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THE COMPOSITE SPECTRA OF FU ORIONIS STARS

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ABSTRACT

Fourier transform spectra (4000–7000 cm^{-1}) of FU Ori and V1057 Cyg show strong water vapor and weak CO in absorption. Their optical spectra remain those of F–G supergiants, however. The new infrared spectra demand reappraisal of the FU Orionis phenomenon. Three models are discussed: (ii) a single star with a circumstellar dust shell; (ii) a binary in a common circumstellar envelope; and (iii) a rapidly rotating star with a flattened, possibly disklike, shell. The first model can clearly no longer explain the observations; of the other two models, the rapid rotator appears the more promising, although neither can be strongly preferred on the basis of the present data.

Subject headings: stars: circumstellar shells — stars: pre–main-sequence — stars: supergiants

I. INTRODUCTION

The association of FU Orionis stars with dark clouds and their direct link with T Tauri stars have emphasized the importance of the FU Orionis class in the study of pre–main-sequence evolution. The detailed history of Fu Ori, V1057 Cyg, and the most recent addition, V1515 Cyg, has been discussed by Herbig (1977) in a comprehensive review. We summarize below the important properties of the class, and refer the reader to his review for particulars of the individual stars.

1. FU Orionis stars are distinguished by an outburst of ~5 mag from a previous T Tauri–like state. Grasdalen (1973) argued that this was an evolutionary change. The difference in relative formation rates of a factor of ~100 (Herbig 1977) suggests, however, that FU Orionis stars are a recurrent phase in T Tauri evolution.

2. The spectra are those of F–G supergiants, although the apparent spectral type is later in the red region than in the blue and has systematically advanced since the outburst.

3. A high-velocity shell spectrum is superposed on the stellar spectrum. The stellar lines are broadened by ~60 km s^{-1}, but define a postoutburst radial velocity that is constant within the measuring errors, and in agreement with that of the surrounding molecular cloud.

4. Relative to the above spectral type the optical colors are reddened by 1.0–1.5 mag in $B - V$. From 1 μm onward the spectral energy distribution is flatter than a blackbody.

In this *Letter* we report moderately high-resolution Fourier transform spectra of the 1.5–2.5 μm regions of FU Ori and V1057 Cyg (§ II). The two spectra are markedly similar, but differ significantly from that of an F–G supergiant. In § III we discuss three models which attempt to explain the combined IR and optical data.

II. OBSERVATIONS

Infrared spectra of FU Ori and V1057 Cyg were obtained with a prototype 10 cm FTS (Hall 1977; Ridgway and Capps 1974) at the Mayall 4 m telescope on the nights 1978 January 28 and 1977 October 22, respectively. The selected resolution was 1 cm^{-1} (unapodized), to give a signal-to-rms-noise ratio of 60 at 4500 cm^{-1} in a 1 hour integration. The spectra were corrected for extinction by using a mean atmospheric transmission spectrum obtained from a ratio of α Lyr spectra at high and low air mass. For spectrophotometric standardization, the flux of α Lyr was assumed to be that of an ATLAS model atmosphere (Kurucz 1975). These spectra, together with some comparison spectra obtained under similar conditions, are shown in Figure 1 convolved to 5 cm^{-1} resolution.

The similarity of the infrared spectra of FU Ori and V1057 Cyg is strikingly apparent from Figure 1. The principal features are strong water vapor (compare the cool M dwarf at the bottom), distinct (but fairly weak) CO bands, and the absence of Brackett lines (compare the half-spectrum of δ CMa). We briefly discuss each of these features in turn.

1. The strong 1.9 μm and 1.4 μm water-vapor bands are the clearest contrast with the G supergiant spectrum of ϵ Gem. The presence of H_2O absorption was strongly suggested in low-resolution observations by Cohen (1975). The extension of absorption as far as 4400 cm^{-1} suggests a photospheric excitation temperature for the H_2O absorbers. A lower limit to this temperature of ~1000 K can be set by inspection of the opacity tables of Ferriso, Ludwig, and Thomson (1966).

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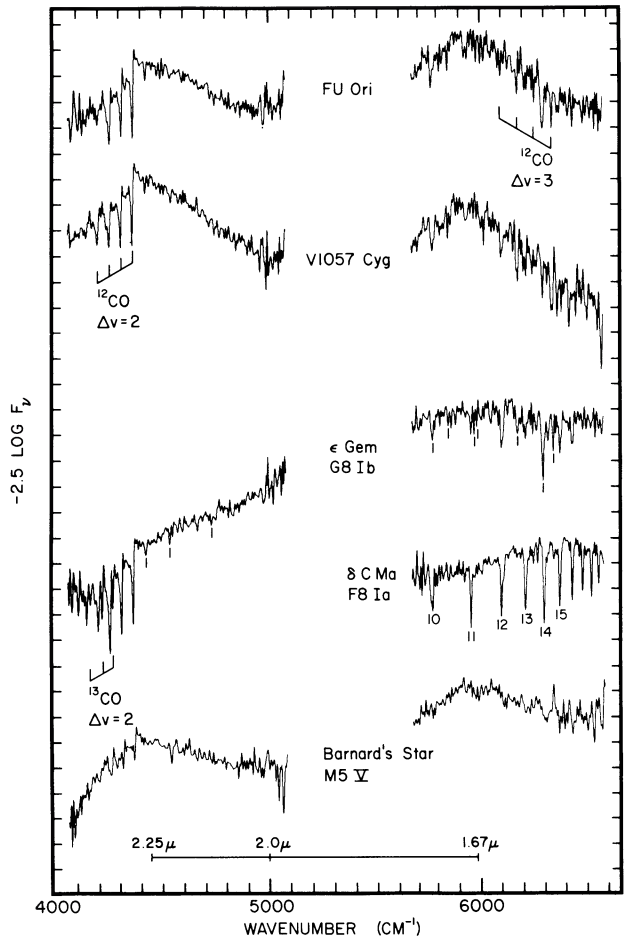


FIG. 1.—Spectrophotometry of FU Ori and V1057 Cyg at 5 cm^{-1} resolution. F and G supergiants and a late M star are shown for comparison. Vertical ticks are separated by 0.1 mag. No data are available for the opaque region 5080–5670 cm^{-1}, and only the blue part of the spectrum of δ CMa is shown. The unlabeled vertical lines mark prominent metal lines which could be identified in the sunspot atlas of Hall (1974). In the noisiest spectrum (FU Ori) the rms signal-to-noise ratio is ~130 at 4500 cm^{-1}. The noise increases substantially for wavenumbers >6500.

2. The first-overtone ^{12}CO bands do not extend to the high excitation seen in ε Gem (indicating lower temperature) and are weaker (suggesting higher gravity or spectral dilution). The second-overtone bands are stronger than in ε Gem, however. Interestingly, we do not see the first-overtone ^{13}CO bands, which are clearly present in ε Gem (^{12}C/^{13}C = 6; Luck 1978). A ^{12}C/^{13}C ratio for these young objects would be highly desirable, but a comprehensive model for the spectra is a prerequisite.

3. The Brackett series of hydrogen is not seen. At this resolution hydrogen lines are undetectable in ε Gem also, but readily apparent in δ CMa. A number of neutral metal lines are visible.

The 1 cm^{-1} resolution of the present spectra permits radial velocities to be measured from several CO and metal lines. The results are +28.2 ± 2.5 km s^{-1} for FU Ori and −13.4 ± 3.5 km s^{-1} for V1057 Cyg (rms errors). These are in good agreement with the mean optical velocity and the velocity of the nearby molecular clouds (see Herbig 1977).

For comparison with our IR spectra, the IIDS spectrum obtained with the intensified image dissector scanner (3600–5400 Å) of V1057 Cyg was obtained on 1977 November 5. The spectral type from the G band/Hγ ratio was G0.

New infrared photometry has also been obtained for both stars on the system of Persson, Aaronson, and Frogel (1977) (see Table 1). The photometric errors are less than 0.02 mag. Relative to Grasdalen's (1973) photometry we note a decline in the 2 μm luminosity of 0.3 mag. This rate is only a quarter of that in the B bandpass. When allowance is made for the reddening and the single-sideband nature of the CO and H_2O indices, the measurements in Table 1 are consistent with the FTS spectra.

III. INTERPRETATION

a) The Dust-Shell Model

The energy distribution of V1057 Cyg, interpolated to the epoch 1977.0, is shown in Figure 2. As there are no recent 10 μm and 20 μm measurements, those of Simon (1975) required extrapolation. To fit the IR energy distribution, the two-component model of Rieke, Lee, and Coyne (1972) remains the only viable one. A hot component (~1700 K) is required to fit the 2–5 μm data; an outer cooler component ($T \approx 200$ K, radius ~300 AU) will fit the longer wavelengths. The alternative suggestion by these authors, of free-free emission from a hot gas shell, has been ruled out (Simon *et al.* 1972) by the absence of the accompanying optical emission.

The present spectra, however, are consistent only with a photospheric origin for the 2 μm radiation. Since grain opacities (Gaustad 1963; Robinson and Hyland 1977) are at least two orders of magnitude greater than water-vapor opacity (Auman 1967), the column density of an optically thin, hot dust shell is insufficient to produce significant water-vapor absorption. Even if we ignore this argument and suppose that a "hot" dust shell can mimic the absorption spectrum of an M-type photosphere, in the IR, we are confronted by the absence of TiO bands in the visible spectrum.

The dust-shell model is thus inconsistent with the observed composite spectrum. Clearly, what is needed is a model which permits the *addition* of photospheric

TABLE 1

RECENT INFRARED PHOTOMETRY

	V1057 Cygni (1977 Nov 1)	FU Orionis (1978 Feb 9)
K.....	5.10	4.84
$J-H$.....	1.02	0.82
$H-K$.....	0.65	0.46
CO.....	−0.045	0.015
H_2O.....	0.385	0.335
Telescope...	KPNO 2.1 m	Hopkins 1.5 m

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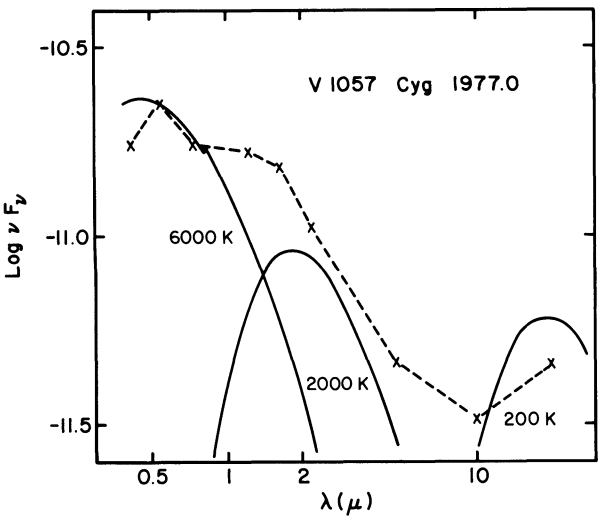


FIG. 2.—The νF_ν (W m^{-2}) energy distribution of V1057 Cyg, interpolated to an epoch 1977.0 (*dashed line*) and de-reddened by $E(B - V) = 1.0$. Sources: Herbig 1977, Simon 1975, Grasdalen 1973, and Table 1. The adopted calibration was that of Wilson *et al.* 1972. The curve labeled 6000 K is a log $g = 2$ model atmosphere of Carbon and Gingerich (1969) normalized at V. The other curves are 2000 K and 200 K blackbodies.

components of different temperatures. We explore two such models below.

b) A Binary Model

A natural explanation of the spectral features discussed in the previous section is that FU Orionis stars are binaries, consisting of a hot component and a cool component, enveloped in a common circumstellar shell. Such a model has been developed for other F–G supergiants by Humphreys (1976). In the case of V1057 Cyg, addition of an M star with $K \approx 5$ mag and a blackbody temperature of 2000 K provides a plausible fit to the photometry (Fig. 2). At Grasdalen's (1973) distance of 600 pc, the luminosity implied for the cool component is $M_{\rm bol} \approx -1$. The parameters for FU Ori are very similar.

Three aspects of this interpretation, however, suggest that it is an ad hoc solution rather than a compelling model.

1. It is not clear whether an overluminous T Tauri star and an underluminous M giant form a consistent evolutionary pair. One possible suggestion is that the M giant is a low-mass star in its Hayashi contraction phase.

2. No radial-velocity variations have been observed. In the edge-on case with both masses approximately solar, a binary separated by less than 10 AU could be detected in Herbig's (1977) optical velocity curve. If we suppose a large mass ratio of the hot to cool components, the agreement between the infrared velocities and the molecular cloud velocities places a similar constraint.

3. The 5 mag outbursts remain a mystery. Mass transfer, although an attractive mechanism, is unlikely, given the minimum separation derived above and a radius for the cool (larger) component of $\sim$0.5 AU.

c) A Rapid Rotator

Herbig (1966, 1977) has suggested that the line broadening (§ I) may result from axial rotation. If we consider the visual luminosity alone for V1057 Cyg and take the effective temperature as solar, the radius of 18 $R_\odot$ implies a centrifugal acceleration of (40/ $\sin^2 i$) cm s^{-2}. This is sufficiently close to Grasdalen's (1973) estimate of the surface gravity (log $g = 2.0 \pm 0.3$) for the star to be considered to be rotating at breakup velocity. In this situation severe gravity darkening will result, together with a negative temperature gradient from pole to equator. The large surface area in the equatorial regions will compensate for the reduced radiant emittance. Rapid rotation of a single star is therefore qualitatively capable of explaining a composite spectrum such as the one observed. Although the theory of rotating stars remains primitive, a simple model constructed according to the precepts[1] of Collins (1963) has mean effective temperatures of 5400, 4200, and 2800 K in three zones of equal projected area, corresponding to polar, intermediate, and equatorial latitudes, respectively. While such a temperature gradient may be too shallow to explain the energy distribution of Figure 2, the model should probably be regarded as only schematic. The 10 and 20 μm infrared excess in this model must still originate in a circumstellar shell, which is probably flattened in the plane of rotation, and perhaps evolving in the manner envisaged by Lynden-Bell and Pringle (1974). It may be possible to explain even the outbursts in this model as successive structural readjustments, when the contracting star periodically spins up and reaches breakup velocity.

Clearly, further observations are required to properly test the binary and rotating models described above. Simultaneous study of the optical and infrared velocities and line profiles at high dispersion may provide a critical test.

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[1] The gravity-darkening law of von Zeipel (1924) is assumed, together with a gray atmosphere.

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Note added in manuscript.—Elias (1978) has recently studied a new FU Orionis–type star, IC 5146 No. 12, and has evaluated the problems associated with the dust-shell and binary models. We are grateful to George Herbig for calling our attention to Dr. Elias's thesis.

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