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Probing outflow activity in very low mass stars and brown dwarfs

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Abstract

The discovery that newborn very low mass stars and brown dwarfs have optical forbidden line spectra similar to low mass young stars was a strong indication that these objects can also launch outflows. Forbidden lines are the traditional tracers of outflow activity in young stars and observations at these wavelengths have contributed much to the understanding of outflows. However in the case of brown dwarfs, the forbidden emission line regions observed are not well resolved spatially. Thus, their origin in an outflow could not be confirmed. Here, the technique of spectro-astrometry as a means of spatially probing the forbidden emission line regions of very low mass stars and brown dwarfs is introduced. Indeed spectro-astrometric data presented here demonstrates, for the first time, that young brown dwarfs that are actively accreting can drive outflows. Also discussed is the important role adaptive optics will play when it comes to spatially resolving the forbidden emission line regions of sub-stellar objects and the potential for developing spectro-astrometry to a 2D form through integral field spectroscopy.

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1. Introduction

Stellar nurseries are the birth places of not only low to high mass stars but very low mass objects (VLMOs) and brown dwarfs (BDs) also. The study of very young BDs in particular has a special importance, as understanding the formation of BDs can only increase our limited knowledge of the processes active in star forming regions and indeed allow the universality of these processes at the lower end of the mass spectrum to be addressed. Different models describing the formation of BDs have been suggested (Reipurth and Clarke, 2001; Kroupa and Bouvier, 2003; Jiang et al., 2004) and it is indeed possible that these objects may have more than one formation mechanism. In any event, a reasonable first step towards answering the question of their formation is to compare the properties of BDs with low mass YSOs, in particular the Classical T Tauri stars (CTTSs). Specifically do BDs undergo accretion and have accretion disks, and if they are accreting material do they drive outflows?

Certainly, evidence for accretion in sub-stellar objects exists. The presence of disks has been confirmed from a study of the SEDs of a number of candidates (Natta et al., 2002; Pascucci et al., 2003) and high resolution optical spectra point to the existence of a T Tauri like accretion phase for BDs (Jayawardhana et al., 2003). To date, any hint that outflows may also be a feature of very low mass sources has only come from the detection of optical forbidden emission lines (FELs) in their spectra (Fernández and Comerón, 2001; Muzerolle et al., 2001; Natta et al., 2004). Any outflow driven by a VLM star or BD, would be difficult to detect (Masciadri and Raga, 2004) and not only will large telescopes be a requirement but it will also be necessary to employ special techniques like spectro-astrometry.

Spectroscopic observations at the wavelengths of optical and near infrared forbidden transitions, have yielded much new information regarding outflow activity in low to intermediate mass YSOs (Davis et al., 2003; Whelan et al., 2004). Using spectroscopy, one can investigate the kinematics and excitation conditions of jets close to where they are launched and the primary constraint to the use of spectroscopy in this manner is the maximum possible spatial resolution achievable. This is where the technique of *spectro-astrometry* comes to the fore. Adaptive optics and interferometry are designed to overcome the limitations placed on the spatial resolution by the atmospheric seeing, however, spectro-astrometry offers the observer information on comparable angular scales. Hence in theory, using this technique to measure any displacement in the FELs found in the spectra of BDs is an ideal method for resolving their outflows. Below the technique of spectro-astrometry is explained and its application to the optical FEL spectra of two objects ρ Oph 102 and LS-RCrA 1 outlined.

2. Spectro-astrometry

Conceptually, the principles of spectro-astrometry are easy to understand. The profile of a star is smeared by atmospheric turbulence to appear gaussian (at least to a first approximation) rather than point-like. Whereas the width of the profile is determined by the so-called seeing, how accurately we can determine the centroid of emission is, in theory for fixed seeing, limited only by the strength of the observed signal to noise ratio. Increasing the total number of detected photons increases the positional, or astrometric, accuracy, so that, in principle, milliarcsecond precision is possible with very large ground based telescopes (Whelan et al., 2004; Takami et al., 2001, 2003).

Consider a long-slit spectrum of a binary consisting of two virtually identical stars. If the separation of the binary is considerably less than the seeing, the profile of the system in the spatial direction will consist of a single gaussian – that is, the system is unresolved and the centroid of emission will lie exactly between the two components. Now suppose that one of the two stars differs slightly from the other in being a strong Hα emitter; in such a case, the emission centroid will shift towards that star in the spectrum at the position of the Hα line. In this way it is possible to resolve certain types of binaries with separations well within the seeing limit. In the case of a jet (pure emission line region) plus star (continuum source), one can go further and interpolate the continuum across a line, thereby allowing its contribution to be removed. It is then possible to measure separately the spatial centroid of the pure emission line region and determine its offset with respect to the continuum, that is, the parent star. Moreover, as the line can be emitted over a range of wavelengths, owing to the Doppler effect, it may also be feasible to recover spatio-kinematic information. For example, if the jet is bipolar, that is, it has oppositely directed blue- and redshifted flows from the source; the emission centroid of the red and blue wings of the line will be displaced to opposite sides of the continuum centre (Whelan et al., 2004).

The detailed method by which we measure offsets can briefly be described as follows (refer also to Fig. 1). First, the centroid of the continuum emission in the spatial direction is determined using a one-dimensional gaussian fit. The line of such centroids, in the dispersion direction but excluding any region where emission lines are present, is then fitted with a second-order polynomial. In this way, instrumental curvature and tilting, with a characteristic frequency many times larger than the width of any line, is determined. The fit,

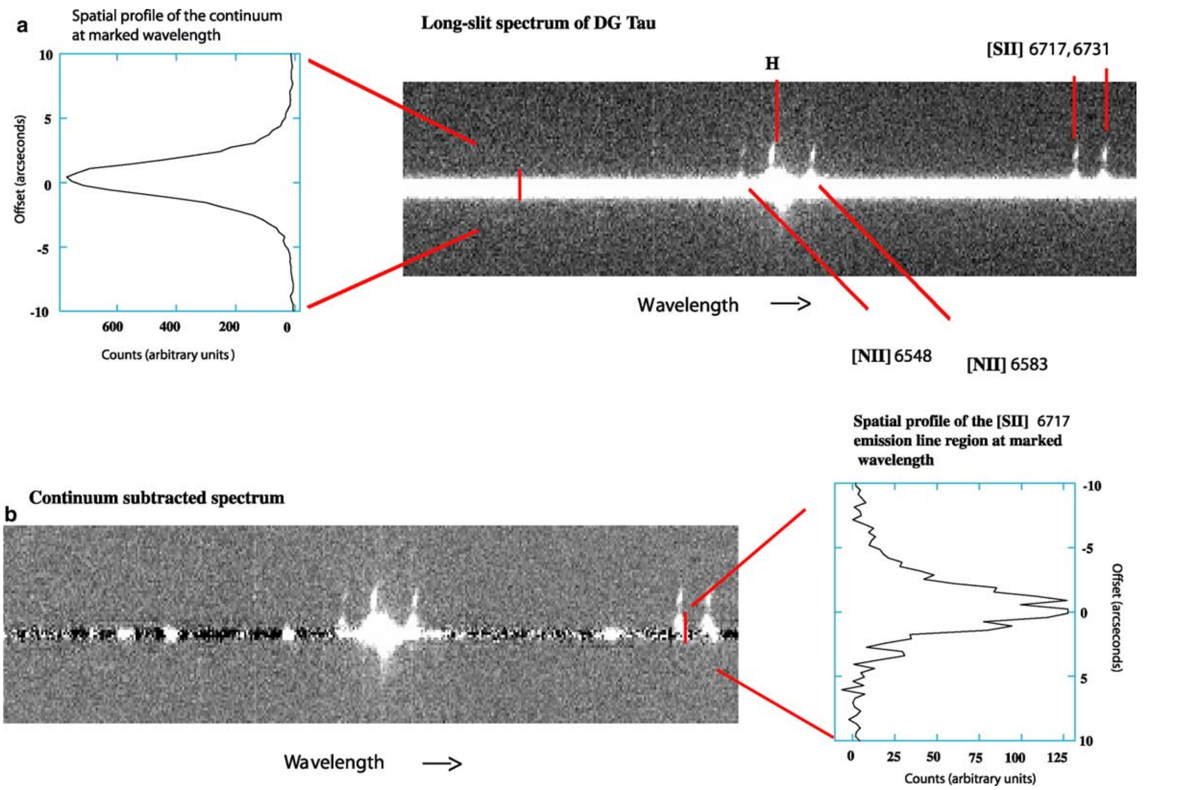

Fig. 1. Example of applying spectro-astrometry to the long-slit spectrum of a typical CTTS DG Tau. The extraction of a 1D spatial profile from first the continuum emission and then from an emission line region in the continuum subtracted spectrum is illustrated. Note, how easily the continuum can be removed leaving the pure emission line regions exposed.

to the centre of the continuum, is then subtracted from the actual measured centroids, leaving residuals that are evenly scattered about the abscissa (that is, the fit defines the zero offset line). Finally, the two-dimensional fit to the continuum, broadened to take account of the point spread function, is subtracted from the emission lines. Any emission line offsets are then measured.

The accuracy (in arcseconds) of the method is set by the error in the centroid of the gaussian fit, which depends on the seeing and the number of detected photons, N. Formally, the error is given by

$$\sigma_{\text{centroid}} = \frac{\text{seeing (mas)}}{2.3548\sqrt{N}}, \tag{1}$$

assuming that photon noise is the only source of noise. N, of course, is a function of the binning and the spatial sampling (pixel width). This explains why, for example, we can achieve a higher spectro-astrometric accuracy with a bright line, such as Hα than a weak one, for example, the [SII]λ6731 line. In some cases, it is necessary to bin up a weak line in the dispersion direction, as we have done for ρ Oph 102 (see Section 3 below) to varying degrees for the [OI] doublet and the [SII]λ6731 line, to achieve sufficient signal to noise ratio. Note that we sometimes use different binning factors for the continuum, in comparison with the line, so as to achieve a similar signal to noise ratio in both. This allows us to have comparable offset errors in both components, and to define the common 1σ error lines shown in Fig. 2.

3. ρ Oph 102

The nearby ρ-Ophiuchi cloud is an excellent example of a stellar nursery. This region has been the subject of many surveys and it was as part of a near-infrared survey by Greene and Young (1992) that the BD ρ-Oph 102 was first detected. It was noted by Natta et al. (2004) that the optical spectrum of ρ-Oph 102 contains a number of FELs, suggesting mass outflow and here the results of the application of the spectro-astrometric technique to this spectrum are outlined, (Whelan et al., 2005).

The [OI]$\lambda\lambda$6300, 6363, [NII]λ6583 and [SII]$\lambda\lambda$6716, 6731 lines are all present. The average systemic velocity of the FELs is ~ -41 km s^{-1} which is suggestive of the presence of an outflow. Moreover the blue-shifted asymmetry mirrors what is seen in CTTSs, and points to a disk which is obscuring the red-shifted flow. A second indication that an outflow is present comes from the Hα line. Its profile is clearly asymmetrical, i.e. the blue-shifted wing of the line appears to be absorbed in a P-Cygni like fashion at a similar velocity to the FELs (~ -80 km s^{-1}). However, a classical P-Cygni profile, i.e one that dips below the continuum, is not observed (refer to Fig. 3).

Of the five FELs detected, only the [OI]$\lambda\lambda$6300, 6363 and [SII]λ6731 lines were strong enough for any displacement measurements. In Fig. 2, the emission line profiles of the [OI]$\lambda\lambda$6300, 6363 lines and the corresponding spectro-astrometric plots are shown. A clear offset in the [OI]$\lambda\lambda$6300, 6363 lines is observed. Also shown are the spectro-astrometric plots of Hα and [SII]λ6731. In particular, note that a displacement in the [SII]λ6731 emission line region is recorded at a similar velocity and offset to the [OI]$\lambda\lambda$6300, 6363 lines. Overall, the centroids of all the measurable FELs in the spectrum of ρ-Oph 102 are displaced to the south, i.e. have negative offsets with respect to the continuum and these offsets reach a maximum of 0$''$.08–0$''$.1 at a blue-shifted velocity of ~ -41 km s^{-1}. The scale of this blue-shifted offset would suggest a minimum (projected) disk radius of 0$''$.1 ($\geqslant$15 AU at the distance of the ρ-Ophiuchi cloud) in order to hide any red-shifted component. There is no clear spatial offset in Hα even though its higher signal to noise potentially would allow one to measure even smaller offsets than observed in the forbidden lines. This is in agreement with the idea that most of the Hα emission arises from accretion on much smaller scales than are being probed here (Natta et al., 2004). Lastly, no offset is expected in the Liλ6708 and HeIλ6678 lines as they are photospheric and chromospheric, respectively, and none is found (Whelan et al., 2005). All this spectro-astrometric data confirms that the FELs of ρ Oph 102 originate in an outflow.

The average displacement measured in the FEL regions of ρ Oph 102 are in line with the prediction that a collimated outflow from a BD is expected to

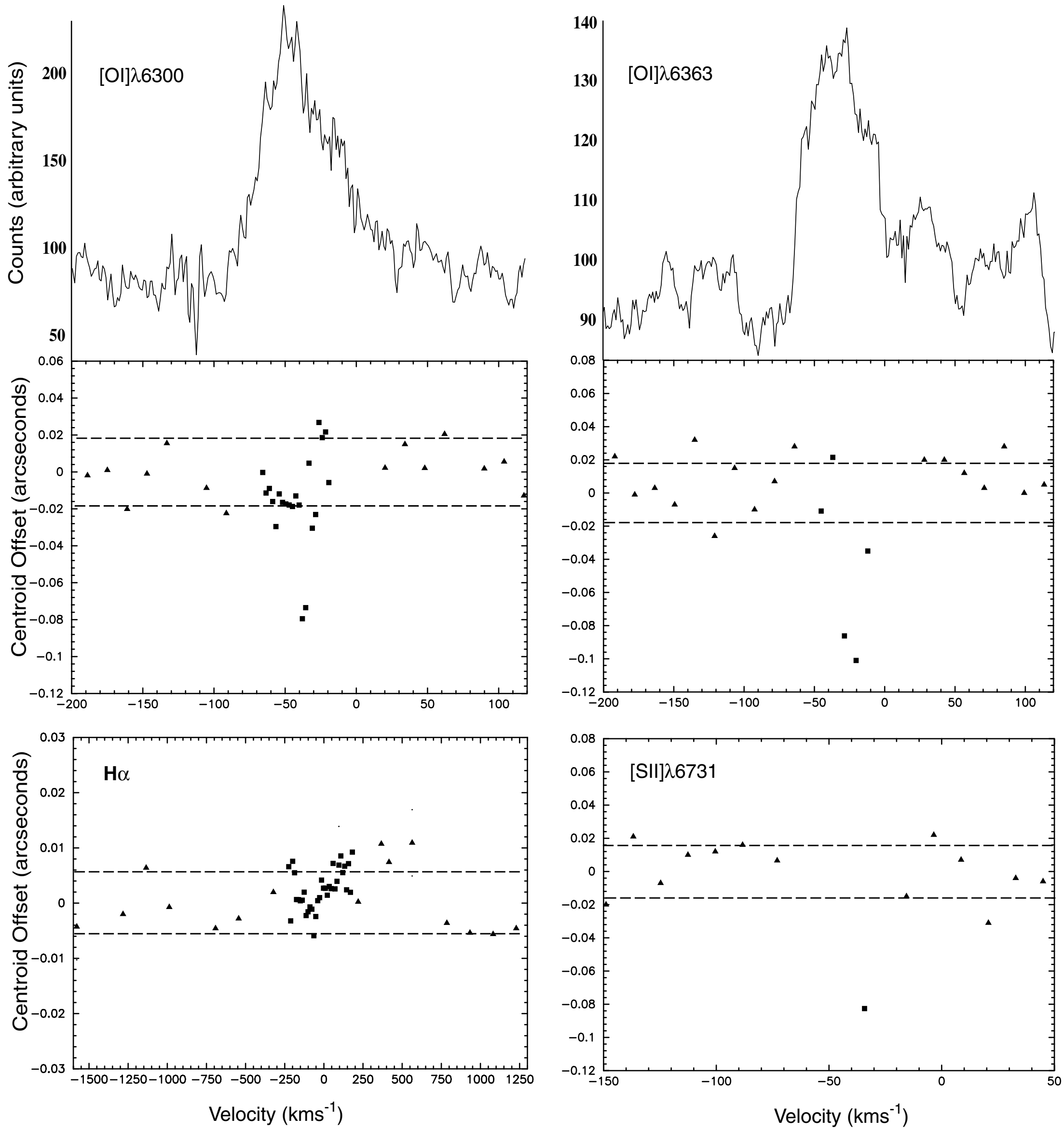

Fig. 2. Line profiles (top row) and spectro-astrometric plots (middle row) for the [OI]λ6300 and [OI]λ6363 doublet and spectro-astrometric plots (bottom row) for the Hα and [SII]λ6731 lines. The much narrower corresponding night-sky lines, peaking around $-9\ \mathrm{km\ s^{-1}}$, have been subtracted although no offset measurements were made in their vicinity (thus accounting for the data point gaps). Continuum and line offset points are represented by black triangles and squares, respectively. All velocities are systemic and spatial offsets are in the north-south direction (in arcseconds) with negative offsets to the south. Dashed lines delineate the $\pm 1\sigma$ error envelope. For Hα, note the much smaller offset scale. The [SII] line is blue-shifted to around $-40\ \mathrm{km\ s^{-1}}$.

reach the critical density for forbidden emission i.e. $n_e \sim 10^6\ \mathrm{cm^{-3}}$, much closer to the source than a CTTS. This prediction is made by considering how the critical density for a forbidden line is expected to scale with the mass flux through the jet, $\dot{M}_{\mathrm{jet}}$, for a BD. Now $\dot{M}_{\mathrm{jet}}$ is given by

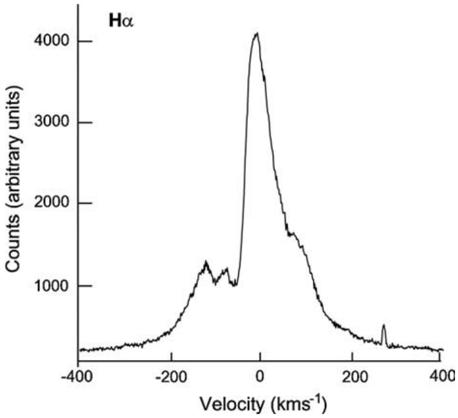

Fig. 3. The P-Cygni-like dip in the line profile is a strong signature of outflow activity. Hα emission from the brown dwarf is absorbed as it passes through material moving outwards along our line of sight. Because this material is moving towards us, the dip is on the blueward side of the line. The dip in the Hα emission of ρ Oph 102 is at approximately the outflow radial velocity determined from the forbidden lines.

$$\dot{M}_{\rm jet} = \pi r^2 \rho V_{\rm jet}, \quad (2)$$

where r, ρ and $V_{\rm jet}$ are the jet radius, density and velocity, respectively. The radius in turn is related to the jet opening angle θ (in radians) by $\theta \approx r/L$, where L is the distance to the source along the jet axis and thus

$$\dot{M}_{\rm jet} \approx \pi \rho V_{\rm jet} \theta^2 L^2. \quad (3)$$

The escape velocity and hence the jet velocity, for a brown dwarf and a T Tauri star should be approximately the same (Masciadri and Raga, 2004). Moreover, the opening angle of such jets seem to be close to their ballistic values, i.e. $\theta \approx 1/\mathscr{M}_{\rm jet}$, where $\mathscr{M}_{\rm jet}$ is the jet Mach number. Since the gas temperature determines the sound speed, and this in turn depends on the type of line emission, the Mach numbers for jets from T Tauri stars and BDs are expected to be close. Thus, their opening angles should also be similar. Finally, the spatial offset observed between the source and the centroid of emission for a forbidden line roughly coincides with the point at which the critical density for a line is reached. From the last equation, this offset is expected to scale with $\dot{M}_{\rm jet}^{0.5}$. As mass loss rates from BDs are anticipated to be 2 orders of magnitude lower than the mass loss rates from CTTSs, typical spatial offsets are thus estimated to be 3–10 times smaller. Offsets of 100 mas are well within this predicted range hence results discussed here and presented for the first time in Whelan et al. (2005) demonstrate that any outflow from a BD is expected to be a scaled-down version of a T Tauri flow.

3.1. LS-RCrA 1

LS-RCrA 1 located in the R Coronae Australis star-forming region was first identified as a VLMO by Fernández and Comerón (2001). The spectrum that I discuss here was originally analysed by Barrado y Navascués et al. (2004). One interesting feature of this source, as discussed by the above authors is that it appears to be sub-luminous or older, compared to other members of this star forming region. The sub-luminous nature of LS-RCrA 1 is reflected in the weakness of the continuum in the optical spectrum. The cold nature of a such a low mass object means that the strength of its continuum emission (or its blackbody spectrum) peaks in the near-infrared (at ~1 μm for $T_{\rm eff} = 2700$ K) and is much weaker at optical wavelengths. However, in this source around the [OI]$\lambda\lambda$6300, 6363 lines the continuum was barely detectable. It has been proposed that this source is surrounded by an edge-on disk. This would not only explain its sub-luminous nature but other features, such as strong forbidden lines combined with low accretion rates, the relatively broad wings seen in the Hα line and the lack of any NIR excess (Fernández and Comerón, 2001; Barrado y Navascués et al., 2004).

As stated, the spectrum contains strong FELs. The [OI]$\lambda\lambda$6300, 6363, [NII]λ6583 and [SII]$\lambda\lambda$-6716, 6731 lines are all present and again they are all blue-shifted pointing to the presence of a disk but the velocity average for the FELs is only about -10 km s^{-1}, which is lower than that seen in ρ-Oph 102. Such a low velocity, however, is *consistent* with the fact that we are looking at this system edge-on. The Hα line is also interesting as there is some very slight evidence for a P-Cygni absorption feature in the blue-wing, similar to what is seen for ρ-Oph 102. Even though the FELs are much more intense than those in the spectrum of ρ-Oph 102 it was almost impossible to measure any displacement in the FEL regions. The weakness of the continuum meant that it was very difficult to measure the position of the source, i.e. the centre of the continuum. Hence, there was no fixed point from which to measure any offset.

4. 2D spectro-astrometry and adaptive optics

It is possible to develop the present long-slit spectro-astrometric technique to a 2D form using spectra taken with an Integral Field Unit (IFU). In this way, both the offset and position angle of an emission line region centroid rather than its displacement in one direction could be determined. This would be in addition to mapping the emission on larger scales. A datacube analogous to the output from an IFU could also be produced using traditional long-slit spectroscopy, by simply stepping the slit across the extended field. This, however, would require a large number of separate exposures significantly reducing the throughput in a fixed time. IFU spectroscopy is more efficient as only one exposure is needed to image the whole field. A second advantage of using an IFU is that they often can be used in conjunction with an adaptive optics system.

The optically adaptive system for imaging spectroscopy (OASIS) which is now at the William Herschel Telescope (WHT) combined with NAOMI is a good example of what can be achieved by uniting integral field spectroscopy with adaptive optics. For example, Lavalley-Fouquet et al. (2000) used OASIS to image the DG Tau micro-jet in [OI]$\lambda\lambda$6300, 6363, Hα, [NII]λ6583 and [SII]$\lambda\lambda$6716, 6731. Despite the seeing reaching 1″, a spatial resolution of 0″.5 was achieved thanks to the adaptive optics correction provided by NAOMI (see Fig. 4). It should be

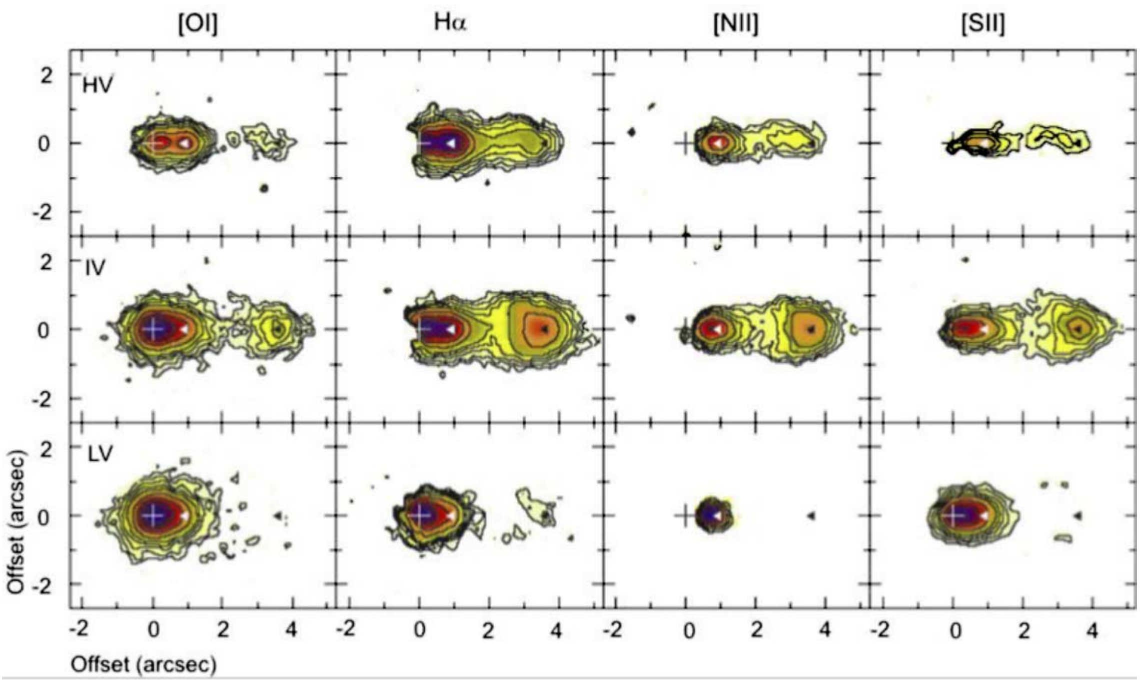

Fig. 4. Continuum subtracted maps of the DG Tau micro-jet in [OI]λ6300, Hα, [NII]λ6583 and [SII]λ6731 made with OASIS used with NAOMI. Velocity ranges are HV [−400, −250] km s^{-1} (top row), IV [−250, −100] km s^{-1} (middle row) and LV [−100, 10] km s^{-1} (bottom row). Contours in units of 10^{-18} Wm$^{-2\prime\prime-2}$ start at 2.4, increasing by factors of $\sqrt{2}$ for the next 4 levels and by factors of 2 for the following ones. A cross indicates the continuum position (0, 0); filled triangles mark the high velocity peak (0″.93) and bow-shock apex (3″.6). This figure is taken from Lavalley-Fouquet et al. (2000) and illustrates how OASIS can be used to spectroscopically image micro-jets at a high spatial resolution.

possible to recover new spatial information from such a 2D spectrum using spectro-astrometry.

5. Conclusion

Using the powerful technique of spectro-astrometry, it is possible for the first time, to spatially map the FELs regions in the spectrum of a BD, thus confirming that BD can power outflows. The discovery the BDs can drive outflows is very important as not only has it repercussions for theories of the formation of BDs but it extends the mass range over which the outflow mechanism is known to operate to nearly 10 orders of magnitude. Outflows are now known to be driven by objects as massive a black holes at the centre of AGNs and as small as BDs. The emphasis now must be on further study of the outflow from ρ Oph 102 and indeed on finding more examples of outflows from BDs. As is clear from the above discussion, LS-RCrA 1 other VLM sources do have strong FELs. Integral field spectroscopy adds another dimension to spectro-astrometric studies of BDs and young stars and the added bonus of an adaptive optics system will greatly improve levels down to which it is possible to recover spatial information with spectro-astrometry.

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References

Barrado y Navascués, D., Mohanty, S., Jayawardhana, R., 2004. Accretion and outflow in the substellar domain: Magellan spectroscopy of LS-RCr A1. Astrophys. J. 604, 284–296.

Davis, C.J., Whelan, E., Ray, T.P., Chrysostomou, A., 2003. Near-IR echelle spectroscopy of Class I protostars: Mapping Forbidden Emission-Line (FEL) regions in [FeII]. Astron. Astrophys. 397, 693–710.

Fernández, M., Comerón, F., 2001. Intense accretion and mass loss of a very low mass young stellar object. Astron. Astrophys. 380, 264–276.

Greene, T.P., Young, E.T., 1992. Near-infrared observations of young stellar objects in the rho Ophiuchi dark cloud. Astrophys. J. 395, 516–528.

Jayawardhana, R., Mohanty, S., Basri, G., 2003. Evidence for a T Tauri phase in young brown dwarfs. Astrophys. J. 592, 282–287.

Jiang, I., Laughlin, G., Lin, D.N.C., 2004. On the formation of brown dwarfs. Astron. J. 127, 455–459.

Kroupa, P., Bouvier, J., 2003. On the origin of brown dwarfs and free-floating planetary-mass objects. Mon. Not. R. Astron. Soc. 346, 369–380.

Lavalley-Fouquet, C., Cabrit, S., Dougados, C., 2000. DG Tau a shocking jet. Astron. Astrophys. 356, L41–L44.

Masciadri, E., Raga, A.C., 2004. Looking for outflows from brown dwarfs. Astrophys. J. 615, 850–854.

Muzerolle, J., Calvet, N., Hartmann, L., 2001. Emission-line diagnostics of T Tauri magnetospheric accretion. II. Improved model tests and insights into accretion physics. Astrophys. J. 550, 944–961.

Natta, A., Testi, L., Comerón, F., Oliva, E., D'Antona, F., Baffa, C., Comoretto, G., Gennari, S., 2002. Exploring brown dwarf disks in rho Ophiuchi. Astron. Astrophys. 393, 597–609.

Natta, A., Testi, L., Muzerolle, J., Randich, S., Comerón, F., Persi, P., 2004. Accretion in brown dwarfs: an infrared view. Astron. Astrophys. 424, 603–612.

Pascucci, I., Apai, D., Henning, T., Dullemond, C.P., 2003. The first detailed look at a brown dwarf disk. Astrophys. J. 590, L111–L114.

Reipurth, B., Clarke, C., 2001. The formation of brown dwarfs as ejected stellar embryos. Astron. J. 122, 432–439.

Takami, M., Bailey, J., Gledhill, T.M., Chrysostomou, A., Hough, J.H., 2001. Circumstellar structure of RU Lupi down to AU scales. Mon. Not. R. Astron. Soc. 323, 177–187.

Takami, M., Bailey, J., Chrysostomou, A., 2003. A spectro-astrometric study of southern pre-main sequence stars. Binaries, outflows, and disc structure down to AU scales. Astron. Astrophys. 397, 675–691.

Whelan, E.T., Ray, T.P., Davis, C.J., 2004. Paschen beta emission as a tracer of outflow activity from T-Tauri stars, as compared to optical forbidden emission. Astron. Astrophys. 417, 247–261.

Whelan, E.T., Ray, T.P., Bacciotti, F., Natta, A., Testi, L., Randich, S., 2005. A resolved outflow of matter from a brown dwarf. Nature 435, 652–654.