Investigating Proper Motions in the 2M1207A Jet*

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Summary

The 24 M_{jup} brown dwarf (BD), 2MASSJ12073347-3932540 (2M1207A), was first discovered to be driving an outflow through the spectro-astrometric analysis of its [OI]6300 emission region (Whelan et al. 2007). It is now known to drive a bipolar outflow with a position angle (PA) of 65°. [SII] narrowband images obtained by us revealed a series of knots along the PA of the outflow (Whelan et al. 2012). The furthest knot from the BD was bow-shock shaped and these results confirmed for the first time that BD outflows could be well collimated i.e. are jets, and episodic. In order to conduct a proper motion study of the knots we obtained follow-up images in [SII] and Hα using FORS-2 / VLT, in Feb / Jan 2013. The proper motion of the source is an important consideration as it is approximately along the same direction as the jet and likely has a similar magnitude. While no significant proper motion is detected in the [SII] knots there are morphological changes. It is possible that the velocity of the knots has slowed significantly with distance. From the comparison of the [SII] and Hα images, Hα seems to trace the shock fronts whereas [SII] the cooling zone behind the shock front. Future work includes simulations the jet to try to understand how the proper motion of source effects the morphology of the jet and the analysis of spectra of the knots. Spectra will facilitate the measurement of the knot velocities.

Outflow Discovery

Whelan et al. 2007 reported the discovery of an outflow from the 24 M_{JUP} BD 2M1207A. The presence of an outflow was confirmed by applying spectro-astrometry (SA) to the study the origin of the [OI]λ6300 emission line region. The data was taken with UVES on the ESO VLT. The [OI]λ6300 line was double peaked and SA revealed that the red and blue-shifted emission was offset in opposing directions and thus was tracing a bipolar outflow. 2M1207A was already known to have a near edge-on disk (Mohanty et al. 2007). The detection of both blue and red-shifted outflow lobes plus the small radial velocities of the lobes were consistent with an edge-on disk scenario. The radial velocities of the blue and red lobes were measured at +4 kms^{-1} and -8 kms^{-1} respectively. A second UVES spectrum at an approximately orthogonal position angle to the first was obtained in August 2008 (Whelan et al. 2012). The spectro-astrometric analysis was repeated and the results confirmed. As the two spectra were taken at orthogonal PAs they could be combined to recover the PA of the outflow. The PA of the blue-shifted outflow is 65° +/- 10°. In Figure 1 the SA of the [OI]λ6300 line in the 2008 spectrum is shown. Figure 2 demonstrates how the the two spectra were combined to constrain the PA of the jet.

This was an important result as 2M1207A is the lowest mass object known to drive an outflow, thus a study of the properties of this outflow can help to constrain how outflows behave at the lowest masses. At this stage in the investigation of this outflow it was not known if the outflow was collimated i.e. was a jet.

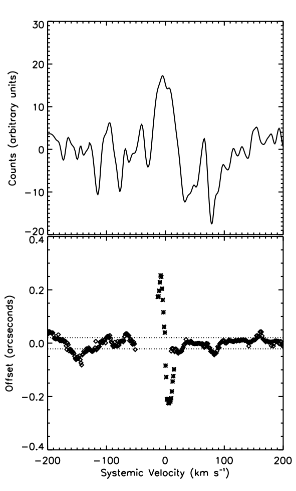

Figure 1: SA of the 2008 [OI]λ6300 line. The SA clearly confirms the Whelan et al. 2007 results, that the blue and red peaks are offset in opposing directions. The dashed line marks the 1-σ error in the centroid fitting.

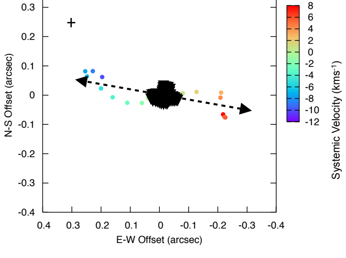

Figure 2: The spectro-astrometric signatures measured in the [OI]λ6300 line in 2006 and 2008 are combined to constrain the outflow PA. Note that the x and y axes do not represent orthogonal slit PAs but rather PAs of 0° and 80°.

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*** This work is based on data taken with UVES and FORS 1/2 on the eso VLT**

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It's a Jet

VLT / FORS-1 images of 2M1207A in [SII], I and R were also obtained in 2008 (Whelan et al. 2012). The point spread function (PSF) of 2M1207A in the [SII] images was found to be elongated in the direction of the outflow as suggested by the spectro-astrometric analysis. This elongation was not seen in other stars in the image or in the R and I band images and thus was strong evidence of the detection of the outflow. Additionally 4 knot-like features (labelled A to D) were detected along the PA of the outflow and the final feature was bow-shock shaped with the apex pointing away from 2M1207A. While this was compelling evidence that these features were shocks in the 2M1207A outflow further confirmation was needed. To test that A to D were Herbig-Haro (HH) objects we prepared a [SII]-I v R-I color-color diagram (Figure 4). A HH object is expected to display a blue broadband R-I color due to the contribution of the Halpha and [SII] 6716, 6731 lines to the R band, and an even bluer [SII]-I color caused by the larger fraction of the [SII] filter passband in which [SII] emission is detectable. This is in contrast with the redder R-I and [SII]-I colors of continuum- dominated sources like stars and normal galaxies. Therefore this analysis should separate any HH objects from stars and galaxies. B and C were omitted from this test as they were too faint for their colors to be measured.
It is clear from Figure 4 that A is either a star or galaxy while D is a HH object. This conclusion is further strengthened by comparison with the knots in the ESO-Hα 574 outflow. ESO-Hα 574 powers a well-developed bipolar jet first observed by Comeron & Reipurth (2006).

This detection of knots in the 2M1207A outflow demonstrates that it is well-collimated. This observation confirms that BD outflows can be collimated like low mass protostellar jets, further adding to the properties they share. Thus the 2M1207A outflow is more accurately described as a jet. Also note that it is episodic analogous to protostellar jets.

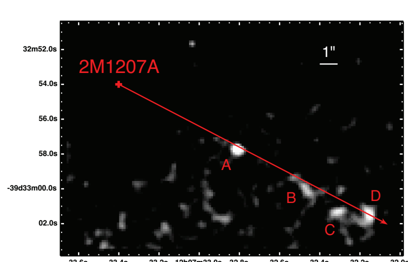

Figure 3: Gaussian smoothed [SII]-I image. 4 separate emission features are revealed with the final one having a clear bow-shock shape. The positions of the features are well fitted with a PA of 245° which is the same PA as estimated from the spectro-astrometry. These knots lie in the direction of the red-shifted flow

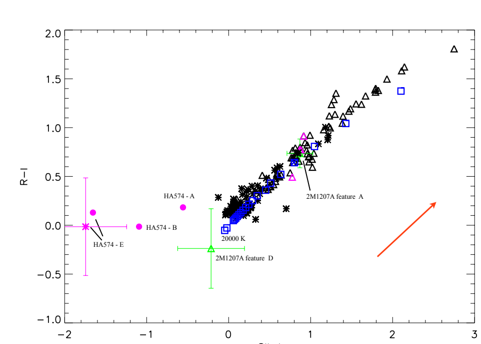

Figure 4: The aim of this analysis is to compare the colors of the objects in the TW Hya images with synthetic colors and with an analysis of the protostar ESO-HA 574 and its associated HH objects, in order to test if the faint knot-like features A and D are also HH objects. The squares represent synthetic colors, the circles colors estimated from spectra, the triangles represent objects in TW Hya included in the FOV of the 2M1207 images and the asterisks represent objects in Cha I included in the FOV of the ESO-HA 574 images. The red arrow is the reddening vector. Specifically the blue squares are synthetic colors for blackbodies in the range 20000 K to 1500 K, calculated in the range of the FORS1 filters. The purple circles are the color estimates for the knots HA574-A, HA574-B and HA574-E, calculated from XSHOOTER spectra. The black asterisks are stars in Cha I and the purple asterisk marks the color of HA574-E measured from the image. The black triangles are stars in the TW Hya region, the purple triangles are identified galaxies and the green triangles features A and D. The marked errors in the colors for HA574-E and A, D are quite large while the errors for the other points are found to be < 0.02. The position of feature D, the bow-shock shaped feature lies with the other known HH objects while A lies amongst the stars and galaxies. Based on this analysis and other evidence discussed we conclude that D is a shock in the 2M1207A outflow

2013 Images

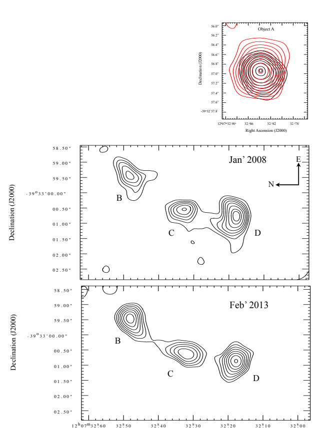

Figure 5: Comparing knots B, C and D as imaged in [SII] in Jan 2008 and Jan 2013. Feature A, identified as a background star or galaxy is also shown to demonstrate that this feature is well-aligned between the two epochs. There is no significant shift in the knots, which could be expected if the jet velocity has slowed with distance from the source. Also the effect of the proper motion of the source on PA and relative positions of the knots needs to be investigated. While there is no shift in position the morphology of the knots does appear to have changed.

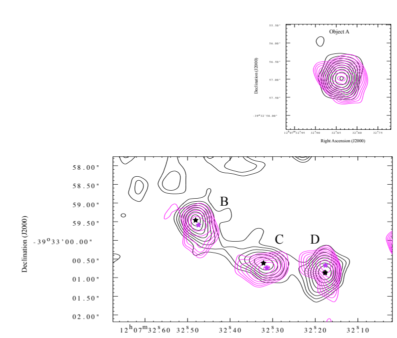

Figure 6: Comparing the knots in Hα (pink) and [SII]. The Hα is shifted towards the front of the knots as compared to the [SII]. This would support a scenario where the Hα is tracing the shock front and the [SII] the cooling zone behind the shock. This is typically seen in HH objects

To follow-up from the 2008 imaging study [SII] and Hα FORS-2 images were observed in early 2013. The motivation was to look for proper motions in the knots by comparing the two sets of [SII] images and to also compared the knots in [SII] and Hα. By combining the radial velocity measurements with an estimate of 69o for the disk inclination angle (Riaz et al. 2012) an estimate of 20 kms^{-1} can be made for the jet velocity. This would mean a movement of 0".5 between the two images.
A very important consideration here is the proper motion of the driving source itself. Song et al. 2006 report the proper motion to be α = -62.7 mas and δ = -19.9 mas. The resultant motion is approximately 18 kms^{-1} along a PA of 252°. Thus the proper motion of the jet is comparable to the proper motion of 2M1207A and is in the same general direction. An important consequence of this is that the driving source would have moved by a significant amount in between the ejections of knots B, C and D. This would effect their relative positions and thus the morphology of the jet.

In Figure 5 we compare the [SII] jet in 2008 and 2013. The motion of the source has been removed and so any motion is intrinsic to the jet. While the morphology of the knots does seem to have changed there is no significant motion over the 5 year period. The radial velocity of the jet was estimated from the [OI] line at the source position. It is likely that the knots could have slowed by an amount large enough to make their proper motion undetectable in this study.

In Figure 6 we compare the [SII] (black contours) and Hα (pink contours) images of the knots. What is striking is that the Hα knots have a different morphology, especially D, are shifted with respect to the [SII] knots and appear to trace the front part of the knots. This is what we expect if the Hα is tracing the hot material at the shock front and the [SII] the cooling zone behind.