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THE FU ORIONIS VARIABLE STARS: ACCRETION IN ACTION

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RESUMEN

Las variables del tipo FU Orionis – FUors – son estrellas eruptivas de la presecuencia principal. En la mayoría de ellas se han producido erupciones en el rango óptico de 3 a 6 magnitudes, con sus espectros ópticos asemejándose a los de las estrellas supergigantes F-G de rápida rotación. Estas variables presentan también nebulosas de reflexión muy características, grandes excesos, tanto en el infrarrojo como en el ultravioleta, tipos espectrales que dependen de la longitud de onda, y perfiles de líneas ópticas (y en algunos casos también infrarrojas) con dos picos. Varias otras estrellas de la presecuencia principal relativamente luminosas han sido consideradas como de tipo FUor, dado que poseen las características tanto fotométricas como espectrales descritas anteriormente. Sin embargo, en esas estrellas no se han observado erupciones.

En este trabajo se presenta una revisión de nuestro conocimiento de las erupciones de tipo FUor. Las observaciones de los discos y de las nebulosas que rodean a estas variables proporcionan estimaciones autoconsistentes del tiempo de evolución de los ciclos eruptivos, colocando a las FUors en etapas relativamente tempranas de la vida de las estrellas de la presecuencia principal. Estos resultados indican que las FUors juegan un papel importante (si no dominante) en la evolución de las estrellas de la presecuencia principal y de los núcleos moleculares.

ABSTRACT

The FU Orionis variables – FUors – are eruptive pre-main sequence stars. Most FUors have undergone 3–6 mag optical eruptions and resemble rapidly-rotating F–G supergiants on optical spectra. They also display distinctive reflection nebulae, large ultraviolet and infrared excesses of radiation, wavelength dependent spectral types, and "double-peaked" absorption line profiles at optical – and sometimes infrared – wavelengths. Several other luminous pre-main sequence stars have been added to the FUor class because they display the characteristic photometric and spectroscopic features described above but have not been observed to undergo an eruption.

This paper reviews our understanding of FUor eruptions. Observations of FUor disks and their surrounding nebulae provide a self-consistent picture for the time-evolution of the eruption cycle and place FUors at a relatively early stage in the life of a pre-main sequence star. These results indicate that FUors play an important – if not dominant – role in the evolution of pre-main sequence stars and molecular cloud cores.

Key words: **ACCRETION, ACCRETION DISKS — STARS: MASS LOSS — STARS: PRE-MAIN-SEQUENCE — STARS: VARIABLES**

1. INTRODUCTION

In the Popul Vuh – the K'iche' Maya Book of the Dawn of Life – earth began when the gods Heart of Sky and Sovereign Plumed Serpent "said 'Earth.' It arose suddenly, just like a cloud, like a mist, now forming, unfolding." (Tedlock 1985). After they created mountains, plants, and animals, the gods tried several times to people their new world. They finally succeeded when corn dough proved more durable than mud or wood. The Mayan world of human beings began on 4 Ahaw 8 Kumk'u (13 August 3114 BC) according to inscriptions at Koba (Freidel, Schele, & Parker 1993). Their calendar returns to the creation date $\sim 4 \times 10^{28}$ years hence.

Nowadays, we have a more complicated – and perhaps equally mythical – view of our world's formation. In modern tales, earth began as widely separated gas molecules and dust motes in a dense molecular cloud core. This dense core eventually collapsed. Material with low specific angular momentum fell into a protostar at the cloud's center; higher angular momentum gas landed in a circumstellar disk. The cloud was initially optically thick, absorbed the accretion energy of infalling gas, and radiated this energy at far-IR wavelengths. As the collapse continued, the cloud became optically thin and allowed optical and near-IR radiation to escape. Once infall ended, the disk evolved on its own. Some disk material flowed onto the star; some was ejected. The rest condensed into planets and other solid bodies.

Although the Mayan and modern creation accounts have some similar features – clouds, for example – they obviously differ in many important aspects. For example, circumstellar disks have played a major role in solar system models since the time of Kant and Laplace, and a flattened, dusty nebula now dominates our picture of the early evolution of any planetary system (see Adams & Lin 1993). Mayans did not include accretion disks in any of their myths. Yet the three hearthstones of Mayan creation – along with the turtle of rebirth and the cords of heaven – lie curiously close to FU Orionis, a system that probably provides the best evidence for disk accretion among pre-main sequence stars.

This paper presents an observationally oriented review of accretion in FU Ori variables (see also Hartmann et al. 1993). My discussion begins with a very brief introduction of useful disk properties, moves on to a short summary of basic FU Orionis data, continues with applications of disk physics to these data, and concludes with a brief discussion of the impact disk eruptions have on a surrounding molecular cloud.

2. DISK PROPERTIES

We have been fortunate to learn much about accretion disks in the past two decades. Most interacting binaries – Algol systems, cataclysmic binaries, symbiotic stars, VV Cephei stars, and X-ray binaries – contain rapidly-evolving disks. More slowly-evolving, dusty disks surround our Sun and β Pic. Active galactic nuclei apparently contain massive gaseous disks around a supermassive black hole. Each type of system has been studied in great detail to improve and to test our understanding of disks in a wide variety of physical situations. These studies indicate that much of the internal physics of disks is universal. Figure 1 shows light curves for SS Cyg – a cataclysmic binary with an orbital period of P_{orb} = 6.6 hr; CI Cyg – a symbiotic binary with P_{orb} = 855 days; and V1057 Cyg – an FU Ori variable that is apparently a single star. The 3–5 mag eruptions of these systems occur when the accretion rate through the disk increases. Aside from the deep eclipses observed at JD 2700 and JD 3550 in CI Cyg, the three light curves look very similar and indicate that the same physical processes govern the evolution of disks ranging in size from 0.5 $R_\odot$ to several tens of AU.

Spectral energy distributions (SEDs) also probe the physical structure of a circumstellar disk. Simple models assume disks have some radial temperature law, $T(R) \propto R^{-q}$, and radiate as blackbodies. Most studies incorrectly assume that $q(R)$ = constant. In a *steady-state* accretion disk, the temperature law has $q = 3/4$ for $R \gtrsim 10R_\star$ and $3/4 \lesssim q \lesssim 1$ for $R \gtrsim 10R_\star$ ($R_\star$ is the stellar radius). A flat *reprocessing disk* – which absorbs and reradiates light from the central star – has a similar temperature law. A disk can have $q < 3/4$ only if (i) the accretion rate is not steady; (ii) the disk is not perfectly flat; or (iii) some non-local mechanism – such as a density wave – transports energy through the disk (Adams & Lin 1993).

Actual disk temperature distributions have been derived from eclipse light curves similar to those shown in Figure 1 for CI Cyg. K. Horne and collaborators (see Horne 1993) have used maximum entropy techniques to recover $T(R)$ from multi-wavelength light curves assuming (i) the disk is azimuthally symmetric and (ii) the brightness temperature is close to the local blackbody temperature. Their results indicate that quiescent disks are rarely close to steady-state, with temperature distributions usually much flatter than $T(R) \propto R^{-3/4}$. Systems in eruption – dwarf novae and symbiotic stars at maximum light – more closely resemble, but never achieve, the steady-state temperature distribution with $q = 3/4$ (Horne 1993).

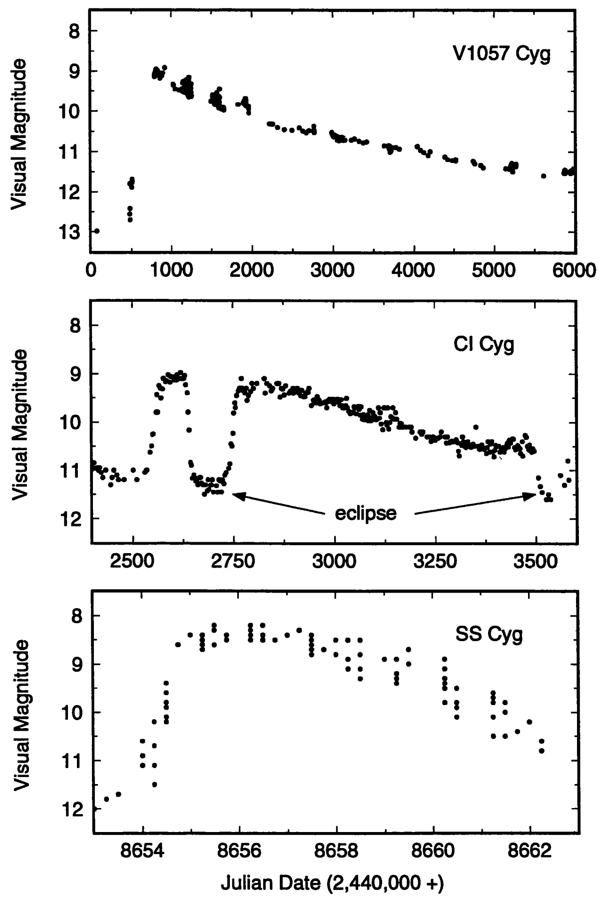

Fig. 1.— Light curves for SS Cyg, a cataclysmic binary; CI Cyg, a symbiotic binary; and V1057 Cyg, an FU Ori variable star. Despite a different size scale in each system, the light curves are very similar and indicate a similarity in the underlying disk physics.

3. BASIC PROPERTIES OF FU ORIONIS VARIABLES

In 1939, A. A. Wachman discovered a 10th magnitude star at the apex of a fan-shaped nebula in the dark cloud B35 near λ Orionis. Wachman could not find the nebula on previous plates of the region and proposed that both the star and its nebula had brightened by over a factor of one hundred in 100–200 days. He suggested this flare-up might be caused by the emergenece of the star from an obscuring dust screen with a thickness of $\lesssim 1$ pc for $n \gtrsim 10^4$ cm^{-3}.

George Herbig first associated the eruption of FU Orionis with an intrinsic phenomenon of early stellar evolution rather than a purely geometric effect. Herbig (1966) showed that the star must move at speeds of 10-100 km s^{-1} relative to the dust screen to achieve a 5 mag rise in 100 days, yet his optical spectra demonstrated the observed relative velocity of the star and the dark cloud is less than 1 km s^{-1}. In addition, Herbig's spectra of FU Ori resembled spectra of G-type supergiants, with the unusually broad absorption lines and very strong Li I λ6707 absorption that are characteristic of young stars.

FU Ori's eruption remained a unique phenomenon of early stellar evolution until 1970, when Welin noted a 5 mag brightening of a faint emission line star in the H II region NGC 7000. The sole pre-outburst spectrum of this star – which soon became known as V1057 Cygni – resembled spectra of some T Tauri stars. At maximum, however, V1057 Cyg resembled an A-type supergiant. Shortly after maximum, V1057 Cyg developed an eccentric ring of reflection nebulosity whose brightness has closely followed the optical light curve (see Figure 2).

Herbig (1960) first noted V1515 Cyg as a faint variable embedded in arc-shaped nebulosity during a search for Hα emission-line stars in the reflection nebula NGC 6914. Spectra acquired in 1974 revealed a striking similarity to FU Ori and V1057 Cyg; archival photographic photometry showed a slow rise from $m_{pg} \approx 15.5$ in the late 1940s to $m_{pg} \approx 13.5$ in the late 1970s (Herbig 1977). The brightness continued to increase until 1980, when it experienced a dramatic decline due to dust formation in its outflowing wind (Kolotilov & Petrov 1983; Kenyon et al. 1991). The system gradually recovered from this event and may now be slowly declining.

Many new FU Ori objects – which are often called FUors – have been discovered since V1515 Cyg. The catalogued number now stands at $\sim$ 12. Most have been observed to rise 3–5 mag in less than one year. V1515 Cyg is the only known example to require a decade to rise to visual maximum, but the historical light curves for some systems are poorly documented. A few objects have been called FUors based on common spectroscopic properties, which are described more completely below. Most recent FUors are more intimately associated with dark clouds than the first members of the class, which suggests that many eruptions might have been missed.

All FUors share a very distinct set of morphological, photometric, and spectroscopic characteristics. Goodrich (1987) first showed that FUors possess delicate fan-shaped or comma-shaped nebulae; Goodrich & Reipurth (1991) separately noted that such reflection nebulae are much more common among FUors than optically visible T Tauri stars. Many also display optical jets or HH objects (Reipurth 1991; Hartmann et al. 1993); most appear associated with large-scale molecular outflows (Evans et al. 1994). These features – together with broad, blue-shifted Na I and H I absorption features – demonstrate that FUors drive powerful winds that interact with the surrounding medium (Bastian & Mundt 1985; Croswell et al. 1986).

In addition to these similarities, FUors have very distinctive SEDs. Optically visible sources have F–G optical spectra; the reflection nebulae of several embedded FUors also show G-type absorption features (Stocke et al. 1988). All FUors but Z CMa and V346 Nor have very deep CO absorption bands on near-IR spectra at 1.6 μm and 2.3 μm (see, for example, Mould et al. 1978; Elias 1978; Carr et al. 1987; Kenyon et al. 1993a). These features resemble the CO absorption bands observed in red giants and are much stronger than those observed in any other pre-main sequence star. CO absorption in Z CMa is weakened by dust emission from an embedded companion; V346 Nor has no obvious excuse for its lack of CO absorption. Many FUors also display strong water absorption features, which strengthens the evidence for a $\sim$ 2000 K photosphere.

All FUors show large *excesses* of radiation over normal G supergiants at both ultraviolet and infrared wavelengths. The near-IR excess is clearly photospheric in origin, because the CO and H_2O absorption features

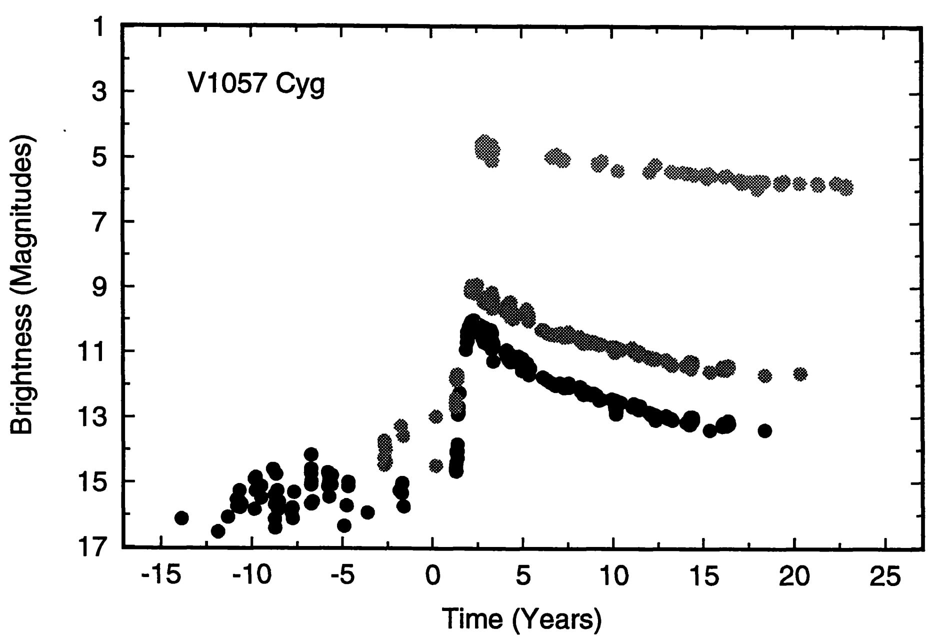

Fig. 2 — Light curves for V1057 Cyg. The system varied erratically at B = 14–17 prior to outside and then rose 5–6 mag in less than one year (dark circles). The visual observations indicate a similar rise time, although few pre-outburst observations are available (medium circles). No pre-outburst near-IR data exist; K-band observations began shortly after the outburst was detected (light circles). The amplitude of the decline clearly depends on wavelength, with larger amplitudes at shorter wavelengths.

are so intense. The UV excesses in Z CMa and FU Ori appear associated with an A- or F-type photosphere that is hotter than the G-type photosphere observed at longer wavelengths (Kenyon et al. 1989).

Herbig (1977) first noted broad absorption lines on optical spectra of several FUors. Hartmann & Kenyon (1985) confirmed large rotational velocities of $v \sin i \approx$ 15–60 km s^{-1} for V1057 Cyg, V1515 Cyg, and FU Ori. This property is now characteristic of the class; all FUors have broad optical or infrared absorption lines (Hartmann et al. 1989; Staude & Neckel 1991, 1992; Kenyon et al. 1993). The rotational velocity further depends on wavelength. Hartmann & Kenyon (1987a,b) showed that the near-IR CO lines in FU Ori and V1057 Cyg have significantly smaller rotational velocities than optical lines. Welty et al. (1991) later determined that the optical rotational velocity smoothly increases with decreasing wavelength in V1057 Cyg. They did not find a similar relation in FU Ori; this system has a more powerful wind that distorts weak features.

Many FUors display *doubled* absorption lines on optical and near-IR spectra (Hartmann & Kenyon 1985, 1987a,b; Kenyon et al. 1988; Hartmann et al. 1988; Staude & Neckel 1991, 1992). The two absorption components in V1057 Cyg are separated by 30–40 km s^{-1}; these features have much larger separations in Z CMa and FU Ori. The long-term stability of the doubled absorption lines indicates that the lines are not produced by two stellar components in a binary system (Kenyon et al. 1988).

Most FUors also show strong evidence for mass loss. Practically every FUor displays deep, blueshifted absorption components on Hα and Na I D; Hartmann & Kenyon (1987b) noted weak blueshifted CO absorption might be present in FU Ori. The optical line profiles can also change on month to year time scales (Bastian & Mundt 1985; Croswell et al. 1986; Welty et al. 1992). Both V1057 Cyg and V1515 Cyg have very pronounced line profile changes and dips in their optical light curves. These fluctuations suggest dust formation in a variable wind, but the data are not very extensive.

Finally, FUor eruptions must be repetitive (Herbig 1977; Hartmann & Kenyon 1985). If we have found all FUors that have erupted in the past 50 yr, the FUor rate is roughly 0.1–0.2 yr^{-1}. All FUors lie within 1 kpc. The star formation rate within this volume is roughly 0.01 yr^{-1}. On average, then, a young star must undergo 10–20 FUor eruptions before it reaches the main sequence. This estimate is clearly very crude. Some current FUors probably began their eruptions prior to the 1940s – for example, Z CMa and BBW 76 – while others certainly were missed. The FUor 'detection rate" has increased considerably during the past two decades; the eruption frequency estimated above thus may be a lower limit to the true eruption frequency.

4. WHAT MAKES FU ORI ERUPTIONS?

The preceding discussion places severe constraints on possible FUor outburst mechanisms. First, we need an event that produces roughly 10^{45} to 10^{46} ergs during a 100 yr outburst. This process must repeat every 10^5 yr or so assuming a typical pre-main sequence lifetime of 1–3 $\times$ 10^6 yr. It must also produce an object that resembles a rapidly rotating F-G supergiant in the optical and an M giant in the infrared. It must be unique to young (single) stars, because we have not observed a FUor event in an older star system.

Thermonuclear reactions and accretion events are the most obvious physical processes that can release large amounts of energy on relatively short time scales (Herbig 1977 discusses other proposals). S. Stahler has noted the possibility that deuterium burning might produce a single FUor eruption under appropriate circumstances. A young star needs to burn roughly 10^{-6} M$_\odot$ of deuterium to power a single eruption and then must replenish this fuel supply in 10^5 yr. For a standard cosmic deuterium abundance of D/H $\sim 10^{-5}$, an accretion rate of 10^{-6} M$_\odot$ yr^{-1} can add enough deuterium for the next eruption. The star then has an appreciable accretion luminosity of $\sim$ 10 L$_\odot$. This luminosity is larger than the typical luminosity of a T Tauri star, $\sim$ 1 L$_\odot$, but is comparable to that of a continuum + emission T Tauri star. It is not clear, however, how an ordinary T Tauri star avoids burning deuterium as its contracts towards the main sequence.

Accretion is a much more plausible energy source for FUor eruptions. A young star must accrete material at $\sim 10^{-4}$ M$_\odot$ yr^{-1} during an eruption to power the observed luminosity. For an adopted outburst duration of 100 yr, this accretion rate results in a total accreted mass of $\sim$ 0.01 M$_\odot$ per eruption. The total mass accreted during a FUor eruption must be replenished during the 10^5 yr quiescent period in between outburst, which results in an accretion rate of $\sim 10^{-7}$ M$_\odot$ yr^{-1}. This rate is close to that estimated for many T Tauri stars.

The accretion model thus envisions that *a pre-main sequence star lies in* one *of two accretion rate states.* In the low state, the accretion rate into the disk from the surrounding cloud exceeds the accretion rate through the disk onto the central pre-main sequence star. In the high state, the disk accretion rate onto the star exceeds the infall rate from the cloud into the disk by several orders of magnitude. The system cycles between these two states as long as the surrounding cloud can replenish the disk between outbursts. Once the cloud cannot supply the disk with new material, the disk gradually empties onto the central star and eventually begins to form planets. Bell (1995) in these Proceedings describes the physical reasons for this 'limit-cycle' behavior in FUors and other accreting systems, such as cataclysmic variables and symbiotic stars (Figure 1; Lin & Papaloizou 1985).

Although accretion provides a natural way to produce FUor eruptions, can high $\dot{M}$ disks explain the properties described in §3 Hartmann & Kenyon (1985) first applied simple disk models to FUor observations and have supported this picture with various observational analyses (Hartmann & Kenyon 1987a,b; Kenyon et al. 1988, 1989, 1991, 1993; Hartmann et al. 1989; Kenyon & Hartmann 1989, 1991; Calvet et al. 1991, 1993). The next few paragraphs summarize these results; Herbig & Petrov (1992) present a different interpretation.

Figure 2 shows light curves for V1057 Cyg, one of the best-studied FUors. These light curves closely resemble those of other accreting systems and provide strong support for an accretion model. The amplitude of the decline is largest in the UV and decreases monotonically from 0.3 μm to 5 μm. This behavior is characteristic of accreting systems, which evolve towards cooler temperatures as the luminosity declines. The spectral type variation also agrees with disk model predictions. If we assign stellar effective temperatures to the optical spectrum at maximum (A5 star) and at the current epoch (G5 star), the UBV decline indicates a source with a roughly constant radius. This requirement is easy to achieve with an accretion disk if the radius of the central star remains constant. Most stars cannot evolve at constant radius if their effective temperatures change.

Disk models also successfully explain FUor SEDs. Figure 3 shows dereddened SEDs for V1057 Cyg and V1515 Cyg. The deep UV and near-IR absorption features indicate that the UV and IR excesses over a G-type supergiant spectrum are photospheric. We thus assume FUors radiate like stars at the effective temperatures appropriate for the observed absorption features. With this assumption, SEDs for V1057 Cyg, V1515 Cyg, and other FUors require *the surface area of the emitting region to increase with increasing wavelength.* In particular, the surface area of the near-IR source must be 10–20 times larger than the surface area of the optical source. Similarly, the 300 K material responsible for the 10 μm excess must have roughly 100 times the emitting area of the optical continuum region. A disk in which the temperature decreases radially outward (§2) naturally explains this observation. Hartmann & Kenyon (1985) showed that disk models could account for the 0.3–10 μm SED of V1057 Cyg quite well (Figure 3; see Adams et al. 1987; Kenyon et al. 1988; Kenyon & Hartmann 1991). Disk models also fit data for V1515 Cyg (Figure 3; Kenyon et al. 1991).

The disk model *fails* to explain 10–100 μm data of many FUors, although the model fits both FU Ori and BBW 76 from 1–100 μm (Kenyon & Hartmann 1991; Hartmann et al. 1993). Kenyon & Hartmann (1991) noted

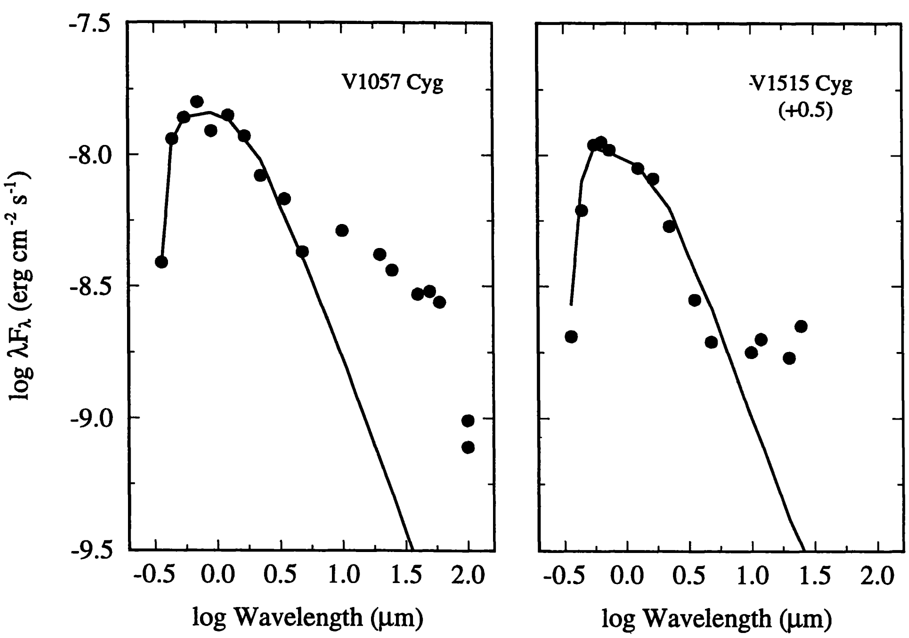

Fig. 3 — Spectral energy distributions for V1057 Cyg and V1515 Cyg. The solid line is the energy distribution of a disk model that accounts for the optical G-type spectrum in both systems. The far-IR flux is probably produced by a surrounding nebula.

that the decline of the 10–20 μm light of V1057 Cyg followed the optical light curve very closely. They proposed that the mid-IR radiation is optical light absorbed and reradiated by a surrounding envelope and developed a simple model to explain the 10–100 μm SED. Their model requires an infall rate of 1–5 $\times$ 10^{-6} $M_\odot$ yr^{-1} to produce an envelope with sufficient optical depth to reprocess optical light from the inner disk. This rate is sufficient to replenish the disk in 1000 yr, which allows recurrent FUor eruptions in this system.

Finally, an accretion disk also naturally explains the optical and IR line profiles observed in some FUors (Hartmann & Kenyon 1987a,b; Kenyon et al. 1988). The gradual decrease in the rotational velocity with increasing wavelength occurs because (i) the longer wavelength emission is produced at larger disk radii than the short wavelength emission and (ii) the outer portions of the disk rotate more slowly than the inner disk regions (see also Welty et al. 1991). At a given disk temperature, a larger fraction of the disk surface rotates at high line-of-sight velocities and the lines appear doubled (Kenyon et al. 1988; Calvet et al. 1993).

5. FUORS AND CLASS I PROTOSTARS

C. Lada and collaborators have popularized a simple scheme to classify pre-main sequence SEDs (Lada 1987; Adams et al. 1987). Class I sources have SEDs that peak at 30–100 μm. These optically invisible, embedded sources typically drive low velocity, poorly collimated molecular outflows; illuminate extended optical/near-IR reflection nebulae; and lie in the densest gas (see Kenyon et al. 1993b,c and Greene et al. 1994 for detailed summaries of Ophiuchus and Taurus class I sources). Optically visible T Tauri stars are more numerous than class I sources in nearby clouds and have SEDs similar to a cool stellar photosphere. They rarely possess reflection nebulae or molecular outflows and often lie off the densest portions of the cloud. Lada (1987) divided T Tauri stars into class II and class III sources based on their far-IR SEDs. Class II sources display excess IR emission compared to a reddened stellar photosphere; class III sources have little or no excess IR emission.

As a group, FUors have many observed features in common with the class I protostars. All FUors possess very distinctive optical and near-IR reflection nebulae (Goodrich 1987). Nearly all FUors display large far-IR excesses and drive molecular outflows (Kenyon & Hartmann 1991; Evans et al. 1994). Finally, at least 1/3 are associated with jets or HH objects (Reipurth 1991). These properties show that FUors are much younger than most T Tauri stars – which usually have none of these qualities – and more similar to class I sources. Thus, FUors generally occur during the class I phase and must have comparable ages, $\tau \sim$ a few $\times$ 10^5 yr.

Although the statistics are very crude, young stars clearly accrete a large fraction of their final mass in FUor eruptions. If pre-main sequence stars really do undergo 20 or more outbursts and a typical outburst lasts $\sim$ 100 yr, a star accretes at least 0.2 $M_\odot$ – almost half of a typical stellar mass – from a circumstellar disk.

The FUor frequency needed to accrete *all* of a typical stellar mass can be estimated by assuming that a young star spends its class I lifetime either in the high accretion – FUor – state **or** in a state with much lower $\dot{M}$ (which could be a T Tauri star). The quiescent state lasts until the disk mass becomes high enough to trigger an outburst; the outburst continues until the disk empties of material (Bell et al. 1995 and this volume). This cycle repeats until infall from the cloud ceases. The fraction of time in the FUor state is simply the ratio of the infall rate to the FUor accretion rate: $f \sim \dot{M}_i/\dot{M}_{FU}$. FUor disk models require $\dot{M}_{FU} \sim 10^{-4}$ $M_\odot$ yr^{-1}, so $f \sim 0.05$ for a typical infall rate of $\dot{M}_i \sim 5 \times 10^{-6}$ $M_\odot$ yr^{-1}. Thus, a young star must spend $\sim$ 5% of its class I lifetime as a FUor to accrete all of its mass in this high $\dot{M}$ state.

FUors also eject considerable amounts of mass and momentum. For example, FU Ori itself has lost material with a momentum of $\sim$ 0.3 $M_\odot$ km s^{-1} since its eruption began. This value represents a modest fraction of typical outflow momenta, $(Mv)_o$ $\sim$ 1–100 $M_\odot$ km s^{-1}, but a FUor event lasting several millenia – or a series of eruptions – could significantly impact the central star and the surrounding cloud.

Can FUor winds provide enough momentum for a typical outflow? If the mass loss rate in the disk wind scales with the accretion rate, the total momentum in the wind – over a time scale τ – is

$$(Mv)_w \sim \dot{M}_w \; \tau \; v_w \sim 0.1 \; \dot{M}_a \; \tau \; v_w \; , \tag{1}$$

where v_w is the wind velocity. This expression assumes the mass loss rate is roughly 10% of the accretion rate (Hartmann, this volume). If the disk processes most of a typical stellar mass, $M_\star \sim \dot{M}_a\tau$; the outflow momentum is

$$(Mv)_w \;\sim\; 20 \, (M_\star/M_\odot) \; M_\odot \; \mathrm{km \; s^{-1}} \tag{2}$$

for a typical wind velocity of 200 km s^{-1}. The observed range of outflow momenta – $(Mv)_o$ = 1–100 $M_\odot$ km s^{-1} (Fukui 1989) – requires typical stellar masses of $M_\star$ ~ 0.1–5 $M_\odot$ if the flows conserve momentum. Thus, *a young stellar system must eject ~ 10% of its final mass to produce a typical molecular outflow.* A disk wind can power the outflow **if** a young star accretes most of its material through the disk.

This discussion establishes that FUor eruptions can power molecular outflows if 5% of class I sources are FUors. This possibility can be tested by deriving the FUor frequency among class I sources in many molecular clouds. For example, the Taurus dark cloud contains ~ 20 class I sources and one object – L1551 IRS 5 – in the FUor state, which agrees with the simple prediction (perhaps fortuitously). Source statistics for class I sources in other clouds are not as good as in Taurus and the FUor population in these clouds is even less well-known. However, both of these numbers can be improved with sensitive photometric and spectroscopic surveys of nearby molecular clouds to identify class I sources and then determine which – if any – of these objects display the characteristic spectroscopic properties of FUors. If the FUor frequency among class I sources turns out to be more than a few per cent, then FUors may represent the main accretion phase of early stellar evolution.

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