THE ASTROPHYSICAL JOURNAL, 217:693–715, 1977 November 1

ERUPTIVE PHENOMENA IN EARLY STELLAR EVOLUTION*†

G. H. HERBIG
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz
Received 1977 February 22; accepted 1977 April 25

ABSTRACT

The second and third members of the FU Ori class have now been discovered: V1057 Cyg reached maximum in 1970 after a rise time of about 390^{d}, and has since declined by 1.7 mag (pg) in 6 years. V1515 Cyg has risen very much more slowly from mag 17, requiring at least 12 years (or possibly more than 27) to brighten the last 2 mag. FU Ori itself has since 1960 faded very slightly, by about 0.2 mag (in *B*). All the spectra are much alike: F or G supergiants having wide absorption lines, P Cygni structure at Hα, displaced shell components, and strong Li I λ6707. Much detailed information is now available for V1057 Cyg, which is definitely known to have been a T Tau star before its outburst. The 5.5 mag brightening was due to a large rise in surface brightness and a moderate increase in radius. This took place rather slowly, but several high-velocity shells were apparently also ejected. Some of the spectral peculiarities can be understood qualitatively if the observable part of the stellar atmosphere is very thick, with a depth-dependent velocity of expansion that disappeared in a few years after the outburst. In all three cases, their radial velocities show that the stars share the motion of the molecular clouds upon which they are projected. Similarly, all three stars have strong infrared excesses and are attached to arc-shaped reflection nebulae which became visible when the stars brightened. The observed frequency of three eruptions in about 80 years, together with the known number of T Tau stars of that luminosity in the nearer associations, indicates that unless there is some fundamental misunderstanding of the situation, FU Ori-type eruptions are repetitive and recur in the average T Tau star after roughly 10^4 years. There is a speculative possibility that similar activity on a minor but more frequent level occurs in a few peculiar T Tau stars, as might be expected if the phenomenon decays as the star ages. The cause of the outbursts remains unknown, but the fact that they represent an activity intrinsic to the star shows that shell-clearing hypotheses at least are untenable.

Subject headings: nebulae: general — stars: evolution — stars: pre–main-sequence — stars: variables

I. INTRODUCTION

About a decade ago it was argued that the 1936–1937 flare-up of FU Ori represented not a nova outburst but rather a phenomenon of early stellar evolution (Herbig 1966). However, because only one such event had been observed, because FU Ori remained near maximum light with little change, and because nothing was known of the preoutburst state of the star, further progress seemed blocked. In 1970, however, a second example of the phenomenon was recognized when V1057 Cyg rose to maximum light; and in 1974 a third case, V1515 Cyg, was discovered. A great deal of new observational information is now available, on V1057 Cyg in particular, and it is the purpose of this paper to discuss the optical material now on hand and to offer some tentative ideas upon the nature and frequency of this phenomenon.

II. FU ORIONIS

The history and spectrum of FU Ori has already been discussed (Herbig 1966), and although one important characteristic of the star—its infrared excess—was discovered subsequently, that as well as some other of its properties will be considered later in connection with V1057 Cyg (§ III) or in the general discussion (§ V). At this point, only the star's more recent photometric behavior and new evidence on its association with interstellar matter will be described.

Figure 1 shows the photographic/*B* light curve of FU Ori from 1936 to the present, compiled from all available sources (identified in the legend). The sudden fading about 2 years following initial rise, and a slow oscillation that had disappeared by 1960, are apparent. Since that time, there has been a slow but definite fading of about 0.2 mag (in *B*) in 15 years.

No spectrograms of adequate dispersion to resolve the line splitting ($\Delta v = 80$ km s^{-1}) in the blue have been obtained at Lick since 1963 (Herbig 1966); at lower resolutions, the spectrum is a confused mix of star and shell lines. A 1976 Mauna Kea plate shows that this "composite" spectrum appears approximately as on the last Lick spectrogram. The sharp, longward emissions in H and K remain strong. In the red, a 34 Å mm^{-1} Lick coudé spectrogram of 1975 August showed the strong Na I D_{12} absorptions at a displacement of -98 km s^{-1}, while on plates of

* The Henry Norris Russell Lecture of the American Astronomical Society, given in Chicago, Illinois, on 1975 December 8 before the 147th Meeting of the Society.

† *Lick Observatory Bulletin*, No. 763.

1977ApJ...217..693H

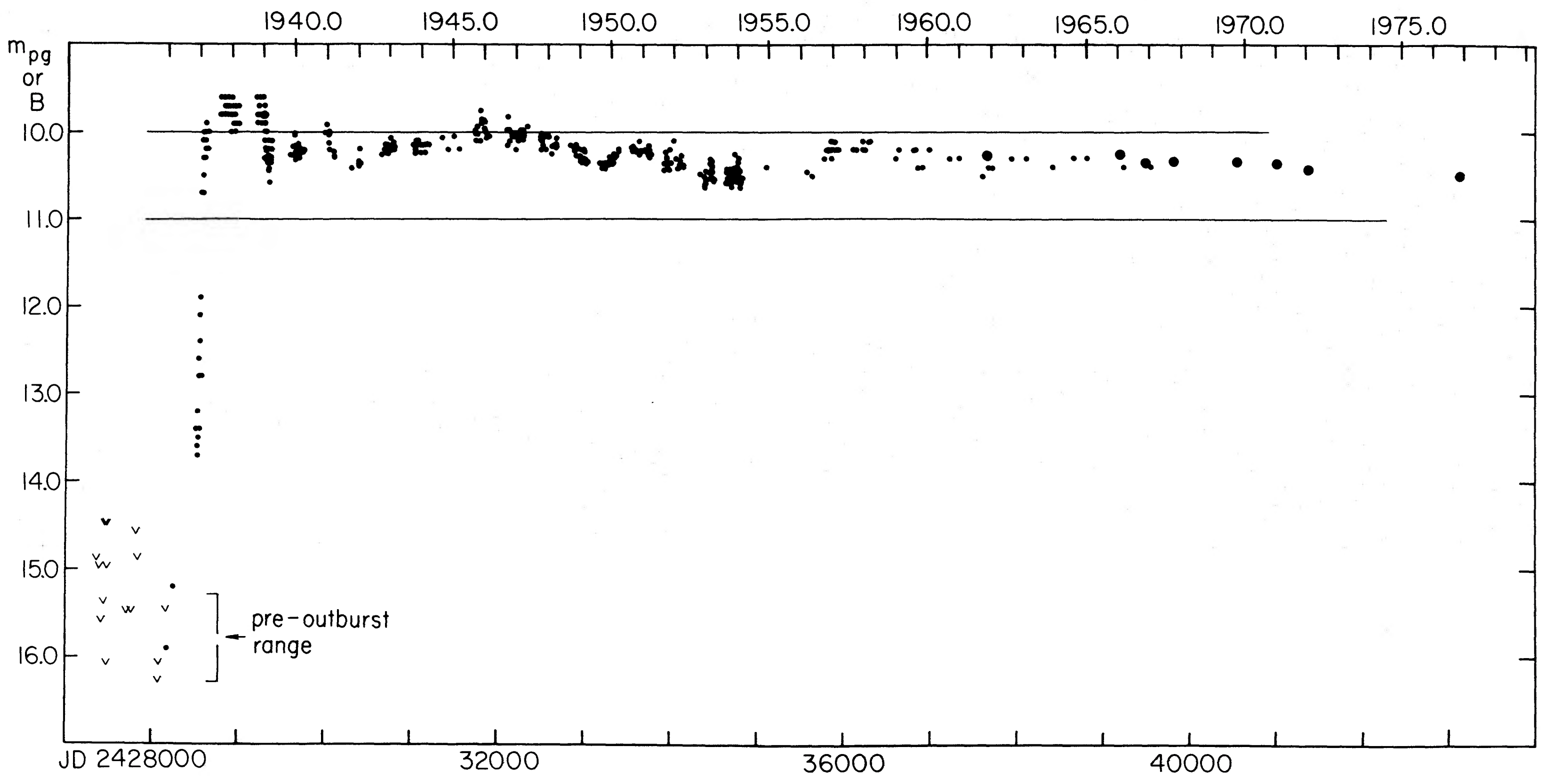

FIG. 1.—The photographic/*B* light curve of FU Ori through 1976. Small points represent photographic observations by Hoffleit (1939), Wachmann (1954), and Weber (1956, 1961, 1964, 1967). The larger points are photoelectric measures of *B* by Smak (Herbig 1966), Mendoza (1968), Dibai and Zaitseva (1968), Lee (1970), Lee and Low as quoted by Rieke *et al.* (1972), Landolt (1972), Schweitzer (1975, private communication), and Stone (unpublished).

TABLE 1

RADIAL VELOCITIES OF FU ORIONIS AND OF THE ASSOCIATED INTERSTELLAR MATERIAL

Source	$v_{\odot} \pm \sigma_v$ (km s^{-1})	Reference
Star:		
3 16 Å mm^{-1} spectrograms, 1962–63	+30 ± 2	Herbig 1966
3 34 Å mm^{-1} spectrograms, 1975–76	+27 ± 3	This paper
Cloud:		
Hα in λ Ori H II region (S264)	+23.8 ± 8	Georgelin and Georgelin 1970
Hα in bright rim, B35	+27.5 ± 1.5	Hippelein 1976, private communication
CO emission, B35	+28	Lo 1975, private communication
CO emission, B35	+27.9 ± 0.1	Lada 1976, private communication

1975 December and 1976 August they were at −76 km s^{-1}. On the same spectrograms, the powerful absorption at Hα, fringed on occasion by longward emission, moved from −165 to −110 km s^{-1}. It is apparent that although FU Ori is now photometrically quiescent, there are still short-term changes taking place in its shell structure.

The radial velocity of FU Ori was measured on these three red-region spectrograms, using lines uncontaminated by shell components and with empirical wavelengths established by F–G supergiant velocity standards observed with the same equipment. The individual plate velocities, based on 9–12 lines per plate, showed somewhat more scatter than expected at this resolution, perhaps because of the rather wide stellar lines. The mean velocity is given in Table 1, together with radial velocities from the radiofrequency CO lines in the dark cloud B35 which contains FU Ori, from the Hα emission line in the H II region S264 which surrounds B35, and from Hα in the bright western edge of B35. Within the uncertainties, FU Ori shares the radial velocity of the neighboring interstellar matter. It will be shown later that V1057 and V1515 Cyg have similarly close kinetic associations with cloud material.

III. V1057 CYGNI

a) *Early History*

V1057 Cyg lies in a very dense dust pocket in the H II region NGC 7000. It was first noted as one of the many emission-Hα stars in the area (Herbig 1958; Haro 1971). Light variations were subsequently discovered by Wenzel (1963), and confirmed by Robinson and Harwood (1971), Welin (1971*b*), Filin (1974), and Mandel (1975*a*, *b*). No periodicity was apparent; the extreme range reported was $m_{pg} = 14.7$ to 16.4. At this time the star was rather red: Haro (1972) estimated that $R - I = +1.8$ in 1965, while the shift between Mandel's photographic and photovisual light curves corresponds to an average color index of about +2 mag. The only information on the premaximum spectrum of V1057 Cyg comes from a single Lick 430 Å mm^{-1} spectrogram obtained in 1957 (Herbig 1958), which showed Balmer, Ca II, Fe I, Fe II emission lines typical of a T Tau star. The slope of the continuum was like a late-type star, but no absorption lines were visible and no type could be assigned. This spectrogram is shown in Figure 2 (Plate 5).

About 1969.6, V1057 Cyg began to brighten and reached maximum at about $m_{pg} = 10.5$ on 1970.7. On some magnitude systems, the peak was 0.2–0.3 mag brighter than this value. The photographic/*B* light curve, compiled from all available observations, is shown in Figure 3. There is some indication that there was a change of slope on the rise, in that the star brightened more rapidly before it reached $m_{pg} = 12$ than afterward. The total rise time was about 390 days. The slow postmaximum decline has been smooth, with no sign of the abrupt drop of about 1 mag shown by FU Ori two years after its initial rise (Fig. 1). The fading of V1057 Cyg has been at the average rate of $\Delta m_{pg} = 1.7$ in 6 years.

The 1970 brightening of V1057 Cyg was discovered by Welin (1971*a*), and the announcement circulated about 4 months after the star had passed through maximum. A few observations were made at Lick almost immediately but the star was then nearly in conjunction with the Sun, and spectroscopy could not begin in earnest until 1971 April. It is therefore of some importance to derive what information one can from the earlier spectrograms.

b) *Spectral Classification*

The first spectrogram known to have been obtained after the eruption was under way was that by Welin in 1970 September, very nearly at maximum light. Dr. Welin has very kindly furnished a copy of this unique objective-prism plate, which is shown in Figure 2 together with the Lick 1957 preoutburst spectrogram. Clearly the spectra of V1057 Cyg at minimum and maximum were quite different: the cool continuum with T Tau-type emission lines had been replaced by a hotter spectrum showing only Balmer absorptions. There is some disagreement about the spectral type on Welin's plate. He classified it tentatively as B3, although early A would be equally acceptable because He I is not present and Ca II λ3933 is weak. At the bottom of Figure 2 is another low-dispersion spectrogram obtained at Lick about 4½ months following Welin's; this exposure was taken by Mr. E. A. Harlan just following the receipt of Welin's announcement, when the star was almost lost in the west (low in the lights of the Santa Clara Valley: note

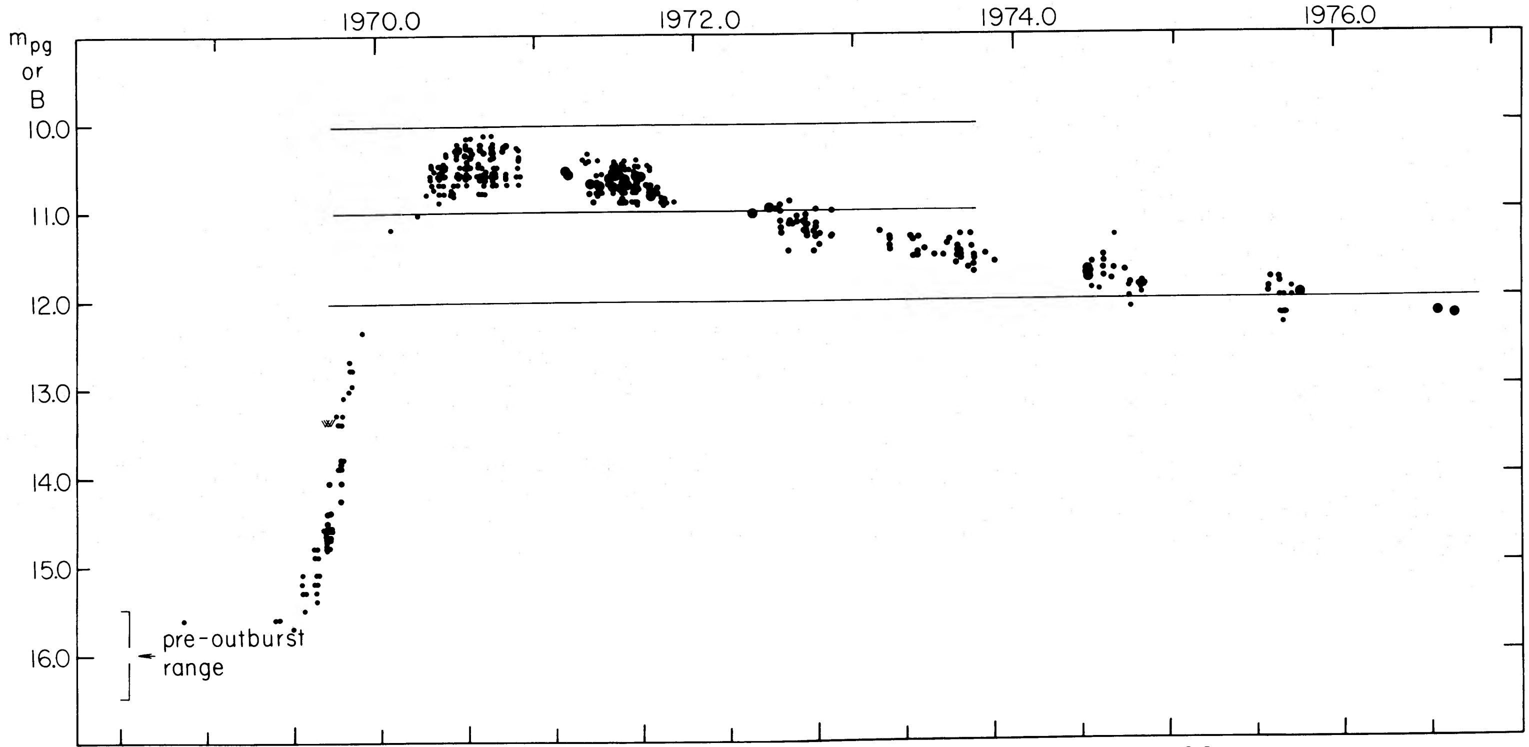

FIG. 3.—The photographic/*B* light curve of V1057 Cyg through 1976, compiled largely from published sources. The small points are photographic observations by Meinunger and Wenzel (1971), Gieseking (1973, 1974), Filin (1974), Landolt (1975), Mandel (1975*a*, *b*), Hoffleit (1975, private communication), and Tsvetkov (1976). The larger points are photoelectric B measurements by Mendoza (1971), Rieke *et al.* (1972), Schwartz and Snow (1972), Bossen (1972), Landolt (1975), and unpublished measures by P. Pesch, L. Cathey, and R. Stone.

the very strong Hg I lines). The spectrum of V1057 Cyg appears essentially the same on this as on Welin's exposure: the type has not changed significantly in those $4\frac{1}{2}$ months. The first Lick coudé spectrogram was taken just $1\frac{1}{2}$ months later, in 1971 March. It in turn looks very much the same, and on that plate the type is certainly not B3. If the earliest coudé plates are classified in the conventional way, using the Balmer lines and metallic lines too weak to be seen at the resolutions of Figure 2, then the type is early A and of fairly high luminosity. In other words, there is no evidence that the type changed significantly between 1970 September and 1971 March, so the tentative classification of B3 for 1970 September is best disregarded.

TABLE 2A

LICK SPECTROGRAMS OF V1057 CYGNI

Plate	Date (UT)	Disp. (Å mm^{-1})	Central λ	Note
CS-5771...	1971 Jan. 21	350	3950	1
5772...	1971 Jan. 23	350	3950	1
EC-9290...	1971 Feb. 10	34	6300	
9380...	1971 Mar. 8	48	4300	1
9405...	1971 Apr. 8	48	4300	3
9410...	1971 Apr. 13	34	6300	
9411...	1971 Apr. 13	34	8200	
9414...	1971 Apr. 15	34	6500	3
LS-44522...	1971 May 9	75	4340	1
44525...	1971 May 11	75	4340	1
44529...	1971 May 16	130	4340	1
EC-9740...	1971 May 16	34	6400	
9471...	1971 May 16	34	8300	
9472...	1971 May 16	34	6100	
9499...	1971 June 5	16	4200	2
9504...	1971 June 6	16	4200	2
9591...	1971 June 29	16	4000	
9702...	1971 July 27	16	4200	2
9707...	1971 July 28	16	4000	
9864...	1971 Sep. 7	16	4200	2
10043...	1971 Nov. 8	34	6500	3
10256...	1972 Mar. 4	34	6350	
10294...	1972 Mar. 6	17	5900	
10295...	1972 Mar. 6	34	8200	
10454...	1972 May 24	16	4200	2
10668...	1972 June 27	16	4000	
10700...	1972 July 22	34	6350	
10713...	1972 July 23	34	8200	
10714...	1972 July 23	34	6350	
10957...	1972 Sep. 22	16	4000	
11379...	1973 Mar. 24	34	6350	
11406...	1973 Apr. 22	16	4050	1
11505...	1973 July 14	40	4000	3
11632...	1973 Aug. 13	34	6350	
11659...	1973 Aug. 15	16	4000	
12022...	1973 Dec. 9	11	6560	
12392...	1974 June 4	34	6350	
12627...	1974 Aug. 29	34	8200	
12628...	1974 Aug. 29	34	6300	
12629...	1974 Aug. 29	11	6560	
13195...	1975 Apr. 29	34	6300	
13451...	1975 Aug. 16	34	6300	
13661...	1975 Oct. 28	34	6350	
13662...	1975 Oct. 28	17	5800	
13663...	1975 Oct. 28	11	6560	
13674...	1975 Nov. 14	34	6350	

NOTES TO TABLE 2A

1) Plate taken by E. A. Harlan.
2) Plate taken by L. V. Kuhi.
3) Plate taken by R. P. Kraft.
4) The plate prefixes have the following meanings. CS, Crossley reflector, nebular spectrograph. LS, 36 inch refractor. EC, 120 inch coudé spectrograph. All the latter spectrograms except those centered at 4000–4300 Å were obtained with 40 mm image intensifiers.

The coudé plates show, however, that classification at such low dispersion is of limited significance because the Balmer and Ca II lines have complex and variable structures. Table 2 lists all the Lick spectrograms of V1057 Cyg obtained to date, together with radial velocities and other data. The 16 Å mm^{-1} series covering the photographic region are the most instructive, but they span only the years 1971–1973, after which the star became too faint. The 3900–4000 Å region on a number of these spectrograms is shown in Figure 4 (Plate 6). The metallic lines were not sharp; expressed as an axial rotation, their widths corresponded to about $v \sin i = 70$ km s^{-1}. As the star faded, the increasing complexity of the metallic-line spectrum in Figure 4 is apparent (the Ca II line structure will be discussed later), and corresponds to a progressive change in spectral type from A3–5 II to early F, II or III over these 2 years, if H and Ca II are ignored. In finer detail, however, the spectrum does not match these compromise types: a number of temperature-sensitive line ratios are discrepant. Such inconsistencies are encountered in the F-type spectrum of FU Ori also. It is not surprising that the spectra of these eruptive objects are peculiar in detail.

One unexpected feature is that the spectral types of V1057 Cyg in the 3900–4300 Å region are systematically earlier than those determined from 6000–6600 Å lines. The 120 inch (3 m) 34 Å mm^{-1} coudé plates covering the yellow-red in 1971–1973 concur with the blue in indicating a cooling of the star, but from about F5 II to G0 Ib. Subsequently, in 1974 and 1975 during which time no blue spectrograms were taken, the type in the red continued to change slowly, to G2–5 and luminosity class Ib or II. Unfortunately the features available in the 8000 Å region are not sufficiently temperature-sensitive to establish whether this trend continues to still longer wavelengths, but the fact that Shanin, Shevchenko, and Shcherbakov (1975) estimated the type as about F5 in the 1.0 μm region in 1974 suggests that it does not.

c) *Radial Velocities and Line Structure*

Another manifestation of the same effect seems to be present in the radial velocities. In Figure 5 are plotted against time the velocities measured from unblended metallic lines in the 3800–4400 Å region, and between 6000 and 6600 Å. Lines of H, Ca II, and Na I have been excluded. In the blue, the first spectrograms of 1971 March and April showed a large negative velocity, -40 to -50 km s^{-1}, which through the 1971 season relaxed to -20 km s^{-1}, probably declined further from -18 to -14 km s^{-1} in 1972, and was at -13 km s^{-1} on the single 16 Å mm^{-1} blue spectrogram of 1973. During this entire episode and in 1974–1975 the red region showed only a scatter around an average of -15 km s^{-1}. In the red during 1971

TABLE 2B

Data from Spectrograms of the 5800–6700 Å Region

Plate	Red Spectral Type	Metallic Lines v	Metallic Lines n	Metallic Lines σ_v	Radial Velocities (km s^{-1}) Hα Em.*	Radial Velocities (km s^{-1}) Hα Abs.	Na I λλ5889, 5895	
EC-9290......	F5 II	−18	9	4	−34	−558	−32:	...
9410......	F5: II	−26	10	4	(−54)	−474	−38	−156
9414......	...	−10	7	4	−25	−457		†
9470......	F5 II	−18	13	3	−38	−369, −517	−27	...
9472......	...	−9	11	2		†	−28	...
10043‡.....	F5 II	−30	11	2	−41	−370	−50	...
10256......	F7: II	−18	10	3	−31	−281	−26	−284
10294......	...	−13	2	–		†	−23	...
10700......	F5–G0 II	−10	10	3	−31	−274, −357	−10	−200
10714......	F8–G0 Ib, II	−17	12	2	(−35)	−277, −355	−22	−199
11379......	G0 Ib	−15	13	2	−20	−246	−23	−189
11632......	G0 Ib	−11	16	2	−17	−285	−17	−173
12022......	...	−16	2	–	−15	−229, −318		‡
12392......	G0 Ib	−9	13	2	(−7)	−285	−11	−125:
12628......	G0–2 Ib	−12	11	2	−21	−266	−13	−169
12629......	...	−17	3	–	−14	−244		†
13195......	G5 Ib	−10	15	2	−17	−157, −350	−17:	p
13451......	G2–5 Ib, II	−13	13	2	−17	−277	−16	−116
13661......	G2–5 Ib, II	−16	12	2	−24	−213, −383§		†
13662......	...		...			†	−11	−128, −185§
13663......	...		...		−19	−211, −371§		†
13674......	G2–5 Ib, II	−6	13	2	−9	−227	−9	−143:

* The displacement given is of the point of peak intensity in the emission line. The velocity is in parentheses when the center of gravity of the whole line was measured instead.

† The feature was either off the plate or outside the region of good definition.

‡ The comparison spectrum is overexposed, which may account for the somewhat discrepant velocities from this spectrogram.

§ The component of lesser displacement is the stronger.

Note.—v is the mean velocity from n lines, and σ_v is the standard deviation of v, from internal agreement.

TABLE 2C

Data from Spectrograms of the 3800–4800 Å Region

Plate	Blue Spectral Type*	Metallic Lines v	Metallic Lines n	Metallic Lines σ_v	Radial Velocities (km s^{-1}) Balmer Cores v	Radial Velocities (km s^{-1}) Balmer Cores n	Ca II Absorption Components			
EC-9380......	An	−52:	6	7	−89:	3		Unresolved		
9405......	An	−40:	2	...	−67:	5		Unresolved		
9499......	A3–5 II	−26	12	3	−69	3	−18	−99	−209	p
9504......	A3–5 II	−30	13	2	−68	2	−17	−102	−212	−304
9591......	A5 II	−26	32	1	−71	2†	−15	−105	−206	−368
9702......	A2: II	−26	20	2	−26	5	−16	−107	−208	−311
9707......	A5 II	−29	23	2	−55	5‡	−18	−107	−210	−311
9864......	A5 II	−20	12	3	−54	5	−15:	−105	−197	−288
10454......	A5–F0 II	−18	12	3	−68:	3	−20:	−154:		−276:
10668......	A7–F1 II	−16	26	1	−41:	2	−29	−168		...
10957......	A7–F1 II	−13	19	1	−38	2		Underexposed		
11406......	...	−16:	6	4	−26:	2		Underexposed		
11659......	F0–3 II, III	−13	17	2	−27:	5		Underexposed		

* These types are not of high accuracy. The spectrum is difficult to classify, and in detail there are a number of conflicts and inconsistencies.

† Absorption components were present in Hβ, Hγ, Hδ at −366 km s^{-1}, which corresponds to the displacement of the Ca II features at −368 km s^{-1}. These velocities were measured on only this plate.

‡ A component of Hβ was present at −296 km s^{-1}.

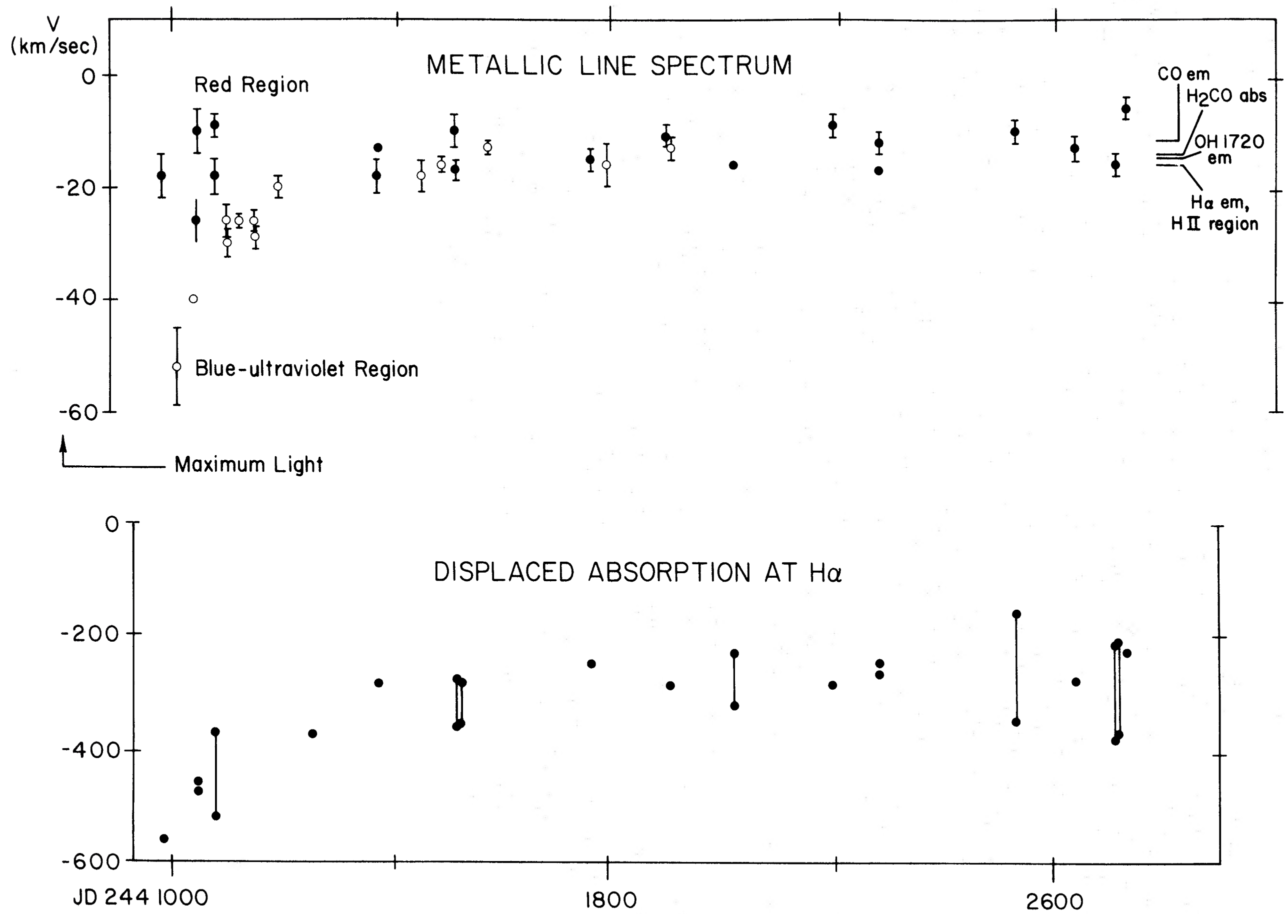

FIG. 5.—*Upper panel*, radial velocities from the metallic-line spectrum of V1057 Cyg in the blue-ultraviolet (*open circles*) and in red (*filled circles*) during 1971–1975. The error bars indicate $\pm 1\ \sigma$, from internal agreement. By 1973, when the 16 Å mm^{-1} series ceased, the large negative shift of the blue-region lines in 1971 had come into essential agreement with the stellar velocity of about -13 km s^{-1}. The red-region velocities showed no clear departure from a mean of about -15 km s^{-1} during the entire episode. The interstellar velocities (from Table 3) are indicated on the right. *Lower panel*, the decrease of the displacement of the P Cyg absorption component of Hα following maximum (note the velocity scale differs from that in the upper panel). Bars connect velocities measured when the line was resolvable into two components.

there was no sign of the large negative velocities measured in the blue. The P Cygni absorption component of Hα did decline from -560 km s^{-1} on the first plate of 1971 February to an asymptote of about -220 km s^{-1} in 1975 (Fig. 5 and Fig. 6 [Pl. 7]), but this was on a velocity scale entirely different from that in the blue. The velocity of -13 to -15 km s^{-1} at which the metallic line velocities stabilized must be identified with the velocity of the H II region and molecular cloud upon which V1057 Cyg is projected. A number of independent determinations of that velocity are listed in Table 3. As for ordinary T Tau stars (Herbig 1977), the close kinematic relationship between V1057 Cyg and the surrounding interstellar material is beyond question.

Presumably this wavelength dependence of radial velocity and of spectral type is due to stratification in a deep envelope, in which one sees to depths that depend upon wavelength and line strength. Unfortunately, the Lick spectrograms do not permit determination of velocity from lines below the Balmer limit, which would provide a test of the role played by the continuous opacity in this phenomenon.

The velocity structure of the ejected material is best seen in the H, K lines. The reason that this absorption structure is visible at all against the Ca II line of an A5 star is that through the 1971 season the stellar line was filled approximately to the continuum level by a broad emission feature: see Figure 4. These wide emissions in H, K disappeared during the seasonal gap between 1971 September and 1972 May. Consequently only the gross Ca II shell structure was measurable against the stellar line in 1972, and not at all thereafter.[1] On the exposures of Figure 4, the strongest Ca II absorption component remains at about -210 km s^{-1} through 1971. The next strongest is also of constant

[1] Emission components were present in the infrared Ca II triplet through 1971 and early 1972. They were weaker later in 1972, and had in effect disappeared by 1974, as noted by Shanin, Shevchenko, and Shcherbakov (1975).

TABLE 3

INTERSTELLAR CLOUD VELOCITIES NEAR V1057 CYGNI

Source	$v_{\odot}$ (km s^{-1})	Reference
Transient 1720 MHz OH maser emission.....	−14.6	Lo and Bechis 1974
CO cloud emission..........................	−11.8	Bechis and Lo 1975
H_2CO cloud absorption....................	−14.4	Lo (Bechis and Lo 1975), Minn and Greenberg 1973
Hα emission, NGC 7000....................	−16	Hippelein 1973

velocity, −105 km s^{-1}. A weaker component was measured near −310 km s^{-1} on most of these spectrograms, although on one plate (that of 1971 June 29) it was broader and stronger and shifted to −368 km s^{-1}. In 1972, against the depressed background of the star line, only a single wide component near −160 km s^{-1} could be measured. This was probably a blend of the −105 and −210 km s^{-1} components. On all the 16 Å mm^{-1} plates, narrow features were also present at −16 km s^{-1}. These must be the interstellar Ca II lines, which in bright stars in this area have been measured by Adams (1949) near velocities of about −14 km s^{-1}.[2]

The Ca II components at −210 and −310 km s^{-1} probably correspond to minima at about −230 and −320 km s^{-1} that were measured in the Hα line on an 11 Å mm^{-1} spectrogram of late 1973. This duplicity of the P Cygni absorption at Hα was consistently detectable on only the better high-dispersion plates; the entries in Table 2b usually refer to the blend. The measurements by Kolotilov (1975) of the structure of Hα on five spectrograms in 1974 seem compatible with the Lick data.

The Na I D_{12} lines showed only a single displaced component which appeared early in 1972 and remained near −150 km s^{-1} through 1973–1975; this could be a blend of the Ca II components at −105 and −210 km s^{-1}. No component was ever measured in Hα that corresponded to the Ca II line at −105 km s^{-1}. To summarize, during the 2 years following maximum there were three well-defined expanding shells: a low-excitation one near −105 km s^{-1} seen only in Na I and Ca II; one of medium excitation near −210 km s^{-1} shown by H, Na I, and Ca II; and a higher excitation shell near −310 km s^{-1} seen strongly in H, weakly in Ca II, and not at all in Na I. The early decline in the shortward shift of the Hα absorption was probably due to the fading out of one or more absorption systems at even larger displacement. Such a component at −517 km s^{-1} can be seen on the third spectrogram of Figure 6. Judging from the continuing presence of the displaced although usually unresolved Hα and Na I structure, the three shells of lesser velocity still existed through 1975. If they were ejected at the beginning of the rise to maximum light, that material must by then have expanded to distances of 100–330 AU from the star.[3]

The velocity of the P Cygni *emission* component at Hα followed the pattern of the whole blue absorption spectrum: it was negatively shifted in 1971 and later assumed a mean velocity near −20 km s^{-1}, not significantly different from that of the star. The broad emissions in H, K in 1971 were too poorly defined for velocity measurement, but there is some indication that the infrared Ca II emission lines also showed a positive drift through 1971–1972, before they disappeared. The O I λ8446 line was also present in emission at that time; like the Ca II and Hα emission, it moved slowly longward during the time it was measurable.

On the 1971 spectrograms covering the photographic region, the only emission lines observed were those in H and K, but Hα was a strong emission line whose absorption component fluctuated in strength as the emission faded: see the stack of spectrograms in Figure 6. A few early plates showed shortward absorption components at the higher Balmer lines having the same displacement as at Hα, but the main lines remained in absorption. Their cores, however, always showed a persistent shortward shift with respect to the metallic lines in the blue, by an amount which decreased from about −40 km s^{-1} in 1971 to −15 km s^{-1} in 1973.

An interesting postmaximum phenomenon that had been observed in FU Ori was the appearance and strengthening of rather narrow emission components longward of the centers of the H, K lines (Herbig 1966). First detected 11 years past maximum light, they are now quite strong. The same features have now appeared in V1057 Cyg. They were detected, in fair strength, on a 27 Å mm^{-1} Mauna Kea plate taken in 1976, 6 years past maximum, and were discovered independently at about the same time by Welin (1976). They might have been detectable earlier, but no adequate spectrograms were obtained at Lick in 1973–1975. In FU Ori at 16 Å mm^{-1} the features are seen to be asymmetric, the shortward edges being obliterated by overlying Ca II absorption of the shortward-shifted shell. The similar longward shift of the emission in V1057 Cyg may mean that that star has now developed a similar shell, which in FU Ori

[2] It is this mass of unresolved Ca II structure that appears as a weak K line on the early low-dispersion spectrograms in Fig. 2.

[3] Displaced components at velocities up to −300 km s^{-1} are observed in T Tau stars (Herbig 1977), and indeed there was indirect evidence for such structure in the Balmer lines of V1057 Cyg at minimum (§ VI). The possibility cannot be excluded that some of these shells predate the 1970 eruption. The changes of the P Cygni absorption at Hα (Fig. 6), however, suggest rather some connection with the outburst.

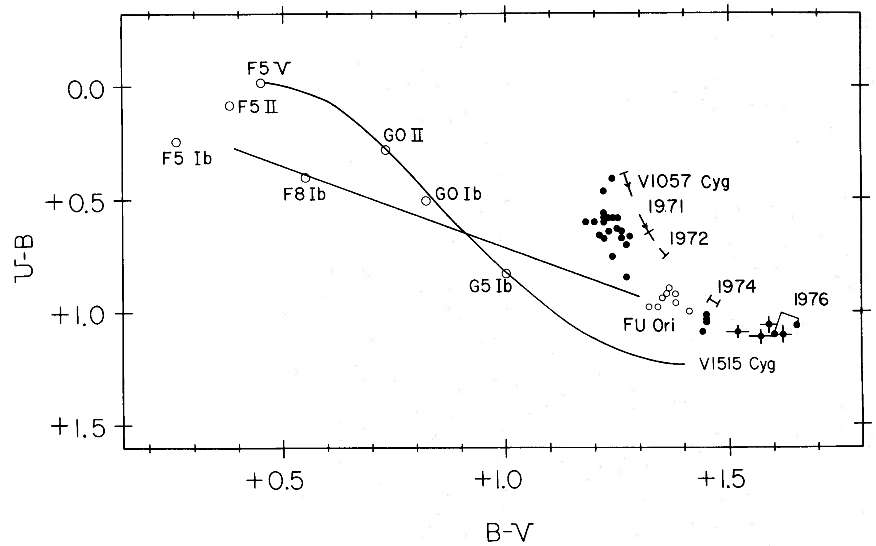

FIG. 7.—FU Ori and V1515 Cyg in the two-color diagram, and the migration of V1057 Cyg between 1971 and 1976. The data for FU Ori and V1057 Cyg are from the sources cited in Figs. 1 and 3, while those for V1515 Cyg are Stone's observations (Table 7). The sinuous line is the main sequence $U - B$, $B - V$ relationship. The straight line is a conventional reddening path from the region of normal colors corresponding to the 1975–1976 red spectral types of these stars. The peculiar position of V1057 Cyg in 1971 and 1972 is believed to be caused by its abnormally bright blue-ultraviolet. Even though the color *difference* between blue and red persisted as the star cooled, in later years both the corresponding colors lay near a single reddening line such as that shown.

is composed of low-level lines of neutral and ionized metals. The Mauna Kea plate of V1057 Cyg is of inadequate resolution to show such a second set of absorption lines directly. The relationship of this inferred dense shell to the more displaced structures that were seen earlier in Ca II is unknown. These newly appeared Ca II emission lines are stronger and narrower, and are quite distinct from the very broad emissions that filled the H, K lines of V1057 Cyg for the first year following maximum light.

d) *Colors and Spectrophotometry*

Multicolor photometry of V1057 Cyg began in 1971 February and has continued to the present time. The slow movement of the star in the $(U-B, B-V)$-plane is shown in Figure 7, together with the locations of FU Ori and V1515 Cyg; the sources of the data are given in the caption. The reason for the three-color behavior of V1057 Cyg is clearer, however, if the scanner spectrophotometry is first examined. The Crossley scanner observations of 1975–1976 discussed here were made by Mr. R. Stone. The details are given in Table 4; the equipment was the same as that used by Grasdalen (1973). In Figure 8 are plotted the magnitude differences between V1057 Cyg and a de-reddened reference star whose spectral type is an approximate match for the *red* type of V1057 Cyg at the time. For comparison with Grasdalen's 1971 scans, the reference star chosen is 41 Cyg, F5 II, de-reddened for $E(B-V) = 0.03$ by the straight-line approximations to Whitford's extinction curve given by Miller and Mathews (1972). For comparison with Stone's 1975–1976 spectrophotometry, the reference stars are β Dra [G2 II, $E(B-V) = 0.09$] and α Aqr [G2 Ib, $E(B-V) = 0.10$]. In all cases, the reference star data were taken from the compilation by Breger (1976). These plots show that the continuum of V1057 Cyg, instead of continuing shortward of about 4800 Å at the 5000–8000 Å slope, rises systematically through the blue-violet. It is possible in principle to fit another straight line through these $\lambda < 5000$ Å

TABLE 4

SCANNER SPECTROPHOTOMETRY OF V1057 CYGNI*

λ (Å)	1975 Nov. 18	1976 July 27	1976 Aug. 25
3704......	2.94	3.19	3.31
3862......	2.62	2.73	2.80
4036......	1.95	2.22	2.22
4167......	1.97	1.92	2.02
4255......	1.70	1.79	1.87
4464......	1.53	1.46	1.52
4566......	1.30	1.28	1.36
4785......	0.92	0.90	0.98
5000......	0.73	0.70	0.78
5263......	0.40	0.45	0.45
5556......	0.00	0.00	0.00
5840......	−0.32	−0.29	−0.25
6056......	−0.46	−0.46	−0.42
6436......	−0.67	−0.67	−0.65
6790......	−0.94	−1.00	−0.95
7100......	−1.11	−1.16	−1.14
7550......	−1.38	−1.37	−1.35
7780......	−1.78	−1.56	−1.51
8090......	−1.82	−1.65	−1.58
8370......	−2.36	−1.77	−1.75
m(5556)...	10.43	10.45	10.48

* The observations are by R. Stone. The quantities tabulated are $m(\lambda) = -2.5 \log F_\nu +$ const. The bandpasses were 49 Å shortward of λ5263, 32 Å longward.

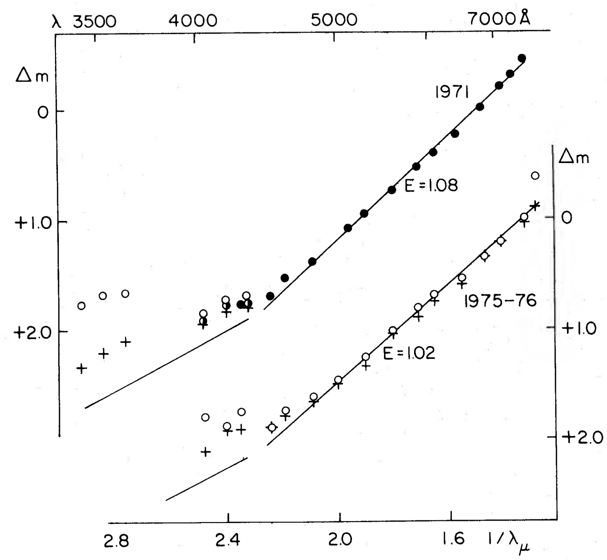

FIG. 8.—Differential scanner spectrophotometry of V1057 Cyg. The upper plot is magnitude differences between the variable in 1971, as measured by Grasdalen (1973), and 41 Cyg (F5 II) after correction for reddening. Since the red spectral type of V1057 Cyg at that time was about F5 II, the slope gives its reddening; the straight line segments correspond to reddening according to Whitford's extinction curve with $E(B-V) = 1.08$. The abnormal brightness of V1057 Cyg shortward of about 4800 Å can be seen. Filled circles represent mean points for three nights; when the separation is sufficient to be apparent at this scale, data from 1971 Apr. 1 are shown as open circles, from 1971 June 23 as half-filled circles, and from 1971 Sept. 19 as crosses. The lower plot represents the variable as measured in 1975–1976 by Stone (Table 4) *minus* de-reddened β Dra (G2 II) and α Aqr (G2 Ib). Open circles now represent the data of 1975 Nov. 18, and crosses the mean of 1976 July 27 and Aug. 25. V1057 Cyg is seen still to be too bright shortward of 4800 Å. The reddening inferred is now $E(B-V) = 1.02$. A value of 1.0 has been adopted in the text. The wavelengths shown were chosen to avoid strong spectral features. The zero points of the ordinates are arbitrary.

points, to correct that slope for the reddening derived from the fit for $\lambda < 5000$ Å, and to read from a table of $(B-V)_0$ versus MK type (FitzGerald 1970) the spectral type of the corresponding star. However, the wavelength range below 5000 Å available for this fit is small, and the scatter of the data rather large so that the results in Table 5 must be considered as only indicative. The progressive change during 1971 in particular is probably below the real resolution of the observations. Nevertheless, it is striking that these spectral types corresponding to the slope of the blue continuum are not far from the types estimated directly from the spectrograms of that region. There is thus further evidence, in addition to that from the spectral types and radial velocities, that in the blue-violet one sees a deeper and hotter region of the object than in the yellow-red.

The only scanner data on the continuum of V1057 Cyg below the Balmer limit remain those of Grasdalen, for two nights in 1971. He compared this region with a Carbon-Gingerich model atmosphere, and noted that the jump in V1057 Cyg was much smaller than expected. This discrepancy is not so striking if the variable is differenced against a real A5 III star. It is not obvious how large a jump would be expected in the stratified-envelope picture that is suggested by the other evidence.

To return to the broad-band photometry, the starting position of V1057 Cyg in the $(U-B, B-V)$-plane (Fig. 7) must reflect this "composite" energy distribution: the U band falls in the region where the type is A and across a possibly abnormal Balmer jump, the B band is central in the A-type region, while the V lies largely in the range where the star has an F type. As the star faded after maximum light, the discrepancy between the continuum slopes shortward and longward of about 4800 Å was maintained (Table 5) but the effect of a diminishing Balmer jump upon U should drive the star in the sense it was indeed observed to move in Figure 7.

All three FU Ori stars are now grouped together in a remarkably small region of Figure 7. In 1975–1976, their red-region types were not greatly different: FU Ori, F5–G0p Ib; V1515 Cyg, G0–G2 Ib; V1057 Cyg, G2–5 Ib or II. The corresponding normal colors lie near the reddening line drawn in Figure 7, so any perturbation of U and B must now be small. If the intrinsic colors are all the same, then the interstellar reddening of each can be estimated by adopting the scanner value of $E(B-V) = 1.0$ for V1057 Cyg, from which the relative positions in Figure 7 yield $E(B-V) = 0.8$ for FU Ori and 1.0 for V1515 Cyg.

e) *Dimensions of V1057 Cygni*

The radius of V1057 Cyg can be calculated from the de-reddened colors or energy distribution longward of 5000 Å, under the assumptions that the

TABLE 5

SPECTRAL TYPE INFERRED FROM THE CONTINUUM SLOPE OF V1057 CYGNI, 4000–4800 Å

Date	Observer	Assumed MK Type, $\lambda > 5000$ Å	$E(B-V)$ From Fit $\lambda > 5000$ Å	$(B-V)_0$ For 4000–4800 Å	Corresponding MK Type, if Class II
1971 Apr. 1	Grasdalen			+0.07:	A3
1971 June 23	Grasdalen	F5 II	1.08	0.17:	A8–9
1971 Sept. 19	Grasdalen			0.23:	F0:
1975 Nov. 18	Stone	G2 Ib, II	1.00	0.20:	F0:
1976 Aug.*	Stone		1.05	0.33:	F3:

* Mean of the scans of 1976 July 27 and Aug. 25.

TABLE 6

Calculated Radii of V1057 Cygni*

A. Preoutburst Radii

Assumption	If $V_0 = 11.0$ and $E(B-V) = 1.0$	or $E(B-V) = 1.2$	If $V_0 = 11.5$ and $E(B-V) = 1.0$	or $E(B-V) = 1.2$
K0 surface brightness..............	4.4	5.8	3.5	4.6
$R - I = +1.8$ at minimum.........	11.9	11.8	9.5	9.3

B. Postmaximum Radii

Date†	With $E(B-V) = 1.0$	But if $E(B-V) = 1.2$:
1971 Mar. 12.............	16.0	14.8
1971 May 8...............	17.7	16.4
1971 June 28..............	15.8	14.6
1971 Sept. 22–24..........	16.9	15.6
1975 Nov. 18.............	13.6	12.6
1976 July 27..............	14.8	13.6
1976 Aug. 25.............	14.3	13.2

* In solar units.

† The 1971 dates are those of the multicolor observations by Rieke *et al.* 1972. The 1975–76 dates are those of the scans by Stone (Table 4).

extinction is normal and not time-dependent. The visual surface brightness in magnitudes, S_V, can be obtained from relationships given by Wesselink (1969) and recently recalibrated in terms of intrinsic $R-I$ and $V-R$ colors by Barnes, Evans, and Parsons (1976). The surface brightness is expressed as

$$S_V = -10(a - bC) + 27.21 , \qquad (1)$$

where C is the color and a and b are given by Barnes *et al.* Or, the radius can be obtained directly from

$$\log R = \log d - 0.2V_0 - 2(a - bC) - 0.174 , \qquad (2)$$

where d is the distance in the same units as R, and V_0 is the V magnitude corrected for extinction.

The preoutburst radius probably is best obtained by assuming that the surface brightness of V1057 Cyg was then approximately that of a dK0 star, which is the type observed for the more luminous T Tauri stars such as T Tau and RY Tau (Herbig 1977). (But this is only a conjecture because the 1957 plate of V1057 Cyg is not classifiable.) The value of V_0 can be taken either as Herbig's (1958) $m_{pg} = 16.0$ at some unknown phase, corrected for Mandel's (1975) color index and the $E(B-V) = 1.0$ of § III*d*, so that $V_0 \approx 11.0$; or an average $m_v \approx 14.5$ can be read from Mandel's photovisual data, whence as before $V_0 \approx 11.5$. A distance of 600 pc, essentially that of Grasdalen (1973), is adopted, and the resulting radii are given in Table 6. The amount of extinction does not enter crucially; as an illustration, a second set of radii are shown for the case of $E(B-V) = 1.2$.

A preoutburst radius is also calculable from Haro's estimate that $R - I = +1.8$. Corrected for reddening of amount $E(R - I) = 0.82E(B - V)$, this color leads to much larger radii (Table 6) because it corresponds to a much lower surface brightness, of about type M1. The result is quite sensitive to the value assumed for $R - I$. Haro's value is only an estimate; if it were in error by the not unreasonable amount of 0.3 mag, the resulting radius change is by a factor of 1.7. For this reason, the previous value is preferred.

Following maximum light, both *VR* photometry and scanner data are available for 1971, and scanner observations alone in 1975–1976. (Because of the peculiar energy distribution, *UBV* data are unsuitable for determining the radius in this way.) Once the relationship between $V - R$ and the scanner colors m(5556 Å) minus m(7100 Å) is determined for interstellar reddening, the surface brightnesses and radii follow as before: Table 6.

These results show that the star expanded when rising from minimum to maximum light, and that subsequently it has become slightly smaller. If the radial expansion by about 13 $R_\odot$ took place over the photometric rise time, then the average radial velocity of the photosphere was only about 0.3 km s^{-1}. Clearly, the large expansion velocities measured on the early 1971 spectrograms (40 km s^{-1} from the metallic spectrum in the blue, 60 km s^{-1} from the Balmer cores, 500 km s^{-1} from the P Cygni structure of Hα) refer not to the motion of this surface, but rather to rapidly rising shells that are optically thin in their visual continua.

f) *Infrared Excesses*

Infrared photometry of V1057 Cyg (Cohen and Woolf 1971; Cohen 1973*a*; Rieke, Lee, and Coyne 1972) began in 1971 March, about 6 months after maximum light, and revealed that the star was then very bright in the 20μ region. In Figure 9 is plotted the infrared excess observed in 1971, displayed as magnitudes above the continuum of an F5 II star having the same V; conventional reddening has been removed. It has been shown by Simon *et al.* (1972) and by

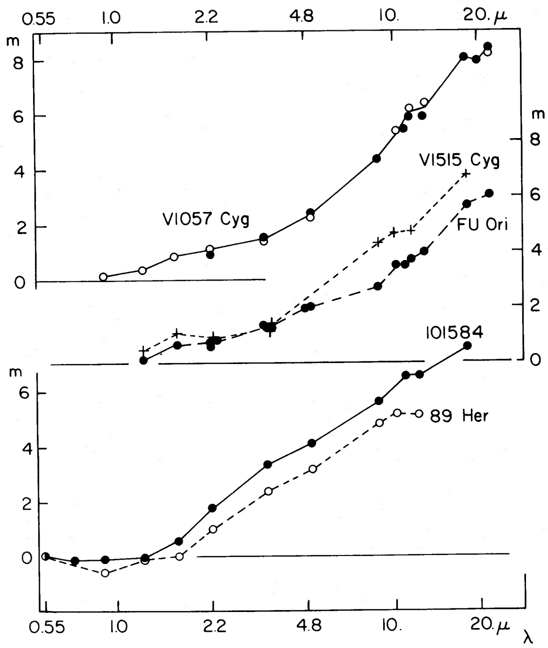

FIG. 9.—The infrared excesses of V1057 Cyg (means for 1971), V1515 Cyg and FU Ori, referred to a baseline defined by the V magnitude and extended to longer wavelengths by normal colors corresponding to the red spectral type at the time. Normal reddening, of amount corresponding to the $E(B-V)$'s given in § III*d*, has been removed. The lower section shows the infrared excesses of the F supergiants HD 101584 and 89 Her in the same format; the data are from Humphreys and Ney (1974). The V1057 Cyg photometry is by Cohen (1973*a*, 1975) and by Rieke *et al.* (1972). The observations of V1515 Cyg are by Cohen (1974) and by K. M. Merrill (1976, private communication). Those of FU Ori are by Lee and Low as quoted by Rieke *et al.*, and by Cohen (1973*b*, 1975).

Rieke, Lee, and Coyne (1972) that this excess cannot be fitted by thermal dust emission at a single temperature: a component near 200 K is required for the 10–20 μm region, and a much hotter component at about 1800 K for 1–5 μm. (An alternative proposal that the latter is due to free-free emission encounters difficulties in the visual region.) The possibility that the entire infrared excess is due to a single thick dust shell having a major temperature gradient and nongray particle emissivity has not been explored.

A very rough estimate of the dimensions of the region where the 20 μm excess originates can be made as follows. The ratio of fluxes at 10 and 20 μm measured by Simon (1975) can be converted to a temperature if the grains are transparent (see Andriesse 1976 for a justification) and if the ratio of emissivities at those wavelengths is known. The conventional assumption is that $\epsilon_\lambda \propto \lambda^{-1}$ (Greenberg 1968), so that $T_s \approx 185$ K. If this temperature is produced by the dilute radiation field of an F5 II star having $T_{\rm eff} = 6500$ K, then the corresponding shell radius $R_s^{(1)} \leq \frac{1}{2}R_*(T_*/T_s)^{5/2} = 270$ AU. On the other hand, the effective emitting area of the shell at 20 μm in stellar units is $L_s B_*/L_* \epsilon_{20\,\mu\rm m} B_s$, where the B's are the respective Planck functions, $\epsilon_{20\,\mu\rm m}$ is the grain emissivity, and L_s/L_* corresponds to the 8 mag excess, all at 20 μm. If the shell is represented in projection by a circular emitting surface, the radius of that surface is $R_s^{(2)} = 60/\epsilon_{20\,\mu\rm m}$ AU. The correct value of $\epsilon_{20\,\mu\rm m}$ to be used is uncertain, but it may be of the order of 0.1 (Bussoletti and Zambetta 1976), whence $R_s^{(2)} \approx 600$ AU. Finally, a high upper limit on the radius of the emitting region is provided by the observation of Rieke, Lee, and Coyne (1972) that at 22 μm its diameter was no larger than 1″.5, from which $R_s^{(3)} \lesssim 900$ AU. A similar limit results from the tolerances upon the coincidence between the optical position of the star and that of the OH maser source (Lo and Bechis 1974). A compromise value of $R_s \approx 300$ AU will be used for illustrative purposes, but it is clearly a most uncertain number.

The 10 and 20 μm fluxes decreased by nearly 1 mag between 1971 and 1974, but their ratio has been very nearly preserved, so this does not represent a decrease of T_s (Simon 1975). One might expect some response in the infrared excess to the arrival of the high-speed gas of the shells seen in Ca II, Na I, and Hα. If these were launched ballistically about 1969.6 when the eruption began, the 310 km s^{-1} shell should have reached the distance of $R_s = 300$ AU in 1974, and the 210 km s^{-1} system in 1977. It is imaginable that the passage of one of these shells was responsible for the quenching of the transient OH 1720 MHz emission which was fading even at the time of its discovery in 1973.5, and had disappeared by 1974.8 (Lo and Bechis 1974; Lo, private communication 1975). It is important that the infrared photometry of V1057 Cyg continue, not only so that such effects might be detected but also so that the general evolution of the dust shell can be followed.

It seems probable that this circumstellar dust was present near the star before the eruption, as a "solar nebula" such as those suspected to exist around many T Tau stars, and is now radiating rethermalized stellar energy at a correspondingly higher level. As pointed out by Simon, the alternative of an expanding dust cloud ejected from the star in 1969 is untenable: it should by now have cooled perceptibly, contrary to observation. There are reasons to suspect that the dust nebulae around young stars are disk shaped; if so, then we may be viewing that at V1057 Cyg approximately pole-on. The reasons are individually subject to some dispute, but collectively carry a certain weight. They are: the shape of the reflection nebulosity surrounding the star, which Bechis and Lo (1975) interpret as a conical nebula seen approximately axially; the lack of a significant amount of circumstellar plane polarization or of circumstellar extinction, as would be expected if the disk of scatterers were being viewed from a high latitude; the interpretation of the variable circular polarization by Wolstencroft and Simon (1975) in terms of a disk seen approximately pole-on. If such is indeed the geometry, then spherical models which account for the infrared excess by equating it to line-of-sight extinction of the star at shorter wavelengths are of course unnecessary. If future work should show that FU Ori and V1515 Cyg also require a pole-on geometry, this would not be grounds for questioning the interpretation on grounds of improbability, because such events seen from low latitudes through their disks would be very faint optically, and might well have been missed.

The presence of infrared excesses in all three members of the class is probably significant: at 18 μm these amount (Fig. 9) to 8.0 mag for V1057 Cyg in 1971 (which had fallen to 7.5 mag by 1974), 6.7 mag for V1515 Cyg at the time of Cohen's (1974) observation, and 5.7 mag for FU Ori in 1970–1972. Yet it is to be noted that such excesses are not a unique characteristic of pre–main-sequence stars, because several bright F- and G-type supergiants which have no apparent connection with interstellar matter or with very young stars are known to display infrared excesses of the same type (Humphreys, Strecker, and Ney 1971; Humphreys and Ney 1974*a*, *b*). The excesses of two of these objects, HD 101584 and 89 Her, are shown in Figure 9. Both are single-line spectroscopic binaries, and Humphreys (1976) has suggested that in HD 101584 the excess arises in circumstellar dust shed by the cool component.

g) *The Reflection Nebulae*

Welin (1971*a*) discovered that an eccentric ring of nebulosity surrounding V1057 Cyg had appeared shortly following maximum light; both his material and the Palomar Sky Survey plate show that it had not been present at minimum. The nebulosity appears on large-scale photographs (Fig. 10 [Pl. 8]) as a broken, elliptical ring about 60″ by 90″, with the variable just inside its southwest edge; the brightest section of the ring is that nearest the variable, about 12″ west and southwest. There is considerable structure in the ring, and a large section along the north side is absent. Fainter nebulosity is visible also outside the ellipse, about 95″ northeast of the star. The spectrum of the ring has apparently not been obtained, but filter photographs including and excluding Hα (Fig. 10) demonstrate that it is reflection.

This nebulosity must be a preexisting structure that was illuminated as the star brightened, as was the case at FU Ori. In both cases, one can be certain that the nebulosity was not ejected from the star at the recent outburst: the direct photographs show that no cross motions at the required velocity are present. Furthermore, at V1057 Cyg, CO observations of the ring west of the star by Bechis and Lo (1975) show that the radial velocity in that area is the same as in the surrounding molecular cloud.

The wave of illumination from V1057 Cyg would, at 600 pc, cross the cloud at the rate of 1″ in 3.5 days. The first known photograph of the nebulosity is that reproduced by Welin (1971*a*, Fig. 2*b*), taken on 1970 December 22, approximately 100^d after maximum light. That exposure is not strong, but one does have the impression that on it, the section of the ring lying 60″ northeast of the star is fainter with respect to the nebulosity nearer the star than on later photographs. The light travel time to that point would be 210^d, but 210^d before that plate was exposed the variable was only about 0.2–0.3 mag fainter, and such a small differential would probably be imperceptible. However, the projection factor is unknown, and it is not unreasonable that that arc actually lies far enough behind the plane of the sky for its illumination to be delayed significantly longer. One notes that in fact the model of the nebula proposed by Bechis and Lo (1975) postulates just that location for that particular arc. Unless some forgotten photograph of the region taken in mid-1970 should be found, however, the matter is likely to remain as only an interesting possibility.

A series of direct plates of V1057 Cyg was begun immediately after discovery with the Crossley reflector at Lick by Mr. E. A. Harlan, and has continued to the present time. These negatives, all taken with the same telescope, filter, exposure time, and emulsion type, show that since 1971 the whole nebula has slowly faded in brightness without any obvious change in structure. The 1971–1975 plates are reproduced in Figure 11 (Plate 9). Presumably this fading is in response to the postmaximum decline in the star's brightness, which amounted to about 1.0 mag in *R* over the interval represented in Figure 11. Detection of light-time effects in the nebula as the variable declines will be difficult because the fading is slow. A photometric study of these negatives is under way.

A nearly complete elliptical ring of nebulosity is present at V1515 Cyg (see § IV), and at FU Ori a bright arc extending from the star is embedded in an amorphous mass of reflection nebulosity. Such dust arcs or incomplete rings are associated with a number of pre–main-sequence stars (see the photographs in Herbig 1960), so they are not an exclusive property of FU Orionis–like objects. In the case of the nearly complete ring at V1057 Cyg, Lo and Bechis (1975) have proposed that it is a conical surface viewed tangentially to the southwest side. Another possibility is that it represents the surface of a cavity to whose boundary the intervening dust has been driven by gas ejected from the star at an earlier eruption.

IV. V1515 CYGNI

About 1954, in connection with the search for emission-Hα stars near the reflection nebula NGC 6914 (Herbig 1960), a faint variable star was discovered in the same obscured area, 8′ southwest of BD +41°3731. The variable was noted as about 3 mag brighter on a 1954 Crossley plate than on one of 1912, but despite this unusually large range and the fact that a curious arc of nebulosity protruded from the photographic image, no follow-up observations were made at Lick until 1974. At that time, Cohen (1974) published a brief note on the star and its nebulous tail, but on the assumption that it was the cometary nebula Parsamyan 22, which in fact lies about 9′ east. Two 120 inch coudé spectrograms of the red region taken soon thereafter revealed a spectrum very much like that of FU Ori: an early G-type star of high

TABLE 7

UBV OBSERVATIONS OF V1515 CYGNI BY R. STONE*

Date (UT)	V	$B-V$	$U-B$
1975 Sept. 24......	12.27 (2)	+1.57 (3)	+1.11 (4)
1975 Sept. 25......	12.30 (2)	1.52 (3)	1.09 (3)
1976 Aug. 28......	12.13 (1)	1.59 (2)	1.06 (7)
1976 Sept. 23......	11.93 (2)	1.62 (3)	1.10 (5)

* The numbers in parentheses are the estimated uncertainties of the tabular values, in units of 0.01 mag.

luminosity with broad lines, P Cygni structure at Hα, powerful shortward-displaced absorptions at Na I D_{12}, and a strong Li I λ6707 line. Furthermore, the star was significantly brighter than it had been in 1954; the rise is shown in the reproductions of Crossley plates of 1912, 1954, and 1975 in Figure 12 (Plate 10).

At my request, the photometric history of the star was shortly thereafter investigated by Wenzel and Gessner (1975) on Sonneberg plates, and by Hoffleit (1975, private communication) at Nantucket. I am very much indebted to these astronomers for their cooperation, and for placing this material at my disposal in advance of publication. The photographic light curve of V1515 Cyg since 1922 is shown in Figure 13, to which have been added several observations of B made at Lick in 1975–1976 by Mr. R. Stone (Table 7).

The variable was below the limit of both series from the first (Nantucket) plates in 1920 until 1948, when it became visible near $m_{pg} = 15.5$. The star continued to brighten slowly. Between 1957 and 1970 there is, however, a discrepancy between the two series. Its sense is that the Sonneberg observations (Fig. 13, *open circles*), which show nearly constant light from 1960 to 1975, are 0.5–1.0 mag brighter than the Nantucket estimates; the latter (*filled circles*) indicate a slower but continuous rise from about 1956 to 1975. The reason for this difference is not understood. It does not lie in the magnitude systems: Miss Hoffleit has established that the two comparison-star sequences are compatible in this range to about 0.1 mag. The star is near the edge of most Nantucket plates, and Miss Hoffleit has remarked that the image character of the variable is frequently different from those of the comparison stars. The difficulty could be due to a color effect, or to the influence of the small nebulosity upon one or the other series.

Whatever the reason, since 1970 the two series have once again come into essential agreement and are compatible with the photoelectric observations. The star in 1975–1976 has been near $B = 13.7$, but whether it has attained maximum light or will continue to brighten is not obvious. Both Wenzel and Gessner and Hoffleit have noted additional fluctuations, less than 1 mag in amplitude, superposed upon the slow secular brightening. Their reality is confirmed by Stone's *UBV* observations in Table 7.

Only fragmentary information exists on the earlier history of V1515 Cyg. The comparison-star m_{pg}'s of Wenzel and Gessner have been extended to mag 18 by a single exposure obtained with the Lick 20 inch Astrograph and a $\Delta m = 4.0$ mag objective grating. Estimates of the variable's brightness with respect to this extended sequence, on early plates taken with a variety of instruments at Lick, Heidelberg, and Mount Wilson are given in Table 8. The star maintained an approximately level brightness, averaging about $m_{pg} =$ 17.4, between 1901 and 1920. There are considerable uncertainties in these magnitudes because the star was usually either near the plate limit or outside the field of good definition. Therefore it is not certain that the indicated range of over 0.6 mag at minimum light is real.

TABLE 8

EARLY MAGNITUDES OF V1515 CYGNI

Date	Observatory	Telescope	m_{pg}
1894 June 7........	Lick	Willard	>15.8
1901 July 16, 18....	Königstuhl	Bruce	17.5:
1903 Sept. 21.......	Königstuhl	Bruce	>17.6
1912 Aug. 13.......	Lick	Crossley	17.0
1919 Oct. 27.......	Mt. Wilson	100 inch	17.3
1920 Aug. 11.......	Mt. Wilson	100 inch	17.4

Unfortunately there are no observations of the spectrum of V1515 Cyg at minimum. The first red-region Crossley slitless spectrogram of the NGC 6914 field was taken on 1954 October 1, when the star was already at $m_{pg} = 14.5$, on its rise. On that low-resolution plate, the variable shows essentially a continuous spectrum, but there does appear to be a broad shallow absorption at Hα.

The Lick, Mount Wilson, and Palomar Atlas direct plates between 1948 and 1954 show a narrow arc of bright nebulosity extending about 14″ to the north and west of the image of V1515 Cyg. This feature does not appear on any of the earlier Lick or Heidelberg plates taken at minimum light, but it may be present in the heavily comatic image of the star on a Mount Wilson 100 inch negative of 1920. Crossley and 120 inch plates of 1975 show this northwest arc as still present but much fainter, while a new and brighter arc extending to the south and west has in the meantime appeared. There is no sign of this new nebulosity on any of the earlier exposures. Thus the variable now lies on the eastern edge of a nearly complete elliptical ring of 16″ by 21″.

The radial velocity of V1515 Cyg was measured on three 34 Å mm^{-1} coudé spectrograms of the red region taken in 1974–75. The mean velocity is -12 ± 2 km s^{-1}. A heliocentric velocity of -12 km s^{-1} has also been measured by Loren, Vanden Bout, and Davis (1973) and by Knapp *et al.* (1977) for the CO emission around the nearby +41°3731. The kinematic association of V1515 Cyg with its molecular cloud is thus demonstrated; the same situation has already been shown to hold for FU Ori and V1057 Cyg.

V. GENERAL DISCUSSION

a) Spectral Characteristics

It has here been implicitly assumed that the eruptions of V1057 and V1515 Cyg are both manifestations of

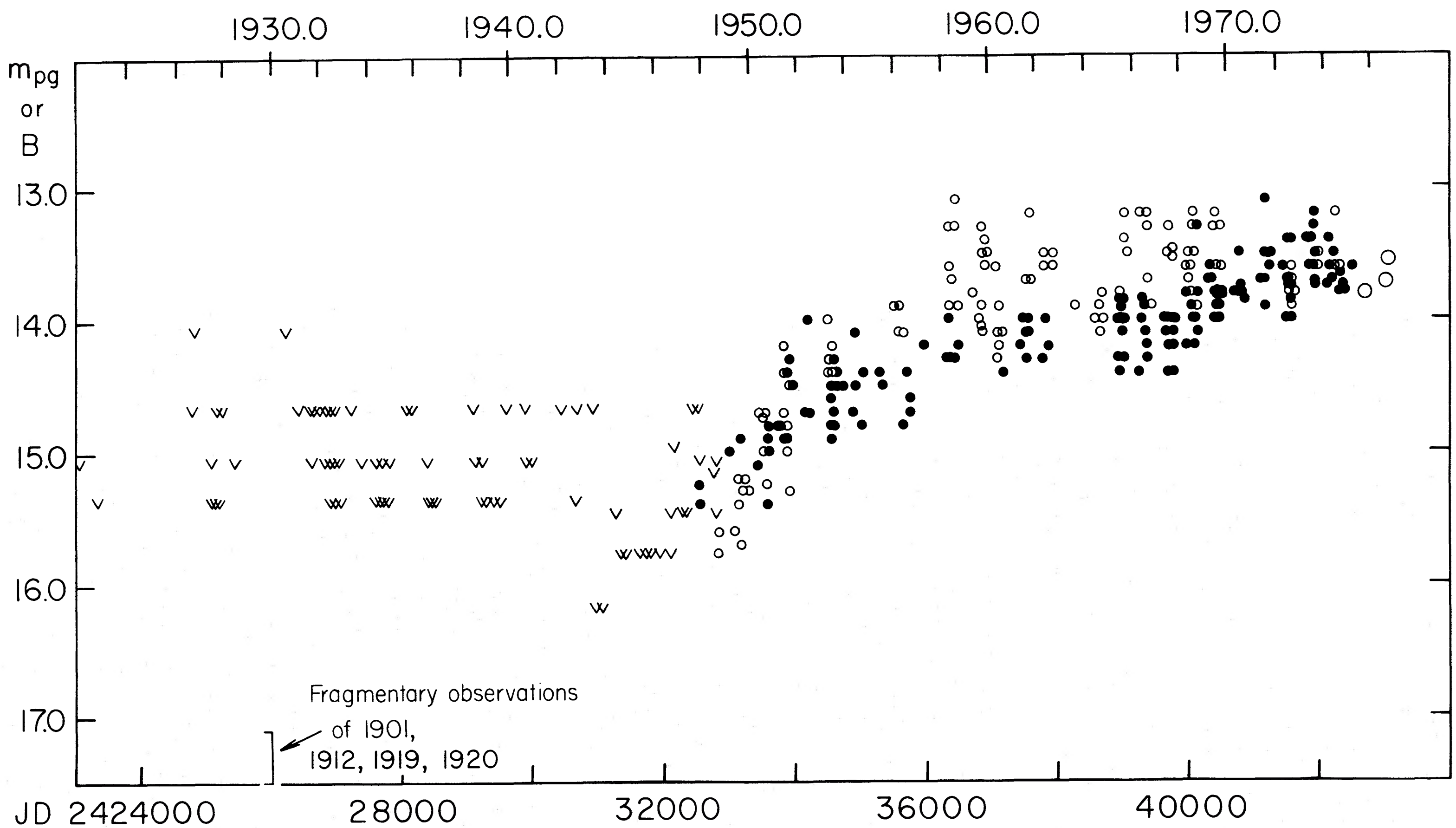

FIG. 13.—The photographic light curve of V1515 Cyg to 1976. The small filled circles are estimates by Hoffleit (1975, private communication) on Nantucket plates, and the small open circles are Sonneberg observations by Wenzel and Gessner (1975). The larger points in 1975–1976 are the photoelectric *B* observations by Stone from Table 7. The discrepancy between the Nantucket and Sonneberg magnitudes 1957–1970 is discussed in § IV.

the FU Ori phenomenon, despite the relatively slow photometric development of V1515 Cyg. An essential basis for this belief is spectroscopic. The postmaximum spectra are not precisely identical but have certain common and distinctive characteristics: late F or G types of luminosity class Ib or II (in the red) with somewhat diffuse absorption lines, Li I λ6707 present at a strength approximating chondritic or T Tauri–like lithium abundance, and shortward shell components at Hα and D_{12}, while the only conspicuous line emission is in the P Cygni structure at Hα. The three variables having these characteristics have as well some secondary properties that are not unique: the infrared excesses, the peculiar reflection nebulae, the similar absolute magnitudes at minimum. The fact that all three were observed to rise from a minimum magnitude of long duration was of course the primary consideration, but in future cases that information may not always be available. For example, SU Aur has an interesting resemblance to these three objects, yet it has been near its present brightness since at least the 1850s.

A number of questions about the spectroscopic properties of the FU Ori variables remain unanswered. For example, the evidence is inadequate to establish whether these stars all have the same spectral type at maximum light. The data is best for V1057 Cyg: about 0.7 years (0.7^y) after maximum it was classified as A3–5 II in the blue, F5 II in the red. The first blue classification of FU Ori was at $+2^y$; this Yerkes spectrogram of 1939 February has been classified F0 Iab by W. W. Morgan.[4] A less precise classification of A8 at about the same time, from the H and Ca II lines alone, was given by Wellmann and Hachenberg (1939). Whether the type had been substantially earlier 2 years before is impossible to say, but one notes that at $+26^y$ the blue type was given as F2:p I–II, so no large change is suggested. The information on V1515 Cyg is of little help: there is as yet no information in the blue, while the red type is 1975–1976 was G0–G2 Ib. But it is not certain that this star is yet at maximum.

Another unresolved issue is whether the curious differences in spectral type, radial velocity, energy distribution, and circular polarization of V1057 Cyg between blue and red are separated by a discontinuity near 4800 Å, or if they vary continuously with wavelength. Nor is it known whether the same phenomenon occurs in the other stars; what little evidence that is available for FU Ori up to about 1960 is conflicting (Wellmann and Hachenberg 1939; Bartaya 1962), but scanner observations by Stone show that in 1976 the energy distribution was normal.

The observations of V1057 Cyg have demonstrated, however, that the eruption was accompanied by intrinsic changes in the star: the spectra at maximum and at minimum were completely different; there were major changes in the radial velocity and line structure in the year following maximum; there has been a continuing change in the spectral type and radius as the star has faded. All these show that the flare-up was not the result of the simple removal of a screen. Furthermore, the increase of radius from minimum to maximum demonstrates that the flare-up was not caused when a large cool shell was dissipated to reveal a smaller, hotter star within. This does not mean that preexisting circumstellar dust or gas has not been disturbed or redistributed as a result of the outburst. That may well have happened (§ V*d*), but the observations indicate that it happened in response to the star's outburst, not the converse.

b) *Statistics and a Frequency Estimate*

Some useful parameters for the three known FU Ori variables are listed in Table 9A. It is interesting that the M_{pg} values at minimum (taken at an intermediate point in the preoutburst ranges) are +3 to +4, although it must be remembered that somewhat uncertain corrections for distance and extinction are involved. These objects at minimum clearly have luminosities comparable with those of the more luminous T Tau stars.

Consider what generalizations might be made from the observed frequency of the FU Ori phenomenon, with due reservation about conclusions based upon a sample size of 3. This number is surely a lower limit on the number of such events that were observable during the past 80 years[5] of photographic variable star studies. Almost certainly some examples have been missed, judging from the circumstances under which two of the three examples were discovered. That is, V1515 Cyg was not found in a variable star survey at all, and the flare-up of V1057 Cyg might have gone undetected for some time had it not been for Welin's thesis study of the NGC 7000 region, which fortunately was under way at just the right time.

To proceed, the fundamental assumptions are now made that (*a*) no other such events have occurred within 1 kpc in the northern sky during the past 80 years, and (*b*) it is not some special minority of T Tau stars which is susceptible to the FU Ori phenomenon, but rather the total population of T Tau stars brighter than about $M_{pg} = +4$ in this volume are candidates (because the M_{pg}'s at minimum of the three known examples range from +3 to +4). Specifically, it is assumed that these three cases are drawn from the T Tau stars brighter than $M'_{pg} \equiv M_{pg} + A_{pg} \approx +8.0$ in those three associations; the photographic absolute magnitude uncorrected for extinction must be used in comparisons with the T Tau survey statistics. This particular M'_{pg} limit comes from the fact that the M'_{pg}'s at minimum light for all three stars lie between +7.0 and +7.5 (Table 9B). The Lick survey for emission-Hα stars in these three associations is complete to different

[4] I am very grateful to Dr. Morgan for his recent classification of this spectrogram on the MK system, and for allowing me to examine all the early 40 inch negatives of FU Ori. These films were taken originally by P. C. Keenan, and are those mentioned by Struve (1939).

[5] This number comes from the empirical fact that the rate of discovery of galactic *novae* rose sharply just before 1900, as a consequence of the introduction of photography. It does not allow for the fact that, in recent decades, routine surveys for variable stars have been less extensive than earlier.

TABLE 9A

SOME STATISTICS OF THE FU ORIONIS VARIABLES

Star	Year of Maximum	Rise Time (days)	Distance (pc)	$E(B-V)$ (mag.)	M_{pg} max.	M_{pg} min.
FU Ori.......	1937.1	> 120[d] but < 380	500	0.8	−2.1	+4.1 var
V1057 Cyg...	1970.7	390	600	1.0	−2.4	+3.1 var*
V1515 Cyg...	{if 1960 / if 1975}	{> 4000 / > 10,000}	1050†	1.0	≤ −0.6	+3.3

TABLE 9B

COMPARISON OF FU ORIONIS VARIABLES AND ERUPTIVE T TAURI STARS

Star	Duration of Maximum (days)	Pg Range (mag.)	M'_{pg} at Minimum	Spectral Type at Minimum‡
FU Ori......	> 14,600	6.2	+7.2	...
V1057 Cyg...	7,500?	5.5*	+7.1	et
V1515 Cyg...	> 4,000	≥ 3.9	+7.3	...
EX Lup......	200–1800	2.0	+6:§	M0:eV(Li)
VY Tau......	150– 700	3.3 mean	+8.1	M0eαV(Li)
UZ Tau E....	150?	3.9	+8.9	M1,3eV(Li)

* A mean m_{pg} of 16.0 at minimum is assumed.

† The distance is that of Racine 1968.

‡ These classifications are from Herbig 1977.

§ There is no reliable determination of the distance, so M'_{pg} may be substantially in error.

M'_{pg}'s. Reduction to the +8.0 limit is made by assuming that the $N(M'_{pg})$ versus M'_{pg} relationship that holds in the Taurus-Auriga dark clouds applies to these other groups of T Tau stars as well. The details of these corrections are shown in Table 10. An example of such a correction and its statistical uncertainty is given in Herbig (1962, p. 75). In this way, the total number of candidates is estimated to be about 120. On this basis, the mean time between successive FU Orionis–like outbursts in an individual T Tau star is $\tau_{FU} = 80 \times 120/3 \approx 3 \times 10^3$ years. If some examples have indeed been missed, τ_{FU} is shorter; if less luminous T Tau stars are also susceptible, it is longer.

But this assumes that the only candidates are T Tau stars in those three associations. Where are all the FU Orionis–like events that on this basis would be expected in rich associations like the Orion Nebula and NGC 2264? Surely some have been missed; perhaps for unknown reasons some associations are more active than others. If one takes the view that these three events are truly all that have taken place within the past 80 years in *all* the northern associations within 1 kpc for which T Tau survey statistics are available, then the number of eligible stars is increased by a factor of about 4.2, so $\tau_{FU} = 13 \times 10^3$ years. Note that no allowance is made for heavily obscured T Tau stars that do not appear in the statistics at all. The round value of $\tau_{FU} \approx 10^4$ years will be used in what follows, but it is clear that because of the huge uncertainties involved, this number is extremely uncertain.

This suggestion that the FU Ori phenomenon is

TABLE 10

ESTIMATED NUMBERS OF T TAURI STARS BRIGHTER THAN $M'_{pg} = +8.0$

Association or Cloud (1)	Total Number of Known Emission-Hα Stars (2)	Limiting M'_{pg} of Hα Survey (3)	Correction Factor to Extend to $M'_{pg} = +8.0$ (4)	Estimated Number to $M'_{pg} = +8.0$ (5)
NGC 7000/IC 5070......	30	+6.25	3.2	98.
λ Ori.................	40?	+11.25	0.23	9. ?
NGC 6914..............	4	+6.75:	2.6	10.
Total..................				120:

EXPLANATION.—The data in cols. (2) and (3) are from the Lick Hα surveys, supplemented in the case of λ Ori by Tonantzintla results. The correction factors in col. (4) are obtained from the assumption that the shape of the luminosity function for T Tau stars in the Tau–Aur clouds is general.

recurrent, and with a spacing of only about 10^4 years in a given star, is unexpected.[6] But consider the obvious alternative, namely, to assume that such a flare-up occurs only once in a life of a given T Tau star. This requires that all known candidates will have been exhausted in several times 10^4 years, which means that new T Tau stars must be supplied on the same time scale, and this implies that the duration of the T Tau phase is only about 10^4 years.

A claim that the T Tau phase is of such short duration would be in conflict with the following observational considerations. (1) The rate of star formation required to maintain the number of intermediate-mass main-sequence stars in the solar vicinity can be estimated. If this is compared with the number of T Tau stars in the same volume, then the appropriate contraction and main-sequence lifetimes lead to a mean duration of the T Tau phase of about 5×10^6 years (Herbig 1970). This is only a rough estimate, but it seems unlikely that it could be in error by a factor of 500. (2) A representative age for a young cluster such as Orion or NGC 2264 is 1 to 5×10^6 years. If the duration of the T Tau phase were only 10^4 years, then one would expect to find, for every T Tau star in such a cluster, 100 to 500 other stars which had had their single eruption sometime in the past. There would be two possible present states for such former T Tau stars: (*a*) They might be faint, above the main sequence, but without the T Tau characteristics, in which case there would be 100 to 500 such members of young clusters for every T Tau star; this is not observed. (*b*) They might remain bright, in which case young clusters would contain large numbers of peculiar F–G supergiants like FU Ori; again, this is not observed. Such stars could readily be recognized, yet they must be very rare, for example, in the Orion Nebula where a fairly thorough search at Lick was quite unsuccessful.

For these reasons, the "only-once-per-star" assumption for the FU Ori phenomenon is dismissed. The point of view taken here is that such an eruption represents a relatively superficial event after which the star returns to essentially its former state. The relatively rapid fading of V1057 Cyg, which has clearly departed from the state which Grasdalen (1973) studied, and the slow decline of FU Ori both support this idea. There is obviously no unique value of the rate of return to minimum light. It might be that some of the dispersion in luminosities of T Tau stars is contributed by variables that have not completely declined from their most recent eruption.

c) Can Vestiges of the Phenomenon Be Found in Other Stars?

If the eruptions occur in T Tau stars but are absent on the main sequence, then in a given object they probably weaken in intensity, duration, or frequency as the star evolves toward the main sequence, instead of ceasing abruptly. If so, minor activity reminiscent of the FU Ori phenomenon might be present in older T Tau stars or post–T Tau objects. The question whether such activity exists is not easily answered because all T Tau stars are erratically variable to some degree; however, among the hundreds known, three unusual stars can be cited.

EX Lupi was at first thought to be a nova-like variable on the basis of five observed flare-ups occurring at spacings of 5 to 13 years (McLaughlin 1946). One Harvard objective-prism plate obtained when the star was bright showed emission lines of H, Ca II, and Fe II, which are not characteristic of novae. Slit spectrograms taken at an intermediate magnitude demonstrated that the object was in fact a T Tau star (Herbig 1950). A recent Lick spectrogram of the red region, with the variable at minimum, confirms this: the absorption spectrum is about M0 V with Hα and He I in emission, and a strong Li I λ6707 absorption. The best-observed maximum was in 1955–1956, shown in Figure 14. The star was bright for about 250 days; unfortunately, the spectrum was not observed during this event.

VY Tauri is at the edge of the Taurus-Auriga dark clouds, and is at times quite active, rising quickly from minimum light for intervals of 150 to 700 days before subsiding again (see Fig. 15). During the most active episodes, these almost U Geminorum–like maxima occur with spacings of 1–2 years. Then for long intervals the star can remain quiescent. At minimum, the spectrum in the red is unmistakably that of a T Tau star, with Hα in emission and Li I λ6707 strong; the type is M0 V. The spectrum near maximum has been observed at Lick, but it is quite unlike that of FU Ori or of any other T Tau star: it is crowded with rather narrow low-excitation lines, notably of Fe I.

UZ Tauri was for many years regarded as a nova because of major maxima observed in 1921 (Bohlin 1923) and in 1924 (Esch 1924), the first of which attained $m_{pg} = 11.0$. A fragmentary light curve for the 1921–1922 maximum is shown as part of Figure 16. Several other maxima of lesser amplitude probably took place in 1894, in 1943, perhaps more than once between 1946 and 1950, and in 1974. Normally, UZ Tau appears as a double T Tau star of 3″ separation and small Δm. The two together at minimum light correspond to about $V = 12.9$, $B - V = +1.3$. Measures of the position of the photocenter of the unresolved image of UZ Tau on Bohlin's plates show that in 1921 it was the eastern component that erupted (Herbig, unpublished). Joy (1942, 1943, 1945), as the 1943 maximum was just beginning, showed that again it was the eastern star that was active. Even though the object had then brightened only by about 0.4 mag (visually), a rich emission-line spectrum of the T Tau type had appeared. About 5 weeks later, the variable was 1 mag still brighter (in integrated light), but unfortunately no spectroscopic observations were made at that time. The only information available on the spectrum of UZ Tau at full maximum light is Bohlin's (1923) remark, from a visual observation with

[6] An alternative assumption would have been that it is only a special subgroup of T Tau stars that undergoes such eruptions. This would of course require that minority to erupt at a correspondingly higher frequency than 10^{-4} yr^{-1} star^{-1} to maintain the observed rate. There is no evidence either in support of or in contradiction to this more complicated counterproposal, so it seems preferable to remain with the simpler hypothesis.

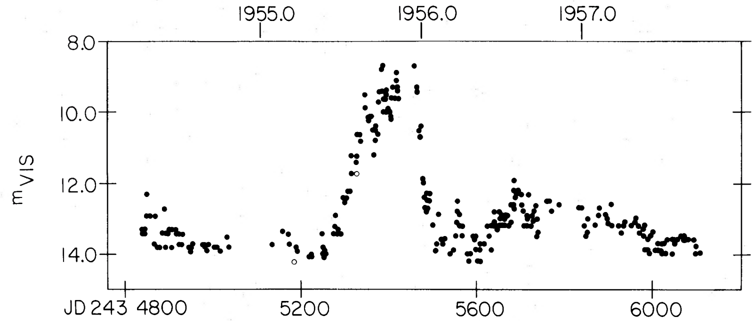

FIG. 14.—The 1955–1956 maximum of EX Lup. The observations are visual estimates (Bateson and Jones 1957).

an ocular spectroscope on the Stockholm 16 cm refractor, that the spectrum appeared continuous. The eastern component at minimum has been classified in the blue as dM1.5e by Joy (Joy and Abt 1974) and in the red as M1 to M3 V by Herbig (1977); emission lines of H, He I, [O I] are present, Li I λ6707 is strong, and the spectrum is that of a conventional T Tau star.

Table 9B contains data on the light variations and M'_{pg} values for these three variables, and Figure 16 shows sections of their light curves to the same scale as the FU Ori stars. The eruptive activity of the T Tau variables is of smaller range and shorter duration than the FU Ori outbursts, but is much more frequent. The details of the behavior of the T Tau stars are not the same: the very active VY Tau stands apart from the other two rarely eruptive stars. But this may not be a fundamental matter. The spectra are essentially identical at minimum, and the simplest hypothesis is surely the only one justified at this time, namely, that the physical mechanisms responsible for these spasmodic eruptions is the same in all three, that it is a process limited to a minority of young stars, and that it can operate at different scales in different objects.

However, the larger step, to claim that these relatively active small-range variables are driven by the same phenomenon that one sees on a larger scale in the FU Ori variables, cannot be taken. Unless some theoretical guidance can be provided, a convincing connection between the two families will require the discovery of examples having intermediate properties.

d) *Applications to the Early Solar System*

If the young Sun underwent one or more FU Orionis–like eruptions, then some of the effects upon matter in the inner solar nebula can be hypothesized. Certainly, dust grains near the star would be melted or vaporized. If, as for V1057 Cyg near maximum, $T_{\rm eff} = 6500$ K when $R = 17\,R_\odot$, then large grains with an albedo $A \approx 0.5$ would have their temperatures raised to $T_g = 1500$ K at a distance of

$$r = (T_*/T_g)^2 \tfrac{1}{2} R_* (1 - A)^{1/2} = 0.5\ \text{AU}\,. \quad (3)$$

Very small particles such as those considered in connection with the infrared excess (§ III*f*) would attain the same temperature at about 1.5 AU. It is possible that the chondrules—primitive, roundish millimeter-sized objects found embedded in chondritic meteorites—may have frozen from dust melted on such an occasion. It would be interesting if the record in the meteorites could provide some evidence whether in the case of the Sun there was more than one remelting episode.

It also seems that the high-velocity gas ejected from V1057 Cyg could exert a significant dynamic effect on circumstellar dust. The particle size range in which it would be effective can be estimated as follows. The complex structure of the Ca II lines observed in 1971 (Fig. 4) was seen against a broad emission feature that essentially filled the star line. It is difficult to reconstruct this background "continuum," but an attempt to do so leads to a rough value for the equivalent width of the -210 km s^{-1} component of λ3933 of $W_\lambda = 685$ mÅ. From λ3933 alone, one can relate $\log W_\lambda/b_\lambda$ to $\log \tau_0 = \log \pi^{1/2}e^2 f \lambda^2 N/mc^2 b_\lambda$, where N is the Ca II column density and b_λ is the Doppler parameter, by a standard curve of growth. With an oscillator strength $f = 0.69$, one finds that (for example) if $b = b_\lambda c/\lambda = 8$ km s^{-1}, then $N = 1 \times 10^{16}$ ions cm^{-2}; if $b = 12$ km s^{-1}, $N = 1.5 \times 10^{14}$ ions cm^{-2}; if $b = 20$ km s^{-1}, $N = 2 \times 10^{13}$ ions cm^{-2}. Unfortunately, although the same feature at -210 km s^{-1} is present in the Ca II λ3968 line also, the background there is much too confused by the presence of Hε for an estimate of W_λ to be made, and a value of b to be determined. Furthermore, the resolution of these spectrograms is too low for a direct determination of b. If it is assumed that $b \approx 10$ km s^{-1}, then $N \approx 10^{15}$ ions cm^{-2} at that time. If $1/y$ is the fraction of Ca atoms that exist as Ca II, and if the solar system mass ratio of all elements to Ca by mass, $x = 1.4 \times 10^4$, holds, then the average density in the high-speed shell is $\rho = Nxym_{\rm Ca}/z$ g cm^{-3}, where $m_{\rm Ca}$ is the mass of a Ca atom and z is the line-of-sight thickness of the shell. For the latter, one can say only that the shells must be thinner than their separation at that time, which was about 5×10^9 km if they were ejected at the start of the outburst; therefore, $z \approx 10^{14}$ cm.

The force exerted by this material arriving at velocity v upon a dust particle of radius a is

$$F = \pi \rho v^2 r_0^2 a^2/r^2\,, \quad (4)$$

where r_0^2/r^2 expresses the dependence of ρ upon r,

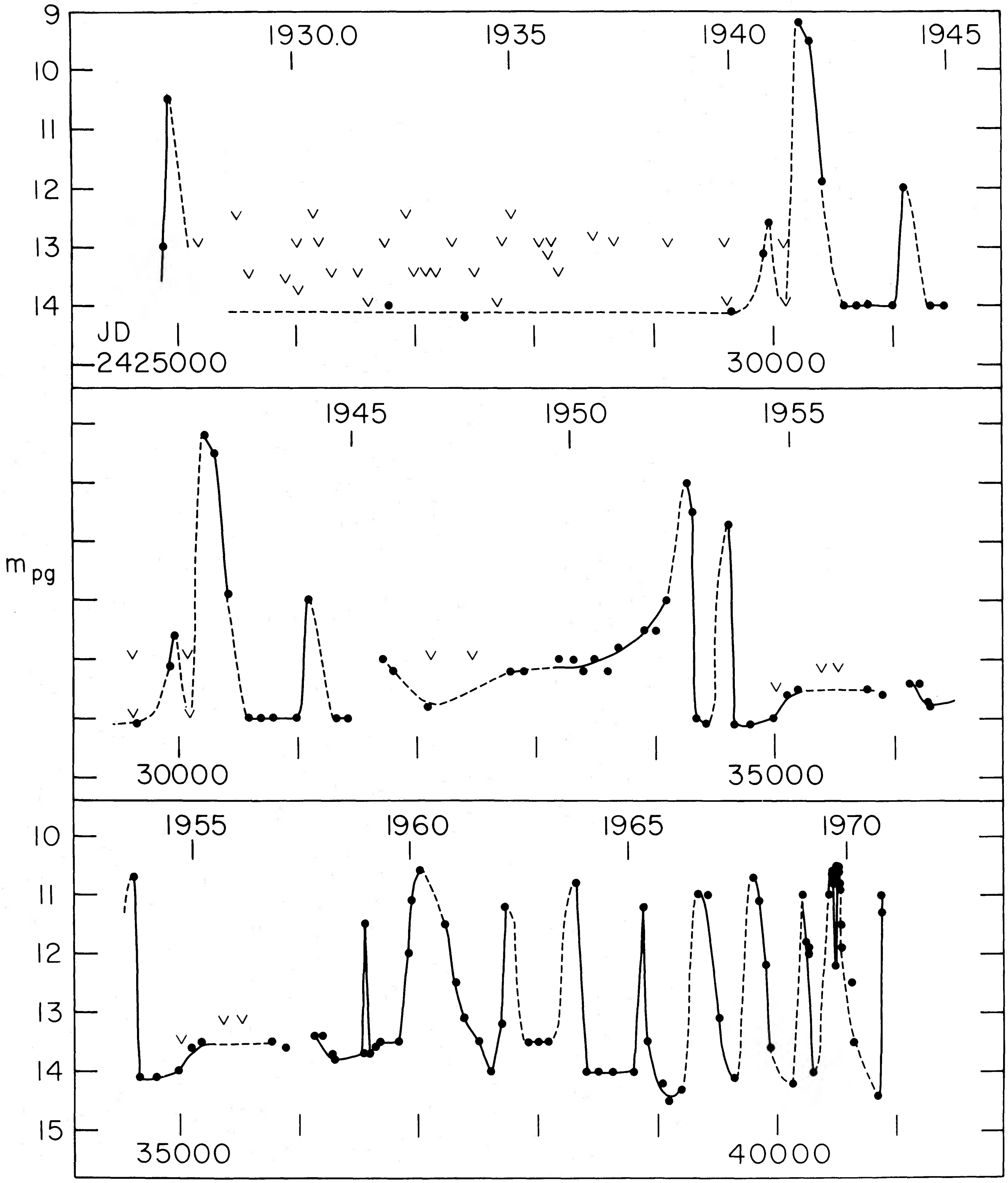

FIG. 15.—The photographic light curve of VY Tau, from Meinunger (1969, 1971)

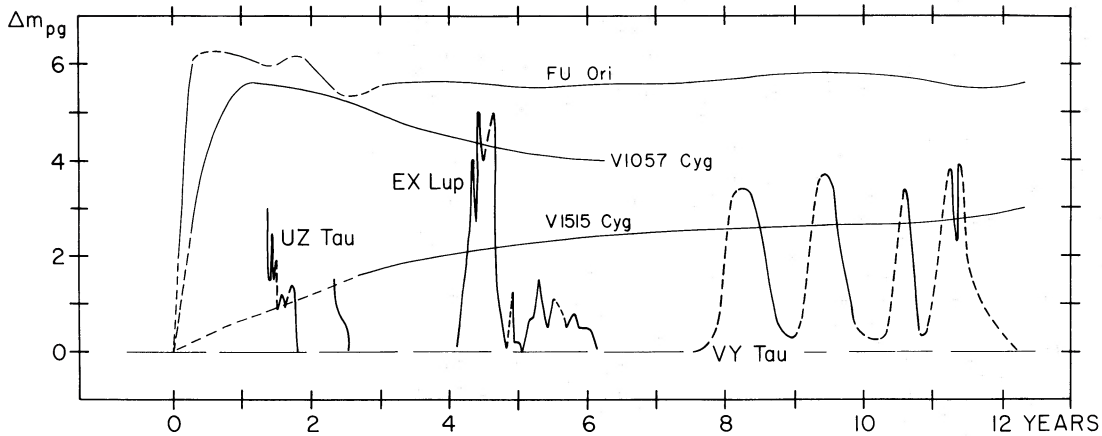

FIG. 16.—Comparison of sections of the early light curves of FU Ori, V1057 Cyg, and V1515 Cyg with fragments of the light curves of UZ Tau, EX Lup, and VY Tau. The magnitudes of EX Lup are visual; all others are photographic.

the distance from the star. On the other hand, the gravitational force upon that particle is

$$F_G = 4\pi G \mathfrak{M}_* a^3 s / 3r^2 , \quad (5)$$

where $s = 3$ g cm^{-3} is the density of the solid. Thus

$$\frac{F}{F_G} = \frac{3Nxym_{\rm Ca} r_0{}^2 v^2}{4zsG\mathfrak{M}_* a} , \quad (6)$$

and particle pressure exceeds gravity, $F/F_G > 1$, for all particles smaller than a critical radius $a_c = 4 \times 10^{-16}\, Ny$ cm. The ionization correction for Ca, y, is not known; but certainly $y \gg 1$. Therefore under this set of circumstances, circumstellar particles of less than about centimetric size will be driven outward for as long as the gas is impinging upon them: for a time z/v, or several months under these assumptions. The large uncertainties involved, particularly in the values of N and y, make this estimate of a_c very approximate. Nevertheless, it does appear that the high-speed shells from these eruptions will have the effect of driving the finer dust and gas further out in the solar nebula, leaving behind the larger lumps. This is a role that, in the past, speculation has also assigned to the so-called "T Tauri solar wind."

VI. COMMENTS ON SUGGESTED EXPLANATIONS OF THE PHENOMENON

There has been no lack of proposals for the cause of the outbursts. These suggestions are classifiable under several general headings, which will be criticized in light of the present results. The first two of these categories represent once-only events, which face the objections of § V*b*.

1. *Dissipation of a circumstellar screen.* As emphasized in § V*a*, such explanations (Poveda 1965; Larson 1972; Cohen and Woolf 1972; Welin 1973) seem ruled out: the spectroscopic activity and the continuing changes in $T_{\rm eff}$ and R of V1057 Cyg show that the basic phenomenon is intrinsic to the star.

2. *Permanent structural readjustment of the star.* The proposal (Grasdalen 1973) that V1057 Cyg was a star of 8 $\mathfrak{M}_\odot$ which following the outburst had finally moved to its proper radiative-equilibrium evolutionary track now seems improbable as the star fades and grows cooler. The spectral peculiarities would in any case make a conventional atmospheric analysis, such as that which led to Grasdalen's mass estimate, suspect. On the possibility that the initial brightening represents the emergence of a shock wave at the stellar surface (Appenzeller and Tscharnuter 1974, 1975), the duration of the rise in FU Ori and V1057 Cyg (hundreds of days) is too long; the rise time for V1515 Cyg was at least an order of magnitude longer. The concept of a slow thermal pulse is more in accord with the observations. Ulrich and Drake (1975, unpublished) have suggested that there was a structural readjustment in response to a rapid accretionary buildup from about 1 to 8 $\mathfrak{M}_\odot$. As indicated, the claim that V1057 Cyg is really a star of 8 $\mathfrak{M}_\odot$ is most unconvincing, nor is there any evidence that accretion on that scale has recently taken place. In fact, what evidence exists points in the opposite sense. The spectrum of V1057 Cyg at minimum (Fig. 2) shows the Ca II λ3933 line strongly in emission, while Ca II λ3968 is absent. This has been observed in other T Tau stars, and is caused by the suppression of λ3968 by the shortward absorption component of Hε λ3970. Therefore at that time the star appeared to be *ejecting* material. The suggestion that the flare-up represents rapid collapse across the forbidden region to a Hayashi track (Herbig 1966) now also appears untenable, because none of the known examples came up from invisibility as a pure infrared source, and because the radius change during the flare-up, of V1057 Cyg at least, was in the opposite sense.

3. *Result of the infall of a large object onto the star.* If an object like Jupiter fell to the surface of a 1 $\mathfrak{M}_\odot$ star, the kinetic and nuclear energy released would be about 5×10^{45} ergs. The present luminosity of FU Ori is about $10^3\, L_\odot$, and this could in principle be maintained by the energy released in such an event for several decades. However, the initial flare-up of the

star would be very sudden and not of the extended durations actually observed.

4. *Subsurface nuclear reactions*. This mechanism is purely ad hoc, and faces serious difficulties. The proposal is that D might be produced over a long period of time by surface reactions as are believed to take place in some solar flares (Anglin 1975), stored in a convection zone too shallow to reach the temperature required for D burning until the D concentration reaches the point where ignition begins at the bottom; and as the temperature then rises, D(p, γ)^{3}He reactions rapidly consume the remainder. Although this idea has attractive features, such as the ability to explain recurrent outbursts and the subsidence of the activity as the star ages, an enormous rate of D production would be required over the 10^4 years between eruptions. But it is doubtful that a real star of the mass (about 3 $\mathfrak{M}_\odot$) appropriate for such a shallow zone would behave in this way. Shevchenko (1975) has considered other nuclear explanations for the phenomenon.

5. *Strong surface magnetic field*. Gershberg and Petrov (1976) have proposed that T Tau stars have strong surface fields which interact with convective motions and, much as in one theory of the sunspot phenomenon, transfer most of the subphotospheric energy into the high atmosphere via magnetohydrodynamic waves, so that the visual surface brightness is depressed by the corresponding factor. If the surface field should for some reason drop below a critical value (a few thousand gauss) normal convection would abruptly resume, and the surface brightness would rise to the full radiative value, thus causing the FU Orionis–like flareup. The idea is attractive in that repetitive flaring, and a decay of the activity with age, would be understandable. On the other hand, it conflicts with the point of view of this paper in its implication that the normal state of the star is maximum light; i.e., that when the magnetic activity finally subsides, the star will proceed to the main sequence on a track appropriate to a large mass.

6. *Thermalization by ejected material of the energy in a preexisting envelope of fast particles*. Ambartsumian's (1971) suggestion is supported by observation to the extent that material was certainly ejected by the star, and that an optically thick layer did form above the original stellar surface. But why the star should suddenly begin to eject matter is unexplained. It is simpler to assume that the ejection and the luminosity increase are both the consequences of some internal perturbation.

In short, no convincing explanation of the FU Ori phenomenon is as yet available.

VII. FINAL REMARKS

The enlargement of the number of known examples of the FU Ori class from one to three has not led to a proportional increase in understanding of the phenomenon, although the elimination of some seemingly plausible explanations is a forward step. Some facts are now established: based on a single fortunate preoutburst spectrogram of V1057 Cyg and reasonable inference for the others, the progenitors are T Tau stars; there is no chance, for example, that they are accreting interlopers such as white dwarfs. The luminosity increase of V1057 Cyg is now seen to be the result of a large increase in surface brightness and a modest increase in effective radius. These take place rather slowly, in contrast to the ejection of shells of high-velocity gas, although it is unproved that all the shells observed at V1057 Cyg were launched at the time of the eruption. It is clear also that the time rate of the brightening and of the subsequent decline can differ greatly from one star to another. No model of the outer layers of the star has been constructed; there are major peculiarities to be explained, but possibly a deep atmosphere with depth-dependent expansion velocity can account for some. The significance of the ubiquitous dust remains conjectural: nearby material is probably responsible for the large infrared excesses, while more distant dust produces the curiously ordered reflection nebulae. Unless the observed rate of three events in about 80 years is a statistical accident—and if anything that number should be a lower limit—it is difficult not to conclude that the eruptions are repetitive, and with a surprisingly high frequency. The value of 10^{-4} year^{-1} star^{-1} that results from the simplest interpretation of the data will be superseded when more cases are discovered and careful allowance is made for incompleteness. In a few decades, some questions will be clarified: V1057 Cyg may by then have returned to minimum light, and it should be obvious whether it resumes the appearance of a normal T Tau star. Not only should new examples erupt, but perhaps some past events that were overlooked can be detected in T Tauri–rich regions on old photographs. On the theoretical side, the tightened boundary conditions that observation has now provided should encourage serious consideration of the problem, as distinct from qualitative or untestable conjecture.

I am deeply indebted to the many colleagues who have helped me in one way or another during the work described in this Lecture. Space limitation prohibits specific acknowledgment, so I can only say that Drs. P. Bodenheimer, G. Grasdalen, H. Hippelein, D. Hoffleit, G. R. Knapp, L. V. Kuhi, B. V. Kukarkin, C. Lada, F. Lo, K. M. Merrill, W. W. Morgan, G. Welin, and W. Wenzel have been exceedingly generous, and I am most grateful. Drs. A. M. Boesgaard, T. Simon, and S. C. Wolff have provided much good advice. Messrs. E. A. Harlan and R. P. S. Stone at Mount Hamilton have contributed absolutely essential spectrograms and direct photographs, and *UBV* photometry and photoelectric scans, respectively. I acknowledge also the courtesies extended by Directors H. W. Babcock of the Hale Observatories, I. Appenzeller of the Landessternwarte, Heidelberg, and P.-O. Lindblad of the Stockholm Observatory in allowing me to examine plates in their files. Mr. D. R. Soderblom has provided invaluable computing and observational assistance, and I have received superb cooperation from the scientific, technical, and administrative groups at Santa Cruz and Mount Hamilton. Much of the final draft of this paper was written at the Institute for Astronomy, University of Hawaii, and I appreciate very much the hospitality of Director J. T. Jefferies and his staff. Finally, I thank the National Science Foundation for its support throughout, without which this investigation would probably have been impossible.

REFERENCES

Adams, W. S. 1949, *Ap. J.*, **109**, 354.
Ambartsumian, V. A. 1971, *Astrofizika*, **7**, 557.
Andriesse, C. D. 1976, *M.N.R.A.S.*, **175**, 13P.
Anglin, J. D. 1975, *Ap. J.*, **198**, 733.
Appenzeller, I., and Tscharnuter, W. 1974, *Astr. Ap.*, **30**, 423.
———. 1975, *Astr. Ap.*, **40**, 397.
Barnes, T. G., Evans, D. S., and Parsons, S. B. 1976, *M.N.R.A.S.*, **174**, 503.
Bartaya, R. A. 1962, *Astr. Zh.*, **39**, 159 (English transl. in *Soviet Astr.—AJ*, **6**, 119).
Bateson, F. M., and Jones, A. F. 1957, *Circ. R.A.S. New Zealand, Var. Star Sec.*, No. 79.
Bechis, K. P., and Lo, K. Y. 1975, *Ap. J.*, **201**, 118.
Bohlin, K. 1923, *Astr. Nach.*, **218**, 203.
Bossen, H. 1972, *Inf. Bull. Var. Stars*, No. 722.
Breger, M. 1976, *Ap. J. Suppl.*, **32**, 1.
Bussoletti, E., and Zambetta, A. M. 1976, *Astr. Ap. Suppl.*, **25**, 549.
Cohen, M. 1973*a*, *M.N.R.A.S.*, **161**, 85.
———. 1973*b*, *M.N.R.A.S.*, **161**, 105.
———. 1974, *Pub. A.S.P.*, **86**, 813.
———. 1975, *M.N.R.A.S.*, **173**, 279.
Cohen, M., and Woolf, N. J. 1971, *Ap. J.*, **169**, 543.
Dibai, E. A., and Zaitseva, G. V. 1968, *Astr. Circ. USSR*, No. 481, p. 7.
Esch, M. 1924, *Beob-Zirk.*, **6**, 5.
Filin, A. Ja. 1974, *Var. Stars Suppl.*, **2**, 63.
FitzGerald, M. P. 1970, *Astr. Ap.*, **4**, 234.
Georgelin, Y. P., and Georgelin, Y. M. 1970, *Astr. Ap.*, **6**, 349.
Gershberg, R. E., and Petrov, P. P. 1976, *Soviet Astr. Letters*, in press.
Gieseking, F. 1973, *Inf. Bull. Var. Stars*, No. 806.
———. 1975, *Astr. Ap.*, **31**, 117.
Grasdalen, G. L. 1973, *Ap. J.*, **182**, 781.
Greenberg, J. M. 1968, in *Nebulae and Interstellar Matter*, ed. B. M. Middlehurst and L. H. Aller (Chicago: University of Chicago Press), chap. 6.
Haro, G. 1971, *Inf. Bull. Var. Stars*, No. 565.
———. 1972, *Inf. Bull. Var. Stars*, No. 714.
Herbig, G. H. 1950, *Pub. A.S.P.*, **62**, 211.
———. 1958, *Ap. J.*, **128**, 259.
———. 1960, *Ap. J. Suppl.*, **4**, 337.
———. 1962, *Adv. Astr. Ap.*, **1**, 47.
———. 1966, *Vistas in Astronomy*, Vol. **8**, ed. A. Beer and K. Aa. Strand (Oxford: Pergamon), p. 109.
———. 1970, in *Spectroscopic Astrophysics*, ed. G. H. Herbig (Berkeley: University of California Press), p. 237.
———. 1977, *Ap. J.*, **214**, 747.
Hippelein, H. H. 1973, *Astr. Ap.*, **25**, 59.
Hoffleit, D. 1939, *Harv. Bull.* No. 911, p. 41.
Humphreys, R. M. 1976, *Ap. J.*, **206**, 122.
Humphreys, R. M., and Ney, E. P. 1974*a*, *Ap. J.*, **190**, 339.
———. 1974*b*, *Pub. A.S.P.*, **86**, 444.
Humphreys, R. M., Strecker, D. W., and Ney, E. P. 1971, *Ap. J.* (*Letters*), **167**, L35.
Joy, A. H. 1942, *Pub. A.S.P.*, **54**, 33.
———. 1943, *Pub. A.S.P.*, **55**, 38.
Joy, A. H. 1945, *Ap. J.*, **102**, 168.
Joy, A. H., and Abt, H. A. 1974, *Ap. J. Suppl.*, **28**, 1.
Knapp, G. R., Kuiper, T. B. H., Knapp, S. L., and Brown, R. L. 1977, *Ap. J.*, **214**, 78.
Kolotilov, E. A. 1975, *Astr. Circ. USSR*, No. 873, p. 4.
Landolt, A. U. 1972, *Inf. Bull. Var. Stars*, No. 642.
———. 1975, *Pub. A.S.P.*, **87**, 379.
Larson, R. B. 1972, *M.N.R.A.S.*, **157**, 121.
Lee, T. A. 1970, *Pub. A.S.P.*, **82**, 765.
Lo, K. Y., and Bechis, K. P. 1974, *Ap. J.* (*Letters*), **190**, L125.
Loren, R. B., Vanden Bout, P. A., and Davis, J. H. 1973, *Ap. J.* (*Letters*), **185**, L67.
Mandel, O. E. 1975*a*, *Var. Stars*, **20**, 123.
———. 1975*b*, in *IAU Symposium No. 67, Variable Stars and Stellar Evolution*, ed. V. E. Sherwood and L. Plaut (Dordrecht: Reidel), p. 123.
McLaughlin, D. B. 1946, *A.J.*, **52**, 109.
Meinunger, L. 1969, *Mitt. Ver. Sterne*, **5**, 47.
———. 1971, *Mitt. Ver. Sterne*, **5**, 173.
Meinunger, L., and Wenzel, W. 1971, *Mitt. Ver. Sterne*, **5**, 170.
Mendoza, E. E. 1968, *Ap. J.*, **151**, 977.
———. 1971, *Ap. J.* (*Letters*), **169**, L117.
Miller, J. S., and Mathews, W. G. 1972, *Ap. J.*, **172**, 593.
Minn, Y. K., and Greenberg, J. M. 1973, *Astr. Ap.*, **22**, 13.
Poveda, A. 1965, *Bol. Obs. Tonantzintla y Tacubaya*, **4**, 15.
Racine, R. 1968, *A.J.*, **73**, 233.
Rieke, G., Lee, T., and Coyne, G. 1972, *Pub. A.S.P.*, **84**, 37.
Robinson, L. J., and Harwood, M. 1971, *Inf. Bull. Var. Stars*, No. 568.
Schwartz, R. D., and Snow, T. P. 1972, *Ap. J.* (*Letters*), **177**, L85.
Shanin, G. I., Shevchenko, V. S., and Shcherbakov, A. G. 1975, in *IAU Symposium No. 67, Variable Stars and Stellar Evolution*, ed. V. Sherwood and L. Plaut (Dordrecht: Reidel), p. 117.
Shevchenko, V. S. 1975, *Var. Stars*, **20**, 179.
Simon, T. 1975, *Pub. A.S.P.*, **87**, 317.
Simon, T., Morrison, N. D., Wolff, S. C., and Morrison, D. 1972, *Astr. Ap.*, **20**, 99.
Struve, O. 1939, *Beob. Zirk.*, **21**, 60.
Tsvetkov, M. K. 1976, *Inf. Bull. Var. Stars*, No. 1120.
Wachmann, A. A. 1954, *Zs. f. Ap.*, **35**, 74.
Weber, R. 1956, *L'Obs.*, **70**, 193.
———. 1961, *J. d'Obs.*, **44**, 275.
———. 1964, *Bull. Station Astrophot. Mainterne*, No. 2, p. 6.
———. 1967, *Bull. Station Astrophot. Mainterne*, No. 15, p. 58.
Welin, G. 1971*a*, *Astr. Ap.*, **12**, 312.
———. 1971*b*, *Inf. Bull. Var. Stars*, No. 581.
———. 1973, *Astr. Ap. Suppl.*, **9**, 183.
———. 1976, *Inf. Bull. Var. Stars*, No. 1195.
Wellmann, P., and Hachenberg, O. 1939, *Astr. Nach.*, **268**, 213.
Wenzel, W. 1963, *Mitt. Ver. Sterne*, No. 730.
Wenzel, W., and Gessner, H. 1975, *Mitt. Ver. Sterne*, **7**, 23.
Wesselink, A. J. 1969, *M.N.R.A.S.*, **144**, 297.
Wolstencroft, R. D., and Simon, T. 1975, *Ap. J.* (*Letters*), **199**, L169.

G. H. HERBIG: Lick Observatory, University of California, Santa Cruz, CA 95064

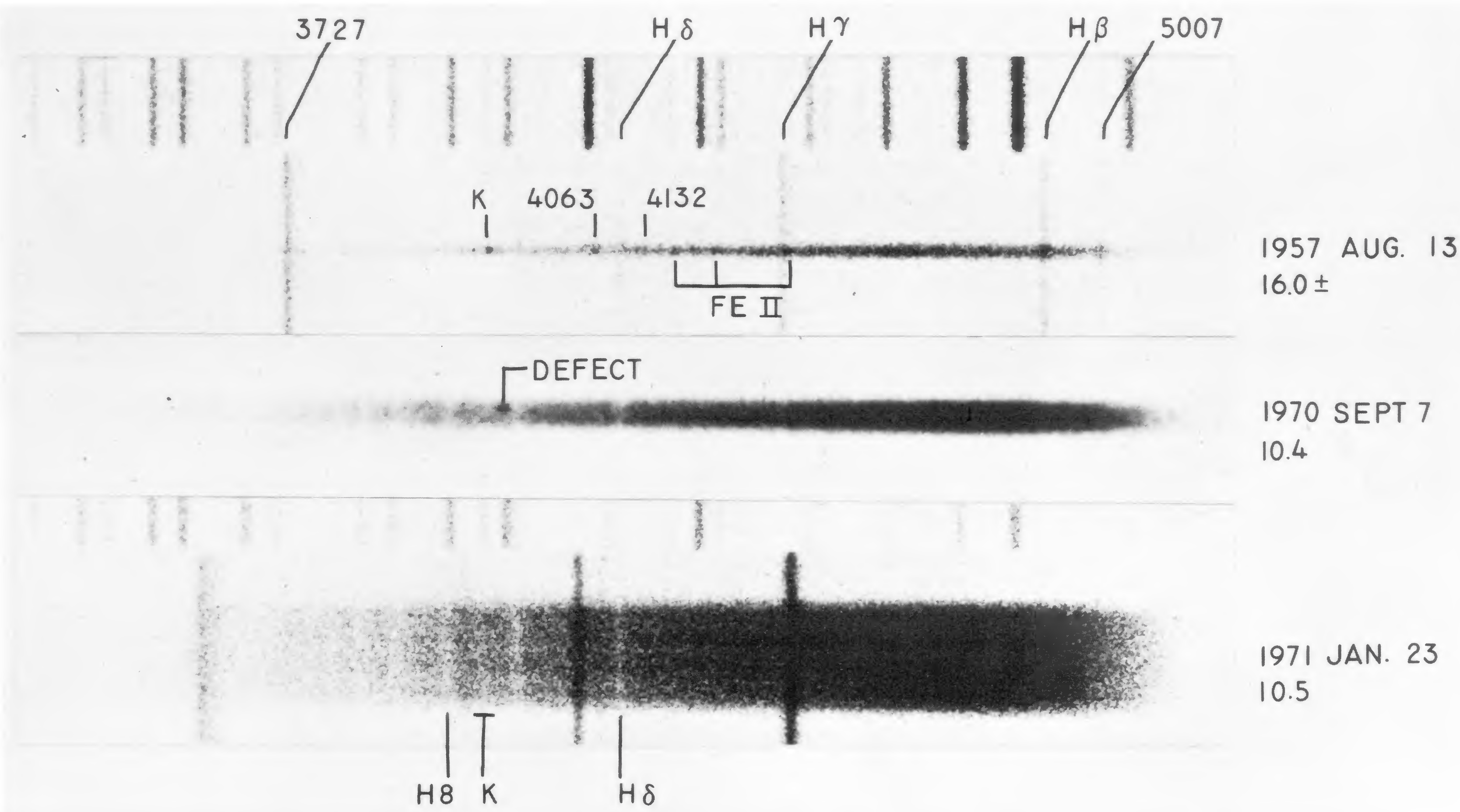

FIG. 2.—Low-dispersion spectrograms of V1057 Cyg. The upper and lower spectrograms (original dispersion 430 Å mm^{-1} at Hγ) were obtained with the nebular spectrograph of the Crossley reflector. The upper was taken 12 years before maximum, the lower shortly after maximum light; m_{pg} appears below the exposure date. In the upper spectrogram, the emission lines crossing the full spectrum are from the H II region NGC 7000. In the lower exposure, they are from artificial lighting. The upper spectrogram of V1057 Cyg resembles that of a normal T Tau star; all those characteristic emission lines have vanished in the lower spectrum. The central spectrogram, reproduced through the courtesy of Dr. G. Welin, is an Uppsala/Kvistaberg objective-prism plate (dispersion about 260 Å mm^{-1}), enlarged to the same scale as the others. It shows the spectrum of V1057 Cyg very near maximum light.

HERBIG (*see* page 695)

1977ApJ...217..693H

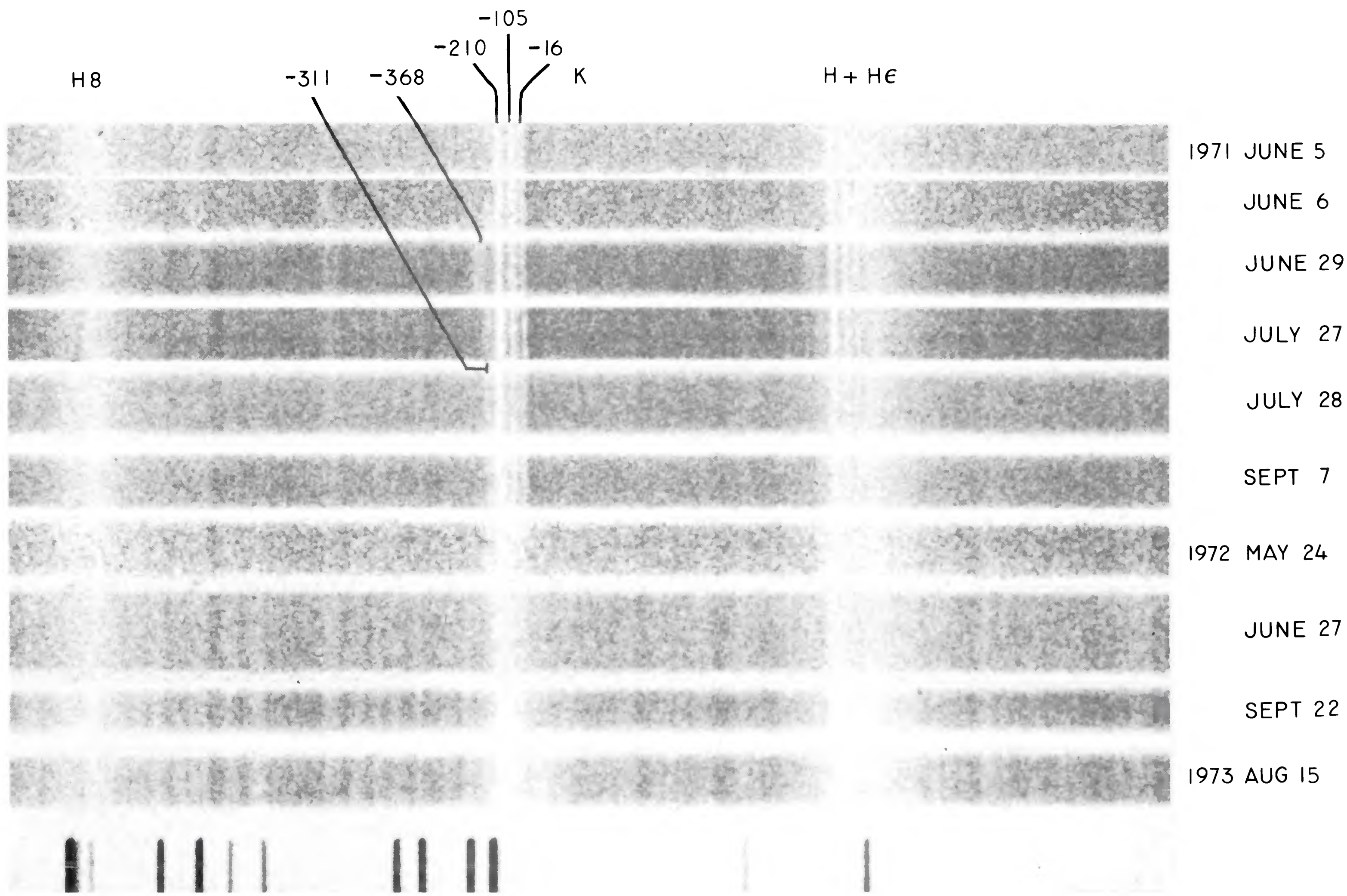

FIG. 4.—The structure of the Ca II H and K lines in V1057 Cyg, 1971–1973. The wing of the broad emission line that filled K during 1971 can be seen just longward of the complex shell absorptions. The anomalous strength and displacement of the -310 km s^{-1} feature in H and K on the single exposure of 1971 June 29 is obvious. In 1972 and 1973, the Ca II shell components may still have been present but were almost lost in the stellar H and K. The Ca II line at -16 km s^{-1} is interstellar. The original dispersion was 16 Å mm^{-1}, coudé spectrograph, 120 inch reflector.

HERBIG (*see* page 697)

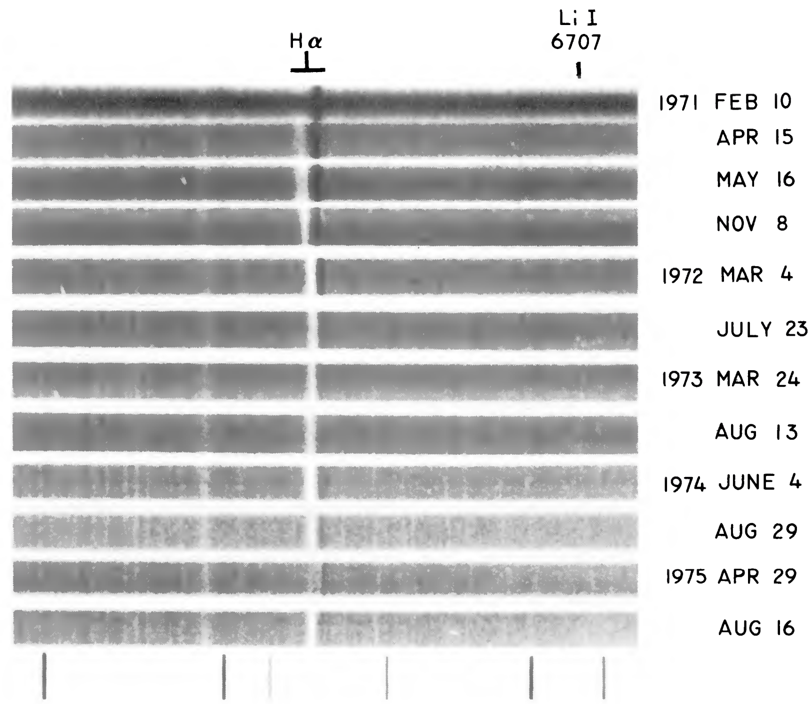

FIG. 6.—The Hα region of V1057 Cyg from 1971 to 1975. The fading of the emission component of Hα, and the changes in structure and displacement of the absorption component, are conspicuous. The growing complexity of the absorption spectrum reflects the increasingly later type. These spectrograms were taken with several image intensifiers, and plate scales could not be well matched, hence the staggered appearance of the lines especially on the right. The original dispersion was 34 Å mm^{-1}, coudé spectrograph, 120 inch reflector.

HERBIG (*see* page 699)

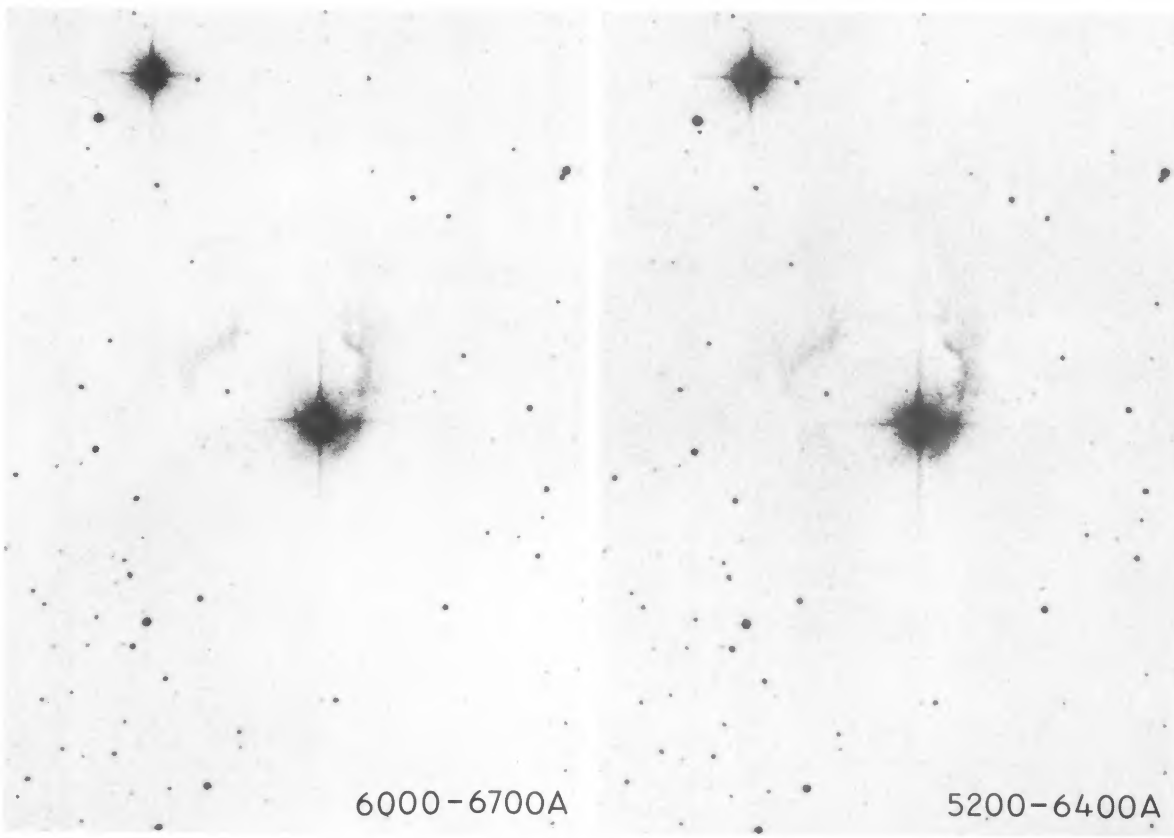

Fig. 10.—Direct photographs of the nebulosity at V1057 Cyg, taken in 1971 April and May with the Crossley reflector, by E. A. Harlan. The two passbands include and exclude Hα; the comparable density of the nebulosity on both shows that it cannot have an emission spectrum. The scale of this and Fig. 11 can be obtained from the fact that the angular distance between the two bright stars is about 166″. In this and the following direct photographs, north is above and east to the left.

Herbig (*see* page 705)

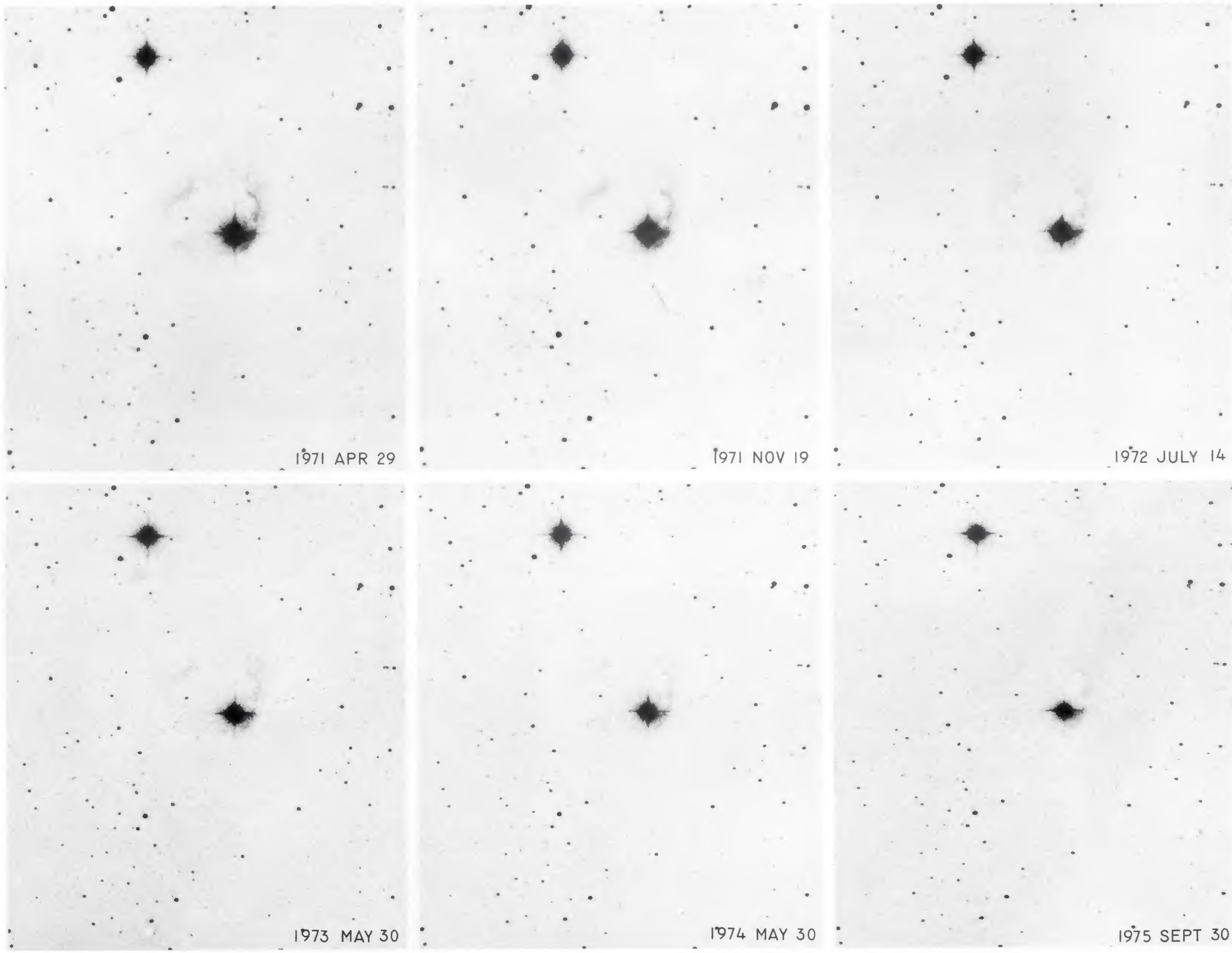

FIG. 11.—Direct photographs of the nebulosity at V1057 Cyg between 1971 and 1975, showing the slow fading of both nebula and star. These plates were taken in red light (6000–6700 Å) with the Crossley reflector; the exposure time was 1 hour on Kodak 103a-E emulsion behind a Schott RG-1 filter.

HERBIG (*see* page 705)

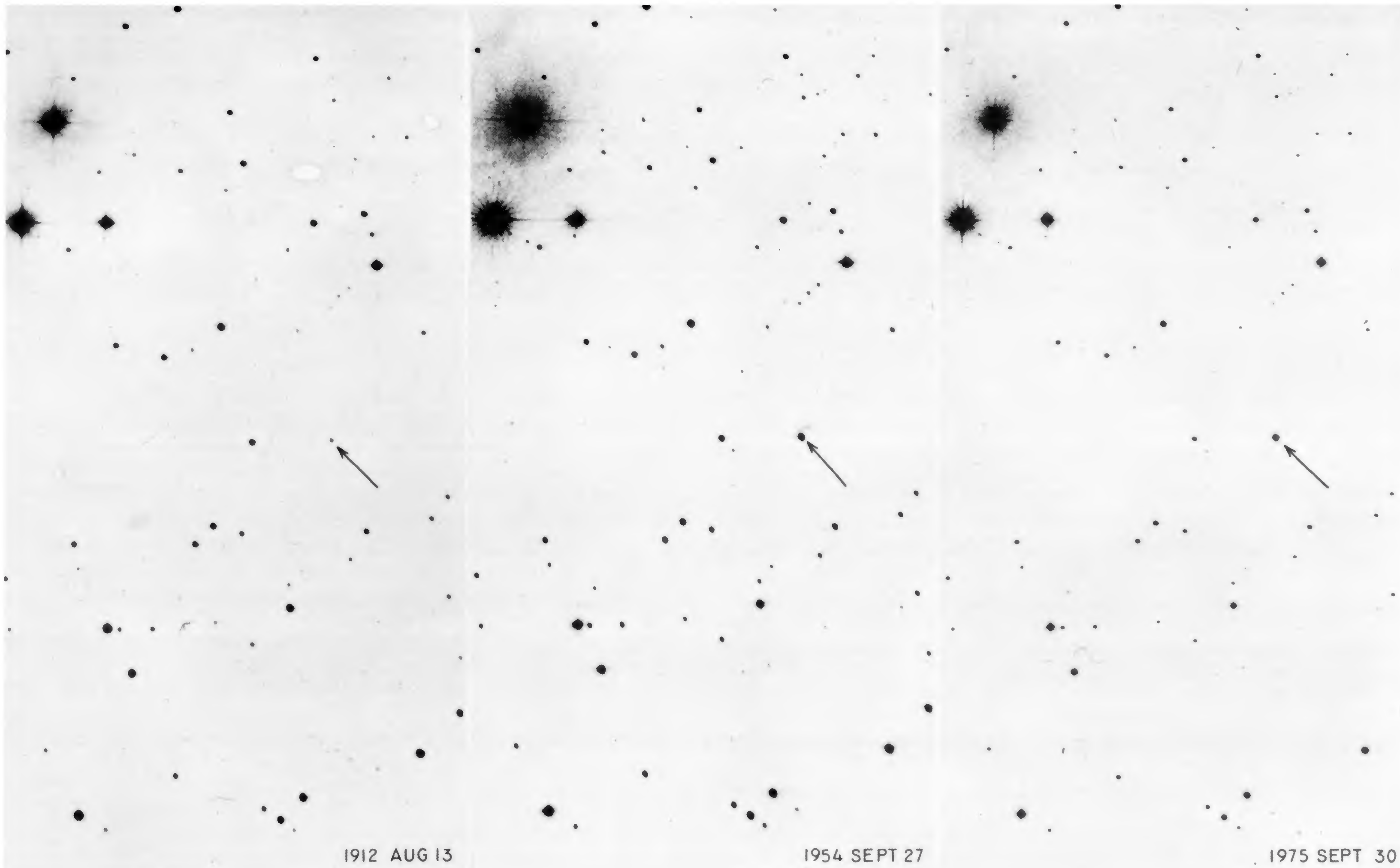

FIG. 12.—Direct photographs taken with the Crossley reflector, showing the brightening of V1515 Cyg between 1912 and 1975. The first two plates were centered on NGC 6914, which is out of the area shown here. The bright nebulous star in the upper left is BD +41°3731.

HERBIG (*see* page 706)