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HERBIG-HARO OBJECTS IN THE ORION NEBULA

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RESUMEN

Se estudia la cinemática de un conjunto de objetos Herbig-Haro al norte del cúmulo del Trapecio. Los movimientos propios se han determinado a partir de dos conjuntos de imágenes obtenidas con el *HST* con cuatro años de separación, usando filtros de banda angosta. Las velocidades radiales se obtuvieron de espectros de rendija larga y de alta resolución. Se ha usado un modelo de choque de proa para ajustar los datos espectroscópicos y proponer posibles soluciones físicas para estos objetos.

ABSTRACT

The kinematics of a group of Herbig-Haro objects to the north of the Trapezium cluster is investigated. Their proper motions have been determined from two sets of *HST* narrow band filter images that were taken four years apart. Radial velocities have been obtained from high resolution long-slit spectra. A bowshock model has been used to fit the spectroscopic data and a possible physical solution for these objects is proposed.

Key words: **ISM: INDIVIDUAL OBJECTS: THE ORION NEBULA — LINE: PROFILES**

1. INTRODUCTION

As an active star forming region, the Orion nebula contains numerous high velocity flows associated with the interaction between young stars and ambient gases. There are ten objects in the OMC-1 region that have been identified as Herbig-Haro objects, where all of them have characteristic high velocity blue wings in the low-excitation lines. These objects have been designated as HH201 through 210 (Reipurth 1994). Except for HH203 and 204, all the objects are located to the north of the Trapezium cluster and most of them were first discovered and studied by Axon & Taylor (1984). Spectroscopic data of [O I] λ6300 with velocity resolution of 30 km s^{-1} revealed that the maximum radial velocities of these objects ranges between -100 and -380 km s^{-1} with respect to the ambient [O I] gas. Subsequently, Jones & Walker (1985) performed a proper motion study of HH201, 205 and 210, finding very high proper motions (up to 11$''$ per century) and tangential velocities tending to head away from common sources; e.g., for the embedded young infrared sources, primarily the Becklin-Neugebauer object (Becklin & Neugebauer 1967) and the younger, more luminous IRc2 (Downes et al. 1981). The association of these objects with the infrared sources was confirmed later in the infrared study of Allen & Burton (1993). The "finger" shaped objects in their images, detected in [Fe II] and H_2 shock-excited infrared emission, really help us to see that these HH objects originate from common infrared sources.

Based on all these previous studies, we present here new results on these interesting Herbig-Haro objects, both in terms of proper motions from *HST* observations and radial velocities derived from our high resolution spectra. Furthermore, a bowshock model calculation for these objects has been done in order to explain our spectroscopic data quantitatively.

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2. OBSERVATIONS

Being aware from previous studies that the objects we are interested in probably have proper motions as large as 11″ per century (0.1″ per year) , we realized that it is possible to determine accurately the motion of these objects in only a few years, using high resolution images taken by *HST*. Two sets of *HST* WF/PC and WF/PC2 narrow band filter images were used in the comparison of positions. The first set was taken in August 1990 (Hester et al. 1991), and the other set was taken in December 1994 and have much better image quality due to the successful refurbishment mission. Both sets of data have been reduced using the standard reduction packages available at the time of observation. Routine procedures like flat-fielding, cosmic ray removal and mosaicing have been done to both sets of data. The Lucy deconvolution (Lucy 1974) was applied (using the PSF calculated by Burrows et al. (1991) only to the earlier set of data, and geometric distortion corrections have been applied only to the second set of data during the process of mosaicing. A pair of [N II] λ6583 filter images was used and the exposure time for the 1990 data was 600 s while 500 s exposure times were used for the 1994 data. For both sets of data the spatial resolution is about 0.1″, which corresponds to 48 AU at Orion's distance (480 pc).

To carry out a detailed kinematic study of these HH objects, long-slit, high spectral resolution spectra were obtained using the Coudé Feed spectrograph at the Kitt Peak National Observatory (Willmarth 1992) in December 1994. An Echelle grating was used in combination with a cross-dispersion grism to obtain multiple orders on the CCD detector during the same exposure. In this manner we were able to get most low ionization lines such as [O I] λ6300, [S II] $\lambda\lambda$6716,6731 doublet, [N II] $\lambda\lambda$6548,6583 doublet and Hα on a single exposure. It is easy to imagine that the overlap of orders could be a major problem when we use a long slit as well as a guiding star on the slit, since the object we are interested in could fall on the stellar continuum image from another order. We avoided this problem by carefully positioning the slit using an offset from a reference star, and used a marker on the TV screen to do the guiding instead of putting our slit cross the star itself. Another problem is that the overlap of orders makes it hard to do any flat-fielding of the spectra, though we feel this is not really necessary for the purpose of our kinematic study. Other routine reduction procedures such as overscan, zero correction, and wavelength calibration were applied to our data. Cosmic ray hits were removed by combining multiple identical-setting exposures which we took for this purpose. Using the Ford3k (3072 × 1024) CCD we were able to achieve a velocity resolution along dispersion as high as 1.3 km s^{-1} per pixel, and the spatial resolution along the slit was 1.38″ per pixel. This kind of resolution makes possible the detailed modeling of emission line profiles.

3. RESULTS

3.1. Proper Motion

For the *HST* 1994 images, three different fields-of-view were required to cover our targeting region partially. So we first found field stars in their overlapping area and registered them to make one mosaic image that covers the whole region of interest. Then the astrometric solution had to be resolved for both 1990 and 1994 data. We have done this by measuring bright field star center coordinates on the plate and found corresponding world coordinates from Jones & Walker (1988). Finally, the plate scale and the field rotation were solved by doing a multiple regression fit using IRAF task ctio.coord and one of our local programs.

We then aligned the two images by rotating one of them. A small amount of magnification for one of the images was necessary to match the slightly different plate scales. At last we chose three Herbig-Haro objects HH201, HH205, HH206 to do the comparison by registering one star close to the object. The results are shown in Table 1.

TABLE 1

RESULTS OF THE PROPER MOTION STUDY

	This study				Jones & Walker (1985)	
	μ_x (″ per century)	μ_y (″ per century)	V (km s^{-1})	PA (deg)	V (km s^{-1})	PA (deg)
HH201	4.6	6.9	178	324	167	304
HH205	3.4	23.2	500	351	236	344
HH206	5.5	10.9	261	333	–	–
HH210	–	–	–	–	215	16

3.2. Radial Velocity

To look at the emission from HH objects, we chose a smooth nebular region along the slit that is close to the object and did a "background subtraction" for each object. All the spectral line profiles presented here are background subtracted.

From Figure 1, we can easily see that HH201 and HH210 have similar general line shapes, where the flux concentrates at low velocity and both of them have very high velocity blue wings extending as far as 300 and 400 km s^{-1} respectively. The line shape for HH205 is quite different from the other two. For this source the flux concentrates at low velocity but the profile has both red and blue wings almost symmetric about zero velocity, extending to about 70 km s^{-1}. Combined with the tangential velocities from the previous section, we obtain spatial motions of HH201, HH205 and HH210 as high as 350, 505, and 454 km s^{-1} respectively.

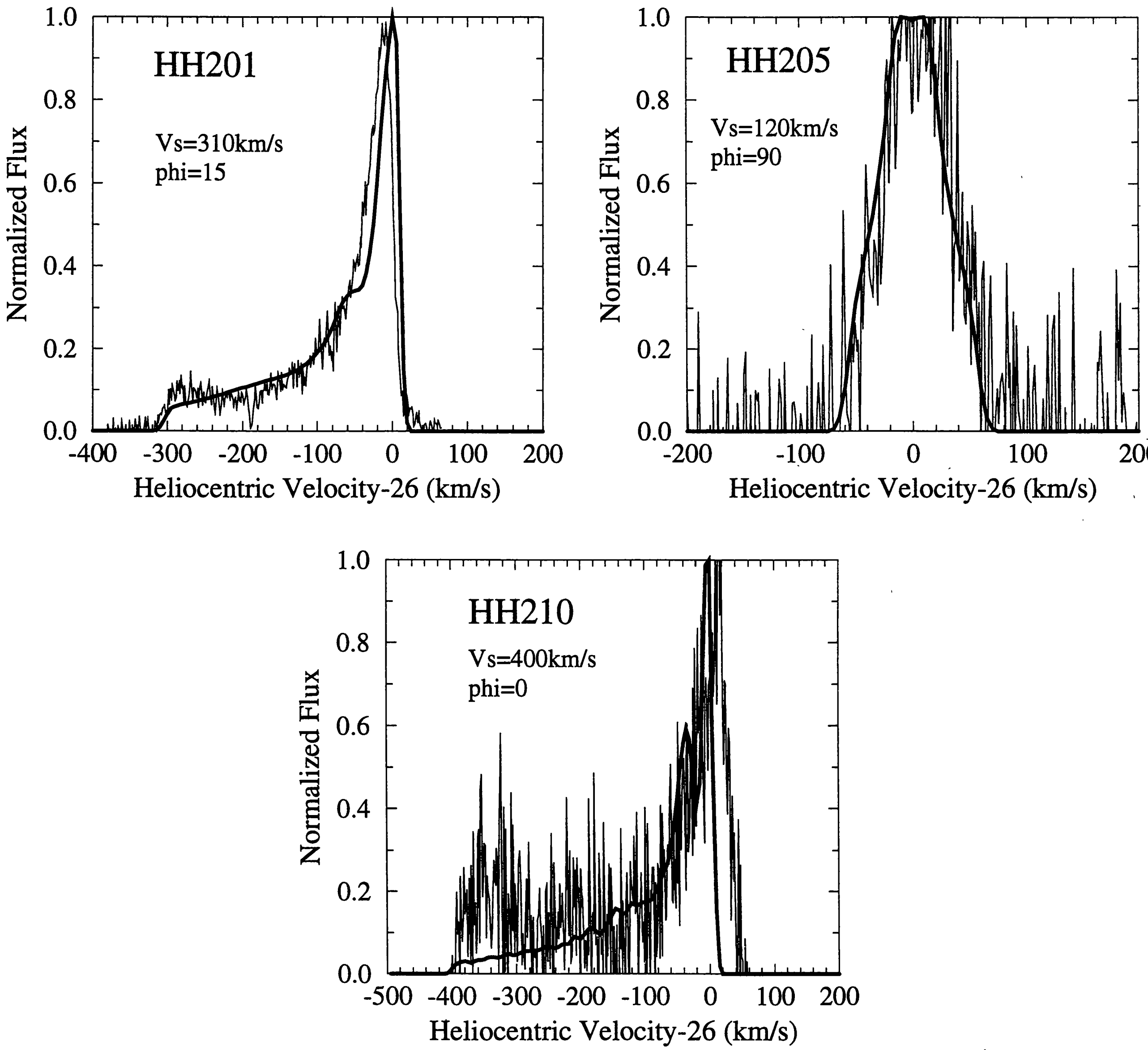

Fig. 1. Line profiles derived from the bowshock model are fitted to the observed data. The "Bullet" model was used with a density = 10^4 cm^{-3}, the distance to the objects is 480 pc, pre-shock materials are assumed to be equilibrium ionized. The observed spectra are presented in the frame of the molecular cloud which is moving away from us at 26 km s^{-1}.

4. DISCUSSION

The large proper motions and radial velocities of these Herbig-Haro objects imply that their motions are highly supersonic. It is generally accepted that the radiation from these objects is line emission occurring as gas cools behind a shock (Schwartz 1983). Various shock models have been proposed and a bowshock model is favored for our objects, based on the infrared study by Allen & Burton (1993). Hartigan, Raymond, & Hartmann (1987) constructed a bowshock model using a collection of 43 radiative planar shock models. Their model can be used to predict observed line ratios and line profiles as well as to estimate the shock velocity and bowshock orientation.

We have run the modeling code adopted from Hartigan et al. (1987) to fit the observed line profiles of HH201, 205 and 210. The physical parameters of the Orion nebula in that region were fed to the code and the shock velocities were first estimated using the line width measurement as suggested in the Hartigan et al. study. It turned out (see Fig. 1) that the observed line profiles are fitted very well by this general model, except that the fitted profiles have various velocity differences (less than 20 km s^{-1}) with respect to the observed profiles. Since the profiles given by the modeling calculation are in the frame of the driving sources of the HH objects, we argue that the velocity differences come from the motion of driving sources relative to the molecular cloud. As the general bowshock model gives a good fit to our observed line profiles, the parameters we used in the calculation tend to be a set of physical solutions for these objects. In our calculation, the "bullet" model (Norman & Silk 1979) was used succesfully for all three objects, which implies that this group of HH objects are more likely excited by bowshocks formed around a dense clump of gas ejected into the ambient cloud. Other parameters or assumptions we used include: equilibrium ionized pre-shock material, pre-shock density around 10^4 cm^{-3}, the objects are at 480 pc, the whole object falls within our slit and the objects are about 2″ in angular diameter. The bowshock shape is more arbitrary compared with other parameters. For HH205 we used shape "A" ($z = 0.42r^2+1.0r^4$) as referred by Hartigan et al. (1987) and for HH201,210, a bowshock of shape $z = 0.05r^2$ was used. The bowshock velocities used for HH201,205,210 are 310,120, and 400 km s^{-1} respectively, while the orientations of the bowshock with respect to the line of sight are 15°, 90°, and 0°. Looking again at the geometry of these objects and their driving sources (Allen & Burton 1993), our results confirm that these Herbig-Haro objects have been ejected from the IRc2 region around the same time (approximately 600 – 700 years ago) according to the tangential velocities of objects. On the other hand, the observed radial and tangential velocities of these objects agree within 15° with the prediction of the bowshock model on the orientation of motion of these three Herbig-Haro objects. For example, HH201 is heading almost toward us at approximately 20° with respect to the line of sight, and has a smaller projected distance from the sources on the plane of the sky, while HH205 is moving almost in the plane of the sky and has the largest projected distance to IR sources.

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