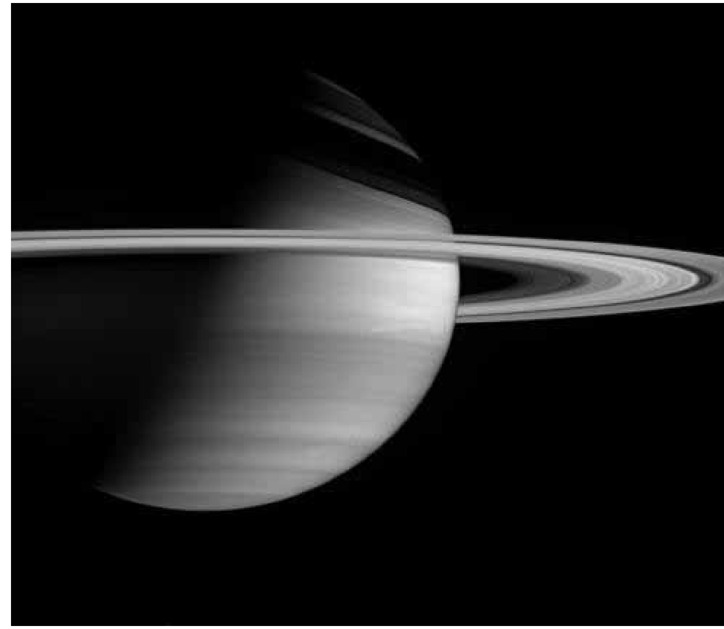

Formation of Stars and Planets

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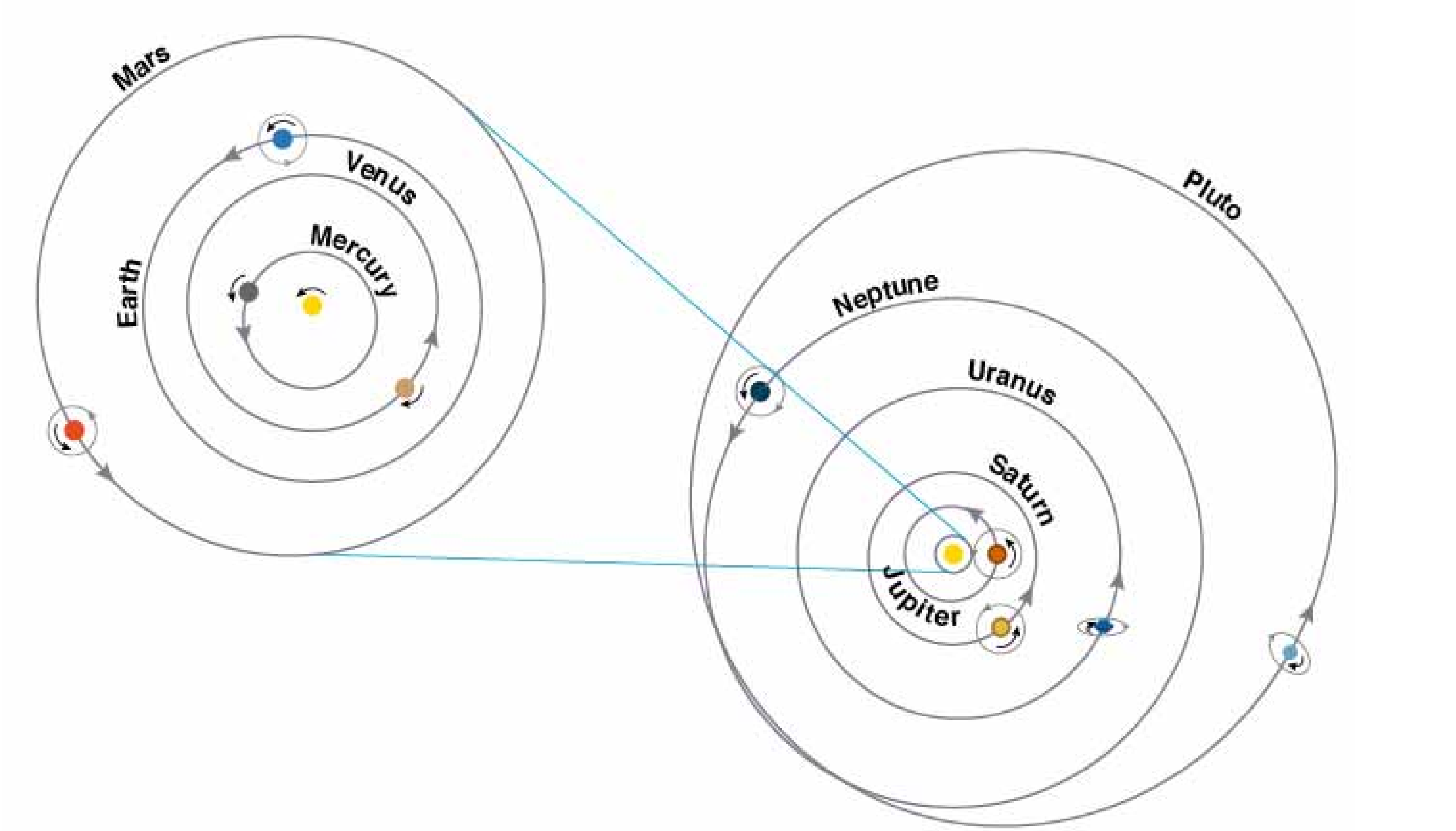
2 March 2005

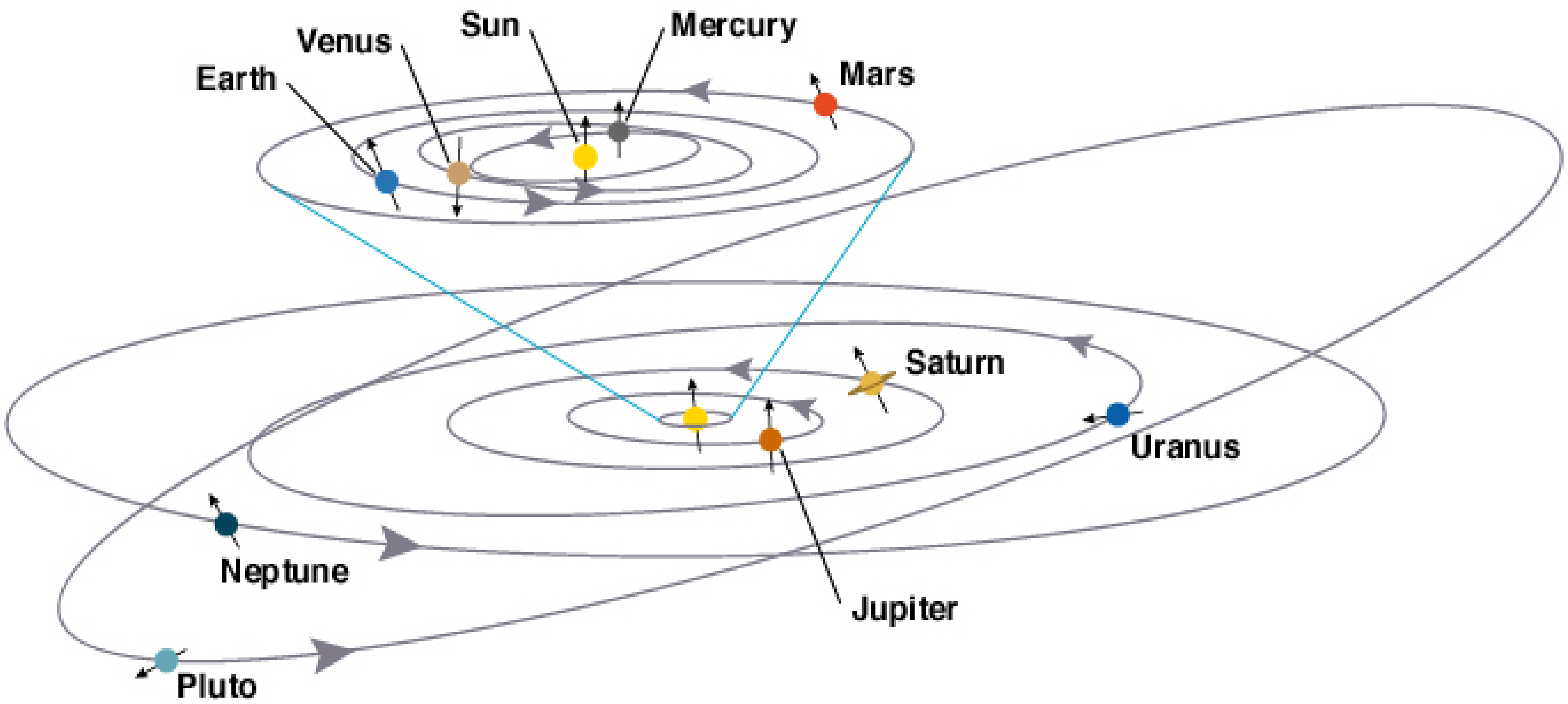
Outline of Talk

- Origin of solar system – review of classical ideas
- Modern theory of star formation
  - Four phases of star formation
  - Contraction of molecular cloud cores
  - Gravitational collapse and disk formation
  - The initial mass function
  - X-wind outflow and YSO jets
  - The inner disk edge
  - Migration of planets

Planets Revolve in Mostly Circular Orbits in Same Direction as Sun Spins



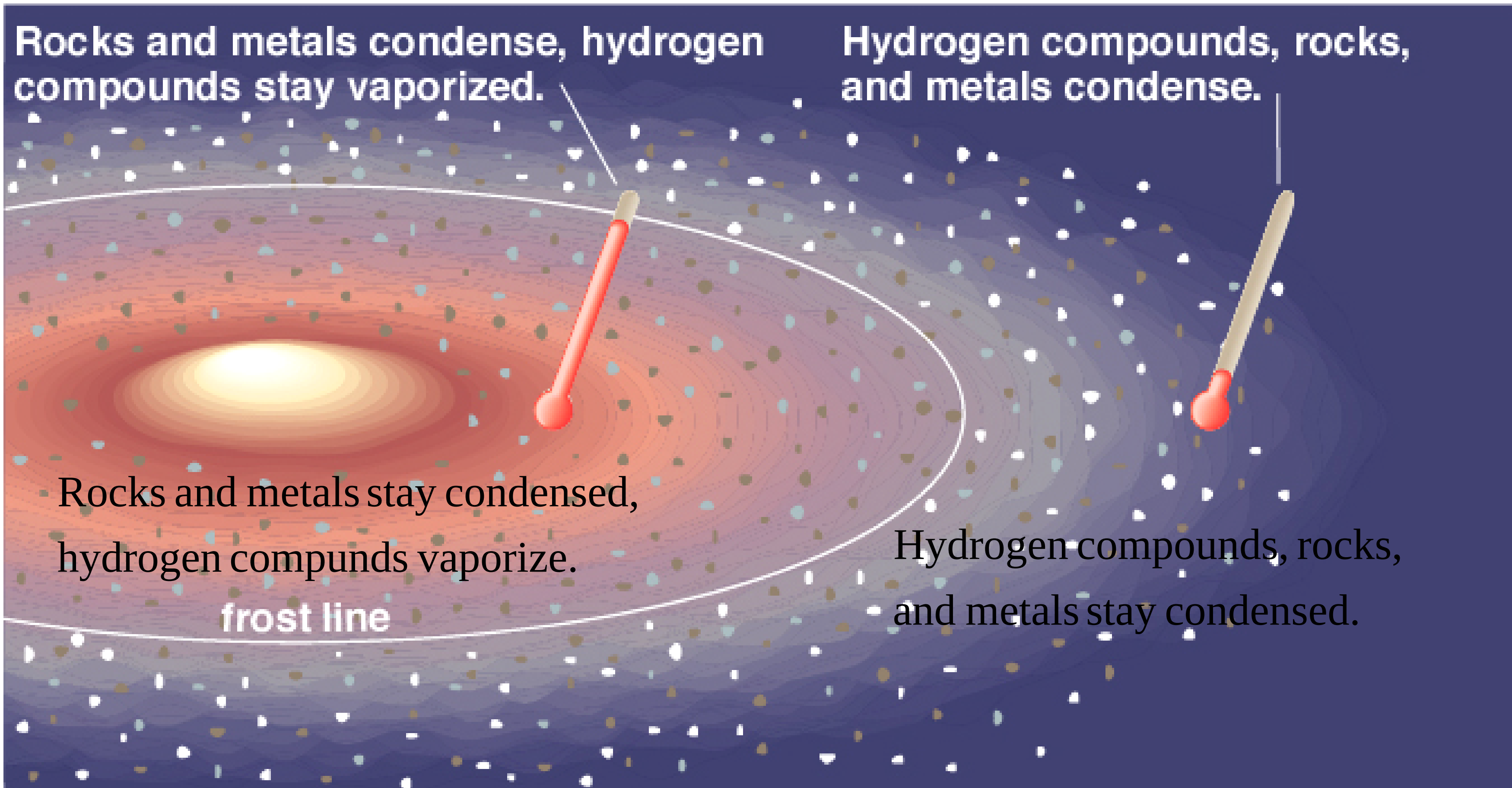
Planetary Orbits Nearly Lie in a Single Plane with Exception of Pluto & Mercury



Laplace’s Nebular Hypothesis

Photo Credit: NASA/JPL

Snowline in the Solar Nebula

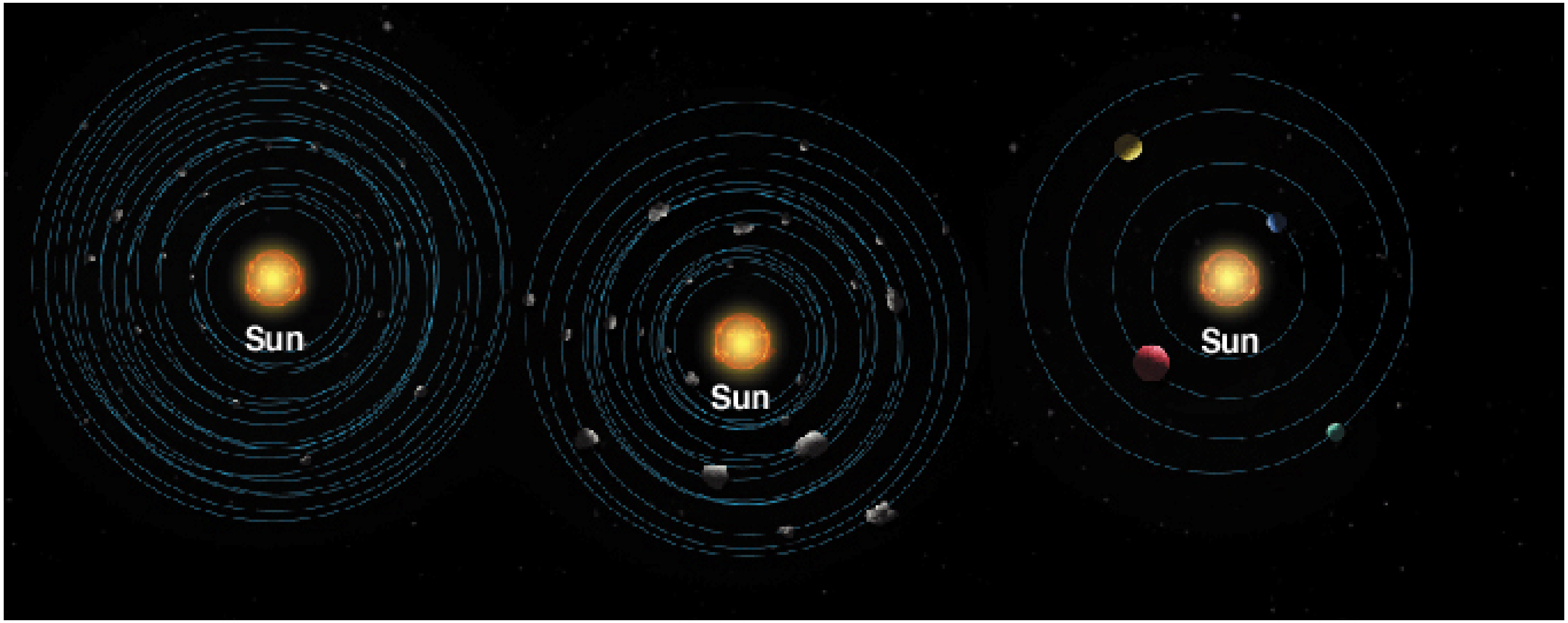


Relative Abundance of Condensates

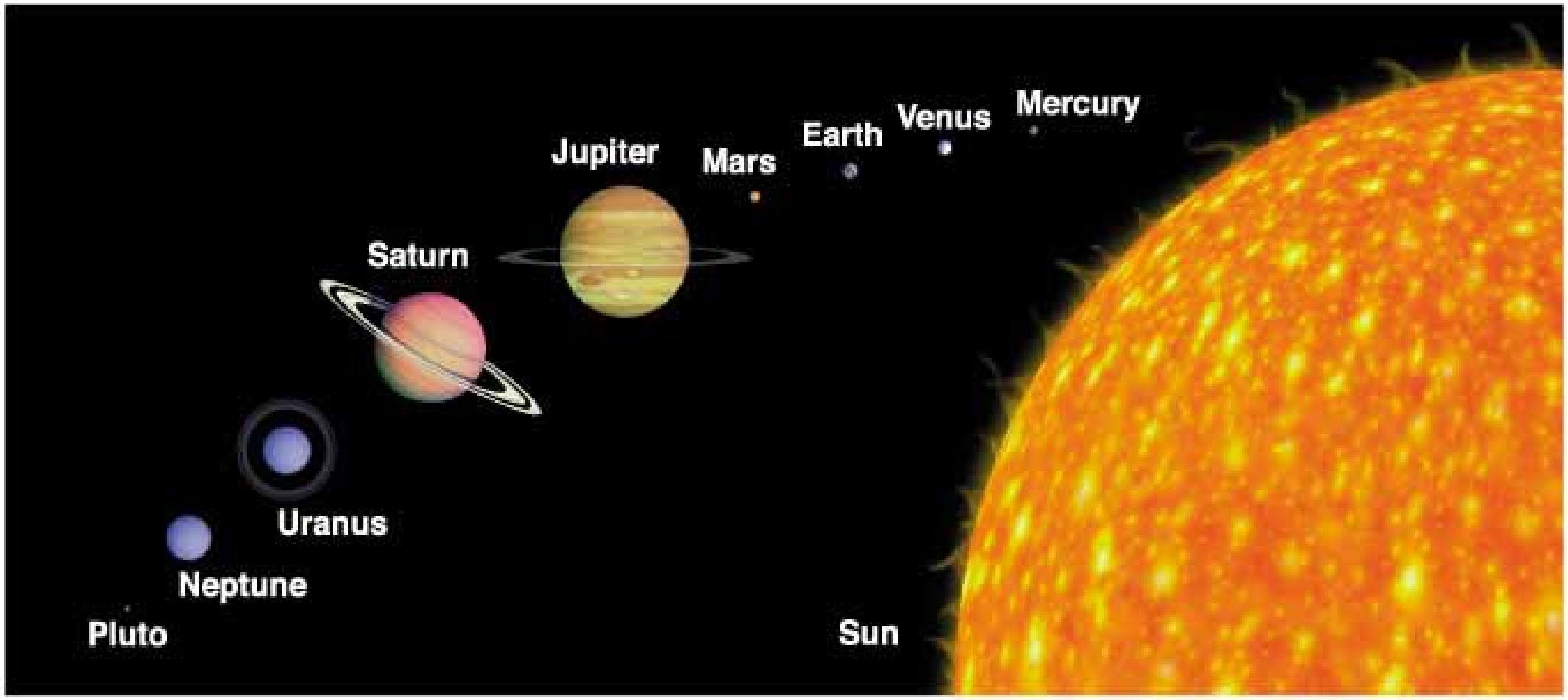
Materials in the Solar Nebula

	Metals	Rocks	Hydrogen Compounds	Light Gases
				
Examples	iron, nickel, aluminum	silicates	water (H_2O) methane (CH_4) ammonia (NH_3)	hydrogen, helium
Typical Condensation Temperature	1,000–1,600 K	500–1,300 K	<150 K	(do not condense in nebula)
Relative Abundance (by mass)	(0.2%)	(0.4%)	(1.4%)	(98%)

Agglomeration of Planets



The Formed Solar System



Four Phases of Star Formation

- Formation of recognizable cores in Giant Molecular Cloud (GMC) by ambipolar diffusion (AD) and decay of turbulence:

  Δt **= 1 – 3 Myr**

- Rotating, magnetized gravitational collapse:

  Δt **= ?**

- Strong jets & bipolar outflows; reversal of gravitational infall:

  Δt **= 0.1 – 0.4 Myr**

- Star and protoplanetary disk with lifetime:

  Δt **= 1 – 5 Myr**

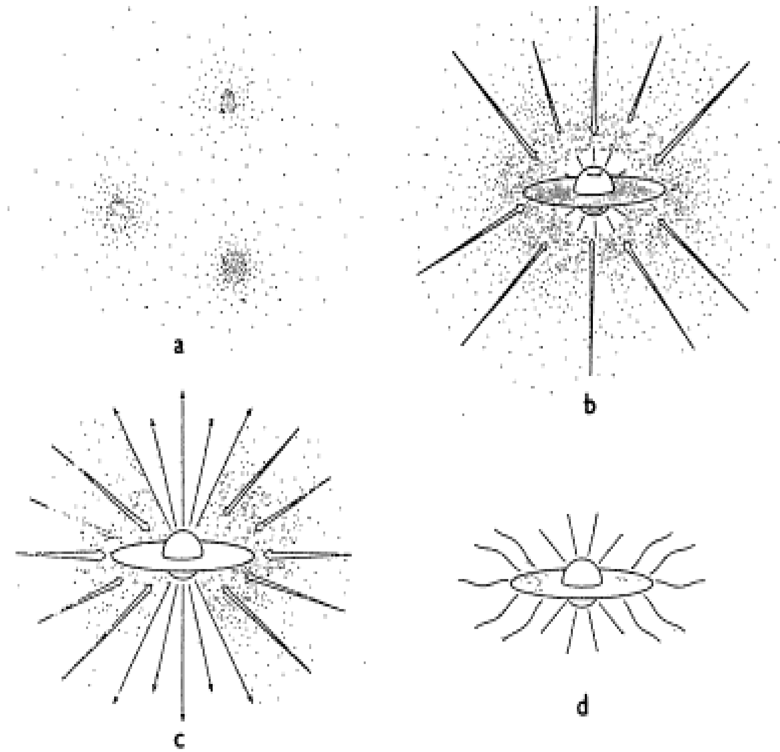


Figure 7 The four stages of star formation. (*a*) Cores form within molecular clouds as magnetic and turbulent support is lost through ambipolar diffusion. (*b*) A protostar with a surrounding nebular disk forms at the center of a cloud core collapsing from inside-out. (*c*) A stellar wind breaks out along the rotational axis of the system, creating a bipolar flow. (*d*) The infall terminates, revealing a newly formed star with a circumstellar disk.

Shu, Adams, & Lizano (1987)

Equations of Non-Ideal MHD for an Isothermal Gas

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{u} \right) = 0,$$

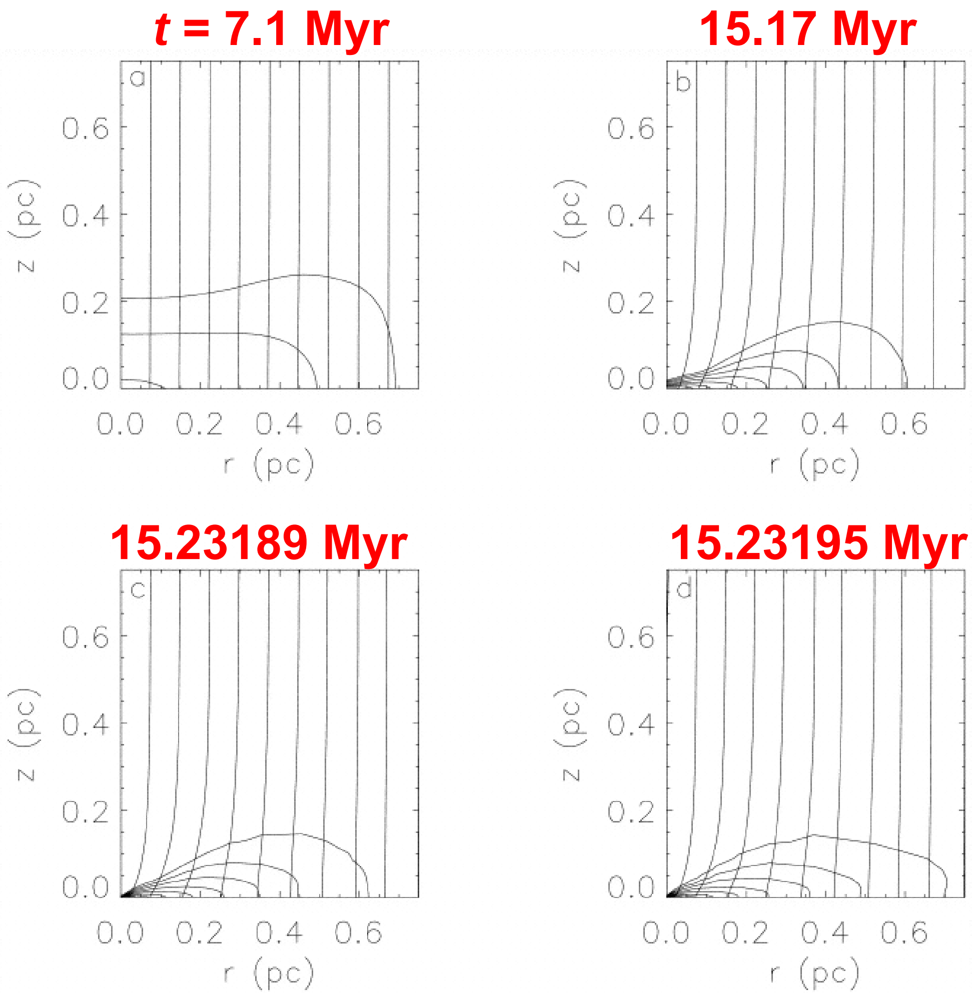
$$\frac{\partial \vec{u}}{\partial t} + \nabla \left(\frac{1}{2} u^2 \right) + (\nabla \times \vec{u}) \times \vec{u} = -\nabla U - \frac{a^2}{\rho} \nabla \rho + \frac{1}{4\pi\rho} \left(\nabla \times \vec{B} \right) \times \vec{B},$$

$$\nabla^2 U = 4\pi G \rho,$$

$$\frac{\partial \vec{B}}{\partial t} + \nabla \times (\vec{B} \times \vec{u}) = \nabla \times \left(-\eta \nabla \times \vec{B} + \frac{\tau \vec{B}}{4\pi\rho} \times \left[\vec{B} \times (\nabla \times \vec{B}) \right] \right),$$

with $a^2 = kT/m = \text{const}$ and η (electrical resistivity) and τ (neutral-ion collision time) specified by microphysics. Neutral-ion collision time is greatly increased when region is shielded from UV ionization (perpendicular $A_V > 4$ mag). Ideal MHD corresponds to $\eta = 0$ and $\tau = 0$.

Cloud-Core Evolution by Ambipolar Diffusion



Displayed time scale for laminar evolution is in conflict with statistics of starless cores versus cores with stars by factor of 3 - 10 (Lee & Myers1999; Jajina, Adams, & Myers 1999).

15.23195 Myr → Reset to 0 (pivotal state).

Turbulent decay (Myers & Lazarian 1999) and turbulent diffusion (Zweibel 2002, Fatuzzo & Adams 2002) may reduce actual time to 1 - 3 Myr.

Desch & Mouschovias (2001).

See also Nakano (1979); Lizano & Shu (1989).

Pivotal *t* = 0 States: Magnetized Singular Isothermal Toroids

AD leads to gravomagneto catastrophe, whereby center formally tries to reach infinite density in finite time – seems to be nonlinear attractor state with $\rho \sim 1/r^2$, $B \sim 1/r$, $\Omega \sim 1/r$. If we approximate the pivotal state as static, it satisfies

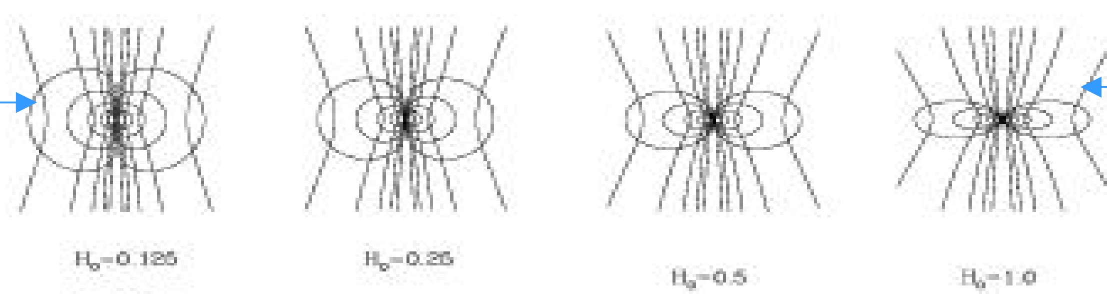
$$\rho(r,\theta) = \frac{a^2}{2\pi G r^2} R(\theta),\ \ \Phi(r,\theta) = \frac{4\pi a^2 r}{G^{1/2}} \phi(\theta)\ \text{ with } \int_0^{\pi/2} R(\theta)\sin\theta\, d\theta = 1 + H_0.$$

$$\frac{1}{\sin\theta}\frac{d}{d\theta}\left[\sin\theta\left(2H_0\frac{\phi'}{\phi} - \frac{R'}{R}\right)\right] = 2(R - 1 - H_0),$$

$$\phi\frac{d}{d\theta}\left(\frac{\phi'}{\sin\theta}\right) = -H_0 R\sin\theta.$$

N.B. solution for H_0 = 0: R = 1, Φ= 0 (Shu 1977).

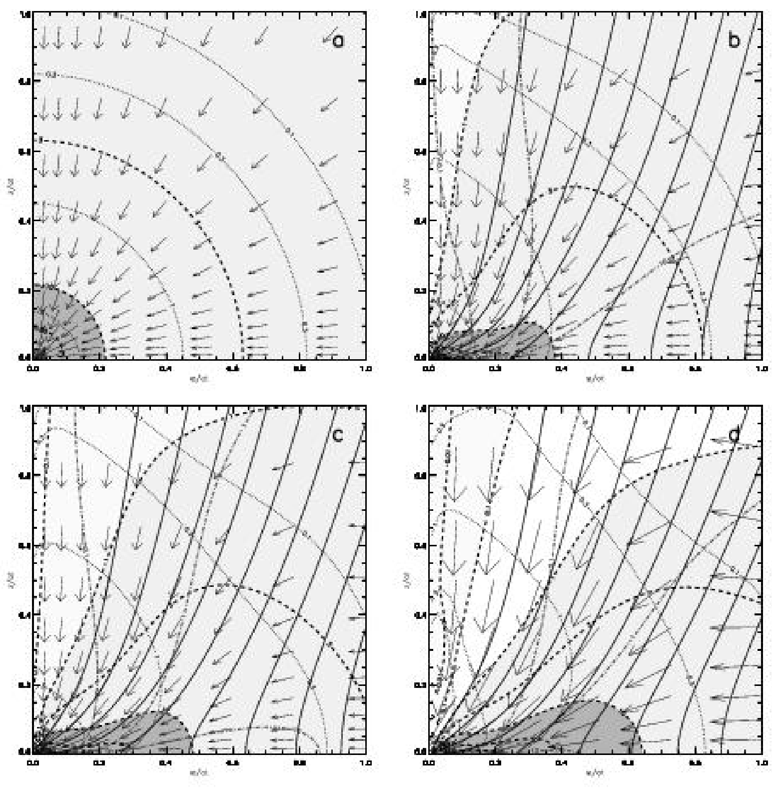
Isodensity contours



Magnetic field lines

Li & Shu (1996)

Collapse of
H_0 = 0.0, 0.125, 0.25, 0.5 Toroids



Allen, Shu, & Li (2003)

Case H_0 = 0 agrees with known analytical solution for SIS (Shu 1977) or numerical simulations without *B* (Boss & Black1982).

Formation of pseudodisk when H_0 > 0 as anticipated in perturbational analysis by Galli & Shu (1993).

Note trapping of field at origin produces split monopole with long lever arm for magnetic braking.

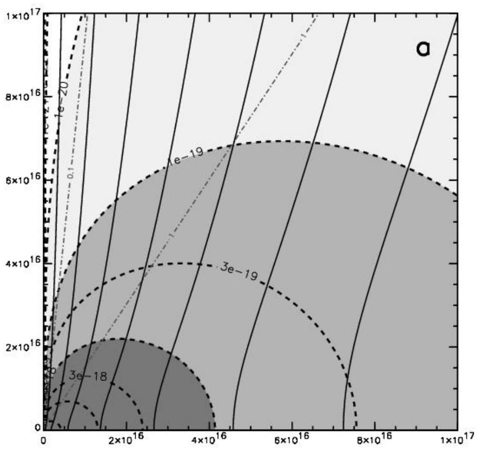
Mass infall rate into center:

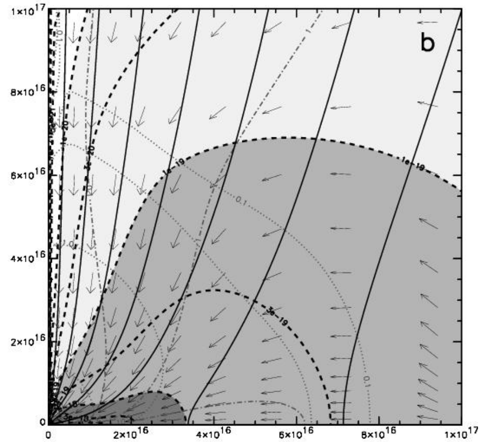
$$\dot{M} = 0.975\,(1 + H_0)a^3/G$$

gives 0.17 Myr to form 0.5 M_{sun} star.

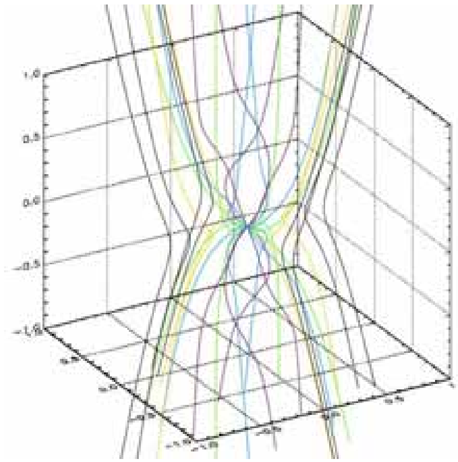
Mass infall rate doubled if there is initial inward velocity at 0.5 *a*.

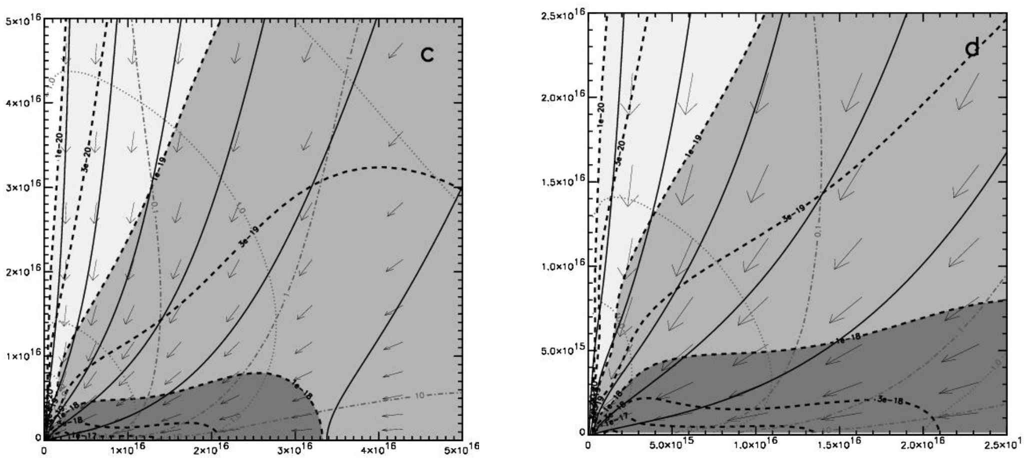
Catastrophic Magnetic Braking if Fields Are Perfectly Frozen

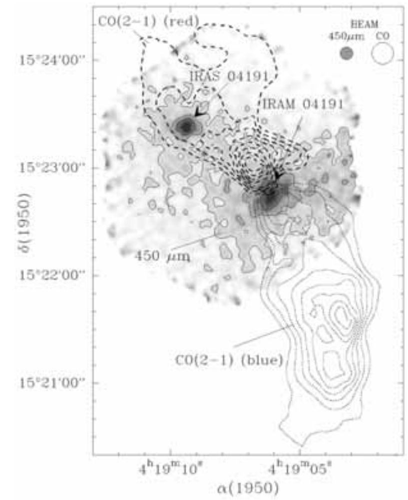




Low-speed rotating outflow (cf. Uchida & Shibata 1985) not high-speed jet





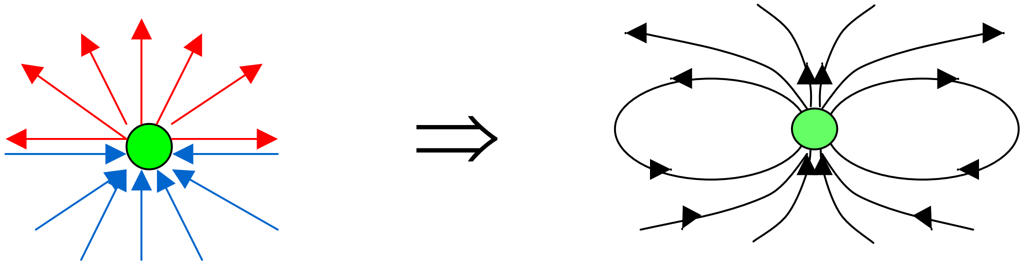


Andre, Motte, & Bacmann (1999); also Boogert et al. (2003)

Allen, Li, & Shu (2003) – Initial rotation in range specified by Goodman et al. (1993). Some braking is needed, but frozen-in value is far too much (**no Keplerian disk forms**).

Breakdown of Ideal MHD

- Low-mass stars need 10 megagauss fields to stop infall from pseudodisk by static levitation (if envelope subcritical).
- Combined with rapid rotation in a surrounding Keplerian disk, such stars need only 2 kilogauss fields to halt infall by X-winds (dynamical levitation).



- Appearance of Keplerian disks requires breakdown of ideal MHD (Allen, Li, & Shu 2003).
- Annihilation of split monopole is replaced by multipoles of stellar field sustained by dynamo action.
- Latter fields are measured in T Tauri stars through Zeeman broadening by Basri, Marcy, & Valenti (1992) and Johns-Krull, Valenti, & Koresko (1999).

Computed Steady X-Wind Filling All Space

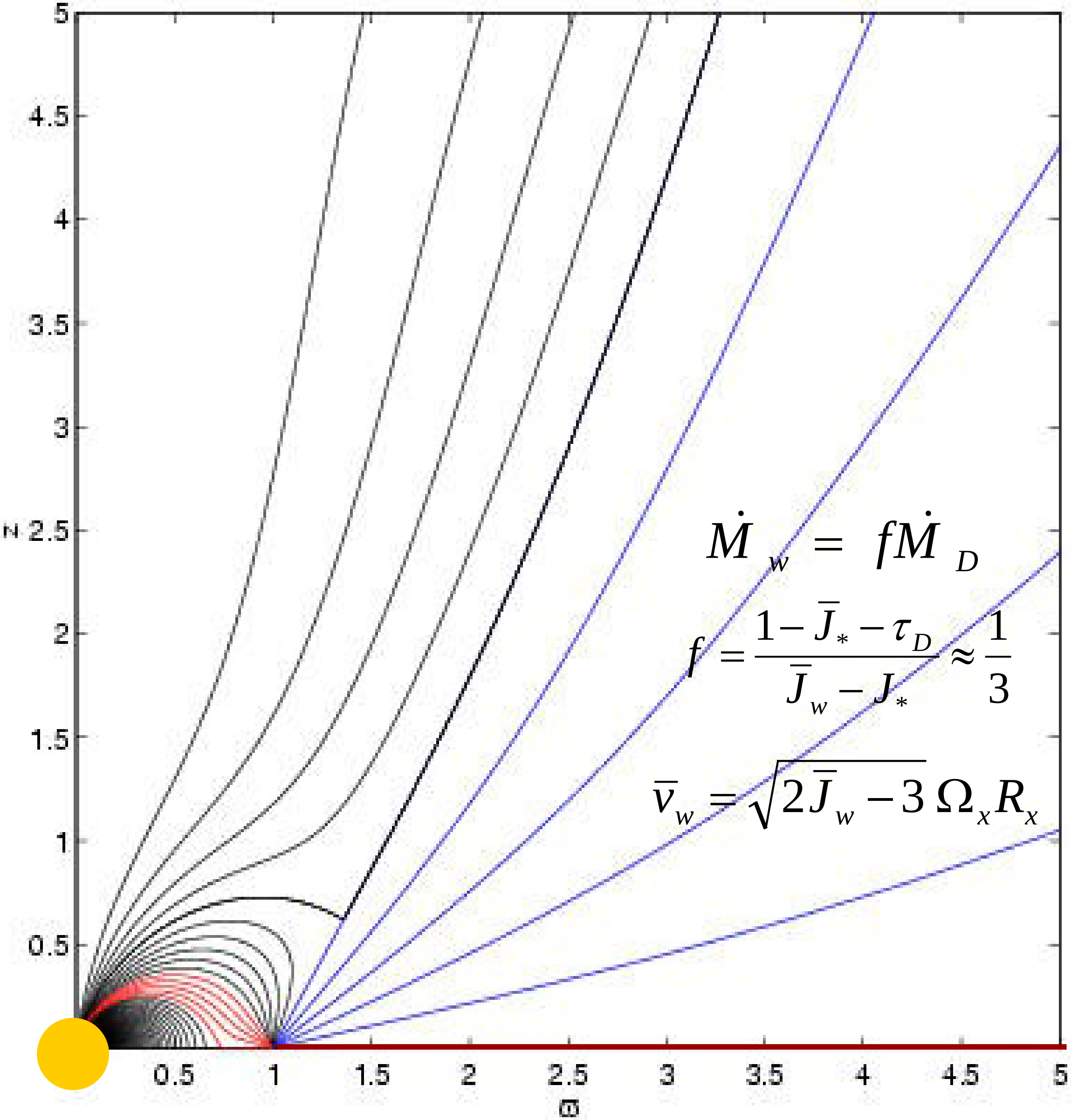
Apart from details of mass loading onto field lines, only free parameters are

$$\dot{M}_D, M_*, \mu_*.$$

$$R_x = 0.923\left(\frac{\mu_*^{\ 4}}{GM_*\dot{M}_D^{\ 2}}\right)^{1/7},$$

$$\Omega_x = \left(\frac{GM_*}{R_x^{\ 3}}\right)^{1/2},$$

$$\Omega_* = \Omega_x \text{ (disk locking).}$$



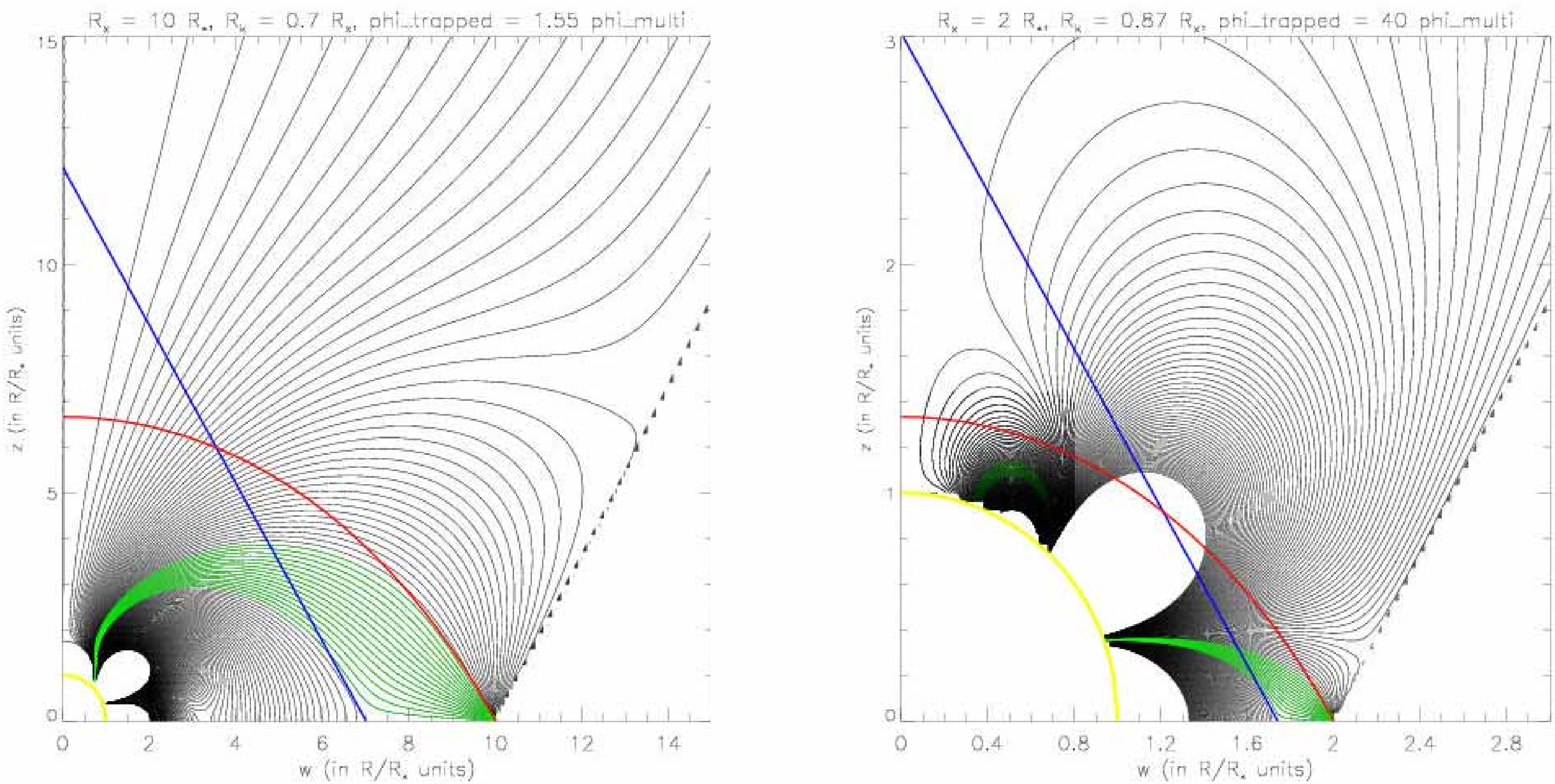
$$\dot{M}_w = f\dot{M}_D$$

$$f = \frac{1-\bar{J}_* - \tau_D}{\bar{J}_w - \bar{J}_*} \approx \frac{1}{3}$$

$$\bar{v}_w = \sqrt{2\bar{J}_w - 3}\,\Omega_x R_x$$

Ostriker & Shu (1995) Najita & Shu (1994)

Multipole Solutions Change Funnel Flow but not X-wind

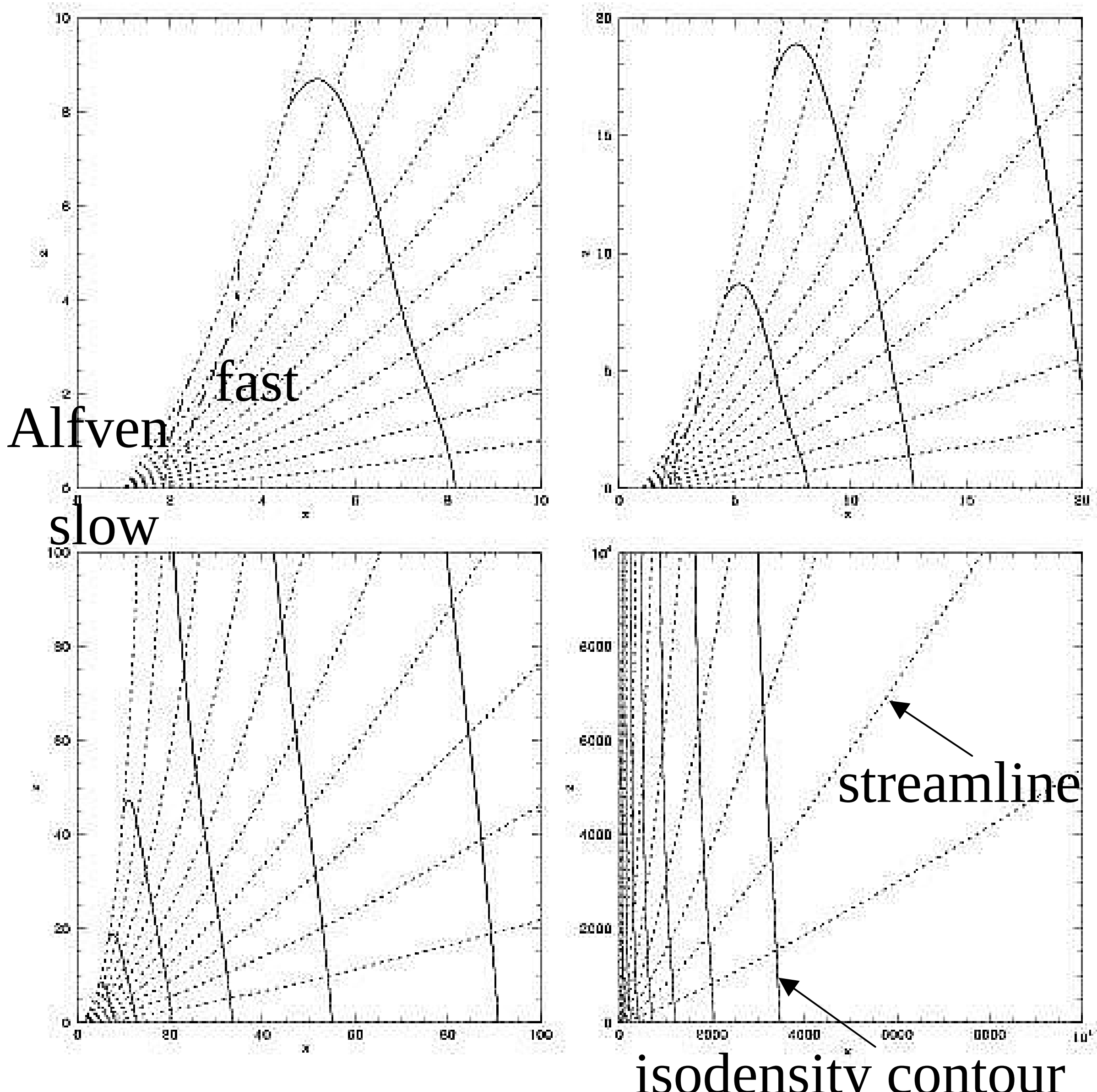


Mohanty & Shu (2005)

What's important is trapped flux at X-point (Johns-Krull & Gafford 2002).

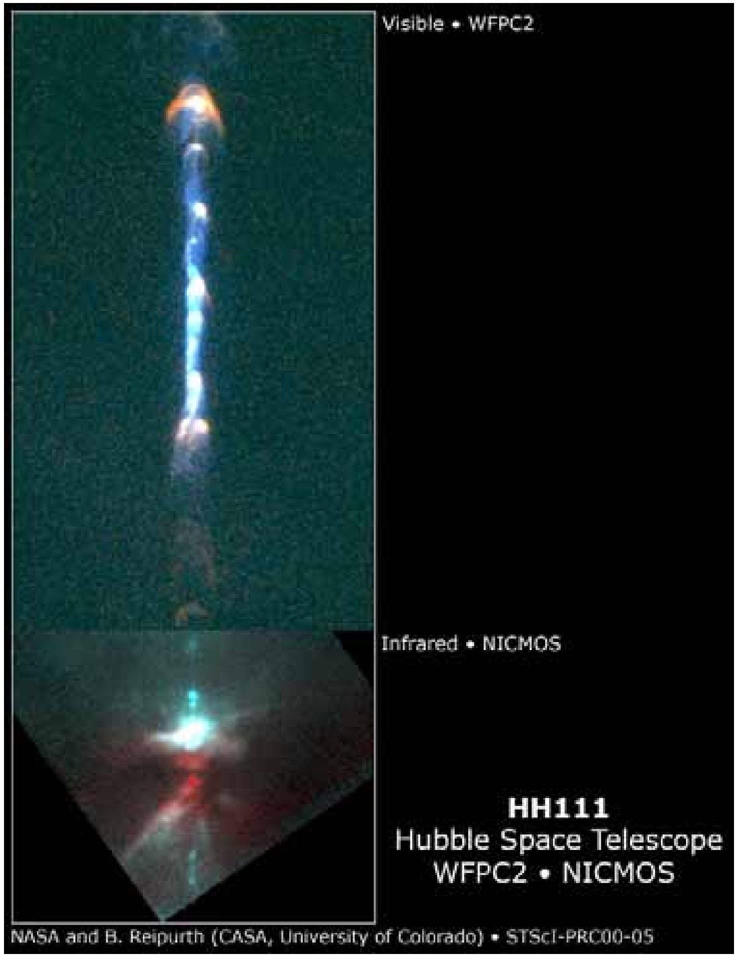
Prototypical X-Wind Model

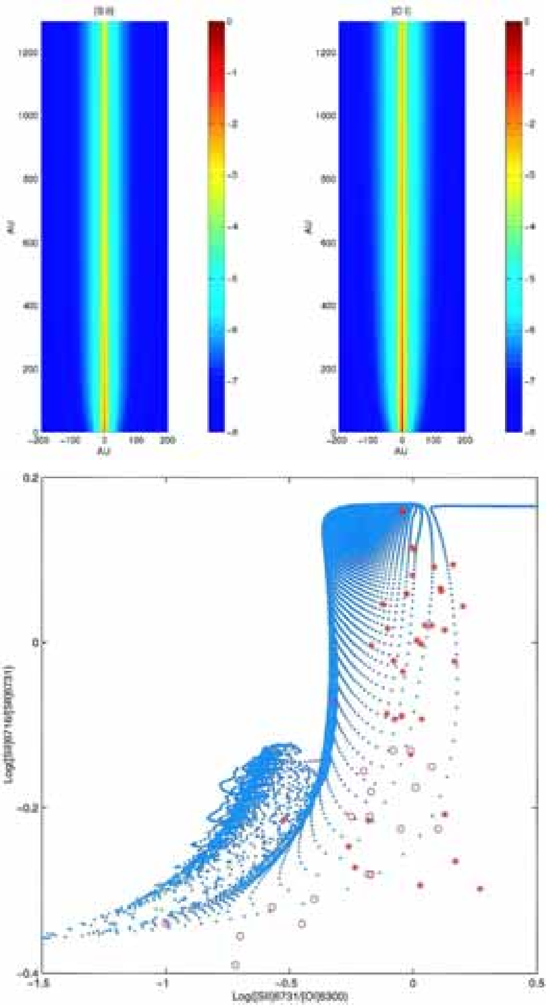
$(1\,R_x \approx 0.06\ \mathrm{AU}\ \text{typically})$



Shu, Najita, Ostriker, & Shang (1995)

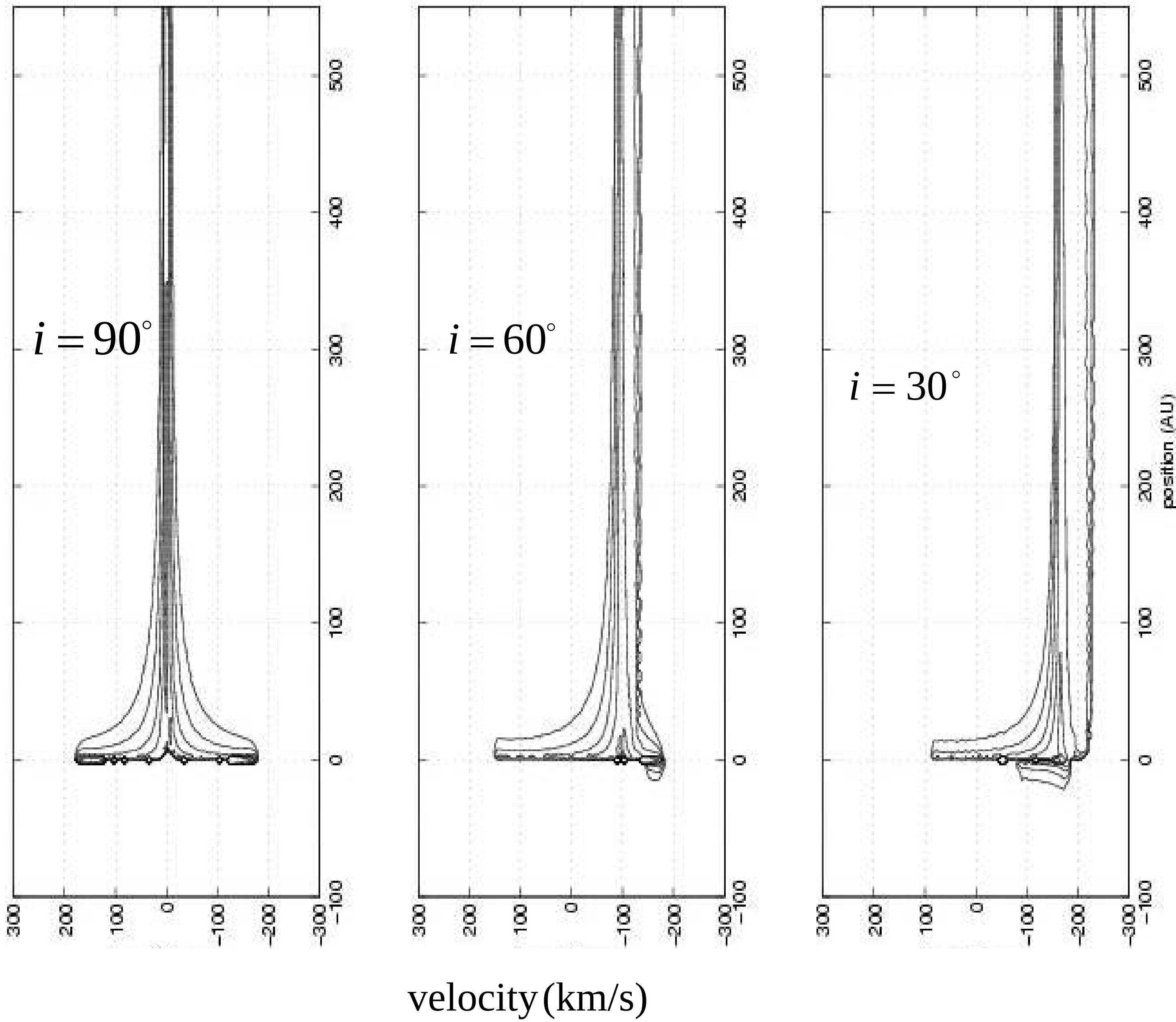
Gas: YSO Jets Are Often Pulsed Magnetic Cycles?





Shang, Glassgold, Shu, & Lizano (2002)

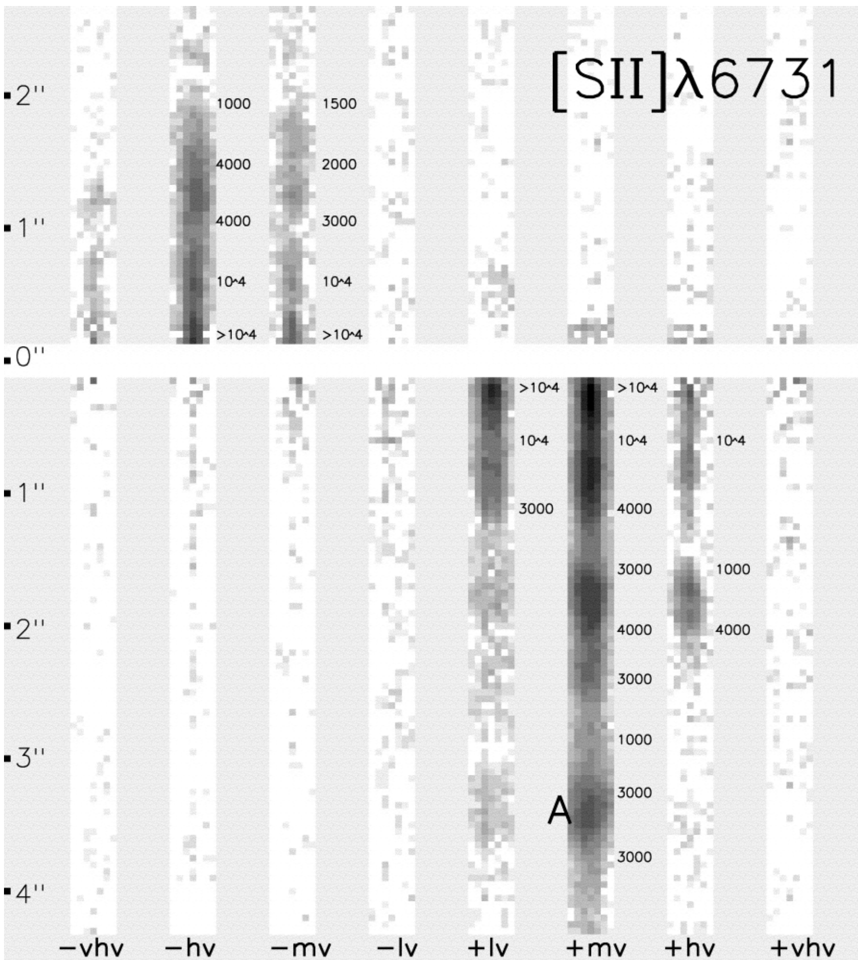
Synthetic Long-Slit Spectra



Shang, Shu, & Glassgold (1998)

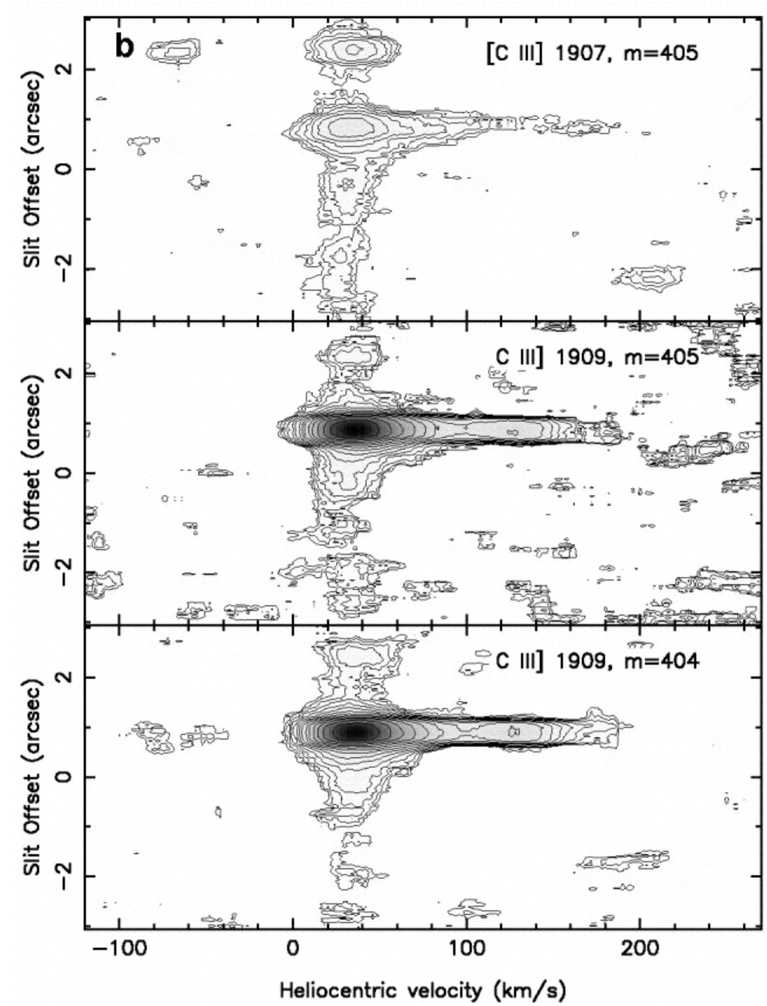
Position-Velocity Spectrogram

Jet/Counterjet R W Tauri



Woitas, Ray, Bacciotti, Davis, & Eisloffel (2002)

LV2 Microjet in Orion Proplyd



Henney, O'Dell, Meaburn, & Garrington (2002)

Relationships Among Core Mass, Stellar Mass, & Turbulence

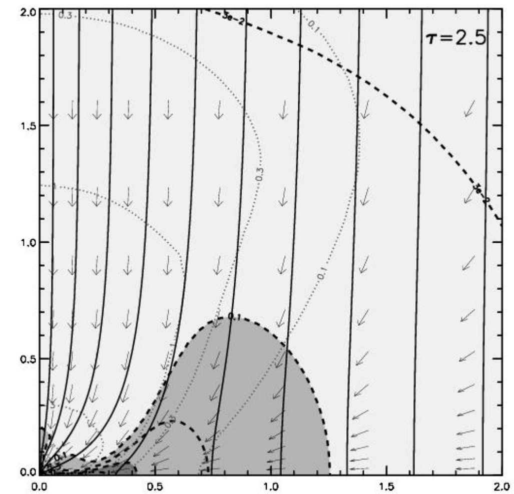
- Conjecture: Outflows break out when infall weakens and widens after center has accumulated some fraction (50%?) of core mass (1/3 of which is ejected in X-wind). Physical content of Class 0? (Andre, Ward-Thompson & Barsony 1993)
- Stellar mass is therefore defined by X-wind as 1/3 of core mass

  $M_0 = m_0 (a^2 + v^2)^2 / G^{3/2} B_0$.

  Distribution of $m_0 \le \pi^2$.
- Ambipolar diffusion and turbulence driven by outflows lead to distribution of

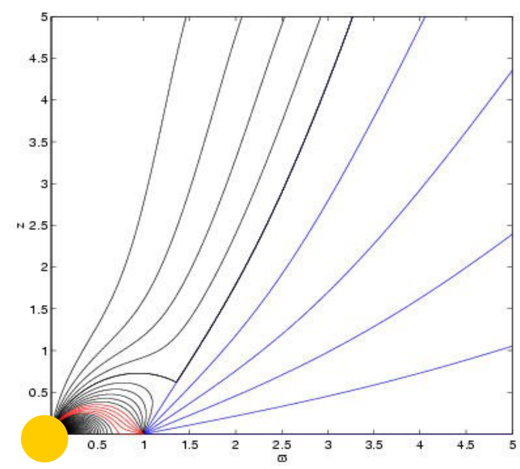
  $(a^2 + v^2)^2 / B_0$

  that yields core mass function.



Shu, Li, & Allen (2004)

1 (r_0) above is 200,000 times bigger than 1 (R_x) below



Shang, Ostriker, & Shu (1995)

Attack by matched asymptotic expansions

Core Mass with Magnetic Fields and Turbulence

- Pivotal state produced by AD (Mestel & Spitzer 1956, Nakano 1979, Lizano & Shu 1989, Basu & Mouschovias 1994, Desch & Mouschovias 2004):

$$\bar{\lambda} \equiv \frac{2\pi G^{1/2} M_0}{\pi r_0^{\,2} B_0} = 2.$$

Core mass: part which is supercritical

- Virial equilibrium:

$$\mathbf{2} \cdot \frac{3}{2} M_0 (a^2 + v^2) = \frac{G M_0^{\,2}}{r_0}.$$

Differs from barely bound in factor 2.

- Solve for

$$M_0 = \frac{9(a^2+v^2)^2}{G^{3/2} B_0}, \quad r_0 = \frac{3(a^2+v^2)}{G^{1/2} B_0}.$$

- Compare with SIS threaded by uniform field:

$$M_0 = \frac{\pi^2 a^4}{G^{3/2} B_0}, \quad r_0 = \frac{\pi a^2}{G^{1/2} B_0}.$$

M_0 = 1.5 solar mass for a = 0.2 km/s, B_0 = 30 μG

Divide mass by 4 if barely bound

Simple "Derivation" for IMF when $v^2 >> a^2$

Bipolar outflows: $\boxed{\mathrm{M}(v)dv \propto v^{-2}dv\,.}$ (Shu, Ruden, Lada, & Lizano 1990; Masson & Chernin 1992; Li & Shu 1996)

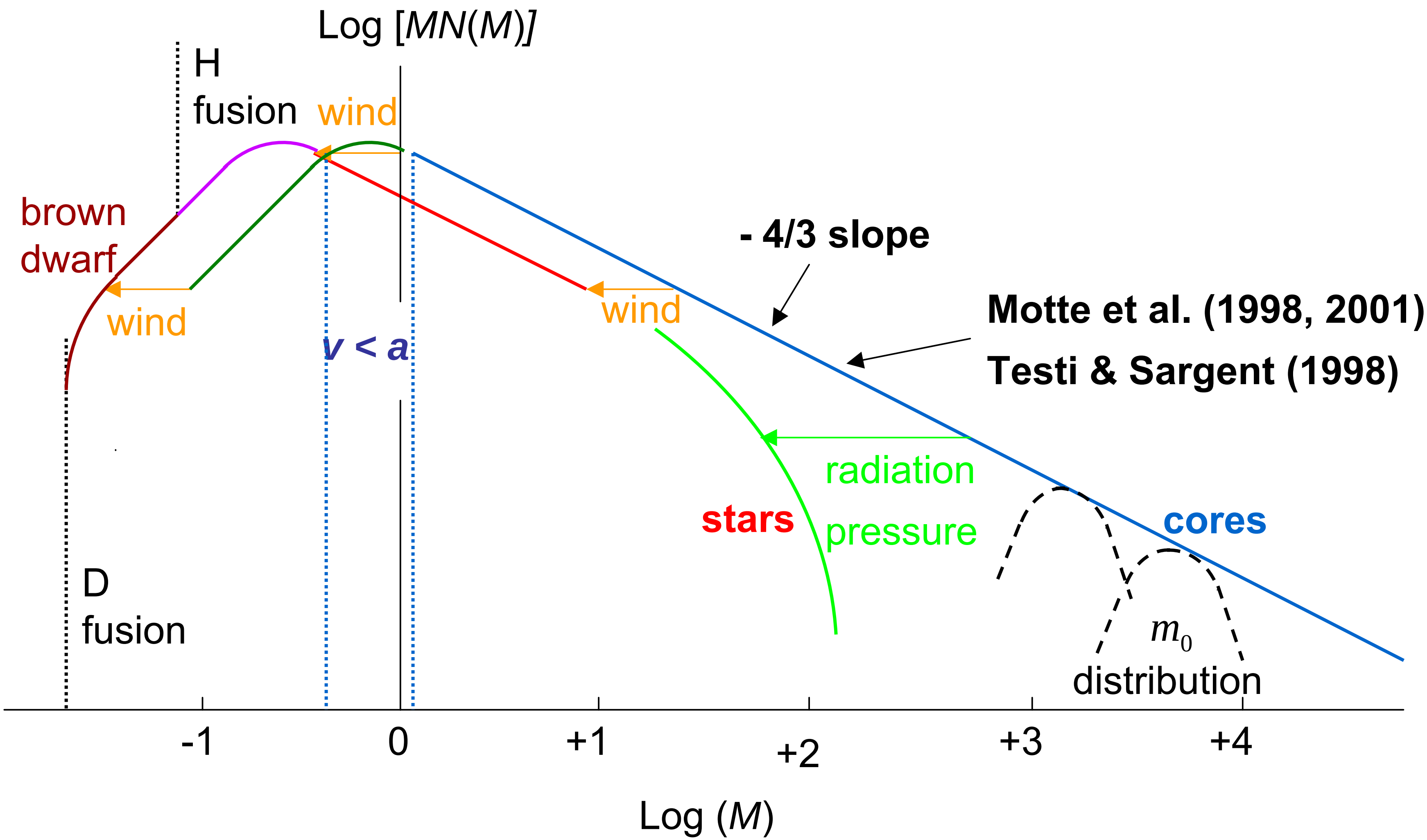
When $v^2 >> a^2$:

(Shu, Li, & Allen 2004)

which is Salpeter IMF at intermediate masses (peak at $\pi^2 a^4/3G^{3/2}B_0 \approx 0.5\, M_{\rm sun}$; steeper at high stellar masses because of radiation pressure on dust grains).

NB: SFE = 1/3 when F = 1 (cf. Lada & Lada 2003).

Schematic IMF



The Orion Embedded Cluster

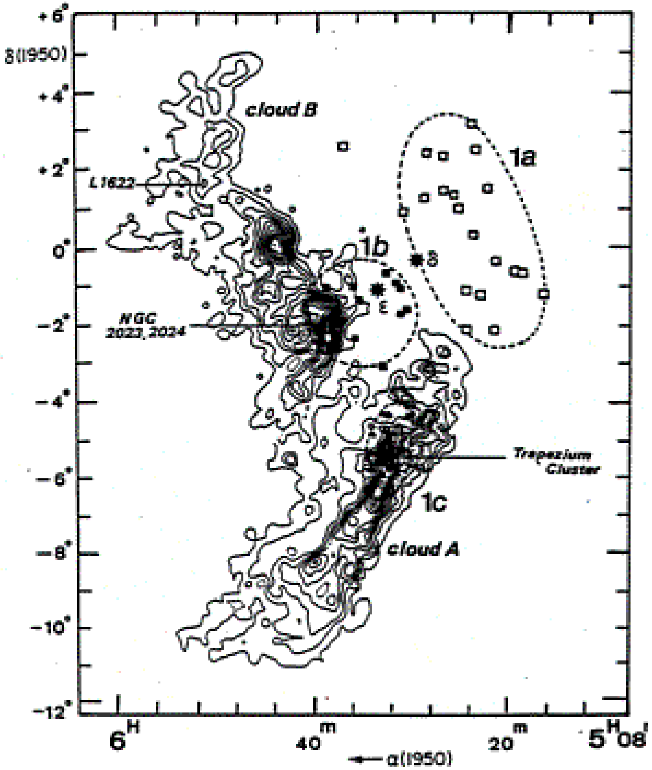
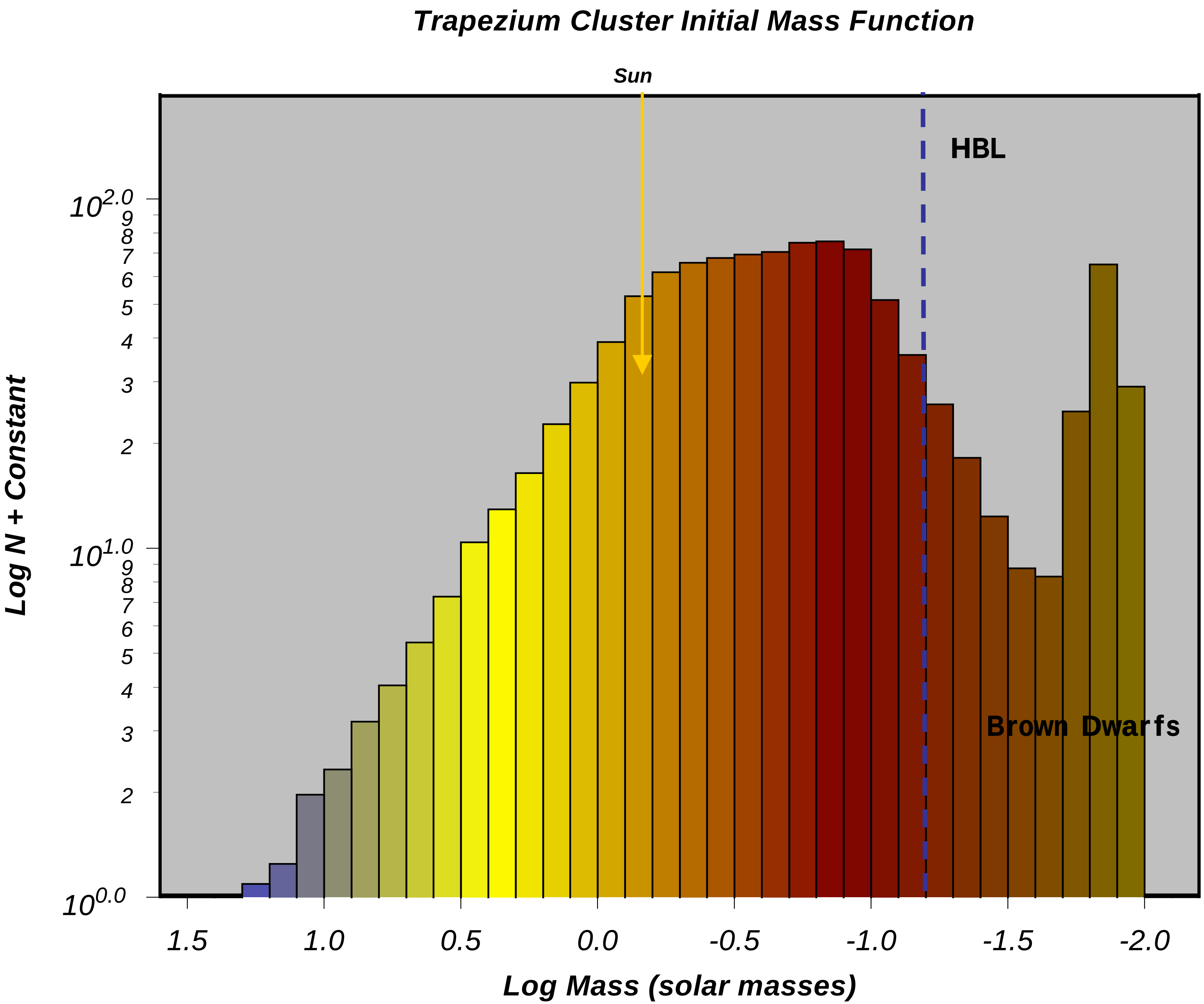


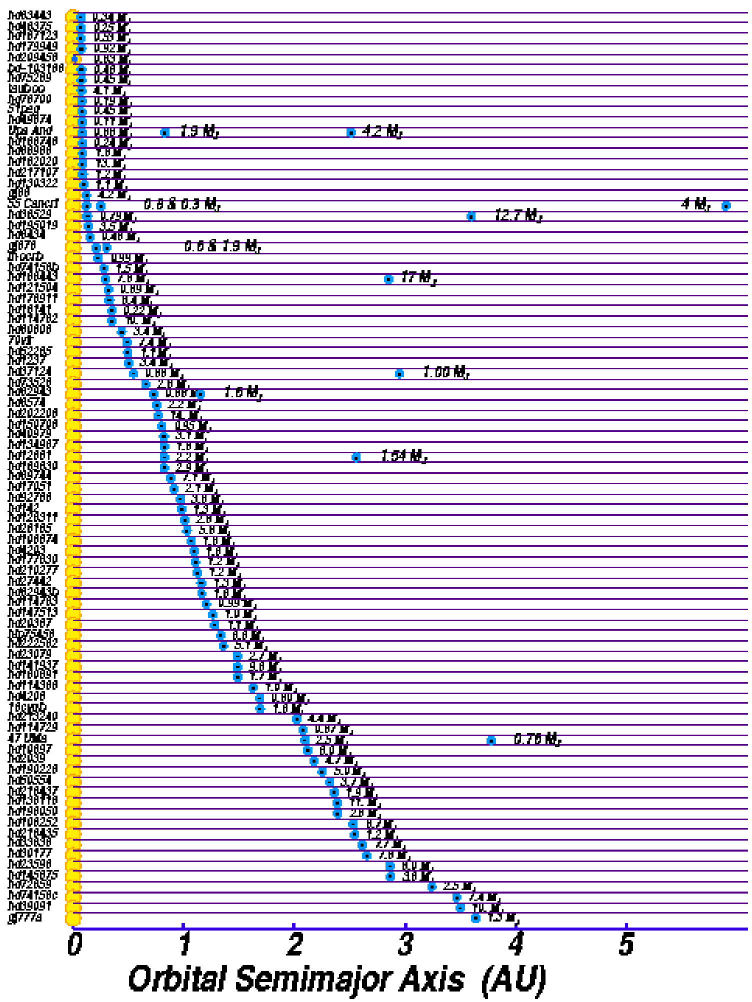
Figure 3. The ORI OB1 association and its Giant Molecular Cloud Complex. Th subgroups of sequentially differing age are enclosed by dashed lines. The oldest (1a) significantly more expanded than the youngest (Trapezium Cluster). Figure taken fr Blaauw (1991).



At stellar birth (Lada & Lada 2003), IMF is given by Salpeter (1955) IMF.

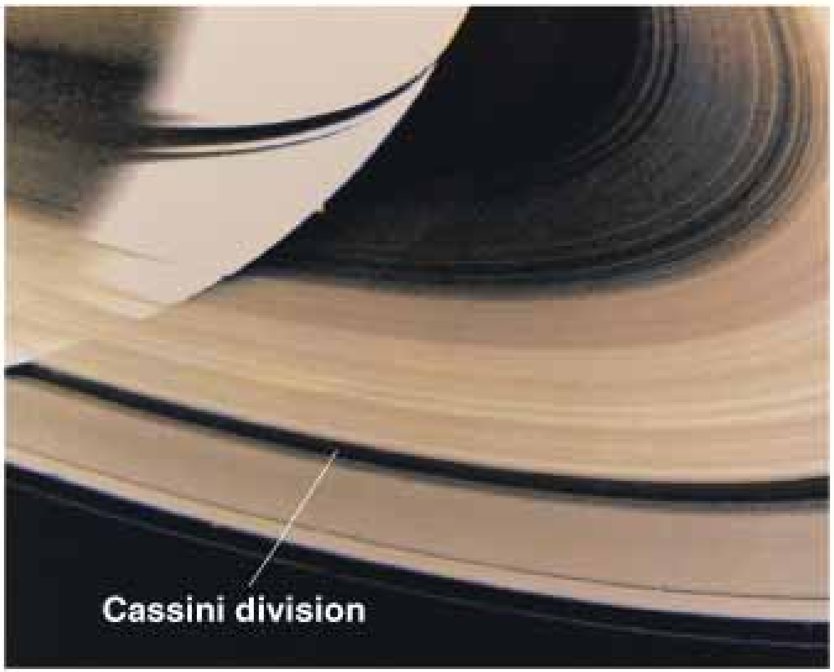
Almost 100% of Young Stars in Orion Cluster Are Born with Disks

Discovery of Extrasolar Planets

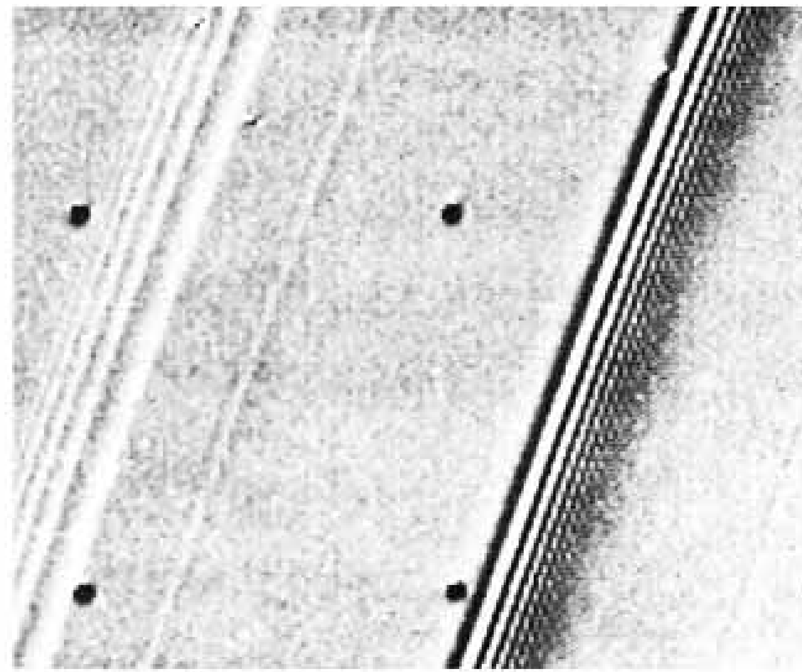


Marcy webpage

Driven Spiral Density and Bending Waves in Saturn's Rings



(a)



(b)

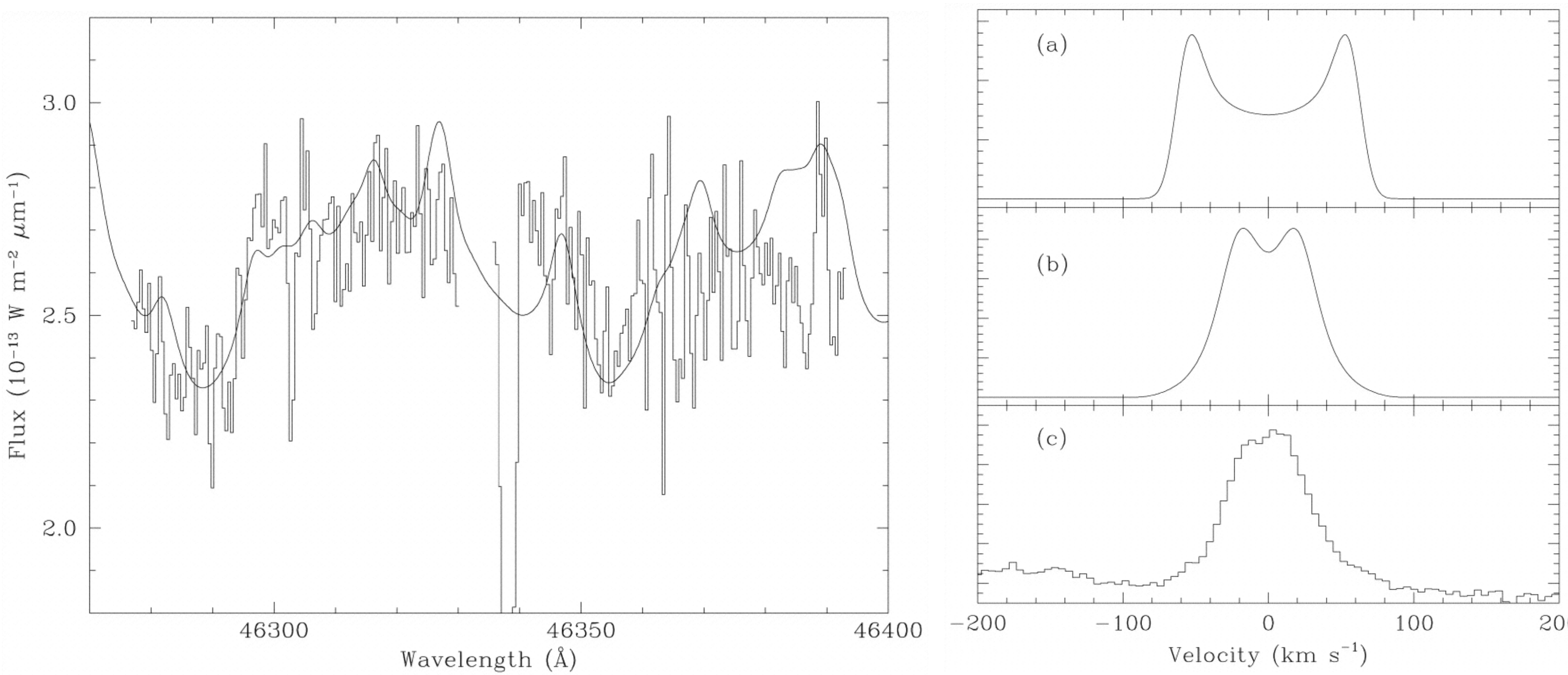
Shu, Cuzzi, & Lissauer (1983)

Implications for planet migration due to planet-disk interaction

Shepherd Satellites Predicted by Goldreich & Tremaine

Photo credit: Cassini-Huygens/NASA

Model Fit to CO Fundamental ($v = 1 \rightarrow 0$, $\Delta J = \pm 1$)



Inferred gas temperature ≤ 1200 K; kinematics gives location of inner disk edge.

Najita et al. (2003)

Size of Inner Hole in Rough Agreement with Disk Locking

TABLE 8

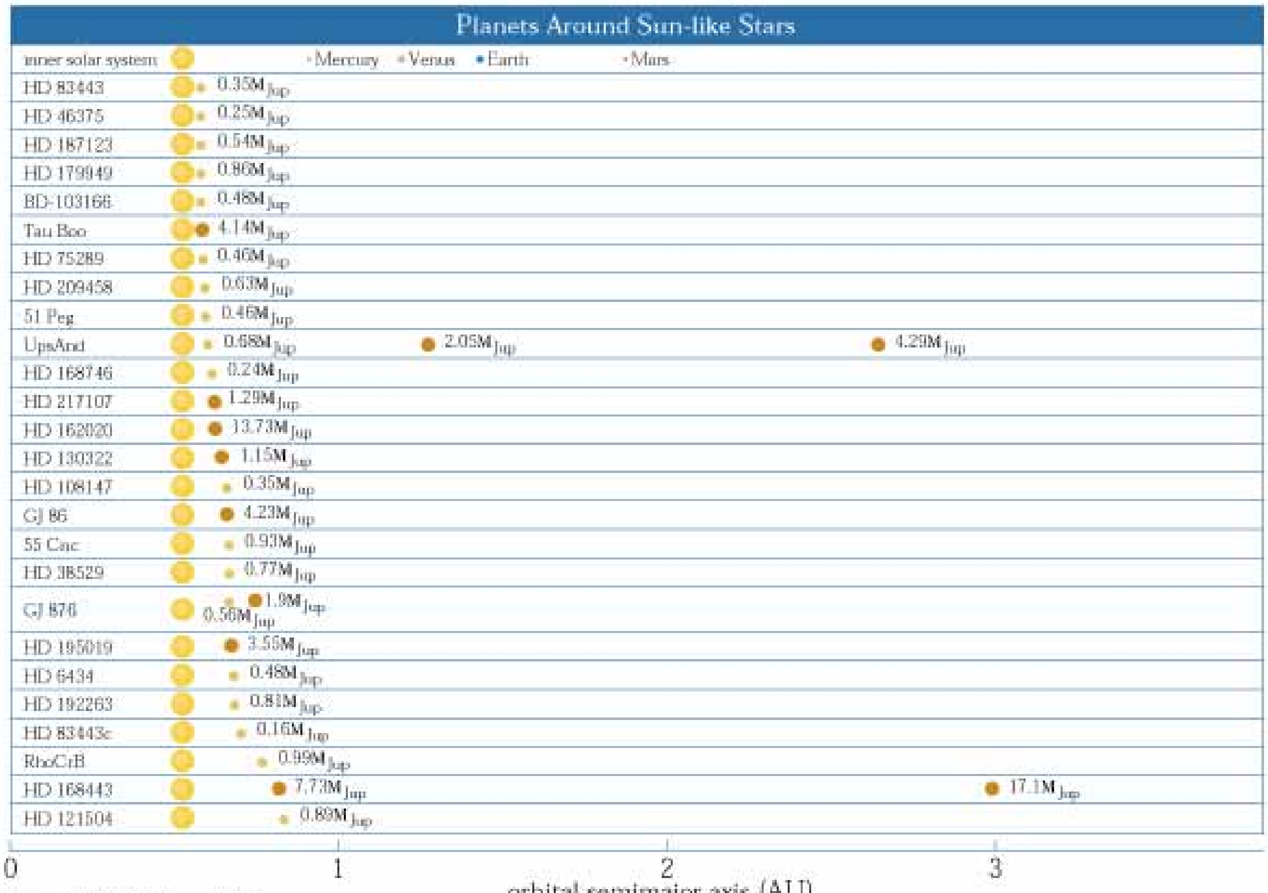
SINGLE-STAR PARAMETERS AND CO EMISSION RADII

Star	P_*[a] (days)	M_* ($M_\odot$)	i	V_{max} (km s^{-1})	R_{in} (AU)	R_c[b] (AU)	R_{out}(min)[c] (AU)
LkCa 15	5.85	0.97[d]	52[d]	80 ± 20	0.093	0.083	0.78
GG Tau A.............	10.3	0.8[e]	37[d]	105 ± 10	0.023	0.086	0.23
BP Tau..................	7.6	1.24[d]	30[d]	80 ± 5	0.043	0.081	0.44
CY Tau..................	7.5	0.55[d]	30[d]	60 ± 10	0.034	0.062	0.17
GK Tau	4.65	0.75[f]	52[g]	96 ± 5	0.045	0.050	0.62
IQ Tau	6.25	0.52[f]	49[g]	80 ± 10	0.041	0.054	0.21

[a] Periods from the compilation in Bouvier et al. 1995.
[b] Corotation radius.
[c] Minimum radius for the outer extent of the CO emission.
[d] Simon et al. 2000.
[e] Simon et al. 2000; assumed 0.8 $M_\odot$ for the mass of Aa.
[f] Mass derived from stellar evolutionary tracks (see text).
[g] Inclination obtained from P_*, $v \sin i$, T_*, and L_*.

Najita et al (2003)

Parking Hot Jupiters



Thank you, everyone!