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News on two jets in Lupus 3⋆

F. Comerón[1] and M. Fernández[2]

[1] ESO, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany
e-mail: fcomeron@eso.org
[2] Instituto de Astrofísica de Andalucía, CSIC, Glorieta de la Astronomía 3, E-18008 Granada, Spain
e-mail: matilde@iaa.es

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ABSTRACT

Context. Jets from solar type and low-mass stars are typical manifestations of stellar youth. Shocks along these jets produce visible, generally fast-moving Herbig-Haro objects whose proper motions are easily measured in nearby star forming regions using images taken just a few years apart. Herbig-Haro objects have now been observed in association with objects close to the substellar boundary.
Aims. We present second-epoch observations of the central area of the Lupus 3 star forming region that include two of its most interesting Herbig-Haro systems. One is HH 228, produced by the classical T Tauri star Th 28 (=Sz 102), whereas the other is HH 600 and has its origin in the very low-mass star Par-Lup3-4.
Methods. Narrow-band imaging through filters centered respectively on the Hα and the [SII] lines has been obtained with the FORS2 instrument at the Very Large Telescope (VLT) in mid-2010. The images obtained are compared to others obtained in early 2003, which led to the discovery of HH 600.
Results. New Herbig-Haro objects associated with Th 28 are found at large distances from it, representing an extension of the HH 228 jet to a projected distance of 0.32 pc from Th 28. The farthest Herbig-Haro object is HH 989, whose possible relationship with Th 28 had been already suggested in a previous study but is now kinematically confirmed. We find other likely Herbig-Haro objects whose proper motions make less obvious the connection with Th 28, but which may be caused by oblique shocks near the outer walls of its jet. Regarding the HH 600 jet, the knot discovered by us in 2003 to the southeast of Par-Lup3-4 is found to have clearly moved and faded. Using high resolution spectroscopy obtained in 2003 and the proper motion that we can measure now, we determine a spatial velocity of 170 ± 30 km s^{-1}. The northeastern jet is found to have grown in prominence in the intervening years. The possible relationship of other Herbig-Haro objects in the region with Th 28, Par-Lup3-4, and other young stellar objects in the area is discussed.

Key words. Stars: formation. Stars: individual: Th 28, Par-Lup3-4. Herbig-Haro objects. ISM: individual objects: HH 228, HH 600, HH 989

1. Introduction

Collimated jets are an ubiquitous feature of the earliest stages of star formation. They are produced in the innermost regions of the inner regions of the environment of low- and intermediate-mass stars, resulting from the interaction between the magnetic fields of a newly formed young stellar object and its surrounding disk and envelope (Hartmann 1998, Bally et al. 2007, Shang et al. 2007, Ray et al. 2007, Pudritz et al. 2007). Time variations and sudden changes in the ejection velocities of the jets, instabilities in their launching region, and interactions with the surrounding interstellar medium give rise to shocks that are visible as the compact, fast-moving nebula composing Herbig-Haro (HH) objects. HH objects thus provide a record of the past history of an outflow, over timescales that can be in some instances as long as the entire duration of the protostellar stage of its central source (Bally 2009). In the nearest star-forming regions their high spatial velocities translate into large proper motions easy to measure in only a few years, thus providing an accessible tool to study the evolution of the mechanical properties of the jets and the timing of past events. Proper motions provide in addition a simple way to confirm the nature of HH objects and to unambiguously link them to their central sources, which may not be straightforward in regions densely populated by young stellar objects.

Near the center of the T Tauri association Lupus 3 are two remarkable young stellar objects driving spatially resolved outflows. The T Tauri star Th 28 (Thé 1962), also known as Sz 102 (Schwartz 1977) or Krautter's star, is the source of the fast bipolar jet HH 228 (Krautter 1986, Graham & Heyer 1988). Another object in the same region, Par-Lup3-4 (Comerón et al. 2003), is a very low-mass star close to the substellar limit that was found by Fernández & Comerón (2005) to have a faint associated jet, HH 600 (Comerón & Reipurth 2006), being one of the lowest mass objects known to drive a spatially resolved jet.

In this paper we report the discovery of new, faint HH objects to the east of Th 28 that happen to be closely aligned with the axis defined by the known knots of HH 228. Proper motions are measured for all of them, as well as for HH 989, first identified by Wang & Henning (2009) and whose relationship to Th 28 we are able to confirm kinematically. The distance of the newly identified knots related to Th 28 extends the size of the detectable jet to ~ 0.3 pc from the central star, and provide a fossil record of its outflow activity over the last thousand years. We also present second-epoch observations of the HH 600 jet that allow us to obtain the first measurement of its proper motion. This complements the observations of Fernández & Comerón (2005), lead-

Send offprint requests to: F. Comerón, e-mail: fcomeron@eso.org
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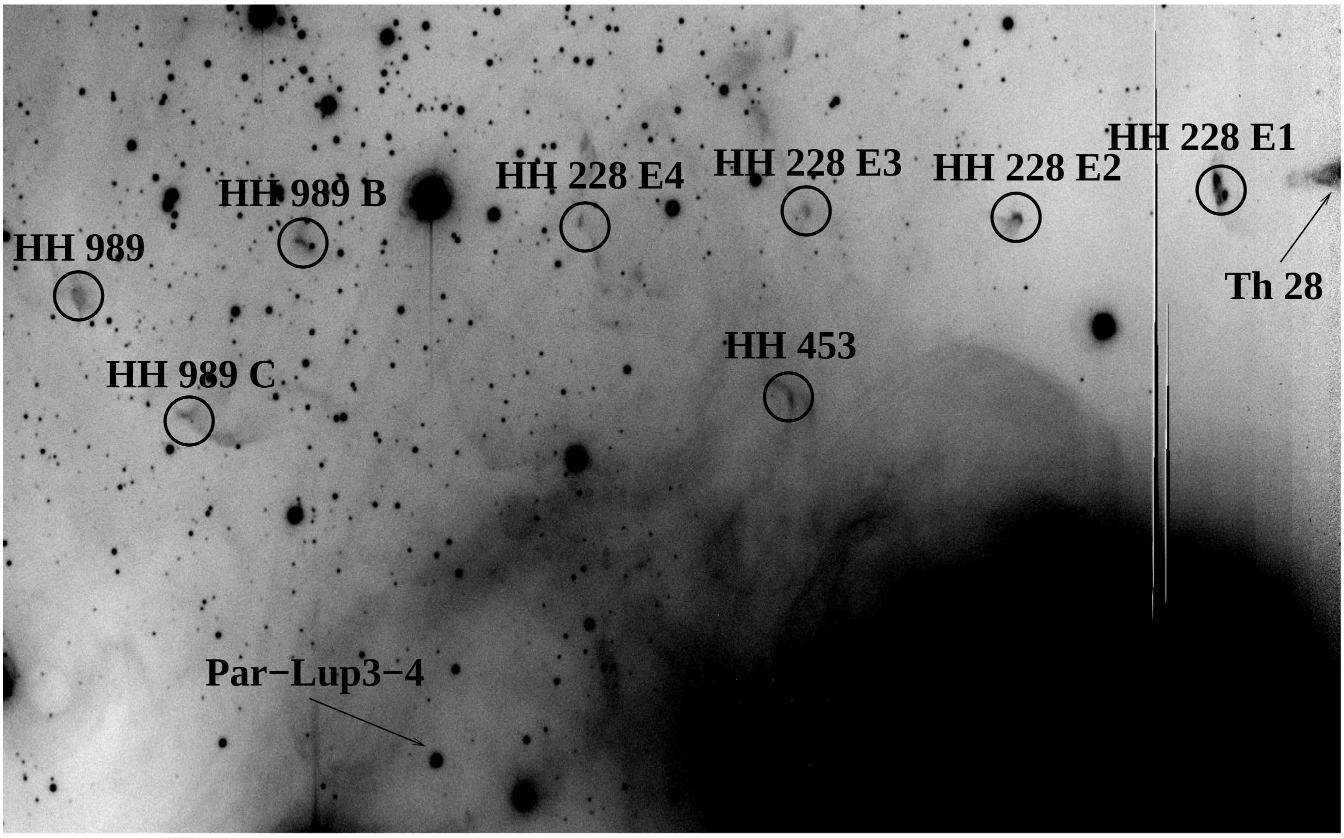

Fig. 1. A general Hα view of the field covered by our observations, obtained from our FORS1 observations in 2003. The objects discussed in the present study are marked. Th 28 is just outside the right edge of the frame, but its inner jet and the knots composing HH 228 can be identified. The field covers an area of $6'1 \times 3'3$, with north to the top and east to the left.

ing to the determination of the spatial velocity of the jet, and confirms its orientation close to the plane of the sky.

2. Observations and measurements

The new observations reported here were obtained on the nights of 15/16 April, 5/6 May, and 6/7 May 2010 using the FORS2 camera and spectrograph at the VLT in imaging mode. Two narrow-band filters, covering respectively the Hα line at 6563 Å and the [SII] lines at 6716 Å and 6731 Å, were used to obtain relatively deep images of a small region of the Lupus 3 cloud roughly centered on Par-Lup3-4. The images were obtained with the high-resolution collimator of FORS2 yielding a scale of $0''126$ pixel^{-1} on the detector, which we used in the standard 2×2 binned mode. The field covered by each individual frame is $4'3 \times 4'3$, with vignetting toward the corners caused by the collimator optics. The observations in each filter consisted of three separate pointings, each with an exposure time of 1043 s, with telescope offsets in between. Due to the combination of pointing geometry and corner vignetting, the coadded frame in each filter has an irregular contour, the longest dimensions in the east-west and north-south directions being $5'0$ across.

The area covered by these observations nicely overlaps with our previous images obtained with the FORS1 instrument at the VLT and very similar narrow-band filters in February 2003, reported in Fernández & Comerón (2005). The reader is referred to that paper for a description of the FORS1 observations. The 7.2 years elapsed between both sets of observations, and the similar sensitivity reached in both, allow us to obtain the first measurement of the proper motion of HH 600. They also allow us to search for possible faint, previously unidentified HH objects in the region that should be easily noticeable due to their clear displacement between both epochs, caused by their large spatial velocities. The area covered by both sets of observations includes much of the region east of Th 28, and is thus almost ideally suited to search for further extensions of the HH 228 system of HH objects beyond the knots that have been identified thus far.

The February 2003 images were astrometrically calibrated using the cataloged positions of 2MASS stars in the field as a reference. Then, the images obtained in 2010 were distortion-corrected to match the 2003 images and resampled by means of the `GEOMAP` and `GEOTRANS` tasks on IRAF, this time taking as reference all the common, non-saturated stars detected above the 5σ level between the 2003 and 2010 images. The quality of the distortion correction varies across the field, as the most obscured areas are rather devoid of stars and only a coarse reference grid can be established for them.

Proper motions for the new HH objects identified in this work and associated with Th 28, as well as the proper motion of HH 453 (see Sect. 3), were measured with respect to their nearest stars in the images, which are in all cases unrelated to the Lupus clouds. The proper motions of background stars in the direction of Lupus are centered very near $(\mu_\alpha \cos\delta, \mu_\delta) = (0, 0)$ (Mugrauer & Neuhäuser 2005), where $\mu_\alpha \cos\delta$ and μ_δ are the proper motions in right ascension and declination, respectively. Therefore, no correction was made to the proper motions of the HH objects measured with respect to their reference stars. For HH 600, the proper motion of the jet knot was determined relative to its central source, Par-Lup3-4.

Given the extension of the objects, their irregular shapes, the noise in the images, and perhaps the slightly evolving intrinsic morphology, it was found that careful visual inspection leading to the identification of specific, easily recognizable features within each object turned out to be the most reliable way of choosing a reference point for the measurement of the proper motions. This could be done with a varying degree of accuracy depending on the morphology and brightness of each object. The uncertainty in the location of this reference point is the dominant source of uncertainty, except in the case of HH 453 (see Sect. 3) where the uncertainty due to the scarcity of nearby reference stars is comparable.

3. Results

3.1. Th 28 and the HH 228/HH 989 jet

The system of HH objects associated with Th 28 is oriented close to the East-West direction and appears to be moving in a direction nearly perpendicular to the line of sight, as inferred from the large proper motions (Krautter 1986) when compared to their radial velocities (Graham & Heyer 1988). This is consistent with the faintness of the central source, which is probably due to the obscuration by a circumstellar disk seen nearly edge-on (Hughes et al. 1994), despite the lack of the pronounced dip in the mid-infrared spectral energy distribution near 8μm (Chapman et al. 2007) that is characteristic of a near edge-on viewing geometry (D'Alessio et al. 1999). The basis of the jet has been studied in depth thanks to the high spatial resolution observations provided by STIS at the Hubble Space Telescope, which have allowed a detailed analysis of the physical conditions near the launching region both along and across the jet, as well as the identification of hints of rotation (Coffey et al. 2004, 2007) and an estimate of the mass loss rate in the outflow, which is found to be a remarkably high $\sim 1.2 \times 10^{-8}$ $M_\odot$ yr^{-1} (Coffey et al. 2008). Further probing of the innermost region of the jet using near-infrared hydrogen and [FeII] lines has been recently presented by the same authors (Coffey et al. 2010). The different outflow and inflow components in the immediate circumstellar environments of Th 28 have been discussed by Comerón & Fernández (2010) based on spatially unresolved high resolution spectroscopy of a variety of emission lines. An accretion rate of $\sim 6.3 \times 10^{-8}$ $M_\odot$ yr^{-1} is inferred from these observations which, with the caveat of the uncertainties in both estimates, suggests a high outflow-to-inflow mass ratio. The system of knots composing HH 228 is also discussed in that paper, as well as in the recent work by Wang & Henning (2009), who provide a complete census of HH objects known thus far in the Lupus 3 region.

The observations discussed here map most of the Eastern jet of Th 28. This component of the jet has a significant negative radial velocity, measured at −62 and −82 km s^{-1} at the positions of HH 228 E_1 and HH 228 E_2 respectively (Graham & Heyer 1988). Our comparison between the Hα images obtained in 2003 and 2010 reveals five previously unidentified faint nebulae in the proximities of Th 28 or the axis of its jet that show significant or suspected displacement between both epochs. The new objects are HH 228 E_3, HH 228 E_4, HH 453, HH 989 B, and HH 989 C. The somewhat confusing nomenclature is meant to preserve the denominations already assigned to the previously known objects HH 228 E_1, HH 228 E_2 and HH 989, and to reflect the likely association and proximity of the new objects to them. HH 453 is most likely unrelated to the Th 28 jet, and thus a different, unused HH catalog number has been assigned to it. The location of these nebulae, as well as the already known HH 989, is shown in Figure 1. The new HH objects are fainter and more extended than those closer to Th 28, thus making it difficult to determine their proper motion to the same level of accuracy attainable for the previously known HH objects, due to both the compactness and the longer time baseline over which the latter have been measured. However, the 7.2 yr baseline available for the new objects provides a sound basis to assess their possible relationship to known young stellar objects in the region, particularly to HH 228.

Table 2. Position and proper motion of HH 453

α (2000)	16:08:43.0
δ (2000)	-39:04:05
$\mu_\alpha \cos\delta$ (arcsec yr^{-1})	-0.088 ± 0.07
μ_δ (arcsec yr^{-1})	$+0.035 \pm 0.07$
Reference point	peak intensity at the arc feature

A close-up view of each of these knots in Hα is presented in Figure 2. The high proper motions of most of them are already apparent upon visual inspection. Table 1 shows the positions, proper motions relative to Th 28 ($\Delta\mu_\alpha \cos\delta$, $\Delta\mu_\delta$), angular distances to Th 28 projected along the axis of its jet (λ), and velocity on the plane of the sky with respect to Th 28 (v). The adopted proper motion for Th 28 is taken from the UCAC3 catalog (Zacharias et al. 2010) as ($\mu_\alpha \cos\delta$, μ_δ) = (+0″0046 yr^{-1}, −0″0310 yr^{-1}), which is somewhat different from the bulk proper motion of the Lupus clouds derived by Makarov (2007) of ($\mu_\alpha \cos\delta$, μ_δ) = (−0″017 yr^{-1}, −0″027 yr^{-1}). Data for HH 453 are separately presented in Table 2. With the single exception of HH 989, the knots are detected in Hα alone, being undetected in the [SII] images.

3.2. Par-Lup3-4 and HH 600

The faint object Par-Lup3-4 was first identified by Comerón et al. (2003) thanks to its outstanding emission-line spectrum, superimposed on a faint continuum corresponding to a M5 spectral type. Par-Lup3-4 is surrounded by large amounts of circumstellar material, which make it one of the brightest young stellar objects in the Lupus 3 region at mid-infrared wavelengths (Merín et al. 2008). An analysis of its visible-to-mid infrared spectral energy distribution shows that it can be well modelled by a very low-mass star surrounded by a thick flaring disk seen nearly edge-on, thus explaining the unusually low luminosity of the central object at visible and near-infrared wavelengths, in which it is mostly seen in scattered light (Huélamo et al. 2010). A short bipolar jet, HH 600, was found by Fernández & Comerón (2005), who presented high-resolution spectroscopy indicating velocities of only 20.1 km s^{-1} along the line of sight.

The new observations of Par-Lup3-4 show important differences in its system of jets, as seen in Figure 3. In the 2003 observations, reported in Fernández & Comerón (2005), the most outstanding feature was a knot located 1″3 from the central star. The knot stood out in the [SII] image and could be seen in the Hα image as well. A faint extension of the jet pointing southeast was visible beyond the knot, as well as traces of a counterjet toward the northwest. In the image of 2010 the appearance of both jets is much more symmetric with both the southeast and the northwest jet displaying similar intensities. The southeast jet ends in a distinct condensation at 2"55 from Par-Lup3-4, which most likely is the knot seen in the 2003 images much closer to the star, thus allowing us to easily measure its proper motion rel-

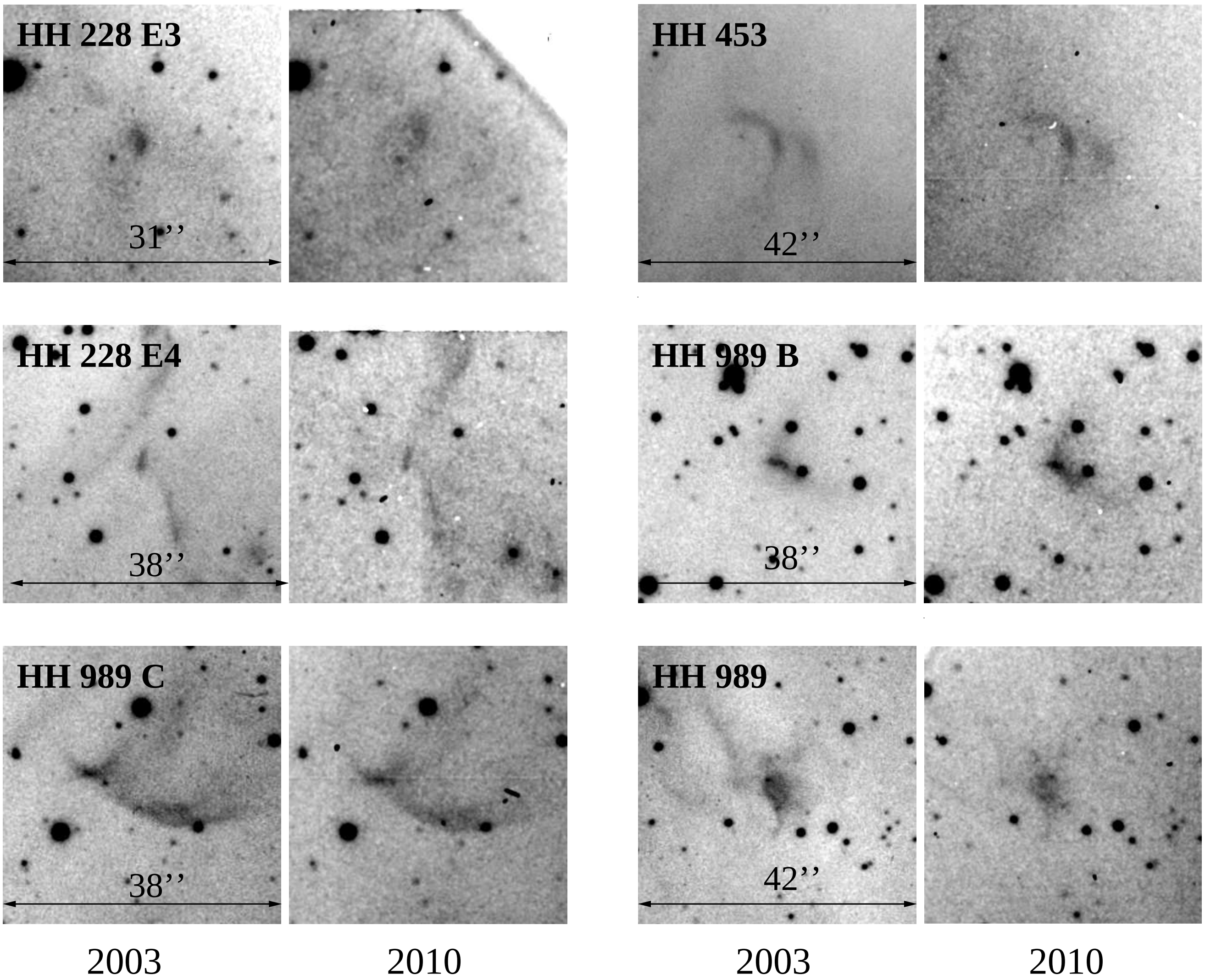

Fig. 2. Hα images obtained in 2003 and 2010 of the five moving knots in the proximities of the Th 28 jet, plus a possibly moving arc-shaped nebula southeast of Th 28. The displacement in the intervening 7.2 years images can be noticed for most of them by comparison with stars in the field. North is up and East to the left. Note the different scales of the images.

Table 1. Positions, relative proper motions and velocities of knots associated with Th 28

Object	α (2000) (Epoch 2010.4)	δ (2000)	$\Delta\mu_\alpha \cos\delta$ (arcsec yr^{-1})	$\Delta\mu_\delta$	λ (arcsec)	v (km s^{-1})	Reference point
HH 228 E_3	16:08:42.4	-39:03:30	+0.118 ± 0.05	+0.294 ± 0.05	147	300	center of the nebula
HH 228 E_4	16 08 48.3	-39:03:23	+0.371 ± 0.03	+0.066 ± 0.05	210	357	peak of the central condensation
HH 989 B	16:08:54.7	-39:03:28	+0.135 ± 0.07	−0.022 ± 0.03	287	130	center of the condensation
HH 989 C	16:08:57.7	-39:04:17	−0.058 ± 0.05	−0.092 ± 0.03	322	103	peak of the eastern condensation
HH 989	16:09:00.1	-39:03:41	+0.328 ± 0.05	+0.049 ± 0.05	347	314	approximate center of the condensation

ative to it. Interestingly, all this structure is revealed by the [SII] image only, and no trace of the jet down to the level of sensitivity of our observations is seen in the Hα images. This is in sharp contrast with most of the knots belonging to the Th 28 jet or in its proximities where, as noted above, the opposite situation happens.

4. Discussion

4.1. The distant extensions of the HH 228 jet

The positions and proper motions of two of the objects listed in Table 1, HH 228 E_4 and HH 989, clearly indicate their association with HH 228 and extend the known length of the jet. Their location is very close to the axis defined by the HH 228 E_1 and E_2 knots (Graham & Heyer 1988), and their proper motions point directly away from Th 28. HH 228 E_4 is moving through a region that projects it against possibly unrelated nebulosity, as can be inferred from Figure 2 by noting that an upper ridge of emission running approximately north-south remains fixed in the images, whereas the bright, compact patch near the center of the image and the nebulosity south of it are rapidly proceeding eastward. HH 989 is composed by a compact nebulosity preceded by nebulous wisps toward the east, which also share its motion across space. The nature of HH 989 as the extension of HH 228 was already suggested by Wang & Henning (2009), and is now unambiguously confirmed by us. HH 989 is the only knot that we detect in both Hα and [SII] images. The peak intensity of HH 228 E_4 in Hα is similar to that of HH 989, but its non-detection in our [SII] images as well as in those used by Wang & Henning for their study indicates that the excitation of HH 989 is higher than that of knot HH 228 E_4 and possibly the other knots.

Assuming a distance of 200 pc to the Sun, the tangential velocities of HH 228 E_4 and HH 989 are very high, 357 ± 30 km s^{-1} and 314 ± 50 km s^{-1} respectively. The relative proper motions are however below those measured for HH 228 E_1 and HH 228 E_2, for which Fernández & Comerón (2005) find respectively 0.43 ± 0.03 arcsec yr^{-1} and 0.47 ± 0.03 arcsec yr^{-1}. Assuming that the jet knots have been moving away from Th 28 at a constant velocity since the outflow events that produced them, we infer that such events took place approximately 95, 207, 558 and 1042 years ago for HH 228 E_1, HH 228 E_2, HH 228 E_4 and HH 989, respectively. Taken at face value, this might indicate that the pace of outflow events triggering the formation of knots has been increasing in recent centuries. However, it is also possible that knots resulting from old outflow events in between have faded away and are not recognizable anymore.

HH 989 represents the most distant extension of the Th 28 eastern jet discovered thus far, setting its length at 0.34 pc. Given that it lies near the edge of the field covered by our observations, the presence of detectable HH objects located even further away cannot be discarded, although none has been identified by Wang & Henning (2009), whose images cover regions further east of the one examined by us. Those authors speculate that a bright and more distant object, HH 78 (Reipurth & Graham 1988), which lies near but not exactly on the axis of the Th 28 jet, may represent a further extension of this structure. We believe that this is extremely unlikely, though. Deep infrared observations of the region (Nakajima et al. 2003) show that the visible portion of HH 78 can be traced as a well collimated jet up to the precise position of the Class 0 object Lupus 3 MMS (Tachihara et al. 2007), which is almost surely at the origin of this jet. The near-infrared part of the jet is bright in the K_S band, probably due to shock-excited H_2 emission coincident with the molecular outflow detected by Tachihara et al. (2007). The relative arrangement in the sky of the infrared and visible portions suggests that the jet originates deeply embedded in the cloud hosting Lupus 3 MMS and moves toward the side of the cloud facing in our direction, revealing itself as the visible counterpart of HH 78 where it emerges from it.

HH 228 E_3 and HH 989 C also display large proper motions, but not as extreme as those of the four HH knots just discussed. They are both offset from the axis of the jet and moving away from it. Their positional/kinematical association with Th 28 is thus not as straightforward as that of HH 228 E_1, E_2, E_4 and HH 989. Nevertheless, the formation of such slower outward moving, off-axis knots is a feature reproduced by hydrodynamical simulations of pulsed jets. They appear as the bow shock produced by an ejection event, moving in the wake of a previously produced knot, interacts with material near the walls of the jet, driving an oblique shock into it; see for instance Figure 8 of Bonito et al. (2010). The plausibility of this scenario according to numerical simulations, and the absence of any known sources that might be viable candidates to be the driving engines of HH 228 E_3 and HH 989 C, inclines us in favor of this explanation concerning the location and motion of those two objects.

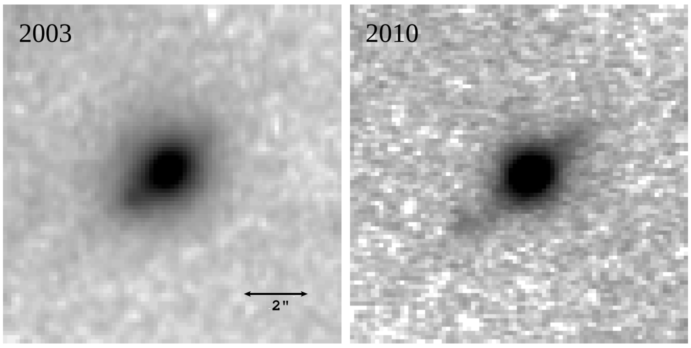

Fig. 3. [SII] images of Par-Lup3-4 and its faint jets. The grey scale is logarithmic in both images to enhance the structure of the jet. North is up and East to the left.

The nature of HH 989 B is somewhat more uncertain. It appears as a bright patch very close to the axis of the jet, but its proper motion is small. Our proper motion measurement takes as reference point the center of the brightest condensation, which is elongated in the east-west direction, the same as the presumed direction of motion. However, given the different depths of the images from 2003 and 2010 and perhaps the morphological evolution of the nebula over this period, it is possible that the proper motion that we derive may actually be a spurious effect of noise in the images or of a physical change of shape of the knot. If the reported proper motion is confirmed by future observations spanning a longer time, it is likely that HH 989 B has then a similar origin as that discussed above for HH 228 E_3 and HH 989 C. However, the possibility that it is an unrelated object, and perhaps not even a HH object, remains open.

The fairly regular distribution of the string of knots, and the timescales on the order of a century involved between the production of consecutive knots, suggests that the episodic activity may be due to a close eccentric binary (Reipurth 2000), in which the knots are produced by bursts repeated on an orbital timescale around the time of the periastron passage of the companion. Although no evidence for binarity has been found in Th 28, future high spatial resolution observations may provide support for this scenario.

Finally, HH 453 is almost certainly unrelated to Th 28, and it is listed here only for completeness. Its proper motion is uncertain, partly due to the scarcity of reference stars in that part of the region, which may lead to an inaccurate correction for differential field distortion between the 2003 and 2010 images. Its westward proper motion is consistent with the arc shape of the knot, which is reminiscent of a bow shock. Very similar morphologies are observed in other HH objects such as HH 61, HH 63, Re 6, or HH 77 (Reipurth & Graham 1988).

The source of HH 453 is uncertain. The apsis of the bow shock points backwards toward the proximities of Sz 109, a very low mass star with spectral type M6.5 (Comerón et al. 2003) located 60" away. However, contrarily to the case with most HH-driving sources, Sz 109 has a very modest emission-line spectrum, where the only emission line is Hα with an equivalent width of only 15 Å. Another intriguing possibility is that HH 453 might actually be associated with Par-Lup3-4, as discussed in Section 4.2.

4.2. The evolution of the HH 600 jet

Being close to the borderline between very low-mass stars and brown dwarfs, Par-Lup3-4 is an important object for the study of the properties of jets produced in that range of masses. Increasing evidence is being found for jets driven by very low-mass stars (Stecklum and Meusinger 2007) and brown dwarfs (Whelan et al. 2009). In the latter case, the evidence for jets is mostly found in the close proximity of the central object and can be resolved only by high-resolution spectroastrometric techniques, although evidence for a spatially well resolved molecular outflow driven by a brown dwarf has been recently presented by Phan-Bao et al. (2008). Par-Lup3-4 thus provides a case in which an optical jet from a very low mass star can be both spatially and kinematically resolved, and where its evolution with time over short timescales can be followed in detail.

The clear displacement of the knot in HH 600 in the intervening 7.2 years allows us to easily determine its velocity in the plane of the sky relative to Par-Lup3-4, which amounts to $(\Delta\mu_\alpha \cos\delta, \Delta\mu_\delta) = (+0.136 \pm 0.015, -0.107 \pm 0.015)$ arcsec yr^{-1}, translating into a velocity of (168 ± 30) km s^{-1} in the plane of the sky at the adopted distance of 200 pc. This velocity is in the typical range for classical T Tauri stars, and above those of the brown dwarf jets investigated by Whelan et al. (2009), although the latter compose a statistically small sample. Together with the radial velocity of 20.1 ± 1.5 km s^{-1} determined by Fernández & Comerón (2005), we obtain a spatial velocity of 170 km s^{-1} and an inclination of the jet with respect to the plane of the sky of only 6°7 ± 1°4. This confirms that the as yet unresolved disk of Par-Lup3-4 is indeed very close to edge-on, as already hinted by Fernández & Comerón (2005) and independently supported by Huélamo et al. (2010). The ejection event that caused the knot is thus estimated to have happened in early 1995.

Whereas the northwestern jet of HH 600 has brightened since 2003, the knot in the southeastern jet has faded significantly and we estimate its [SII] flux to have dropped to 30% of the brightness recorded in 2003. Fernández & Comerón (2005) noted that the knot could be seen in the 2003 Hα images, which is not the case in the 2010 images. If the observed knot is a typical product of the pulses of Par-Lup3-4 we conclude that those structures fade away too quickly to be observed at angular distances from Par-Lup3-4 longer than a few arcseconds. Interestingly, the opposite behavior between both epochs is observed in Par-Lup3-4 itself, as its flux in both the [SII] and Hα passbands has increased in 2010 by $\sim$ 30 − 40% since 2003. This increase could be due to enhanced emission lines in 2010 with respect to 2003, perhaps indicating a higher level of outflow activity. The increase could also be due to variability in the continuum level, which is known to happen according to the broad-band imaging of Comerón et al. (2003). Unfortunately no broad-band observations are available in 2010 allowing us to decide between both possibilities. In either case, continued monitoring of Par-Lup3-4 might soon reveal the birth of another jet knot.

The quick fading of the knot in the HH 600 jet appears to be in contrast with the recent suggestion by Wang & Henning (2009) that two distant HH objects discovered by them, HH 900 and HH 991, might have their origin in Par-Lup3-4. Their suggestion is based on the location of those two objects along the extension of the Par-Lup3-4 jet only, and unfortunately we are unable to check this interpretation through kinematics as both objects are outside the field of our 2010 observations. We note that an alternative, and perhaps likelier source for HH 990 is Lupus 3 MMS, already mentioned in Sect. 4.1, as HH 990 is also in the extension of the HH 78 jet. The origin of HH 991, located at 177” from Par-Lup3-4, remains however uncertain. On the other hand it is intriguing that HH 453, discussed in Sect. 4.1, also lies approximately along the extension of the HH 600 northwestern jet although at a shorter distance (131”) than HH 991. The limited precision of our kinematic measurements cannot rule out that HH 453 might be moving radially away from Par-Lup3-4. Should further observations confirm the association of some of those three objects with Par-Lup3-4, it would be evidence for a much more active outflow ejection history having taken place several centuries ago.

5. Summary

New narrow-band [SII] and H α imaging has been presented of a field containing the eastern jet of Th 28 and the very low mass young stellar object Par-Lup3-4. A comparison with observations obtained with similar instrumentation over seven years earlier leads to the following conclusions:

- The eastern jet powered by Th 28, which contains the Herbig-Haro objects HH 228 E_1 and E_2, is found to continue up to a distance of at least 0.3 pc from the central source. The most distant part of the jet identified thus far is HH 989, whose association with Th 28 and HH 228 we are able to confirm kinematically.
- Four additional HH objects are identified near the axis defined by Th 28 and HH 989, which we denominate HH 228 E_3, HH 228 E_4, HH 989 B and HH 989 C. Proper motions are measured for these objects. The proper motion of HH 228 E_4 is very high and similar to those of HH 228 E_1, E_2 and HH 989, confirming its association with the jet. HH 228 E_3, HH 989 B and HH 989 C have measurable proper motions that differ from those of HH 228 E_1, E_2, E_4 and HH 989, but given their proximity to the axis of the jet and the direction of motion we suggest that they are caused by oblique shocks near the walls of the jet. Unlike HH 228 E_1, E_2 and HH 989, the new HH objects are detected only in Hα and not in [SII]. The known and new HH objects trace variability in the jet powered by Th 28 over the last millenium, and hint to major variability events on the timescals of one century.
- The small bipolar jet powered by the very low-mass star Par-Lup3-4, HH 600, is also detected in our new observations. A compact knot in the jet, detected 1″3 from the central star in both Hα and [SII] images obtained in 2003, is found to have moved to 2″55 after 7.2 years, implying a velocity in the plane of the sky of 168 ± 30 km s^{-1} and a direction of motion nearly perpendicular to the line of sight when the proper motion measurement is combined with the radial velocity obtained from observations in 2003. The knot is not detected in Hα in the new images, and has faded significantly in [SII]. At the same time, the opposite side of the jet has gained prominence in the intervening years, whereas Par-Lup3-4 itself is 30 − 40% brighter in the 2010 observations than in the 2003 ones.
- A likely, arc-shaped new HH object, HH 453, is detected in the proximities of HH 228. It is almost certainly unrelated to Th 28, but its powering source remains uncertain. Based on its position and shape it might be associated with Par-Lup3-4, like another likely HH object, HH 991, located at a comparable distance on the opposite side of Par-Lup3-4. However, the actual association of both HH objects with Par-Lup3-4 still awaits confirmation.

The results presented in this paper underscore the importance of deep imaging and monitoring in revealing the evolution of the jets associated with young stellar objects over widely different timescales, ranging from millenia to a few years. They also encourage further observations of the two systems studied here in order to further explore both possible major outbursts in the distant past, and near-real time follow-up of new ejection events in the coming years.

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