A molecular outflow driven by the brown dwarf binary FU Tau

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ABSTRACT

We report the detection of a molecular outflow driven by the brown dwarf binary FU Tau. Using the IRAM 30 m telescope we observed the CO(2-1) line as we moved away from the source position. An integrated map of the wing emission between 3 kms$^{-1}$ and 5 kms$^{-1}$ reveals a blue-shifted lobe at a position of $\sim 20''$ from the FU Tau system and at a position angle of $\sim 20^\circ$. The beam size of the observations is $1''$ hence it is not possible to distinguish between the two components of the FU Tau binary. However as optical forbidden emission, a strong tracer of the shocks caused by outflow activity, has been detected in the spectrum of FU Tau A we assume this component to be the driving source of the molecular outflow.

We estimate the mass and mass outflow rate of the outflow at $4 \times 10^{-6}$ $M_\odot$ and $6 \times 10^{-10}$ $M_\odot$/yr respectively. These results agree well with previous estimates for BD molecular outflows. FU Tau A is now the third BD found to be associated with molecular outflow activity and this discovery adds to the already extensive list of the interesting properties of FU Tau.

Key words. radio lines: ISM – stars: winds, outflows – (stars:) brown dwarfs – stars: pre-main sequence – stars: formation

1. Introduction

Young brown dwarfs (BDs) occupy the mass regime between stars and planets and are therefore significant to any theory describing activity in star forming regions. Thus they have become the subjects of increased scrutiny in recent years (Luhman 2012). Their formation mechanism is at present much debated and indeed it has been postulated that they may form by more than one mechanism (Whitworth et al. 2006). The simplest idea is that they form in the same manner as low mass stars i.e. through the gravitational collapse of substellar mass cores (Padoan & Nordlund 2004). These cores occur directly by the process of turbulent fragmentation. In this scenario, BDs are just scaled-down versions of low mass stars. Detailed studies of the circumstellar environments of young BDs provide critical constraints to different formation mechanisms and are needed to identify the dominant mechanism. In particular, if BDs form like low mass stars we expect their accretion/outflow properties to be analogous. As a low mass star forms it displays a series of ubiquitous observational properties, for example accretion disks, outflows, excess emission in the near-infrared and visual absorption.

The observational evidences gathered to date in various wavelength domains indicate that young BDs show accretion and ejection behavior similar to low mass stars. For example they demonstrate T Tauri-like accretion (Jayawardhana et al. 2003; Natta et al. 2004; Monin et al. 2010; Rigliaco et al. 2011) and both optical and molecular outflows, driven by BDs, have been detected. ISO-Oph 102 is a good example. It is an accretor with an observed accretion disk (Natta et al. 2002, 2004) and recent ALMA observations have detected millimetre sized grains in its disk (Ricci et al. 2012). Its optical jet was discovered by Whelan et al. (2005) through the spectro-astrometric analysis of the [O],6300 emission line. Forbidden emission lines (FELs) like [O],6300 are important coolants in shocks and therefore good tracers of jets. Traditionally jets from classical T Tauri stars (CTTSs) are investigated by studying their FEL regions. Phan-Bao et al. (2008) also detected a CO molecular outflow driven by ISO-Oph 102. The orientation of the blue and red lobes agreed with the optical observations.

The question of outflow activity in BDs is an important one, as a sufficiently efficient outflow activity could provide an explanation as to why the central object mass does not reach the H burning limit (Bacciotti et al. 2011; Whelan et al. 2009; Machida et al. 2009). Molecular outflows are an important large-scale expression of jet launching. Indeed, molecular outflows were one of the first observational manifestations of this process to be studied (Reipurth & Bally 2001; Bachiller 1996). While giant Herbig-Haro (HH) flows are optically visible and composed of many HH objects, each group representing different episodes of mass ejection, molecular outflows begin when the powerful bipolar jets accelerate and drive outwards the molecular gas in the vicinity of their parent star. Although it is accepted that they are powered by the primary jet from the protostar, the exact way in which the jet interacts with the material is still uncertain (Cabrit et al. 1997; Downes & Ray 1999; Downes & Cabrit 2007). Molecular outflows are primarily detected in the CO molecule and thus millimeter observations have dominated the search for them. These outflows are mainly detected from Class 0 and 1 low mass stars which are still embedded in their natal material. Observations of molecular outflows driven by the more evolved Class II CTTSs are much rarer (Cabrit et al. 2011).

As of today, only two detections of molecular outflows from optically visible young BDs have been made so far (Phan-Bao et al. 2011).
et al. 2008, 2011), although it is postulated that due to the colder environment of BDs, molecular outflows may be more common than in CTTS. We have conducted a survey of young BDs with the IRAM 30m telescope in the $^{12}$CO(1-0) and $^{12}$CO(2-1) to test this hypothesis (Whelan et al. 2013, in prep.). Their approach is to target BDs known to be accreting and which also show evidence of outflow activity primarily in form of FELs, in a mass range of 0.02 $M_\odot$ to 0.13 $M_\odot$, including a few very low mass stars (VLMSs). In this letter we report the detection of a remarkable molecular outflow in FU Tau, as part of our IRAM survey.

FU Tau (04'23''35.4'', +25'03''03 (03'05)) is a BD-BD binary with a projected angular separation of 5'7 or 800 AU at the distance to Taurus and a position angle (PA) of $\sim$ 145° (Luhman et al. 2009). Its membership of the Taurus molecular cloud has been known for some time (Jones & Herbig 1979) and it is situated in a relatively isolated region of the cloud. Luhman et al. (2009) give the spectral type of FU Tau A at M7.25, corresponding to a mass of 50 $M_\odot$, and the spectral type and mass of the companion at M9.5 and 15 $M_\odot$ respectively. The wide nature of the FU Tau binary challenges models which suggest that BDs form when their accretion is halted due to ejection from their natal clouds, since the system appears to have formed irrespectively of dynamical interaction with nearby stars. A further intriguing property of FU Tau A is its over-luminosity with respect to other members of the Taurus star-forming region of the same spectral type (Luhman et al. 2009; Scholz et al. 2011). The spectral energy distributions (SEDs) of both components show excess emission indicating the presence of circumstellar disks and their disks are classified as being Class II by Luhman et al. (2009). Furthermore, optical spectra clearly show that accretion is on-going in FU Tau A. Stelzer et al. (2010) estimated the mass accretion rate from both the H$\alpha$ and He I ($\lambda$5876) lines with $\dot{M}_{\text{H}\alpha}$ = 3.5 $\times$ 10^{-10} $M_\odot$ yr^{-1} and $\dot{M}_{\text{HeI}}$ = 7.5 $\times$ 10^{-10} $M_\odot$ yr^{-1}. Evidence of outflow activity comes from the detection of the [O I]λ5577 and [O I]λ6300 forbidden lines in an optical spectrum of FU Tau A (Stelzer et al. 2010). All of these facts combined show that the FU Tau system is probably a rarity amongst BDs and thus it is of considerable interest to test models describing the formation and evolution of BDs. For this reason we chose to publish the discovery of its molecular outflow separately from the global presentation of our IRAM survey.

2. Observations and Data Reduction

Observations of the CO(2-1) line emission were carried out at the IRAM 30m telescope on July 16th-18th 2011 using the EMIR receivers at 1.3mm. In a first step, deep integrations were performed towards the protostar and at a reference position located 20'' away. In a second step, in case of significant variations of the CO emission between both positions, i.e. beyond the 3σ intensity level, more extended mapping at 12'' sampling was performed. The CO emission map detected toward FU Tau is displayed in Fig 1.

Observations were carried out in Frequency Switch mode using a throw of 14.3 MHz at 1.3mm, with a phase time of 0.2 second. An autocorrelator providing us with a spectral resolution of 40 kHz was used as spectrometer. The weather conditions were rather good and stable, with system temperatures $T_{sys}$ varying between 200 and 400 K. Each position was observed so to reach a final rms of about 40 mK unless exception per velocity interval of 0.1 km.s^{-1}, after averaging both polarizations.

Pointing was checked every 1.5 to 2 hours and was found to be very stable, with pointing offsets corrections less than 3''. The telescope parameters are adopted from the IRAM webpage. At the frequency of the CO(2-1) line, the main-beam efficiency of the telescope is 0.59 and the half-power beamwidth is 11''. The intensities of the measurements are expressed in units of main-beam brightness temperature $T_{mb}$.

The data were reduced using the Continuum and Line Analysis Single dish Software (CLASS, a GILDAS software1). In some of the sources, the CO mesospheric emission line was detected close to the cloud emission, which peaks at $v_{lsr}$ $\approx$ +6 km.s^{-1}, on the red side of the spectrum. For all our observations we have adjusted a gaussian to the CO mesospheric line profile and subtracted it out. The CO mesospheric line profile is typically a few K bright, with a linewith of about 1 km.s^{-1} (CHECK), much less than the velocity range of the cloud emission and the outflow wing emission. When the outflow feature is on the blueshifted part of the line spectrum, the mesospheric CO is absolutely harmless. When the observed outflow wing is on the redshifted side, we checked that the CO mesospheric line is much narrower than the wing velocity range, hence does not hamper the detection of the latter.

Fig. 1. A Map showing the positions of the 11 spectra obtained for FU Tau. The CO(2-1) line is shown here. The scale of the grid is 0-15 kmps^{-1} and -0.6-6 K in x and y respectively. For all spectra except the (0,-20) and (+20,+20) positions, the noise is less than 40 mK. For the (0,-20) and (+20,+20) positions the noise is $\sim$ 80 mK.

3. Results and Discussion

3.1. Outflow signature

In Fig. 2 a magnified view of the wings of the CO(2-1) emission line at each point in the map of FU Tau (Fig. 1) is shown. The central (0,0) position spectrum is repeated as a dark solid line in all the plots, superimposed on the color lines observed at the other positions. As the beam is $\approx$ 11'' wide it encompasses both FU Tau A and FU Tau B. The bulk of the CO(2-1) emission comes from the cloud and is centered on the cloud velocity at

1 http://iram.fr/IRAMFR/GILDAS/
6 km.s$^{-1}$, and we search for outflow signature from variations in the CO(2-1) wing emission with respect to the emission on the central source. The outflow emission which is shifted in velocity with respect to the cloud is much fainter than the cloud emission and therefore it will be detected in the wings of the CO(2-1) emission line. Fig. 2 shows that a blue component develops in the wing as we move towards the north, with an excess wing emission seen at the (0, 20), (10, 20) and (0, 30) positions between a velocity of 3 km.s$^{-1}$ and 5 km.s$^{-1}$. There is also a hint of blue-shifted excess emission at the (0, 10) position, and a red wing appears in the 8-10 km.s$^{-1}$ range in the (0, -20) position spectrum. The detection of this excess emission strongly points to a molecular outflow driven by FU Tau. In Fig. 3 we present an integrated intensity map of the blue-shifted wing emission in the velocity range 3 km.s$^{-1}$ to 6 km.s$^{-1}$. The black squares mark the positions at which data was collected and we have superimposed an optical image (WFCAM/UKIRT) of the FU Tau binary taken from Luhman et al. (2009). The detection of the outflow in the form of a blue-shifted lobe towards the north-east is clear. Without further data, we estimate a PA of $\sim 20^\circ$ for the outflow axis.

### 3.2. Outflow Parameters

Following Bachiller et al. (1990) we compute the CO column density in the blue lobe of the outflow with the following equation.

$$N_{\text{CO}}(\text{cm}^{-2}) = 1.06 \times 10^{13} \frac{T_{\text{mb}}}{T_{\text{mb}}} \exp \left( \frac{16.5}{T_{\text{mb}}} \right) \int T_{\nu}(2 - 1) \; dv$$

Adopting a gas excitation temperature $T_{\text{mb}} \approx 15$ K, with an H$_2$/CO ratio of $10^4$ and the results of Figure 3, we compute a mass in the blue lobe of the flow of $M_{\text{B}}$ = $4 \pm 0.8 \times 10^8 M_{\odot}$.

If we suppose that the momentum of the underlying jet has entirely been transferred to the molecular component that we observe today, we can write:

$$M_{\text{B}}(\text{H}_2) \times v_{\text{max}} = M_{\text{jet}} \times v_{\text{jet}} \times \tau_{\text{dyn}}$$

We measure $v_{\text{max}} = 3$ km.s$^{-1}$, and we take a canonical value $v_{\text{jet}} = 100$ km.s$^{-1}$; together with $\tau_{\text{dyn}} = 200$ yr (see § 3.3, first paragraph), we obtain a mass loss rate for the blue-shifted lobe of $M_{\text{out}} = 6 \pm 1.3 \times 10^{-10} M_{\odot}$/yr. This value can be modified by various factors. For instance, we can adopt a correction factor to take into account the fact that the jet might have been episodic in the past. (Phan-Bao et al. 2011) use a factor of 10 for this purpose. Also, the excitation temperature is uncertain although the $T_{\text{mb}} \exp(16.5/T_{\text{mb}})$ factor does not vary much over $T_{21} = 10 - 25$ K range. We could also take into account extinction effects and the fact that we are only measuring half of the flow emission. Thus this value must be taken as a first order estimation of the outflow rate and most probably underestimates the rate of the underlying jet. The outflow parameters are summarized in Table 1.

### 3.3. Outflow powering source

Although we cannot disentangle FU Tau A from FU Tau B it is most likely that the outflow is driven by the primary as forbidden emission associated with the primary has already been detected (Stelzer et al. 2010). Thus for the rest of the discussion we will assume that FU Tau A is the driver of the outflow. The peak of the blue lobe is measured at $\sim 20''$ from the central source, projected on the plane of the sky. Adopting a projection angle of 60" (Stelzer et al. 2013), the linear distance is $\approx 50''$, corresponding to 7000 AU at the distance of Taurus (140 pc). At 100 km.s$^{-1}$, this yields a dynamical age $\tau_{\text{dyn}} \approx 200$ yrs for the observed outflow event.

Previous to the results presented here, ISO-Oph 102 and MHO 5 with masses of 60 $M_{\text{Jup}}$ and 90 $M_{\text{Jup}}$ were the lowest mass objects for which molecular outflows were detected (Phan-Bao et al. 2008, 2011). The outflow mass and mass outflow rate were estimated at $M_{\text{out}} = 1.6 \times 10^{-5} M_{\odot}$; $M_{\text{out}} = 1.4 \times 10^{-9}$ $M_{\odot}$/yr and $M_{\text{out}} = 7.0 \times 10^{-5} M_{\odot}$; $M_{\text{out}} = 9.0 \times 10^{-10} M_{\odot}$/yr respectively. Thus our estimates of the mass and mass outflow rate of the FU Tau outflow agree with previous results and are in line with the fact that FU Tau A has the smallest mass of the three objects. The derived values of $M_{\text{out}}$ are also consistent with $M_{\text{out}}$ measured for the optical components of BD outflows (Whelan et al. 2009). For ISO-Oph 102 the outflow rate in the molecular component was found to be slightly higher than the optical component. However, it is reasonable that $M_{\text{out}}$ for a molecular outflow could be greater than the outflow rate in the underlying jet. Assuming that the jet is powering the molecular outflow

| PA  | N(CO) | M(H$_2$) | $\dot{M}$(H$_2$) |
|-----|-------|---------|------------------|
| i   | (°)   | (°)     | ($\text{cm}^{-2}$) | ($M_{\odot}$/yr) |
| 20  | 60    | $3.6 \times 10^{16}$ | $4 \pm 1 \times 10^{-6}$ | 5 $\pm 1 \times 10^{-10}$ |

**Table 1.** FU Tau outflow parameters
4. Summary

The discovery of a molecular outflow driven by FU Tau A adds significantly to the interesting properties of this source and its binary companion. The FU Tau binary has a large separation compared to other binary systems and is thought to have formed in relative isolation. Both components harbor Class II accretion disks and FU Tau A is somewhat over-luminous for its spectral type. The fact that FU Tau A is driving an outflow demonstrates that despite having unusual characteristics it still exhibits properties which are strongly linked to the formation of low mass protostars. The mass, scale and mass outflow rate we measure for the FU Tau A CO outflow agrees with previous observations of BD molecular outflows. While this result is a further important piece of evidence linking how BDs form to low mass star formation the derived ratio of mass outflow to accretion rates is much higher than what is observed in low mass protostars and in particular the T Tauri stars. For other BDs the two rates have been found to be comparable thus these new results for the FU Tau system support other studies of BD outflow activity (Bacciotti et al. 2011; Whelan et al. 2009). $M_{\text{out}}/M_{\text{acc}} \approx 1$ in the current known series of BD sources could be due to an observational bias, because the first currently available observations could be only sensitive to the most extreme jets in brown dwarfs. More sensitive observations are thus needed to solve this issue.

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References

Bacciotti, F., Whelan, E. T., Alcalá, J. M., et al. 2011, ApJ, 737, L26
Bachiller, R. 1996, ARA&A, 34, 111
Bachiller, R., Martin-Pintado, J., Tafalla, M., Cernicharo, J., & Lazareff, B. 1990, A&A, 231, 174
Cabrit, S., Ferreira, J., & Dougados, C. 2011, in IAU Symposium, Vol. 275, IAU Symposium, ed. G. E. Romero, R. A. Sunyaev, & T. Belloni, 374–382
Cabrit, S., Raga, A., & Güeth, F. 1997, in IAU Symposium, Vol. 182, Herbig-Haro Flows and the Birth of Stars, ed. B. Reipurth & C. Bertout, 163–180
Downes, T. P. & Cabrit, S. 2007, A&A, 471, 873
Downes, T. P. & Ray, T. P. 1999, A&A, 345, 977
Jayawardhana, R., Mohanty, S., & Basri, G. 2003, ApJ, 592, 282
Jones, B. F. & Herbig, G. H. 1979, AJ, 84, 1872
Luhman, K. L. 2012, ARA&A, 50, 65
Luhman, K. L., Mamajek, E. E., Allen, P. R., Muench, A. A., & Finkbeiner, D. P. 2009, ApJ, 691, 1265
Machida, M. N., Inutsuka, S.-i., & Matsumoto, T. 2009, ApJ, 699, L157
Monin, J.-L., Guieu, S., Pinte, C., et al. 2010, A&A, 515, A91
Natta, A., Testi, L., Comeron, F., et al. 2002, A&A, 393, 597
Natta, A., Testi, L., Muzerolle, J., et al. 2004, A&A, 424, 603
Padoan, P. & Nordlund, A. 2004, ApJ, 617, 559
Pflugor-Bao, N., Lee, C.-F., Ho, P. T. P., & Fang, Y.-W. 2011, ApJ, 735, 14
Pflugor-Bao, N., Riaz, B., Lee, C.-F., et al. 2008, ApJ, 689, L141
Reipurth, B. & Bally, J. 2001, ARA&A, 39, 403
Ricci, L., Testi, L., Natta, A., Scholz, A., & de Gregorio-Monsalvo, I. 2012, ArXiv e-prints
Rigliaco, E., Natta, A., Randich, S., et al. 2011, A&A, 526, L6
Scholz, A., Stelzer, B., Coolijn, G., et al. 2011, MNRAS, 730
Stelzer, B., Alcalá, J., Scholz, A., et al. 2013, ArXiv 1301.0410v1
Stelzer, B., Scholz, A., Argiroffi, C., & Micela, G. 2010, MNRAS, 408, 1095
Whelan, E. T., Ray, T. P., Bacciotti, F., et al. 2005, Nature, 435, 652
Whelan, E. T., Ray, T. P., Podio, L., Bacciotti, F., & Randich, S. 2009, ApJ, 706, 1054
Whitworth, A., Bate, M. R., Nordlund, A., Reipurth, B., & Zinnecker, H. 2006, ArXiv Astrophysics e-prints

Fig. 3. An Integrated map of the blue-shifted wing emission in the velocity range $3.5 \text{ km s}^{-1}$. The LSR velocity of the BD is $+6 \text{ km s}^{-1}$. The black squares mark the positions at which observations we made. The level are 0.1, 0.15, 0.2, and 0.25 $\text{K km s}^{-1}$. Clearly we see a blue outflow lobe at a PA of $\sim 20^\circ$. We have superimposed a UKIDSS K-band image taken from Luhman et al. (2009) of the BD binary at the same scale and assuming that FU Tau-A is at the central position.

Article number, page 4 of 4