FU ORIONIS ERUPTIONS

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ABSTRACT

Five stars are now known whose spectra and photometric behavior identify them as classic FUors, although there are real differences in rise time (from 1 to more than 10 years) and in spectroscopic details. Most physical arguments about the FUor phenomenon are based on FU Ori and V1057 Cyg, for which there is a wealth of detailed information. There is another class of eruptive variables (here called EXors), but which have lower minimum luminosities and smaller ranges than the FUors, and whose outbursts are generally repetitive. The EXors also differ in having T Tauri-like emission spectra at maximum light, rather than the classic F- or G-type absorption spectrum with rather minor line emission (except for P Cyg structure at Hα). FUor outbursts must be repetitive, with a frequency depending upon the nature of the stars which erupt. There is reason to suspect that FUor eruptions are most likely in stars having strong mass outflows. A central issue is whether the optical spectra of FUors are produced by a self-luminous accretion disk or by a peculiar, rapidly-rotating central star with a deep semi-transparent atmosphere plus circumstellar material. A variety of evidence bearing upon this issue is discussed, and it is concluded (i) that the disk interpretation at the very least requires considerable elaboration to account for the observations, and (ii) that alternative models cannot be excluded.

1. Introduction

The stars that we call FUors originally drew attention to themselves by their distinctive photometric behavior. The 5 stars now considered members on that basis show quite similar spectroscopic characteristics near maximum light: a predominantly absorption spectrum resembling an F- or G-type supergiant (although V1057 Cyg was of type A for a time following maximum) with broad lines, striking P Cyg structure at Hα, and a strong Li I λ6707 line (Table 1). These stars rose to maximum on quite different time scales, the rise times ranging from about 1 year to 10 years or more. Only one (again, V1057 Cyg) has faded substantially from maximum light since discovery.

Given these distinctive spectroscopic characteristics, a number of other stars that have similar spectra and luminosities to the classic FUors have been suggested as members of the FUor group. None of these additional stars have shown the characteristic photometric behavior of the classic FUors in historic time. Four of these are listed in Table 2.

It is now recognized that there are also a substantial number of other stars which mimic the FUors, on a somewhat smaller scale, in showing sudden flareups from minimum light at irregular intervals. However, near maximum light these stars do not resemble the FUors spectroscopically at all because their spectra are dominated by T Tauri-like emission lines. Any stellar absorption spectra are masked or undetectable. These objects are less luminous than the FUors, their outbursts are relatively short-lived, and in many cases have been observed to repeat. DR Tau (Fig. 1) is the slowest-developing member of this group. Not only the powerful emission-line spectrum but the rapid, large range photometric activity superimposed upon the secular variation distinguish DR Tau from the more sedate FUors. For short, I refer to this species as EXors, after the example first recognized, EX Lupi. Table 3 lists the known examples.

Table 1
Established Members of the FU Ori Class

Star	Date of maximum	Extreme range (mag.)	Rise time	Was emission Hα present at minimum?	Note
FU Ori	1937	6 pg	120-380^d	?	
V1057 Cyg	1970	5.5 pg	390^d	Yes	
V1515 Cyg	1980?	~ 4 pg	< 13 yr	?	
V1735 Cyg	>1952, <1965	> 5 R	?	?	1
V346 Nor	>1984	> 2:V	≤ 7 yr	?	2

Notes: (1) = Elias 12. (2) In HH-57.

Table 2
Stars Proposed, or Mentioned, as Possible Members on Spectroscopic Grounds

Star	Reason
L1551/IRS 5	Type F-K with P Cyg structure at Hα, 2μm CO
Z CMa	Large mass outflow, double line structure, 2μm CO
HP Tau/G2	Rapidly rotating G III with Hα emission, Li I λ6707
SU Aur	(as HP Tau/G2)

Table 3
Stars Exhibiting Large-range Outbursts, but Having TTS-like spectra when Bright

Star	Number of observed maxima	Extreme range (mag.)	Rise time	Duration of maxima	Emission Hα at minimum?	Note
PV Cep	≥ 2	5 r	100^d ?	200^d, > 2 yr	Probably	
EX Lup	≥ 7	5 vis	150-700^d	200-1800^d	Yes	1
NY Ori	≥ 2	> 2.7 vis	?	≥ 100^d	?	
V1118 Ori	1	3.5 pg	?	> 400^d	Not seen	2
V1143 Ori	1	3.5 pg	~ 200^d	1500^d	Weak	3
UZ Tau E	≥ 6	3.9 pg	?	150^d ?	Yes	
VY Tau	Many	4 pg	80-200^d	150-700^d	Yes	
DR Tau	2	4 pg	~ 18 yr	?	Yes	
Anon	1	3.5 r?	?	> 200^d	?	4

Notes:
(1) The photographic range (from McLaughlin 1946) is much less than the visual range of Bateson and Jones (1957), but the latter scale needs to be checked photoelectrically.
(2) = NSV 2229 = Chanal's variable; Parsamaian and Gasparian (1987) give references to earlier work. The second outburst was reported by Gasparian and Ohanian (1989).
(3) = Sugano's variable, but detected independently by Natsvlishvili; the latest reference is Mirzoyan et al (1988).
(4) Gyulbudaghian et al 1978, and private correspondence.

2. FUor Outbursts Must Be Recurrent

Five FUors are known to have occurred within 1 kpc of the Sun since the beginning of the century, corresponding to an eruption rate of 0.06 yr^{-1}. An equally reasonable rate is 0.10 yr^{-1}, obtained by ignoring that fraction of of the century prior to the discovery of FU Ori during which no examples were detected. Both must be lower limits: additional examples whose initial rise was missed surely remain to be found. A question of some importance which hinges upon this eruption rate is: how often does a given pre-main sequence star undergo a FUor eruption? There are two ways of approaching an answer.

(a) Assume that the objects which erupt are recognizable T Tauri stars (TTS) with luminosities brighter than $M_{pg} \approx +4$, that limit resting solely upon the pre-outburst magnitudes of FU Ori, V1057 Cyg and V1515 Cyg. It has been estimated (Herbig 1977) that there are about 500 such stars within 1 kpc, from which number and a rate of 0.1 yr^{-1} one concludes that after about 5×10^3 years every such star will have erupted once. Now, a member of this very luminous fraction of the TTS population will not remain on the vertical branch of its Hayashi track, where the TTS characteristics tend to be the more prominent, for very long. An interval of about 3×10^5 years would seem a reasonable duration, given log L/L(sun) ≥ +0.8 and the isochrones of Cohen and Kuhi (1979). Therefore, on the average each of these stars would be required to erupt about 60 times during its TTS phase.

(b) A less restrictive assumption was made by Hartmann and Kenyon (1985, hereafter HK), namely that every newly-formed star is susceptible to FUor outbursts. An average star-formation rate can be obtained from the number of stars that have accumulated in the solar neighborhood over the lifetime of the Galaxy. Such birthrates have been estimated by Miller and Scalo (1979) under various assumptions as to the age of the Galaxy and the variation of birthrate since the beginning. For the case of an age of 12×10^9 years and a constant birthrate, a value of the present birthrate for any mass interval can be obtained. Values for the mass range believed to be appropriate for TTS are given in Table 4.

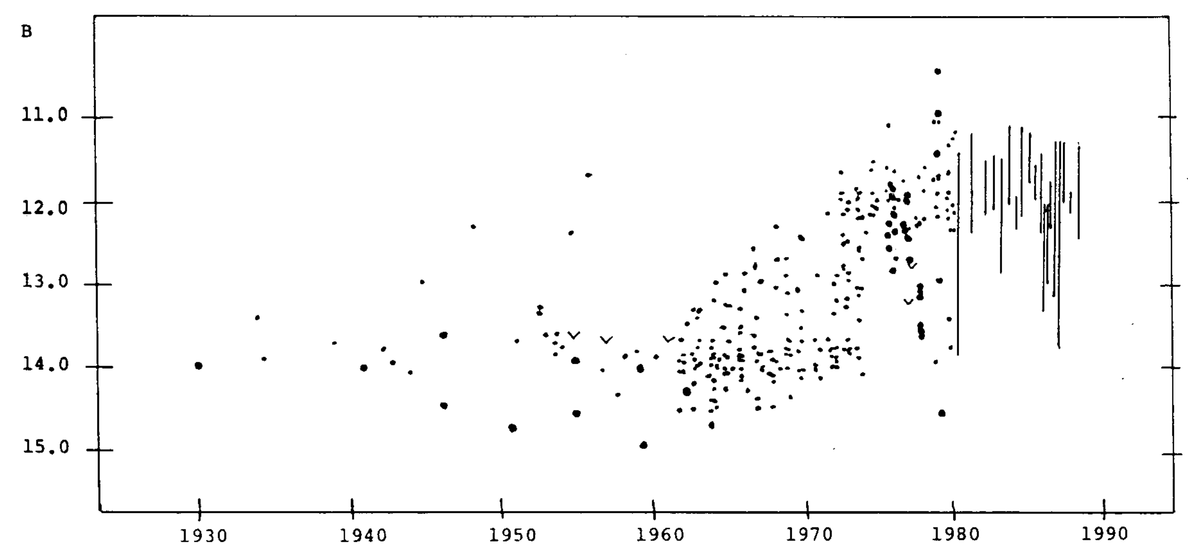

Fig. 1.- The photographic light curve of DR Tauri. The individual observations are from Götz (1980). Subsequent seasons (or groups of observations), also from observations by Götz, are represented by vertical lines connecting the brightest and faintest magnitudes. Major night-to-night variations are superimposed upon the slow brightness increase that began about 1961.

Table 4

Estimate of the Number of Recurrent FUor Eruptions

In the mass range: (unit:solar masses)	The number of stars born/yr within 1 kpc is:	So if stars in this mass range are to maintain the FUor rate of 0.1/yr then each must erupt this many times:
1.00 - 2.51	0.0022	45
0.40 - 1.00	0.0053	19
0.10 - 0.40	0.0136	7
All	0.0211	5

One sees that the results from (a) and (b) are not very different for the mass range in common, i.e. greater than about 1.5 solar masses, and agree in showing that the FUor event must be repetitive. Since 0.1 yr^{-1} is only a lower limit, the actual repetition rates must be correspondingly higher.

It is tempting to ask whether the predilection for eruptive activity in pre-main sequence stars may extend over a considerable range of masses. If so, then the FUors might be drawn from the upper part of the mass range of Table 4, the EXors from intermediate values, and the low-luminosity "flash" variables that are found in molecular clouds from the lower part.

3. Are There Undetected FUors, Still Near Maximum Light, Within 1 kpc?

If the rate of 0.1 yr^{-1} is to be taken literally, then one concludes that several bright FUors remain to be detected. More cannot be said until more is known about the duration of eruptions. That is, is FU Ori itself which has been near maximum for 50 years more representative than V1057 Cyg, which has faded about 2.5 mag. (in V) in the last 20 years? Clarification will come only from the discovery of more examples, either in old plate archives or other records, or from spectroscopic examination of likely candidates.

As example of the former possibility, namely of what we might now recognize as evidence of a FUor outburst, was pointed out by Welin (1987): there is today no bright star at the position of +43° 3749, noted by Argelander about 1855 as a star of BD magnitude 9.5. But near that place today is LkHα 172, a TTS associated with IC 5070, of m(pg) = 16.0 and type about K4. However, the BD coordinates of +43° 3749 differ from those of LkHα 172 by +24", +6" while the mean (absolute) residual for faint BD stars in the same region, with respect to modern positions, is only 4", 11". Although it is tempting to speculate that this might represent a FUor event of the last century, the positional discrepancy gives one reason to hesitate.

A more direct procedure would be to look for bright F or G stars that are closely associated with molecular clouds, and which illuminate nearby reflection nebulae and have strong, displaced P Cyg-like absorptions at Hα, probably accompanied by weak longward emission. Strong Li I λ6707 is a necessary but not sufficient condition, because λ6707 appears in some post-main sequence giants and subgiants.

The rather limited searches that have been made on this basis have, to date, been unsuccessful. None of the bright G and K giants near NGC 2264 qualify. There are a number of bright G and K stars in and around the Orion Nebula but although many have interesting spectra, none resemble FU Ori or V1057 Cyg. From the number of pre-main

sequence stars in the Orion area, one would think it a likely region for a FUor to have occurred. The photometric history of all the variables known up to about 1954 was exhaustively compiled by Parenago (1954), but none behaved as one would expect a FUor to do. The one possible exception was NY Ori, but that is known to be an EXor. The fact that the EXors V1118 and V1143 Ori did not appear in the material available to Parenago indicates that some interesting objects still await discovery there, but they will probably be much fainter than are of interest in the present connection: a classic FUor in the Orion Nebula region would be of mag. 9-10 at maximum light.

4. Is There Any Way To Identify Future FUors?

If all TTS are repetitive FUors, the question is pointless. So one should ask whether some signature of an impending outburst exists. The only hint comes from what little we know of V1057 Cyg before outburst. Thirteen years before, at very low spectroscopic resolution the star appeared to differ from most other TTS in only one respect: namely that the K line of Ca II (3933 A) was rather strongly in emission while the H line (3968 A) was absent. This has been observed in a few other TTS, the best examples being V1331 Cyg (Kuhi 1964, Fig. 2) and V1352 Aql (= AS 353A: Herbig and Jones 1983), where clearly the P Cygni absorption component of Hε (3970 A) is responsible for the obliteration of the H line. The same effect is seen also in R Mon (Herbig 1968), although that is not a conventional TTS, and curiously, also in FU Ori following maximum light (see Figs. 5 and 6 of Herbig 1966). Among published spectra of TTS that cover the H,K region, only about 5% of that sample show the effect, although a number of intermediate values of the K/H ratio do occur.

It will be recalled that Welin (1976) included V1331 Cyg among his list of possible pre-outburst FUors, although for different reasons, and that Mundt (1985) and Bastien and Mundt (1985) have speculated that powerful mass outflows may distinguish those stars likely to undergo a FUor event. One can only hope that the next FUor event will occur in a nearby TTS having a solid spectroscopic and photometric history so that there will be a firmer basis for such conjectures.

Kenyon and Hartmann (1987b, hereafter KH) have also speculated that if, given their accretion disk hypothesis, the instability which initiates the flareup begins far out in the disk and propagates inward, then the star will give warning by beginning to brighten in the infrared several years before it does so in the optical region. However, that would not be a signature unique to an accretion disk because scenarios can be imagined in which an outburst could begin with a gentle warming of the source, whatever its structure.

5. The Accretion Disk Hypothesis For FUors

The preceding remarks indicate that I am not completely comfortable with the accretion disk hypothesis so eloquently put forward and elaborated in a series of papers by HK and their co-workers. At issue is not whether some kind of flattened circumstellar structures exist around FUors (and TTS), -- that I regard as highly likely -- but whether the observations *demand* interpretation of the FUor phenomenon in terms of Lynden Bell and Pringle-type self-luminous accretion disks. I believe that other possibilities have not been ruled out, given the present state of the evidence and the fact that the disk hypothesis is not without its own difficulties (Sec. 6, below).

The most compelling evidence is likely to be spectroscopic. But it will be recalled that Adams, Lada and Shu (1987) were able to represent the energy distribution of FU Ori equally well with an accretion disk model or with a F giant plus a reprocessing disk that intercepted about 10% of the light from the central star. So energy distributions alone permit no decision. One then asks what can be learned from the line spectra of FUors. These have two unique characteristics which have to be explained:

(a) The absorption line profiles which (especially at longer optical wavelengths) resemble the near-superposition of two broad, overlapping lines. There is no evidence that the amount of this 'splitting' varies with time, as one would expect for a double-line spectroscopic binary. I do not believe that anyone now thinks that there are two separate stars involved, because there are other objections as well to that interpretation. At shorter wavelengths, a set of sharp, shortward-displaced absorption lines is produced by a wind or shell; these will be described later (Sec. 7, below).

(b) There is a striking variation of spectral type with wavelength in V1057 Cyg and FU Ori. In FU Ori, it ranges from A5 near 2650 A (Kenyon, Hartmann, Imhoff and Cassatella 1989; but note the caution in Sec. 7) through F in the optical, to a still later type in the infrared: the H_2O and CO absorptions at 1-2 microns are as strong as in an M giant. There have been hints that such an effect may exist in TTS spectra also.

A kind of Doppler imaging of the object ought to be possible by correlating line structure with the rotational/orbital velocity over the projected surface. At the very least, one would suppose it possible to establish the shape of the source, whether flat, self-luminous Keplerian disk or some kind of single star. As will appear, the results to date are ambiguous.

Historically, the first test was simply whether the line widths were consistent with a disk interpretation. The initial proposal that the FUor outburst might be due to instability in an orbiting accretion disk was made by Paczynski (1976). At the suggestion of V. Trimble, I therefore examined some early Lick spectra of both FU Ori and V1057 Cyg for a dependence of absorption line widths, or duplicity, on excitation potential, in the thought that lower-excitation lines ought to be narrower if they arise in cooler regions of the disk having smaller orbital velocities. No such effect was found. Had it been detected, its significance could have been questioned because it now known that line-widths increase with excitation potential even in such a conventional star as the Sun (Babii 1988). Obviously, any such extraneous effect would have to be understood and removed before line-width dependence can be used as an argument for or against Keplerian disks in FUors.

Those old observations have now been repeated with superior material, and the negative result confirmed. Fig. 2 shows that on modern high-resolution spectra of FU Ori there is no major variation of line width with excitation potential. One sees that the widths of a series of unblended Fe I lines having lower excitation potentials from 1.0 to 3.6 ev are closely the same (the differences in central structure are discussed later).

The same phenomenon might be expected to appear as a dependence of line width on wavelength, as the place of origin on the source moves radially in response to the temperature gradient. However, the disk model for FU Ori (HK 1985) predicts only a small variation across the optical region (a decrease of about 10% between 4500 and 6300 A). High resolution spectra of FU Ori confirm: there is certainly no progressive change of v sin i over that wavelength range *greater* than 10%.

In order to increase the wavelength baseline, KH (1987a; 1989) have extended observations into the infrared and have measured widths in the rotational structure of the CO absorption bands at 2 microns in FU Ori and V1057 Cyg. They found values for v sin i about 30% smaller than obtained from the atomic absorption lines in the optical region. This is indeed in the sense expected if the CO absorptions arise in the cooler peripheral regions of a Keplerian disk. It has been taken as strong evidence in support of the disk hypothesis.

But another, quite different interpretation of this observation is possible. Imagine that a FUor is not a luminous disk at all, but rather a single, rapidly rotating star having a deep, extended atmosphere fed by slow outflow from below (plus more distant circumstellar material). Then the optical boundary at any wavelength is merely the level at which τ_λ=1. If the upper levels are not rigidly coupled to the lower, then in the limit the measured rotational velocity will fall

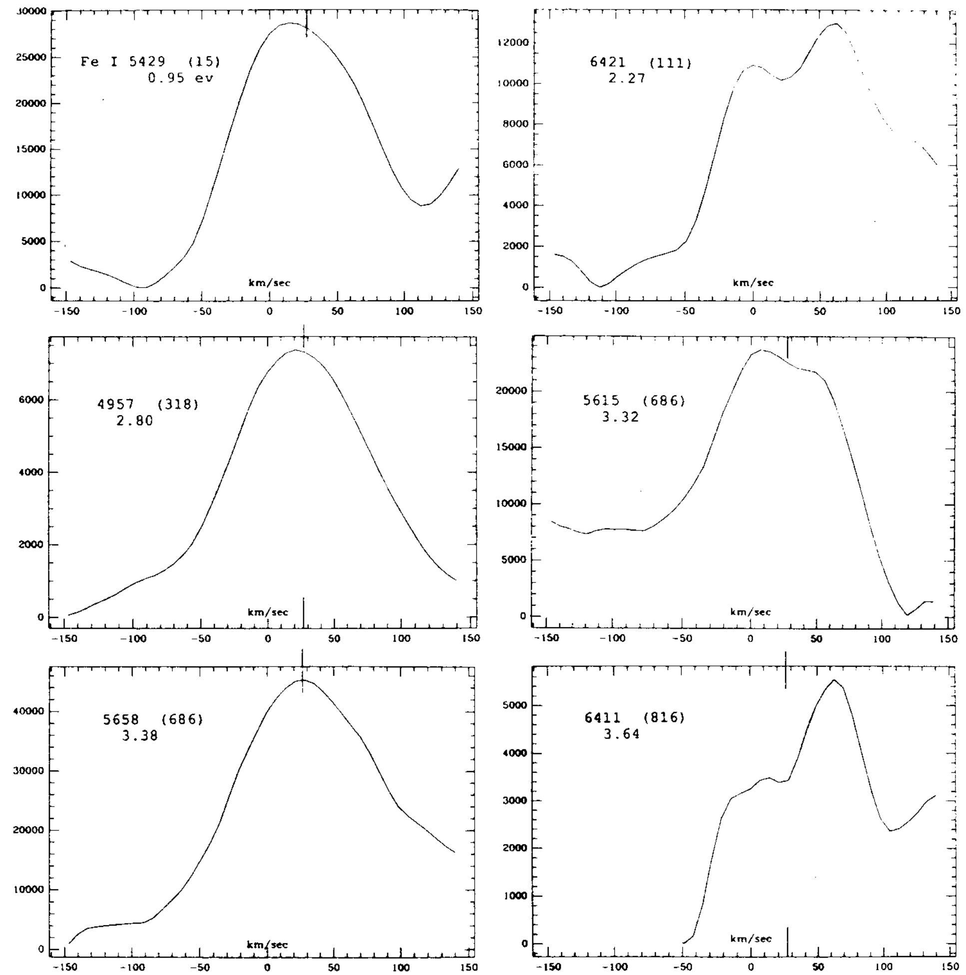

Fig. 2.- Cross-correlation profiles of individual almost-unblended Fe I lines in FU Ori, from a high-resolution spectrogram of 1987 Jan. 11. The reference star is 25 Gem (G5 Ib). The lower excitation potential and RMT multiplet number are shown for each line. The vertical bars at +28 km s^{-1} mark the stellar velocity. There are remarkable changes in the profile from line to line, but there is no obvious dependence on excitation or type of transition.

off with height as R^{-1}. It is well known that the infrared CO lines in the solar spectrum are formed near the temperature minimum (Goldberg and Muller 1953) and still higher in G and K giants (Wiedemann 1989). Consequently CO lines formed high in the atmosphere of this hypothetical star will naturally have smaller rotational line widths, in agreement with observation. Some dependence of spectral type upon wavelength (i.e. height) would also be expected. Whether it could be in the direction and of the amount observed in FUors has not been demonstrated.

Consider now the curious absorption line profiles in FU Ori and V1057 Cyg, with their suggestion (seen best at wavelengths longward of about 6000 A) of unresolved duplicity. They are symmetric about the velocity of the star (as inferred from the molecular-line velocity of the surrounding molecular cloud). This I regard as the most powerful argument for the self-luminous Keplerian disk, because it is not easy to find alternatives. One can compute the line profiles to be expected in the integrated light of a single spherical rotating star under various assumptions. Some examples: the 'dimple' at the bottom of the observed lines cannot be reproduced by introducing latitude-dependent rotation rates, or by darker zones at the poles, or by limb brightening alone. But an absorption line with a cusp near the two edges and thus a slight peak at the center can be produced by a combination of limb brightening and a high-latitude cutoff, as if there were polar holes (Fig. 3). One can produce a similar effect by having the spectrum go into emission near the poles. So the line doubling phenomenon, like the narrower infrared CO lines, is not necessarily the signature of a Keplerian disk.

The duplicity that one sees in FUor profiles is really, in most cases, a rather subtle effect, to a degree that often it is obvious only when a extended spectral region containing a number of lines is cross-correlated against a sharp-line standard. Typically, this 'dimple' in the center of a cross-correlation peak amounts to only about 5% of the total peak amplitude. The disk model ascribes the maxima on either side of the dimple to the contributions of the two disk ansae, smeared out over a range of orbital velocities. There are at least two puzzling consequences if that interpretation were accepted.

In Fig. 4 are shown such cross-correlation peaks for the same 90 A region of the spectrum of FU Ori from four Lick Reticon spectra taken over a 2-year period. One sees that the peak position and total width is preserved, but that at times the duplicity is not present, while at others the relative contributions of the two 'components' is reversed. One would have to conclude that if this structure is indeed due to approaching and receding halves of an inclined disk, then the surface brightness of that disk is not uniform. If produced by a rotating star, surface patchiness would explain the effect.

Another unexplained fact is that some lines show duplicity more clearly than others. This is apparent in the cross-correlation peaks of the Fe I lines in Fig. 2, where one sees that there is no obvious dependence of line structure upon excitation, although the highest excitation line, Fe I λ6411, shows an asymmetric splitting quite different from the others. This peculiarity of λ6411 is always present; it was in fact, the very obvious duplicity of λ6411 that first drew the attention of Herbig and Petrov to this phenomenon in 1983.

The most striking line splitting in FU Ori is shown by Li I λ6707 and Ca I λ6717, where the 'dimple' at line center has an amplitude 40-50% of the line depth, and the total feature can be quite accurately be fitted by two Gaussians (Fig. 5). This duplicity of λ6707 is not a transient phenomenon, being present on the first Lick coude spectrograms of FU Ori in 1963. The same doubling of λλ6707, 6717 has been observed by Hartmann et al. (1989) in Z CMa, which they believe to be an old FUor.

In summary, I do not regard these remarkable line structures and their variation with time and from line to line as absolutely incompatible with the disk model, only that they do demand a significant elaboration of that picture. They can, it is also clear, be explained by the single-rotator model.

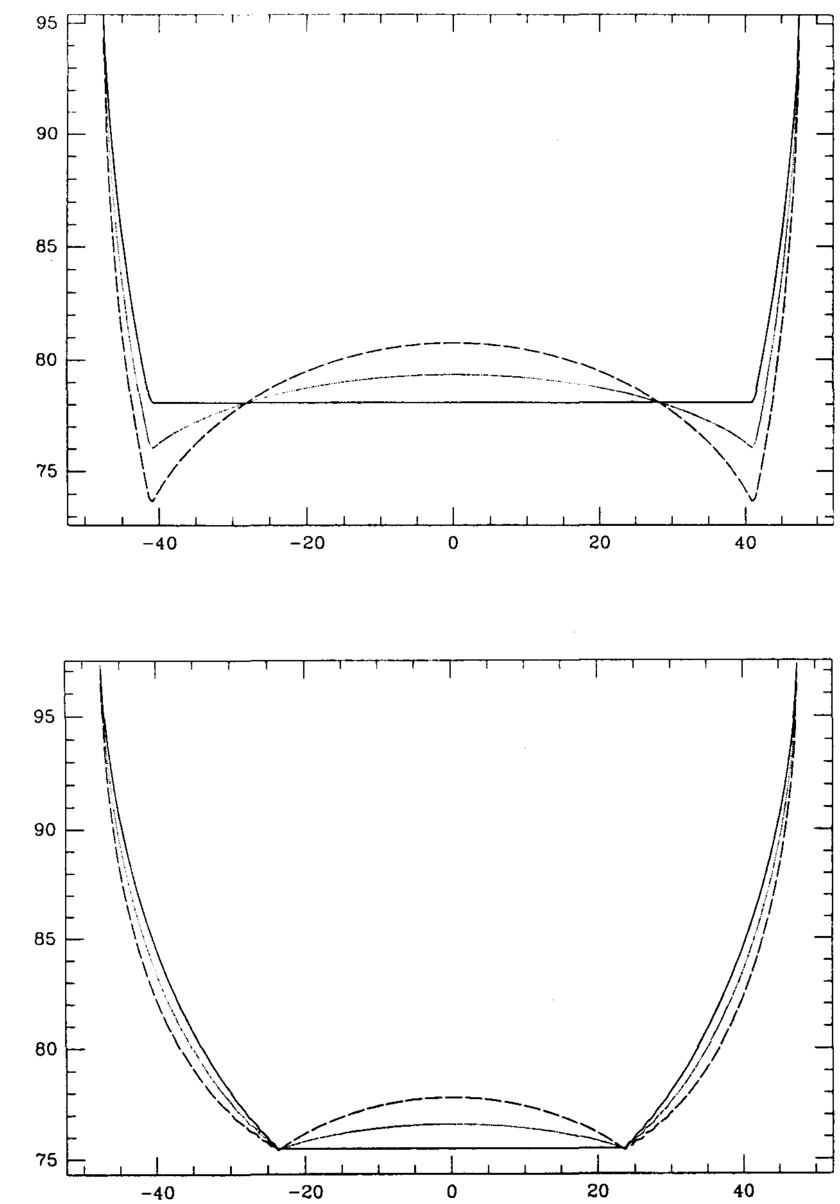

Fig. 3.- Theoretical profiles for a rotating star with different degrees of limb brightening (the solid line is for a uniform disk, the dotted line for u = -0.3, the dashed for u= -0.7 in the limb-darkening expression $F(\theta)/F(0) = 1 - u + u \cos\theta$). The upper panel is for a star cut off above latitudes 30°, the lower for a cutoff above latitudes 60°. The abscissae are in km s^{-1}; other parameters are P(rot)=18 days, R/R(sun) = 17.

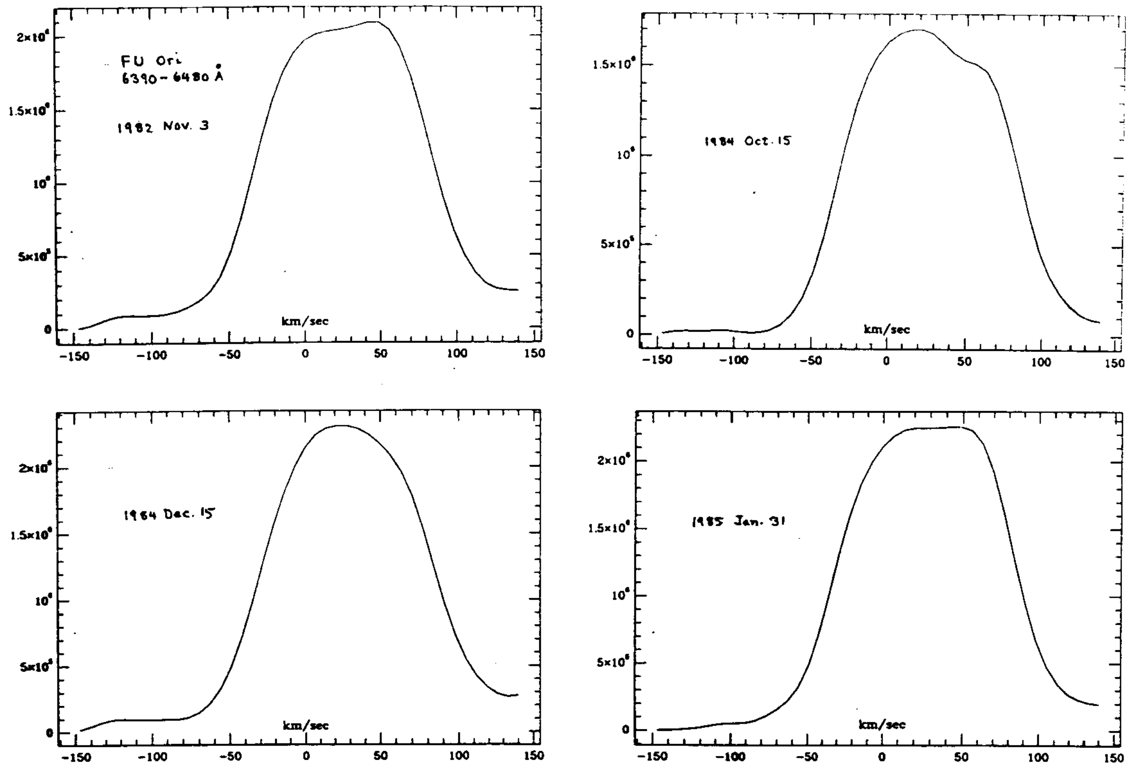

Fig. 4.- Cross-correlation profiles of FU Ori vs. ζ Mon (G2 Ib) for the region 6390-6480 A on four dates 1982-1985, from Reticon spectra. The changes in shape of the profile, although it remains centered at the stellar velocity of +28 km s^{-1}, are real and reflect either azimuthal variations in the surface brightness of the disk (in the disk picture) or surface patchiness on the rotating star (in the single-rotator scenario).

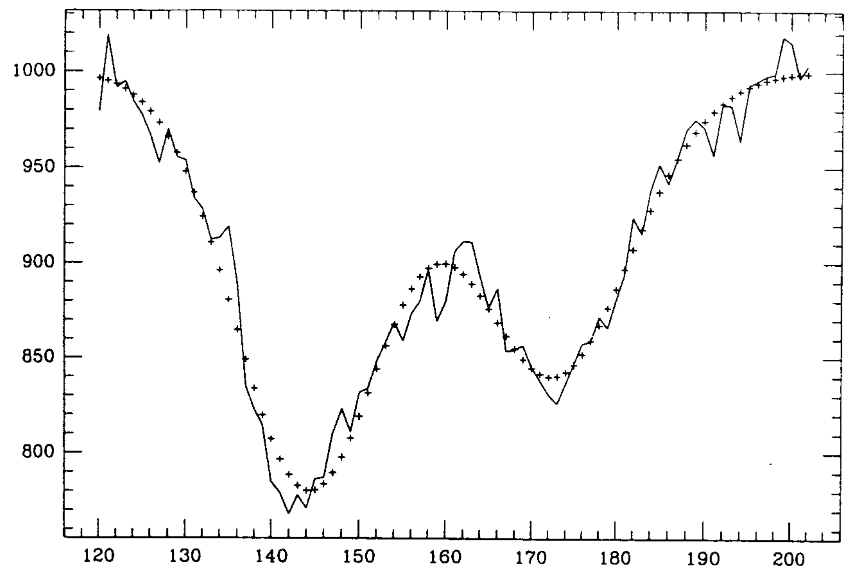

Fig. 5.- The profile of Li I λ6707 on the high-resolution scan of FU Ori of 1987 Jan. 11. The abscissa is in pixels, each of which is 0.058 A. The solid line connects data points, while the crosses outline the sum of two gaussians fitted to the profile as if it were two separate lines. The separation of the two peaks is 73 km s^{-1}, which is slightly greater than that of the two peaks seen in cross-correlation profiles of Fe I and other lines in this spectrum. The profile of Ca I λ6717 is very similar.

6. Other Problems Of Accretion Disk Models

Having pointed out that an alternative may exist, and that complications abound, I would like to note some other features of the FUor phenomenon which do not fit comfortably into the disk picture.

(a) To quote HK (1985), "the outbursts of an accretion disk are presumably due to the pileup of material, followed by a change in [disk] viscosity which allows the accumulated material to be dumped onto the central star. The luminosity subsequently decreases as the disk runs out of material." They (HK 1988) interpreted the post-maximum fading of a FUor as consequence of the disk being drained into the star, so that as the surface brightness decreases it becomes more concentrated toward smaller radii. Since the Keplerian velocity is higher there, line widths ought to increase as the star fades. But in the case of V1057 Cyg, the line widths are now *smaller* than in 1973, when v sin i was about 70 km s^{-1}; the present value is about 45 km s^{-1}. HK were inclined to reject the 1973 value on the ground that displaced shell components may have caused the lines to appear spuriously wide. However, if displaced shell structure had caused such an effect earlier, the Lick data show that its contribution was not significant by 1973. I regard this as a clear conflict with the disk model.

(b) If the 1969 outburst of V1057 Cyg is a consequence of the brightening of its accretion disk, and the central star is a passive participant in this phenomenon, then one can ask whether the Hα emission of the pre-outburst TTS should still be observable. A rough estimate can be made as follows. High resolution profiles of Hα in 1981-82 have been published by Bastian and Mundt (1985). At that time the R magnitude was about 9.9 (Kopatskaya 1984), as compared to the pre-outburst value of R = 12.7 estimated by Haro (1972).

(Haro's pass band was centered at 0.64-0.65 microns, as compared to the effective wavelength of Johnson R, 0.70 microns. It is believed that the error, given the color of pre-outburst V1057 Cyg, can be no more than about 0.1 mag., which is probably less than the uncertainty of the estimate itself.)

The flux in the continuum near Hα was therefore about 13 times greater in 1982 than in 1965. No measurement of the equivalent width of Hα emission at minimum was made, but Herbig (1958) placed it in his class *m* (for "medium strength"), which Marcy (1980) has found corresponds to equivalent widths ranging from about 15 to 40 A. Therefore, that same emission line would have had $W_\lambda \approx$ 1 to 3 A against the 1982 continuum of V1057 Cyg. No such emission spike is apparent in the published reproductions; an emission line having $W_\lambda \approx$ 0.3 A would have been readily detectable, if it had the shape seen in typical TTS. Such a line would have been safely longward of the powerful P Cyg-type absorption component of Hα, so quenching by that feature cannot be the explanation. Nor would it seem that extinction of the star by material being accreted from the disk be blamed, because the disk model of V1057 Cyg requires that we view the system from very high latitudes (HK 1988). Clearly, some elaboration of the accretion disk model is required to account for the suppression of Hα.

(c) HK in several papers have pointed out that their disk models of FUors demand very high accretion rates, of the order of 10^{-4} solar masses yr^{-1}, as compared to values of 10^{-7} to 10^{-8} yr^{-1} that are usually estimated for TTS. If the bright-line spectra and ultraviolet continua of active TTS are correctly ascribed to boundary layer emission, then one would expect an exaggeration of those features in FUors. Of course that is not the case: the emission lines of most FUors in the optical region are not strong. Furthermore, Kenyon, Hartmann, Imhoff and Cassatella (1989) have found no indication of a hot boundary-layer continuum in the ultraviolet of FU Ori near 2650 A. These facts conflict with expectation that the boundary layer luminosity should be comparable to that of the disk. Kenyon et al. estimate that the level of boundary layer emission must be lower than the model prediction by a factor of at least 10. There has been some speculation about ways in which such a large amount of energy might be concealed, but one would have more confidence in the model if that were not so necessary.

(d) Lastly, I only mention the fact, discussed by Simon and Joyce (1988), that the infrared energy distribution of V1057 Cyg in decline departs significantly from the predictions of the (admittedly very crude) time-dependent disk models. Its sense is that as the star faded, the fluxes longward of about 2 microns declined much more slowly than expected for a cooling disk, as if there was an increasingly significant contribution from an independent infrared source.

The foregoing represent tests which the accretion disk model does not pass satisfactorily, or which it can explain only by elaboration of the basic picture.

7. The Expanding Shell

One of the most striking features of the spectrum of FU Ori is the set of strong, shortward-shifted absorption that, particularly at the time of the first coude observations in 1963, flanked the low-level lines of neutral and ionized metals (Fe I, Al I, Cr I, Ti II, Sr II, Sc II...) shortward of about 4600 A. This spectrum apparently was present at the time of the earliest medium-dispersion spectrograms of FU Ori (Wellmann 1951) but was not recognized until higher resolution became available about 1963. Modern spectroscopy at still higher resolution and S/N shows that this structure, although weaker than in 1963, was still present at the stronger Mg I, Fe II and Ti II lines in 1987 (Fig. 6). These shell lines are now displaced 40 to 50 km s^{-1} shortward of the stellar velocity of FU Ori, so that at some lines there is confusion between the shell feature and the shortward 'component' of the doubled lines of the central source. One supposes that the same rising material produces the complex shortward-shifted absorption components at Hα, CaII K, and Na I λλ 5889, 5895.

The increasing prominence of shell features as one moves from the blue into the near ultraviolet (the spectrograms of adequate resolution that are currently available extend only to about 3750 A) raises the suspicion that at still shorter wavelengths the shell may dominate the line spectrum of FU Ori and hence give the spurious impression of an earlier spectral type. This possibility could be checked by accurate measurements of radial velocity from the ultraviolet lines.

8. Conclusions

I conclude that, as appealing as the self-luminous accretion disk hypothesis of FUors may be, it remains unproven. Much of the observational evidence that has been cited in its support can be reproduced equally well by a rather peculiar, rotating single star (admittedly having poorly-defined, *ad hoc* physical properties). Some of the difficulties of the hypothesis that are described here might be accommodated by embellishment or special assumptions, but as that picture becomes more complicated it tends to lose some of its original appeal.

The conjecture that eruptive phenomena as seen in the FUors, the EXors and in the flash variables may represent a common physical phenomenon which spans a substantial range of stellar masses in the pre-main sequence domain deserves some consideration.

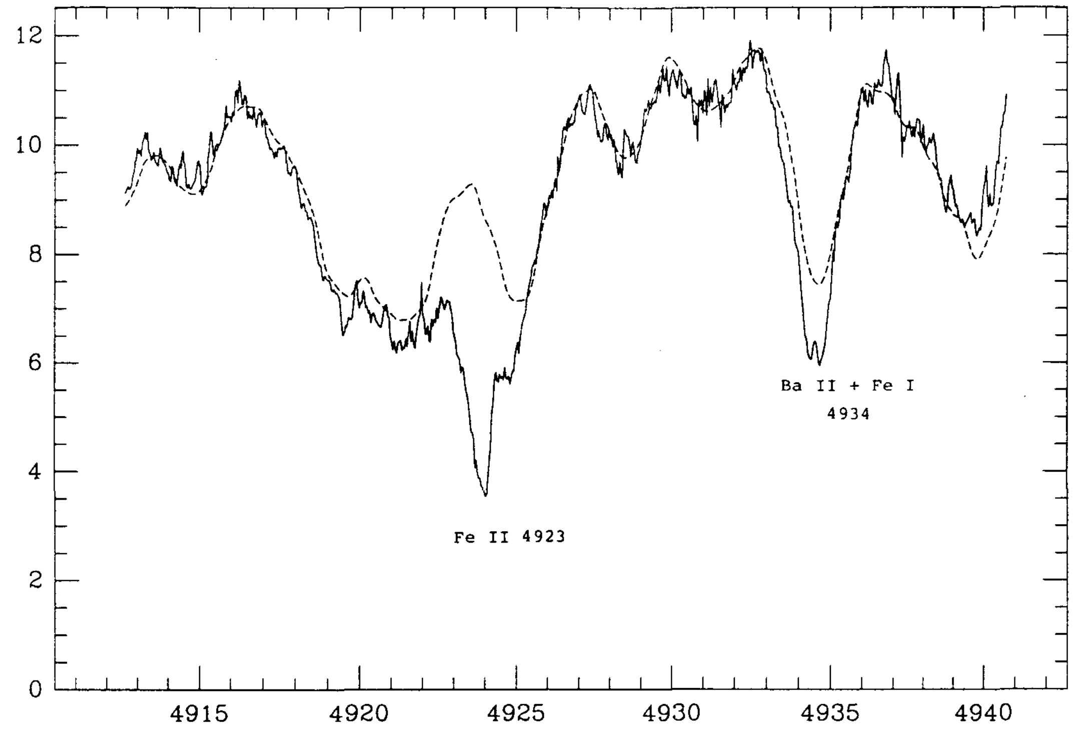

Fig. 6.- A section of the high-resolution scan of FU Ori (solid line) and of 25 Gem blurred artificially by a rotational broadening function of v sin i = 65 km s^{-1} (dashed line). The two have been shifted into wavelength coincidence. The broadened 25 Gem spectrum represents that of FU Ori quite well in this region, except at the strong Fe II line λ4923 and at Ba II λ4934, where the contribution of the shortward-shifted shell spectrum of FU Ori is conspicuous.

A central barrier to progress in FUor studies is the paucity of certified examples. There is good reason to suspect that there may be bright FUors as yet undetected, and so it is important that spectroscopic and photometric searches for more examples be carried out.

I would like to acknowledge that much of the work on the spectrum of FU Ori described here was done in collaboration and consultation with Peter Petrov over the past 4 years. He does not appear as co-author simply for lack of time for the two of us adequately to discuss the present text. Therefore responsibility for any errors or misstatements is mine alone. I also acknowledge that the high-resolution echelle spectrogram of FU Ori that has been discussed here was obtained with the Hamilton spectrograph of the Lick 120-inch reflector through the kindness of Dr. S. Vogt. I am also indebted to Dr. T. Simon for stimulating discussions.

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