GEMINI-IFU SPECTROSCOPY OF HH 111\(^*\)

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ABSTRACT

We present new optical observations of the Herbig–Haro (HH) 111 jet using the Gemini Multi Object Spectrograph in its Integral Field Unit mode. Eight fields of 5″ × 3′/5 have been positioned along and across the HH 111 jet, covering the spatial region from knot E to L in HH 111 (namely, knots E, F, G, H, J, K, and L). We present images and velocity channel maps for the [O i] 6300+6360, Hα, [N ii] 6548+6583, and [S ii] 6716+6730 lines, as well as for the [S ii] 6716/6730 line ratio. We find that the HH 111 jet has an inner region with lower excitation and higher radial velocity, surrounded by a broader region of higher excitation and lower radial velocity. Also, we find higher electron densities at lower radial velocities. These results imply that the HH 111 jet has a fast, axial region with lower velocity shocks surrounded by a lower velocity sheath with higher velocity shocks.

Key words: Herbig–Haro objects – ISM: individual objects (HH 111) – ISM: jets and outflows – ISM: kinematics and dynamics

1. INTRODUCTION

HH 111 (discovered by Reipurth 1989) is one of the two most remarkable and better studied Herbig–Haro (HH) jets, the other one being HH 34 (shown to be a jet by Reipurth et al. 1986). The past observational studies of HH 111 include:

1. ground-based (Reipurth et al. 1992; Podio et al. 2006) and Hubble Space Telescope (HST) (Raga et al. 2002a) high and low resolution long-slit spectra,
2. optical (ground-based: Reipurth et al. 1992; HST: Hartigan et al. 2001) and IR (Coppin et al. 1998) proper motions,
3. evidence of multiplicity of the outflow source (Gredel & Reipurth 1993; Reipurth et al. 1999, 2000; Noriega-Crespo et al. 2011),
4. discovery of an associated giant jet (Reipurth et al. 1997a), and
5. detection of an associated, very well collimated molecular outflow (Cernicharo & Reipurth 1996; Nagar et al. 1997; Hatchell et al. 1999; Lefloch et al. 2007).

Numerical simulations of variable jets calculated specifically for modeling the observational properties of HH 111 were presented by Masciardi et al. (2002) and Raga et al. (2002b).

Optically, the HH 111 system has a one-sided jet that appears at ~15″ from an obscured source (detected at radio wavelengths by Reipurth et al. 1999), extending to a distance of ~40″ from the source. However, a much more symmetric jet/counterjet structure extending down to the position of the source is observed in ground-based (Davis et al. 1994; Gredel & Reipurth 1994), HST (Reipurth et al. 1999), and Spitzer (Noriega-Crespo et al. 2011) IR images. At angular scales >2′ from the source, both of the outflow lobes are detected optically, with total extent of ~20″ for the whole system (see Reipurth et al. 1997a).

The kinematics of the HH 34 jet have been studied spectroscopically (for a limited set of optical emission lines) with full spatial coverage by Beck et al. (2007) and Rodríguez-González et al. (2012). Our present paper describes similar observations (i.e., high resolution spectroscopy with full spatial coverage), but for the HH 111 jet. In our Integral Field Unit (IFU) Gemini South spectra the [S ii] 6730, 6716; Hα; [N ii] 6583, 6548; and [O i] 6360, 6300 are detected, and have a high enough signal-to-noise ratio so that velocity channel maps can be generated.

The paper is organized as follows. In Section 2 we describe the observations and the data reduction. The results are described in Section 3. Finally, the work is summarized in Section 4.

2. OBSERVATIONS AND DATA REDUCTION

2.1. The Observations

HH 111 was observed at GEMINI North observatory on 2007 October and 2010 November, using the GMOS instrument in IFU mode (Allington-Smith et al. 2002) under the program GN-2007B-Q-9. We used the IFU in the single slit mode with the R831_G5302 grating, giving a R = 4396 resolution at 7570 Å. In the single slit mode, the IFU field of view is 5″ × 3′5, each lens covering 0.7″ on the sky.

The observations have made under exceptional seeing conditions. Using the R-band images, the seeing estimates range from 0.44 to 0.51 for the first epoch observations (2007) and from 0.55 to 0.60 for the second one (2010).

Hα narrow-band filter pre-images (on and off) were also taken (on 2007 August 22) to position the IFU field with higher accuracy. In order to cover the target, we observed the eight fields shown in Figure 1. Each field was observed with a total exposure of 1200s (three 400s exposures, which were then median averaged to reduce the cosmic ray contamination). Fields 1–6 were observed on 2007 October 19 and fields 7 and 8 on 2007 November 16. Fields 1–6 were re-observed on 2010...
are given in arcseconds, and refer to displacements μi μfi nomenclature provided by Reipurth inside the HH 111 jet are labeled by capital letters from E to L, following the Telescope. The observed positions of the 1500 lenses on the frame. Twilight images have been bias corrected, trimmed, and position angle (αfi – δfi) were recorded. All raw images have been bias corrected, trimmed, and flat fielded. Flat-field images have also been used to locate the fields observed with the GMOS-IFU fields. The offsets between each field are indicated in Table 1. The N–E axes are indicated in the figure, as well as a distance scale.

November 2, due to bad CCD settings during the original observations. Overlaps between the different fields have been set to 0′.4 (corresponding to two rows of IFU lenses).

Table 1 gives the coordinates of the HH 111 IRS outflow source (IRAS 05491+0247; see Rodríguez and Reipurth 1994; Reipurth et al. 2000) and the exact offsets of the GMOS-IFU observed fields. The offsets are in arcseconds and are taken with respect to the center of field 1 (center of knot J, see Figure 1). The offsets are perpendicular (Δp) and parallel (Δq) to the HH 111 outflow axis, which is at a PA = −83.94° position angle (Raga et al. 2002a).

2.2. Data Reduction

Data have been reduced using a special reduction package provided by Gemini Staff5 using the IRAF reduction package. All raw images have been bias corrected, trimmed, and flat fielded. Flat-field images have also been used to locate the positions of the 1500 lenses on the frame. Twilight images were used to estimate the grating response and after the extraction of spectra for each lens, each one has been corrected using this normalized response. Arcs, from the CuAr lamp, have also been taken for the wavelength calibration. Using the bright OI night sky line at 5577.338 Å, we have estimated the wavelength calibration accuracy to 0.1 Å. The last step of the reduction was the sky subtraction using the field located at 1′ from the science field. Finally the data cube has been created with the GFCUBE task using a spatial resampling of 0′.1 per pixel. The total spectral coverage goes from 4835.896 Å to 6957.800 Å. The spectral sampling is 0.339 Å per spectral pixel. We then extracted sub-cubes near the Hα, [O i]λλ 6300, 6364, [N ii]λλ 6548, 6584, and [S ii]λλ 6716, 6731 emission lines, for each the eight observed fields.

Further image treatment has been conducted using the pipeline developed by Menezes et al. (2014; see also Ricci et al. 2011). It consists of (i) a spatial filtering process to remove high-spatial frequency noise, (ii) a Principal Component Analysis (PCA) to remove instrumental spatial fingerprints, and (iii) a Richardson–Lucy deconvolution process. In order to remove the high spatial frequency noise, we first calculate discrete Fourier transforms of the images resulting from each data cube, and apply a low-pass band filter in the frequency space (Gonzalez & Woods 2002). To this effect we follow the procedure described in Menezes et al. (2014). In particular, we use a Butterworth H(u, v) filter of order n = 6 (see Equation (7) in Menezes et al. 2014). An inverse Fourier transform is then applied to the filtered data. We should mention that a similar noise filtering process has been already applied in the context of long slit spectroscopy of HH jets (Raga & Mateo 1988). The high-frequency cleaned data still show low-frequency noise which we remove using the PCA (see Ricci et al. 2011 and Steiner et al. 2009 for a detailed discussion and method presentation). The scope of this paper is not to present this technique. However, it is worth mentioning briefly how it works. The PCA technique allows us to describe the data cube as a linear combination of an orthogonal basis, which are the eigenvectors of a 2D covariance matrix. Such a covariance matrix is obtained after scaling all the intensities in the 3D data cube with the transformation:

\[
\beta = \mu (i - 1) + j
\]

in a data cube with the spatial dimensions \( n = \mu \times \nu; 1 \leq i \leq \mu, 1 \leq j \leq \nu \). For each spaxel intensity, \( I_{ij} \), one defines a 2D intensity matrix \( \mathbf{I}_{2D} \) which will be the subject of the PCA analysis. Its covariance matrix is calculated, and the eigenvectors with their associated variances are obtained (e.g., Steiner et al. 2009). The higher its variance, the more representative of the data is a given eigenvector. As the orthogonality is ensured, we can compose a tomogram, which is an image that represents the projection of the original data onto a selected eigenvector (or

\[\text{Table 1 Target Coordinates and Offsets}\]

| Target          | R.A.         | Decl.         | Δp   | Δq   |
|-----------------|--------------|---------------|------|------|
| IRAS 05491+0247 | 05:51:46.25  | 02:48:29.5    | ...  | ...  |
| Field 1         | 05:51:43.7   | 02:48:34.1    | ...  | ...  |
| Field 2         | ...          | 0             | 4.4  | ...  |
| Field 3         | ...          | 0             | 8.8  | ...  |
| Field 4         | ...          | 2.9           | 5.6  | ...  |
| Field 5         | ...          | −2.9          | 5.6  | ...  |
| Field 6         | 0            | −4.4          | ...  | ...  |
| Field 7         | ...          | 0.214         | −9.07| ...  |
| Field 8         | ...          | 0.214         | −13.43| ...  |

5 http://www.gemini.edu/node/10795
6 Image Reduction and Analysis Facility is a software developed by the National Optical Astronomy Observatory—http://iraf.noao.edu

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In Figure 2 we show a specific observed field (field 8 in Figure 1), for a given emission line (H\(\alpha\)), before any filtering process (a), after the filtering process but extracting the emission line from data (b), and the (a)–(b) subtraction in (c). We should mention that the tomogram in (b) was obtained by adding the first two eigenvectors (without the emission line), which we assume to correspond to the low-frequency noise, or the instrumental fingerprint, as described in Ricci et al. (2011).

Finally, we have applied a Richardson–Lucy deconvolution procedure with a Gaussian point-spread function (PSF), with a constant FWHM of 0\(^{\prime\prime}\)44 for fields 7 and 8, and a constant FWHM of 0\(^{\prime\prime}\)55 for fields 1–6, as suggested by the seeing in our observations. Six interactions have been used in order to deconvolve the original data with the PSF (see Equation (10) in Menezes et al. 2014). The whole procedure (spatial resampling, low-noise filtering process, instrumental fingerprint removal technique, and Richardson–Lucy deconvolution) is explained in detail in Menezes et al. (2014), who has developed the technique.7

3. RESULTS

3.1. Images and Velocity Channel Maps

We present the spatially resolved line profiles as “velocity channel maps” in three velocity intervals:

Figure 3. From left to right: mosaics of [S\(\text{II}\)]\(\lambda\)6716+\(\lambda\)6731 for the integrated line profile (left), and for three different radial velocity intervals: high velocity (HVC), medium velocity (MVC), and low velocity (LVC) components. The intervals are defined by: \(v_{\text{rad}} < -100 \text{ km s}^{-1}\) for HVC, \(-100 < v_{\text{rad}} < -70\) (in \(\text{km s}^{-1}\)) for the MVC, and \(v_{\text{rad}} > -70 \text{ km s}^{-1}\) for the LVC. The coordinate axes are in arcseconds (the origin coincides with the position of the driving source) and the color bars are in arbitrary units.

7 The routines are available electronically at the following address: http://www.astro.iag.usp.br/~pcatomography/.
1. HVC: a high (negative) velocity channel, with radial velocities $v_{\text{rad}} < -100$ km s$^{-1}$,
2. MVC: a medium velocity channel, with $-100$ km s$^{-1} < v_{\text{rad}} < -70$ km s$^{-1}$,
3. LVC: a low velocity channel, with $v_{\text{rad}} > -70$ km s$^{-1}$.

We also present an image (for each spectral line) which consists of an addition of these three velocity channel maps.

The channel maps and the images have been computed for mosaics composed of the eight observed IFU fields (see Figure 1), and cover the emission of the HH 111 jet at distances $\approx 24'' \rightarrow 50''$ from the outflow source. The mosaics have been built taking into account the offsets (given in Table 1).

In Figures 3–6 we show the images and velocity channel maps for $\text{[S II]} \lambda 6716+\lambda 6731$, $\text{H}_\alpha$, $\text{[N II]} \lambda 6548+\lambda 6584$, and $\text{[O i]} \lambda 6300+\lambda 6360$, respectively. In the $\text{[S II]}$ image (left frame of Figure 3) we see knots E through L, which can be clearly...
recognized comparing the image with the identifications of Reipurth et al. (1992) and Reipurth et al. (1997b).

In the channel maps of all of the observed lines, it is clear that there is a general trend of increasing jet width as a function of decreasing velocity (i.e., in all of the observed emission lines the jet becomes narrower as we go from the HVC to the MVC and to the LVC, see Figures 3–6). This result is in qualitative agreement with the observations of Riera et al. (2001), who found velocities decreasing away from the outflow axis in two long-slit spectra cutting the HH 111 jet at the approximate positions of knots D (not detected in the present observations) and F.

3.2. Width Versus Radial Velocity Dependence

In order to illustrate the broadening of the jet at lower (i.e., less negative) radial velocities, in Figure 7 we show the LVC–HVC channel map subtraction for the Hα line. This subtraction map shows that at all positions along the observed region of HH 111, the high radial velocity emission is restricted to a narrow, central region of the jet cross section.

One can quantify the width versus radial velocity dependence by measuring the FWHM of the emission on the HVC, MVC, and LVC channel maps. For all of the emission lines, we measure the widths on the three channel maps at the positions of knots E, F, G, H, J, and L, integrating the emission in bins of 1″ along the jet bin (centered at the positions of the knots). The results of this procedure are shown in Figure 8, which shows the following features:

1. there is a systematic increase of width as a function of decreasing radial velocity for all the knots, and in all emission lines,
2. with the exception of the very broad knot E, there is a general trend of increasing width versus distance from the source,
3. in the lower excitation lines ([O i] and [S ii]), the widths are somewhat lower than in the higher excitation lines (Hα and [N ii]).

This last effect has been noted by Reipurth et al. (1997), who note that the Hα emission is broader than the [S ii] emission (see their Figure 6, in which they present an Hα–[S ii] subtraction.

Figure 6. Same as in Figure 3 but for [O i]λ6300+λ6360.

Figure 7. Low-velocity and high-velocity components mosaic subtraction in Hα emission. Left: LVC – 2 × HVC. Right: LVC – 4×HVC.

The determination of the FWHM for the knots G1, J, K1, and L using the [N ii] and [O i] lines show high uncertainties due to their low S/N (see Figures 5 and 6). In a few cases (knots G1, H, and K1; see Figure 8) we were not able to determine the [N ii] FWHM for some (if not all) velocity components.
some knots and for some velocity components
positions of knots E, F, G, H, J, and L
the knot L has the FWHM axis divided by a factor of 2.
electron density
for the HVC, MVC, and LVC maps. This ratio gives the
and that the
subtraction map
FWHM ("")
FWHM ("")
for the HH 111 jet.

Figure 8. FWHM (in arcseconds) of the emission on the HVC, MVC, and LVC channel maps for all of the emission lines (indicated on the top of the figure), at the positions of knots E, F, G, H, J, and L (indicated on the right of the figure). The FWHM has been obtained integrating the emission in bins of 1.0 along the jet (centered at the positions of the knots) and fitting a Gaussian to each knot longitudinal profile. For [N ii] line we found it difficult to adjust a profile due to low S/N in some knots and for some velocity components (see also Figure 5). For these cases, the FWHM appears in the histogram as an zero. The Hα and [N ii] histograms for the knot L has the FWHM axis divided by a factor of 2.

Superimposed on the spatial distribution of the electron density are the (logarithmic spaced) iso-contours of the [S ii] λ6716+λ6731 integrated intensity. The integrated map (left) shows that the electron density ranges from \( \sim 1.5 \times 10^3 \) cm\(^{-3}\) at knot E (at \( \sim 26 \) arcsec from the outflow source) up to \( 5 \times 10^3 \) cm\(^{-3}\) in knot F (at \( \sim 2''5 \) from knot E; see Figure 9). It then drops to \( \sim 2 \times 10^3 \) cm\(^{-3}\) between knots F and H. In knot H, the electron density has a strong peak of \( n_e \sim 3.5 \times 10^3 \) cm\(^{-3}\).

Interestingly, the electron density maps of the three velocity channels show systematically increasing densities for decreasing radial velocities. This is can be clearly seen at the positions of knots E, F, and J. Also, an increase in \( n_e \) can be seen in the region between knots F and G when going from the MVC to the LVC electron density maps (see the two frames on the right of Figure 9).

3.3. The [S ii] 6716/6731 Line Ratios

In Figure 9 we present the spatial distribution of the [S ii] λ6716/[S ii] λ6731 line ratio for the integrated line profiles and for the HVC, MVC, and LVC maps. This ratio gives the electron density \( (n_e) \) of the medium Osterbrock (1989). For calculating \( n_e \) we assume a temperature of \( 10^4 \) K, consistent with the temperature of \( \sim 1.3 \times 10^4 \) K found by Podio et al. (2006) for the HH 111 jet.
3.4. Knot E

We now focus on the interesting structure of knot E (at \( \approx 26'' \) from the source, see Figures 3–7). The structures observed in the images and channel maps of this knot are shown in Figure 10.

We see that in the H\( \alpha \) and [N \( \text{ii} \)] images (2nd and 3rd rows of the far left column of Figure 10) knot E shows two side-by-side peaks. These peaks have been observed in previous ground-based (Reipurth et al. 1992) and HST (Reipurth et al. 1997) H\( \alpha \) images of HH 111. Most interestingly, the two side-by-side peaks are well separated in the LVC H\( \alpha \) and [N \( \text{ii} \)] maps (right column of Figure 10), approach each other in the MVC map, and merge into a single, central peak in the HVC map. Therefore, we find that the two side-by-side peaks (previously observed in H\( \alpha \) images, see Reipurth et al. 1997) actually enclose a fainter, higher radial velocity emission region.

In the lower excitation [S \( \text{ii} \)] and [O \( \text{i} \)] lines, knot E shows two low intensity side-by-side peaks only in the LVC maps (1st and 4th rows of the far right column of Figure 10), and these peaks are not present in the MVC and HVC maps. The images of knot E in these lines (1st and 4th rows of the far left column of Figure 10) show a conical structure which resembles the MVC emission.

4. SUMMARY

We have obtained IFU spectra of the HH 111 jet at distances of 24 \( \rightarrow 49'' \) from the outflow source. From the spectra, we obtain position–velocity cubes for the [S \( \text{ii} \)] 6716, 6731; H\( \alpha \); [N \( \text{ii} \)] 6548, 6583; and [O \( \text{i} \)] 6300, 6360 emission lines.

We find a number of interesting results.

1. We find that for all emission lines we have an increase in the observed width of the jet for decreasing radial velocities. This effect can be seen directly in the velocity channel maps (Figures 3–6), in subtractions of pairs of velocity channel maps (Figure 7) or more quantitatively in the widths measured for the jet knots (Figure 8). A broadening in the HH 111 jet for decreasing velocities has been previously observed by Riera et al. (2001), and a qualitatively similar effect is seen in the CO emission (but at widths in excess of \( \approx 10'' \), see Lefloch et al. 2007).

2. We find that the HH 111 jet is narrower in the lower ([S \( \text{ii} \)] and [O \( \text{i} \)]) than in the higher (H\( \alpha \) and [N \( \text{ii} \)]) excitation lines at the vicinity of some knots (namely, knots E, F, K1, and L). This effect has been previously seen in the H\( \alpha \) and [S \( \text{ii} \)] HST images of Reipurth et al. (1997). These previous observations suggested that we might be seeing a sheath of non-radiative shocks (seen only in H\( \alpha \)) surrounding the HH 111 jet beam, but the detection of broad [N \( \text{ii} \)] emission indicates that the shocks in the sheath are indeed radiative.

3. From the [S \( \text{ii} \)] 6716/6731 line ratio we systematically find larger electron densities at lower radial velocities (see Figure 9).

4. The “twin peak” structure of knot E is clearly seen in the H\( \alpha \) and [N \( \text{ii} \)] images, but these two peaks merge into a central peak in the [O \( \text{i} \)] and [S \( \text{ii} \)] images. In all of the lines, the twin peaks are seen at low radial velocities (see the LVC maps of Figure 10), but they approach and merge into a single peak at higher radial velocities.

These characteristics can be qualitatively explained in terms of an “internal working surface” model, in which the knots are produced as a result of an outflow velocity time-variability. In such a model, the variability produces pairs of shocks that travel down the jet beam, producing a high pressure region that ejects material into the cocoon of the jet. The observations of larger widths for the higher excitation emission would then be interpreted as higher velocity shocks produced by the material in this sideways ejection against a slower moving cocoon. The low excitation emission would be interpreted as coming from
Figure 10. From left to right: integrated emission, HVC, MVC, and LVC for (from top to bottom) \([\text{S}\ \text{ii}]\), \(\text{H}\alpha\), \([\text{N}\ \text{ii}]\), and \([\text{O}\ \text{i}]\) for field 8 which contains knot E. The axes are in arcseconds and indicate the distance from the driving source. The maps are in arbitrary units (as seen at the color bars).
lower velocity shocks within the jet beam (produced by the outflow velocity variability).

The shock structure of internal working surfaces was described by Raga et al. (1990), and numerical simulations have been done for reproducing Hα images (Raga et al. 2002b) and long-slit spectra (Masciadri et al. 2002) of the HH 111 jet. The data presented here clearly provide a substantial increase in the observational constraints, which should be a challenging test for future models of jet knots produced by an outflow variability or by other mechanisms (see e.g., Micono et al. 1998). In particular, our data will give interesting constraints on the nature of the cross section of the outflow (Raga et al. 2011) or of the possible presence of two distinct components (Tejíleán et al. 2014).

We can speculate that MHD effects might be present, and might help to shape the morphology of the HH 111 emission knots as well as their line profiles. It is worth noting that recent and sophisticated MHD models predict that beam recollimation (by the hoop stress) plays an important role in order to enhance the brightness near the jet axis, as well as to accelerate the inner jet beam, making it faster than the surrounding jet material. This general result was obtained by Tejíleán et al. (2014), Hansen et al. (2014), and Staff et al. (2015), in spite of the differences in the initial setup in these works. In Hansen et al. (2014), a pure toroidal magnetic field is used to study the jet propagation, while the disk wind solution is incorporated in the models from Staff et al. (2015) and Tejíleán et al. (2014), who actually introduced a two component (stellar jet plus disk wind) flow.

Another feature shown by some HH jets (including some of the knots studied here) is an increase of the FWHM of the jet beam with distance from the driving source. This feature has been predicted in the models presented by Tejíleán et al. (2014) and compared with available data from RW Aur, HH 30, and HL Tau, while the solutions presented in Staff et al. (2015) were compared with data from DG Tau, HN Tau, RW Aur, and UZ Tau. In both cases, the distances covered by the simulations were suitable for the study of the microjets (~100 AU). Whether or not these effects are still important farther away from the driving source (knot E is at ~10,000 AU from the VLA 1 source) is an issue that should be addressed properly in future work.

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Facilities: Gemini: Gillett.

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