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A BINARY ORIGIN FOR FU ORIONIS STARS

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ABSTRACT

We explore the possibility that the FU Orionis phenomenon is due to the binary nature of the stellar source. In our model, tidal effects from a companion induce enhanced accretion rates. In an eccentric system the effects are greatest at closest approach. Additionally, mass transfer from the primary's to the secondary's disk at closest approach can provide the necessary matter that is accreted. Accretion rates by this process can exceed $1 \times 10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$ and lead to significant increases in the masses of the components. The outbursts are periodic, occurring at each closest approach, in good agreement with the observed statistics. The binary nature of the exciting source is expected to be at least partially obscured by the differential reddening expected due to the accretion processes in an unequal mass binary system. The system is thus composed by an optically visible secondary with an infrared companion as the primary. The detection of an infrared companion to the FUor star Z CMa lends credence to our model.

Subject headings: accretion, accretion disks — binaries: close — stars: formation — stars: individual (Z CMa) — stars: pre–main-sequence

1. INTRODUCTION

FU Orionis (FUor) variables are objects which undergo a rapid increase in luminosity of up to 5 mag in a period of years with decay times of tens of years to greater than a hundred years (Hartmann 1991). Episodic phenomena in pre–main-sequence stellar evolution has received much attention since the determination that the FUor variables are pre–main-sequence (PMS) objects. Evidence for the youth of the FUor stars comes from their reddening, the abundance of lithium, and the pre-outburst spectrum of V1057 Cyg (Herbig 1958), which was that of a classical T Tauri star (Herbig 1977) and had an outburst in 1970. FUors, with their rapid increase in luminosity, slow decline, and spectra resembling F or G supergiants with broad Hα absorption (Hartmann 1991), have been successfully modeled by an accretion disk (Hartmann & Kenyon 1985) similar to that envisioned around CTTS (Bertout, Basri, & Bouvier 1988) but with accretion rates $\gtrsim 10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$ (Kenyon, Hartmann, & Hewett 1988). An alternative interpretation to explain FUor spectra has recently been proposed by Petrov & Herbig (1992).

Hartmann (1991) lists eight FUor objects, some of which are classified as such due to their spectral signatures even though no outburst has been observed. One of these, Z CMa, has recently been observed to be a binary (Koresko et al. 1991; Haas et al. 1992). The binary is composed of an optically visible component, the one associated with the FUor signatures, and an infrared (IR) component, which is actually more luminous. In addition to the two components and their respective disks, the observations indicate the presence of an outer, circumbinary disk. Since the IR companion is more luminous and still embedded while its companion is optically visible, it is conceivably the more massive component. Models of the accretion onto an unequal mass binary system (Bonnell & Bastien 1992, hereafter BB92) show that the more massive component has a stronger tendency to be obscured by the surrounding medium and also has the more massive disk. This is due to its relative position closer to the center of mass of the system. Most of the infalling matter either falls directly toward the center of mass and hence the more massive component or else forms a disk around it. The less massive component is located further away from the center of mass and is thus likely to be less obscured. Observations have shown recently that ≈10% of PMS stars have IR companions (Zinnecker & Wilking 1992).

Recent surveys of T Tauri stars have found that the binary frequency is high (Ghez, Neugebauer, & Matthews 1992; Simon 1992; Zinnecker, Brandner, & Reipurth 1992), possibly even greater than on the main sequence (e.g., Duquennoy & Mayor 1991). BB92 has shown that the binary nature can have a large effect on the accretion process. The possibility that FUor eruptions are due to perturbations in a circumstellar disk caused by the passage of a companion on an eccentric orbit has been suggested by A. Toomre (Kenyon et al. 1988). It is therefore interesting to explore the possibility that the FUor phenomenon is due to binarity.

In § 2 we develop the model for the tidally induced accretion in a binary system. In § 3 we discuss the relevance of our model with past work and observations. Our conclusions are presented in § 4.

2. EPISODIC ACCRETION AND FUORS

Tidally induced accretion in a binary system has recently been studied in the context of cataclysmic binaries (Livio & Spruit 1991; Matsuda et al. 1990). The tidal forces of a companion develop into coherent spiral shocks which are responsible for an increase in the accretion rate. In an eccentric system, tidal effects will vary with the separation.

The collapse and fragmentation of elongated clouds has been shown to form binary systems with large eccentricities (Bonnell et al. 1991; BB92). Small density gradients, expressed in terms of the density contrast from one end of the cloud to

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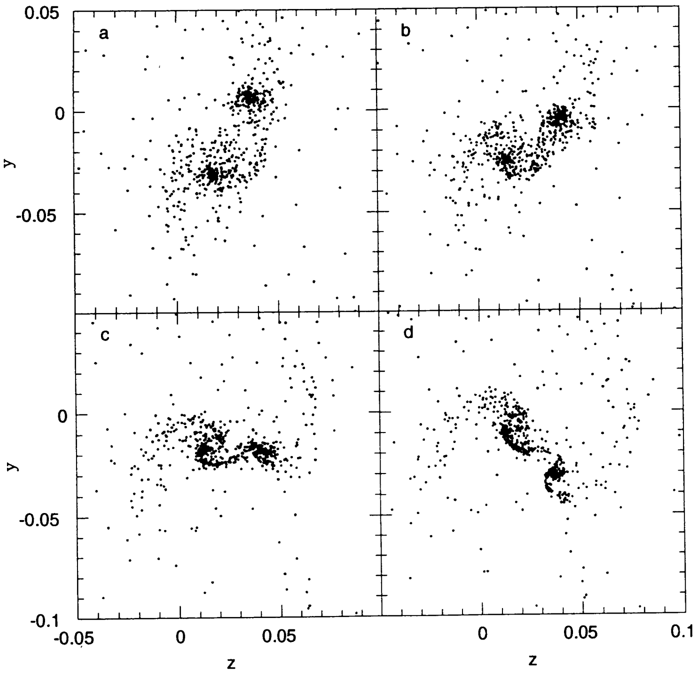

FIG. 1.—Temporal evolution of an equal mass binary system near closest approach. The SPH particles are plotted projected onto a plane perpendicular to the rotation axis for the simulation 1X from BB92.

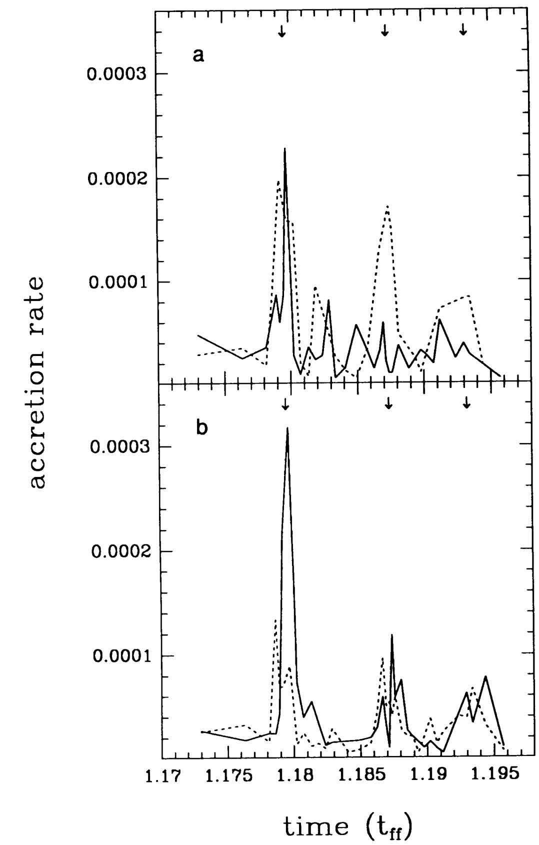

FIG. 2.—Accretion rate onto the primary (*a*) and secondary (*b*) in units of $M_\odot$ yr^{-1}, as a function of time in units of the free-fall time, $t_{ff} = 9.7513 \times 10^{12}$ s, for the simulation 1G from BB92. The continuous and dotted curves represent the accretion rate at radii of 11.5 and 23 AU, respectively. The arrows indicate the times of the closest approaches. At the end of the calculations, the masses of the two components are ≈ 0.42 and 0.28 $M_\odot$ ($q = 0.67$).

the other, are sufficient to form unequal mass binary systems with mass ratios varying from ≈ 0.1 to 1 (BB92).

In these simulations, tidal interactions induce enhanced accretion at closest approach (BB92). The tidally induced accretion rate depends on the mass ratio such that a lower mass companion induces a smaller accretion rate (see also Matsuda et al. 1990). Thus in an unequal mass binary system the tidally enhanced accretion onto the lower mass secondary will be much larger than that onto the primary. Additionally, the secondary will pass close to the outer edge of the primary's disk at closest approach, allowing it to pirate matter from this disk, which can subsequently be accreted. The evolution of an unequal mass binary system at the first closest approach is illustrated in Figure 1. A spiral arm structure develops in the primary's disk as well as an overall distortion in the disk shape. Matter in the primary's disk closest to the secondary is pulled toward the secondary and can be captured by the secondary at closest approach. A "bridge" of matter between the two components is formed by the matter transferred from the primary's disk to that of the secondary. This transfer of matter is evident in the figures of the primary's and secondary's mass evolution reported in BB92. The mass contained in the primary's disk is reduced while the secondary's suddenly increases at closest approach. Infall from the surrounding matter continues to replenish both circumstellar disks throughout the orbit. When infall onto the binary system has stopped, the disks will be slowly depleted by subsequent closest approaches. As the disk mass is lowered, the strength of the eruptions will decrease. In this way a logical evolution from FUors to EXors to quiescent PMS stars can be envisioned (Hartmann, Kenyon, & Hartigan 1992).

The temporal evolution of the accretion rate onto each component of an unequal mass binary is plotted in Figure 2. The strongly enhanced accretion rates at closest approaches are evident over three orbits for both the primary and the secondary. Accretion rates can exceed 1×10^{-4} $M_\odot$ yr^{-1} with a maximum value of $\approx 3 \times 10^{-4}$ $M_\odot$ yr^{-1}). (Other calculations had a maximum accretion rate of $\approx 4 \times 10^{-4}$ $M_\odot$ yr^{-1}.) This maximum value is probably an underestimate due to the resolution limits. Smaller volumes demonstrate larger accretion rates (BB92). The total mass accreted during the first encounter can be estimated from Figure 2 to be 0.05 and 0.03 $M_\odot$ for the secondary and primary, respectively. The peak accretion rates decrease with each closest approach.

Figure 3 plots the accretion rate as a function of time for a simulation with a lower mass ratio. The accretion rate onto the primary is smaller due to the smaller mass ratio. Furthermore, the maximum accretion rate does not necessarily have to decline with each successive closest approach as it does in Figure 2. The evolution of the maximum accretion rate is determined by the balance between two tendencies: the replenishment of disk material by matter infalling from the common envelope, and the accretion onto the central protostars. Initially, the maximum accretion rate may increase for a few closest approaches, but in the long run the transition from FUor to EXor is expected. The difference in shape of the accretion rate profile is also evident. This is most probably due to the dynamical differences in disk structure at each closest approach. The total mass accreted by the secondary during the

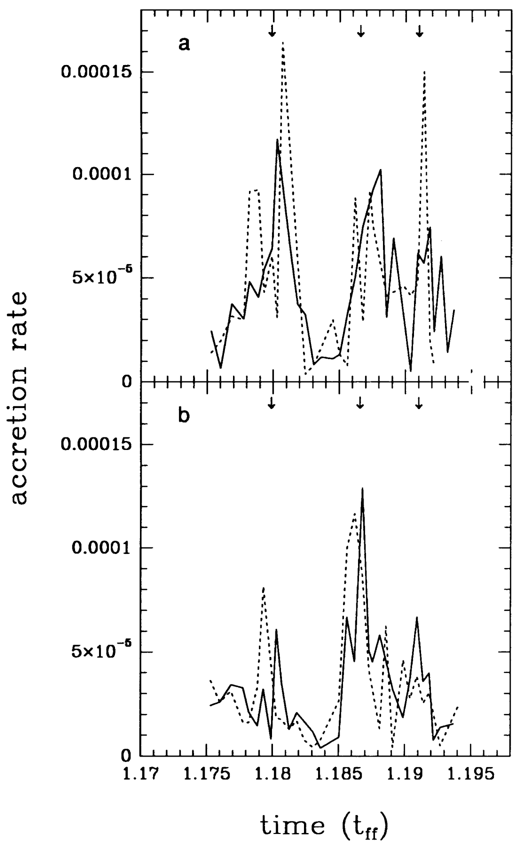

FIG. 3.—Same as Fig. 2 except for a lower mass ratio (simulation 1O from BB92). At the end of the calculations, the masses of the two components are ≈ 0.50 and 0.21 $M_\odot$ ($q = 0.42$).

second encounter is ≈ 0.05 $M_\odot$ because of the longer accretion period ($\approx 10^3$ yr).

This scenario of tidally induced accretion in an eccentric system could explain the rapid increase and slow decline in luminosity of FUors. The rapid increase comes from the greatly increased tidal forces, inducing enhanced accretion onto one or both components. Even more encouraging is the sudden increase of matter in the secondary's disk, stolen from the primary's disk, coupled with the enhanced accretion due to the tidal forces of its more massive companion. Due to the comparable orbital velocity of the secondary and the rotational velocity of the outer parts of the primary's disk at closest approach, the matter stolen from the primary's disk has little rotational velocity in the secondary's reference frame. This matter can then be deposited at arbitrarily small disk radii or be accreted directly. Matter with greater rotational velocity in the secondary's reference frame will be deposited at larger radii. The rise time in the light curve cannot be directly evaluated from the calculations to date, but the sudden increase of the secondary's disk mass coupled with direct accretion where no dissipation of angular momentum is necessary could conceivably produce rise times that vary from periods as small as one year to decades.

Both primary and secondary will undergo enhanced disk accretion producing the infrared spectrum, while accretion onto the secondary could preferentially produce the optical spectrum. In this scenario the primary could then be an embedded object, only visible in the IR, explaining why few FUors have been determined to be binaries. This is consistent with the infrared observations of FUors (Kenyon & Hartmann 1991). They interpret the heavy optical extinction and excess emission compared to an accretion disk model as coming from an infalling flattened dusty envelope. In our model the infalling matter would predominantly fall toward the system's center of mass, which is approximately the position of the primary. This infalling matter will then obscure the primary and form a disk around it. The secondary can accrete matter directly from this disk and will therefore suffer less extinction. Additionally, the large far-IR excess commonly observed can be explained by the presence of the IR companion (Bonnell & Bastien 1993).

3. DISCUSSION

FUor outbursts have been modeled by perturbations in an accretion disk triggering a thermal instability (Clarke, Lin, & Pringle 1990). Clarke et al. (1990) also speculate on the mechanism that produces the perturbation. Two possibilities are the passing of a companion on an eccentric orbit and the tidal disruption of a nearby cloud. The passage of a companion will perturb a preexisting disk, while the disruption of a nearby cloud will increase the amount of matter in the disk or generate one in its absence. The model proposed here combines both possibilities in the companion on an eccentric orbit and its surrounding disk which can be partially disrupted to increase the material comprising the accretion disk.

Due to frequency statistics, Herbig (1977) noted that each star probably undergoes 100 FUor outbursts in its pre–main-sequence lifetime. Hartmann (1991) also concludes that between 10 and 100 outbursts would be typical. This supposed periodicity greatly encourages a binary scenario where repeated outbursts find a logical and periodic cause. The differences in FUor outbursts, accretion rates, and time scales could all be provided by differences in binary parameters (mass ratio, period, eccentricity) and protostellar disk evolution.

One other FUor that is worthwhile noting here is L1551 IRS5. This source, deeply embedded, has both an optical jet and a CO bipolar envelope. The possibilities of this source's binarity have already been discussed by Bonnell & Bastien (1993). A number of HH objects also exist. Reipurth (1991) stresses the repetitive nature of HH flows and suggests a possible dependency on FUor eruptions as the energy sources. In this scenario, the massive, high-velocity winds that accompany the increase in accretion rate would be the source of the HH objects. In L1551 IRS5, the HH objects are periodically placed, but on a line which would indicate that the HH flow has been precessing (Stocke et al. 1988). A precessing HH flow could be explained by this disk being tilted by interactions with a companion at each closest approach (Heller 1991). Multiple ejections in HH flows have also been found in HH47 (Hartigan, Raymond, & Meaburn 1990) and in HH34 (Reipurth & Heathcote 1992), indicating periods of 2000 and 400 yr, respectively. The periodic ejection of HH objects supports the periodicity of FUor outbursts, and the time interval is appropriate for a binary system.

T Tau S, the IR component in the pre–main-sequence binary T Tau, has recently undergone an increase of 2 mag at wavelengths between 2 and 10 μm (Ghez et al. 1991). Modeling this flare with a FUor-type accretion disk gives a factor 20 increase in the accretion rate. A FUor-like (or EXor-like) explanation of the binary T Tau would strengthen binarity as a possible FUor cause. Another noteworthy factor is the observation of the bridge of emission between the optical, T Tau N, and IR, T Tau S, components (Schwartz, Simon, & Campbell 1986). If this feature is not due to the initial conditions of the formation of the binary system, then it might be due to an interaction at closest approach which is in the process of transferring matter from the primary's to the secondary's disk. A feature extending from the IR component in the direction opposite to that of the optical component could then indicate the presence of a spiral arm. A spiral arm is expected to form at closest approach due to the tidal forces of the companion (see Bonnell et al. 1991; BB92).

Chelli et al. (1988) note that Glass I, a binary composed of an optical T Tauri star and a more luminous infrared companion, has a reduced overall luminosity compared to the observations of Glass (1979). Assuming that the difference comes solely from the optical component, Chelli et al. (1988) deduce that the two components must have had similar luminosities and the optical component significant infrared excess. Attributing the greater luminosity and infrared excess to a larger rate of disk accretion, it is another example of episodic accretion in a binary system involving an optical component and a more massive IR companion.

4. CONCLUSIONS

The episodic accretion due to tidal effects reported in BB92 may have a bearing on the evolution of classical T Tauri stars through one or many FUor phases. Tidal effects in an eccentric system are largest at closest approach. Furthermore, the accretion rate increases with the mass ratio such that the secondary will have the largest accretion rate in an unequal mass binary. Combining this with the secondary's direct accretion of matter from the primary's disk at closest approach, an effective method of suddenly increasing the accretion rate is possible. Accretion rates from these processes can exceed $10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$. The presence of an IR companion in the system helps explain the lack of binary detection in FUors, while one FUor, Z CMa, has recently been found to have an IR companion (Koresko et al. 1991). The expected periodicity of FUors then have a natural explanation in terms of the orbital period.

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