The Formation and Evolution of Protostellar Disks

Shantanu Basu

(*The* **University** *of* **Western Ontario**)

&

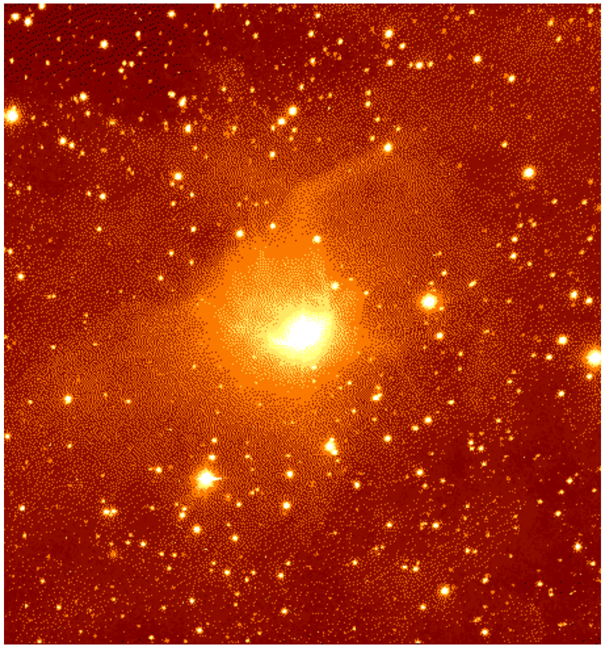
E. I. Vorobyov (ICA, St. Mary's University)

Spitzer's View of Disks, Pasadena, CA
October 28, 2008

The Envelope-Disk Connection

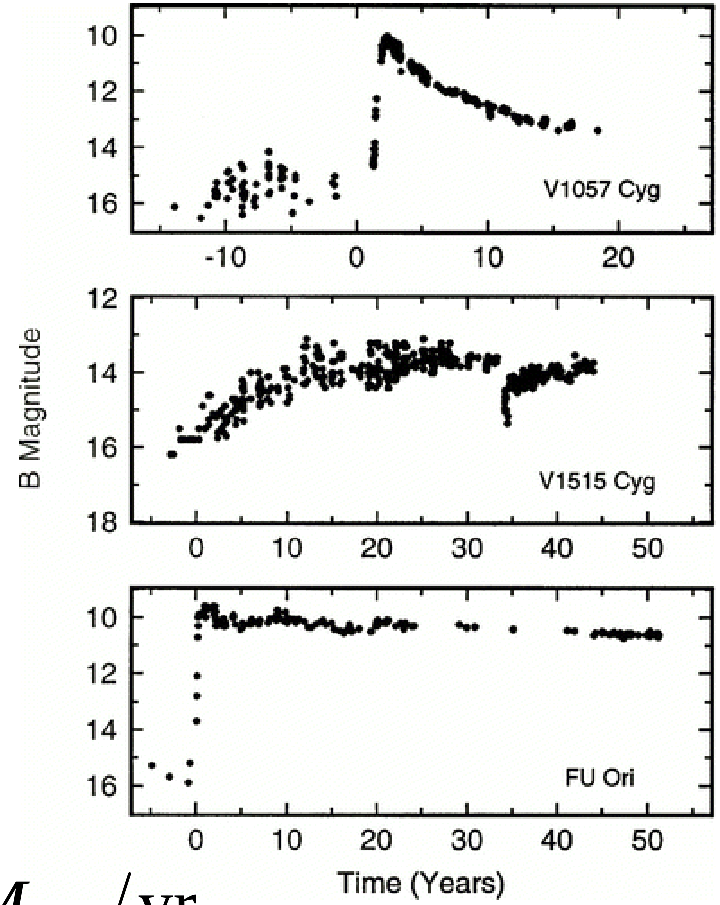
FU Ori

C. Briceno



FUor's are YSO's with significant circumstellar material.

Calvet, Hartmann, & Strom (1999)

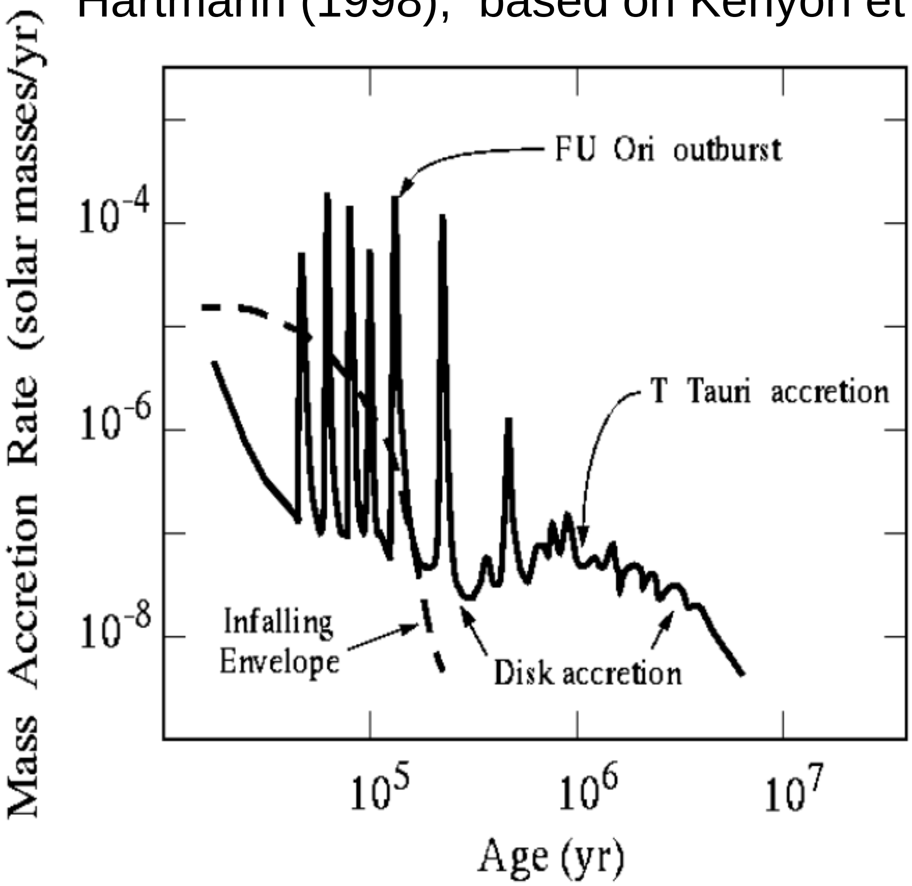


Typical disk accretion: $\approx 10^{-8} - 10^{-7}\ M_{sun}/\mathrm{yr}$

FU Ori: $\approx 10^{-4}\ M_{sun}/\mathrm{yr}$

Empirical Inference of YSO Accretion History

Hartmann (1998), based on Kenyon et al. (1990)



New evidence from Spitzer (luminosity problem) also reveals need for episodic accretion - talk by Neal Evans.

Observed frequency of FU Ori eruptions (last 50 years) is several times greater than the low-mass star formation rate within 1 kpc ➔ It is thought that all YSO's undergo multiple eruptions.

Global Core → Disk Formation/Accretion Simulations

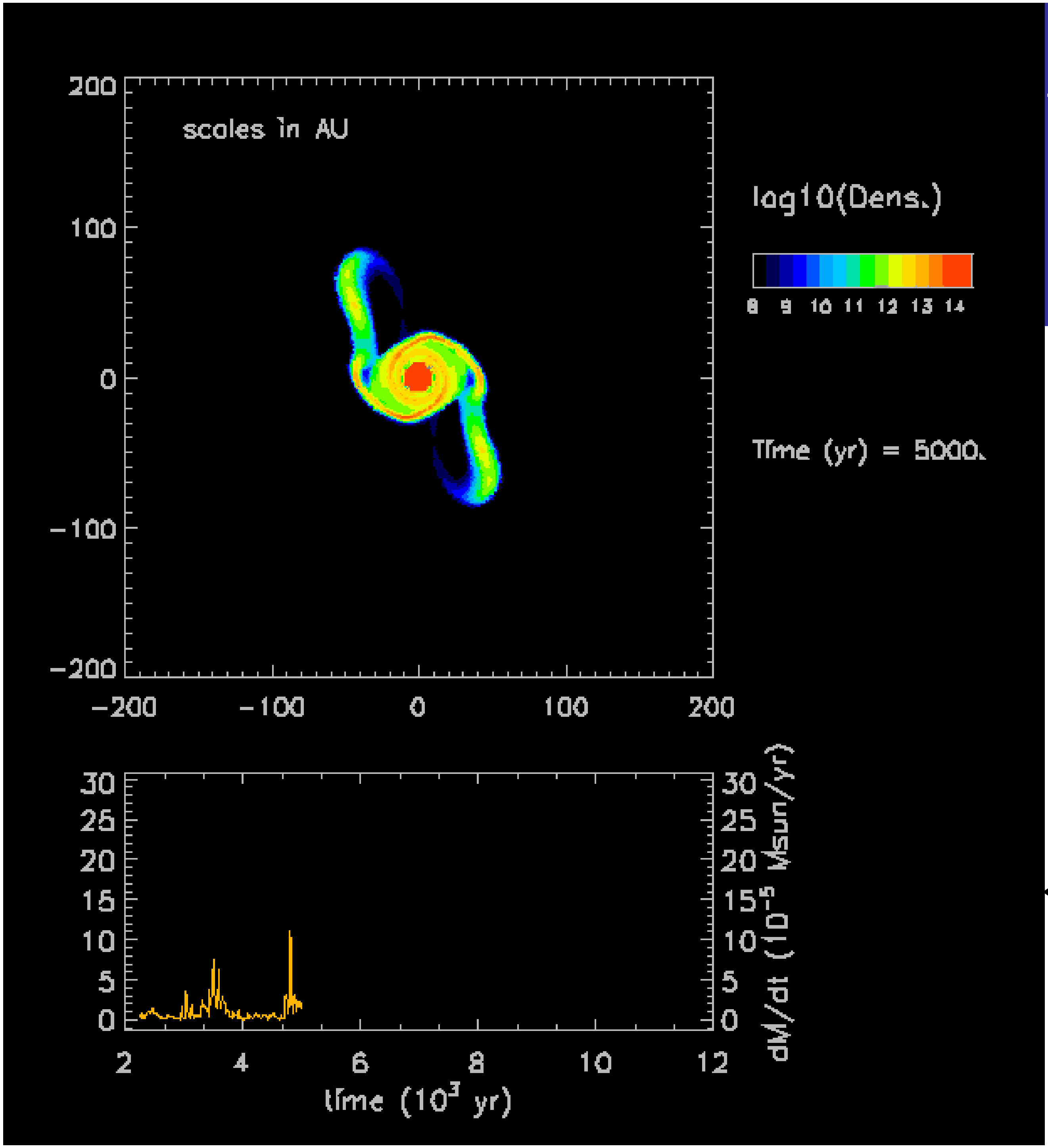
We Employ the Thin-Disk Approximation
(Vorobyov & Basu (2006) has details):

- Integrate vertically (in *z*-direction) through cloud. Solve time-dependent equations for profiles in (r,ϕ) directions. IC's from self-similar core collapse calculations.
- With nonuniform mesh, can study large dynamic range of spatial scales, ~ 10^4 AU down to several AU
- Allows efficient calculation of long-term evolution even with very small time stepping due to nonuniform mesh. Can study disk accretion for ~ 10^6 yr rather than ~10^3 yr (for 3D)
- Can run a very large number of simulations – for statistics and parameter study
- Last two still not possible for 3D simulations

What’s not included in this model (for now)

- Magnetic braking
- Ambipolar diffusion or other non-ideal MHD effects
- Physics of inner disk (~ 5 AU) inside central sink cell
- Magnetorotational instability (can’t occur in thin-disk model)
- Stellar irradiation effects on disk
- Radiative transfer in disk - we use $P = P(\rho)$, barotropic relation
- Photoevaporation of outer disk

Self-consistent formation of the protostellar disk and envelope-induced evolution



← Evolution of the protostellar disk

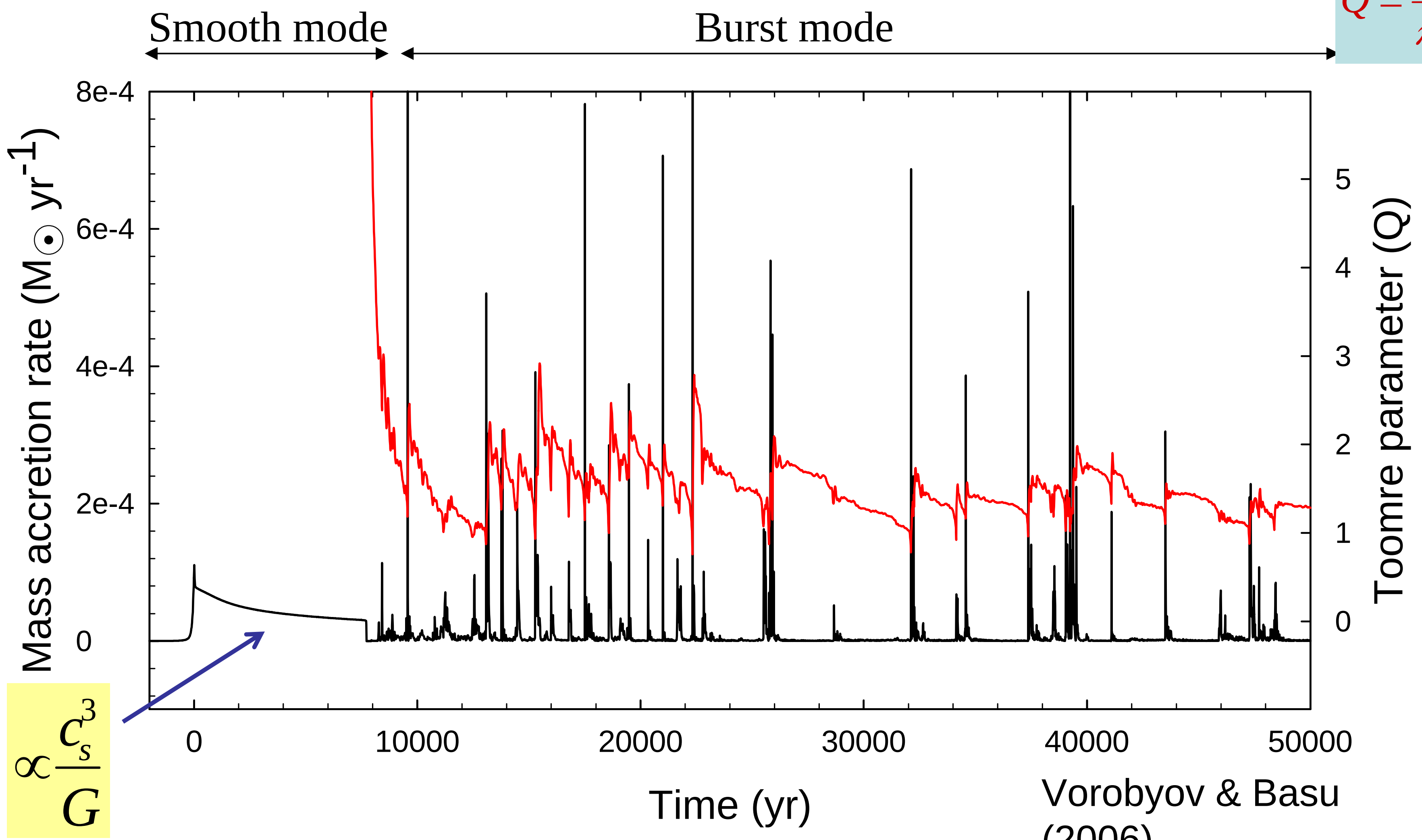
← Mass infall rate onto the protostar

Full animation at
www.astro.uwo.ca/~basu/

Mass accretion bursts and the Q-parameter

Black line - mass accretion rate onto the central sink; **Red line** – the Q-parameter

$$Q = \frac{c_s \kappa}{\pi G \Sigma}$$

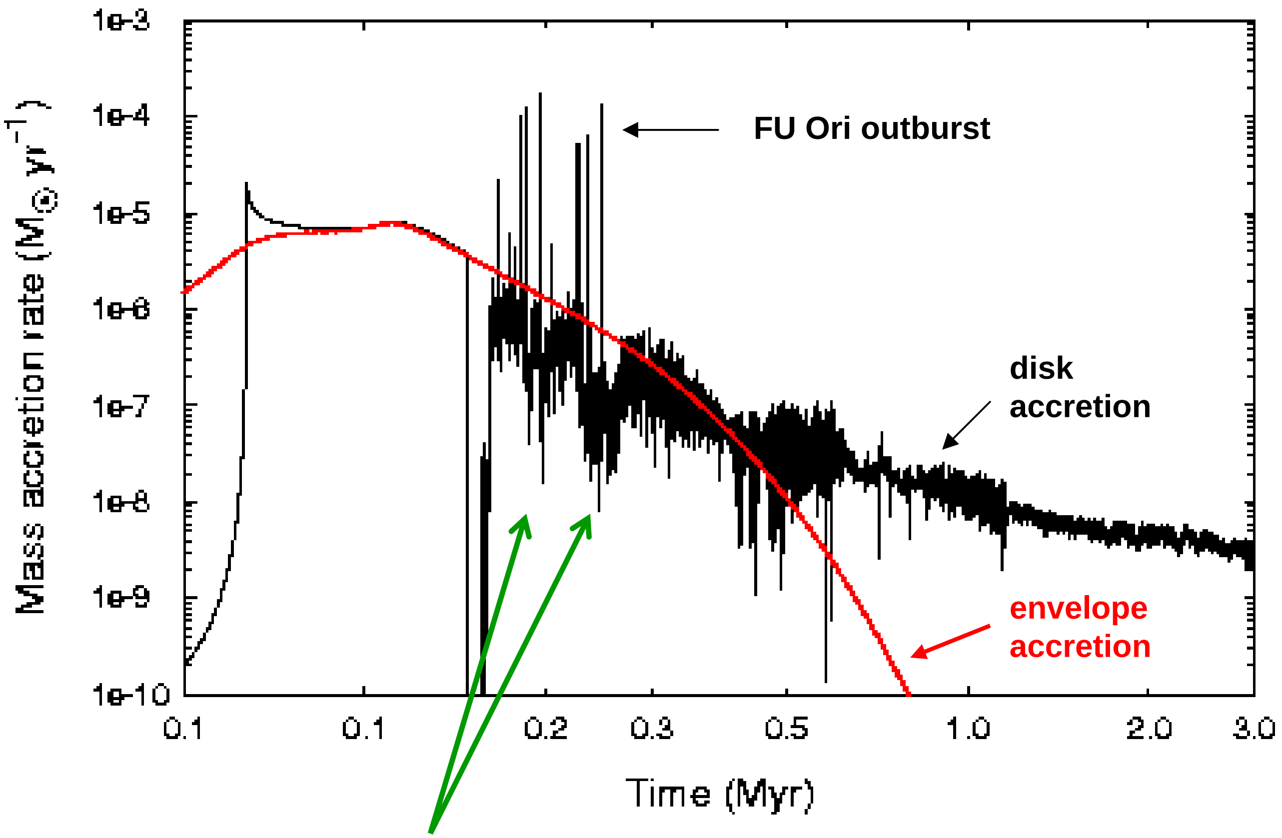


$\propto \frac{c_s^3}{G}$

Vorobyov & Basu (2006)

The disk is strongly gravitationally unstable when the bursts occur

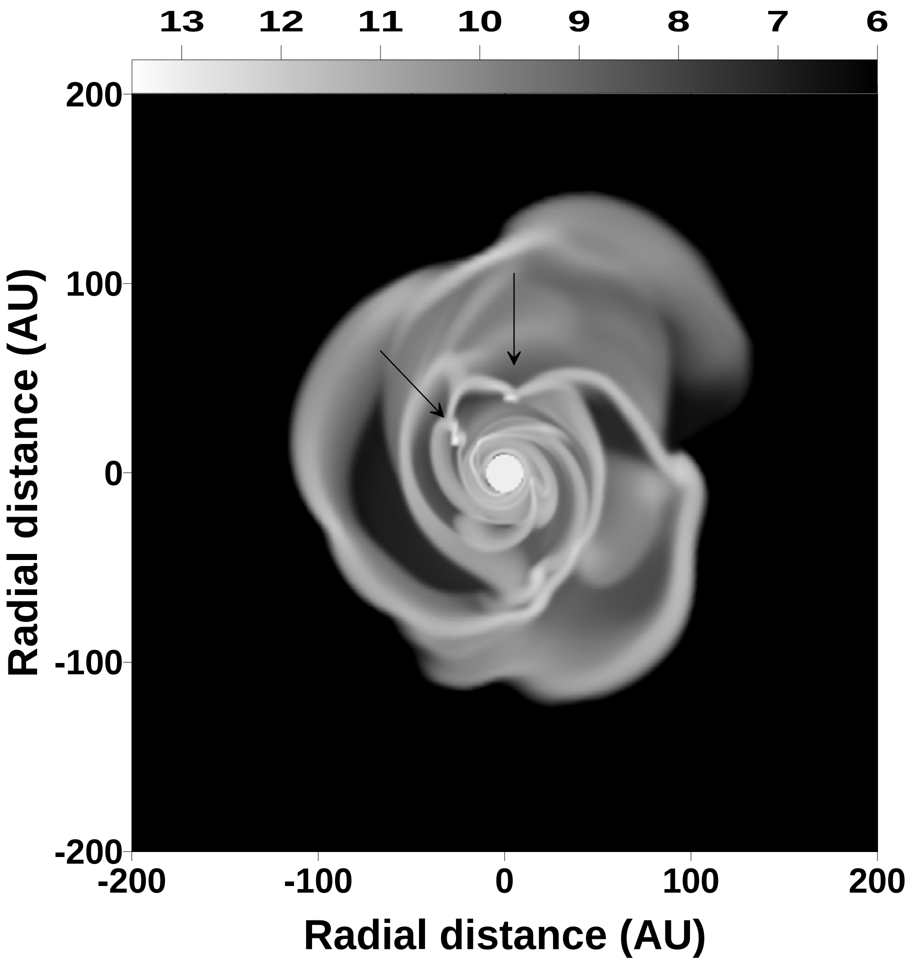
Accretion history of young protostars



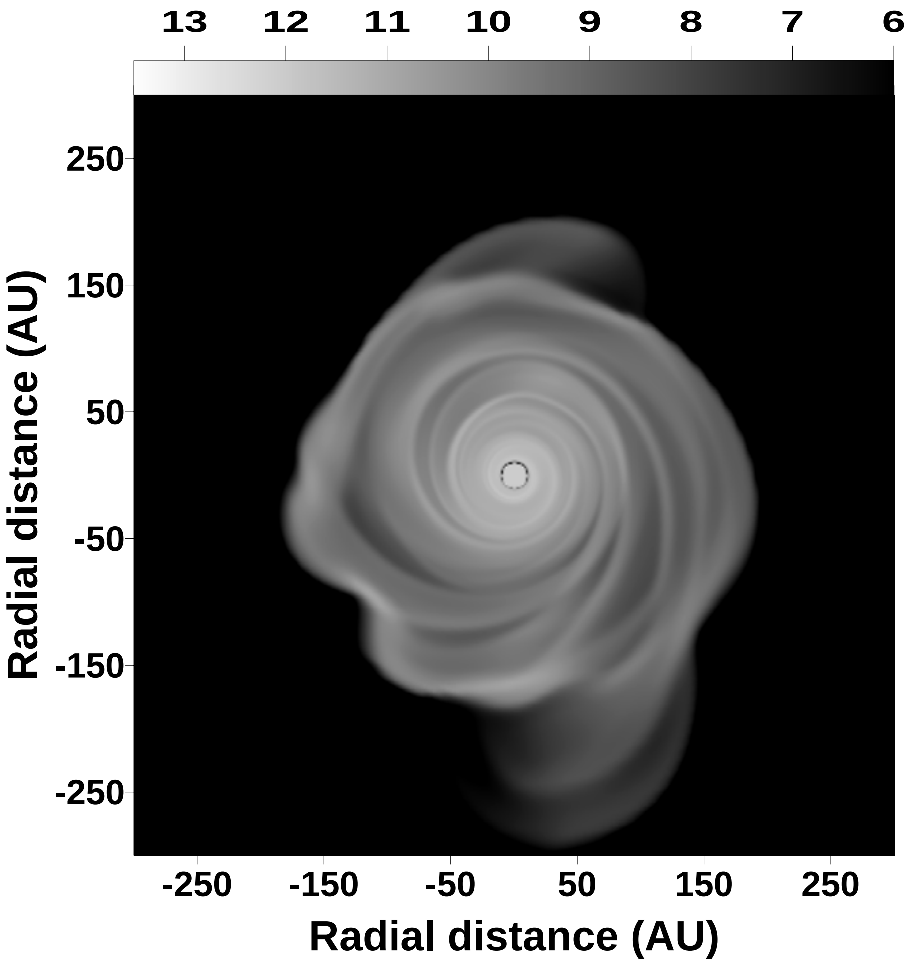
VeLLO’s?

Vorobyov & Basu (2007)

Spiral structure and clump formation



Just before a burst

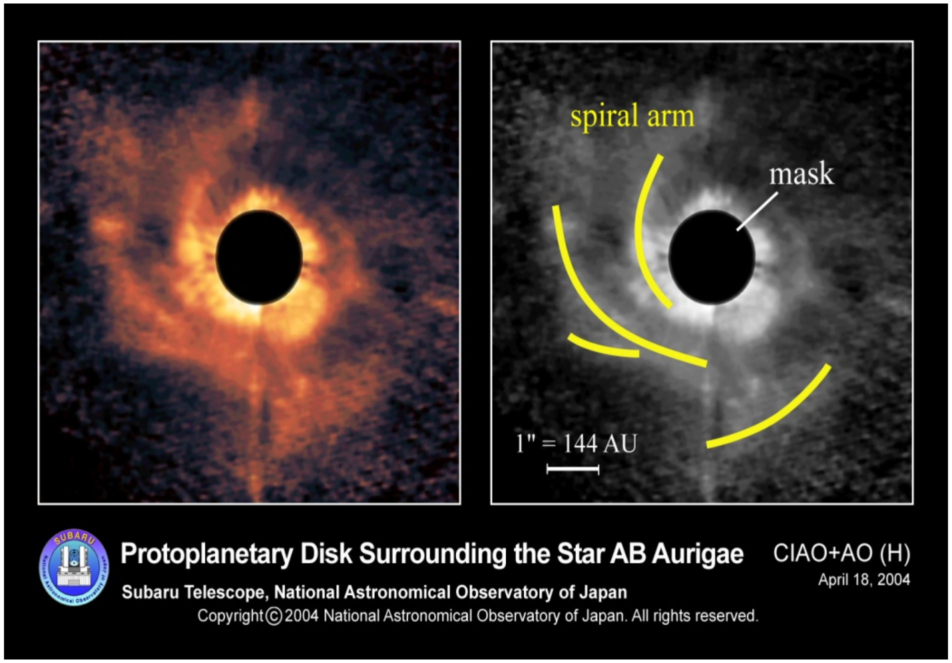


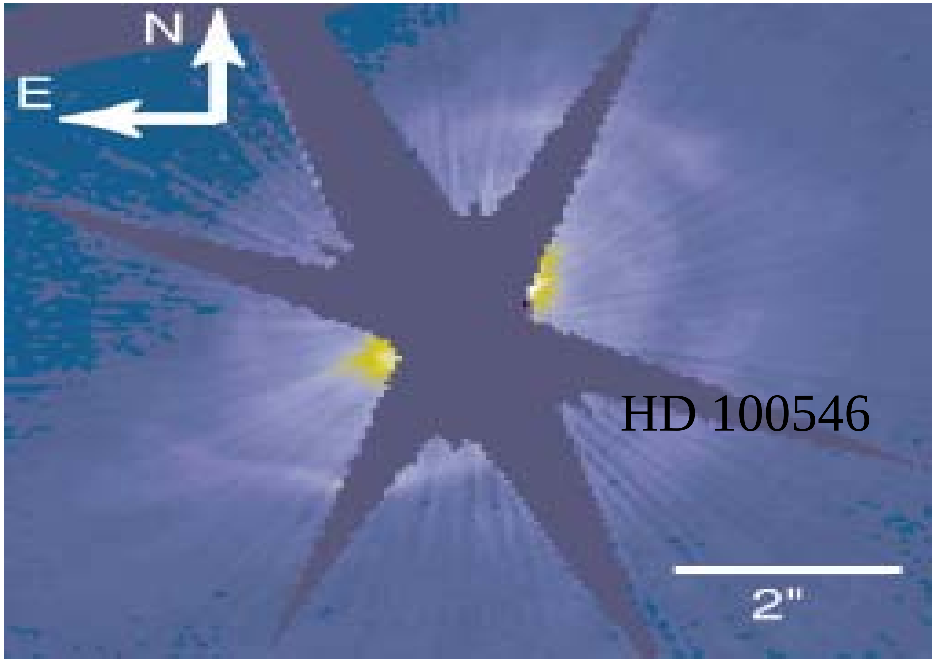
Quiescent phase

VB06

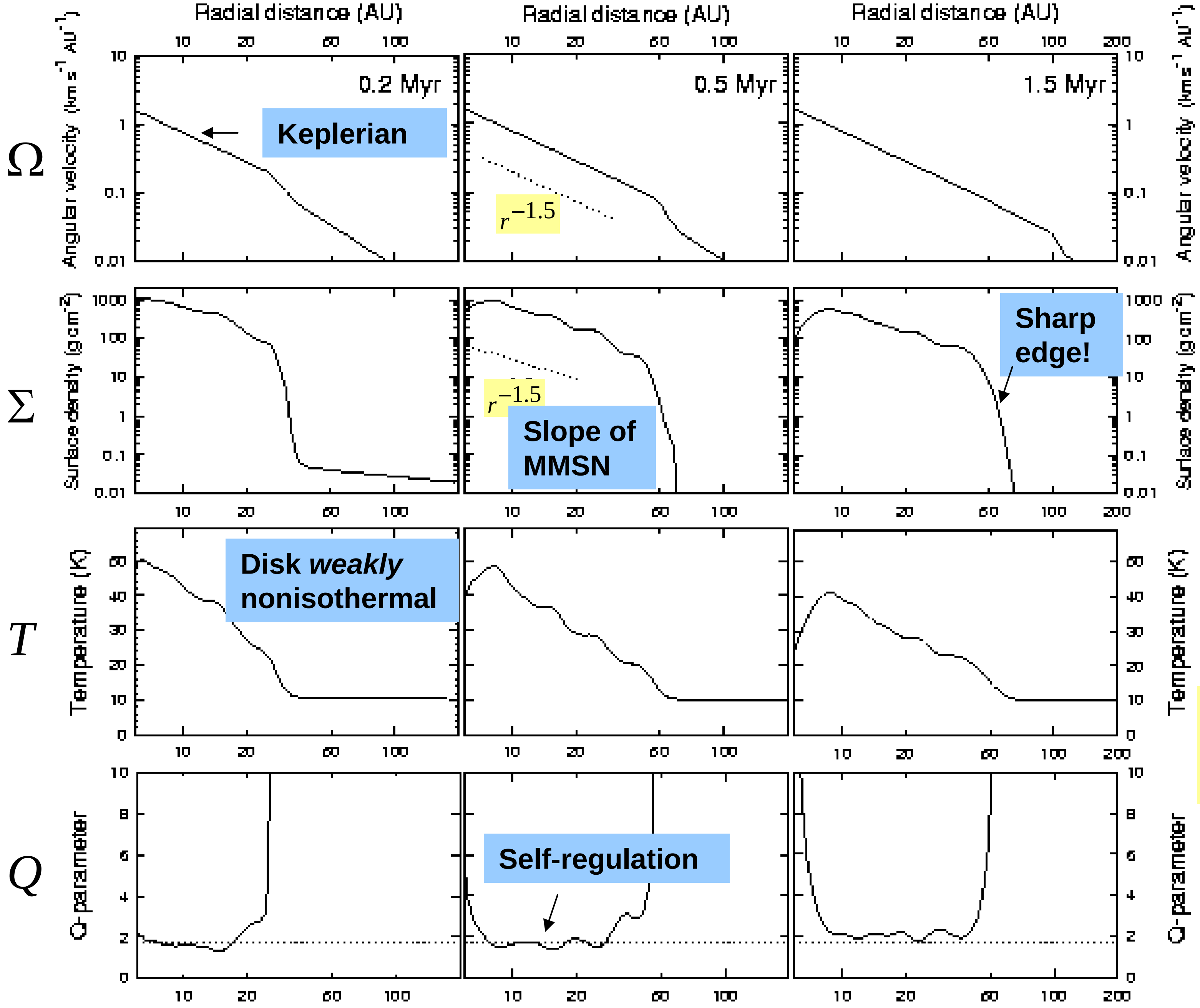
Gravitationally driven accretion?

- Observations of non-axisymmetric structures in protostellar disks of Herbig Ae/Be stars AB Aurigae (Fukagawa et al. 2004) and HD 100546 (Grady et al. 2001)





Azimuthally Averaged Spatial Profiles



Keplerian

$r^{-1.5}$

$r^{-1.5}$

Slope of MMSN

Sharp edge!

Disk *weakly* nonisothermal

Self-regulation

$$Q = \frac{c_s \kappa}{\pi G \Sigma}$$

Accretion and instability help to self-regulate disks to a near-uniform Q distribution

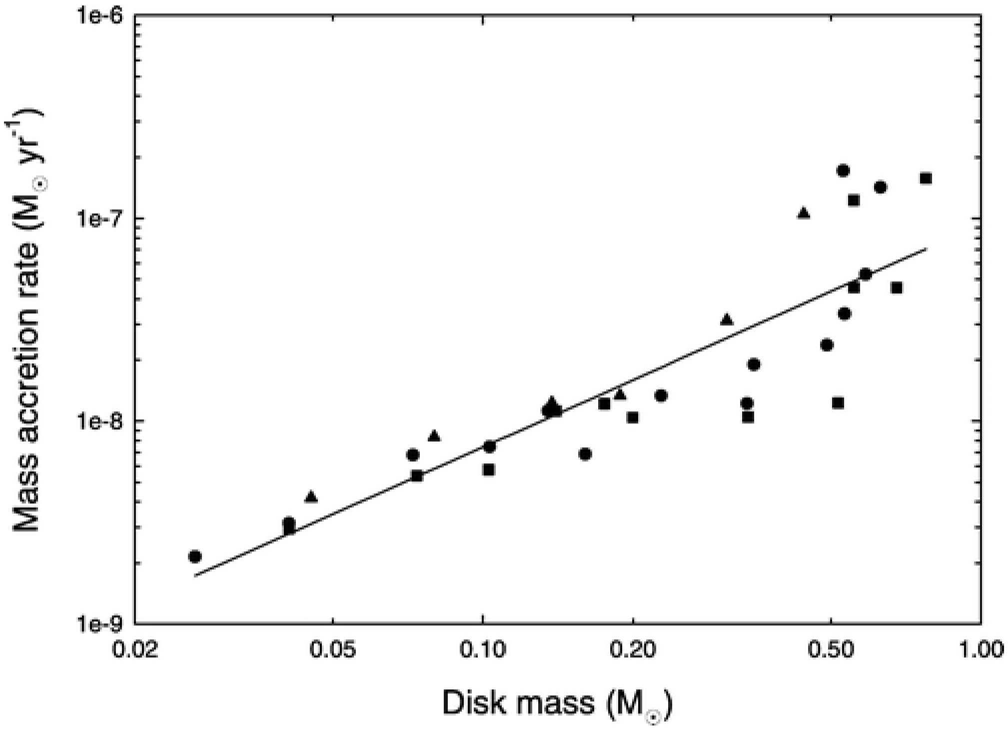
➔ $\Sigma \propto r^{-3/2}$.

Nonaxisymmetry is essential for this result.

Vorobyov & Basu (2007)

Accretion Rate Correlates with Model Disk Mass

A parameter study of a range of initial core masses



Working defn of "disk": region with $\Sigma > 0.1$ g cm^{-2}.

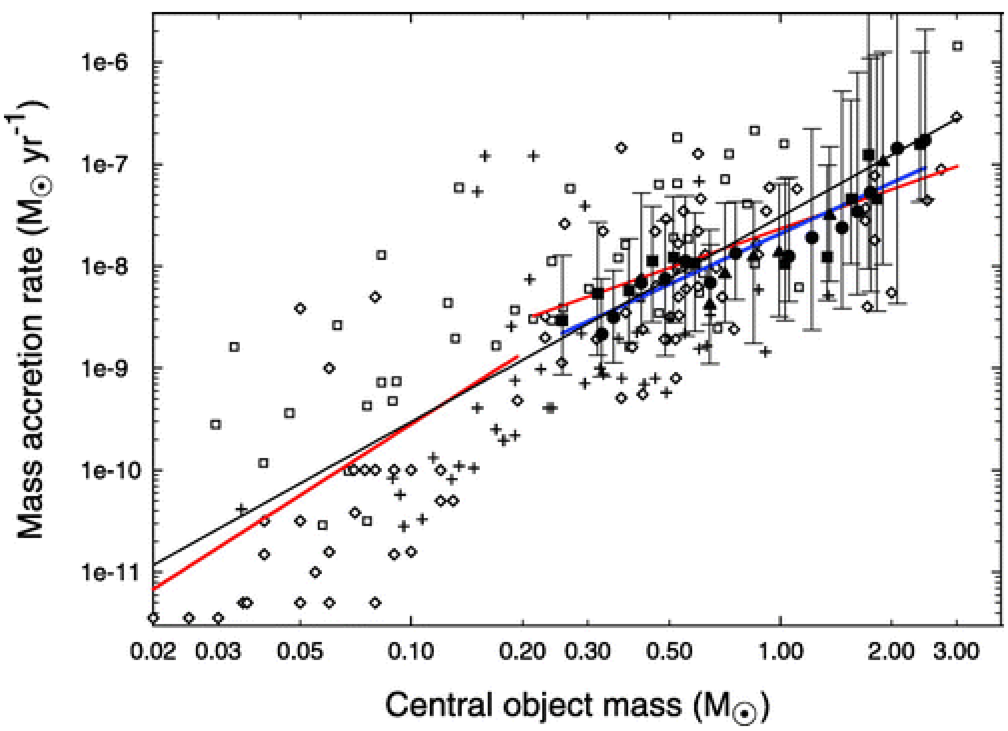
Time averaged values over 0.5 Myr to 3 Myr after protostar formation on both sides.

Vorobyov & Basu (2008)

Accretion Rate also Correlated to Central Object Mass

Solid circles: time-average (class II phase) values from models with differing initial mass. Bars represent variations from mean during same time period.

Blue line – best fit to simulation averages. **Black line** – best fit to all data points. Red lines – best fits to low and higher mass regimes of data.



All other symbols: data from Muzerolle et al. (2005) and Natta et al. (2006).

Blue line: $\dot{M} \propto M_*^{1.7}$

Vorobyov & Basu (2008)

Bottom Line from Parameter Study

- Can fit mean observed accretion rates using a model of gravitational torque driven accretion

- Model also produces near-Keplerian rotation and $r^{-3/2}$ surface density profile in disk

- However, disk masses and disk-to-star mass ratios are a factor ~10 greater than observational estimates for TTSs and BDs (Andrews & Williams 2005; Scholz et al. 2006)

Observed disk masses underestimated?

- Grain growth in disks already significant. Standard opacity requires grain growth to 1 mm at ~100 AU, but what if they grow further? Larger grains would lead to higher disk mass estimates (Andrews & Williams 2007; Hartmann et al. 2006)

- Upper envelope of TTS accretion rate dM/dt ~ 10^{-7} M_{sun}/yr implies M_{disk} ~ dM/dt x 1 Myr ~ 0.1 M_{sun}
- MMSN contains ~ 0.01 M_{sun} material, barely enough to make Jupiter. Extrasolar systems with M sin *i* up to several Jupiter masses imply $M_{disk} >> 0.01\ M_{sun}$
- Chondrule formation models (Desch & Connolly 2002; Boss & Durisen 2005) require a high density and M_{disk} ~ 0.1 M_{sun}

Summary

- Protostellar disks that form self-consistently undergo an **early phase** of episodic vigorous gravitational instability → formation of clumps → FU Ori-type bursts. Very low accretion states may correspond to VeLLO's.
- Even at **late (~ Myr) stages**, disks have a sharp edge and maintain persistent nonaxisymmetric density fluctuations → non-radial gravitational forces → torques that drive accretion at rates comparable to that of CTTSs
- Self-regulation of disk leads to $Q \sim$ const. and to surface density profile $\Sigma \sim r^{-3/2}$; same slope as MMSN
- For models with ~ 0.5 M_{sun} and above, can fit observed dM/dt vs. M_* relation.
- Disk mass stays well below stellar mass, but factor ~ 10 larger than observational estimates. Observed disk masses systematically underestimated?
- The future: detailed comparison of models and data