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THE *(V, B–V)* DIAGRAM AND THE DRIVING SOURCES OF HERBIG-HARO OBJECTS

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RESUMEN

Se busca un criterio que facilite el descubrimiento de objetos Herbig-Haro (HH) de una manera sistemática, utilizando las propiedades ópticas de sus fuentes excitadoras. Para ello, buscamos en la literatura fuentes excitadoras de objetos HH con fotometría en el óptico publicada. Encontramos sólo 23 estrellas con datos confiables. Se encuentra que 65% de estas estrellas se localizan por debajo o en la secuencia principal de la edad cero (SPEC) en el diagrama (V,$B-V$). De éstas, el 73% están muy veladas y todas ellas tienen fuertes excesos infrarrojos. El restante 35% de la muestra se encuentra arriba y a la derecha de la SPEC, de éstas el 75% son estrellas Ae/Be de Herbig, y en el 75% de los casos, están muy enrojecidas, con un desplazamiento en el diagrama (V,$B-V$) de $\delta(B-V) \geq 1.0$ con respecto a la posición esperada de acuerdo a sus tipos espectrales. Dentro de estas últimas se encuentran dos estrellas FUOR, dos de ellas son sistemas múltiples, y cuatro de ellas son objetos distantes (d $\geq$ 1 kpc), lo que hace que sus posiciones en el diagrama (V,$B-V$) sean inciertas.

ABSTRACT

We are looking for a criterion that helps us to find Herbig–Haro (HH) objects in a systematic way by making use of the optical properties of their exciting sources. To find it, we searched for exciting sources of HH objects with published optical photometric data. Only 23 stars with reliable data were found. We find that 65% of the stars in the sample are objects lying below or very near the zero age main sequence (ZAMS) in the (V,$B-V$) diagram. Of these, 73% are strongly veiled and all of them have strong near-IR excesses. The remaining 35% of the stars are located above and to the right of the ZAMS. From these, 75% are Herbig Ae/Be stars and 75% are very reddened, shifted in the (V,$B-V$) diagram by $\delta(B-V) \geq$ 1.0 relative to the position expected from their spectral types. For the latter stars we also found that two of them are FUOR stars, two of them are multiple systems and four of them are distant objects (d $\geq$ 1 kpc), facts that make their location in the (V,$B-V$) diagram uncertain.

Key words: **STARS: FORMATION — STARS: PRE–MAIN SEQUENCE**

1. INTRODUCTION.

In the past, HH objects have been discovered accidentally (usually on deep plates). Since their discovery (Herbig 1951, 1952; Haro 1952, 1953), these nebulosities attracted much attention due to their intense Hα and forbidden (e.g., [S II] and [N II]) emission lines. Their low surface brightness and the sensitivity of the photographic emulsions were the major limiting factors in discovering them. With the arrival of larger telescopes in both hemispheres, and with the discovery of new techniques and detectors, their number has increased drastically with time. In 1974 Herbig published a catalogue containing 44 HH objects. Fourteen years later, von Hippel, Burnell, & Williams (1989) gave a list of 89 objects. More recently, Reipurth (1994) published a list of about 250 HH objects. Today we are certain that they are associated with star forming regions (SFRs) and we understand their nature. Despite the spatial limitation and the fact that we now know more about their physics, many of these regions are too extended for large CCDs, and the telescope time available is very limited, complicating the search for new objects. Once a HH object is discovered, one surveys its surroundings looking for the exciting source. In some cases the geometrical configuration of the nebulosities helps to localize the driving sources. Once the exciting star has been localized, one searches for its properties and nature. It appears that the exciting sources are T Tauri stars or Herbig Ae/Be stars (cf., Herbig & Bell 1988; Reipurth 1994).

The aim of the present work is to find an alternative way to look for undiscovered HH objects. We have searched for new HH objects in a more systematic way, based on the optical properties of their driving sources. Driving sources that are deeply embedded in dark clouds or are highly reddened by their associated circumstellar shell fall beyond the scope of this research.

TABLE 1

HH OBJECTS AND THEIR OPTICAL COUNTERPARTS

#	HH	HBC	star	other designation	*V*	*B–V*
1	162	325	V376 Cas	V376Cas/HH	15.6	1.8
2	220	25n	CW Tau	MHα 259-3	12.36	1.23
3	156	375	CoKu Tau/1	CoKu Tau/1 jet	19.3:	—
4	155	35n	T Tau	HH1555 +19° 706	9.90	1.19
5	158	37n	DG Tau	DG Tau jet	12.01	0.93
6	184	389n	Haro 6-10	Haro 6-10/HH	17.2:	2.0:
7	150	49n	HL Tau	HL Tau/jet Haro 6-14	14.57	1.36
8	152	50	XZ Tau	XZ Tau/jet	13.30	0.74
9	123	410n	L1642-2A	—	17.7:	1.8:
10	230	67	DO Tau	MHα 259-15 DO Tau/jet	14.01	1.42
11	231	70	DP Tau	HHα 259-19 DP Tau/jet	14.22	1.28
12	229	80	RW Aur A	+30° 792 RW Aur/jet	10.12	0.65
13	271	198	Bretz 4	GGD17/HH1	15.0:	—
14	160	243n	Z CMa	HD53179 Z CMa/jet	9.35	1.21
15	140	596n	vBH 65b	SS 1-44	12.75	1.13
16	186	248n	Sz68	CoD-33° 1068 S Sz68/jet	10.31	1.27
17	57	646n	V346 Nor	HH57/IRS8	16.3v	2.1v
18	82	286	S CrA	—	11.12	0.78
19	104	288n	R CrA	—	10.74	0.56
20	32	292n	V352 Aql	AS 353 A IrCh34	12.46	1.05
21	221	687n	Par 21	PP 88	14.16	1.12
22	165	688n	1548 C 27	1548C27/jet	15:	—
23	215	696n	PV Cep	GM 1-29	17.8v	—
24	167	309	LKHα 234	LKHα 234/jet	11.9	0.8
25	7-11	—	SVS13	—	20.35	2.52
26	170	317n	MWC1080	MWC1080/HH	11.67	1.43

2. HH OBJECTS AND THEIR OPTICAL DRIVING SOURCES

We used the general catalogue of HH objects by Reipurth (1994) to pinpoint the HH objects, their sky positions, their associated star forming regions, the corresponding distances to the nebulosities, back references, and, most importantly, suspected exciting sources. Once the exciting sources were identified, we looked for optical photometry and spectral types of the associated stars in the catalog by Herbig & Bell (1988). A total of 25 stars were found to have a visual magnitude estimate, but for only 20 of them were the colors also given.

In an attempt to improve our numbers, we searched quickly in the A&A Abstracts for more driving sources of HH objects. Three additional sources were found in this first glance. The few objects with optical counterparts detected is the major restriction of our present study. The basic information of the HH objects and their optical driving sources are summarized in Table 1.

3. PROPERTIES OF THE OPTICAL COUNTERPARTS OF HH OBJECTS

The majority of the stars driving HH objects in our sample have a strong emission-line spectrum and belong to the Orion population, i.e., they are T Tauri stars and Herbig Ae/Be stars (see Herbig & Bell 1988 for a complete discussion). Another important property is that the driving sources of HH objects radiate strongly at IR wavelengths and many of them are *IRAS* sources. In this early stage of evolution, the circumstellar dust particles associated with the exciting sources are large in comparison with the optical wavelengths and thus the extinction coefficient is roughly color independent. Consequently, the outcoming light from the embedded star will suffer neutral or gray extinction and the central object will appear sub-luminous for a given color in a magnitude–color diagram. These emission-line stars are veiled. Veiling also causes a star to appear sub-luminous because its spectral energy distribution increases strongly towards shorter wavelengths, making a star appear much bluer for its spectral type and mimicking a sub-luminous effect in a magnitude–color diagram.

4. DATA

The sources of the sample are dispersed all over the sky; they are at different distances and suffer different amounts of extinction, making their intercomparison difficult. To overcome this problem, we corrected each object for its distance, referring it to the Taurus/Aurigae region (d = 140 pc), where 13 of the original 26 optical counterparts are located. The nearest object is located in L1642 at d = 100 pc and the more distant (2 objects) are at d $\geq$ 2000 pc. In a first approximation, we assumed that all the objects are affected by the same amount of extinction. We then plotted them in the $(V, B-V)$ diagram (see Figure 1). A mean visual IS extinction of A_V = 1 mag ($E(B-V) = 0.33$) was adopted to redden the zero age main sequence (ZAMS) given by Schmidt-Kaler (1982) and then we shifted it to 140 pc, in order to compare it with the driving stars of the HH objects (Figure 1).

5. PRELIMINARY RESULTS AND DISCUSSION

By comparing the location of the exciting sources with that of the reddened ZAMS at 140 pc in the magnitude–color diagram we find the following:

- Stars 5, 7, 8, 9, 10, 11, 12, 18, 19, and 21 (that is, 44% of the sample in Table 1) fall below the ZAMS. We call them "below main sequence stars" (BMSS) after Neri, Chavarría, & de Lara (1993).
- Stars 2, 6 13, 20, and 25 (22% of the sample) fall very near but above the ZAMS. These stars are, without doubt, apparently sub-luminous when compared to the loci normally occupied by T Tauri stars. We call them "additional sub-luminous stars" (ASS) after Neri et al. (1993).
- Stars 1, 4, 14, 15, 16, 17, 24, and 26 (35% of the total) are above and to the right of the ZAMS.
- Eight of the ten BMSS (5, 7, 8, 9, 10, 11, 18, and 19) and three of the five ASS (13, 21, and 25) are strongly veiled. That represents 73% of the sub-luminous stars inspected.
- Six of the eight stars lying above the ZAMS (1, 14, 15, 17, 24, and 26) are very red for their spectral types (shifted by $\delta(B-V) \geq 1$ in the abscissa). A displacement of the star position along a reddening vector diminishes their luminosities.

- Six of the eight stars lying above the ZAMS are Herbig Ae/Be stars (75%). The remaining two (4 and 16) are the tight multiple star systems T Tauri and CoD-33° 1068.
- Two of the eight luminous objects (14 and 17) have been classified as FUOR stars, another two (T Tau and Z CMa) are double or multiple systems and four (stars 14, 15, 24, and 26) have d $\geq$ 1000 pc. These properties make their position in the magnitude–color diagram uncertain.

The above results provide us with search guidelines for discovering new HH objects in a systematic way, but due to the limited size of the sample and to the lack of optical driving sources of HH objects that have been properly observed, they should be considered preliminary. Only deep CCD observations of sub-luminous stars in Hα and forbidden lines or more observations of known optical counterparts of HH objects will improve or reinforce the results of this work. To conclude, if we assume that the remaining three optical driving sources given in Table 1 have normal colors and suffer $A_V = 1$ mag (normal) IS extinction, the above frequency numbers are reinforced.

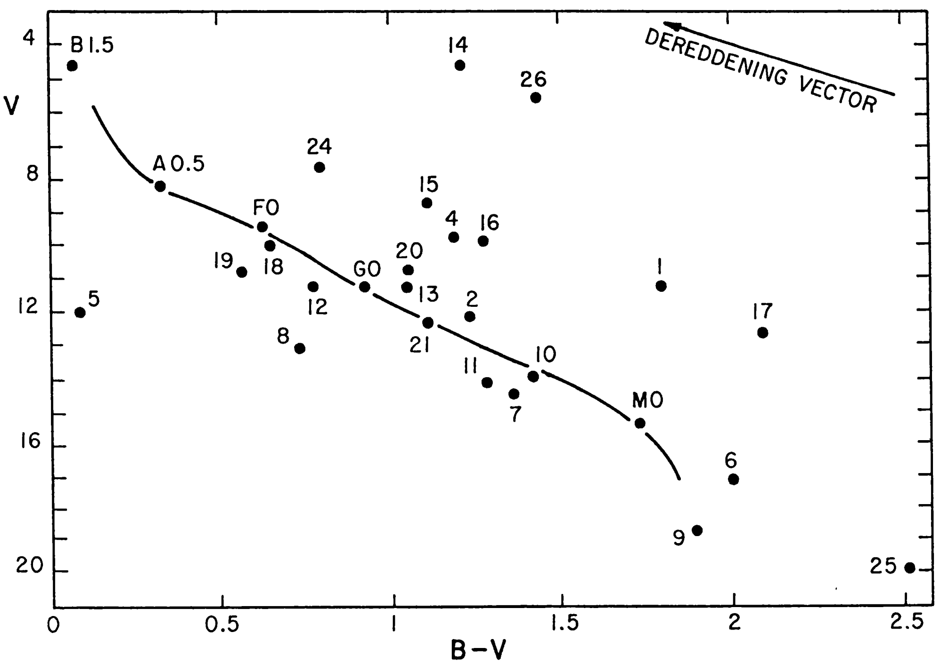

Fig. 1. The magnitude–color diagram for the driving sources of the HH objects discussed here.

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