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FINAL REPORT TO NASA: ORIGINS OF SOLAR SYSTEMS PROGRAM
(NAGW 4456)

# Effects of FU Orionis Outbursts on Protoplanetary Disks

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## 1. Introduction

This project was funded for the period from March 1, 1995 to February 28, 1997. Although we received only half of our requested budget for a two year period instead of the requested three, considerable progress was made in accomplishing the aims of the initial proposal. Four papers (three of which are refereed Astrophysical Journal articles) were completed during this time and are listed here.

- *Bell, K. R., Lin, D. N. C., Hartmann, L. W., & Kenyon, S. J. 1995, ApJ, 444, 376, "The FU Orionis Outburst as a Thermal Accretion Event: Observational Constraints for Protostellar Disk Models"*

- *Bell, K. R., Cassen, P. M., Klahr, H. H., & Henning, T. 1997, ApJ, 486, 372, "The Structure and Appearance of Protostellar Accretion Disks: Limits on Disk Flaring"*

- *Turner, N. J. J., Bodenheimer, P., & Bell, K. R. 1997, ApJ, 480, 754, "Models of the Spectral Energy Distributions of FU Orionis Stars"*

- *Bell, K. R. & Chick, K. C. 1997, IAU Symposium No. 182: Herbig-Haro Flows and the Birth of Low Mass Stars held in Chamonix, France, January 1997, p. 407, "The Radiative Impact of FU Orionis Outbursts on Protostellar Envelopes"*

Two other closely related papers were published during this period:

- *Różyczka, M., Bodenheimer, P., & Lin, D. N. C. 1996, ApJ, 450, 371, "A Numerical Study of Magnetic Buoyancy in an Accretion Disk "*

- *Różyczka, M, Turner, N., & Bodenheimer, P. 1996, M.N.R.A.S., 276, 1179-1184, " A simple model of a buoyant magnetic dynamo in accretion disks"*

## 2. Background

An FU Orionis outburst is a sudden increase in the mass flow through the inner portion of the accretion disk around a low mass, young stellar object. System luminosities of about $1L_{\odot}$ increase to some $100L_{\odot}$ over timescales of several years (Herbig 1977). Outbursts last for many decades and probably recur on a thousand year timescale. The enhanced mass flux during outburst is most likely the result of a thermal ionization instability in the inner protoplanetary disk (Hartmann & Kenyon 1985, Lin & Papaloizou 1985, Bell & Lin 1994). From observational statistics, it is argued that all low mass systems go through such outbursts many times in the first few hundred thousand years of their formation. The precursor to our own planetary system, the solar nebula, was probably subject to several such outbursts. This luminous event may have an impact on the surrounding protosolar disk, possibly disrupting the formation of planets or creating global fractionations. Our proposal was designed to investigate the impact of these outbursts on the protosolar nebula. During the course of this two year proposal we made considerable progress toward achieving this goal.

## 3. Outburst Simulations: the Inner Disk

In the early stages of work under this grant, we developed simulations to match the light curves of the three best studied systems: FU Ori, V1515 Cyg, & V1057 Cyg (Bell et al. 1995). We compared the details of model results to observations to test the validity of the thermal ionization instability model for outburst. In this paper, we were able to answer several of the key objections to the accretion disk outburst model for the FU Orionis phenomenon (eg. Herbig 1989). The declines in line width and reddening observed in V1057 Cyg following peak light had been used as arguments against the disk instability model. We showed these effects to be natural consequences of the slow outward progression and limited radial excursion of the ionization front during outburst.

Only the "inner disk" ($r \lesssim 1/3$ au) actively participates in the outburst, and it serves as an illumination source for the remainder of the disk. From the outburst simulations, we have a detailed picture of the temperature structure and shape of this luminous region. The inner few stellar radii of the outbursting region slope steeply outward, directing a great deal of the luminosity along the poles. The magnitude of illumination received by the planet forming region or the "outer disk" (1 – 10 au), depends sensitively on the shape of its surface.

## 4. Disk Structure: the Planet Forming Region

The shape of the photosphere of the outer disk is critical to its absorption of the photons emitted by the inner disk. In the next stage of the work (Bell et al. 1997), we calculated the shape and temperature structure of the surface of the planet forming region of the disk using detailed vertical structure routines developed in Bell & Lin (1994). These simulations led to analytic derivations of radial midplane temperature, optical depth, and surface density distributions which can be used to produce accurate estimates of the conditions in any accretion disk or in the solar nebula at various stages given a global mass flux, viscous efficiency, and opacity law.

Our results challenge the conventional assumption that relative disk thickness (i. e. $H/r$)

increases indefinitely with radius in protostellar systems (eg. Kenyon & Hartmann 1987). Under the assumption of a locally generated accretion energy with $\alpha$-law viscosity, we find that, outside the outbursting region, the disk only increases in relative thickness to a specific radius which is between one half and a few au depending on the input mass flux. Beyond this radius the photosphere begins to decrease in $H/r$ and is shielded from radiation emitted near the center of the system. Only parts of the disk inside this critical radius (five to ten au for outbursting systems) will be exposed to outburst luminosity. An analytic derivation shows that this result is not dependent on the details of the highly uncertain local energy generation rate (i. e. the viscosity) but is governed by the local opacity law. Throughout most of the disk, where the opacity is dominated by dust and ice grains, the disk decreases in relative thickness with increasing radius and is therefore shielded from radiation from the central object. Bodies in the inner few au where the disk does flare may therefore experience significant fluctuations in ambient energy during outbursts while those in the outer disk, tilted away from the center of the system, remain unaffected.

## 5. The Effect of the Protostellar Envelope

By the end of the grant period, we had begun combining the inner and outer disk models to derive the radiation expected in the planet forming region of the disk. A crucial step in this was the development of a radiative transfer model of the complete inner and outer disk system (Turner, Bodenheimer, & Bell 1997). In this work, wavelength dependent opacities were used to synthesize images and spectral energy distributions of FU Ori objects. New detailed opacities provided by Alexander (1995) allowed the resolution of coarse features such as silicate emission lines. Data for the fits were taken from the time dependent simulations in Bell et al. (1995) to which was added the effect of disk to disk or "self"-reprocessing which accounts for the illumination of the outer disk by the inner disk (Bell 1998). To fit the long wavelength data ($\lambda \gtrsim 10\mu$m), an envelope with parameterized thickness, radial extent and temperature distribution was found to be necessary. Envelopes have been suspected in these outbursting systems on the basis of spectral energy distributions (Kenyon & Hartmann 1991). Envelopes are also reasonable from the model necessity of supplying a steady, large mass inflow rate to the inner disk throughout the period in which a system is subject to FU Ori outbursts. Excellent agreement was obtained between model spectral energy distributions and recently observed distributions of the objects FU Ori, V1057 Cyg, and V1515 Cyg. The radiative transfer calculation was also used to obtain a time sequence of theoretical B band images, which show the expected progression of an outburst.

The inclusion of a cocooning envelope and the effect it would have on the transport of radiation throughout the system formed the basis for the final stage of our work (Bell & Chick 1997). Because the disk itself is the source of photons, radiation is emitted in a highly anisotropic way: more strongly along the poles than the equator. Using a radiative transfer model developed by Ken Chick (Chick, Pollack, & Cassen 1996), we self-consistently calculated the temperature in the envelope exposed to a source of radiation which was either isotropic or focused toward the poles. At large radii, the equatorial temperature distribution of the two models converged as the radiation was isotropized by transport through the envelope. Thus at large radii, the protostellar disk may continue to be illuminated by backscattering from the envelope even though a direct line of sight to the central outbursting region is obscured by the folds of the disk.

## 6. Towards a Unified Model

Through the course of work on this grant we have made considerable progress in computing detailed models of both the active outburst region of the disk and the outer quiescent disk. We have begun an investigation into the effects of a cocooning envelope. Direct comparisons with observations lend confidence that the basic underlying assumptions of the outburst model are reasonable. We are now ready to build upon these results to investigate the effects of outbursts on the central star and on the accumulation of small particles in the planet-forming regions.

## References


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