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AN FU ORIONIS STAR ASSOCIATED WITH HERBIG-HARO OBJECT 57

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ABSTRACT

We describe a variable star of the FU Orionis type which has appeared on the edge of Herbig-Haro object 57. The star was discovered in 1983, although it had evidently begun to flare optically about 3 yr before. Past and present photographs of the region are reproduced. We present and discuss photometry out to 20 μm. The photometry shows a strong infrared excess and is consistent with an F star surrounded by a two-component dust shell with temperatures of 2000 K and 325 K in addition to a stellar energy distribution appropriate to 6500 K.

Spectroscopic observations show that the star is ejecting an optically thin shell which is producing a strong and broad P Cygni absorption profile at Hα with a violet absorption edge at -440 km s^{-1}. The Hα emission is sharp and at near zero velocity. Its intensity appears to vary significantly over a period of a month. In the λ8500 region, the Ca II triplet is observed in emission, also at near zero velocity. The line ratios indicate saturation and show that this emission is probably taking place close to the surface of the star. [S II] is seen in emission in the star but with a heliocentric velocity of -85 km s^{-1} suggesting that Herbig-Haro activity may also be occurring close to the stellar surface.

Reference is made to the probable importance of FU Orionis events in the early stages of planetary system formation.

Subject headings: infrared: sources — stars: circumstellar shells — stars: pre–main-sequence — stars: variables

I. INTRODUCTION

Much of the recent progress in our understanding of star formation has been made possible by infrared and millimeter-wave techniques, which can penetrate heavy optical obscuration and, as well, reveal high concentrations of molecular gas. IR and mm results are joining together with the available optical observations to form an increasingly clear picture of the early stages of stellar evolution. For example, the nature and origin of the Herbig-Haro objects has become evident following the work of Strom and collaborators (e.g., Strom, Grasdalen, and Strom 1974), who showed that HH objects are often associated with point IR sources. These sources have subsequently been identified with very young stars or proto-stars which are deeply embedded in an envelope of dust and molecular gas.

It is now believed that HH objects form in the cooling regions of shock waves brought about by strong winds from the young stellar or prestellar objects. Several instances are known in which the HH objects are aligned with the central source and are moving away from it with high space velocities (Cohen and Schwartz 1983; Mundt, Stocke, and Stockman 1983; Graham and Elias 1983). The winds from the source objects also produce the bipolar material observed in CO line radiation (Edwards and Snell 1983). In the few cases where optical observation is possible, the source is a low-luminosity star with T Tauri characteristics. These stars are known to be losing mass through strong stellar winds. The winds do not, however, appear on the average to be sufficiently powerful to provide the observed energies which are contained in the HH objects and high-velocity molecular gas. This discrepancy can be reduced if we can show that the stellar wind is highly anisotropic or if the energy input from the source is occasionally much greater than in the normal average state. Both factors may be important (Hartmann and Mundt 1983).

In this paper, we report on an energetic outburst which occurred recently in a star on the NE edge of HH object 57. The discovery was announced by Graham (1983). The spectrum of the star unambiguously identifies it as an FU Orionis object. FU Orionis stars are rare, and only four others are known (Herbig 1977; Elias 1978). FU Ori itself and V1057 Cygni are those which have been best observed. The new example is the first which is directly associated with a HH object. We present optical and IR photometry and also some spectroscopic observations made in the red and near-infrared.

II. HISTORY

The FU Orionis star in HH 57 was first noticed at Cerro Tololo Inter-American Observatory (CTIO) on 1983 March 16 during a routine photographic survey of HH objects with the Yale 1 m telescope. It was recognized at once that the object was not visible on the 1976 photographs which accompanied Schwartz's (1977) announcement of the HH 57 discovery. Two other plates were taken on 1983 March 17 which confirmed the stellar appearance and demonstrated that the radiation was mainly in continuum light and was quite red.

The new star is not visible on the Whiteoak extension of the Palomar Observatory Sky Survey; the relevant photograph was taken on 1964 June 14. A faint diffuse patch is seen on the ESO-SERC *J* transparency taken on 1975 June 9. This is described by Reipurth (1981). Another prediscovery constraint has been provided by M. A. Dopita, who mentioned to one of us (J. A. G.) that HH 57 was observed in 1978 April for spectrophotometry (Schwartz and Dopita 1980), and he is sure that the star would have been noticed then if it had been as bright as it is now.

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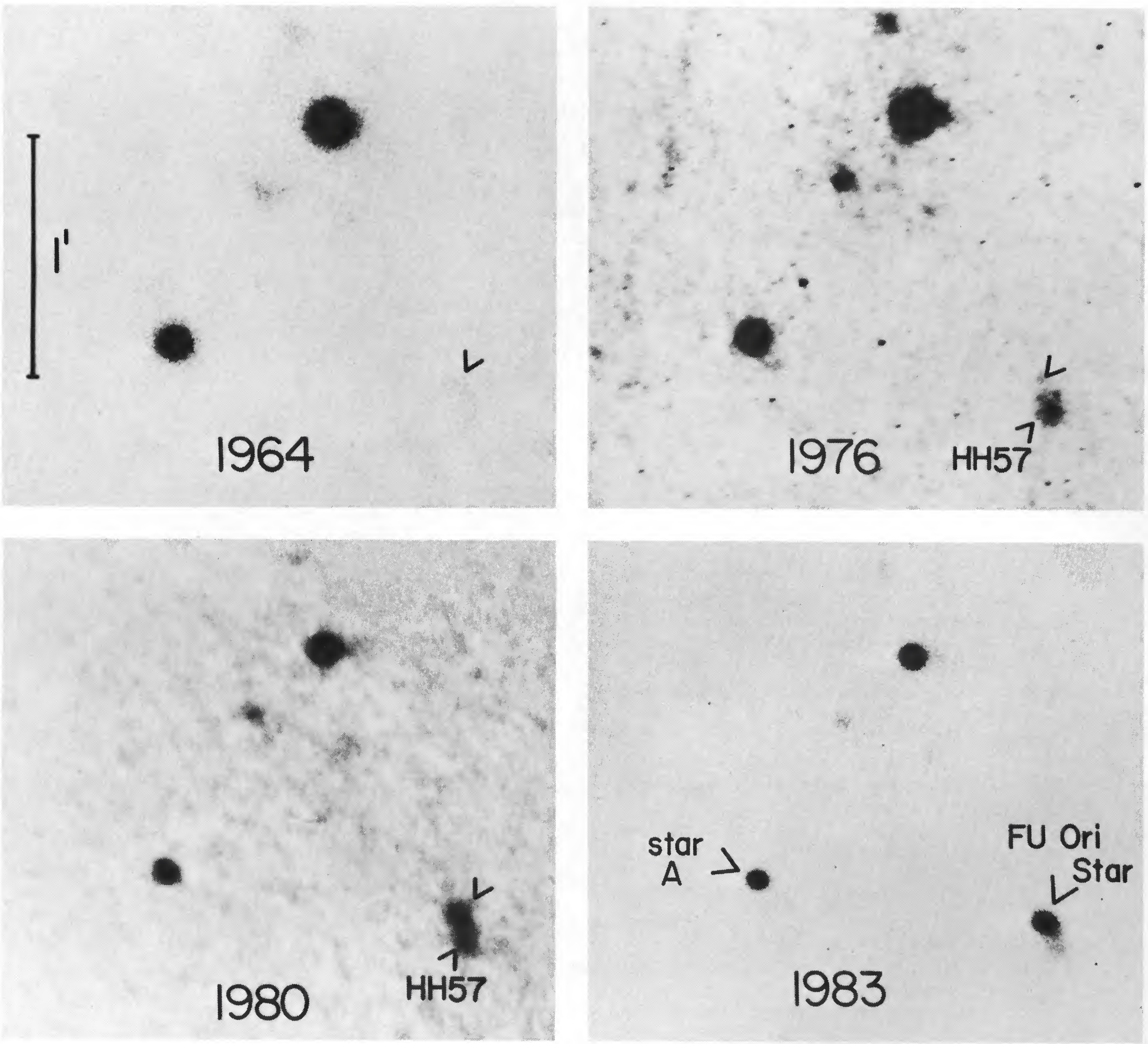

FIG. 1.—Photographic record of the HH 57 star. The 1964 photograph is reproduced from the National Geographical Society–Palomar Observatory Sky Survey, Whiteoak Extension (bandpass 6000–6600 Å). The 1976 photograph has been kindly made available by R. D. Schwartz. Its bandpass is 6100–6900 Å. The 1980 photograph is reproduced from the ESO-SERC sky atlas (the *SR* negative, bandpass 6300–7000 Å). The 1983 photograph was obtained with the 1 m Yale telescope at CTIO on March 17 with a Carnegie image tube and *R* filter (bandpass 5700–7000 Å). N is to the top, and E to the left in each photo. The field star marked A is referred to in the text.

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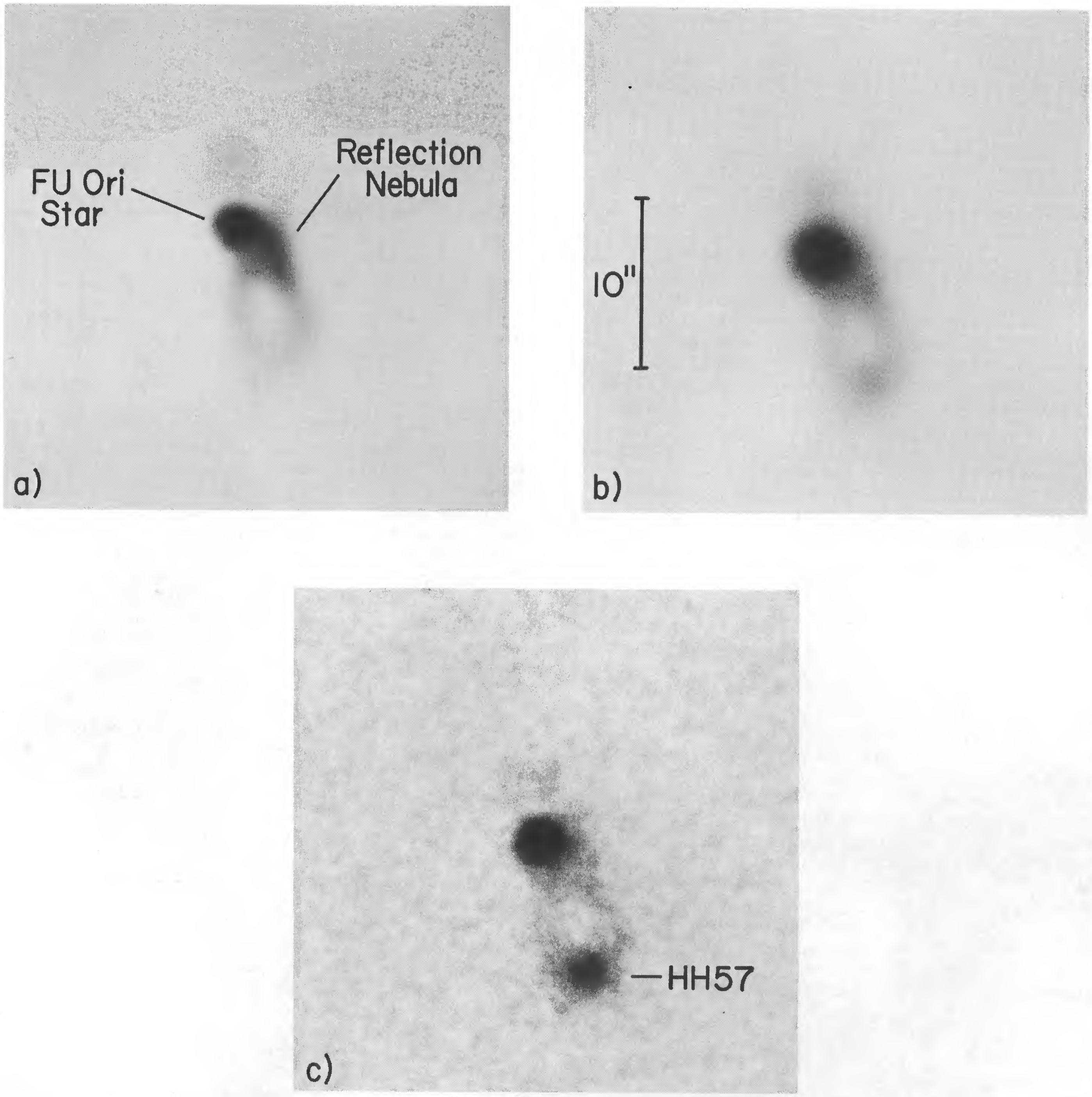

FIG. 2.—The HH 57 star and its associated nebula. N is to the top, and E to the left in each picture. (*a*) A CCD image with *V* filter (bandpass 4900–5700 Å). The image was made from the sum of four CCD frames, each exposure of 1 minute, taken on 1983 May 23. The original image has been defocused slightly to diminish the visual impact of the individual pixels. Continuum radiation is emphasized here, and that part of the nebula which reflects light from the FU Orionis star is shown the most clearly. (*b*) A direct photograph taken with the 4 m prime-focus camera, exposure 15 minutes, IIIa-F emulsion, OG570 filter. The light transmitted covers the range 5700–7000 Å and thus represents mainly continuum radiation but includes also emission-line radiation from the HH object. The date is 1984 January 28. (*c*) A direct photograph taken with the 4 m prime-focus camera, exposure 50 minutes, 098-04 emulsion, Hα interference filter. The light transmitted covers the range 6510–6610 Å and thus emphasizes the HH 57 knot, which radiates strongly in the Hα and [N II] lines. The date is 1984 January 29.

The star was apparently already brightening by 1980 August 1 when photographs for the ESO-SERC *SR* and *I* surveys were taken. On these transparencies, the FU Orionis star is seen to be much brighter than on the Schwartz 1976 plates but fainter than at discovery in 1983 March. The images appear slightly diffuse, but this is partly an effect of the limited resolution of the photographs. Coincident with the new object, there is an IR source, which was measured by Elias (1980) and Reipurth and Wamsteker (1983) in 1979 February and 1979 August/September, respectively. Reproductions of some photographs are shown in Figure 1 to demonstrate the recent optical brightening. Note that even on the 1964 POSS image, a faint nebulous arc is seen extending from the position of the new star to the core of the HH object SW. The different appearance of the HH object itself relative to the surrounding stars in the photographs can be understood from a consideration of the various detector/filter bandpasses which were used. All bandpasses include the emission lines [O I] $\lambda\lambda$6300, 6363, [N II] $\lambda\lambda$6548, 6584, and Hα, which are characteristic spectral features of HH objects. All, except the 1964 photograph, register as well the generally strong [S II] doublet $\lambda\lambda$6716, 6713. The overall bandpass widths are similar for the 1964, 1976, and 1980 images, but that used for the 1983 picture is wider by a factor 2, thereby rendering the HH object, which radiates almost entirely in emission lines, less conspicuous when compared with the adjacent stars, which radiate predominantly in continuum light. The star marked A in Figure 1 was measured photometrically and is referred to in §§ III and V.

Figure 2 shows some images taken with the CTIO 4 m telescope which reveal greater spatial detail. The first is reproduced from the sum of four CCD frames, each exposure of 1 minute taken in visual light on 1983 May 23 by P. Seitzer. No emission lines are expected from the HH object within the 4900–5700 Å bandpass of this frame. Here the FU Orionis star and an accompanying bright reflection nebula are the most prominent. The second image is a photograph taken through a broad-band orange-red filter (5700–7000 Å) and includes both continuum and emission-line radiation. Here, already, the HH object can be seen through the registration of its emission-line radiation. The third image comes from a photograph taken with a narrow interference filter 100 Å wide centered on Hα but also transmitting the [N II] lines $\lambda\lambda$6548, 6584. Here HH 57 itself is seen very clearly, but little light from the reflection nebula of Figure 2*a* is recorded. The reflection nebula seems similar to the one which appeared around V1057 Cyg at the time of its outburst (Duncan, Harlan, and Herbig 1981), and it may be expected to slowly fade along with the star in coming years.

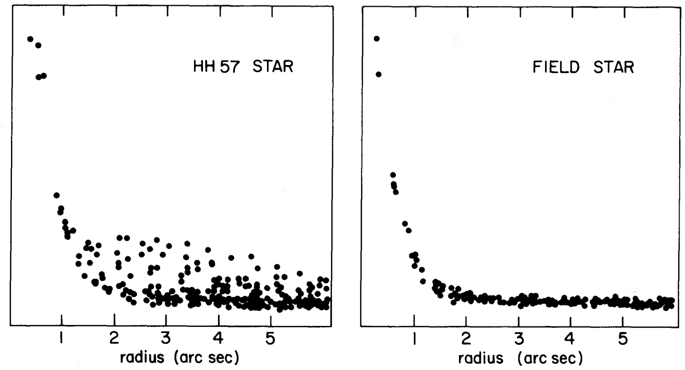

FIG. 3.—Image profiles from CCD frame in *V* light. Shown are radial profiles of the FU Orionis star in HH 57 and a nearby field star (star A in Fig. 1). In each case the FWHM width is 1".2, showing that to this level the HH 57 object is stellar at visual wavelengths. Note the variable background level around the HH 57 star caused by the reflection nebulosity.

III. RECENT PHOTOMETRY

Since discovery, photometric observations have been made when possible through standard *V* and *B* filters and also in the infrared. The former were made mainly with the prime-focus CCD camera on the CTIO 4 m telescope. The filters are such that bright emission lines are largely avoided, and they are sufficiently broad to give good measures of the continuum radiation from the star. Exposures were either 30 s or 1 minute and zero points were fixed by observation of E region standard stars (Graham 1982). In visual light, the FU Orionis star indeed appears as a point object. Figure 3 shows profiles taken from a typical CCD frame. A centering routine was used to determine the centroid of each image. The radial distance of each surrounding pixel was then calculated to reconstruct the image intensity profile. The profile of the FU Orionis star is compared with that of star A (Fig. 1). The seeing was good, and the FWHM width of each image is about 1".2. Notice the irregular sky background produced by the nebulosity. The magnitudes were determined by integrating the stellar profiles over a radius of 3" and subtracting a representative sky background determined from the mode of the intensity distribution in a surrounding annulus. The visual photometry is given in Table 1. The 1983 May 23 observation was made by P. Seitzer. The 1984 January 30 observation is from a photographic plate taken by J. A. G. The precision of the CCD observations is about 0.05 mag in *V* and 0.10 mag in $B-V$. The adjacent nebulosity is not included in the measurement. The photographic estimate is uncertain to about 0.1 mag.

Soon after the initial discovery of the stellar source in HH 57, Frogel and Graham (1983) found the object to be a strong 2–10 μm source. Additional IR data have since been obtained with CTIO's D2 bolometer system and D3 InSb system on the 4 m and 1.5 m telescopes equipped with f/30 chopping secondaries. Since the stellar source was visible with the on-axis acquisition TV, it was easy to verify that the peak IR signal indeed coincides with the FU Orionis star to better than $\pm$0".5. The IR data are given in Table 2 and are on the CTIO/CIT photometric system as defined by the standard stars of Elias *et al.* (1982). The 1983 May and September data were obtained for us by B. Carney. The *K*- and *L*-values measured with the D2 system are probably not significantly different from the values obtained with D3. Included in Table 2 are the data from Elias (1980) and Reipurth and Wamsteker (1983). Expected errors in each band are within 0.1 mag except at 20 μm, where the uncertainty is closer to 0.2 mag.

There is evidence for variability at wavelengths shorter than 3.5 μm. Some care must be taken in comparing observations

TABLE 1

VISUAL PHOTOMETRY

Date	V	$B-V$
1983 Mar 19	17.23	2.26
May 23	16.81	...
Oct 11	16.68	1.93
1984 Jan 30	17.0	...
Mar 10	16.61	1.87

TABLE 2

INFRARED PHOTOMETRY

Date	Aperture Size (arcsec)	Ref.	J(1.2 μm) (mag)	H(1.6 μm) (mag)	K(2.2 μm) (mag)	L(3.5 μm) (mag)	4.8 μm (mag)	10 μm (mag)	20 μm (mag)	H_2O (mag)	CO (mag)
1979 Feb 11	10	1	12.20	10.01	8.18	...	...	...	...	...	...
Aug/Sep	12	2	11.96	9.87	8.19	6.18	...	...	...	...	...
1983 Mar 26	5.0	3	...	...	7.45	6.19	4.99	2.12	0.10	...	...
Apr 25	7.1	4	9.98	8.86	7.59	6.22	...	...	...	0.41	−0.245
May 10........	9.1	5	9.97	8.65	7.56	...	...	...	...	...	...
Sep 19	7.1	5	10.08	8.67	7.66	...	...	...	...	...	...
Sep 21	7.1	5	10.12	8.73	7.70	6.34	...	...	...	...	...
Oct 23	7.1	4	9.99	8.68	7.61	6.25	...	...	...	0.42	−0.22

REFERENCES.—(1) Elias 1980. (2) Reipurth and Wamsteker 1983. (3) Frogel (D2 System). (4) Frogel (D3 System). (5) Carney (D3 System).

made with different telescopes. Despite the claim by Reipurth and Wamsteker (1983), Elias informs us that, in his opinion, the differences between the 1979 ESO measures and his own are barely significant in view of the larger ESO beam size. Allowing for observational uncertainties, however, there is no doubt that the IR source is now much brighter and is significantly bluer at JHK than in 1979. Curiously, at L the star seems to have stayed almost constant. Visually the star brightened by about 0.5 mag during 1983, and the corresponding and significant decrease in $B-V$ suggests that this may have resulted from a temporary clearing of the interstellar dust. Cohen *et al.* (1984) have reported some IR measurements made in 1983 April which do not agree with ours. They find magnitudes of 3.05 ± 0.07 at 10 μm and 3.39 ± 0.06 at 11.7 μm. Our 10 μm measurement made in late March is more than 1 mag brighter and at 11.7 μm, 1.7 mag brighter. We are unable to explain such a gross difference. Our data were obtained under photometric conditions and were well tied into seven standard stars with a mean residual of 0.09 mag.

Linear polarization appears to be low. A series of four photographs were taken on 1983 June 8 through a piece of Polaroid which was rotated by 45° between each exposure. The filter/plate combination was OG570 + IIIa-F. To date, the photographs have only been compared visually, but it is clear that the magnitude of the FU Orionis star remains constant to within 0.1 mag as the Polaroid sheet rotated. Precise measurements are clearly in order. There is evidence that, at the 0.2% level, the intrinsic linear and circular polarization of FU Orionis stars may vary with time (Bastien 1982; Wolstencroft and Simon 1975). Our coarse estimate indicates only that anisotropic scattering of starlight by material either close to the star or from the dark cloud itself is small, and that an extreme example (e.g., the star HL Tau [Cohen 1983], for which the linear polarization amounts to 13%) is not being observed in this instance.

IV. SPECTROSCOPY AND SPECTROPHOTOMETRY

Over the past year we have collected some spectroscopic and spectrophotometric data in the course of other observing programs. All observations were made with the CTIO 4 m telescope and its Cassegrain spectrograph. The material consists of one 50 Å mm^{-1} spectrogram obtained with the Carnegie image tube and four scans with a CCD (GEC chip) as detector. Of the scans, three were at moderate dispersion in the Hα–[S II] region of the spectrum, and one was at low dispersion covering $\lambda\lambda$7000–9000.

The single image-tube spectrum was taken on 1983 May 19 with exposure time 1 hr. The spectrum was centered near λ6300 and extended from λ5550 to λ7000. The slit was 1″.6 (250 μm) wide, 25″ long, and oriented at P.A. 15°. In this way the spectrogram included both the new object and the HH 57 emission knot. Part of the spectrum near Hα is reproduced as Figure 4. The most striking feature of the stellar spectrum is the broad, blue-displaced absorption at Hα. On its redward edge at near zero velocity, a sharp emission peak is observed. The Na I D lines at $\lambda\lambda$5890, 5896 are themselves very strong in absorp-

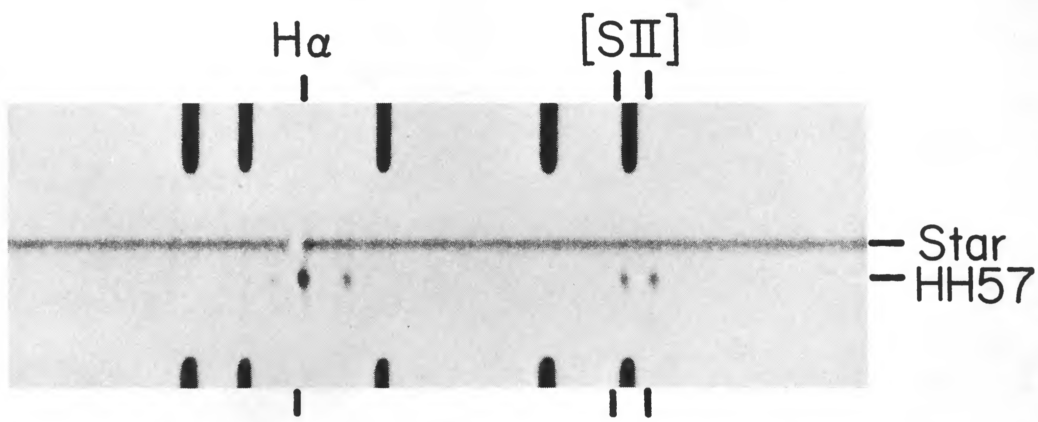

FIG. 4.—Spectrogram of Hα region of HH 57 and its FU Orionis star. This spectrogram was taken on 1983 May 19 with the CTIO 4 m telescope, Cassegrain spectrograph, original dispersion 50 Å mm^{-1}. The slit was oriented in P.A. 15° so as to include both the FU Orionis star and the Herbig-Haro emission patch. The comparison spectrum is neon.

TABLE 3

IMAGE-TUBE SPECTROGRAM VELOCITIES

Object	Spectral Feature	Heliocentric Velocity (km s^{-1})	Velocity with respect to LSR (km s^{-1})
HH 57 star	Hα absn. blue edge	−445	−441
	Hα absn. red edge	− 60	− 56
	Hα emission peak	+ 9	+ 13
HH 57 knot	[N II] λ6548	− 64	...
	Hα	− 76	...
	[N II] λ6548	− 57	...
	[S II] λ6716	− 46	...
	[S II] λ6731	− 53	...
Average velocity		− 59	− 55

tion and fuse together to produce a single broad feature which is also displaced toward the blue when compared with the Na I D night-sky lines. The HH object has a characteristic low-excitation spectrum with [O I] λλ6300, 6363, [N II] λλ6548, 6584, Hα, and [S II] λλ6713, 6737. The intensities seem qualitatively unchanged from those values listed by Schwartz and Dopita (1980). The [S II] emission extends faintly between the star and the bright HH knot. Some weak Hα may be present too, but it is confused with the Hα night-sky line. Wavelengths have been measured from the spectrogram with respect to the neon comparison lines, and heliocentric velocities have been computed. Velocities with respect to the local standard of rest are calculated by assuming a solar velocity of 20 km s^{-1} toward R.A. 18^h, decl. +30°. These data are given in Table 3.

The intermediate-resolution CCD scans near Hα were taken with a 1200 lines mm^{-1} grating, yielding a resolution of 0.6 Å per pixel. Sky subtraction was made from areas of the spectrum adjacent to the star. Coverage was over a spectral range λλ6400–6735 with a slit width of 220 μm spreading comparison spectrum lines over 1.5–2 pixels (FWHM). The slit was aligned E-W. Scans have been obtained so far on three nights: 1983 May 24 (30 minutes), 1984 February 15 (60 minutes), and 1984 June 6 (90 minutes). All nights have good wavelength calibration, but only the second and third have usable intensity calibrations. We reproduce the second night's scan in its entirety as Figure 5. The P Cygni type profile at Hα can be seen here clearly. Weak [S II] λλ6716, 6731 is also present. Examination of the original frame shows that this [S II] emission comes from the stellar image, not from surrounding nebulosity.

The spectral features of the star shown in Figures 4 and 5 are very characteristic of an FU Orionis star observed a few years after maximum (Herbig 1977). Reipurth and Krautter (1983) have reported an observation made on 1981 June 4, when the outburst must have been well along but still in its early stages. They state that their scan shows a red continuum with two pronounced features: Hα is in absorption and blueshifted by 200 km s^{-1}, and the Li I line at 6708 Å is strong and broad. They make no mention of an intense Hα emission peak which should have been obvious had it been present. In our spectra

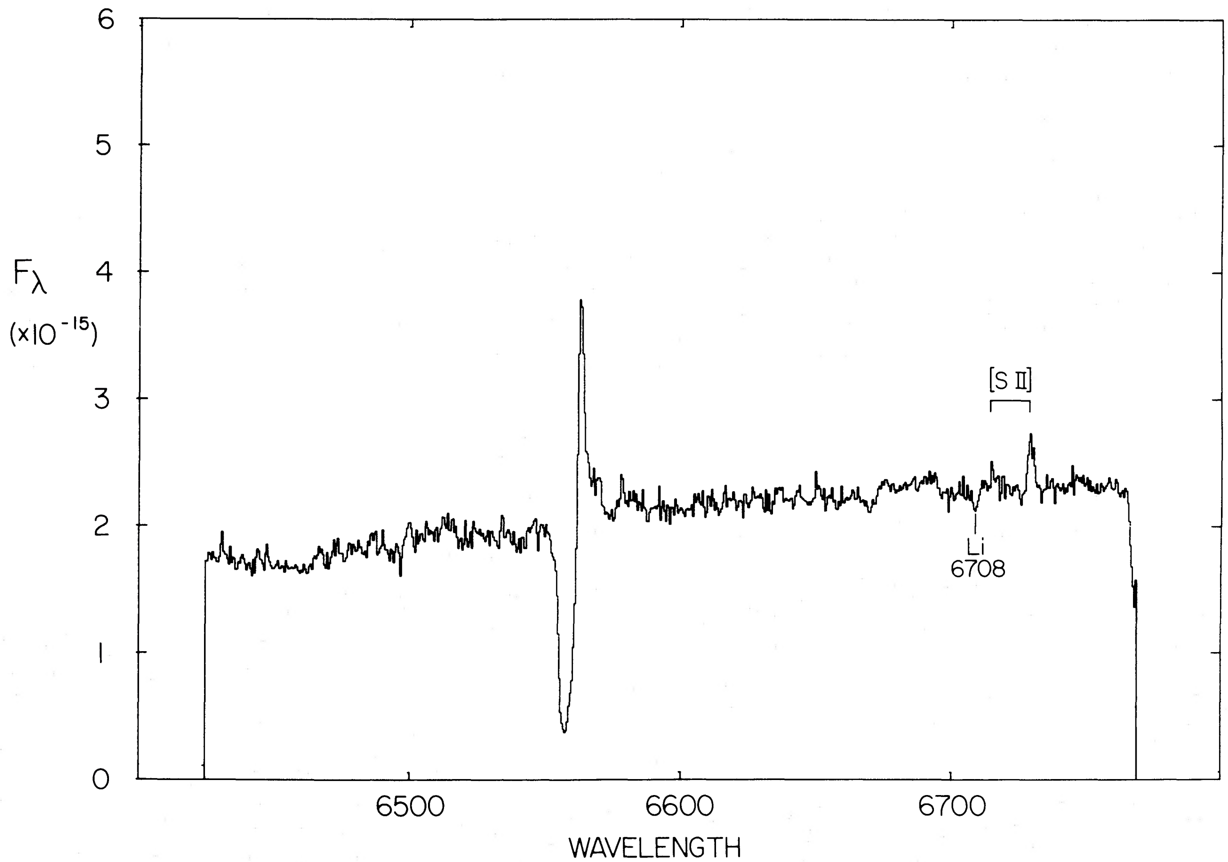

FIG. 5.—Scan of the λλ6450–6750 region in the HH 57 star. This scan was made on 1984 February 15. The CTIO 4 m telescope was used with Cassegrain spectrograph and a CCD detector at a resolution of 0.6 Å mm^{-1}. Note the Hα emission and strong violet-displaced P Cygni absorption.

Li I λ6708 is present but weak. On all three CCD scans which cover this region there is a slight dip in the continuum at this wavelength. In Figure 5 this is barely distinguishable from noise and corresponds to an equivalent width of 0.2 Å. The only other absorption lines seen in the three scans are those due to Ca I, Fe I, and possibly Ba II at λλ6493, 6495, 6496. An absorption-line spectrum of type F is consistent with the fragmentary data that we have to date. Lines which would be expected from a G or K type absorption spectrum are absent. The velocities measured from the image-tube spectrogram agree well with velocities measured from the CCD scan 6 nights later. On that scan, the Hα peaks at heliocentric velocity $+13$ km s^{-1}, while the half-intensity level of the violet edge of the Hα absorption feature is at -440 km s^{-1}. The [S II] lines λλ6713, 6731 in combination are about 25% of the strength of the Hα emission. On the 1984 February 15 scan, the λ6731 line is much the stronger of the two although the noise prevents an accurate determination of the ratio. The measurements are consistent with $F_\lambda(6716)/F_\lambda(6731)$ being close to 0.4, the high-density limit where collisional excitation and de-excitation dominate. Unlike the Hα emission peak, both [S II] lines are blueshifted and, on the 1984 February 15 scan, show a heliocentric velocity of -85 ± 5 km s^{-1}. This is significantly more negative than the velocity (-59 km s^{-1}) of the HH 57 knot (see Table 3) and may be indicative of new HH activity close to the surface of the star.

The character of the Hα feature evidently varies over a period of months. This is shown in Figure 6, where the region around Hα on three dates can be compared in detail. It should be emphasized that special care was taken to have the observing parameters as close as possible on these three nights in order to obtain the same spectral resolution. On 1983 May 24, the P Cygni absorption profile is significantly wider than on the two later dates, although the effective wavelength and central depth remain the same within measuring errors. The strength of the Hα emission was low on 1984 February 15, but by 1984 June 6 it has recovered to its former intensity. The velocity of the Hα peak stays effectively constant at near zero velocity. Quantitative data are given in Table 4.

The low-resolution spectral scan was made on 1983 October 17 with a 158 lines mm^{-1} grating which gave a resolution of 4.6 Å per pixel on the CCD. The continuum is very red, and, apart from the usual features contributed by Earth's atmosphere, only the Ca II lines, in *emission*, at λλ8498, 8542, 8662 are prominent in the stellar spectrum. This Ca II triplet was also seen in emission in V1057 Cyg by Herbig and Harlan (1971).

The equivalent widths of the Ca II lines in the HH 57 star are 3.3, 1.5, and 1.8 Å, with a continuum flux from the star of 3.0×10^{-15} ergs s^{-1} cm^{-1} Å^{-1}. In measuring the line intensities, no correction was made for the closely coincident Paschen lines at λλ8502, 8545, and 8665. However, the weakness of the λ8598 line shows that this must a negligible correction. Note that, as in T Tauri stars, the line ratios are unusual. Herbig and Soderblom (1980) point out that these lines are evidently saturated, and that the optically thick emission region is probably close to the stellar surface. With the 4.6 Å per pixel resolution, meaningful velocity measurements are not

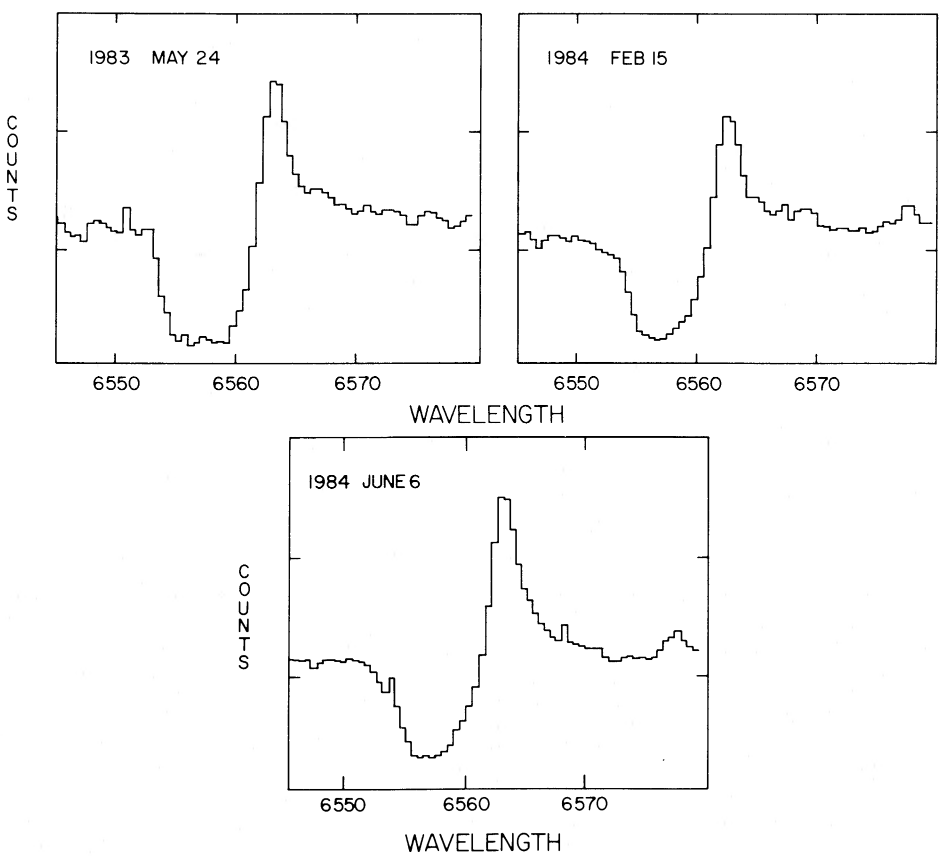

FIG. 6.—Comparison between Hα profiles taken 1983 May 24, 1984 February 15, and 1984 June 6. Counts are plotted against wavelength.

TABLE 4

CHANGES IN Hα ABSORPTION-EMISSION FEATURE

Parameter	1983 May 24	1984 Feb 15	1984 June 6
	Hα Emission		
Emission peak (continuum units)	1.00	0.83	1.17
Peak velocity (*hc*)	$+13$ km s^{-1}	-5 km s^{-1}	-6 km s^{-1}
Emission flux (ergs cm^{-2} s^{-1})	...	5.7×10^{-15}	9.5×10^{-15}
Equiv. width (Å)	3.2	2.8	3.7
	Hα Absorption		
Central depth (continuum units)	0.82	0.78	0.75
Central velocity (*hc*)	-265 km s^{-1}	-275 km s^{-1}	-271 km s^{-1}
Velocity width (FWHM)	340 km s^{-1}	280 km s^{-1}	270 km s^{-1}
Equiv. width (Å)	5.8	4.7	4.5

possible. The best we can say is that these Ca II velocities are within 30 km s^{-1} of zero, and that they do not have the high blueshifts associated with the [S II] emission lines or the Hα absorption feature.

V. DISTANCE AND ENERGY DISTRIBUTION

a) Distance to HH 57

HH 57 and its FU Orionis star are located within a dense, filamentary dust cloud, which extends about $2' \times 38'$ in position angle 107° as seen on the POSS print. The cloud is no. 187 in the catalog of Sandqvist (1977). It is a strong emitter of CO radiation and evidently contains a high concentration of molecular gas. The ^{12}CO line has a well-defined peak velocity near -7 km s^{-1}. The CO observations are discussed in detail by Alvarez *et al.* (1985). We can only approximately estimate its distance with data available at present. HH 57 is at $l^{\rm II}$ 338°.5, $b^{\rm II}$ + 2°.1,. It is quite close to the prominent concentration of OB stars known as Ara OB1, which also includes the open cluster NGC 6193. There is general agreement that the majority of these stars are at distance 1300 pc with an uncertainty of about 200 pc (Whiteoak 1963; Herbst and Havlen 1977). Inspection of the Southern Milky Way Atlas of Rodgers *et al.* (1960) shows that the HH 57 dust cloud is seen in front of this stellar concentration. We conclude that the maximum distance to HH 57 is 1300 pc.

At longitude 338°, galactic rotation causes a mild velocity gradient with distance. Using an Oort constant of 13 km s^{-1} kpc^{-1}, one would expect a velocity dependence $V = -9r$ with respect to the local standard of rest (r in kpc). Unfortunately, any effect is masked by the peculiar velocity of the cloud itself, which may amount to 7 km s^{-1} (Kerr 1968). The CO velocity of the cloud with respect to the local standard of rest is -3 km s^{-1}. Thus the component due to galactic rotation is probably between 0 and -10 km s^{-1}. An upper limit of 1100 pc is set by this datum. A similar limit is set by the small number of foreground stars in front of the dark nebula (Bok and Cordwell 1973).

Other rough estimates come from the measurement of V and B magnitudes for some of these stars. One such, marked as star A in Figure 1, has $V = 16.4$ mag, $B-V = 1.3$ mag. There are few fainter stars, and those at greater distance are obscured by the dust. Assuming the above star is a typical G dwarf with $M_V = +4.5$ mag, $B-V = 0.6$ mag, and correcting for foreground interstellar absorption with a ratio $A_V/E_{B-V} = 3.5$ (Herbst and Havlen 1977), it would be at a distance of 660 pc. Corresponding values for F0 and K0 dwarfs would be 1 kpc and 500 pc, respectively.

Cohen *et al.* (1984) suggest a distance, admittedly uncertain, of 200 pc. It is based on a possible connection with the clouds that extend into Lupus and the region of the variable star RV Lupi. From examination of the ESO-SERC J transparencies, we note that the Lupus clouds are both larger and more diffuse than the filamentary cloud associated with HH 57. A visual comparison, in fact, suggests that a scaling in angular diameter (and thus in distance) by a factor of 3 would make the HH 57 cloud and the Lupus clouds morphologically comparable. For the purposes of discussion, we adopt a distance of 700 pc, noting that it is uncertain to about 50% and could be improved by a more detailed analysis of the number and colors of foreground and background stars.

b) Energy Distribution

If it is assumed that the $B-V$ color of the FU Orionis star is typical for an F star reddened by normal interstellar dust (which can in part be circumstellar), a value of $E(B-V) = 2.0$ is estimated for the time period of the IR observations reported here. Note that this is greater than the reddenings determined for FU Ori itself or V1057 Cyg. This is partly due to the greater distance of HH 57 and the appreciable foreground reddening in this part of the Milky Way.

The energy distribution of the HH 57 star is similar but not identical to those of other FU Orionis objects. Figure 7 displays a selection of observations from Tables 1 and 2. Also shown are observations of other objects which are considered to be examples of the FU Orionis phenomenon. These data were normalized to the L datum for the HH 57 star. At 10 and 20 μm, the HH 57 star has a markedly bluer color (is hotter) than V1057 Cyg (data from Rieke, Lee, and Coyne 1972) but is only slightly hotter than object 12 in IC 5146 (Elias 1978). On the other hand, the HH 57 star is strongly redder from L to 10 μm than is the IC 5146 source, but it is not very different from V1057 Cyg. Shortward of L, the HH 57 star and object 12 in IC 5146 have similar energy distributions, whereas V1057 Cyg is bluer than either. Note in particular the huge energy difference at B and V between V1057 Cyg and the other two objects.

Models of the energy distributions of the few known exam-

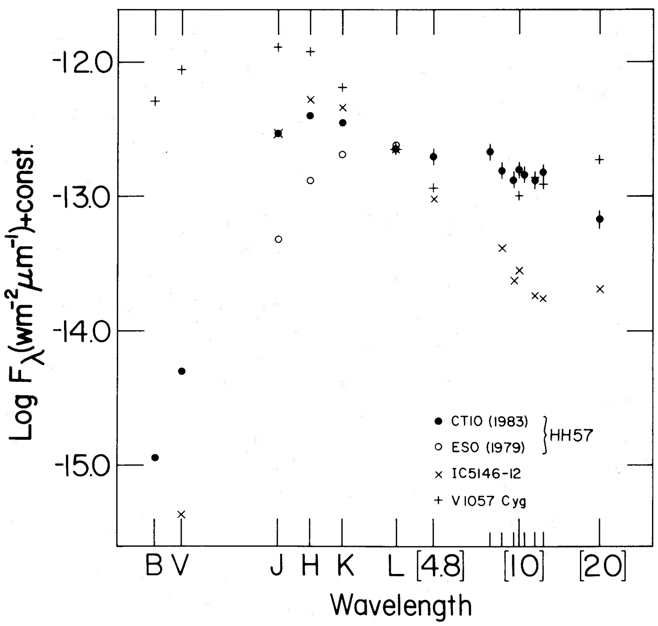

FIG. 7.—IR photometry of HH 57 star and of other FU Orionis stars. Data are normalized to the L datum point of the HH 57 star.

ples of FU Orionis objects have been formulated with some success by the use of three different components: a reddened luminous star of early spectral type (A to G) and hot and cold dust components (Rieke, Lee, and Coyne 1972; Elias 1978). If it is assumed that the reddening of the HH 57 star is by dust of normal (i.e., interstellar) composition, the dereddened energy distribution of Figure 7 is obtained. The reddening laws given by Cohen *et al.* (1981) and by Rieke and Lebofsky (1985) were combined to derive this energy distribution. In Figure 8, we show our attempt at modeling the energy distribution of the HH 57 star. A 6500 K blackbody (chosen as a simple representation of an F star spectrum) was fitted through the V point, and the predicted fluxes were subtracted from the J, H, and K points. The short lines extending downward from these points show the result of the subtraction. With assumed emissivity proportional to λ^{-1}, blackbody temperatures were calculated for adjacent pairs of points. These ranged from 2100 K for J-H to 1200 K for K-L and 250 K for 20-10 μm. It was impossible to fit more than two points with a single temperature. On the other hand, an emissivity independent of wavelength resulted in a simple model for the IR observations which consists of blackbodies at only two temperatures. A 2000 K blackbody chosen to fit the J and L points comes reasonably close to the H and K points as well. A 325 K blackbody was chosen to fit the 10 and 20 μm points. The sum of these two blackbodies provides an excellent fit to the 4.8 μm point and to the narrow-band filter observations in the 10 μm window as well. It is unlikely that dust grains can survive for any extended period of time at 2000 K. However, in view of the transitory nature of the phenomenon that we are observing and the possibility that the dust is being replenished (§ VI), we will adopt this model as an aid in calculating the luminosity of the two sources.

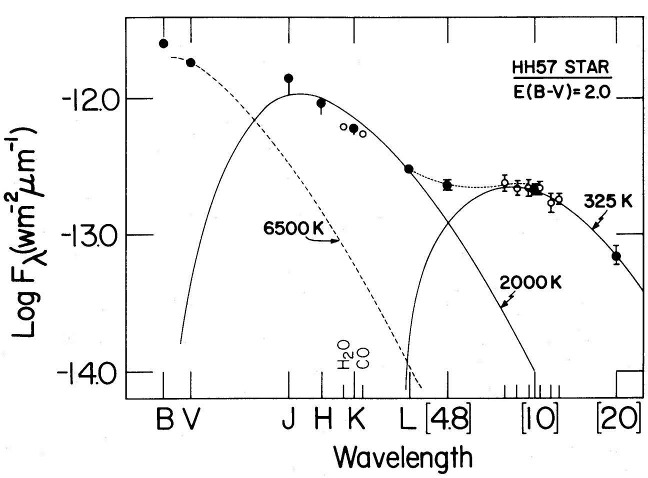

FIG. 8.—Suggested energy distribution for the HH 57 star. (See text for details of fitting procedure.)

Two important differences between the HH 57 star and other FU Orionis stars are evident in Figure 8. First, the HH 57 star shows no sign of any CO absorption at 2.3 μm. At 1.9 μm there is at most only weak absorption due to H_2O in the form of steam. Second, the dereddened narrow-band 10 μm observations do not reveal the presence of any emission or absorption features. Other FU Orionis stars display both strong CO and strong H_2O absorption (Cohen 1975; Elias 1978) and an emission feature at 10 μm (Cohen 1973; Rieke, Lee, and Coyne 1972). However, Elias (1978) does not see this emission feature in IC 5146, object 12.

Elias proposed that the hot blackbody component in the models for FU Orionis stars is not due to dust but rather to the presence of a late-type companion to the F star. Only at wavelengths longward of 5 μm does dust emission become important in his model. While this model is consistent with other FU Orionis objects, two characteristics which Elias cites in support of the binary hypothesis are not present in the HH 57 star, viz., the CO and H_2O absorptions, which are spectral signatures of cool stars in the 2.2 μm region, and variability. The ratio of the *JHKL* color changes in the HH 57 object between 1979 and 1983 is apparently inconsistent with just a simple reduction in reddening and flux changes to produce the flux constancy observed at L.

The radii and luminosities of the HH 57 model components can be easily calculated if we assume that the two dust components have spherical geometry and unit emissivity. For a distance of 700 pc, the resulting values are, for the 2000 K component, 0.23 AU and 37 $L_\odot$ and, for the 325 K component, 9.9 AU and 45 $L_\odot$. The combined M_{bol} is 0.0 mag. These results are summarized in Table 5. The F star component in Figure 8 contributes negligibly to the total flux. For spherical geometry, the calculated radius is inversely proportional to the

TABLE 5

TWO-COMPONENT MODEL

Parameter	Hot Component	Cool Component
T_e	2000 K	325 K
R (AU)	0.23	9.9
$L/L_\odot$	37	45
$L/L_\odot$ (far-IR)[a]	86	

NOTE.—A distance of 700 pc is used. Geometrical effects and changes caused by assuming different sensitivities are discussed in the text.

[a] This value is from Cohen *et al.* 1984, with a distance of 700 pc rather than the 200 pc which they used.

square root of the grain emissivity, so the tabulated values may be regarded as lower limits.

Contrary to the claim of Cohen *et al.* (1984), we find that inclusion of the far-IR data results only in a factor of 2 increase in the bolometric luminosity calculated above (see Table 5). The difference comes about, first, because a significant amount of power from HH 57 is being emitted shortward of 10 μm, and second, because our measured flux at 10 μm is 2.5 times greater than that determined by Cohen *et al.* (see § III). Our calculated luminosity for the HH 57 star is about 2 mag fainter in the 1–20 μm region than that obtained for V1057 Cyg, FU Ori, and IC 5146, object 12. Still, the sample is small, and discoveries of this type of object may be subject to selection effects. This difference presents yet another problem for the binary star hypothesis—$M_{\rm bol}$ is too faint to be consistent with an M giant. Indeed, the total luminosity is not consistent with a normal luminous star of the observed F spectral type, and much of the energy must be provided by stellar winds from the star or by expanding shells of the sort we are observing in the present eruption.

As an alternative to the binary star hypothesis, Mould *et al.* (1978) have suggested that the 6000 K and 2000 K components may come from different areas of a single pre–main-sequence star which is highly flattened through rapid rotation. The model has not been developed in detail, and, as they themselves point out, it probably cannot produce the required temperature range in every case. Like the binary star model, it runs into difficulty in the present case because spectral features characteristic of cool stars are not observed in the IR. If the F type spectrum is produced at the polar region of the star, we would expect to see in our optical spectra prominent features arising from intermediate latitudes which are characteristic of G and K type stars. On the whole, the model does not seem to be easily applicable to the FU Orionis star in HH 57.

VI. THE HH 57 STAR AND EARLY STELLAR EVOLUTION

FU Orionis stars and the HH 57 star in particular are rare examples of the earliest visible stages of stellar evolution. Evidence is accumulating that the circumstellar material associated with young stellar objects often has disklike geometry. The inclination of the disk may in turn determine a preferred direction for the stellar wind which energizes the HH object. We note that the position angle of HH 57 with respect to the FU Orionis star, 195°, is approximately perpendicular to the long axis of the molecular cloud. In our calculations in the previous section, the assumption of sphericity has the advantage of possessing basically only one free parameter, the radius. This quantity, together with the luminosity, can be calculated directly from the observations as we have done. For a disk, on the other hand, there are at least three parameters: outer radius, thickness, and inclination angle. Unlike the Cohen *et al.* (1984) data, our observations are still consistent with all the 1–20 μm flux arising from a point source since during the process of centering to make the IR measurement, we noted that the full width at half-power was the same ($\pm 0\farcs3$) at 2.2 and 10 μm as that of a standard star. We have no data of our own which can constrain a disk model for the dust distribution. Nevertheless, if such a model is applicable to the HH 57 star, the qualitative effects on the physical parameters of radius and total luminosity are clear. If the emitting region is a disk-shaped structure viewed nearly edge-on, most of the flux would be emitted perpendicular to the line of sight, and our estimate of the bolometric luminosity would be significantly underestimated. In addition, the radius of the disk would be bigger because of the need to have equal surface areas.

Some key observations which need explaining are the brightening of the star at visual wavelengths and the strong increase in brightness at JHK with no apparent change at L. An overestimate in the L flux in 1979 by about 20% combined with a slightly nonstandard reddening law for the circumstellar dust would just allow us to account for the changes in $JHKL$ by assuming a reduction of the reddening by an amount needed to explain the $B-V$ color of the F type star. Unfortunately we have no pre-1983 observations in the far-infrared to test this supposition. The spectroscopic characteristics of the star, on the other hand, do point to a recent outburst and appear to be changing intrinsically from year to year. Looking back toward the past, it is significant that the HH object, discovered in 1976, predates the recent flare-up, and that the HH object appears either as an emission region or as a reflection nebula on the POSS photograph taken in 1964. The optical flare-up that we are now observing may not be the first, and the star was present at least 15 years ago, although most likely in a quiescent state and hidden from view by enveloping dust clouds.

Every young star of approximately solar type may pass through the FU Orionis stage, and it is important to recall that such outbursts must have a profound effect on the residual dust in the vicinity of the star. Assuming that the high-temperature component observed in the IR is due to thermally heated dust, these dust grains are in the process of being rapidly transformed. In the case of V1057 Cyg, a similar situation, Rieke, Lee, and Coyne (1972) noted that many common granular substances, including silicates and graphite particles, are vaporized at the temperature of the hot IR component. Unless replaced, much of the dust will clear within a few years.

Herbig (1977, 1978, 1983) has pointed out that this observation may be relevant to the conditions under which planetary systems form. Within an astronomical unit of the star, all but the largest dust particles may be either vaporized or blown out by radiation pressure into the outer zone of the circumstellar dust envelope. Given the long time scales involved in stellar evolution, it is remarkable that such a key episode, one probably with far-reaching consequences, takes place over just a few years. Further observations will doubtlessly be rewarding, not only in helping us account for the FU Orionis phenomenon itself but, more fundamentally, perhaps, in deepening our understanding of the way that planetary systems may come into being in the natural course of cosmic evolution.

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