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Searching for Jet Rotation Signatures in Class 0 and I Jets - Strengthening the Observational Support for Magnetocentrifugal Ejection

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Abstract In recent years, there has been a number of detections of asymmetries in the radial velocity profile across jets from young stars. The significance of these results is considerable. They may be interpreted as a signature of jet rotation about its symmetry axis, thereby representing the only existing observational indications supporting the theory that jets extract angular momentum from star-disk systems. However, the possibility that we are indeed observing jet rotation in pre-main sequence systems is undergoing active debate. To test the validity of a rotation argument, we must extend the survey to a larger sample. We address this problem by extending our study to younger sources. We present the latest results of a radial velocity analysis on jets from Class 0 and I sources, using high resolution data from the infrared spectrograph GNIRS on GEMINI South. These findings demonstrate the difficulty of conducting this study from the ground, but nevertheless provide a useful statistical addition to support the argument that we are observing jet rotation.

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1 Introduction

Star formation theory demands an explanation for how excess angular momentum is removed from accreting material so that it can collapse onto the newly forming star. Protostellar jets [1] [8] can theoretically be ejected via magneto-centrifugal forces [7] [9], but verification is difficult due to instrumental constraints. A significant observational breakthrough has been made in recent years by our team. We have conducted a series of studies revealing indications of jet rotation.

The first study constituted observations of the Class 0 HH 212 outflow. They revealed a difference in radial velocity of $2\,\mathrm{km\,s^{-1}}$ across the flow in the H_2 2.12 micron near-infrared (NIR) line at 5 arcsec (2 300 AU) from the star [6]. This became the first observational hint of jet rotation, given that the HH 212 disk has the same direction of radial velocity gradient [10]. Optical and near-ultraviolet (NUV) wavelength observations of less embedded Class II jets, harnessing the high resolution of the Hubble Space Telescope (HST), examined jets closer to their ejection point. The DG Tau and RW Aur jets revealed radial velocity asymmetries of $5\text{-}20\,\mathrm{km\,s^{-1}}$ within 100 AU of the star [2] [11]. Furthermore, these asymmetries were sustained for 90 AU along the jet in both cases. A survey was then undertaken of eight jets from six T Tauri systems, i.e. including two bipolar jets. Analysis in the optical and NUV consistently showed asymmetries of typically $15\text{-}25\,\mathrm{km\,s^{-1}}$ close to the ejection point [4] [5]. Asymmetries seemed common amoung Class II jets, but what about earlier evolutionary stages? A pilot study was carried out to check for rotation signatures in Class I flows. Yet again, transverse Doppler gradients were revealed in NIR spectra of HH 26 and HH 72 a at 1 000 AU from the star [3].

As a natural follow up to this pilot study, we now conduct a wider survey of younger sources. We examine three Class 0/I systems in NIR lines. The [Fe II] 1.64 micron emission traces the hot inner parts of the jet while the H_2 emission at 2.12 micron traces the warmer outer regions. Given the high spectral resolution ($R \sim 17\,800$), we chose to use GNIRS on GEMINI South.

2 Observations and Data Reduction

Observations were conducted, in queue mode, with the GEMINI Near InfraRed Spectrograph (GNIRS) on GEMINI South. Spectra were obtained of four jets from Class 0 and I sources, at a distance along the outflow of a few arcsec. Observations were made of the initial channel of the HH 34 jet within 1 arcsec of the source, the H knot in the HH 111 jet, and the first knot in the approaching and receding jet from HH 212, namely NK1 and SK1 respectively. All jet targets were observed in two bands to examine [Fe II] 1.64 micron and H_2 2.12 micron emission. The resulting long slit spectra had a nominal velocity resolution of $17\,\mathrm{km\,s^{-1}}$. Typical seeing varied between 0.5 and 0.8 arcsec. The data were calibrated and reduced according to standard procedure, using dedicated GEMINI IRAF tools.

3 Analysis of Spectra

This study is very demanding in terms of both spatial and spectral resolution, and so obtaining useful observations from the ground is difficult. Fortunately, we can reach beyond the nominal resolution both spatially and spectrally via profile fitting.

As expected, the H_2 emission was found to be spatially broad and so is almost always spatially resolved. We can determine the *magnitude* and *direction* of the implied jet toroidal velocity by profile fitting in the dispersion direction to obtain a jet radial velocity profile transverse to the flow propagation. The [Fe II] emission, however, is more confined to the jet axis, and so in our data it is never spatially extended enough to be resolved, even under excellent seeing conditions. However, just as profile fitting in the dispersion direction effectively achieves higher velocity resolution than the nominal resolution, profile fitting in the spatial direction (i.e. *spectroastrometry*) effectively achieves a spatial resolution higher than the seeing limit of the observations. For our high spectral resolution data, spectroastrometry can be used to identify a systematic asymmetry in the jet radial velocity profile.

In our spectroastrometric analysis, if there is a difference in the radial velocities between the jet borders, the on-axis peak intensity will be 'pulled away' from the centre (jet axis). For example, assume the left side of the jet has a lower radial velocity than the right side. In progressing the spatial Gaussian fitting across the emission line from lower to higher velocities, the centroid will be weighted towards the left side of the jet first and then towards the right side. The net effect is a slope in the spatial profile plot. Thus, we may determine the *sense* of the Doppler shift gradient across the jet. The magnitude of the radial velocity differences cannot be recovered without knowning the relative contributions of the on-axis jet emission compared to the intensity of the jet border itself. However, the very detection of a gradient in the centroids of the spatial fits is enough to signify a that a Doppler gradient exists in a given direction.

4 Results

The **HH 34** jet was clearly detected in both [Fe II] and H_2 emission. The data contained reflected continuum emission from which we measured the seeing. Unfortunately, the jet width is unresolved in both lines. However, the signal-to-noise is excellent and so here we have the perfect case for the application of spectroastrometry. A clear trend is evident from Gaussian fits in the spatial direction, Figures 1. This indirectly indicates a gradient in the Doppler profile less than one arcsec from the driving source. In both emission lines, the south-west side of the approaching jet displays radial velocities which are more blue-shifted than the north-east side of the flow. Furthermore, the two H_2 exposures, taken in October and December respectively, demonstrate the persistance of the sense of Doppler gradient over time. There is currently no available measure of the disk radial velocity profile, and so confirmation of agreement with the sense of disk rotation cannot yet be given.

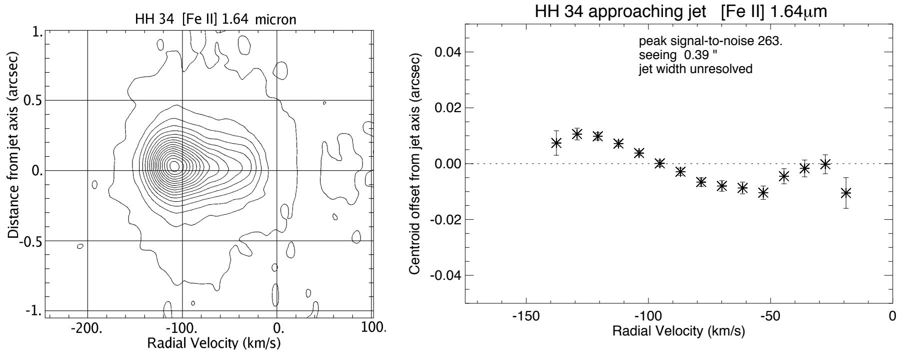

Fig. 1 Left - Position-velocity diagram of [Fe II] emission from the HH 34 approaching jet; Right - Transverse Doppler gradient identifi ed using spectroastrometry.

The **HH 111** jet is clearly detected in both [Fe II] and H_2 emission, although the jet width is unresolved in [Fe II]. H_2 emission is extremely faint in spite of the 2 hour integration. Despite low signal-to-noise, a small gradient trend is apparent in both lines. In H_2 the asymmetry was measured as 3 km s^{-1}. The southern side of the flow is more blue-shifted than the northern side. The direction of the velocity asymmetry is opposite to that of HH 34, in terms of the instrumental set up. Furthermore, the direction matches that of the HH 111 disk [12]. We are observing the flow at a distance far from the source, hence the interpretation of a transverse Doppler gradient may be complicated by environmental effects, such as asymmetric shocking.

The **HH 212 NK1** approaching jet knot reveals a clear [Fe II] detection even though, to date, there has been no [Fe II] emission seen from the outflow of this deeply embedded Class 0 source. The intensity is one third of the signal-to-noise of H_2. The jet width is unresolved in [Fe II], but resolved in H_2 emission. No gradient could be identified in the [Fe II] line. The non-detection of a Doppler gradient is consistent with the H_2 data of [6]. Our H_2 data, on the other hand, shows a slight gradient of 3 km s^{-1}. The direction of the Doppler shift reveals the northwest side of the flow is more blue-shifted than the south-east side.

The **HH 212 SK1** receding jet knot was unresolved in [Fe II], but resolved in H_2 emission. An asymmetry of magnitude 5 km s^{-1} was measured in H_2. The asymmetry sense matches the gradient direction of the NK1 dataset, implying that the sense of derived toroidal velocites in both lobes of the bipolar jet would be in agreement. This sense also matches the direction of the lower resolution H_2 measurements of [6], and the direction of the Doppler gradient reported across the associated disk [10]. However, in both NK1 and SK1, emission is spatially asymmetric on the opposite sides of the flow axis. This causes inaccuracies in spatial Gaussian fits, giving rise to difficulties in identifying the jet axis, and hence the magnitude of the radial velocity differences at equal distance either side of the axis. Furthermore, as in the case of the HH 111 analysis, we are observing at 5 arcsec from the source and so outside factors may influence the jet dynamics which complicate our interpretation.

5 Conclusions

We have conducted a ground-based survey in NIR lines of four jets from Class0/I sources to search for signatures of jet rotation. We strive to overcome the seeing limitations, in our high spectral resolution data, by applying the technique of spectroastrometry. Thus, our results rely on a combination of profile fitting in both spatial and spectral directions. We find a clear gradient in radial velocity of unknown magnitude across the jet from HH 34 within 1 arcsec of the driving source. We find a tentative detection of a gradient of $\sim 3\,\mathrm{km\,s^{-1}}$ across the jet from HH 111 in a direction which matches the disk rotation sense. However, the gradient is small, and the observation is far from the driving source allowing environmental factors to confuse the interpretation. Finally, we detect a gradient of $\sim 5\,\mathrm{km\,s^{-1}}$ in the NK1 and SK1 knots of the HH 212 bipolar flow, which matches the disk rotation sense. Both SK1 and NK1 are at 5 arcsec from the HH 212 Class 0 driving source and so again we must consider that the gradients can be a result of external factors such as asymmetric shocking. Our analysis illustrates the difficulty in conducting this study from the ground, given the combination of high spectral and spatial resolution demands. It is clear that in order to safely interpret Doppler asymmetries as signatures of jet rotation, there is a need for improved statistics via high resolution multi-wavelength jet observation close to the source, and comparison with the associated disk rotation sense to check for agreement.

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