THE ASTROPHYSICAL JOURNAL, 296:620–632, 1985 September 15

OPTICAL SPECTROSCOPY OF KNOWN AND SUSPECTED HERBIG-HARO OBJECTS[1]

MARTIN COHEN
NASA/Ames Research Center; and Radio Astronomy Laboratory, University of California, Berkeley
AND
GARY A. FULLER
Radio Astronomy Laboratory, University of California, Berkeley
Received 1984 November 14; accepted 1985 March 19

ABSTRACT

We present optical spectra of a number of suspected Herbig-Haro objects. From these we determine the nature of these nebulosities. Several of the nebulae are of very high density ($N_e \approx 10{,}000$ cm^{-3}), perhaps due to their extreme youth. Extinctions measured toward DG Tau HH and the L1551 IRS 5 optical jet are in each case substantially less than the stellar values. We suggest that this phenomenon reflects the existence of appreciably thick circumstellar dust disks around these, and two additional, exciting stars. Shock model diagnostics suggest that the emission lines in these Herbig-Haro nebulae arise in modest velocity (40–50 km s^{-1}) shocks with sizable preshock densities in several cases ($N_0 \approx 1000$ cm^{-3}). Radial velocities enable lower limits to be placed on the mass loss rates of those stars that have been detected in the radio continuum. In one case (Haro 6–10) we tentatively identify the exciting star as of spectral type early K on the basis of the nebular continuum which we attribute to scattered starlight.

Subject headings: nebulae: general — shock waves — stars: pre–main-sequence

I. INTRODUCTION

Ground-based and airborne infrared surveys for the exciting stars of Herbig-Haro (HH) objects have successfully located an appreciable number of these stars (Cohen and Schwartz 1983; Cohen *et al.* 1984*a*, *b*). In some cases these stars are deeply embedded in dark dust clouds, rendering them visible only as infrared sources. Only bolometric luminosities and infrared colors can be obtained and, in the absence of optical spectroscopy, the evolutionary status of the exciting stars can be inferred only indirectly. Cohen (1983*a*) has argued that these may be the precursors to visible T Tau stars and may represent low-mass accreting protostars.

In particular, the keystone object, L1551 IRS 5, is associated with a chain of several red nebulous knots, roughly aligned as an optical jet (e.g., Mundt and Fried 1983). This infrared source coincides with the peak of a spatially resolved continuum radio source, whose thinness characterizes it as a "radio jet" (Bieging and Cohen 1985). This jet apparently overlies the southeastmost nebulous knot in this chain (Cohen, Bieging, and Schwartz 1982). An optical spectrum in the vicinity of this knot would have obvious value as a probe of the excitation conditions.

In this paper we describe optical spectra of a number of these nebulosities, intended to establish the character of these nebulae. The optical spectra may provide clues to the nature of their exciting stars and to the velocity fields in their immediate vicinities.

II. OBSERVATIONS OF INDIVIDUAL NEBULAE

The regions that we observed fall into two categories. In some, nebulosities were suspected of being HH objects by virtue of either their morphology or their proximity to far-infrared peaks. In others, the coincidence of infrared sources and VLA peaks of radio continuum emission suggested that these represented embedded, active young stars that may have created HH objects.

All the spectra were taken with the Lick Observatory image-tube scanner (Miller, Robinson, and Wampler 1976) on the Shane 3 m telescope. Spectra were reduced to absolute fluxes by means of observations of flux standard stars (Stone 1974) and the use of Lick mean extinction coefficients. Table 1 presents a journal of our observations, indicating for each object the date, aperture size, and wavelength coverage. The physical stability of the spectrograph and image-tube chain were significantly better during our 1982 and 1984 observations. We were, therefore, able to measure meaningful radial velocities from these more recent spectra, with our 7 Å formal resolution. All velocities cited in this paper are heliocentric. Spectra of the individual objects are described below, in order of right ascension.

a) "*Haro 6–5B*" *Jet*

We observed the conical fan nebula at the western end of the jetlike structure described by Mundt *et al.* (1984, their Fig. 1), which is believed to lie close to the embedded star responsible for this nebulosity. Hα, Hβ, [Fe II], and [O I] are detected. No clear signs of [S II] or [N II] are evident in our spectrum, which also shows a conspicuous, though unclassifiable continuum. Radial velocities can be determined from four emission lines and yield a mean value of $+43 \pm 22$ km s^{-1}.

b) *DG Tau HH*

At 100 μm, Cohen, Harvey, and Schwartz (1985) have found evidence suggestive of an extended (15″ diameter) cool dusty disk around DG Tau, elongated northwest to southeast, in alignment with the electric vector of the appreciable optical polarization for this star (Bastien 1982). Bieging, Cohen, and Schwartz (1984) spatially resolved 6 cm continuum emission from DG Tau, elongated from northeast to southwest in the flow direction from the star but constricted in the plane of this putative far-infrared emitting disk.

[1] Based on observations obtained entirely using the facilities of the Lick Observatory, University of California, Santa Cruz.

TABLE 1

JOURNAL OF OBSERVATIONS

Date	Object	Aperture (arcsec)	Wavelength Coverage (Å)	Tube
1981 Jul 26	GGD 32	2.7 × 4.0	4280–6850	red
	GGD 33a, b	2.7 × 4.0	4280–6850	red
	GGD 34	2.7 × 4.0	4280–6850	red
	GGD 35	2.7 × 4.0	4280–6850	red
	HH 103	2.7 × 4.0	4280–6850	red
	NGC 7129 IRS 1	2.7 × 4.0	4280–6850	red
	RNO 138	2.7 × 4.0	4280–6850	red
1982 Oct 18	L1551 IRS 5	2.7 × 4.0	3200–5500	green
	L1551 IRS 5	2.7 × 4.0	5100–7440	green
	HH 31 D	2.7 × 4.0	5100–7440	green
	Haro 6–10	2.7 × 4.0	5100–7440	green
	NGC 7129 IRS 1	2.7 × 4.0	5100–7440	green
	NGC 7129 IRS 1	2.7 × 4.0	3200–5500	green
	GGD 35	2.7 × 4.0	5100–7440	green
	GGD 33a, b	2.7 × 4.0	5100–7440	green
1984 Jan 10.........	Haro 6–5B jet	2.0 circle	4540–6860	green
	DG Tau HH	2.0 circle	4540–6860	green
1984 Jan 12.........	HH 1 SE Fan	2.8 circle	4540–6860	green

Figure 1 presents the spectrum of the potential HH object, 8″ in p.a. 225° from DG Tau, reported by Mundt and Fried (1983). The emission lines of [O I], [S II], and [N I] clearly identify this as an HH object (Table 2, col. [3]). The radial velocity of this HH object based upon the observed wavelengths of 10 emission lines (Table 2, col. [3]), is -205 ± 15 km s^{-1}.

c) HH 31 Knot D

The nomenclature is that of Herbig (1974) who noted the position of this faint nebula but did not describe its spectrum. Cohen and Schwartz (1983) identified a near-infrared source—HH 31 IRS 2—as responsible for the excitation of HH 31ABC. Their Figure 5 shows the close proximity, if not actual coincidence, of IRS 2 to "HH 31D." Our spectrum (1982 October 17) clearly shows Hα and [O I] 6300 in emission, with very weak [N II] 6583, but we see no sign of [S II]. The observed Hα line flux is 4.28(−15) ergs cm^{-2} s^{-1} and the mean radial velocity is $+131 \pm 55$ km s^{-1} determined from the Hα and [O I] lines.

d) Haro 6–10

Our red spectrum of Haro 6–10 (Fig. 2) shows a wealth of emission lines, as did the earlier spectrum by Elias (1978). We have no spectrum yet blueward of 5100 Å. Observed line intensities are given in Table 2, column (4), as is the mean radial velocity determined from 10 emission lines.

The optical continuum in Haro 6–10 is very prominent. Little appears in absorption, above the noise, but there do appear to be real absorption features at 6400 and 6500 Å. We tentatively identify these with photospheric features, prominent in K stars (e.g., see Cohen and Kuhi 1979, their Table 3). If normal, the stellar photosphere seen in Haro 6–10 cannot be that of a late K-type star for we see no sign of the strong TiO band head near 6159 Å. We therefore suggest that the embedded star may be of early K type. We note also the potential presence in our spectrum of Fe II emission lines between 6000 and 6200 Å (Fig. 2). These are consistent with a strong emission-line T Tau spectrum.

e) L1551 IRS 5

The best available infrared position for IRS 5 (40ˢ22, 01′41″3 from Cohen and Schwartz 1983) coincides with a 5 GHz continuum peak ($4^h28^m40^s.226$, +18°01′42″00 from Bieging, Cohen, and Schwartz 1984), in the center of an extended radio jet. CCD images such as those by Mundt and Fried (1983) show an extremely red object at the eastern end of an optical "jet." The L1551 field is conspicuously lacking in absolute astrometric reference stars so we used blind offsets from Cudworth and Herbig's (1979) "star A" to this eastern extremity, as determined by B. F. Jones (1983, private communication). The spectra were obtained in increments of 4 and 8 minutes, guiding by maximizing the total signal due to the sum of all the scanner's 2048 channels for the aperture including the object, and by repeatedly checking the offset by returning to star A. We estimate that this method held the position to within 1″5 accuracy. We believe that our optical spectra refer to the visible nebulosity closest to the infrared/VLA source, closer than the brighter nebulosity studied by Sarcander, Neckel, and Elsässer (1985).

Figure 3 shows our longer wavelength spectrum, in which the emission lines of [O I], [N II], Hα, [S II], [Fe II], [Ca II] are all visible; at shorter wavelengths only Hβ and [O III] are seen. Clearly this knot near IRS 5 is an HH object. Observed line strengths are given in Table 2 (col. [5]). The average radial velocity of this knot, obtained from 13 emission lines, is -146 ± 15 km s^{-1}.

f) HH 1 SE Fan

The phenomenon of extended far-infrared emission associated with HH nebulae occurs rather infrequently (Cohen *et al.* 1984*a*, *b*; Cohen, Harvey, and Schwartz 1985). In the case of the HH 1/2 system, the structure of this 100 μm emitting zone is bipolar, centered close to their exciting star, the Cohen-Schwartz object (Cohen *et al.* 1984*a*). Some 25″ to the southeast of this star, opposite HH 1 and equidistant from this star, lies another faint fan-shaped red nebulosity. Its location renders it important to determine whether the event which created HH 1 was in fact symmetric, bidirectional, and centered on the Cohen-Schwartz star.

This faint nebulosity shows a spectrum with Hα, [O I], [S II], and weak Hβ, [O III], and [N II]. It is certainly an HH object. Our estimated radial velocity from the five strongest red lines is 12 ± 17 km s^{-1}. We note that the radial velocities of HH 1 and 2 are also small, −8 and +18 km s^{-1}, respectively.

TABLE 2

Observed Line Strengths and Radial Velocities of Suspected HH Objects

Ion (1)	Line (2)	DG Tau HH (3)	Haro 6–10 (4)	L1551 IRS 5 (5)	HH 1 SE Fan (6)	HH 103 (7)	GGD 32 (8)	GGD 35 (9)
O II	3727	...	...	<1.2(−15)	...	...	...	<1.5(−14)
Hβ	4861	4.39(−15)	...	4.32(−16)	3.0(−15)	2.83(−15)	...	5.04 ± 0.2 (−15)
O III	4959	5.33(−16)	...	...	...	...	...	<1.1(−15)
	5007	1.22(−15)	...	4.25(−16)	8.10(−15)	<4.5(−16)	...	<1.1(−15)
Fe II	5158	1.72(−15)	...	...	...	1.5(−15)	...	7.94(−16)
N I	5198	<5.9(−16)	...	<1.5(−16)	...	2.68(−15)	...	7.80(−16)
N II	5755	...	1.39(−15)	<4.5(−16)	...	...	...	...
He I	5876	1.81(−15)	...	<6.5(−16)	...	...	...	...
O I	6300	4.99(−15)	2.90(−14)	6.38(−15)	1.40(−14)	8.37(−15)	7.75(−16)	4.15 ± 0.2 (−15)
	6364	2.00(−15)	1.03(−14)	2.38(−15)	7.23(−15)	2.61(−15)	3.75(−16)	1.56(−15)
N II	6548	2.41(−15)	7.59(−15)	2.45(−15)	...	7.22(−16)	3.38(−16)	2.2 ± 0.7 (−15)
Hα	6563	1.66(−14)	9.60(−14)	1.08(−14)	9.85(−15)	1.00(−14)	2.31(−15)	1.73 ± 0.10(−14)
N II	6584	8.27(−15)	1.96(−14)	5.66(−15)	5.59(−15)	3.10(−15)	1.04(−15)	4.35 ± 0.10(−15)
S II	6716	4.04(−15)	1.18(−14)	3.47(−15)	7.33(−15)	1.08(−14)	1.49(−15)	7.55 ± 0.21(−15)
	6731	7.44(−15)	2.13(−14)	6.82(−15)	8.84(−15)	8.77(−15)	1.01(−15)	6.50 ± 0.06(−15)
Fe II	7155	...	3.22(−15)	2.36(−15)	...	...	...	...
Ca II	7291	...	3.79(−15)	6.51(−15)	...	...	...	2.84(−15)
O II	7325[a]	...	1.42(−14)	5.99(−15)	...	...	...	3.95(−15)
Fe II	7376	...	...	3.14(−15)	...	...	...	...
Vel.	...	−205 ± 18	−21 ± 14	−146 ± 17	+12 ± 17	...	...	−162 ± 18

Note.—Units: W cm^{-2}.

[a] Blend.

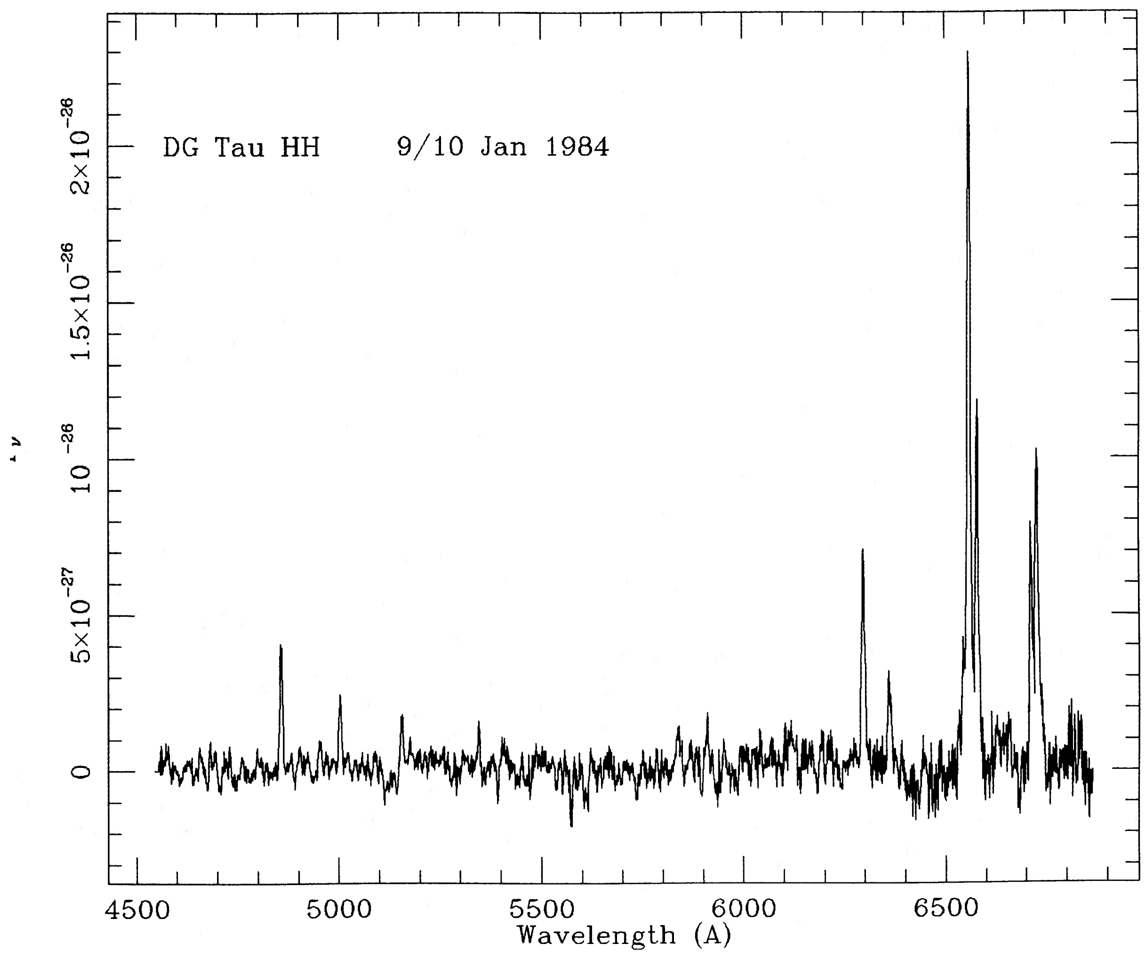

Fig. 1.—Spectrum of DG Tau HH. Ordinate is F_ν, in units of ergs cm^{-2} s^{-1} Hz^{-1}

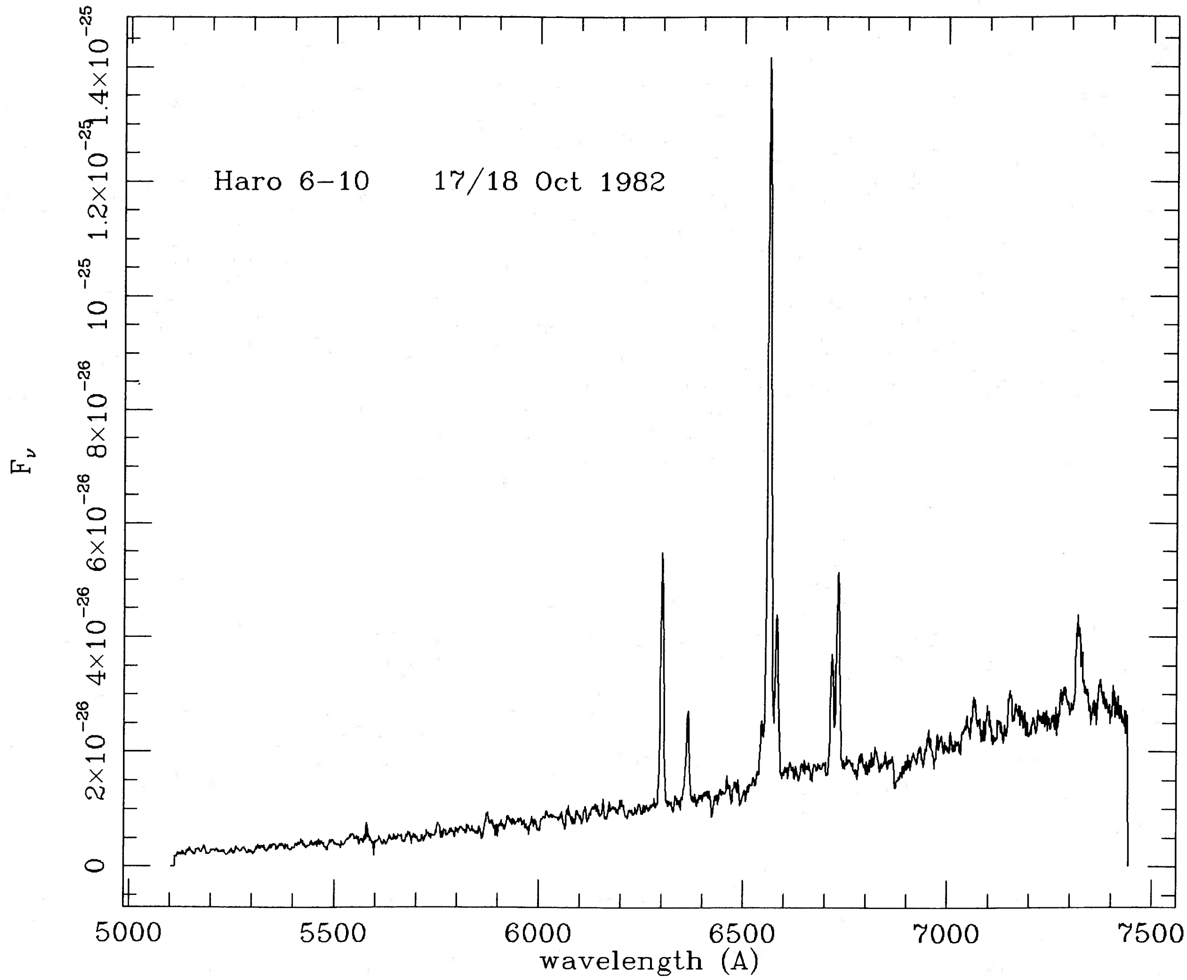

FIG. 2.—Spectrum of Haro 6–10, as Fig. 1

In Table 2, column (6), we present the observed line intensities for this nebula.

g) NGC 7129

The nebulous young cluster NGC 7129 contains substantial far-infrared emission (Harvey, Wilking, and Joy 1982), one established HH object (HH 103) (Strom, Grasdalen, and Strom 1974), and several red nebulae, originally of unknown nature (GGD 32–35: Gyul'budagyan, Glushkov, and Denisyuk 1978). Cohen and Schwartz (1983) noted the alignment of a faint T Tau star (their "NGC 7129 IRS 1") with GGD 33a, b, and 35. Were these nebulae also to be HH objects, IRS 1 could be their exciting star.

We have observed GGD 33a and b on two occasions but have found no evidence for emission lines in either object. Our 3 σ upper limits to the observed intensities of Hα in these two nebulae, based upon both spectra, are 6(−16) and 4.5(−15) ergs cm^{-2} s^{-1}, respectively. For GGD 34 we were unable to locate an emission-line object at the position given by Gyul'budagyan *et al.*, but we cannot preclude the existence of one some few arc seconds away.

In GGD 32 we did not detect Hβ. The red emission lines are, however, much stronger and their observed intensities are given in Table 2 (col. [7]). The spectrum of GGD 35 is presented in Figure 4 and Table 2 (col. [8]). Our 1982 data yield radial velocities for eight red lines, with the mean velocity -162 ± 18 km s^{-1}.

For HH 103, our red line intensities relative to Hβ are very similar to those published by Strom, Grasdalen, and Strom (1974), although for [N I] and Hβ we see 0.5 and about 3 times their published strengths, respectively.

RNO 138 (=GM 1–57: Gyul'budagyan and Magakyan 1977; Cohen 1980) is an arcuate nebula at whose center lies a faint star (=SVS 6: Strom, Vrba, and Strom 1976). The spectra of both nebula and star are shown in Figure 5. Unlike Magakyan (1983) we find that prominent Balmer lines appear in the stellar spectrum. A broad absorption feature lies near 6200 Å which we identify with the TiO gamma system B3-X3 (0, 0) band head. There is also a feature near 5175 Å which we identify with the combination of the Mg "*b*" feature and the TiO alpha system (0, 0) band head. By comparison with the spectra of T Tau stars (Cohen and Kuhi 1979), this star is likely to be a K7 T Tau star. The nebula, RNO 138 itself, shows only very weak Hα emission, and its continuum is essentially unclassifiable. No significant nebular forbidden lines are seen which, together with the sizable continuum, militate against RNO 138 being an HH object.

Finally, Figure 6 presents the spectrum of NGC 7129 IRS 1 (=V350 Cep: designation cited by Magakyan 1983) which appears to be a strong emission-line T Tau star, consistent with

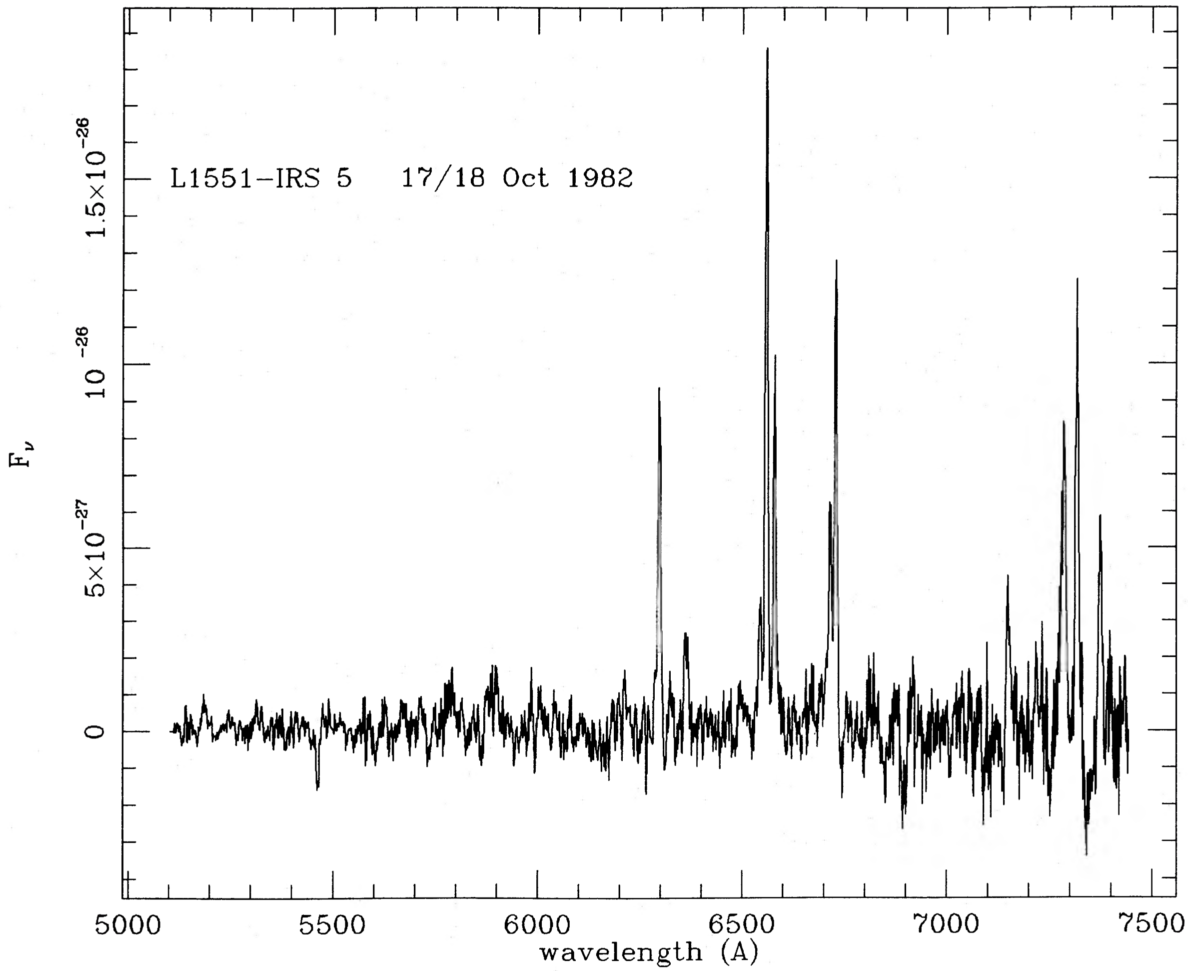

FIG. 3.—Spectrum of L1551 IRS 5, as Fig. 1

the conclusion reached by Magakyan and Amirkhanyan (1979). Other than weak [O I], no nebular lines are seen. Our 1982 red spectrum shows no obvious changes in either the relative, or the absolute, intensities of any of the host of Fe II lines. The Hα peak intensity in 1982 was a little stronger than that seen in 1981, attaining a value of 2.5(−25) ergs cm^{-2} s^{-1} Hz^{-1}. However, the newer red spectrum extends out to 7440 Å, and, beyond Hα, we see two clear, broad, shallow absorptions (Fig. 7). We feel that these represent the TiO A3-X3 gamma-system (1, 0) and (0, 0) triplet band heads, respectively, and we suggest that we see an M2 photosphere. The absence of the usually prominent B3-X3 gamma-system (0, 0) head near 6162 Å must be due to the presence of the T Tau chromosphere, infilling not only atomic but also molecular absorptions. As confirmation of the presence of an appreciable chromosphere, we offer Figure 8, the 1982 blue spectrum of IRS 1. This reveals conspicuous Ca II H and K lines in emission.

III. INTERPRETATIONS

Independently of the reddening, and virtually independently of the electron temperature, T_e, the ratio of intensities of the red [S II] lines, $I(6717)/I(6731)$, yields the postshock electron density. To derive the physical conditions of individual shocks, by comparison with published shock models, requires knowledge of intrinsic line intensities. The published, detailed shock models have two shortcomings: all consider only atomic coolants, and none considers high preshock densities ($N_e > 1000$ cm^{-3}). Only Dopita (1977) presents general shock diagnostics that can accommodate such high preshock densities.

For a typical object we can determine $I(6731)/I(6717)$, $[I(6717) + I(6731)]/I(H\beta)$, $I(5007)/I(6300)$, and the ratio of intrinsic Hβ flux per unit solid angle to preshock density (Dopita 1977, his Figs. 5, 17, 8, and 3, respectively). These often suffice to characterize the immediate postshock temperature and the preshock gas density in a self-consistent fashion. In Table 3 we summarize these basic shock conditions for 5 HH nebulae; for GGD 35 the data are incompatible with any unique set of shock conditions. These postshock temperatures translate into velocities between 37 and 50 km s^{-1}.

In spite of the high preshock densities of three of our nebulae, we find that the ratio of [O III]/Hβ is not only almost reddening free but is insensitive to preshock density and even to specific grid of models (Shull and McKee 1977; Raymond 1979). Consequently, we shall use this ratio to determine the shock velocity for our objects, by comparison with the models by Shull and McKee (1977). Choice of a specific model also implies an intrinsic Balmer decrement which can be used to deredden the spectrum.

A potential clue to the reddening of a line-emitting volume arises if radio continuum emission is also detected. Assuming

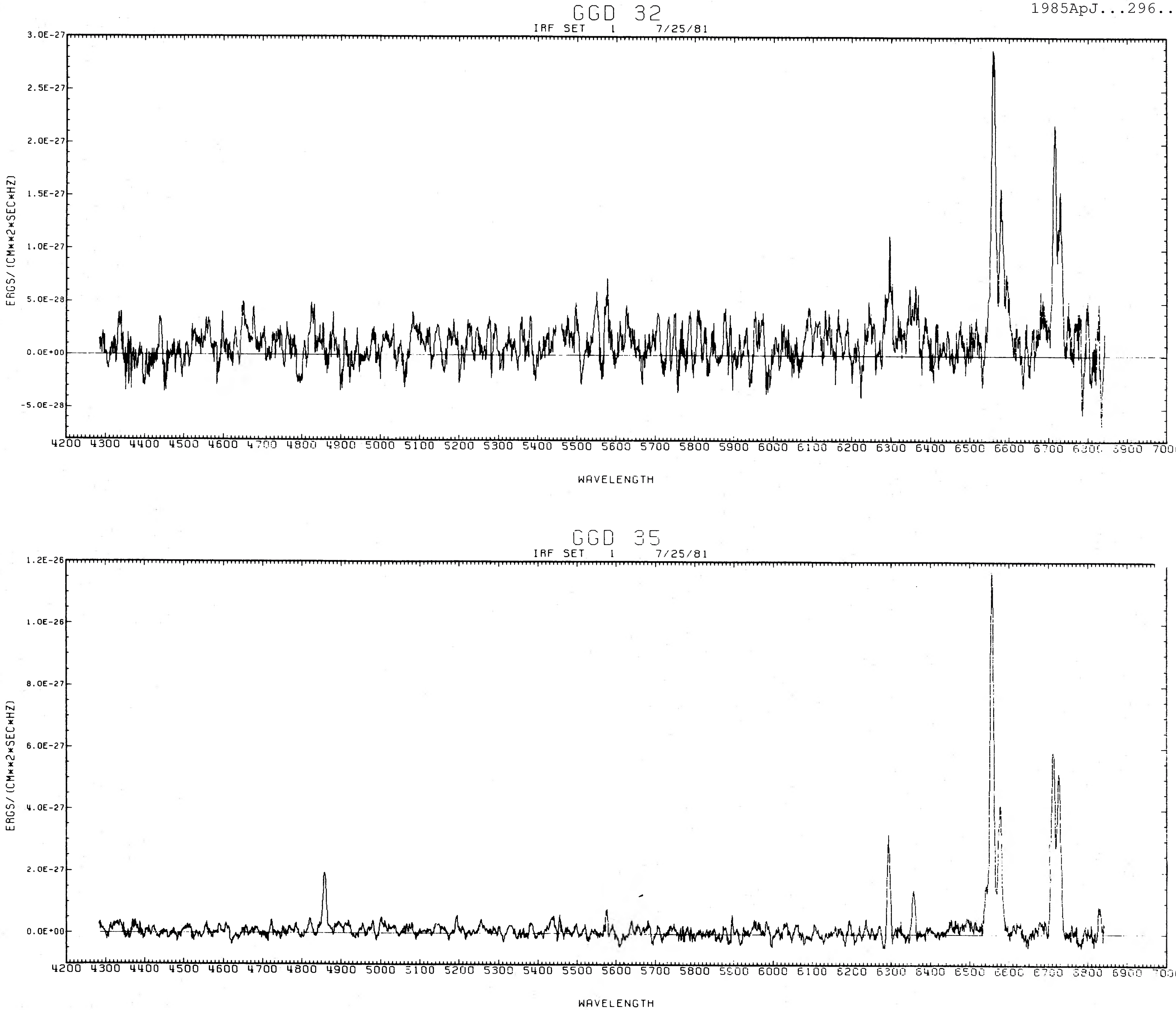

FIG. 4.—Spectra of GGD 32 and GGD 35

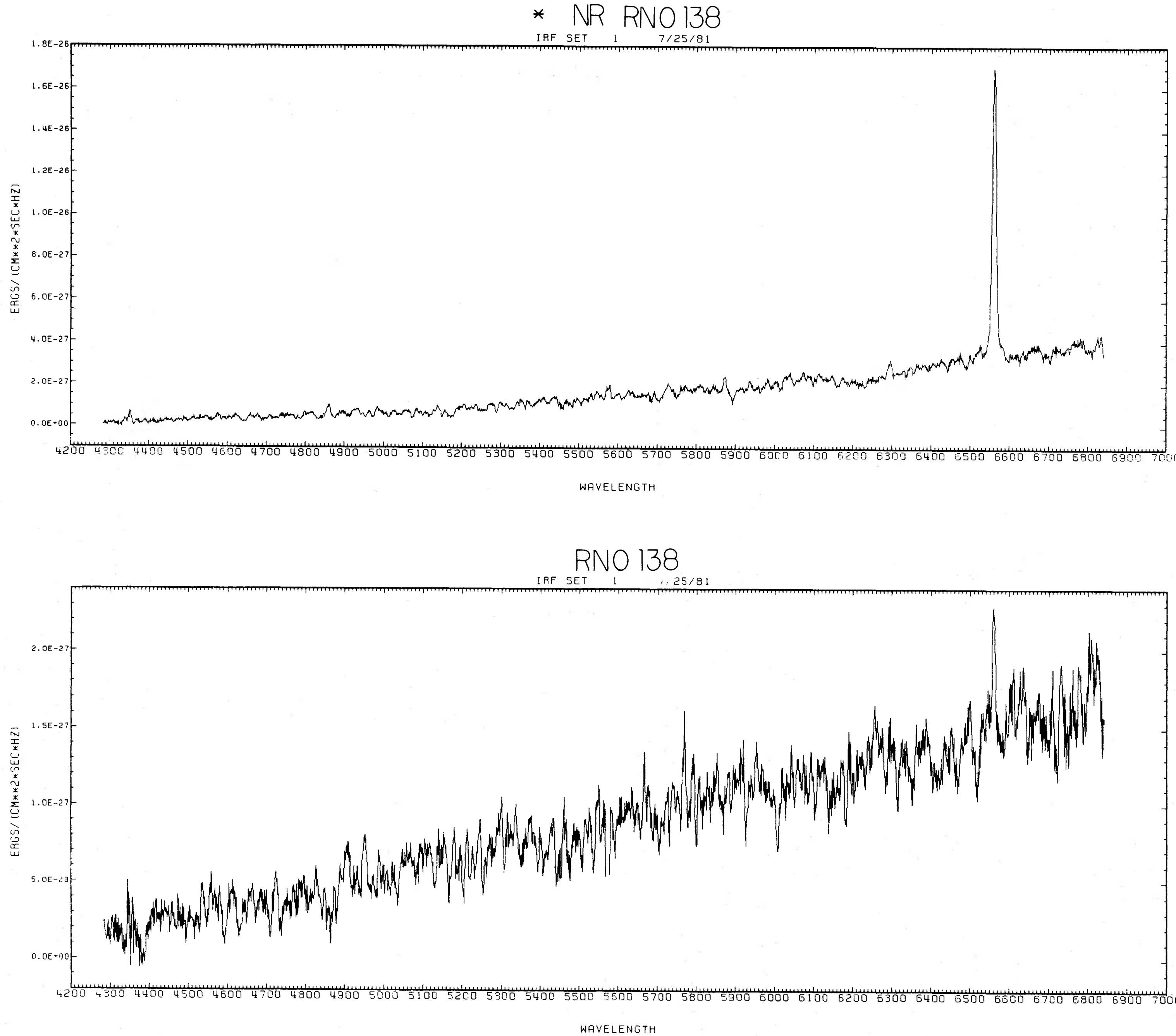

FIG. 5.—Spectra of RNO 138 and its associated star

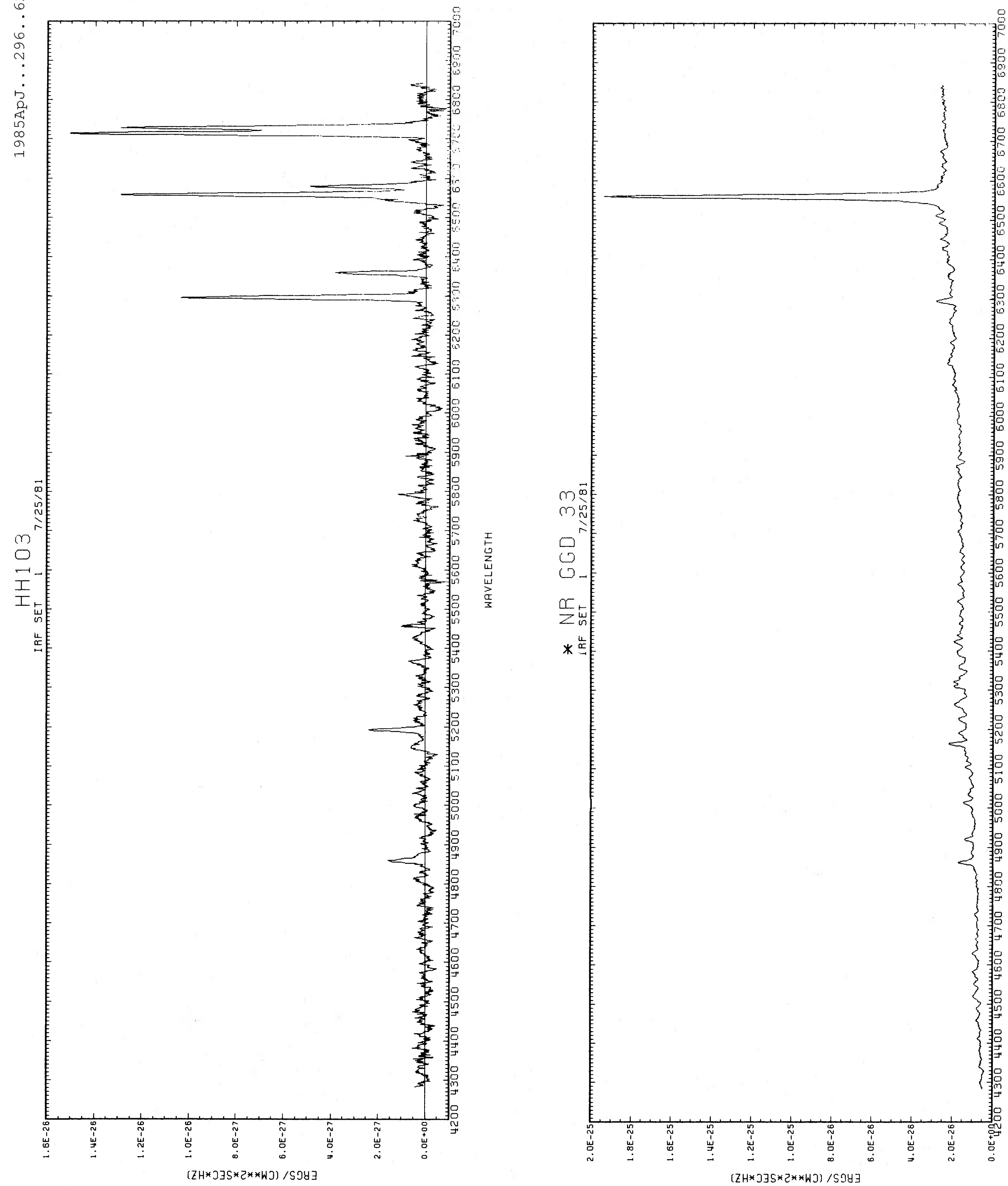

FIG. 6.—Spectra of HH 103 and NGC 7129 IRS 1 ("star near GGD 33")

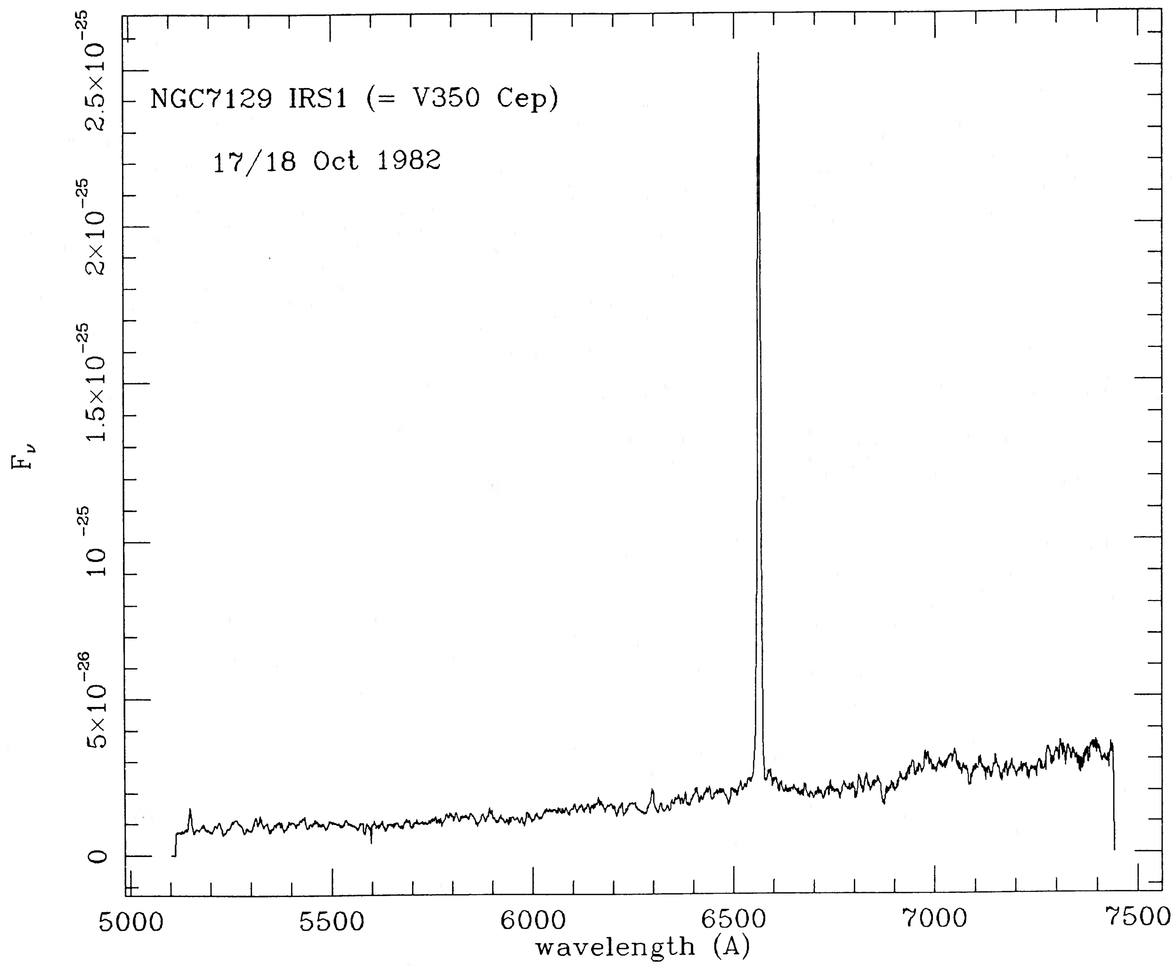

FIG. 7.—Red spectrum of NGC 7129 IRS 1 taken in 1982 and showing two red broad absorption features

that both Hα and the radio emission are due to pure recombination, their intrinsic ratio (Wynn-Williams 1984) yields an estimate of extinction. However, in heavily obscured regions it is likely that only the Hα emission from lightly reddened volumes is observable, whereas maps with the VLA detect all the ionized material. Second, there must be a collisionally excited Hα component in a shock, that does not produce radio emission. Therefore, we prefer to use the Balmer decrements to determine the reddenings. The corrected line fluxes are given in Table 4.

a) "*Haro 6–5B*" *Jet*

This fan nebula is not an HH object, and it is likely that it reflects both the lines and continuum of the responsible star near its apex. To the east of this fan lies a thinner, Hα-emitting (Mundt *et al.* 1984) linear nebula, suggesting that a flow is emerging from the plane of the sky while any associated counterflow must occur within the dark cloud, or dust disk, that obscures the star. The Balmer decrement of the fan nebula suggests that an extinction of $A_v = 3.8$ overlies the hydrogen emission zone.

b) DG Tau HH

The ratio of [O III]/Hβ is rather small (0.4), which suggests a shock velocity close to 80 km s^{-1} (Shull and McKee 1979, "model C"). We can determine the reddening necessary to yield intrinsic Balmer line fluxes in accord with the intensity ratio $I(H\alpha)/I(H\beta)$ of 3.46 for these authors' "model C." An A_v of only 0.39 mag results. Cohen (1984) has estimated the reddening to DG Tau itself, from the ratio of its infrared luminosity (based on data to 160 μm: Cohen, Harvey, and Schwartz 1985) to optical luminosity, namely $A_v = 5.4$. The radical dif-

TABLE 3

SHOCK CONDITIONS DETERMINED FROM DOPITA'S 1977 DIAGNOSTICS

HH Object	Preshock Gas Density (cm^{-2})	Postshock Temperature (K)
DG Tau HH	1800	60,000–70,000
Haro 6–10	1300	60,000–70,000
L1551 IRS 5	2500	70,000
HH 1 SE Fan	160	75,000
HH 103	50	40,000

TABLE 4

INTRINSIC INTENSITIES OF EMISSION LINES COMPARED TO $I(\mathrm{H}\beta) = 100$

Line (1)	DG Tau HH (2)	Haro 6–10 (3)	L1551 IRS 5 (4)	GGD 35 (5)	HH 103 (6)
A_v (mag)	0.39	2.5	5.9	0	0
$I(\mathrm{H}\beta)$	6.69(−15)	1.73(−13)	2.53(−13)	5.04(−15)	2.83(−15)
O II 3727	...	<1600	915	<300	...
O III both	36	...	105	<44	<16
N I 5198	<13	...	<21	16	95
He I 5876	...	9	...	...	...
O I both	141	155	327	114	388
N II both	212	97	239	131	135
Hα	346	346	321	346	353
S II both	227	112	263	281	692
Ca II	...	11	107	...	57
O II 7325	...	39	97	79	...

NOTE.—Units of $I(\mathrm{H}\beta)$ = W cm^{-2}.

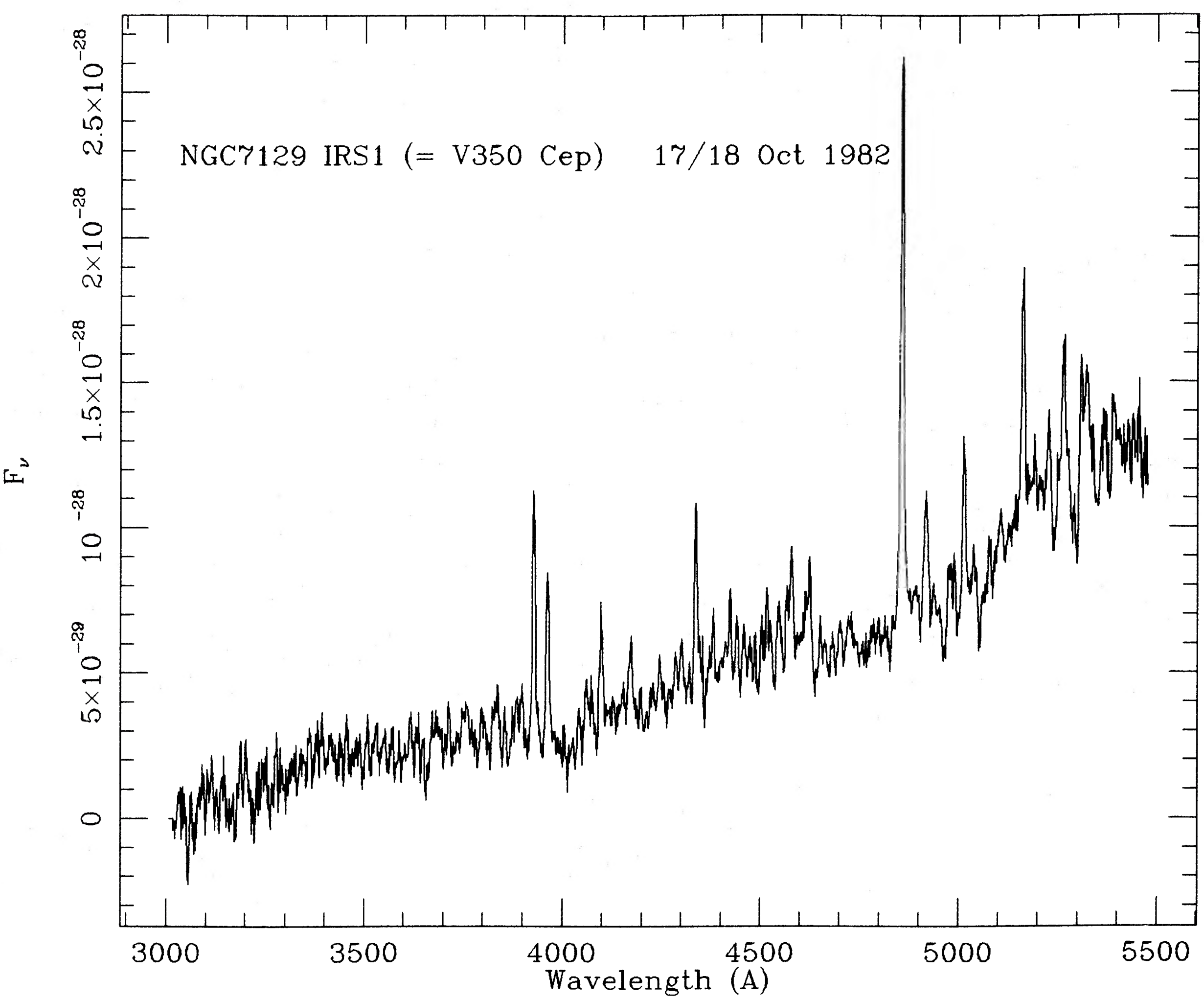

FIG. 8.—Blue spectrum of NGC 7129 IRS 1 showing Ca II H and K lines in emission

ference between the extinctions to DG Tau and to its HH object is reminiscent of the situation found for HH 30, which Cohen and Schmidt (1981) believe is excited by HL Tau. In both cases it is likely that the large stellar extinctions are circumstellar and arise in the plane of almost edge-on circumstellar dust disks, while the HH objects are projected at high stellar latitudes and suffer only interstellar reddening. Therefore, we feel that DG Tau, like HL Tau (Cohen 1983*b*), has a circumstellar dust disk orthogonal to the flow from the star.

If we assume that the radio emission from DG Tau arises in a constant velocity wind with $1/r^2$ density law then we can derive an estimate of the mass loss rate. Schmid-Burgk (1982) has investigated the validity of Wright and Barlow's (1975) description of radio emission from stellar winds when the condition of spherical symmetry is relaxed. He concluded that there would be little difference in the derived mass loss rate and derived spectral index between spherical and nonspherical situations. We therefore use the Wright and Barlow formulation for mass loss rate, with 205 km s^{-1} as the terminal velocity, and a peak 6 cm flux of 0.5 mJy (Bieging, Cohen, and Schwartz 1984). The resultant dM/dt is 3×10^{-8} $M_\odot$ yr^{-1}. Hence dM/dt exceeds L/c by a factor of 34, but this factor is relevant only in the context of radiatively driven, and not too nonspherical (Schmid-Burgk 1982), flows. Of course, multiple scattering of driving ultraviolet photons can also enhance the momentum flux in such a wind. Given the likelihood of highly nonspherical, collimated flows from T Tau stars, the factor of 34 derived above should not be taken to imply the impossibility of DG Tau driving this flow.

The intensity ratio of the red sulfur lines indicates that DG Tau HH is a high-density nebula with N_e of order 10,000 cm^{-3}, only a little less dense than the very dense region observed close to L1551 IRS 5 (see below).

c) HH 31 Knot D

The morphology of HH 31 suggests that the three knots (ABC) are approaching us while any activity to the west of IRS 2 probably recedes into the dark cloud in which HH 31 lies. That we find a positive radial velocity is, therefore, no surprise although we cannot assign knot D to the HH class. Perhaps it is only a reflection nebulosity, that mirrors emission lines formed in the immediate vicinity of IRS 2, but still represents gas receding away from the star into the cloud.

d) Haro 6–10

In order to determine the reddening we have assumed that the present ratio of intensities of Hα to Hβ is the same as when Elias obtained his spectrum. Judging by the comparison of observed line intensities between our data and his, this seems to be a reasonable assumption. From Elias's (1978) data, [O III]/Hβ = 0.24, so the most relevant model in the Shull and McKee (1979) grid of shocks is that for 80 km s^{-1}, their "model C." The predicted Balmer decrement for this model yields $I(\mathrm{H}\alpha)/I(\mathrm{H}\beta)$ of 3.46 compared with Elias's observed ratio of 8.21. Therefore A_v should be close to 2.5 mag. Using this value we have corrected our line fluxes (Table 4).

The weak silicate absorption against Haro 6–10, shown by multifilter photometry (Elias 1978; Cohen and Schwartz 1983), has an optical depth of 0.12. This is a curiously low value, compared with other HH–exciting stars (Cohen and Schwartz 1983, their Fig. 1). It is quite possible that the star has an intrinsic silicate emission feature which suffers absorption by overlying cold silicates. This would lead to a much larger optical depth. However, this can only be tested with higher spectral resolution. Formally, a depth of 0.12 suggests an extinction of order 1.5–2.2, comparable with that derived from the Balmer decrement. It has been suggested (Cohen 1983*b*) that the exciting stars of HH objects may be surrounded by equatorial circumstellar dust disks in which the silicate absorptions arise. If this picture applies to Haro 6–10 then we must view the star from a latitude insufficient to show substantial extinction of the hydrogen-emitting zone, although the small blue shift of the HH lines may imply that our line of sight is still close to perpendicular to the flow from the central star.

Given the likely extreme youth of the exciting stars of HH objects, it would not be surprising were there no recognizable photospheric features in these stars. One might expect to find a strong emission-line T Tau star associated with HH nebulae, by continuity with the properties of HL Tau, DG Tau, and AS 353A, all of which are visible T Tau stars that excite HH objects. Proximity to an HH nebula connotes very recent activity by a star; therefore, the closeness of the infrared source allied with Haro 6–10 (Elias 1978) suggests that its embedded star has generated a recent HH object. The great strength of the optical continuum in Haro 6–10 is certainly consistent with this expectation.

Haro 6–10 seems to be a moderately high-density nebula, as indicated by the sulfur ratio, with N_e about 3400 cm^{-3}. We can also estimate the mass loss rate of the exciting star from the radio flux using our radial velocity to approximate the terminal flow speed. By the formulation of Wright and Barlow (1975), with a 6 cm flux of 0.8 mJy (Bieging, Cohen, and Schwartz 1984), a velocity of 21 km s^{-1} (Table 2), and a distance of 160 pc, we find $dM/dt = 5 \times 10^{-9}$ $M_\odot$ yr^{-1}. It is, however, somewhat unlikely that the true flow speed is as small as our observed radial component, but until proper motions are available for Haro 6–10 we have no other estimate of the terminal velocity.

e) L1551 IRS 5

By comparison with the shock models tabulated by Shull and McKee (1979) we therefore find that these authors' "model D" (shock velocity of 90 km s^{-1}) provides the closest match to the 5007 Å observations of IRS 5. The expected ratio of intensities of Hα to Hβ from this same model is 3.21, which suggests a visual extinction of 5.9 mag to this nebula. Table 4 (col. [3]) presents the intrinsic line intensities for L1551 IRS 5, after correcting the observations for an A_v of 5.9.

The low ratio of [S II] intensities, $I(6717)/I(6731) = 0.50$ (Table 2) indicates a very high density for an HH object. Formally, $N_e = 14{,}000$ cm^{-3}. Support for a high density within this knot also comes from the even higher value deduced by Bieging and Cohen (1985) for the radio-emitting jet (of order 2×10^6 cm^{-3}). We note that the [S II] density that we derive is an order of magnitude greater than highest density observed by Sarcander, Neckel, and Elässer (1985). Likewise, the extinction of our knot substantially exceeds that of the most heavily reddened regions cited by these authors. These comparisons point to the fact that the densest and most heavily obscured region of the jet lies at the easternmost extremity.

That this nebulosity is blueshifted is in accord with the existence of the phenomenon of high-velocity flows to the southwest of IRS 5, namely the blue-lobe CO emission seen by Snell, Loren, and Plambeck (1980) and the rapidly moving HH knots, HH 28 and 29 (Cudworth and Herbig 1979). All the visible signs of activity from IRS 5 occur to the southwest of the source, indicating that the radio emission to the northeast represents a structure that is embedding itself further into the L1551 cloud. An estimate of the extinction toward IRS 5 can be derived, approximately, from the depth of the 10 μm silicate feature, τ(sil) = 1.4 (Cohen and Schwartz 1983). While the exact value of A_v/τ(sil) is still somewhat uncertain, it is of order 10–20 (e.g., see Roche and Aitken 1984 who obtain a value of 18.5 ± 1.5 for the general interstellar medium). From a sample of visible T Tau stars principally lying within the Taurus-Auriga complex, Cohen and Witteborn (1985) suggest an average value of 12.5 for this ratio, which would indicate an A_v of 17.5 mag to IRS 5. The disagreement between this and the value deduced from our optical spectra is to be expected since we will sample only the less heavily reddened regions at visual wavelengths, whereas the silicate feature arises along the total line of sight toward the embedded star.

f) HH 1 SE Fan

The ratio of [O III] to Hβ indicates the great strength of [O III] and suggests a comparison with models D or E of Shull and McKee (90 or 100 km s^{-1}). In spite of the weakness of Hβ, the observed ratio of I(Hα)/I(Hβ) is so close to 3 as to suggest that the hydrogen-emitting region observed in the fan suffers essentially no reddening. The sulfur line ratio argues for a density around 2200 cm^{-3} and suggests a higher preshock density than 100 cm^{-3}. The shock velocity is likely to be of order 100 km s^{-1}.

It appears that the southeast fan partakes of the same flow as do HH 1 and HH 2.

g) NGC 7129

As Figures 4–6 illustrate, the character of their spectra earmarks GGD 32 and 35 as bona fide HH nebulae, a conclusion also reached by Magakyan (1983). The sulfur line ratio suggests that GGD 32 is an extremely low-density HH nebula with N_e around 10 cm^{-3}.

The spectrum of GGD 35 shows I(Hα)/I(Hβ) to be 3.55, suggesting that any extinction toward this nebula is minimal. The ratio of sulfur lines from both spectra is 1.16 ± 0.04, indicating that N_e is close to 600 cm^{-3}. All 1981 line intensities relative to Hβ are confirmed by our 1982 data. The averaged relative strengths appear in Table 4. Its blueshift and the absence of appreciable reddening are consistent with GGD 35 being in front of the dark clouds associated with NGC 7129.

HH 103 also appears to be virtually unreddened [I(Hα)/I(Hβ) = 3.53]. The sulfur line ratio indicates N_e around 320 cm^{-3} and the general shock diagnostics, summarized in Table 1, imply that the preshock density $\sim$50 cm^{-3} which is in the range covered by the Shull and McKee models. The very bright sulfur lines, coupled with the absence of [O III] and the obvious strength of [N I], pose severe problems in matching any published models of shocks. We can suggest only that HH 103 represents a region with a complex, non–planar shock structure, with the [O I], [N I], and [S II] coming from a much lower velocity (<40 km s^{-1}) shock than the other optical lines. The extended arcuate morphology of this nebula is certainly consistent with a shock that is neither monovelocity nor planar.

The Balmer decrement in RNO 138 [log I(Hα)/I(Hβ) = 1.14, log I(Hβ)/I(Hγ) = 0.48] yields $A_v = 3.6 \pm 0.1$. Its narrow-band continuum colors suggest a reddening with $A_v = 2.5 \pm 0.5$ mag. However, its colors are certainly bluer than those of its allied star. It could, therefore, be a reflection nebula. If so, then the very different equivalent widths in the stellar and nebular spectra would demand either a strongly time-varying stellar Hα line or a substantial dependence of stellar Hα intensity on latitude.

The proximity and alignment of GGD 33a and b with IRS 1 are likely to represent a causal relationship. Perhaps these two nebulae are just too faint to present detectable HH emission lines in relatively short integrations at Lick (15–30 minutes). The potential further alignment with GGD 35 could be fortuitous, especially given the great projected distance from IRS 1 to GGD 35 (1.3 pc); however, Cohen and Schwartz (1983) were unable to locate any closer candidate exciting star for GGD 35.

IV. CONCLUSIONS

We conclude that far-infrared emission peaks in dark clouds can often be good indicators of very young stars in whose immediate vicinities one can find HH objects. In this category we place DG Tau HH, Haro 6–10, L1551 IRS 5, and HH 1 SE fan. It is interesting that this limited sample of nebulae includes objects that are denser than average HH objects. There is morphological evidence in the HH 1/2 and HH 38/43 systems, and perhaps in the HH 31A/B/C group too, that the older nebulae have expanded thermally, orthogonal to their motion vectors, and are now diffuse, sometimes even having the appearance of fragmented bubbles. We therefore suspect that the high-density HH objects are simply much younger than typical HH nebulae that lie further from their exciting (and ejecting) stars.

For two nebulae ("Haro 6–5B" jet and "HH 31D") and for the T Tau star, NGC 7129 IRS 1, we see [O I] emission but not a fully fledged HH spectrum. Further, a detailed comparison of Shull and McKee (1979) and Raymond (1979) models with our intrinsic line intensities for bona fide HH objects suggests that, in general, the observed [O I] lines are too strong by factors of 3–10. Enhanced [O I] emission could arise from pervasive low-velocity (10 km s^{-1}) shocks. If this were the situation, then far-infrared observations of lower energy transitions might prove to be valuable probes of these regions.

It is highly interesting that there are now several pairs of exciting stars and HH nebulae in which there is a substantial difference between the stellar and nebular extinctions. Within this paper we have noted DG Tau [A_v(star) = 5, A_v(HH) = 0.4] and L1551 IRS 5 [A_v(star) = 17, A_v(HH) = 6]. There are also the Cohen-Schwartz star [A_v(star) = 6, A_v(HH) = 2–3] and HL Tau [A_v(star) = 7, A_v(HH 30) = 1]. We suggest that these discrepancies indicate the presence of nonspherical circumstellar dust shells around the HH–exciting stars, probably disks of appreciable thickness in relation to their radii. As a consequence it would appear that these protostellar disks have survived both the principal heavy accretion onto the stellar core and the onset of the phenomenon that ejects HH objects.

We thank L. Kuhi for sharing his observing time at Lick with us. M. C. acknowledges the support of NASA/Ames Research Center through cooperative agreement NCC 2-142, and G. A. F. thanks W. J. Welch and C. Heiles for support under the NSF grant AST 82-12058.

REFERENCES

Bastien, P. 1982, *Astr. Ap. Suppl.*, **48**, 153.
Bieging, J., and Cohen, M. 1985, *Ap. J.* (*Letters*), **289**, L5.
Bieging, J., Cohen, M., and Schwartz, P. R. 1984, *Ap. J.*, **282**, 699.
Cohen, M. 1980, *A.J.*, **85**, 29.
———. 1983*a*, *Rev. Mexicana Astr. Ap.*, **7**, 241.
———. 1983*b*, *Ap. J.* (*Letters*), **269**, L70.
———. 1984, poster paper presented at "Protostars and Planets. II" meeting, Tucson, Az.
Cohen, M., Bieging, J., and Schwartz, P. R. 1982, *Ap. J.*, **253**, 707.
Cohen, M., Harvey, P. M., and Schwartz, R. D. 1985, *Ap. J.*, **296**, 633.
Cohen, M., Harvey, P. M., Schwartz, R. D., and Wilking, B. A. 1984*a*, *Ap. J.*, **278**, 671.
Cohen, M., and Kuhi, L. V. 1979, *Ap. J. Suppl.*, **41**, 743.
Cohen, M., and Schmidt, G. D. 1981, *A.J.*, **86**, 1228.
Cohen, M., and Schwartz, R. D. 1979, *Ap. J.* (*Letters*), **233**, L79.
———. 1983, *Ap. J.*, **265**, 877.
Cohen, M., Schwartz, R. D., Harvey, P. M., and Wilking, B. A. 1984*b*, *Ap. J.*, **281**, 250.
Cohen, M., and Witteborn, F. C. 1985, *Ap. J.*, **294**, 345.
Cudworth, K. M., and Herbig, G. H. 1979, *A.J.*, **84**, 548.
Dopita, M. A. 1977, *Ap. J. Suppl.*, **33**, 437.
Elias, J. H. 1978, *Ap. J.*, **224**, 857.
Gyul'budagyan, A. L., Glushkov, Yu. I., and Denisyuk, E. K. 1978, *Ap. J.* (*Letters*), **224**, L131.
Gyul'budagyan, A. L., and Magakyan, T. Yu. 1977, *Soviet Astr. Letters*, **3**, 261.
Harvey, P. M., Wilking, B. A., and Joy, M. 1982, *Bull. AAS*, **14**, No. 2, p. 610.
Herbig, G. H. 1974, *Lick Obs. Bull.*, No. 658.
Magakyan, T. Yu. 1983, *Soviet Astr. Letters*, **9**, 83.
Magakyan, T. Yu., and Amirkhanyan, A. S. 1979, *Astr. Tsirk.*, No. 1038, p. 6.
Miller, J. S., Robinson, L. B., and Wampler, E. J. 1976, in *Advances in Electronics and Electron Physics*, Vol. **40B**, ed. J. W. Glaspey and G. A. H. Walker (New York: Academic Press), p. 693.
Mundt, R., Bührke, Th., Fried, J. W., Neckel, Th., Sarcander, M., and Stocke, J. 1984, *Astr. Ap.*, **140**, 17.
Mundt, R., and Fried, J. W. 1983, *Ap. J.* (*Letters*), **274**, L83.
Raymond, J. C. 1979, *Ap. J. Suppl.*, **39**, 1.
Roche, P. F., and Aitken, D. K. 1984, *M.N.R.A.S.*, **208**, 481.
Sarcander, M., Neckel, Th., and Elässer, H. 1985, *Ap. J.* (*Letters*), **288**, L51.
Schmid-Burgk, J. 1982, *Astr. Ap.*, **108**, 169.
Shull, J. M., and McKee, C. 1979, *Ap. J.*, **227**, 131.
Snell, R. L., Loren, R. B., and Plambeck, R. L. 1980, *Ap. J.* (*Letters*), **239**, L17.
Stone, R. P. S. 1974, *Ap. J.*, **193**, 135.
Strom, S. E., Grasdalen, G. L., and Strom, K. M. 1974, *Ap. J.*, **191**, 111.
Strom, S. E., Vrba, F. J., and Strom, K. M. 1976, *A.J.*, **81**, 638.
Wright, A. E., and Barlow, M. J. 1975, *M.N.R.A.S.*, **170**, 41.
Wynn-Williams, C. G. 1984, in *Galactic and Extragalactic Infrared Spectroscopy*, ed. M. F. Kessler and J. P. Phillips (Dordrecht: Reidel), p. 113.

MARTIN COHEN and GARY A. FULLER: Radio Astronomy Laboratory, 601 Campbell Hall, University of California, Berkeley, CA 94720