ADAPTIVE-OPTICS-ASSISTED NEAR-INFRARED SPECTROSCOPY OF SVS 13 AND ITS JET

C. J. Davis  
Joint Astronomy Centre, 660 North A‘ohoku Place, Hilo, HI 96720; c.davis@jach.hawaii.edu

B. Nisini  
INAF—Osservatorio Astronomico di Roma, via di Frascati 33, 00040 Monteporzio Catone, Italy

M. Takami and T.-S. Pyo  
Subaru Telescope, 650 North A‘ohoku Place, Hilo, HI 96720

M. D. Smith  
Armagh Observatory, College Hill, Armagh, Northern Ireland, UK

E. Whelan and T. P. Ray  
Dublin Institute Advanced Studies, 5 Merrion Square, Dublin 2, Ireland

A. Chrysostomou  
Centre for Astrophysics Research, University of Hertfordshire, Hatfield, Herts AL10 9AB, UK

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ABSTRACT

We present long-slit H- and K-band spectroscopy of the low-mass outflow source SVS 13, obtained with the adaptive-optics-assisted imager-spectrometer NACO on the VLT. With a spatial resolution of <0.025 and a pixel scale of 0.25 and a pixel scale of 0.027, we precisely establish the relative offsets of H2, [Fe ii], CO, H i, and Na i components from the source continuum. The H2 and [Fe ii] peaks are clearly associated with the jet, while the CO, H i, and Na i peaks are spatially unresolved and coincident with the source, as is expected for emission associated with accretion processes. The H2 profile along the slit is resolved into multiple components, which increase in size, although they decrease in intensity, with distance from the source. This trend might be consistent with thermal expansion of packets of gas ejected during periods of increased accretion activity. Indeed, for the brightest component nearest the source, proper-motion measurements indicate a tangential velocity of 0.028 yr^{-1}. It therefore seems unlikely that this emission peak is associated with a stationary zone of warm gas at the base of the jet. However, the same cannot be said for the [Fe ii] peak, for which we see no evidence for motion downwind, even though radial velocity measurements indicate that the emission is associated with higher jet velocities. We postulate that the [Fe ii] could be associated with a collimation shock at the base of the jet.

Subject headings: ISM: Herbig-Haro objects — ISM: jets and outflows — stars: individual (SVS 13) — stars: pre–main-sequence

1. INTRODUCTION

With high spectral resolution observations one can probe emission-line regions at the bases of jets and thereby hope to distinguish between—or at least constrain—models of jet collimation and acceleration. Indeed, there are a number of diagnostic atomic and molecular lines in the near-infrared (near-IR) that are particularly useful for studying the more deeply embedded young stellar objects (YSOs; Davis et al. 2001, 2003; Pyo et al. 2002; Whelan et al. 2004; Takami et al. 2005; Nisini et al. 2005). Most notable are the [Fe ii] and H2 lines, which are found to be bright at the base of a number of jets from Class I protostars. The emission is usually blueshifted, the [Fe ii] tracing a higher velocity component than the H2, and offset along the axis of the jet by a few tens of astronomical units. These two species trace very different flow components: the [Fe ii] derives from hot, dense, partially ionized gas (T ~ 10,000 K), while the H2 traces low-excitation, shocked (or possibly fluoresced) molecular gas (T ~ 2000 K). These forbidden emission-line (FEL) and molecular hydrogen emission-line (MHEL) regions exist within a few hundred astronomical units of each outflow source and are therefore either within or very close to the primary jet collimation and acceleration zone. The H2 may be entrained along the walls of the [Fe ii] jet, or it may trace a cooler molecular disk wind ejected at larger disk radii.

As a further step toward a better understanding of these emission-line regions, here we present adaptive-optics (AO)–corrected H- and K-band spectra of the MHEL and FEL regions associated with SVS 13, the driving source of the HH 7-11 Herbig-Haro (HH) jet and molecular outflow (Chrysostomou et al. 2000; Bachiller et al. 2000). The source is located in the L1450 molecular cloud near the active low-mass star-forming region NGC 1333 in Perseus. SVS 13 is assumed to be at a distance of 300 pc (Cernis 1990; de Zeeuw et al. 1999); modeling of the HH bow shocks in the flow implies an inclination angle of ~30°–50° with respect to the plane of the sky (Hartigan et al. 1987; Smith et al. 2003). The VLT observations presented here complement the earlier UKIRT observations of Davis et al. (2001, 2003), which yielded important kinematic information, although they lacked spatial resolution, and the more recent Subaru Telescope
observations of Takami et al. (2005), in which a thorough excitation analysis has been made.

2. OBSERVATIONS

The combination of NAOS and CONICA at theEuropean Southern Observatory (ESO) Very Large Telescope (VLT) provides AO correction using an IR-bright guide star in conjunction with near-IR spectroscopy. In our case, the jet source itself, SVS 13 (\(J \sim 11.6, K \sim 8.1\)), was used as the AO reference star. The S27-3-SH and S27-3-SK modes used yield a wavelength coverage of 1.37–1.72 and 2.02–2.53 \(\mu\)m at a spectral resolution of \(R \sim 1500\). The slit width was 0.172, the pixel scale along the slit was 0.0270 ± 0.0002 (measured from the offsets of a bright star along the slit), and the slit length was 28″. The \(H\) and \(K\)-band observations were conducted in service mode on 2005 January 13 and 17, respectively. With the slit aligned along the SVS 13 jet axis (position angle = 159° east of north), the telescope was nodded between the object and blank sky six times in each wave band. Two 150 s exposures were obtained at each position.

The individual spectral images were bad-pixel-masked and flat-fielded using observations of a halogen lamp. Sky exposures were subtracted from object frames before wavelength calibration using argon arc spectra. Starlink FIGARO routines were used to correct for distortion along the slit axis, so that the wavelength calibration was constant along the spatial axis (along columns). The continuum associated with SVS 13 was then registered along the slit axis before co-addition of the data. Individual sky-subtracted images were compared to the shifted and co-added data in each wave band to make sure that the spatial resolution had not been compromised by this shifting and averaging process. From Lorentzian fitting to profiles taken through the SVS 13 continuum associated with SVS 13 was then registered along the slit axis before co-addition of the data. Individual sky-subtracted images were compared to the shifted and co-added data in each wave band to make sure that the spatial resolution had not been compromised by this shifting and averaging process. From Lorentzian fitting to profiles taken through the SVS 13 continuum at various wavelengths, the full width at half maximum (FWHM) was found to vary between 0.35 and 1.72, the pixel scale along the slit, and the slit length was 28″. The \(H\)- and \(K\)-band observations were conducted in service mode on 2005 January 13 and 17, respectively. With the slit aligned along the SVS 13 jet axis (position angle = 159° east of north), the telescope was nodded between the object and blank sky six times in each wave band.

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3. NEAR-IR SPECTROSCOPY

\(H\)- and \(K\)-band spectral images are shown in Figures 1, 2, and 3. To more clearly show the line-emission features, the SVS 13 continuum has been removed from each image, row by row, by fitting a second-order polynomial to wavelength regions free of line emission. However, residual shot noise associated with the bright continuum does remain in some parts of the data.

As is the case in other spectroscopic studies (Davis et al. 2001; Takami et al. 2005), extended emission is observed only in \(H_2\). However, for the first time, faint \(H_2\) emission is also observed in the SVS 13 counterjet (positive offsets in Fig. 3). The \(H_2\) Brackett lines in the \(H\) band and the \(CO\), \(Br\), and \(Na\) lines in the \(K\) band all appear as compact peaks coincident with the continuum. The [Fe II] peak is also compact, although it is slightly offset along the blueshifted jet.

In Figure 4 we compare plots of the \(H_2\) 1–0 \(S(1)\) emission. Negative offsets are along the southeastern, blueshifted jet axis. The continuum associated with SVS 13 has been fitted and removed (see text).

![Figure 1: Contour plot extracted from the K-band spectral image showing the H2 1–0 S(1) emission. Negative offsets are along the southeastern, blueshifted jet axis. The continuum associated with SVS 13 has been fitted and removed (see text).](image-url)
units, with the source continuum; we see no evidence for CO or H\textsubscript{i} components associated with the outflow.

The [Fe\textsubscript{ii}] profile is, on the other hand, marginally resolved. In the echelle data of Davis et al. (2003) and Takami et al. (2005) a radial velocity of \(\approx 140\) km s\(^{-1}\) with respect to the systemic velocity was assigned to this component. Presumably this compact, high-velocity emission derives from a discrete knot or shock front near the base of the jet, rather than from an extended emission region.

In the H\textsubscript{2} data, we see an interesting trend in which the size (FWHM) of each component increases with distance from the

Fig. 2.—Contour plots extracted from the \(H\) and \(K\)-band spectral images showing emission in select lines. The continuum has again been removed.
source (Table 1). Moreover, if the H₂ and [Fe ii] trace the same jet material, this trend extends to the [Fe ii] data; the closer a component is to the source continuum, the less extended it appears to be. The H₂ components also decrease in intensity with distance. This behavior could be explained by the cooling, decreased excitation, and expansion of “packets” of gas as they travel away from the source. A decrease in gas density and excitation temperature is inferred from the excitation analysis of the line profiles through the continuum adjacent to each line.

![Profile plots showing the distribution of H₂ 1–0 S(1) and [Fe ii] 1.644 μm emission along the slit. The fine gray lines show Lorentzian fits to the data; one fit for the [Fe ii] peak, but five fits to the H₂ data. The dashed line shows the profile through the continuum adjacent to each line.](image)

![Continuum-subtracted K-band spectral image with a gray-scale stretch set to show the faint H₂ emission along the slit.](image)

### Table 1: Parameters from the Profile Fitting

| Linea | Offset (arcsec) | Offset (AU) | FWHM (arcsec) |
|-------|----------------|-------------|---------------|
| H₂-1  | 0.29 ± 0.009   | 87.8 ± 3    | 0.44          |
| H₂-2  | 1.19 ± 0.018   | 358 ± 6     | 1.3           |
| H₂-3  | 2.0 ± 0.1      | 600 ± 30    | 1.5           |
| H₂-4  | 4.8 ± 0.2      | 1428 ± 30   | 1.8           |
| H₂-5a | 0.28 ± 0.1     | 86 ± 30     | 1.0           |
| [Fe ii] | 0.061 ± 0.004 | 18.3 ± 1.2  | 0.29          |
| Brγ   | 0.001 ± 0.003  | <0.9        | 0.19          |
| CO    | 0.004 ± 0.003  | <1.2        | 0.17          |

a Lorentzian fits to five components in H₂ (see Fig. 4); a single Lorentzian is fitted to the single peak in each of the extracted CO, [Fe ii], and Brγ profiles.  
b Possible component in the redshifted counterflow (positive offsets in Fig. 4).

Takami et al. (2005). A similar trend is also seen in small-scale jets from T Tauri stars (Bacciotti et al. 2000; Woitas et al. 2002).

Directly behind a fast-moving shock the very hot \( T \sim 10^7 – 10^8 \) K postshock gas will radiatively cool very rapidly, before the region has time to expand. However, the bulk of the material in the gas packet, behind the shock-front working surface, may expand adiabatically. If the pressure inside the warm \( T \sim 10^5 \) K postshock gas packet approaches that of the surrounding medium as it expands, decreasing by a factor of \( \sim 10–100 \), and if at the same time the gas temperature in the packet decreases by a factor of 3–10 as it travels a distance of a few arcseconds (equivalent to the interknot spacing), then the packet might be expected to increase in volume by a factor of 1–30 or in diameter by a factor of 1–3. Isothermal expansion would result in greater expansion, while a lower pressure gradient would suppress expansion. Either way, the ratio is potentially consistent with the relative sizes of the H₂ components in Table 1.

### 4. Proper Motions

By comparing the VLT data with the earlier Subaru observations of Takami et al. (2005) we can measure, or at least set upper limits on, the proper motions (PMs) of the [Fe ii] and H₂ components. The Subaru observations, although at higher spectral resolution \( R \sim 1.1 \times 10^6 \), were not obtained with AO correction. However, the Subaru pixel scale \( 0.060 \pm 0.002 \) does fully sample the seeing and the same slit position angle \( 159^\circ \) was used with both instruments. Offsets of emission features along the jet axis can therefore be measured accurately, and a direct comparison can be made between the VLT and Subaru observations (see Table 2). Note, however, that the Subaru slit was slightly wider than the VLT slit, \( 0.30 \) versus \( 0.172 \).

1. In the VLT H-band observations, the single [Fe ii] component in Figure 4 may correspond to the high-velocity peak seen in the Subaru data, for which Takami et al. (2005) assign a radial velocity of \( \approx 140 \) km s\(^{-1}\). Gaussian fitting yields an offset of \( 0.10 \pm 0.01 \) for the Subaru peak. Curiously, the offset of the VLT peak in Table 2 implies that this feature has moved upwind, i.e., closer to the source. We certainly see no evidence for pronounced movement away from the jet source.

2. In the Subaru K-band echelle data two velocity components are resolved in H₂: a bright, low-velocity component (LVC) blueshifted by \( \approx 30 \) km s\(^{-1}\) that is spatially offset along the jet by \( 0.23 \pm 0.01 \) and a fainter, more diffuse, high-velocity component (HVC) blueshifted by \( \approx 100 \) km s\(^{-1}\) that is offset by \( 1.27 \pm 0.02 \). These two peaks, which are spatially as well as kinematically separate, probably correspond to the first two components in
been Gaussian-smoothed to the spatial resolution of the Subaru data. The VLT observations have been brighter than the VLT component 1. Given the wider Subaru slit, one would expect this to be the case if the LVC traced a moving shock front in a heavy jet.

VLT slit, one would expect this to be the case if the LVC traced a broader flow component than the HVC. For the LVC/component 1, the offsets in Table 2 indicate a shift downwind of 0.028 ± 0.007 arcsec/yr. Given the wider Subaru slit, one would expect this to be the case if the LVC traced a broader flow component than the HVC. For the LVC/component 1, the offsets in Table 2 indicate a shift downwind of 0.028 ± 0.007 arcsec/yr over the 783 day time interval between the Subaru and VLT observations. However, the HVC/component 2, like the high-velocity [Fe ii] component, again exhibits no measurable PM away from the source.

Given the radial velocities of the HVC and LVC and assuming an inclination angle of 40° to the line of sight and a distance of 300 pc to SVS 13, then over the time period between the observations the H2 LVC and HVC should have moved by 0.013 (2 AU) and 0.018 (53 AU) on the sky, respectively, while the [Fe ii] feature should have moved by 0.018 (53 AU). Clearly, only the H2 LVC has a PM consistent with the observed radial velocity. Such consistency is expected if, for example, the gas is accelerated by a fast-moving shock front in a heavy jet.

The apparent lack of movement of the H2 HVC could result from (1) the larger errors associated with the positional measurements of this fainter, more extended feature; (2) the blending of component 2 with component 3 (Table 1) in the lower spatial resolution Subaru data, so that the overall peak appears shifted downwind; or (3) the fact that the time interval between the observations is comparable to the molecular cooling time and therefore the timescale for morphological change, which could introduce unknown errors on the PM measurements.

The lack of a measurable PM in the [Fe ii] peak is more difficult to explain. If the [Fe ii] peak were associated with ejected clumps or bullets, then one would perhaps expect to see additional components along the flow axis (as is the case in H2). Instead, the [Fe ii] is confined to a single, very compact peak at the jet base. The [Fe ii] could be associated with a stationary, collimating shock, similar to that described in the models of Ouyed & Pudritz (1994). If this is indeed the case, the collimation point would be at a distance of ~20 AU from the source.

On the other hand, we may be observing two completely independent [Fe ii] peaks in the Subaru and VLT data, rather than the same near-stationary feature. The Subaru feature may have faded, to be replaced by a new peak in the VLT observations. The cooling time, from 20,000 to 7000 K for dense (10^5−10^6 cm^-3), postshock gas will be of the order of weeks or even days (Smith 2003), so morphological changes are certainly possible. This might explain the apparent “upwind” movement of this feature.

A number of groups have attempted to image the emission-line region at the base of the SVS 13 outflow. Davis et al. (2002) used a Fabry-Pérot (FP) etalon to “boost” the line/continuum ratio in their data. The H2 emission at the jet base is certainly evident in their image, although the poor spatial resolution of their observations (~1") somewhat limits their ability to extract spatial information. They do collapse their image along an axis perpendicular to the jet and attempt to subtract the continuum emission from the resulting profile (their Fig. 4). They identify a “peak” and a “plateau” along the jet axis, which may correspond to H2 components 2 and 3 in the VLT data. We list the offsets of these features in Table 2.

Noriega-Crespo et al. (2002) used the HST to obtain high spatial resolution near-IR images of the HH 7-11 outflow. They present a continuum-subtracted H2 image of SVS 13 (their Fig. 3). However, residual artifacts left over from the continuum subtraction, in the bright core but also in a ring of radius ~1", make identifying features within 0.5"−1.0" of SVS 13 more or less impossible. However, they do detect and resolve the H2 emission in the flow at offsets of >1". Within 1"−2" of SVS 13 the H2 appears to comprise at least two knots superposed on a patch of moderately extended emission, suggesting a broad opening angle for the H2 flow. Component 2 in the VLT data (the HVC in the Subaru

![Fig. 5.—Comparison of the Subaru (gray) and VLT (black) H2 profiles. The dashed lines show the adjacent continuum data. The VLT observations have been Gaussian-smoothed to the spatial resolution of the Subaru data.](image-url)
observations) may therefore constitute two knots; we give a combined offset for these two features (measured along the VLT/Subaru slit axis) in Table 2 for reference.

Overall, the results from these two imaging surveys can only be used to confirm the presence of emission features. Uncertainties in the continuum subtraction limit their usefulness when measuring PMs. Notably, the compact LVC evident in both the Subaru and VLT spectroscopy was not extracted from the FP or Hubble Space Telescope (HST) images.

Clearly, follow-up observations with the NACO system are needed to better constrain the PM measurements discussed above, particularly for the [Fe ii] peak and the H2 components further downwind. Confirmation of the "stationary" [Fe ii] peak would add credence to the collimation-shock interpretation. If we also ultimately find that the H2 peaks do not move, then in H2 we could be witnessing a warm, stationary region or perhaps a turbulent mixing layer between the jet and ambient medium at the jet base through which jet material flows, rather than discrete bullets or clumps ejected during episodes of increased accretion. However, given the tentative result for the LVC, and the fact that knots in Herbig-Haro jets and molecular flows typically do have large PMs (Reipurth & Bally 2001), for H2 at least, this seems unlikely.

Finally, we mention that the dynamical age of the H2 LVC/component 1 in the VLT data, when derived from its PM and offset in Table 1, is ~10 yr. Notably, the optical outburst reported by Eisloeffel et al. (1991) occurred roughly 15 yr before the observations reported here. Our results are thus reasonably consistent with the H2 LVC being produced by this outburst and the associated increase in accretion.

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