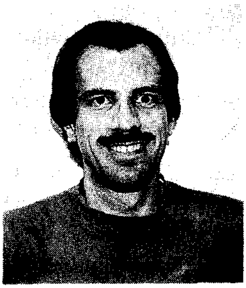
FU ORIONIS OBJECTS AND MOLECULAR OUTFLOWS

Scott J. Kenyon
Harvard-Smithsonian Center for Astrophysics
60 Garden Street, Cambridge, MA 02138 USA



ABSTRACT

FU Orionis variables – FUors – are pre-main sequence stars in which the central star accretes mass from a circumstellar disk at a high rate. FUors also eject material in high velocity winds. The momentum in these winds is sufficient to power a typical molecular outflow providing a young star accretes most of its material through a circumstellar disk. Recent observations suggest FUors do mostly occur during early stages of the star formation process, when the central star-disk system lies deeply embedded within the collapsing circumstellar cloud. The FUor state also appears to last long enough for a young star to accrete a large fraction – perhaps all - of its mass from a circumstellar disk.

1. Introduction

The FU Orionis variables – FUors – are eruptive pre-main sequence stars (Hartmann 1991). Most FUors have undergone 3–6 mag optical eruptions and resemble rapidly-rotating F–G supergiants on optical spectra. These objects also show distinctive optical and/or near-infrared reflection nebulae; large ultraviolet and infrared excesses of radiation; wavelength dependent spectral types; broad, blueshifted Hα and Na I absorption lines; and "double-peaked" absorption line profiles at optical – and sometimes infrared – wavelengths.

We have interpreted observations of FUors with viscous accretion disk models (Hartmann 1991). A disk naturally accounts for the broadband spectral energy distribution (SED), the wavelength dependent spectral types, and the double-peaked absorption profiles. A disk wind explains the blueshifted absorption features; our models suggest this mass loss occurs close to the inner edge of the disk (Calvet *et al.* 1993). Finally, some type of circumstellar envelope – probably material still falling into the disk – produces the ubiquitous reflection nebulae and the large far-IR excess emission (Kenyon & Hartmann 1991).

The FUor state is an exciting time when a young star can accrete a large amount of mass *and* eject a fair amount of momentum and energy into the surrounding molecular cloud. For example, the central star in FU Ori itself has accreted $\sim 0.01\ M_\odot$ and has lost material with a momentum of $\sim 0.3\ M_\odot\ \mathrm{km\,s^{-1}}$ since its eruption began in 1936. These values represent a modest fraction of typical stellar masses, $M_\star \sim 0.5\ M_\odot$, and outflow momenta, $(Mv)_o \sim 1$–100 $M_\odot\ \mathrm{km\,s^{-1}}$, but a FUor event lasting several millenia – or a series of eruptions – could have a significant impact on the central star and the surrounding cloud. The goal of this paper is to estimate the importance of FUor events on stellar masses and molecular outflows.

2. Molecular Outflows and Class I Sources

Current arguments suggest a low mass star accretes most of its mass during an infall phase, when material from the cloud core collapses into a central star-disk system (Shu *et al.* 1987). The cloud is opaque at optical wavelengths and radiates most of the disk and stellar radiation at far-IR wavelengths. IRAS detected many of these class I sources in nearby molecular clouds, and they usually comprise $\sim$ 10% of the pre-main sequence stellar population. These objects appear closely associated with extended optical and near-IR reflection nebulae, lie at the centers of dense cloud cores, and often power low velocity molecular outflows and higher velocity optical jets and Herbig-Haro (HH) objects. They are also among the youngest stellar sources in nearby molecular clouds, with estimated ages of ~ 1–3×10^5 yr (Lada 1991).

The origin of the energetic outflows remains uncertain, although this activity likely begins during – or perhaps even before – the class I phase (e.g., André *et al.* 1993). The available observations show reasonable correlations between the outflow's mechanical luminosity and the central source luminosity, $L_\star$. The initial energy flux in the wind seems comparable to the total system luminosity, which appears to rule out models involving radiation pressure, thermal expansion of a hot corona, or dissipation of Alfvén waves (e.g., Cabrit 1989). Centrifugal winds or disk winds can account for the observed kinematics and luminosity correlations, and both mechanisms require accretion energy to drive the outflow. Indeed, observations of T Tauri stars and FUors suggest the mass loss rate in the wind is closely tied to the mass accretion rate through the disk: $\dot{M}_w \sim \alpha \dot{M}_a$, with $\alpha \sim 0.1$ (e.g., Natta & Giovanardi 1991; Hartmann 1991).

Can disk winds provide enough momentum for a typical outflow? To answer this question, assume that the mass loss rate in the disk wind scales with the accretion rate, as in the previous paragraph. The total momentum in the wind – over a time scale τ – is then $(Mv)_w \sim \dot{M}_w \tau v_w \sim 0.1 \dot{M}_a \tau v_w$, where v_w is the wind velocity. If the disk processes most of a typical stellar mass, then $M_\star \sim \dot{M}_a \tau$, so the outflow momentum is

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

for a typical wind velocity of 200 $km\,s^{-1}$. The observed range of outflow momenta – $(Mv)_\bullet$ = 1–100 $M_\odot \, km\,s^{-1}$ (Fukui 1989) – requires typical stellar masses of $M_\star \sim$ 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.

Current observations suggest some fraction of a typical stellar mass does flow through a circumstellar disk before landing on the central star. Several groups estimate accretion rates of $\sim 10^{-7} \, M_\odot \, yr^{-1}$ for the pre-main sequence T Tauri stars (e.g., Hartigan *et al.* 1991). Source statistics suggests an age of $\sim 10^6$ yr for these objects, so a typical young star accretes ~ 0.1 $M_\odot$ during this optically visible phase of evolution. FUors represent the most active disk accretion phase of pre-main sequence evolution; both the accretion and mass loss rates are a factor of ~ 1000 larger than for T Tauri stars. Thus, a young star might accrete *all* of its mass from a disk if FUors preferentially occur during the class I phase – when the infall occurs – and if the FUor lifetime is a significant fraction of the class I lifetime of 1–3 $\times 10^5$ yr.

3. Age and Lifetime of FUors

As a group, FUors have many observed features in common with class I sources. All FUors possess very distinctive optical and near-IR reflection nebulae (e.g., 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 suggest FUors are much younger than most T Tauri stars – which usually have none of these features – and more similar to class I sources. Thus, FU Ori objects generally occur during the main accretion (class I) phase and have typical ages of $\tau \sim$ a few $\times 10^5$ yr.

FUor statistics are very crude, because only 11 examples are known within ~ 1 kpc. If we have discovered all FUors that have occured since the discovery of FU Ori (~ 50 yr), the FUor frequency is 0.2 yr^{-1}. The local star formation rate within 1 kpc is roughly 0.01 yr^{-1}, so a typical young star must undergo at least 20 eruptions to reach the observed FUor frequency (e.g., Hartmann 1991). If a typical eruption lasts ~ 100 yr, a star accretes ~ 0.2 $M_\odot$ – almost half of a typical stellar mass – in FUor eruptions.

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 $\dot{M} \sim 0$. The quiescent state lasts until the disk mass becomes high enough to trigger an outburst; the outburst continues until the disk empties of material. This cycle repeats until infall from the cloud ceases. The cause of this cycle may not be clear, but it is simple to estimate the fraction of time in the FUor state from the ratio of the infall rate to the FUor accretion rate: $f \sim \dot{M}_i/\dot{M}_{FU}$. FU Ori disk models suggest $\dot{M}_{FU} \sim 10^{-4}$ $M_\odot\,yr^{-1}$, 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.

The discussion in §2 established that a disk wind could power a typical molecular outflow if a young star accretes most of its mass from a circumstellar disk. Thus, 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 $\sim$ 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.

4. References

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