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The observations presented here were obtained as part of
the Science Verification of MUSE and with X-Shooter
(085.C-0238(A)), both of which are ESO VLT instruments

Properties of a Jet from the T Tauri Star TH 28:
a Combined Spectroscopic Study With MUSE and X-Shooter

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Abstract

In this poster we present the first results from a MUSE / X-Shooter study of the jet from the classical T Tauri star TH 28. Young stars exhibit prominent accretion and outflow features such as accretion disks and collimated jets. The interaction of these processes may play a significant role in the formation of the star and the evolution of the surrounding disc. However, the precise mechanism by which they are linked remains unclear. Integral Field Spectroscopy offers a valuable tool for examining the structure and origin of jets. With IFS spectro-images can be extracted in various emission lines and the jet properties investigated not only with distance from the driving source but also with velocity. Broadband spectroscopy is also important for understanding accretion and outflow properties as it allows activity to be investigated in a large number of emission lines and for a robust diagnostic study to be carried out. The combination of MUSE and X-Shooter enables us to take advantage of both spectro-imaging and broadband spectroscopy to comprehensively investigate the TH 28 jet.

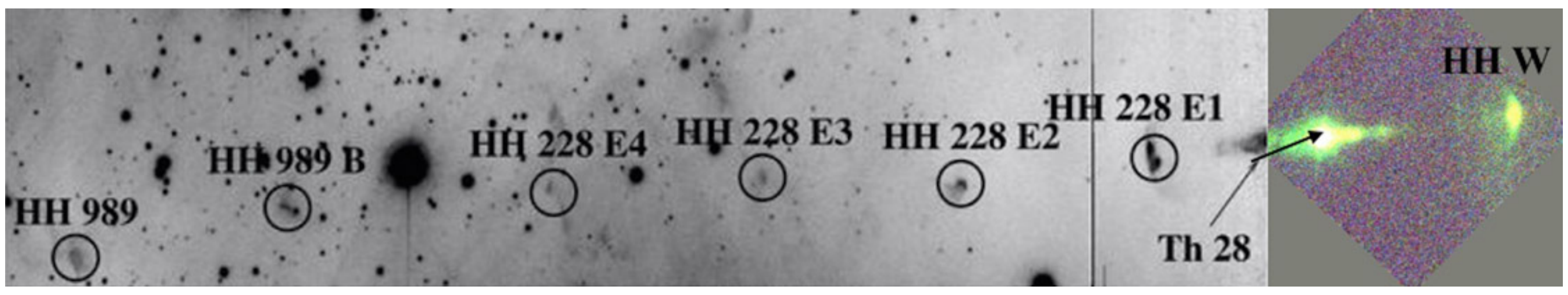


Figure 1. Top: A large-scale view of the TH 28 jet shown in combined FORS (imager on VLT) and MUSE data. With MUSE we primarily observed the red-shifted jet which culminates here with the large bow-shock HH W.

1. Jets from Young Stars

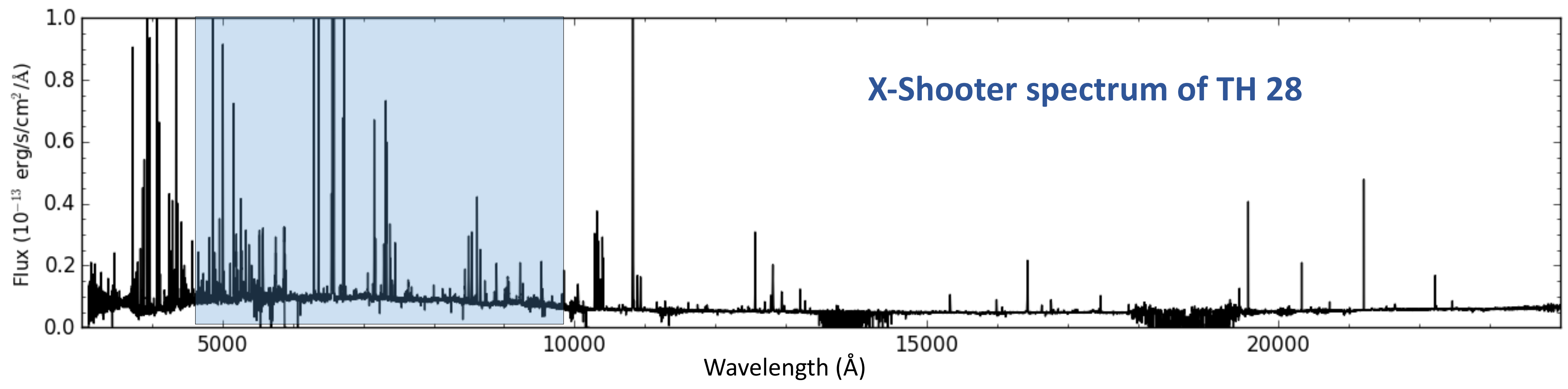
Young stellar objects (YSOs) exhibit prominent accretion and outflow features such as accretion discs and bipolar jets. Magneto-hydrodynamic (MHD) models propose that jets act to remove angular momentum from the star, slowing their rotation and enabling further accretion from the surrounding disk, however many unanswered question remain (Frank et al. 2014). Given these unanswered questions it is important to understand protostellar jets and their connection to accretion discs. However, the link between these processes remains unclear and MHD models differ on the origins and underlying mechanisms of these jets. Observational studies can help to resolve these questions and forbidden emission lines which act as diagnostic measures of physical conditions within the jet are particularly important. Classical T Tauri stars (CTTSs) are young, actively accreting stars which frequently possess jets. They offer particularly good targets for study due to their close proximity and low extinction making it easier to investigate the inner jet regions. The techniques of integral field spectroscopy (IFS) and broadband spectroscopy have proved to be especially useful for studying jets. Both allow diagnostic studies to be carried out. With IFS images of the jets in different outflows tracers can be extracted and therefore maps of the physical conditions in the jets constructed (Maurri et al. 2014). With broadband spectroscopy numerous emission lines are available for diagnostic studies and accretion and outflows activity can be investigated contemporaneously (Whelan et al. 2014b). Here we present results of integral field and broadband spectroscopic observations of the TH 28 jet carried out with the Multi-Unit Spectroscopic Explorer (MUSE) and X-Shooter respectively. Both MUSE and X-Shooter are VLT instruments. The broader spectral coverage and better spectral resolution of X-Shooter enables more precise measurement of emission line ratios across a much broader spectral range, making it complementary to observations taken with MUSE.

2. TH 28

The focus of this study will be on the CTTS TH 28 (also named Sz 102), which is located in the Lupus 3 cloud, approximately 185 pc distant. This is thought to be a G-K type dwarf with an estimated mass of 1-2 solar masses and age < 3.5 Myr (Louvet et. al., 2016). Sz102 possesses a bipolar jet that has been well-resolved in previous optical and infrared studies and has a total known length of 0.32 pc (Comerón & Fernández 2011). TH 28 is significantly underluminous, suggesting an edge-on view of the accretion disc which obscures the star itself. This makes it a useful object for study by enabling a wider extent of both red and blue-shifted jets to be observed close to the star. Previous studies have reported signatures of jet rotation from an optical study with HST STIS (Coffey et. al., 2004). Recent ALMA observations detected a counter-rotation between the disk and the optical jet for TH 28 (Louvet et al. 2016)

3. Observations and Data Reduction

The MUSE observations were made on 23rd June 2014. The average seeing was 0”9 during the observations and MUSE has a field of view of 1’x1’. The observations were taken so that the long axis was aligned with the jet PA and so that the red-shifted jet was mostly within the frame. The total integration time was 600 s. The pixel scale was 0”.2. The wavelength range of the observations was 4570 Å to 9350 Å with a wavelength dependent spectral resolution of between 170 km s^{-1} (4750 Å) and 75 km s^{-1} (9350 Å). The X-Shooter observations were taken on 17th April 2015 in nodding mode. The single-node exposure time was 1260 s, yielding a nominal exposure time of 1.4 hr after 1 ABBA cycle. The average seeing was 1”.0 during the observations. The slit was aligned with the jet axis at a position angle of 95º and the slit widths of the UVB, VIS and NIR arms were 0”.5, 0”.4 and 0”.4 respectively. This choice of slit widths yielded spectral resolutions of 9100, 17400 and 10500 for each arm respectively. The pixel scale is 0”16 for the UVB and VIS arms and 0”21 for the NIR arm. The data were reduced using the ESO pipelines.



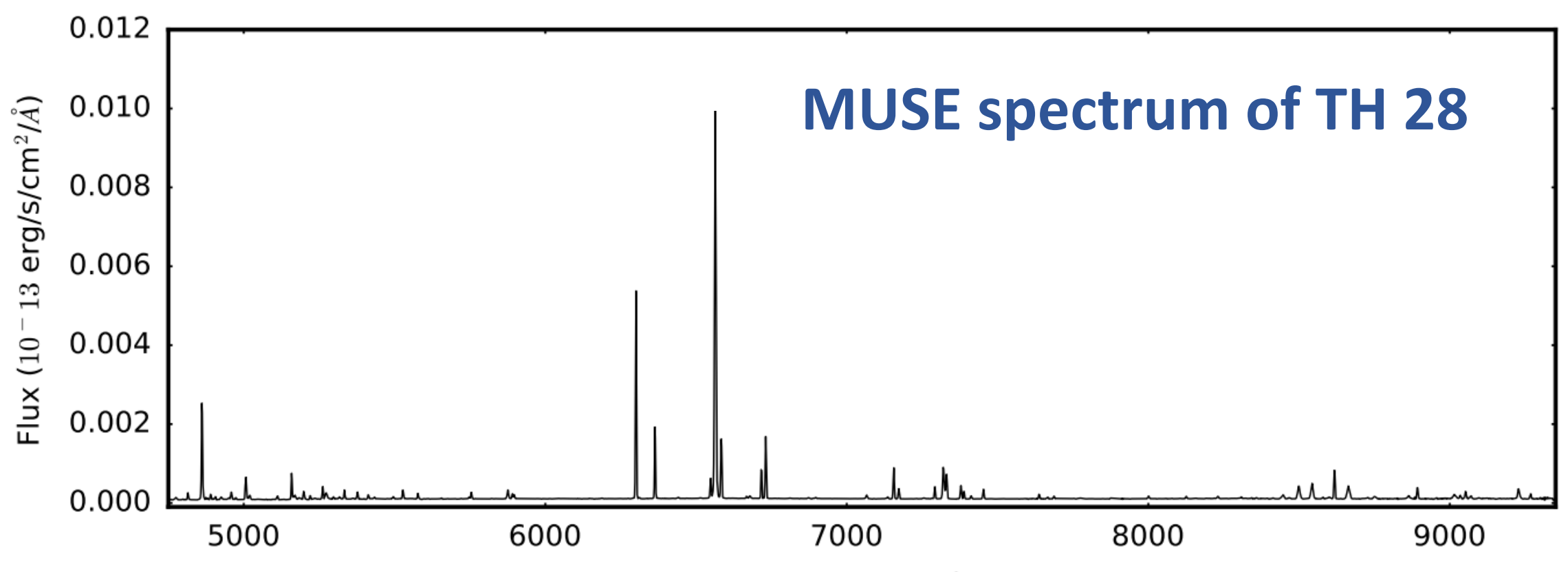


Figure 2. Top: The X-shooter spectrum of TH28 in UV, visible and NIR arms showing numerous emission lines which will be used in a diagnostic study of the jet. For this observation the slit was aligned with the position angle of the jet. The blue window highlights the range of the MUSE observation. Bottom: The MUSE spectrum of TH 28 extracted from the source position. The difference in the fluxes of the two spectra is due to the fact that the spectra were extracted over different regions of the source/jet emission.

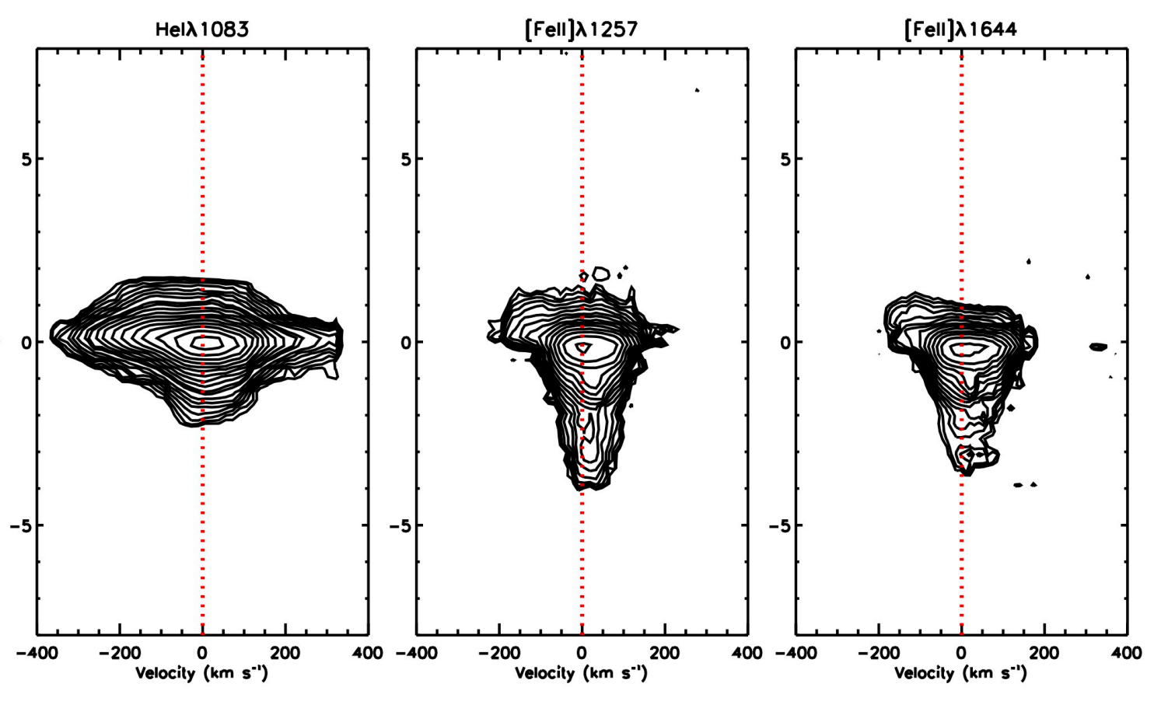


Figure 3. PV plots extracted from the X-shooter NIR arm. Any sky and continuum emission has been subtracted and the velocities are LSR velocities.

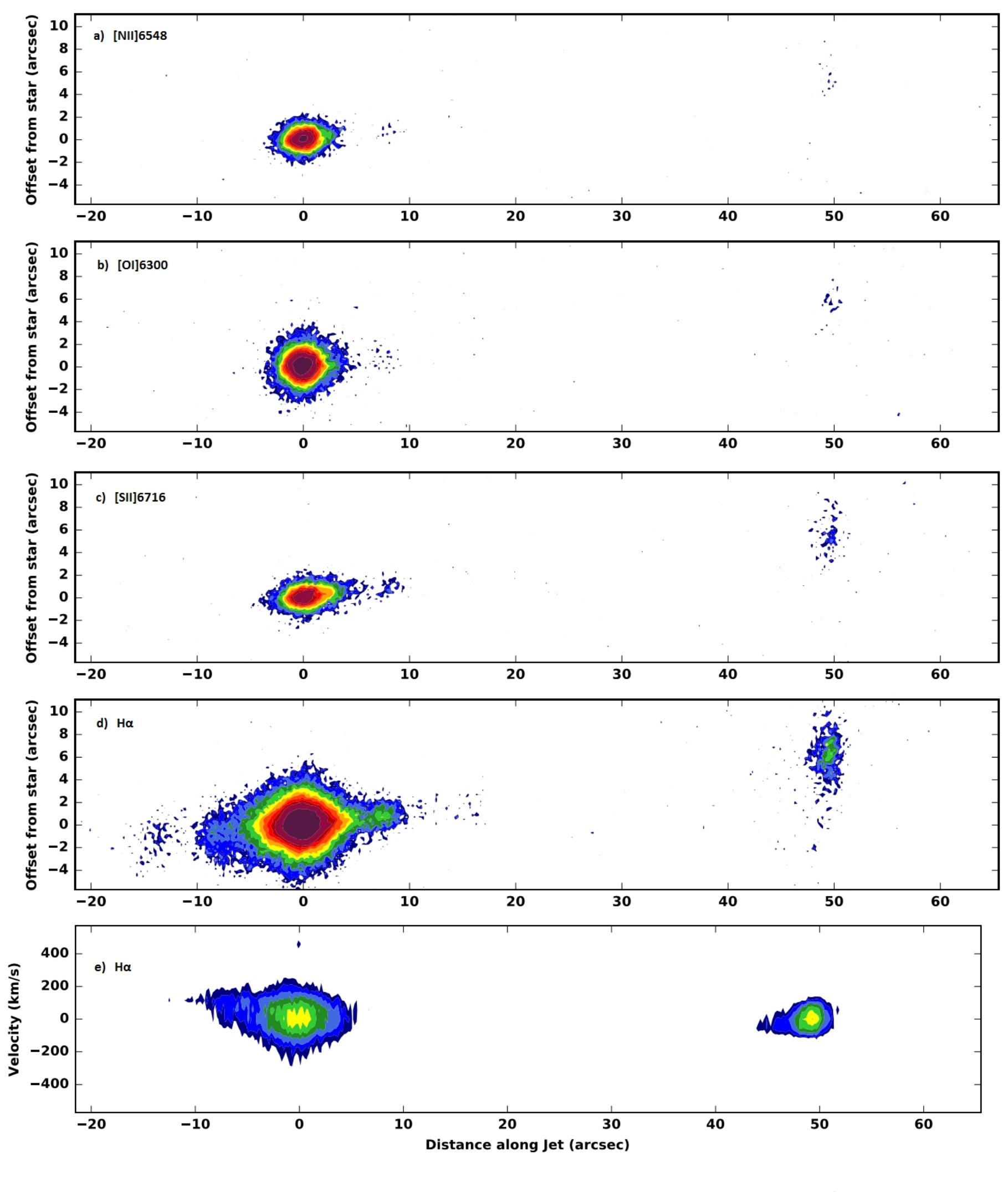


Figure 4. Velocity channel maps and position-velocity diagram of the TH 28 jet. Subfigures a) to d) show a sampling of emission lines binned across approximately the +/- 250 km/s velocity range. Subfigure e) shows the position-velocity diagram corresponding to the Hα emission line. In each case the continuum has been subtracted. Velocities are LSR velocities.

4. Data Analysis

The X-Shooter data was analysed using the usual IRAF routines for spectral analysis. For the MUSE data python routines have been constructed which enable us to obtain images in a given line at a chosen velocity. This allows us to trace different components of the jet as well as ensuring that we are using similar velocity ranges when obtaining important line ratios. Position-velocity diagrams can be obtained using a python routine by extracting a slice of the data along the jet axis. This view shows the distribution of emission for a given line in terms of velocity and distance from the star. This is a valuable tool for examining the variations in emission and velocity components as the jet moves outward from the star. To account for systemic errors in the wavelength calibration of the detector, we extracted two-dimensional slices from regions of the field of view containing no visible background stars. We then compared a number of skylines visible in the data with wavelength values obtained from a UVES catalogue (Hanuschik, 2003) in order to estimate the average velocity offset in each region of the MUSE spectrum. The maximum offset for any line was determined to be approximately 45 km/s, which is significantly less than the velocity resolution of the detector at any wavelength.

5. Results to Date and Future Work

Results to date include:

1. In Figure 2 both the MUSE and X-Shooter spectra are shown. By measuring the fluxes of accretion tracers in both spectra we have estimated the mass accretion rate at $\log(M_{acc}) = -9.4$. We have followed the method of Alcala et al. 2014. The next steps in the analysis of the X-Shooter data are to correct $\log(M_{acc})$ for the sub-luminous nature of the source and to carry out the diagnostic analysis including estimating the mass outflow rate (M_{out}). The same methods as described in Whelan et al. 2014b will be followed.
2. In Figure 3 PV plots of the jet in He I 1μm, [Fe II] 1.257 and [Fe II] 1.644 lines are shown. These are taken from the X-Shooter spectra. One advantage of the X-Shooter data is that it allows us to also study the jet in the near-infrared. Some extension is seen in the He I lines while the inner 5 arcsec of the red-shifted jet is bright in [Fe II]. The ratios of these lines can be used to estimate the extinction of the jet (Nisini et al. 2005).
3. In Figure 4 spectro-images and a Hα PV plot, extracted from the MUSE datacube are presented. A large velocity bin (approx 500 km s^{-1}) is used for the spectro-images. The jet and the bow-shock is brightest in Hα. The red-shifted N-W jet is more collimated while nebulous material is associated with the blue-shifted eastern jet. All of the lines shown here are important for the diagnostic method. The next step in this study will be to apply the diagnostic method of Bacciotti & Eislöffel to the datacube (Maurri et al. 2014).

6. References

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