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PROPER MOTIONS OF HERBIG-HARO OBJECTS

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I. INTRODUCTION

Luyten (1963, 1971) first detected proper motions for Herbig-Haro (H-H) Objects, finding large motions for HH-28 and -29. These motions were later confirmed by Cudworth and Herbig (1979), using more extensive plate material at higher scale. Later observational and theoretical work (Schwartz 1978; Schwartz and Dopita 1980; Norman and Silk 1979; Rodríguez et al. 1980) suggested that high space velocities were a natural consequence of the shock-wave interpretation of H-H Objects.

Because of the large motions of HH-28 and -29 and the expected large motions for H-H Objects in general, George Herbig and myself have undertaken an extensive program to determine proper motions for all Objects for which accessible first epoch plates exist. This program is possible in large part because of the large Lick collection of 120-in and Crossley 36-in plates of fields containing H-H Objects. As work has progressed, it has become clear that HH-28 and -29 are not isolated instances, but rather that high proper motion is a common, although not universal, feature of H-H Objects. The directional information contained in the proper motions has given strong support to ideas of directional mass loss in pre-main sequence stars. They have also led to the identification of probable exciting stars for two Objects, and have put constraints on theoretical models. This paper summarizes the work done at Lick Observatory to the present on the proper motions of H-H Objects.

II. ASTROMETRY

In general, H-H Objects are several seconds of arc in size, and may contain much internal structure. In many Objects, there has been structural change over the period of our plates. Because of the problems of measuring such images on the Lick Automatic Measuring Engine (AME), the H-H Objects were measured on a one-coordinate manual measuring engine, along with a small selection of reference stars. A much larger selection of stars was measured on the AME. The stars in common between the manual and AME measures were used to reduce the H-H measures to the AME system.

In all cases, the measures were reduced using a modified central plate overlap algorithm (Eichhorn and Jefferies 1971). Allowance was made for scale, orientation, zero point, and tangent point differences and, in the case of reflector plates taken with a corrector, radial distortion.

The proper motions we have derived are all relative, in each case, to the mean motion of the stars making up the reference frame. The nature of the reference frame stars varies from field to field. Most H-H Objects lie in heavily obscured areas. In such cases, the stars measured consist primarily of stars physically associated with the obscuration, having a small proper motion dispersion, along with a few foreground stars having large proper motion. We have always excluded such high proper motion stars from the reference frame. The zero point of our proper motions is thus different from the fundamental zero point due to the tangential motion of the cloud as a whole and to the effects of the reflex solar motion. In two cases (HH-39 and HH-32), the reference frame consists of stars background to the Objects. The proper motion zero point for these two Objects is offset from the fundamental zero point due to the effects of the reflex solar motion. Because they are near the galactic plane and our reference frame consists of faint stars, this offset is quite small.

In no case have we attempted to correct our proper motions to a fundamental system. Since no measureable stars appeared on our plates with proper motions known on a fundamental system, such a reduction would have involved a boot-strap operation that would introduce errors comparable to the correction. Such a correction would be small in most cases compared to the motion of the H-H Objects. Moreover, we believe that the relevant motion is that with respect to the cloud or to the probable exciting star.

Since the field sizes of either the Crossley and 120-in are too small to contain appreciable numbers of positional reference stars, Lick Carnegie astrograph plates were used to define a faint secondary positional reference frame for each field, using stars in the AGK3 catalogue as the primary standards. These secondary standards were then used with the Crossley and 120-in measures to determine positions for each of the H-H Objects.

Table 1 gives the positions and proper motions (in units of arcsec cent^{-1}) for all the H-H Objects measured to date. The positions are given for an equator and equinox of 1950.0 and for the epoch 1982.0. Also included in Table 1 are the positions and proper motions for probable exciting stars. In each case, the data for the star follows that for the H-H Object.

III. DISCUSSION OF INDIVIDUAL FIELDS

a) HH-1, -2, and -3

HH-1, -2, -3 are part of the Orion complex at a distance of 460 pc. They lie near the nebulosity NGC 1999 which surrounds V380 Ori, although there is no obvious connection between the H-H Objects and this star. HH-1, -2, -3 lie nearly on a line. Also close to this line, between HH-1 and -2, is a faint, heavily obscured emission line star believed to be the source ultimately responsible for the excitation of the H-H Objects (Cohen and Schwartz 1979; this star is referred to as the C-S star). HH-1 and -2 have shown major structural changes since 1946 (Herbig 1969; Herbig and Jones 1981). HH-1 currently has a cometary shape, with a bright nucleus to the north-west, although 30 years ago the brightest portion was to the south-east. On 120-in plates, several knots can be resolved. HH-2 consists of several knots resolvable on both Crossley and 120-in plates. These knots have changed considerably in relative brightness over the past 35 years, with several new knots appearing.

TABLE 1. Positions and Proper Motions of H-H Objects

Object	α (1950)	δ	μ_x	σ_x	μ_y	σ_y
			(units arcsec cent^{-1})			
HH-1A	$5^h33^m54^s.85$	$-6°47'$ 1".2	-2.7	0.8	6.6	1.3
HH-1C	5 33 54.83	-6 46 59.2	-5.7	0.6	7.4	1.0
HH-1D	5 33 54.70	-6 46 59.0	-6.2	0.9	9.4	0.6
HH-1F	5 33 54.54	-6 46 57.0	-9.9	2.6	12.7	2.0
HH-2A	5 33 59.44	-6 48 59.2	3.0:		-6.3:	
HH-2B	5 33 59.89	-6 48 56.3	1.9	0.5	-4.2	0.6
HH-2C	5 33 59.67	-6 48 55.5	6.9	0.8	13.5	1.1
HH-2D	5 33 59.35	-6 49 4.0	-0.9	0.6	-3.8	1.0
HH-2E	5 34 0.70	-6 49 0.4	-0.3	0.6	-2.8	1.0
HH-2G	5 34 0.11	-6 48 57.1	3.9	0.5	-5.8	0.4
HH-2H	5 33 59.69	-6 49 3.8	5.6	0.4	-9.6	0.6
HH-2I	5 33 59.65	-6 49 8.5	2.8	0.5	-10.5	2.1
HH-3	5 33 45.77	-6 44 53.4	-0.4	0.5	0.8	0.3
C-S STAR	3 33 55.55	-6 47 25.1	-0.4	0.1	0.0	0.3
HH-4	3 26 18.36	31 9 40.2	0.8	2.0	-0.6	2.0
HH-5	3 26 14.78	31 2 32.3	1.8	2.0	-2.1	2.5
HH-7a	3 26 2.78	31 5 10.8	1.4	2.0	2.9	2.0
HH-7b	3 26 2.56	31 5 10.1	3.0	2.1	1.9	2.1
HH-8a	3 26 0.68	31 5 18.7	-2.2	2.0	1.7	2.0
HH-10	3 25 59.83	31 5 29.2	-1.1	2.0	-1.0	2.0
HH-11a	3 25 59.05	31 5 34.7	3.0	0.5	-1.8	0.8
HH-11b	3 25 58.99	31 5 33.1	1.4	2.1	-4.3	2.1
HH-12b	3 25 53.52	31 10 13.0	5.0	0.7	14.4	0.6
HH-12d	3 25 52.39	31 9 51.1	0.5	3.8	5.5	2.0
HH-12e	3 25 53.69	31 9 48.6	1.5	1.7	3.2	1.7
HH-12f	3 25 53.72	31 9 31.0	-3.1	1.2	10.2	1.1
STAR 21	3 25 52.01	31 8 16.4	-0.2		-0.1	
HH-17	3 26 14.74	31 8 16.6	0.0	2.1	0.7	2.1
HH-28			-16.	3.	-13.	3.
HH-29			-13.	1.	-19.	1.
HH-30			1.6	0.6	-2.1	0.9
HL TAU			2.0	0.3	-2.9	0.4
HH-32A	19 18 7.91	10 56 21.7	- 3.8	2.1	0.6	1.5
HH-32B	19 18 8.19	10 56 17.2	-13.2	2.5	5.1	1.5

TABLE 1. Positions and Proper Motions of H-H Objects (continued)

Object	α (1950)	δ	μ_x	σ_x	μ_y	σ_y
			(units arcsec cent^{-1})			
HH-32D	$19^h18^m 9^s.71$	$10^\circ56'10''.4$	-0.3	1.5	-1.8	1.5
AS-353A	19 18 9.41	10 56 14.7	-0.6	1.0	-0.8	1.0
AS-353B	19 18 9.45	10 56 9.0	0.5	1.0	-1.1	1.0
HH-39A	6 36 21.60	8 54 13.2	-1.5	1.1	7.1	0.5
HH-39C	6 36 21.08	8 53 50.0	1.7	0.5	8.0	0.5
HH-39D	6 36 21.43	8 53 40.8	-1.0	0.6	1.2	1.4
HH-39E	6 36 21.54	8 53 48.1	-3.6	0.6	6.3	3.4
R Mon	6 36 26.05	8 46 54.5	-0.2	0.1	-0.5	0.4

The knots of both HH 1 and 2 show large, well-determined proper motions (Herbig and Jones 1981). Thirty two plates of this region were measured, including two Heidelberg Bruce plates taken in 1900 and 1901 and two Harvard Bruce plates taken in 1901 and 1929. Plates have been taken almost yearly between 1954 and the present, using both the Crossley and 120-in. The proper motion vectors for the individual knots within each Object are nearly parallel with each other and with the line joining the two Objects. Moreover, they point directly away from the C-S star.

Although the knots of HH-1 and -2 have relatively small radial velocities, the proper motions correspond to tangential velocities of up to 350 km s^{-1}, suggesting that the line joining HH-1 and -2 is nearly 90° to our line of sight. The proper motions of the individual knots show a large dispersion in tangential velocity, ranging from 155 to 350 km s^{-1} in HH-1 and from 60 to 295 km s^{-1} in HH-2. There is a decrease of the magnitude of the proper motion with increasing distance from the C-S star, with the knots of HH-1 generally having a larger proper motion than the knots of HH-2, and with HH-3 having a small motion, although the motions of the fastest knots of HH-2 are larger than those of the slowest in HH-1.

Although, as discussed below, CO observations of regions containing H-H Objects provide strong evidence of bipolar winds, CO observations of the region of HH-1 and -2 (Snell and Edwards 1982) show no evidence of blue or red shifted wings. Snell and Edwards suggest this may be because the lobes lie at nearly 90° to our line of sight or because mass ejection started relatively recently in this system. A time scale of ~1000 years can be inferred from the time it would take HH-2 to reach its present position with its present motion, but this time scale neglects the small motion of HH-3 and its distance from the C-S star.

b) HH-39 and R Mon

R Mon is a nebulous star at the tip of the cometary reflection nebula NGC 2261 (Hubble's variable nebula). HH-39 is a cluster of diffuse knots $7'.5$ north of R Mon, close to the symmetry axis of NGC 2261, but well beyond it. Although the knots of HH-39 are diffuse and hard to measure, the motions are large and well determined (Jones and Herbig 1982). The proper motion vectors point away from R Mon, and are nearly parallel to the symmetry axis of NGC 2261. The tangential velocities of three knots (A,C,E) are close to 300 km s^{-1}, although one knot (D) has much smaller motion of 60 km s^{-1}.

We observe NGC 2261 via the reflected light of R Mon. Present in the spectrum of NGC 2261 are a set of shell lines that originate close to R Mon itself. The radial velocity of these lines becomes increasingly more negative as one moves up the fan of NGC 2261 away from R Mon, reaching an extreme value of -200 km s^{-1} 76" north of R Mon (Stockton, Chesley, and Chesley 1975; Jones and Herbig 1982). Jones and Herbig were able to show that this increasing negative radial velocity along NGC 2261 is due to a latitude dependence of the stellar wind from R Mon. Their deduced polar wind velocity is the same as the tangential velocity of HH-39. In this case it has been possible to show that the H-H Object is traveling at the wind velocity of the responsible star.

Although there is no corresponding H-H Object to the south of R Mon, the CO observations of Cantó et al. (1981) show both a blue-shifted wing north of R Mon and a red-shifted wing to the south, supporting a bipolar interpretation. Moreover, on long exposure plates, there is a faint nebulosity to the south of R Mon, a possible counterpart to NGC 2261.

c) HH-7 through -11

HH-7 through -11 are a string of H-H Objects associated with the dark cloud B205 (part of which, NGC 1333, is a reflection nebulosity illuminated by BD+30°549). Only HH-11 has a reliable proper motion (Herbig and Jones 1983), the others being too diffuse for accurate measurement. HH-11 is the Object closest to an infrared source discovered by Strom, Grasdalen, and Strom (1974), which lies near a line connecting the H-H Objects. Coincident with the infrared source is the H_2O maser HH-7-11(A) (Haschick et al. 1980). The well determined proper motion vector of HH-11 points away from the infrared source and along the line of the H-H Objects. The infrared source and H_2O maser lie at the waist of a double-lobed CO structure (Snell and Edwards 1981), with the negative CO lobe enclosing HH-7 through -11, which lie along the axis of symmetry of the lobes.

d) HH-12

HH-12 is also associated with the dark cloud B205 and NGC 1333. It is a rather large amorphous nebulosity containing many condensations. Several of these condensations have been measured for proper motion (Herbig and Jones 1983). The proper motions for the knots of HH-12 are all large and well determined. They are nearly parallel. Along their backward extension is an infrared source (Strom et al. 1976; Cohen and Schwartz 1983), whose coordinates match those of star 21 of Herbig and Jones (1983). This star is a heavily obscured (A_V = 8.8) M dwarf with rather strong H emission.

e) HH-28, -29, and -30

Cudworth and Herbig (1979) noted that the backward projections of the proper motion vectors for HH-28 and -29 passed near the infrared source 5 of Strom et al. (1976). The proper motions correspond to tangential velocities of 145 km s^{-1} at a distance of 140 pc for the Taurus dark clouds. Subsequent to the proper motion determinations, Snell, Loren, and Plambeck (1980) observed a double lobed CO source, centered on the infrared source, with HH-28 and -29 in the blue-shifted lobe. A more precise positional determination of the coordinates of the infrared source (Cohen and Schwartz 1983) place it at the tip of an optical jet, which is aligned with the CO lobe and the proper motion vectors. Coincident with the infrared source is an elongated continuum radio source, also aligned with the CO lobes (Cohen, Bieging, and Schwartz 1982).

HH-30 is probably excited by HL Tau (Cohen and Schmidt 1981). Its proper motion is too small compared with the measurement errors to say anything about its motion with respect to HL Tau.

f) HH-32 and AS-353A,B

AS-353A is a bright pre-main sequence star. The well determined proper motion vectors of knots HH-32A and -32B (Herbig and Jones 1983) are directed away from this star, with the fainter HH-32B having the larger proper motion and being closer to AS-353A. Edwards and Snell (1982) have made CO observations, and find a double-lobed source centered on AS-353A with HH-32A,B being in the positive radial velocity lobe. This is consistent with the positive radial velocities of HH-32A and -32B themselves. HH-32A and -32B are unusual among H-H Objects in not only having positive radial velocities, but in also having two sets of emission lines. Herbig and Jones interpret this as due to the viewing of them at a rare aspect angle: we see them in the same direction that they are impacted by the wind from AS-353A. The two sets of emission then presumably arise from the post- and pre-shock stellar wind arriving at the obstruction of the H-H Objects.

g) HH-43

Although work on this object is in progress (Jones and Herbig 1983), preliminary motions were used by Cohen and Schwartz (1983) to search for the exciting star along the background projection of the proper motion vector. That search found an infrared source, not only aligned with the proper motion vector, but also along the line joining HH-43 with HH-38.

IV. SUMMARY AND CONCLUSIONS

Because the proper motions give two components of the motion, it is possible to look backward along the proper motion vector to search for the star responsible for the H-H Object. In every case for which we have reliable motions, there is a pre-main sequence star (or an infrared source) along this backward extension. In most instances, one can make a convincing argument that it is this star that is ultimately responsible for the excitation of the H-H Object.

In only one case, HH-1 and -2 do we find clear evidence for H-H Objects on both sides of the exciting star (although there is another case in the southern hemisphere, HH-46 and -47, but for these no proper motion data exist; Graham and Elias 1982; Dopita, Schwartz, and Evans 1982;

Graham and Elias 1983). One can argue that this is because we only see H-H Objects that are moving towards us, out of the obscuring cloud. The preponderence of negative radial velocities and the fact that most H-H Objects appear in the blue shifted CO lobes support this view. However, there are cases where one should be able to see two sets of H-H Objects on either side of the star, if in fact they existed. HH-32A,B have positive radial velocity and are being driven into a cloud. There are no comparable objects on the other side of AS-353A. The region around R Mon is relatively unobscured, but one sees nothing comparable to HH-39 to the south. Jones and Herbig (1983) present arguments which suggest one should see Objects on the opposite side of the infrared source from HH-7 to -11 if they existed. Even in the case of HH-1, -2, and -3, the motions and travel times are such as to preclude simultaneous ejection.

The proper motion data provide strong evidence for a substantial velocity dispersion among the knots within a single H-H Object. This is most clearly seen in HH-2, where the velocities range from 60 to nearly 300 km s^{-1}, but is also seen among the knots of HH-1, -39, and -12. In these cases, there appears to be no correlation between the velocity of the knot and its position within the H-H Object; i.e., the dispersion does not appear to be the result of acceleration or deceleration. In fact, we find no evidence for acceleration in any of the objects we have looked at. This is shown most clearly for HH-2, which has adequate plate material covering 35 years. Those knots which have appeared during this time have done so with their full velocity, while those which have faded have done so while retaining the motion they had while bright.

Even though there is no evidence for acceleration of individual H-H Objects over the short time of observation, there is such evidence in those cases where there has apparently been repeated ejection of H-H Objects. Thus in HH-1, -2 and -3, the mean motion of the H-H Object decreases with increasing distance from the C-S star. There is a similar situation at HH-32A and B, where B has the larger motion and is closer to AS-353A. Although the proper motions are not sufficiently accurate to demonstrate this at HH-7 to -11, the radial velocities (Strom et al. 1974) show that HH-11, closest to the infrared source, has the largest velocity.

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DISCUSSION

S. Strom: I think that the object you identify as the source for HH 12 is not the object. It is probably the star *directly* south of the object. We find it to be a weak Hα emission object connected by a complete Hα "bridge" to HH 12.

Franco: Is there any correlation between velocities and mass (or size) of the condensations?

Jones: We have not found any.

Snell: The dispersion in velocity and direction of the proper motions of the knots that compose HH 2 indicate that the knots could not all have originated at the C-S star, do you think the knots were more likely accelerated close to their present positions?

Jones: There are two possibilities: 1) They were accelerated close to the C-S star and have subsequently undergone different amounts of deceleration, or 2) they were accelerated (by different amounts) near their present location.

Montmerle: From viewing the slides, I get the impression that the globules in HH-objects are always rather far from the presumed associated star. Is this actually true, or is there an observational bias? Do you find "compact" objects, close to the associated star? What is the minimum (linear) distance at which you find the closest objects?

Jones: The selection effect is in the preparation of the slides, which are at different scales. HH-objects lie at distances from 0.02 pc to over 1 pc from the exciting stars.

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