RevMexAA (Serie de Conferencias), **15**, 112–114 (2003)

PROPER MOTIONS OF STELLAR JETS AS OBSERVED WITH *HST*: THE MOVIES

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RESUMEN

Los chorros estelares más brillantes están lo suficientemente cercanos para que exhiban movimientos propios determinados en un periodo de pocos años cuando se observan con el *Hubble Space Telescope* (*HST*). Están disponibles ya los resultados para los chorros HH 1, HH 34, HH 47, y HH 111, basados en imágenes en Hα y [S II] del *HST* separadas por 5 años. Un nuevo algoritmo interpolador para las nebulosas en movimiento hace posible crear imágenes a tiempos intermedios entre las dos épocas. Aunque el movimiento del flujo de gas parece un movimiento balístico en todos los casos, consistente con las velocidades de choque bajas en un chorro altamente supersónico, las películas muestran una variabilidad fotométrica y un deslizamiento significativos. Este comportamiento es más obvio en las imágenes en Hα de las superficies de trabajo, en donde la estructura del choque es compleja. La variabilidad de la velocidad y la densidad en el choque es la causa más probable de las estructuras de choque observadas.

ABSTRACT

The brightest stellar jets are close enough that they exhibit definite proper motions over a period of a few years when observed with the *Hubble Space Telescope* (*HST*). Results for the HH 1, HH 34, HH 47, and HH 111 jets, based on Hα and [S II] *HST* images separated by about five years, are now available. A new interpolation algorithm for moving nebulae makes it possible to create images at intermediate times between the two epochs. The resulting movies make it much easier to follow photometric variations and shear motions than by simply blinking images taken at two epochs. Although the motion of the outflowing gas resembles ballistic motion in all cases, consistent with low shock velocities in a highly supersonic jet, the movies do show significant photometric variability and shear. This behavior is most evident in the Hα images of working surfaces, where the shock structure is complex. Velocity and density variability in the jet is the most likely cause of the observed shock structures.

Key Words: **ISM: JETS AND OUTFLOWS — STARS: MASS LOSS — STARS: PRE-MAIN SEQUENCE**

1. INTRODUCTION

Observing the universe over a typical human lifetime, it is easy to forget that our Galaxy is a very dynamic place. However, the excellent spatial resolution of the *Hubble Space Telescope* (*HST*) has changed that perspective dramatically for Galactic nebulae. Many well-known objects such as the Crab Nebula (Hester et al. 2002) and the Orion Nebula (Doi, O'Dell, & Hartigan 2002) exhibit striking motions between images taken only a few years, or even a few months apart. Structural changes between epochs indicate the kinds of instabilities that form in the flow and show where new shocks begin to cool, while the motions derived for individual objects identify the location of shocks and the exciting sources of outflows, and provide an overview of how the dynamics of the nebula relates to its morphology.

Observing motions in regions of shocked gas in stellar jets is particularly useful for all of the reasons listed above. In addition, stellar jets are dense enough and the internal shocks have low enough speed that the gas cools radiatively. Images of jets in different emission lines trace different portions of the flow. For example, sharp Hα features identify positions of shock fronts, where neutral gas entering the shock becomes collisionally excited. In contrast, forbidden line emission such as [S II] emits in the cooling zones behind the shocks. Hence, by observing how the shocked emission varies with time, one can follow variations in the shock fronts as well as in the cooling zones (e.g., Hartigan et al. 2000).

Stellar jets have long been known to have high proper motions (Herbig & Jones 1981), but observing more than bulk motion of a few objects has been problematic because the internal structure and brightness of these objects varies substantially over the 20 years or so it takes to see well-defined motions from the ground. With the order of magnitude increase in spatial resolution of *HST* over ground-based observations, motions in stellar jets become visible clearly within a few years, a timescale over which the vast majority of features have not changed their brightness or shape significantly.

A series of three papers written by a team consisting of the author, J. Bally, S. Heathcote, J. Morse, and B. Reipurth have discussed the *HST* results for the jets in HH 111 (Hartigan et al. 2001), HH 34 (Reipurth et al. 2002), and HH 1/2 (Bally et al. 2002), and a paper on the HH 47 jet is in preparation (Heathcote et al. 2003). When looking through the images we found that interpolating between the two epochs at regular intervals to produce a movie helped considerably to identify subtle changes that might otherwise be missed by simply blinking two images. In what follows I summarize this procedure, indicate where the movies may be found, and describe some of the main results from these studies.

2. INTERPOLATING TO MAKE MOVIES

To see how to interpolate between images of nebulae taken at different times, imagine photographing cumulus clouds that are drifting across the sky. If the images are taken only a few seconds apart it will be relatively easy to identify a particular cloud in both images, though the shape of the cloud may change slightly between the images. To interpolate, we need to first correct for the bulk motion of the clouds across the sky, and then take an appropriate time average so the shape of the cloud changes smoothly from one epoch to the next.

Following this idea, the interpolation routines first require initial velocity images $v_x(x,y)$ and $v_y(x,y)$ in the x and y directions, respectively. These velocities are used to shift the first epoch forward in time and the second epoch backward in time before taking a weighted average. Mathematically, if $z_1(x,y)$ is the pixel value at a point (x,y) in the first epoch image taken at time t_1, and $z_2(x,y)$ the corresponding value in the second image taken at time t_2, then the interpolated image $z(x,y)$ at a time t is simply

$$z(x,y) = \frac{z_1(x',y') \times (t_2 - t) + z_2(x'',y'') \times (t - t_1)}{t_2 - t_1},$$

where $x' = x - v_x(t - t_1)$, $y' = y - v_y(t - t_1)$, $x'' = x + v_x(t_2 - t)$, and $y'' = y + v_y(t_2 - t)$.

It is important to remember that this procedure, and the movies it generates, are simply visual aids that make use of the tendency of the human eye to follow an object in motion. All of the results reported in the next section are easily verified by simply blinking the two epochs. Nevertheless, the movies are extremely helpful in identifying features and structures that are easily missed by blinking. This interpolation technique should prove useful for other objects such as η Car (Morse et al. 2001), XZ Tau (Krist et al. 1999), and even the Crab (Hester et al. 2002), where multiple epoch *HST* images exist but the spacing between epochs is nonuniform.

How might the procedure give misleading results? The most obvious shortcoming might seem to be the input velocity images, which change across the field of view. However, the visual impression one obtains from the movies is remarkably independent of these images. Between our two *HST* epochs, the typical motion is about 10 (PC) pixels. Any clump that is moving at a somewhat different speed will appear slightly blurred at intermediate times because the interpolations won't line up exactly. But a slightly trailed image at intermediate times is immediately picked out by the human eye as having a slightly different velocity from the background, which is just what occurs.

The most stringent test is probably the HH 47 region, where the jet coincides with reflected light and a stationary Hα rim. In this case, even when the reflected light and the rim are given a forward motion corresponding to the jet, they still appear stationary to the eye in the movies because their spatial extent is over an arcsecond; hence, the only effect is to blur the left and right edges a bit at intermediate times, which does not appear as net motion. For these reasons the apparent motions of extended objects are quite insensitive to the initial velocities. The only difficulties arise with stars, which show double images at intermediate times unless zero velocities are specified for the stars or they are removed beforehand and added back in to each interpolated image. The other possible drawback is if features appear in only one image. In such cases the movies will show the object to appear or disappear gradually, which may or may not be what happened. Likewise, when a new knot emerges from a T Tauri star, there is no information about the region between the star and the knot at intermediate times.

3. RESULTS

Movies of the HH 1 and HH 2, HH 34, HH 47, and HH 111 jets are available on the web at http://sparky.rice.edu/~hartigan/movies.html. The papers listed in the Introduction summarize the major results from each region. The main lesson to take from the movies is that jets have *complex structure that moves as a unit.* Even though a single image may look like a turbulent flow, to first order the entire complex structure moves together, with only minor deviations from this bulk motion. Such a result is expected from ground-based spectroscopic studies (e.g., Morse et al. 1993) which show low-excitation lines indicative of shock velocities of $\sim 40\,\mathrm{km\,s^{-1}}$ along the jets even though the proper motions are up to an order of magnitude higher than this number. Nevertheless, movies of stellar jets really drive this point home. The easiest way to get this behavior is if the flow has variations in velocity and in density close to the source, which it must have in order to produce the multiple bowshocks observed along many jets.

Results from the movies (Hartigan et al. 2001; Reipurth et al. 2002; Bally et al. 2002) include new knots emerging from the sources that drive the HH 1 and HH 34 jets, and what appears to be a new shock forming near the base of HH 111. The large bowshock HH 34 has a shell-like structure analogous to a supernova remnant, and clumps forming along the leading edge of one of the shells may result from fluid instabilities or from a clumpy flow. We also observe the aftermath of merging bowshocks in HH 111L, entrainment of slower portion of flow in a reverse bowshock in the HH 34 bow, differential motions in HH 2 probably caused by projection effects, and remarkable shear along the edge of the HH 1 bow.

The HH 47 paper (Heathcote et al. 2003) has yet to appear in print, but it is worthwhile to point out some of the features associated with HH 47A (Figure 1), because it is probably the best example in the sky of a working surface where the jet is decelerated by a Mach disk and material ahead of the object is accelerated by a bowshock. The movie shows that individual clumps in the region between the bow and the Mach disk have different speeds. The brightest clump near the apex of the bow, and two clumps within the Mach disk move faster than the surrounding material. Such "mini-bullets" are the likely cause of the bumpy shape of the bowshock; in fact, the fast clump near the apex will catch up to the bowshock in a few decades. The ability to observe such interactions in real time opens up fascinating possibilities for the study of these objects.

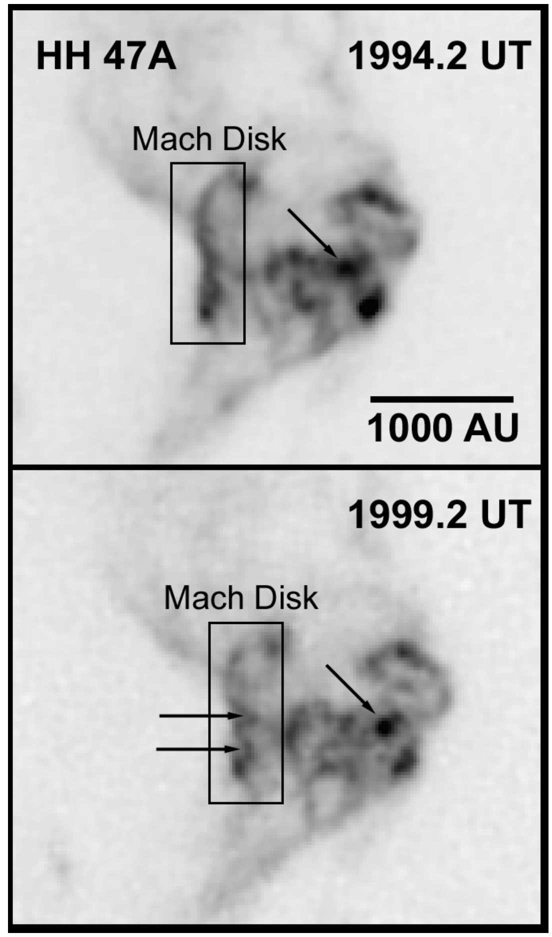

Fig. 1. The bowshock/Mach disk of HH 47A, as imaged in Hα by *HST* in 1994 (top) and 1999 (bottom). The knots labeled with arrows move relatively faster than the adjacent material. The two images are registered in RA and DEC; the shift of the entire object to the right in the bottom image reflects its real motion.

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