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HERBIG-HARO OBJECTS 46 AND 47: EVIDENCE FOR BIPOLAR EJECTION FROM A YOUNG STAR

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ABSTRACT

A new Herbig-Haro Object (HH 47C) has been discovered in the system HH 46/47. Radial velocity measurements indicate that HH 47A is approaching at -128 km s^{-1}, whereas HH 47C is receding at 105 km s^{-1}. Both components appear to have been driven clear in opposite directions from a small dark cloud which harbors HH 46 on a direct line between HH 47A and HH 47C. HH 46 exhibits a combined HH emission spectrum and a T Tauri star reflection spectrum. New spectrophotometric measurements of HH 47C and HH 47D (a "bubble" nebula surrounding HH 47A) are also presented. A model is presented wherein the HH objects are produced by bipolar ejection from a T Tauri star embedded in an accretion disk.

Subject headings: nebulae: general — stars: emission-line — stars: formation — stars: mass loss

I. INTRODUCTION

The Herbig-Haro objects 46 and 47 (Schwartz 1977) are associated with a small dark cloud (ESO 210-6A) embedded in the Gum Nebula. Dopita (1978) has carried out spectrophotometric observations of these objects, revealing that HH 47 is a very low excitation emission nebula with a high negative radial velocity. HH 47 appears in projection to have been impelled outside the sharply rimmed dark cloud, with a faint nebular bridge connecting it to HH 46 which is located inside of the north rim of the cloud. In addition to the weak nebular emission lines characteristic of HH nebulae, HH 46 was found by Dopita to exhibit a prominent red continuum and a strong Hα component, suggesting that at least a portion of the object is produced by reflection from a visibly obscured T Tauri star. Further spectrophotometric observations of the blue-UV continuum in HH 47 in combination with shock wave calculations (Dopita, Binette, and Schwartz 1982, hereafter DBS) suggested that the spectrum is probably produced by a nonequilibrium shock in which two-photon emission from hydrogen receives a strong enhancement.

Examination of the excellent photograph (Fig. 1, Plate L4) obtained by Bok (1978) reveals a wealth of detail suggestive of the dynamics of the HH 46/47 system. In particular, a counter HH object (47C) has been discovered just outside the west rim of the dark cloud on a line which passes through HH 46 and 47A (designated HH 47 by Schwartz 1977). Second, a faint bubble-like nebula (HH 47D) is seen to surround HH 47A, and HH 46 exhibits a conical geometry reminiscent of a lobe of a biconical nebula. In this *Letter* we report new observations of HH 47C, 47A, 46, and 47 D. A schematic bipolar ejection model is presented to account for the observations.

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II. OBSERVATIONS AND DATA REDUCTION

a) *Radial Velocity Data*

High-resolution spectra in the region of [O I] and Hα were obtained on 1982 January 28 and 29 using the 1 m telescope operated by the Australian National University at Siding Spring Observatory. The Perkin-Elmer echelle spectrograph was used with a 79 lines mm^{-1} echelle grating and a cross-disperser grating of 600 lines mm^{-1}, yielding a dispersion of 6.56 Å mm^{-1} at Hα. The detector system used was the two-dimensional Photon Counting Array (PCA) which uses a 25 mm ITT microchannel plate proximity focus intensifier (S20 response) coupled to a single-stage electrostatic focus tube (Stapinski, Rodgers, and Ellis 1981). Data reduction involving flat-field corrections, smoothing, and wave-

FIG. 1.—Bok's Valentine's night (1978 February 14) Cerro Tololo Inter-American Observatory 4 m photograph of the dark cloud (ESO 210-6A) associated with the HH 46/47 system (Bok 1978). North is up and east is to the left. The dark cloud containing HH 46 in the western portion of the photograph is about 3′ in diameter. See Fig. 3 for identification of the HH components.

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TABLE 1

MEASURED RADIAL VELOCITIES IN HH 46/47 COMPLEX

Object	Emission Line	V_{Hel} (km s^{-1})		ΔV (FWHM) (km s^{-1})
HH 46......	[O I] 6300	−160 ± 14	−148	36 ± 7
	Hα	−137 ± 19		33 ± 5
	[N II] 6584	−146 ± 14		16 ± 12
HH 47A ...	[O I] 6300	−129 ± 12	−127	28 ± 6
	Hα	−114 ± 14		53 ± 16
	[N II] 6584	−138 ± 12		20 ± 4
HH 47C ...	Hα	+105 ± 10	+105	36 ± 14

length calibration was accomplished with the PANDORA software at Mount Stromlo and Siding Spring Observatories. The wavelength calibration, internal to each frame, utilized a quadratic least squares fit for a set of nine OH night-sky lines. The radial velocities and full widths at half-maximum measured are listed in Table 1. HH 47C was only marginally detected at [O I] and [N II], so no reliable velocities could be determined using these lines.

The processed spectra at Hα, unsubtracted for sky emission, are shown in Figure 2 for HH 47A, HH 46, and HH 47C respectively. Note that strong [N II] and Hα emission overlies the whole region near the rest wavelengths. This is diffuse emission originating in the Gum Nebula in which the HH complex and dark cloud (ESO 210-6A) are located.

b) *Spectrophotometry*

The low-dispersion spectra were obtained on 1981 January 7 and 8, using the Anglo-Australian 3.9 m telescope at Siding Spring. The RGO spectrograph was used with its 25 cm camera and the detector was the image photon counting system (IPCS) (Boksenberg 1972). A grating of 250 lines mm^{-1} was employed, giving a spectral resolution of 11 Å and a coverage of 3300–7500 Å. The 0.5M word external memory allowed the use of a large format consisting of 50 spectra, each 2044 pixels long, separated by 2″.07 on the sky. Details of the reduction are given by DBS and are not repeated here. Table 2 contains a list of the emission-line fluxes (normalized to Hβ = 100) measured in HH 47A, 47C, and 47D.

III. RESULTS AND DISCUSSION

The reddening correction method of DBS cannot be used in this instance. HH 47C exhibits strong [S II] and [O I] characteristic of HH objects, and its excitation state lies between that of HH 47A and HH 47B (see DBS). Assuming that the intrinsic Balmer decrement also lies between that of HH 47A and HH 47B, we estimate that $H\alpha/H\beta = 3.9$ for HH 47C, which implies a logarithmic reddening constant $C(H\beta) = 0.7$. This higher reddening suggests that HH 47C lies *behind* the dark cloud, a conclusion supported by the faintness of the object and its positive velocity.

The line fluxes in the "bubble" (HH 47D) are quite atypical of most HH objects, suggesting nonequilibrium conditions if due to shock excitation. We assume that the reddening for this object ($C = 0.2$) is the same as the mean of the objects HH 47A and HH 47B which it surrounds. The low-excitation emission lines are exceptionally strong (relative to Hβ) in HH 47D, while at the same time it has very strong [O II] λ3727 emission and an [O III] λ5007 line of greater intensity than that seen in any other HH object. Moreover, the bubble-like shape of this feature makes it morphologically dissimilar from the classical HH objects.

We have attempted to model the spectrum of HH 47D using the modeling code MAPPINGS (DBS; Binette, Dopita, and Tuohy 1983; Binette 1982). Although no model was successful, line ratios approaching that of HH 47D can be generated by a low-velocity, not fully radiative shock moving into a medium that is ionized as in a moderate excitation H II region. Some of the discrepancies between such models and the data would be alleviated if the Hβ line strength was incorrectly measured and was in fact somewhat stronger. This possibility is supported by an apparently high Hα/Hβ ratio which theoretically cannot be produced in an astrophysical plasma of low density. Such a measurement error could result from the very high background emission from the Gum Nebula. We suggest that the "bubble" is probably the result of the interaction of a supersonic stellar wind or jet with the low-density ionized medium of the Gum Nebula, and that the time scale of this interaction has been too brief to allow steady flow conditions to be established.

The radial velocities obtained for HH 47A, HH 46, and HH 47C further illuminate the dynamics of this system. The data in Table 1 and Figure 2 clearly demonstrate that HH 46 and HH 47A have been ejected with large velocity components toward Earth, whereas HH 47C has been ejected in the opposite direction, passing

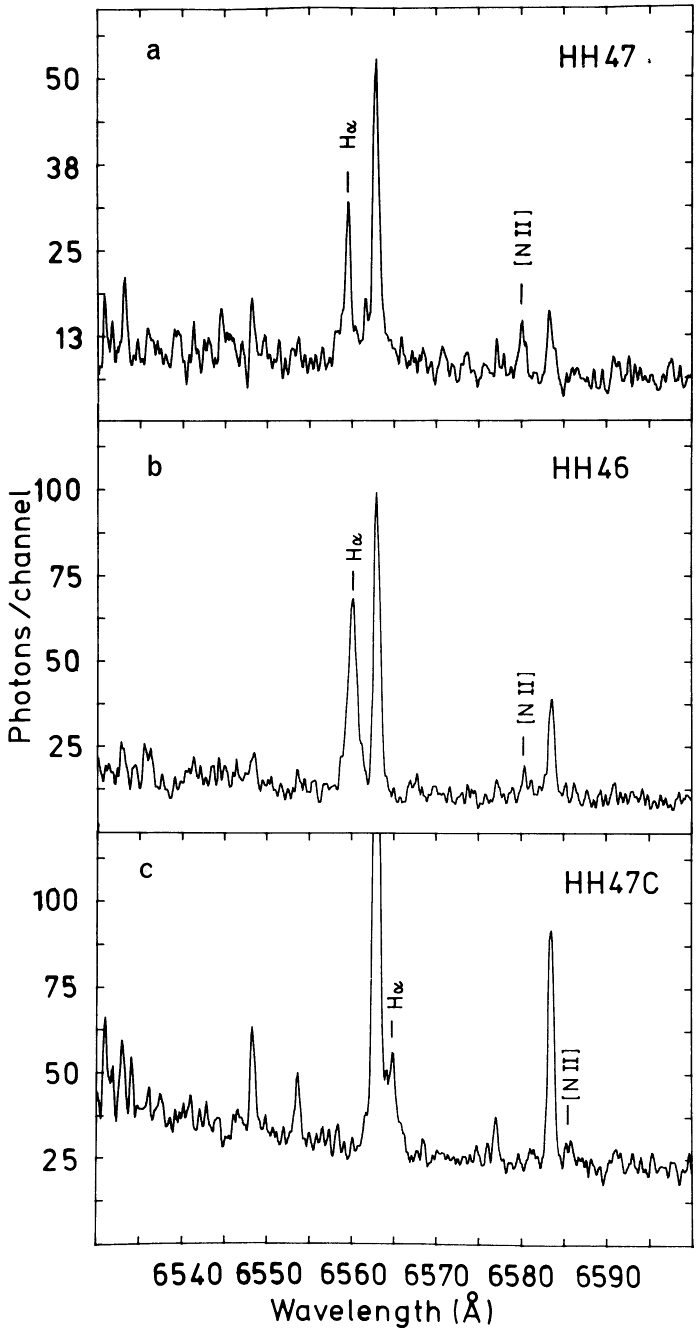

FIG. 2.—Echelle spectra of the Hα region for HH 47A, HH 46, and HH 47C. The strong Hα and [N II] emission components are from the overlying Gum Nebula.

through and behind the dark cloud to appear only "recently" in projection just outside the west edge of the cloud. In Figure 3 we present a schematic model representing an embedded star which produces the observed phenomena via bipolar ejection of material. We propose that a torus or disk of material obscures the star from direct view, but that light escapes through the polar lobe on the front side of the cloud. The light appears in reflection from dust which is associated with HH 46. The remarkable linear alignment of HH 47A, HH 46, and HH 47C suggests a high degree of collimation in the bipolar flow.

This system joins a growing list of HH objects which show evidence of production by bipolar ejection from

TABLE 2

LINE FLUXES IN HH 46/47 COMPLEX

λ (Å)	ID	HH 47A[a] F	HH 47A[a] F_0	HH 47C[b] F	HH 47C[b] F_0	HH 47D[c] F	HH 47D[c] F_0
		LINE FLUX (relative to Hβ = 100.0)					
3727, 9	[O II]	81	87	30 ± 13	48 ± 21	1420 ± 40	1630 ± 55
4068, 76 ...	[S II]	77	81	35 ± 13	48 ± 18	...	...
4340	Hγ	42	44	34 ± 16	42 ± 20	104 ± 50	111 ± 52
4861	Hβ	100		100		100	
5007	[O III]	...	...	...	...	190 ± 70	187 ± 70
5198, 99 ...	[N I]	129	127	83 ± 15	73 ± 13	107 ± 40	103 ± 40
6300	[O I]	342	320	236 ± 32	150 ± 20	344 ± 80	302 ± 80
6363	[O I]	109	101	84 ± 24	52 ± 15	89 ± 27	78 ± 29
6548	[N II]	28	26	30 ± 20	17 ± 12	75 ± 30	64 ± 30
6563	Hα	500	463	670 ± 50	390 ± 30	690 ± 100	590 ± 100
6584	[N II]	72	67	98 ± 20	57 ± 12	430 ± 80	369 ± 80
6717	[S II]	486	448	350 ± 40	197 ± 23	990 ± 130	840 ± 130
6731	[S II]	511	471	270 ± 40	152 ± 23	420 ± 80	360 ± 80
7291	[Ca II]	125	113	...	...	161 ± 60	132 ± 60
7318, 30 ...	[O II], [Ca II]	71	64	...	...	117 ± 65	96 ± 66
C(Hβ)		0.1		0.7		0.2	

[a]From Dopita, Binette, and Schwartz 1982.
[b]Assumed intrinsic Balmer decrement same as mean of HH 47A and HH 47B.
[c]Reddening assumed same as for HH 47.

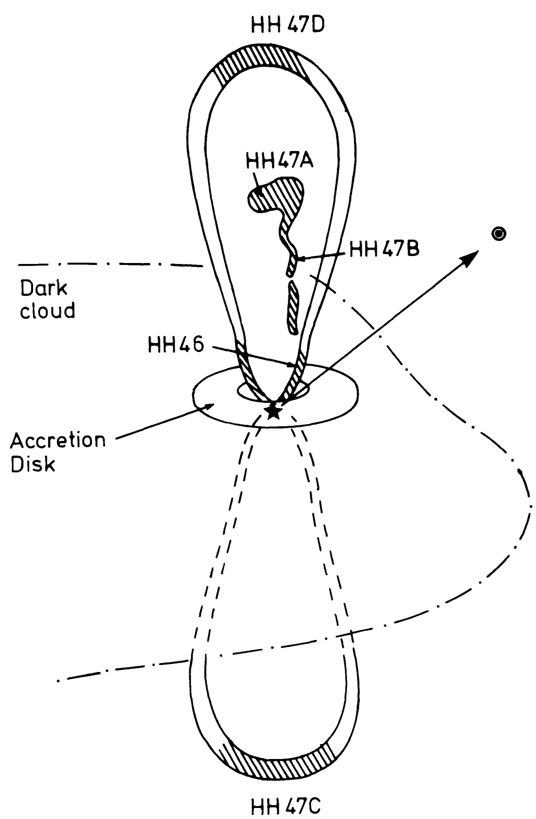

FIG. 3.—Schematic model for the HH 46/47 system. The accretion disk or torus obscures the exciting star from visible observation.

young stars. Bipolar CO flows have been associated with the L1551 IR source, HH 28, and HH 29 (Snell, Loren, and Plambeck 1980; Cudworth and Herbig 1979) and with an IR source in the NGC 1333 complex which is aligned with HH 7-11 (Snell and Edwards 1981). Proper motion measurements of HH 1 and HH 2 (Herbig and Jones 1981) show that they are moving in opposite directions along a line which passes through a T Tauri star (Cohen and Schwartz 1979). Another directed flow is seen in NGC 2261 (Cantó *et al.* 1981) which has produced large proper motions in HH 39 (Jones and Herbig 1982). Cohen (1982) has recently summarized a number of lines of evidence which indicate that mass flows from T Tauri stars may be highly anisotropic.

Theoretical models to explain these phenomena are in a state of infancy, although the work of Barral and Cantó (1981) and Königl (1982) represents significant advances. Common to the models is the idea that a spherically symmetric stellar wind will be focused into bipolar jets upon expansion in a medium such as a circumstellar disk with anisotropic density and pressure distributions. Instabilities in the jets or interaction of the jets with ambient cloudlets could hence be implicated with the production of HH nebulae.

The system HH 46/47 is somewhat unique in that it apparently represents an instance of isolated star formation. No other young stars are evident in the vicinity (two Hα emission stars reported by Schwartz 1977 have proven to be symbiotic and carbon stars).

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