PROPER MOTIONS IN THE KNOTTY, BIPOLAR JET IN HEN 2-90

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ABSTRACT

Using second-epoch *HST* imaging of the unusual, bipolar jet source Hen 2-90, we have discovered proper motions of 0.03 arcsec yr^{-1} in the jet knots. Combining the proper motion with the knots' radial velocity measured from ground-based long-slit data, we find that the jet speed is roughly 150-360 km s^{-1}, the source distance is 1-2.5 kpc, and the inclination (to the sky-plane) of the jet axis is $\theta = 10° - 4°$, although smaller values of θ and larger values of the jet speed and distance are not ruled out. A comparison of the [OIII] and [NII] images shows the central obscuring disk structure directly. The disk, seen nearly edge-on, is embedded within a low-excitation circumstellar region extending from the equator up to a latitudinal angle of about $\pm 62°$, with the remaining latitudinal angular space being occupied by a biconical high-excitation region whose symmetry axis is aligned along the jet. The jet is at least 1400 yr old; the knots are being ejected at the rate of one pair roughly every 35-45 years (independent of the tilt angle and distance to Hen 2-90), and accretion is still occurring since the youngest jet material is only $\sim$10 yr old. The jet can be plausibly driven by an accretion disk around a low-mass companion in an eccentric orbit with a period of $\sim$40 yr, with increased accretion during periastron passage producing the jet knots.

Subject headings: stars: AGB and post-AGB — stars: mass loss — stars: winds, outflows — planetary nebulae: individual (Hen 2-90) — circumstellar matter — ISM: jets and outflows

1. Introduction

In spite of extensive study, stellar evolution from the Asymptotic Giant Branch (AGB) towards the Planetary Nebula (PN) stage is poorly understood. The drastic changes observed in circumstellar structure and kinematics (from spherical, slowly expanding AGB envelopes to bipolar PNe with high polar velocities) are particularly puzzling. Recently, based on results of an unbiased survey of young PN morphologies using *HST*, Sahai & Trauger (1998) have hypothesised that high-speed jet-like outflows are the primary agent for producing these changes.

One of the objects in this survey, Hen 2-90, has been found to possess a highly collimated bipolar jet and a central bipolar nebula bisected by a flaring disk-like structure (Sahai & Nyman 2000, SN00). Thus Hen 2-90, although long considered to be a PN, has a remarkable morphological resemblance to the jet/disk systems in classical young stellar objects (YSOs) (e.g. HH30, Burrows et al. 1996). The linear jet in Hen 2-90 showed at least six pairs of emission knots located symmetrically on either side of the nebular center, with a tangential speed of $\sim$150 km s^{-1}, estimated from the jet opening angle of about 4°. We report here the successful detection of the knots' proper motions by re-imaging this object with *HST* two years after its discovery, as well as ground-based spectroscopic data, which enable us to estimate the intrinsic jet speed and inclination and the source distance.

2. Observations and Results

The following exposures of Hen 2-90 were obtained with the PC camera of WFPC2 on Sept. 25, 2001 – 5 s and 2×600 s with filter F656N (Hα), and 10 s and 2×600 s with each of the filters F658N ([NII]λ6584), F502N ([OIII]λ5007)) and F487N (Hβ). A 2-point dither pattern was used for the long exposures. A geometric distortion correction was applied to

the pipeline-calibrated images, which were then registered to subpixel accuracy, followed by cosmic-ray removal and correction of staurated pixels (as in SN00). Ground-based Hα (900 s) and [NII] (3×240 s) images were taken on Jan 27,'00 and Mar 26,'00, respectively, with ESO's MPI 2.2m/ Wide-Field-Imager and NTT/ EMMI cameras using CCD # 56 (2046×4098, 0.″238 pixels) and #13 (2086×4098, 0.″267 pixels); the seeing was 0.″8 and 0.″9. The nights were not photometric and no standards were observed. A long-slit 360 s spectrum was obtained with EMMI using Grating 6 with a central wavelength of 670 nm through a $1'' \times 30''$ long slit (seeing was $0.9''$) oriented along the jet. The spectra are sampled at a resolution of 0.3096 Å pix^{-1}. The wavelength calibration of the long-slit spectra was done using a He Ar lamp. All images have been bias-subtracted and flat-fielded.

In SN00, we inferred the presence of a flared, edge-on equatorial disk obscuring the central star in Hen 2-90. This disk can now be seen directly in a composite color image made from the F502N (green) and F658N (red) images (Fig. 1). The disk extends (laterally) well beyond the central bipolar source, and appears to be embedded within a low-excitation (i.e with a relatively low [OIII]/[NII] intensity ratio) circumstellar region extending from the equator up to a latitudinal angle of about $\pm 62°$. A biconical high-excitation (i.e. high [OIII]/[NII] intensity ratio) region with its symmetry axis aligned along the jet occupies the remaining latitudinal angular region. The low and high-excitation regions most likely result from anisotropic illumination of the nebula by ultraviolet radiation from the hot central star, with the biconical region surrounding the jet being preferentially illuminated. The linear jet features (labelled J, J') are the highest excitation features in the inner region; whereas knots *a* and *a'* show a layered structure, with an inner (outer) high (low) -excitation part. In the *HST* images, the (surface-brightness limited) jet extent in Hα and [NII] is roughly similar, greatly exceeding that seen in [OIII] ($\sim$3.″2, i.e. up to knots *b, b'*).

The subsampled Hα images (by a factor 2, giving a pixel size of 22.785 mas) from both

epochs were registered using 3 field stars on the PC chip. Intensity cuts through the jets in the two images (Fig. 2) clearly show that the knots have moved outward (the reference point for these cuts is assumed to lie on the jet axis midway between knots *c* and *c'* in the first epoch image). The locations of knots *a–d* and *a'–d'* in each image was estimated using gaussian fits to the knot peaks in the images; we find the radial offset of each of these knots to be larger by 2-3 pix in the 2nd epoch image (measurement uncertainty: $\sim \pm 0.3$ pix). The average knot proper motion is 2.6 pix over 2 years, i.e. 30 mas yr^{-1}.

Although the jet knots appear to be displaced fairly symmetrically about the central source, there are measurable asymmetries in their distribution. We measure differences between the radial offsets for knots *a-a', b-b', d-d', e-e'* and *f-f'* of about 120, -70, 360, 230, and 200 mas from the *HST* [NII] image (Fig. 3). Additional faint, relatively diffuse, knots can be seen beyond *f, f'* with even larger asymmetric displacements about the center – e.g. on the SE side there are two knots, *g'* and *h'*, at 9.″3 and 11.″1, whereas on the NW side there is a local minimum at 9.″3 and a single wide knot *gh* extending from 9.″7-11.″7. Beyond $\sim$12″, the jet in the *HST* image becomes rather faint, but its knotty nature is visible (e.g. knots *ii' and jj'*) in cuts taken from the NTT [NII] image (Fig. 3). The above asymmetries could be due to weak interaction of the jet with a tenuous *circumstellar* medium characterised by a radially-decreasing density, but probably not with the *interstellar* medium because in the latter case, the decreasing jet-to-ambient density ratio would produce increasing perturbations of the jet morphology at larger radial distances, not seen in our data (Lee & Sahai, in preparation). Small differences ($\sim$6%) in the launch velocities of the individual knots (consistent with our proper motion measurement errors) could also lead to the observed asymmetries.

The long-slit [NII]λ6584 spectrum, displayed along-side the *HST* F658N image (Fig. 4), clearly shows blue-shifted (red-shifted) gas in the NW (SE) sides of the bipolar jet. We

infer that the jet's NW (SE) side is tilted towards (away from) us. SN00 infer the same tilt from the asymmetric brightness distribution of the central bipolar nebula, assumed to result from an optically-thick central tilted disk which is orthogonal to the jet axis and partially obscures the SE lobe. Our inferred tilt is opposite of that recently reported by Guerrero et al. (2001) (Getal01) from their long-slit spectroscopy. We have confirmed the jet's specific orientation in our long-slit spectra unambiguously by comparing the relative fluxes of particular knots in the *HST* [NII] image [namely *b*, *c*, & *d* (on the SE side), which are significantly larger than those of knots *b'*, *c'*, & *d'* (on the NW side)] with their counterparts in the long-slit spectra. The larger brightness of the red-shifted knots, relative to the blue-shifted ones, also explains why the red peak is brighter than the blue one in the double-peaked emission lines observed towards the central nebula by Getal01.

The jet shows a constant radial outflow velocity, V_r=26 km s^{-1}, along most of its length (Getal01 find a similar result). Since the tilt of the jet axis to the sky plane, θ equals $\tan^{-1}(V_r/V_t)$, where V_t=D α is the tangential velocity, α is the proper motion and D the source distance, we find that the intrinsic jet speed, V_{jet}=360 (150) km s^{-1}and θ=4°.2 (10°.3) if D=2.5 (1) kpc. The jet speed in He 2-90 is comparable to the range of values ($\sim$ 100 – 400 km s^{-1}) typically observed in YSO jets (e.g. Reipurth & Bally 2001) and the fast (and probably collimated) outflows in evolved stars (e.g. Alcolea et al. 2000). Assuming that the jet and disk axes are co-linear, and that the disk is geometrically thin and circular, we infer from the best-fit (by eye) ellipse to the disk in Figure 1, that $\theta \sim 8° - 10°$. This value is likely to be an *upper limit* because any disk flaring will increase the width of its projected elliptical shape. Thus the geometrically derived disk inclination supports our initial assumption that D$\sim$1–2.5 kpc and possibly larger (if $\theta < 4°$).

The ground-based [NII] & Hα images (not shown) show that the (surface-brightness limited) jet extent is about 2×40″. Using our measured proper motion of the knots, we find

that the minimum jet lifetime is 1400 yr and the knots are being ejected at the rate of one pair roughly every 35-45 years (independent of the tilt angle and distance to Hen 2-90).

The jet Hα surface brightness, S(Hα), is consistent with resulting from photoionisation by the central source – e.g. the ionising flux, N_i (photons/sec) at knot d (computed from the source luminosity and effective temperature given by SN00) is a factor 140 times larger than N_{obs}, the number of Balmer photons emitted per second from knot d (estimated from the Hα intensity and size of knot d), independent of the source distance. Since S(Hα) if found to vary with the radius, r, as $r^{-\gamma}$, where $\gamma \gtrsim 2.2$, N_i exceeds N_{obs} everywhere in the jet. Therefore, although shocked gas may be present in the jet knots, it is not needed for explaining the observed emission (unlike the YSO case).

3. Discussion: The Nature of the Hen 2-90 Jet

The formation (acceleration and collimation) of jets is not fully understood; however it is plausible that most jets are driven by accretion disks (e.g. Livio 1997). The highly-collimated, "pulsed" bipolar jet in Hen 2-90 adds both new excitement (because of its amazing similarity to a YSO jet) and a new mystery (because Hen 2-90 appears so far to be a unique object) to the subject of how astrophysical jets are produced. García-Segura, López, & Franco (2001) suggest that the Hen 2-90's jet knots are self-collimated gaseous structures in a strongly magnetised wind of the progenitor AGB star. We think that this model is invalid for Hen 2-90 because it predicts that the knots should be moving at the same speed as that of the AGB wind (typically $\sim$15–20 km s^{-1}), contrary to our inferred value ($\sim$150-360 km s^{-1}).

If the central engine for the jet in Hen 2-90 is indeed an accretion disk, then the accreting companion can either be a low-mass, main-sequence (MS) star or a white dwarf

(WD). This is because, on theoretical and empirical grounds, the speed of a jet driven from an accretion disk is expected to be of the order of the Keplerian velocity close to the central accreting object (Livio 1997). Although the range of values for the jet speed inferred in § 2 above suggests an MS star, higher values and a WD companion are not ruled out because of the uncertainty in the jet inclination. A binary central star provides a natural explanation for the roughly periodic knotty structure of the jet. If the binary orbit is eccentric, the knots may result from a modulation of the accretion process on the orbital time-scale (see Reipurth (2000) for more details on this mechanism in the YSO context). The modulation may affect the ejected mass and/or the ejection velocity. Variations in the latter can produce a series of shock structures within the jet (internal working surfaces) which may resemble the observed knots (e.g. Biro & Raga 1994). Detailed hydrodynamic simulations, needed to distinguish between mass and/or velocity variations as the mechanism for producing the knots, are in progress (Lee & Sahai 2002, in preparation).

Taking the binary period, P=40 yr, and typical masses of $0.6M_{\odot}$ for the primary and secondary, we find a semi-major axis a of 12 AU. The wiggle produced in the jet's direction because of the companion's orbital velocity (with amplitude V_{MS}), β=V_{MS}/V_{jet}, should not exceed the jet opening angle; we find that for an eccentricity e=0.5, V_{MS}=10.8 km s^{-1} giving $\beta = 2.4°$ for V_{jet}=260 km s^{-1}. The jet's minimum age implies that the accretion disk has been active for at least 1400 yr; accretion is still occurring since the youngest jet material is only ~10 yr old.

If the companion is a WD and the primary a cool red giant with dense mass outflow, then the requirements for accretion, jet activity, and nebular photoionisation are relatively easily met (Sahai et al. 2002, in preparation). E.g., the accretion rate from an AGB wind (with mass loss rate $\dot{M}_w$ at V_w km s^{-1}) onto a companion (mass M_c, radius R_c), is given by $\dot{M}_{acc} \approx 10^{-7}(M_c/M_{\odot})^2(\dot{M}_w/10^{-6}M_{\odot}\ \mathrm{yr}^{-1})$

$(V_{rel}/20\,\mathrm{km\ s^{-1}})^{-3}(V_w/20\,\mathrm{km\ s^{-1}})^{-1}(a/10^{14}cm)^{-2}M_\odot\ \mathrm{yr}^{-1}$ (where V_{rel} is the velocity of the companion relative to the dense wind) (Livio & Warner 1984). Since typically 1-10% of the accreted material can be directed into the jet (Livio 1997), the above rate is adequate for Hen 2-90's jet, which has $\dot{M}_{jet} \sim 10^{-8}M_\odot\ \mathrm{yr}^{-1}$(SN00). If, however, the companion is a MS star, then the primary star must be a post-AGB star with T_{eff} ~50000K, and it becomes necessary to invoke a "backflow" of circumstellar material during the post-AGB phase (Soker 2001) for accretion to power the current jet activity. In this scenario, the observed extended disk in Hen 2-90 could represent the "very slowly expanding (Vexp~1 km s^{-1})" dense equatorial outflow resulting from the binary interaction.

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REFERENCES

Biro, S. & Raga, A.C. 1994, ApJ, 434, 221

Burrows, C.J. et al. 1996, ApJ, 473, 437

Alcolea, J., Bujarrabal, V., Castro-Carrizo, A., & Sńchez Contreras, C. 2000, in Asymmetrical Planetary Nebulae II: From Origins to Microstructures, ASP Conf. Ser. 199, 347

García-Segura, G., López, J.A., & Franco, J. 2001, ApJ, 560, 928

Guerrero, M.A., Miranda, L.F., Chu, Y-H., Rodriguez, M., & Williams, R.M. 2001, ApJ, 563, 883

Livio, M. & Warner, B. 1984, Observatory, 104, 152

Livio, M. 1997, in Accretion Phenomena and Related Outflows, IAU Collq. 163, eds. D.T. Wickramasinghe, L. Ferrario & G.V. Bicknell (San Francisco: ASP), 845

Reipurth, B. 2000, AJ, 120, 3177

Reipurth, B. & Bally, J. 2001, ARAA, 39, 403

Sahai, R. & Nyman, L-Å 2000, ApJ, 537, L145

Sahai, R. & Trauger, J.T. 1998, AJ, 166, 1375

Soker, N. 2001, MNRAS 328, 1081

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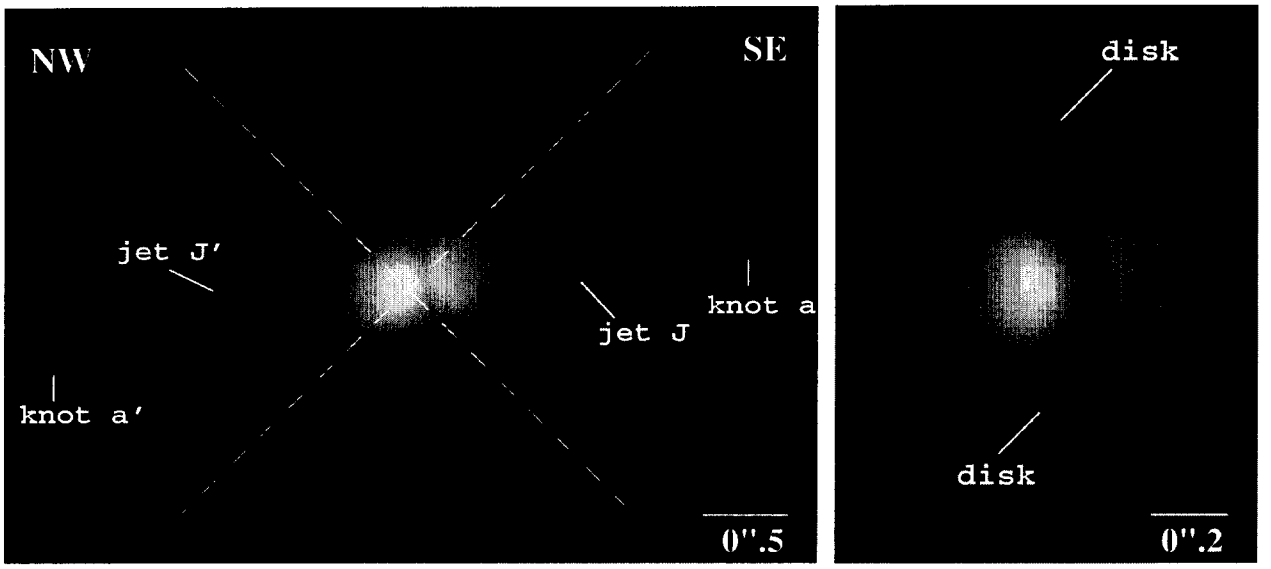

Fig. 1.— A a composite color image of the central region of Hen 2-90 made using the F502N (green) and F658N (red) *HST* images. Note the greenish disk-like structure embedded within a low-excitation circumstellar region (relatively red), and the biconical high-excitation region (relatively green) surrounding the jet. The dashed lines indicate the location of diffraction spikes due to the telescope optics.

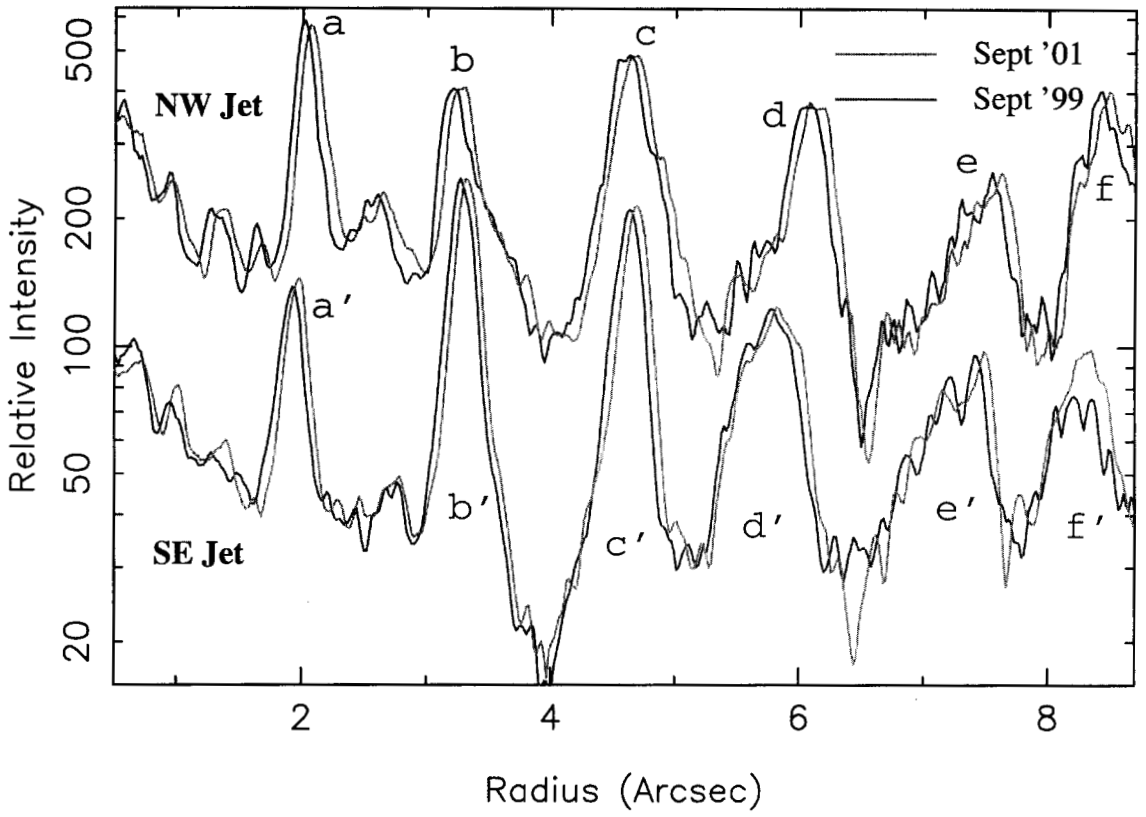

Fig. 2.— Radial Intensity cuts (using an angular wedge encompassing the jet width) along the jet in the Sep'99 (red) and Sep'01 (green) Hα images. The proper motion of the jet material is evident

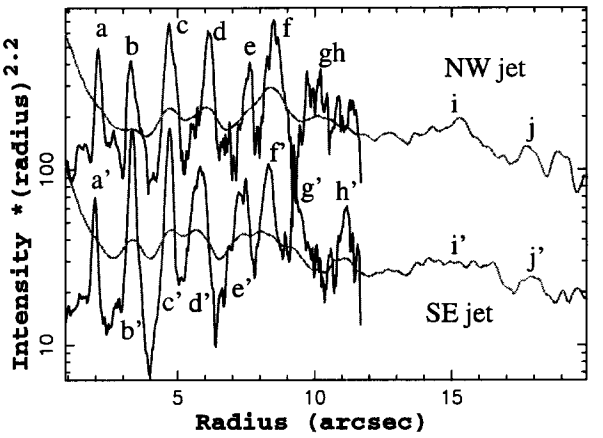

Fig. 3.— Intensity cuts along the jet in the [NII] *HST* (red) and NTT (green) images, showing asymmetries in the radial location and distribution of knots between the two sides of the bipolar jet.

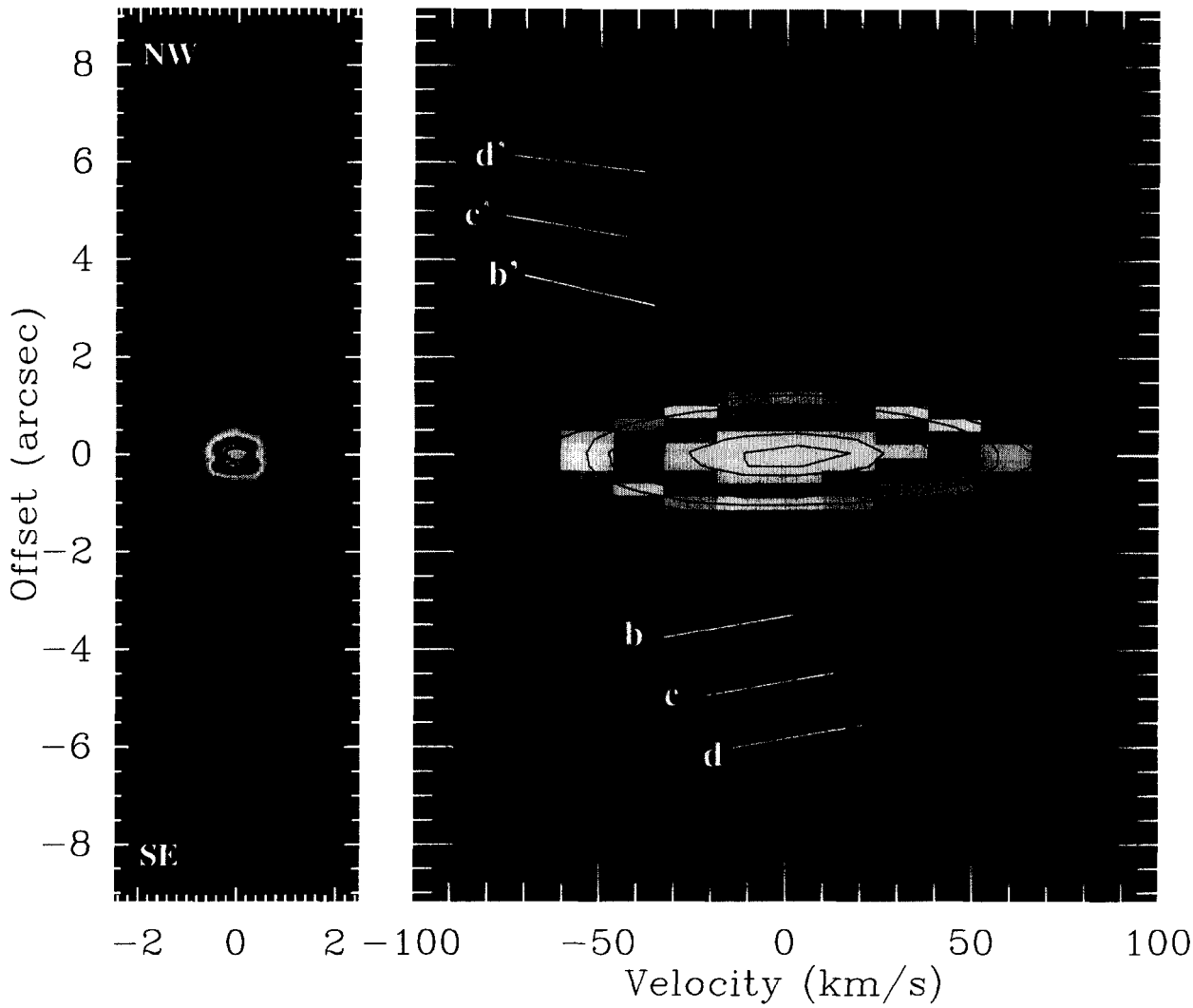

Fig. 4.— Long-slit (EMMI/NTT) [NII] spectrum of the jet in Hen 2-90. The slit is oriented along the jet such that its NW (SE) side are located at the top (bottom) of the slit. Velocities are relative to the systemic velocity. Contours are (in arbitrary units): 4 to 32 (step=3.5), 40-2560 (multiplicative step=2) & 3500. The WFPC2 [NII] image is shown alongside for reference