nine UVES/VLT [O I]λ6300 line profiles. They were all taken with UVES since the HIRES spectra do not cover this line. In the top four "uneclipsed" or "partially eclipsed" profiles, the superimposed stellar absorption spectrum has been subtracted to minimize its effects on the profile shape (see the caption for details). The three 2001 profiles have already been published by Hamilton et al. (2003). In Figure 2, we show five Hα line profiles obtained with UVES and HIRES on various nights during eclipse, which are quite different compared to "uneclipsed" profiles (Hamilton et al. 2003; C. M. Hamilton et al. 2010, in preparation). In both figures, the given velocity scale is relative to the systemic velocity ($v_{hel} = 18.6$ km s^{-1}).

The nine [O I] profiles displayed in Figure 1 are very similar and only small variations are indicated. In consideration of the night sky and flux calibration uncertainties, and the additional noise in the top four profiles due to the absorption spectrum subtraction, it is unclear whether the v_{rad} values and the relative fluxes (f) shown in Figure 1 indicate any significant variation. The only exception is the profile from 2001 December 20, where the flux dropped by about a factor of 2 (see Section 5 for an interpretation). In most profiles in Figure 1, two distinct (but partly blended) peaks at ∼−22 km s^{-1} and ∼+25 km s^{-1} are visible. On the basis of the three 2001 [O I] profiles, Hamilton et al. (2003) interpreted them in terms of a bipolar jet in which the

two jet components lie close to the plane of the sky resulting in relatively small radial velocities. The Hα line profiles obtained during eclipse strengthen this interpretation, since several of them show signatures of bipolar jets similar to the [O I] line profile. A particularly nice example of a double-peaked profile is the middle one in Figure 2 from 2003 December 16. When comparing the [O I] line profiles with the Hα line profiles it is evident that the former indicate lower velocities for the bipolar jets. This could be explained by the presence of a blended and unresolved low-velocity component, which is often observed in the FELs of CTTSs, but not in Hα.

Compared to [O I] the presented Hα line profiles indicate considerable variability, particularly in the red jet component (which is often much fainter than the blue one) and in the broad Hα line wings. The data from all of our observing runs (each run sampling only a small fraction of the orbit) indicate only small variations on a 1–3 d timescale for the blueshifted jet component and larger variations only over months to years. The variations in the broad Hα wings are best illustrated by the unusual profile at the top of Figure 2, with two additional broad peaks at ∼±100 km s⁻¹ and wings extending up to ±250 km s⁻¹. Similarly broad but much fainter wings are visible in all Hα profiles, particularly on the blueshifted side. The nature of these variable Hα wings will be discussed in detail by C. M. Hamilton et al. (2010, in preparation) in terms of magnetospheric accretion using all available profiles.

To estimate the full opening angle α of the jets and the angle, i_{jet}, between the flow axis and the line of sight we only consider the Hα line profiles, because the [O I] profiles could be blended with an unresolved low-velocity component (see above). For this purpose, we assume that the jets can be approximated by a homogeneously emitting cone. We will use v_{rad} and FWHM values of the Hα profile from 2003 December 16 to derive i_{jet} and α from Equation (5) of Mundt et al. (1990). In this profile, the two peaks are at -30 km s⁻¹ (FWHM = 39 km s⁻¹) and +34 km s⁻¹ (FWHM = 48 km s⁻¹). If one assumes a jet velocity, v_{jet}, of 200 (100) km s⁻¹ one derives $i_{jet} = 81°(71°)$ for $| v_{rad} |= 32$ km s⁻¹ and α values of 13°(26°) and 16°(33°) for the redshifted and blueshifted jets, respectively.

4. POSSIBLE JET LAUNCHING MODELS

Before discussing possible models, we like to remind the reader that [O I]λ6300 emission in TTSs with small-scale jets is usually extending over 10–30 AU (e.g., Hirth et al. 1997). We call this spatial extend L_{em}, which is the length over which most of the light from the jet is emitted. Since the KH 15D jet has probably a smaller mass flux than typical CTTSs, L_{em} in [O I] is more likely 10 AU than 30 AU (see also Section 5 for an independent estimate of L_{em}). For $v_{jet} = 100$ km s⁻¹ it takes 180 d to reach 10 AU. If one adopts for KH 15D such values, even a highly modulated outflow with $P_{bin} = 48.4$ d would not cause detectable [O I] flux variations, because the [O I] emission would be averaged out over ∼3.7 periods. Although Hα is probably formed at smaller length scales (∼2–5.5 AU; see Section 5) it is unlikely that $L_{em}(Hα)/v_{jet}$ is much shorter than the binary period and therefore one would expect only a small period modulation of the Hα flux of the jet component. These considerations are fully supported by the small [O I] flux variations indicated by Figure 1 and the lack of periodic [O I] flux and profile variations in the CTTS binaries DQ Tau and UZ Tau E (Basri et al. 1997, Huerta et al. 2005).

Due to the high eccentricity (∼0.6) of the KH 15D binary system the two stars approach as close as ∼18 R_A ($R_A =$ 1.3 $R_⊙$) during periastron, i.e., near periastron any individual circumstellar disks must be much smaller than this value due to tidal truncation. We find it of great astrophysical interest that such a close binary system can launch jets, and it remains as a large theoretical challenge to model such a system, or even closer systems like UZ Tau E. One important guidance for any launching model of the KH 15D jets is the fact that the redshifted and blueshifted jet components in Hα and [O I] show a symmetric velocity shift relative to $v_{sys} = +18.6$ km s⁻¹. In the following, we discuss two possible models which could explain this important result. In the first model, the jets are launched from the innermost part of the CBD. A problem with this idea is the large inferred inner radius of the CBD (∼0.6 AU; Herbst et al. 2008), since at this radius the CBD is rotating with only $v_{rot} \sim 45$ km s⁻¹ ($P = 145$ d, 3:1 inner Lindblad resonance). Magneto-hydrodynamic simulations (e.g., Ouyed & Pudritz 1997; Fendt 2006) for various magnetic field strengths and magnetic field configurations have shown that jet velocities of $v_{jet} \sim 1$–1.5 v_{rot} are normal, although $v_{jet} \sim 2$ v_{rot} is not unusual. This means that $v_{jet} = 100$ km s⁻¹ is not implausible and we adopt this value for the CBD launching model. According to the above i_{jet} calculations, a v_{jet} value of 100 km s⁻¹ would imply $i_{jet} = 71°$ which is roughly consistent with the inclination angle of the binary system ($i_{bin} = 83°$–92°) derived by Winn et al. (2006), in the context of a specific geometric model of the occulting edge. Better consistency might be achieved by allowing for a possible tilt (by ∼10°) between the binary plane and the innermost part of the CBD, provided that this tilt is oriented roughly along the line of sight. According to this model, binaries with shorter periods should on average have higher jet speeds. This is in accordance with the [O I] line profiles of UZ Tau E and DQ Tau, in which the edge of their blue wing indicates $v_{jet} \geqslant 150$ km s⁻¹ and $\geqslant 120$ km s⁻¹, respectively (Huerta et al. 2005).

Although the CBD jet launching idea is attractive we also consider the following second model, which produces higher jet speeds. This model requires that each of the two binary stars launches a magneto-hydrodynamically driven outflow with ∼200 km s⁻¹ from each of the circumstellar disks and that each of these two outflows is of similar mass flux and velocity. At some distance from the system, these two outflows merge to form a common jet. Whether this rather speculative idea would work in the end requires detailed modeling. One complication is the complex and unstable interaction of the magnetospheres of the two outflows which should lead to reconnection of the magnetic field lines. Since in this model the line widths of the jets should be correlated with the radial orbital motions of the individual circumstellar disks (with v_{rad} amplitudes of ∼±50 km s⁻¹), it has to be shown whether this model would agree with the small measured velocity widths of the jet components (FWHM = 40–50 km s⁻¹). This model predicts a periodic modulation of the outflow (see below), which would only be observable with an outflow tracer emitting very close to the source (i.e., $L_{em}/v_{jet} \ll P_{bin}$).

According to the models of Günther & Kley (2002), binary stars with similar masses should have similar mass accretion rates $\dot{M}_{acc}$ from their CBDs. Due to the eccentric orbit ($\epsilon \sim$ 0.6) $\dot{M}_{acc}$ should be highly modulated with the binary period ($\dot{M}_{acc,max}/\dot{M}_{acc,min} \sim 4$–5) and highest near periastron passage. Since in TTSs $\dot{M}_{outflow}$ is highly correlated with $\dot{M}_{acc}$, one would expect for KH 15D similar $\dot{M}_{outflow}$ values for the two stars, which should in addition be highest near periastron. If, quite in contrast to theoretical expectations, only one of the two stars in

the system would still drive the jets one would expect a strongly modulated outflow with a higher fraction of the matter ejected near periastron. Since at this phase each of the binary members has a rather high v_{rad} (± 50 km s^{-1} relative to v_{sys}), it would be hard to explain why the two jet components are not symmetric about a different velocity, despite the fact that the recorded jet emission traces gas ejected over several orbital periods. These considerations make it rather unlikely that the jets of KH 15D are launched from only one of the two binary stars.

5. VARIATIONS OF THE REDSHIFTED JET IN Hα

The large variations in the "eclipsed" Hα line profiles and fluxes relative to the much more stable [O I] line profiles indicate that these two lines cannot be formed in the same region. Most probably the [O I] emission traces more distant and tenuous emission. This may mean that the [O I] emission is quenched in the inner and denser Hα emission region (i.e., $N_e \gg N_{e,crit} \approx 10^6$ cm^{-3}) or that O I is largely ionized there. Whether any emission component in our spectra is modulated with the 48.4 d period cannot be answered with our data because of insufficient time sampling. A jet with 100 km s^{-1} would reach a distance of 2.7 AU within 48.4 d and, as already stated above, any periodic modulation in Hα would only be observable if L_{em} in Hα is much shorter than this value. The shortest timescale variations of the red jet component have been observed between 2001 December 14 and 20. The large flux increase of this component by a factor of 4 within 6 d cannot be explained by the flux correction uncertainties mentioned in Section 2. Perhaps they are related to the unique "accretion event" which happened on 2001 December 20 (see C. M. Hamilton et al. 2010, in preparation). This could have produced sufficient UV radiation to excite more distant neutral sections of the jet causing a corresponding increase in Hα on a small timescale. The increased UV flux might have also ionized O I causing the smaller [O I] line flux observed on 2001 December 20.

We believe that the large variations seen primarily in the redshifted Hα jet component are mainly a result of obscuration by the disk combined with variation of L_{em}. Due to variations in the outflow rate, or the above-mentioned variations in UV excitation, L_{em} for both the blueshifted and redshifted jets will change with time. If the redshifted jet is obscured by the circumstellar disk over a considerable fraction, L_{obsc}, of its emitting section, then any changes in L_{em} will cause corresponding variations. If we assume that the outer disk radius, R_{disk}, is at 5 AU (see Chiang & Murray-Clay 2004) and that the disk plane is inclined toward the line of sight by $\alpha = 15°$, then $L_{obsc} = \sin(\alpha)\, R_{disk} \sim 1.3$ AU. If one assumes that L_{em} (blue) $= L_{em}$(red) and that the jet emission rate per unit length is constant, one can derive from the observed flux ratio of f(blue)$/f$(red) $= f_b/f_r$ the ratio $L_{em}/L_{obsc} = (f_b/f_r)/((f_b/f_r) - 1)$, because $f_b/f_r = L_{em}$(blue) $(L_{em}$(red)$-L_{obsc})$. With the measured f_b/f_r values of ~ 1.3–3.2 (and ignoring the unusual profile of 2001 December 20) one derives for Hα $L_{em} \sim 2$–5.5 AU. For [O I] the average ratio f_b/f_r is 1.14. With the above equation one derives L_{em}([O I]) ~ 10 AU, which is in good accordance with the values derived for other TTSs by spectro-astrometric methods.

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