Accretion-Disk-Instability Model for Outbursts of FU Orionis

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1. Introduction; The FU Orionis objects show us the abrupt brightening by ~5 mag. The two best studied examples, FU Ori and V1057Cyg, brightened and have remained very luminous for years and began to fade gradually (cf. Herbig 1977). On the other hand, a large number of young stellar objects have been discovered with energetic molecular bipolar outflows (Lada 1985, for a review). On high-resolution radio observations, the disks have been detected around the central infrared sources (cf. Kaifu et al. 1984, Hasegawa et al. 1984). Most of the disks seem to be perpendicular to the bipolar outflows. These observations suggests that the disk is strongly related with the energetics phenomena like bipolar outflow in star forming regions. (cf.Okuda and Ikeuchi 1986, Hanami and Sakashita 1986, Pudritz 1985, Shibata and Uchida 1985)

2. Models for Self-Gravitationally Unstable Accretion Disk; Hartmann and Kenyon (1985,1987) have proposed the possibilities that the outburst of FU Ori is similar to those proposed for dwarf nova (e.g. Osaki 1974, Hoshi 1979, Meyer and Meyer-Hofmeister 1981, Smak 1982, Cannizzo and Wheeler 1984, and Mineshige and Osaki 1983). Their analysis is essentially based on the thermal instabilities in accretion disk for standard α-model (Shakura and Sunyaev 1973). On the other hand, recently, Lin and Pringle (1987) propose a new prescription for treating the transfer of angular momentum within a gaseous differentially rotating disk to self-gravitational instability in terms of an effective kinematic viscosity. Then, we consider the unsteady accretion disk model for FU Orionis phenomena with hybrid prescription of self-gravitational instability and the viscosity of standard α-disk. This instability may induce viscosity increase and modulate mass transfer throughout the disk.

3. Hysteresis Feature in ($\nu\Sigma,\Sigma$) Plane; Following Lin and Pringle (1987), we now consider this hybrid prescription. Firstly, according to Toomre (1964), The basic principles of the self-gravitational instability in a thin rotating disk can be elucidated. If the size λ of the disturbances is greater than $\lambda_c \sim G\Sigma\Omega^{-2}$ (Σ; surface density, Ω;angular velocity), the perturbation are stabilized by the shear. Over the size of region λ_c, angular momentum with this turbulent eddies is transferred in time scale Ω^{-1}. Then, we can write $\nu_s \sim \lambda_c{}^2\Omega = (G\Sigma)^2/\Omega^3 \sim Q^{-2}H^2\Omega$, where $Q \sim C_s\Omega/G\Sigma$ (C_s; sound velocity). This viscosity prescription would be valid for $\lambda_j < \lambda_c$, which equivalent to $Q\lesssim 1$, the criterion by Toomre (1964). This criterion give the relation $\Sigma > C_s\Omega/G = \Sigma_{c1}$. This prescription for effective viscosity is equivalent to the standard α model by Shakura and Sunyaev (1973) with replacing α by Q^{-2}, but $Q^{-2} > 1$.

On the other hand, when the self-gravity does not dominate in the accretion disk, the prescription for the effective viscosity should become the standard α-disk prescription in which typical turbulent eddy scale λ is nearly the hight of the disk. According to standard α-disk model, we get for viscosity, $\nu_\alpha = \alpha C_s H = \alpha C_s{}^2/\Omega$. We obtain the criterion of the validity for the standard α-disk prescription $\Sigma < \Omega^2 r/G = \Sigma_{c2}$, from that the self-gravity of disk must be small compared with the centrifugal force. Then, we adopt the $(\nu\Sigma,\Sigma)$ relatioship $\nu\Sigma = G\Sigma^3/\Omega^3$, ($=\alpha C_s^2 \Sigma/\Omega$) in state 1,(2) when $\Sigma > \Sigma_{c1}$,($\Sigma < \Sigma_{c2}$). The hysteresis feature of the relationship in $(\nu\Sigma,\Sigma)$ plane is sketched in a figure below.

3. Applications to Protostellar Disk and Outburst of FU Orionis

We consider the criterion for the validity of giving occasion to the recurrence outburst of FU Orionis in our model. As shown in Figure, there are three condition which must be satisfied for our model. (A) <u>the viscosity due to the prescription of self-gravitational instabilities is higher than that of standard α-disk prescription. $\nu_\alpha < \nu_s$.</u> (B) in the phase plane of $(\nu\Sigma,\Sigma)$, <u>two different prescription branches coexist for the same value of Σ, $\Sigma_{c1} < \Sigma_{c2}$.</u> (C) <u>Σ must increases in low-viscosity state,</u>

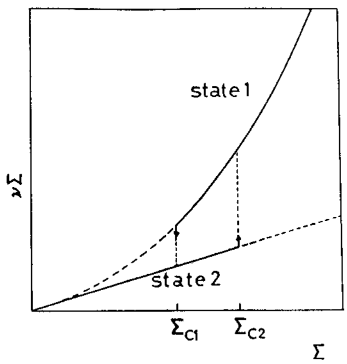
<u>$\dot{M}_{acc} > \nu_\alpha \Sigma$.</u> From (A) and (B),

$$2.2\ M_\odot\ \alpha\left(\frac{C_s}{0.34\mathrm{km/s}}\right)^{-2}\left(\frac{\Sigma}{10^2 g\cdot cm^{-2}}\right)^2\left(\frac{R_d}{2\cdot 10^{15}\ cm}\right)^3 > M_c$$

$$> 0.039\ M_\odot\ \left(\frac{C_s}{0.34\mathrm{km/s}}\right)^2\left(\frac{R_d}{2\cdot 10^{15}\ cm}\right),$$ where R_d and M_c are the radius of a disk and the mass of central star. This mass range constraint naturally explains the reason why FU Orionis phenomenon occurs for only low mass star ($\sim 1M_\odot$) in the early phase of the stellar evolution. From (C),

$$\dot{M}_{acc} > 1.7\times 10^{-5}\ M_\odot\ yr^{-1}\ \alpha^{6/5}\ \left(\frac{\Omega}{10^{-10} s^{-1}}\right)^{-4/5}.$$

The accretion flow with this instability will produce strong accretion shocks, turbulence, and heating of the outer layer of the star. Matter will also be ejected, and this could account for much of the mass and energy from young stars. The luminous FU Ori flare-ups may be important energy source for driving molecular out flows around low mass young stars.



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