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LETTER

Letter to the Editor

Multiplicity of the HH 111 jet source: *Hubble Space Telescope* NICMOS images and VLA maps

Bo Reipurth[1], **Ka Chun Yu**[1], **Luis F. Rodríguez**[2], **Steve Heathcote**[3], **and John Bally**[1]

[1] Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309, USA
[2] Instituto de Astronomía, UNAM, Apdo. Postal 70-264, 04510 México, D.F., México
[3] Cerro Tololo Interamerican Observatory, Casilla 603, La Serena, Chile

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Abstract. We have observed the region around the HH 111 jet source with NICMOS onboard the *Hubble Space Telescope*, using two filters, F160W and F205W, which besides stellar continuum transmit the [FeII] 1.64 μm and H_2 2.12 μm emission lines, respectively. The jet can now be traced to within $2\farcs4$ of the VLA source. In the F205W filter we detect for the first time the driving source in the near-infrared as a faint and highly reddened star. Additionally, we detect in both filters a second source, called star B, about $3''$ further west, which appears to contribute significantly to the illumination of the blueshifted outflow cavity of the HH 111 jet. We present new 3.6 cm VLA maps, which show evidence that the HH 111 energy source drives a quadrupolar flow, suggesting that the source is a close binary with a projected separation of less than $0\farcs1$ (50 AU). We also detect star B at 3.6 cm, demonstrating that it is indeed a young star with its own (unresolved) signature of outflow. The two IR/VLA sources are located on either side of a highly opaque dust lane perpendicular to the HH 111 outflow axis, not inside it as one would expect. We speculate that the VLA 1 binary and the VLA 2 source are at their present locations because they originally formed an unstable non-hierarchical triple system from which VLA 2 was ejected. Such dynamic processes may help to terminate the main accretion phase of the young stars involved.

Key words: ISM: jets and outflows – stars: formation

1. Introduction

It is becoming increasingly evident that Herbig-Haro (HH) flows play a crucial role in the formation process of low mass stars by regulating the delicate balance between mass accretion and angular momentum release, by driving the ubiquitous molecular outflows, and by imparting energy and momentum to their surroundings.

The HH 111 jet in Orion has been extensively studied since its discovery a decade ago (Reipurth 1989). It is very highly collimated, consists of a large number of individual knots, and moves with a velocity of several hundred km s^{-1} at an angle of only 10^o to the plane of the sky (Reipurth, Raga, Heathcote 1992). Recently it was found that the jet is part of a giant HH complex stretching over 7.7 pc (Reipurth, Bally, Devine 1997a). Near-infrared observations have revealed a remarkable symmetry between the optical jet and a near-infrared counterjet, and also show that a second bipolar flow, HH 121, emerges from the source, suggesting that it is a binary (Gredel & Reipurth 1993,1994). The jet is co-axial with a major well collimated molecular outflow (e.g. Cernicharo & Reipurth 1996, Nagar et al. 1997). The jet is driven by IRAS 05491+0247 = VLA 1, a class I source with a luminosity of about 25 $L_\odot$ and surrounded by cold dust (e.g. Stapelfeldt & Scoville 1993, Yang et al. 1997).

2. Observations

The IR images of the HH 111 jet were obtained with the *Hubble Space Telescope's* NICMOS[1] instrument on 1998, March 22, using the NIC2 camera and the wide-band filters F160W and F205W. NIC2 is a 256×256 HgCdTe detector with a plate scale of $0.076''$ pix^{-1}. Exposure times were 768 s and 416 s for each of three dithered positions for the F160W and F205W filters, respectively. Further details on the observations and reductions are discussed in Reipurth et al. (2000).

The 3.6 cm observations of the HH 111 region were made with the Very Large Array of the National Radio Astronomy Observatory[2] in its highest angular resolution A configuration. To obtain the maximum signal to noise ratio we concatenated data taken in three A configurations between 1992 and 1996:

Send offprint requests to: B. Reipurth

[1] Based on observations from the NASA/ESA *Hubble Space Telescope* obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

[2] NRAO is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

Table 1. Sources detected with NICMOS and VLA

Source	α_{2000}	δ_{2000}	F_{160}[a]	F_{205}[a]
Star A	5 51 46.25	+2 48 30.0	–	2.98×10^{-18}
VLA 1	5 51 46.25	+2 48 29.5		
Star B	5 51 46.07	+2 48 31.2	6.51×10^{-19}	3.58×10^{-18}
VLA 2	5 51 46.07	+2 48 30.6		

[a] Fluxes are in erg sec^{-1} cm^{-2} Å^{-1}

1992 Nov 2, Dec 18 and 19; 1994 April 30; and 1996 Nov 11, Dec 28 and 29.

3. Two infrared sources: a wide binary

The F160W and F205W filters transmit, besides stellar continuum, the prominent emission lines [FeII] 1.64 μm and H_2 2.12 μm, which originate in shocks. At the bottom of Fig. 1 we show the entire NIC2 field, with F160W as turquoise and F205W as red. On top we have added the WFPC2 images ([SII] blue and Hα orange) of Reipurth et al.(1997b). The figure shows the entire optical/infrared jet from the energy source to knot L (43$''$ $\simeq$ 20,000 AU at 470 pc) at 0$''$.1 resolution, with a high-extinction gap in the jet near the source of only 2$''$.4.

Additionally, our NICMOS images of the HH 111 source region are shown in each filter as contour plots in Fig. 2. The jet and counter jet are very weak in H_2, but bright and well defined in [FeII]. This difference between the two emission lines is further discussed by Reipurth et al. (2000).

The main features of the double lobed reflection nebula have been discussed by Gredel & Reipurth (1994), but the high resolution of the present images offers some new and unexpected insights. The brightest part is the western nebula, which lies in the blue lobe of the outflow. It has a total extent perpendicular to the flow axis of 8$''$, which at 470 pc corresponds to the very large dimension of about 3500 AU. The nebula has a sharp cut-off towards the source region as seen in the F160W image, suggesting the presence of an extended obscuring region. On the opposite side, the eastern nebula has, besides being much fainter, a rather different morphology, with a much narrower opening angle.

For an object as symmetric as the HH 111 jet, and considering that we are viewing the outflow at an angle of only 10^o to the plane of the sky (Reipurth et al. 1992), the large asymmetry of the illuminated cavities in the two outflow lobes is surprising. However, closer examination of the western lobe reveals the presence of a faint star, which we here call star B. The star is seen in both the F160W and F205W images, with fluxes listed in Table 1. It is located precisely at the tip of a narrow tongue of reflection nebula stretching 5$''$ to the south-west, suggesting a close relation between star and ambient material. We speculate that the large brightness and transverse extension of the western nebula is due to the additional illumination by star B. As discussed in Sect. 4, star B is detected at 3.6 cm (VLA 2), demonstrating that the star is young and has outflow activity.

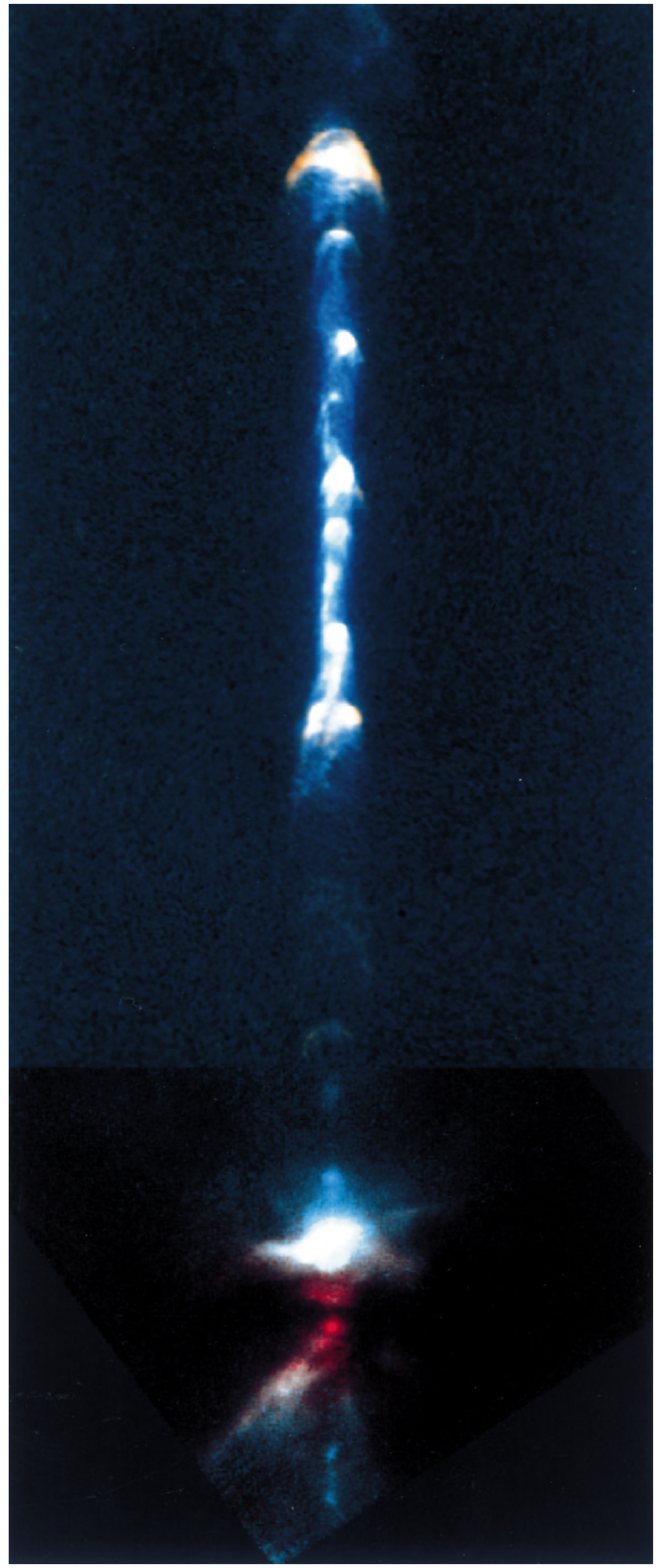

Fig. 1. A mosaic image of HH 111 based on HST NICMOS images (bottom) and WFPC2 images (top). See text for details

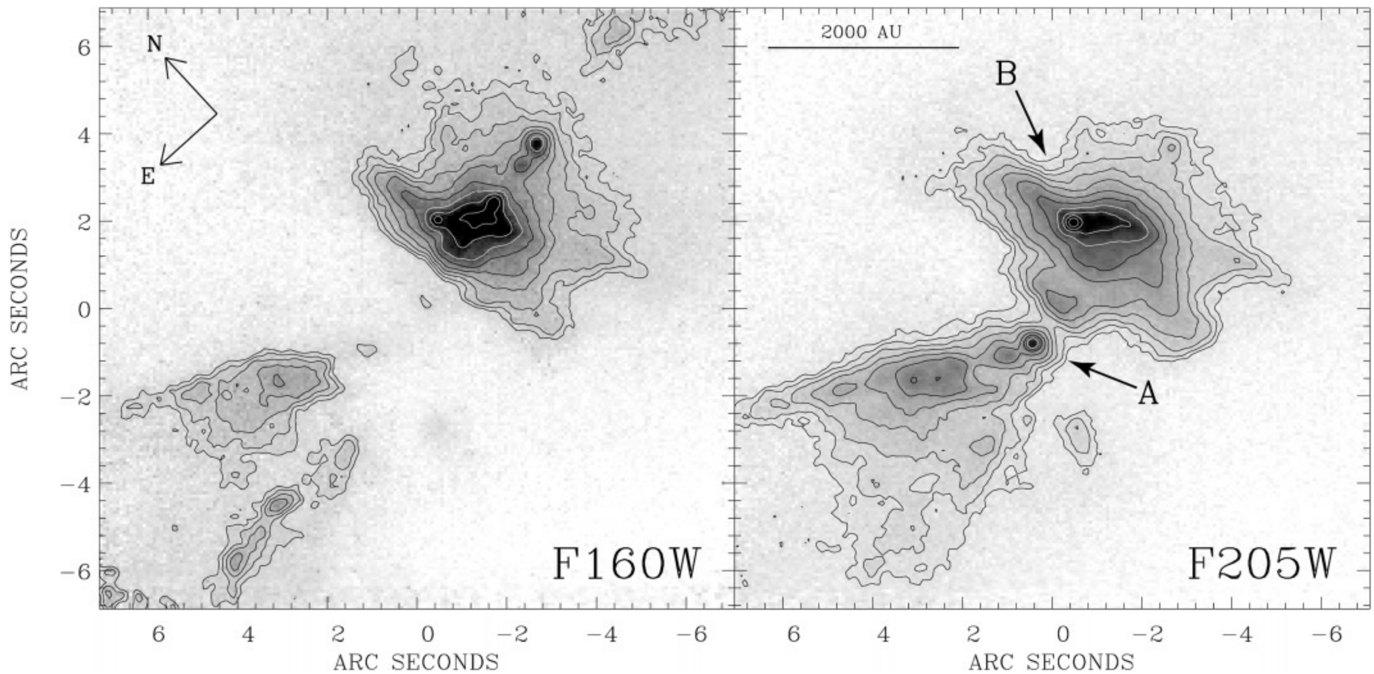

Fig. 2. Contour plots of the HH 111 source region based on HST NICMOS images through F160W and F205W filters

In the F205W image we find an isolated stellar source, here called star A, at the coordinates and with the flux listed in Table 1. The absolute position of star A and VLA 1 coincide to within $0\farcs5$, comparable to the uncertainty of the IR position, which was derived using the plate solution in the NICMOS image header and hence limited by the accuracy of the Guide Star Catalogue, as well as by any zero point difference between the optical and radio coordinate systems. Note that the *separation* of stars A and B is in perfect agreement with that of VLA 1 and VLA 2. Thus star A undoubtedly represents a near-IR detection of the energy source.

It is noteworthy that there is a dark ridge exactly perpendicular to the jet axis, producing a gap between the western and eastern reflection nebulae about $0\farcs5$ (250 AU) wide. This could be interpreted as a dense circumstellar disk of the driving source. However, since the blue lobe of the flow is towards the west, if the source were visible at all at this low flow angle, we would expect it to be on the western, and not the eastern, side of the dark ridge. We discuss this point further in Sect. 5.

4. VLA Observations: a close binary

A small 3.6 cm radio continuum jet was detected around the source by Rodríguez & Reipurth (1994). For their 1992 observations, 0539-057 was used as the phase calibrator. For our newer 1994 and 1996 data presented here we used 0550+032. In 1996 we made observations of both phase calibrators to accurately align the 1992 data with the 1994 and 1996 data. The final alignment of all data is relative to 0550+032. In the upper panel of Fig. 3, we show a map made with natural weighting of the VLA 1 source, identical to star A discussed previously. The source shows, in addition to an elongation along the E-W direction, fainter extensions in the N-S direction, suggesting a quadrupolar morphology.

To enhance the angular resolution of our image, we did a maximum entropy reconstruction using the task VTESS of AIPS, the software package of NRAO. This image is shown in the lower panel of Fig. 3, where the quadrupolar morphology of the source becomes even more evident. The VLA data is suggestive of a quadrupolar jet, with a common origin within $\sim 0\farcs1$ (50 AU). This is consistent with the fact that star A seen in the F205W image is perfectly circular, with no evidence for a companion. This distance is similar to the separation of the binary disk system in L1551 IRS5 (Rodríguez et al. 1998). However, in the case of L1551 IRS5 the jets are approximately parallel, while in HH 111 the jets are orthogonal. The PA of the main radio jet is 277^o (the same as for the optical HH 111 jet), and the smaller side jet has a PA = 184^o. Presumably this little radio jet may be associated with the H_2 flow HH 121, although the flow axes are not precisely the same (Gredel & Reipurth 1993,1994).

The 3.6 cm maps show an additional faint, unresolved source (VLA 2) to the NW of VLA 1 (outside Fig. 3) with a flux density of $20\pm5\,\mu$Jy at the position listed in Table 1. As mentioned in Sect. 3, this is a radio counterpart to star B. Our detection at 3.6 cm shows that this star also has outflow activity.

5. A hierarchical triple system

At a projected separation of only $3''$ (1400 AU), VLA 1 and 2 are likely to be somehow related. Yet, the two sources are rather different, VLA 1 (which appears to be a very close binary) being very reddened and having significant outflow, while VLA 2 shows no optical evidence of outflow and is much less reddened. Most puzzling is the location of both stars *outside* a dark ridge

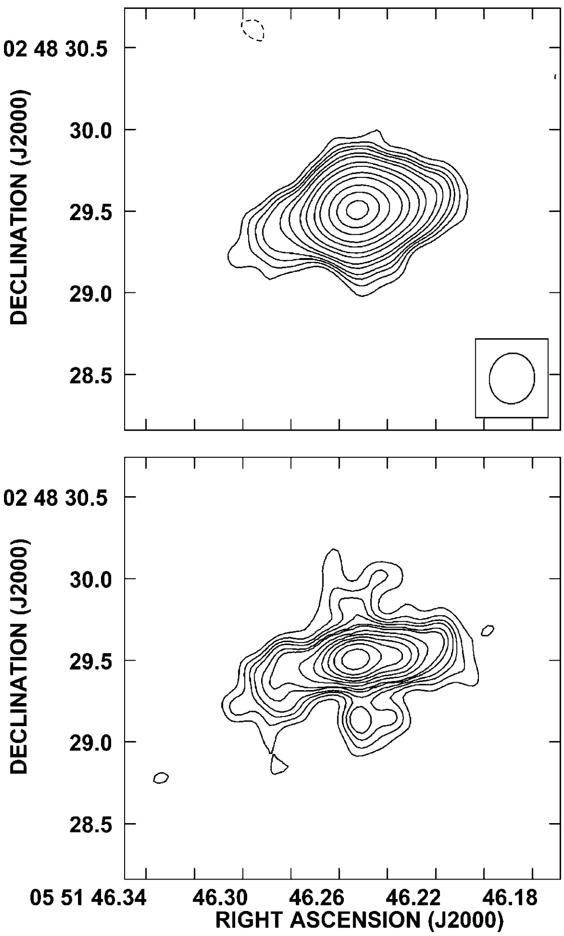

Fig. 3. 3.6 cm VLA maps of the HH 111 source, with natural weighting (upper panel) and maximum entropy reconstruction (lower panel)

which in the cases of other young stars normally suggest the presence of a flattened dense envelope (e.g. Padgett et al. 1999).

We can explain these features if we assume that the three stars were born together and until recently formed a non-hierarchical triple system located inside the dark lane. It is well known from the statistical theory of three-body interactions (e.g. Monaghan 1976, Anosova 1986, Valtonen & Mikkola 1991) that such systems are inherently unstable, and within about a hundred crossing-times will eject a member, while the remaining components contract to form a closer binary. The ejected member may or may not escape entirely, depending on the details of the interaction. If the crossing time is $t_{cr} \sim 0.17(R^3/M)^{1/2}$, where R is a characteristic length scale for the system in AU, M is the total system mass in $M_\odot$ and t_{cr} is in yr (Anosova 1986), and we assume the non-hierarchical triple members were formed within 150 AU of each other with a total mass of 2 $M_\odot$ (e.g. 1.0, 0.6, 0.4 $M_\odot$), then statistically a member is ejected after 22,000 yr. This is comparable with the dynamical age of the giant HH 111 outflow of about 25,000 yr, if one assumes a mean flow velocity of 150 km s^{-1} (Reipurth et al. 1997a).

Assuming VLA 2 is moving with a mean transverse velocity of 2 km s^{-1}, then the ejection took place 2700 yr ago. Since the VLA 1 binary has only travelled one quarter of the distance of VLA 2, it follows that it must be 4 times more massive, consistent with statistical studies which show that usually the component of lowest mass is ejected. It seems probable that VLA 2 will eventually escape, since with a minimum separation of 1400 AU the gravitational binding must be feeble, especially in view of the influence of large nearby cloud structures.

That the above numbers fit together so well is obviously fortuitous given the stochastic nature of the process, and they merely serve to show that a plausible choice of parameters could be consistent with the observed facts. Astrometry a few centuries from now could test this conjecture.

It is interesting to note that VLA 2/Star B is now located *above* the flattened envelope around its supposed birthplace, whereas VLA 1/Star A is below and presumably slowly moving out *behind* it. The difference in extinction is obvious from Figs. 1 and 2. While the stars almost certainly carry their inner circumstellar disks with them, the large scale envelope, which has served as a reservoir to feed the disks, is left behind. Consequently, the supply of material for both the build-up of the stars and the great outflow activity will gradually be choked off. Formation of a hierarchical triple system, especially if the ejected member eventually escapes, may thus *help to terminate the main accretion phase of its members*.

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