

CARMA observations of proto-planetary disks: initial conditions and evolution

Andrea Isella

(Michelson Postdoctoral Fellow at the Department of Astronomy, Caltech)
isella@astro.caltech.edu

John Carpenter (Caltech), Anneila Sargent (Caltech)

Combined Array for Research in Millimeter-wave Astronomy

- six 10.4-meter, nine 6.1-meter, and eight 3.5 meter antennas
- Caltech, UC Berkeley, University of Illinois and University of Maryland
- 85-115 GHz (2.6 -3.5.mm) and 215-270 GHz (1.1 - 1.4 mm)
- Array configurations: A - 250 m - 2 km (0.15" / 0.4")

B - 100 m - 1 km (0.3" / 0.7")

C - 30 m - 350 m (0.9" / 2.2")

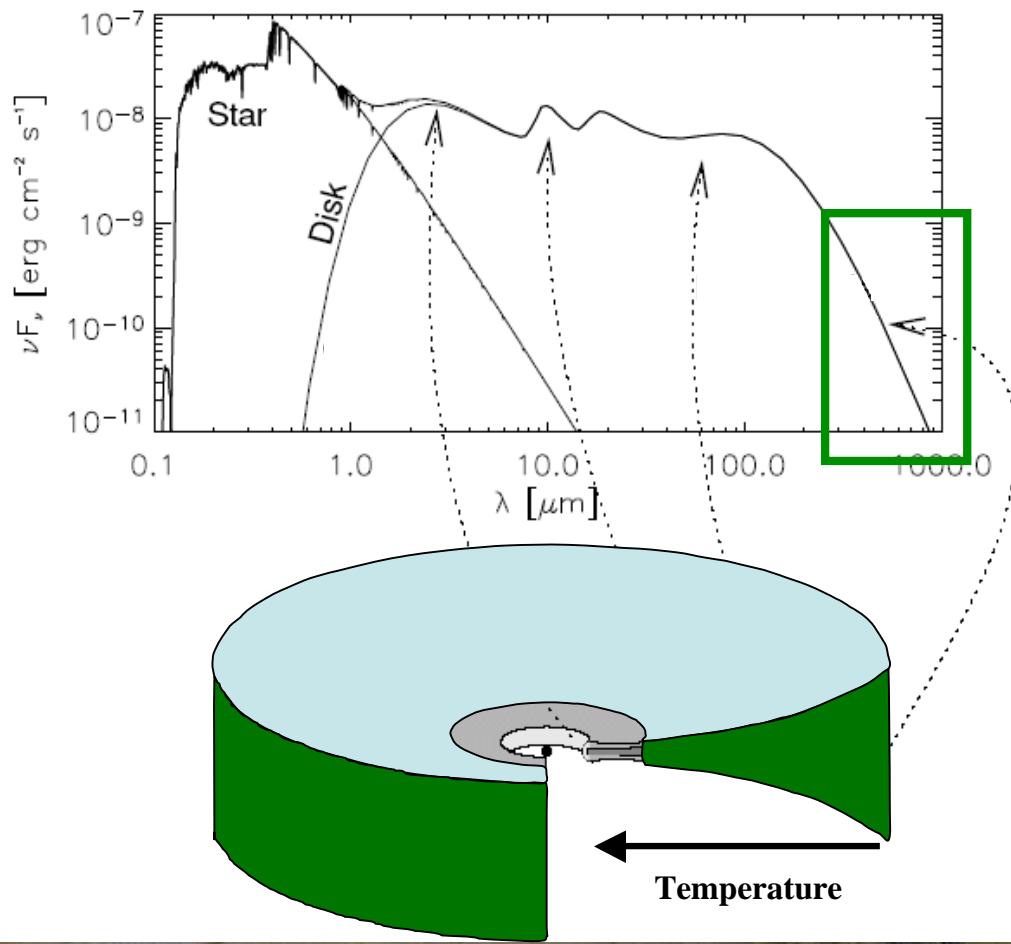
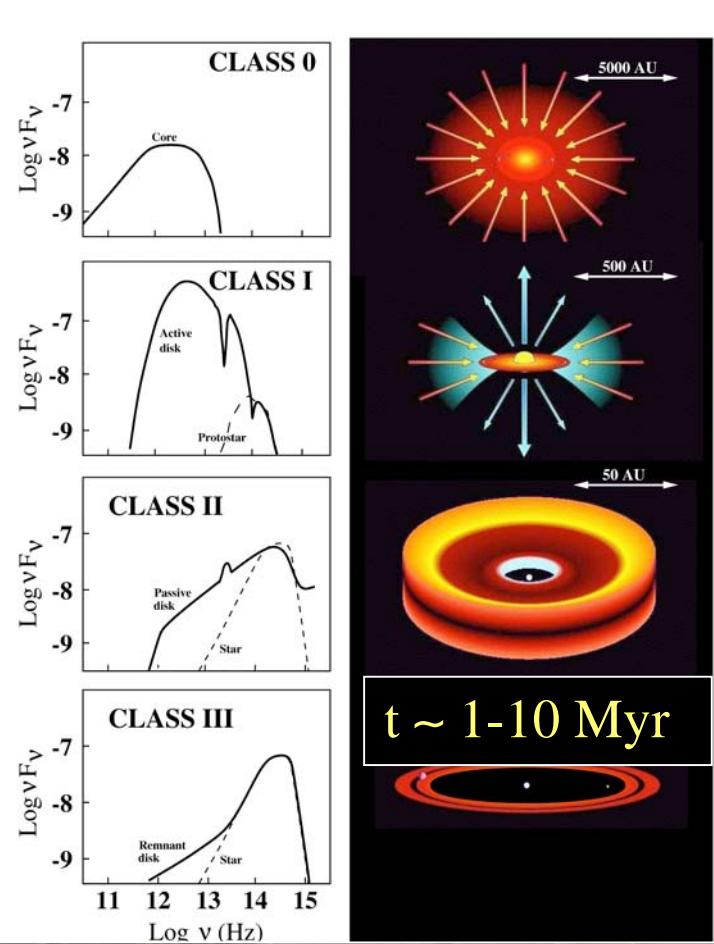
D - 11m - 150 m (2.0" / 4.9")

E - 8 m - 66 m (4.6" / 11.2")

30-40 AU at 150 pc



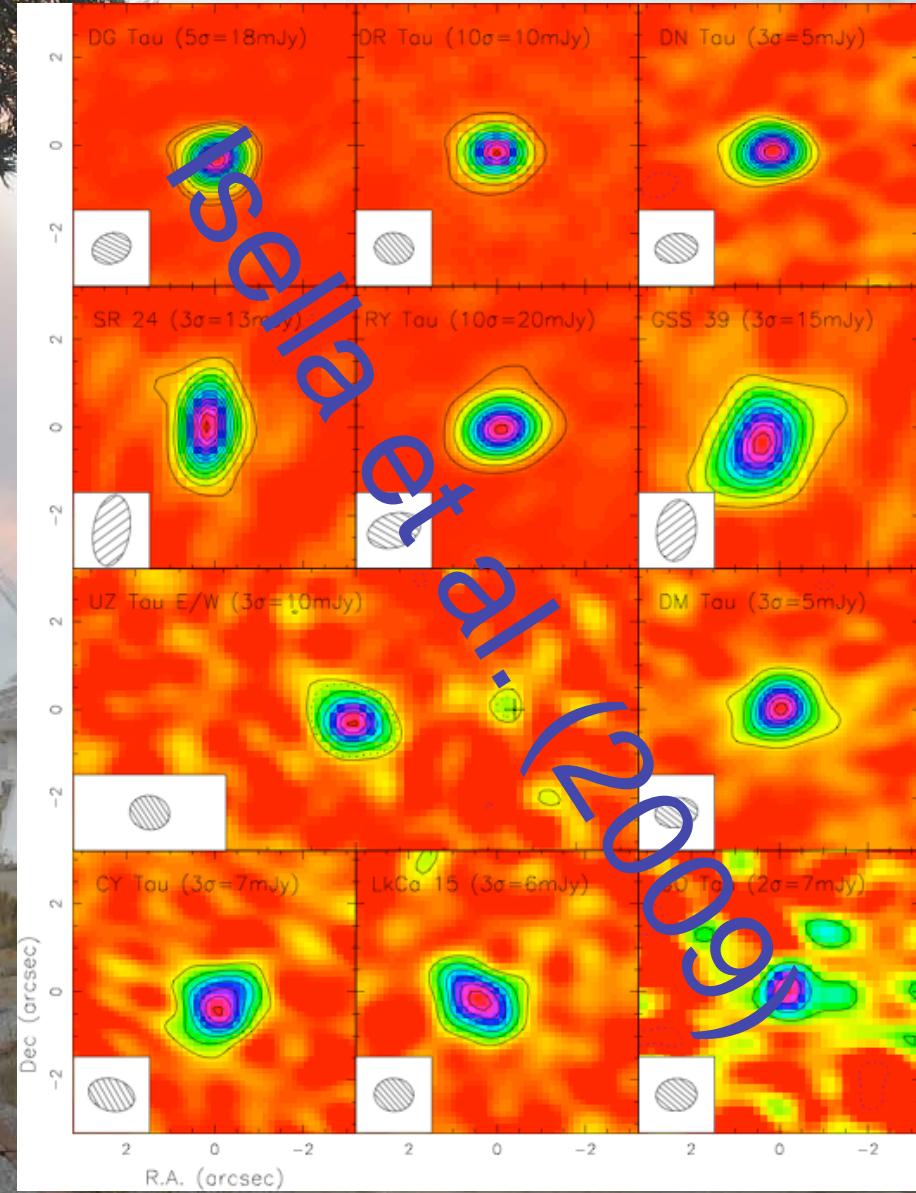
Disk formation and evolution



CARMA observations in the dust continuum at 1.3 mm

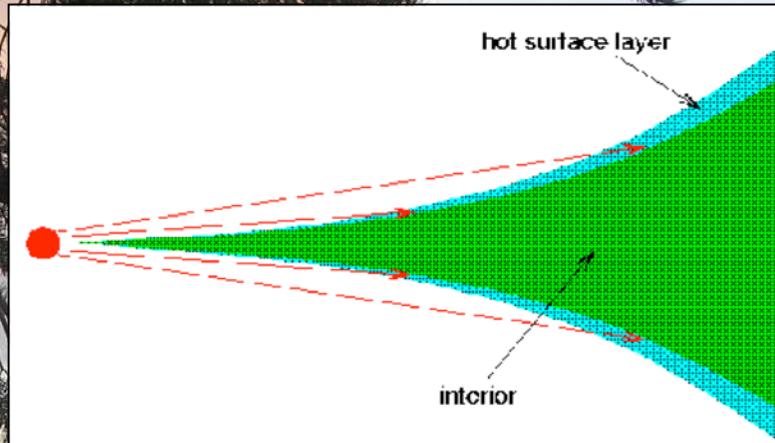
Isella, Carpenter, Sargent (2009)

| Object (1) | ST (4) | Log M _{acc} (10) | M _* (11) | Age (12) |
|---------------|-----------|------------------------------|------------------------|-------------|
| CY Tau | M1 | -8.52 | 0.80 | 3.0 |
| DG Tau | M0 | -6.39 | 1.10 | 1.0 |
| DM Tau | M1 | -8.32 | 0.70 | 8.0 |
| DN Tau | M0 | -8.97 | 1.00 | 2.0 |
| DR Tau | K7 | -6.68 | 1.30 | 0.8 |
| GO Tau | M0 | -8.33 | 0.87 | 10 |
| LkCa15 | K5 | -9.17 | 1.30 | 8.0 |
| RY Tau | G1 | -8.05 | 1.70 | 1.8 |
| UZ Tau E | M1 | -6.90 | 0.85 | 1.5 |
| GM Aur | K7 | -8.55 | 1.1 | 5.0 |
| GSS 39 | M1 | -7.43 | 0.90 | 1.0 |
| SR 24 | K6 | -7.13 | 1.38 | 1.0 |
| TW Hya | K8 | -9.38 | 0.9 | 15 |
| MWC 275 | A1 | -7.12 | 2.3 | 5.0 |



Similarity solution for the disk surface density

The observations are analysed using a 2 layers disk model (see e.g. Isella et al. 2007, Dullemond et al. 2001) adopting a disk surface density described by the similarity solution of the disk surface density shown below.



(Lynden-Bell & Pringle 1974)
(Hartmann et al. 1998)
(Hughes et al. 2008)

If the disk viscosity is $\nu \propto R^\gamma$

$$\Sigma(R, t) = \Sigma_t \left(\frac{R_t}{R} \right)^\gamma \times \exp \left\{ -\frac{1}{2(2-\gamma)} \left[\left(\frac{R}{R_t} \right)^{(2-\gamma)} - 1 \right] \right\}$$

$$R_t \equiv R_1 \left[\frac{T}{2(2-\gamma)} \right]^{1/(2-\gamma)}$$

$$\Sigma_t \propto \frac{M_d(0)}{4\pi R_1^2} T^{-5/(2(2-\gamma))}$$

$$M_{acc}(t) = \frac{M_d(0)}{2(2-\gamma)t_s} T^{-(5/2-\gamma)/(2-\gamma)}$$

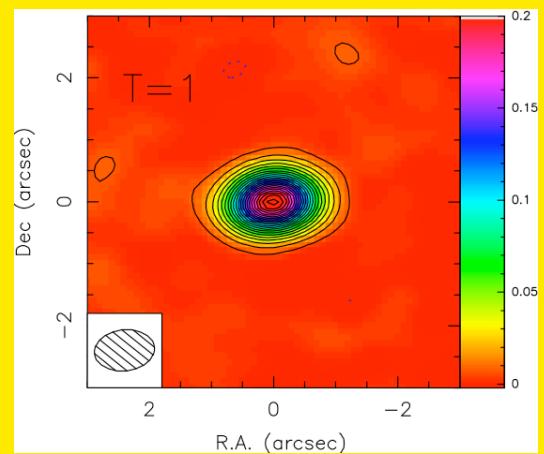
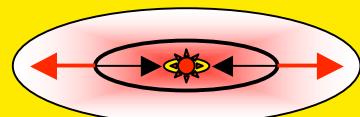
$$\bar{T} = t/t_s + 1$$
$$t_s = \frac{1}{3(2-\gamma)^2} \frac{R_1^2}{\nu_1}.$$

Disk expansion

$R_1 = 40 \text{ AU}$; $M_d(0) = 0.1 \text{ Msun}$; $\gamma = 0$; $k(1.3\text{mm}) = 0.01 \text{ cm}^2 \text{ g}$; $\text{incl}=45 \text{ deg}$; $d=140 \text{ pc}$

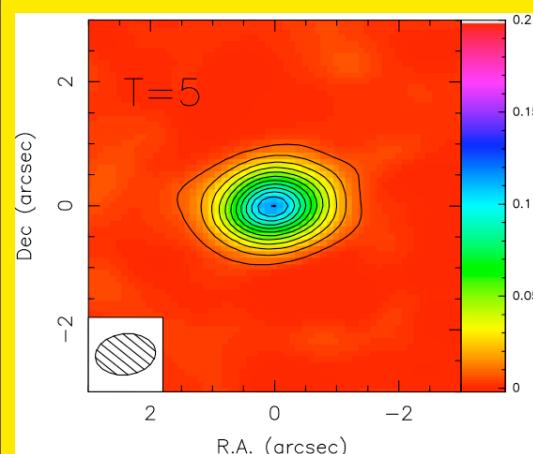
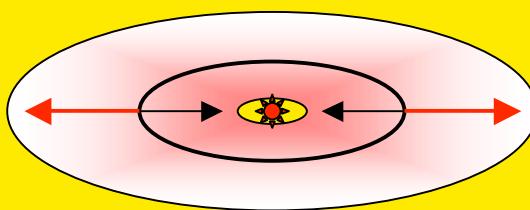
$$T = (t_d/t_s - 1) = 1$$

$R_t = 20 \text{ AU}$
 $R_d = 100 \text{ AU}$
 $\Sigma_t = 140 \text{ g/cm}^2$
 $F(1\text{mm}) = 284 \text{ mJy}$
 $F_{\text{obs}} = 270 \text{ mJy}$



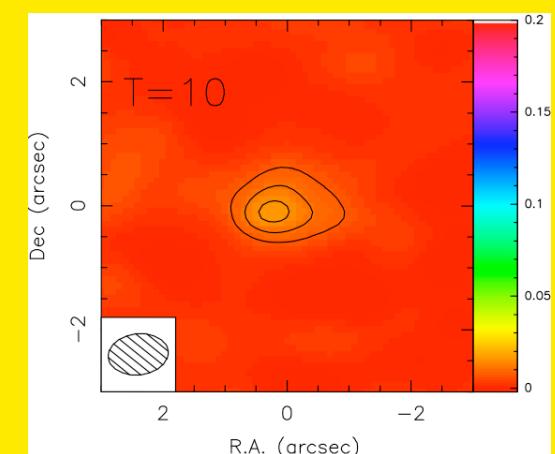
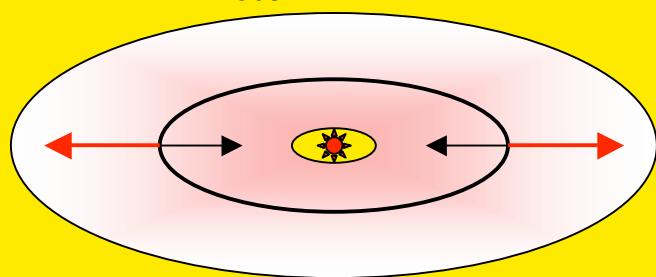
$$T = 5$$

$R_t = 45 \text{ AU}$
 $R_d = 230 \text{ AU}$
 $\Sigma_t = 19 \text{ g/cm}^2$
 $F(1\text{mm}) = 244 \text{ mJy}$
 $F_{\text{obs}} = 225 \text{ mJy}$



$$T = 10$$

$R_t = 80 \text{ AU}$
 $R_d = 340 \text{ AU}$
 $\Sigma_t = 1.4 \text{ g/cm}^2$
 $F(1\text{mm}) = 59 \text{ mJy}$
 $F_{\text{obs}} = 31 \text{ mJy}$

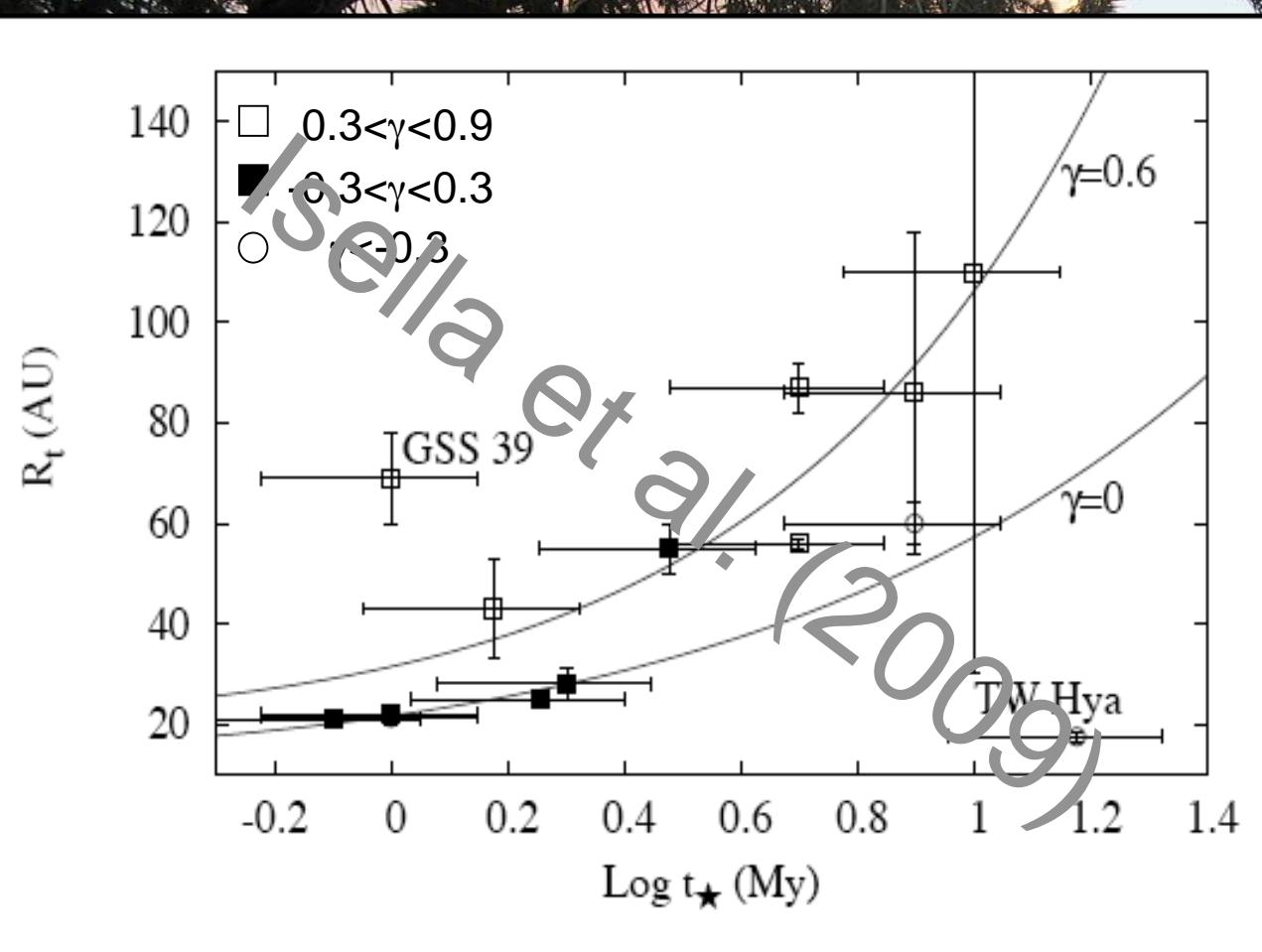


Model fitting results

MODEL FITTING RESULTS

| Object | i (deg) | PA (deg) | R_t (AU) | Σ_t (g/cm ²) | γ | $\log(M_d)$ (M_\odot) |
|---------|------------------|-------------|----------------|------------------------------------|----------------------|------------------------------|
| CY Tau | 54 ± 7 | 148 ± 8 | 55 ± 5 | 13 ± 3 | -0.3 ± 0.3 | -1.27 |
| DG Tau | 18 ± 10 | 15 ± 27 | 21 ± 1 | 490 ± 24 | -0.5 ± 0.2 | -0.73 |
| DM Tau | 25 ± 10 | 3 ± 70 | 86 ± 32 | 3.1 ± 1.6 | 0.8 ± 0.1 | -1.65 |
| DN Tau | 30 ± 10 | 61 ± 13 | 25 ± 3 | 13 ± 3 | 0.0 ± 0.5 | -1.84 |
| DR Tau | 37 ± 3 | 98 ± 5 | 21 ± 1 | 46 ± 2 | -0.3 ± 0.5 | -1.68 |
| GO Tau | 25 ± 25 | - | 110 ± 80 | 4 ± 2 | 0.7 ± 0.4 | -1.41 |
| LkCa15 | 58 ± 4 | 48 ± 4 | 60 ± 4 | 40 ± 7 | -0.8 ± 0.4 | -1.69 |
| RYTau | 60 ± 3 | 25 ± 3 | 25 ± 1 | 140 ± 10 | -0.1 ± 0.4 | -0.95 |
| UZTauE | 43_{-20}^{+10} | 70 ± 5 | 43 ± 10 | 8 ± 5 | 0.8 ± 0.4 | -1.62 |
| GM Aur | 51 ± 2 | 55 ± 2 | 56 ± 1 | 28 ± 1 | 0.4 ± 0.1 | -0.90 |
| GSS39 | 46 ± 7 | 111 ± 7 | 66 ± 10 | 7.1 ± 1.6 | 0.4 ± 0.2 | -1.37 |
| SR24 | 65 ± 7 | 48 ± 4 | 20 ± 2 | 120 ± 5 | 0.1 ± 0.2 | -1.02 |
| TW Hya | 10 ± 2 | 65 ± 3 | 17.5 ± 0.5 | 110 ± 2 | $-0.3_{-0.4}^{+0.1}$ | -1.54 |
| MWC 275 | 51 ± 2 | 125 ± 5 | 85 ± 3 | 4.7 ± 1.2 | 0.3 ± 0.1 | -1.35 |

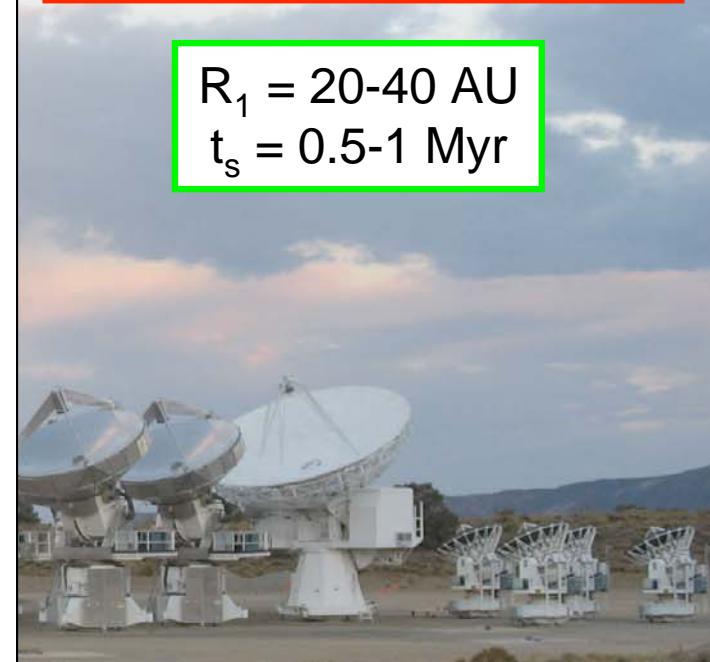
Disk evolution



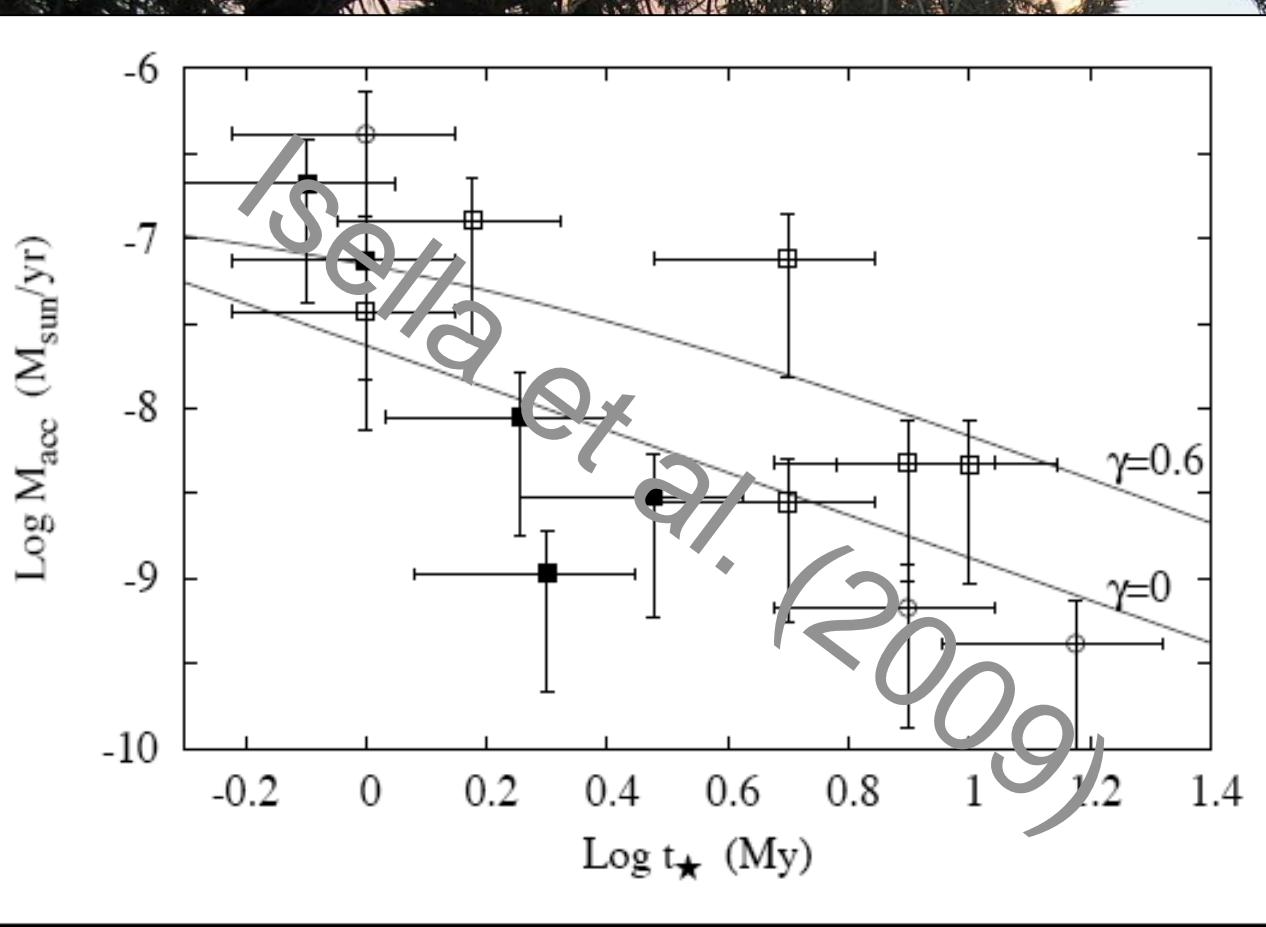
$$R_t = \frac{R_1}{2.1} \left(\frac{t}{t_s} + 1 \right)^{0.71} \text{ for } \gamma = 0.6,$$

$$R_t = \frac{R_1}{2} \left(\frac{t}{t_s} + 1 \right)^{0.5} \text{ for } \gamma = 0$$

$R_1 = 20\text{-}40 \text{ AU}$
 $t_s = 0.5\text{-}1 \text{ Myr}$



Disk evolution



$$R_t = \frac{R_1}{2.1} \left(\frac{t}{t_s} + 1 \right)^{0.71} \text{ for } \gamma = 0.6,$$

$$R_t = \frac{R_1}{2} \left(\frac{t}{t_s} + 1 \right)^{0.5} \text{ for } \gamma = 0$$

$R_1 = 20\text{-}40 \text{ AU}$
 $t_s = 0.5\text{-}1 \text{ Myr}$

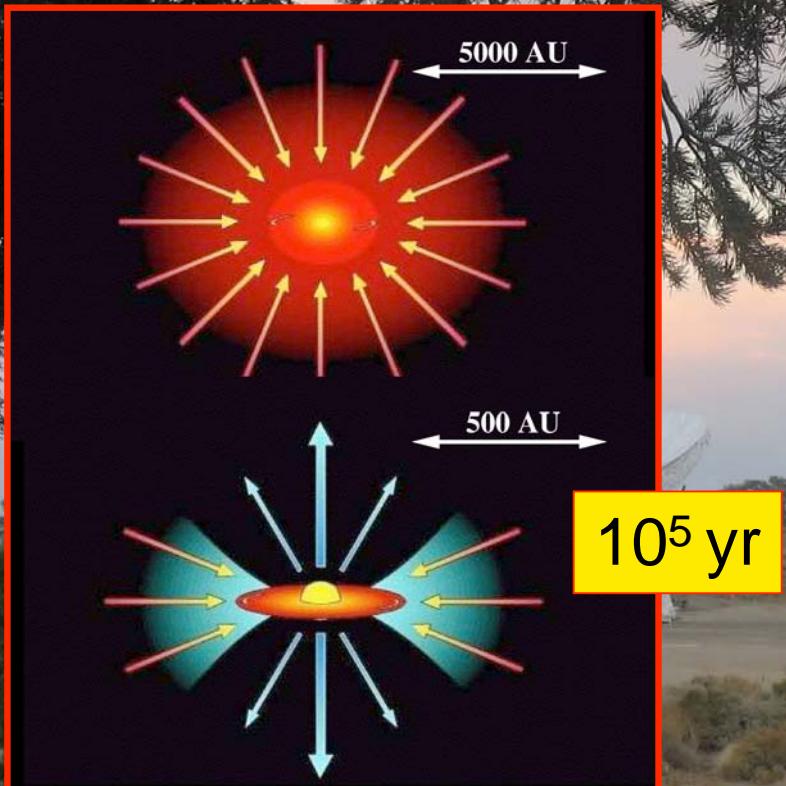
$$M_{acc} = \frac{M_d(0)}{2.8t_s} \left(\frac{t}{t_s} + 1 \right)^{-1.36} \text{ for } \gamma = 0.6$$

$$M_{acc} = \frac{M_d(0)}{4t_s} \left(\frac{t}{t_s} + 1 \right)^{-1.25} \text{ for } \gamma = 0.$$

$M_d(0) = 0.3\text{-}0.5 \text{ Msun}$
 $t_s = 0.1\text{-}1 \text{ Myr}$

Properties of the parent core

$$R_1 = 20-40 \text{ AU}$$
$$t_s = 0.1-1 \text{ Myr}$$



Shu et al. (1977)
Hueso & Guillot (2005)
Dullemond et al. (2006)

Under the following assumption :

1. Rigid rotation
2. Conservation of the angular momentum
3. Centrifugal radius $\sim 2R_1$
4. $M_{\text{core}} \sim M_\star$
5. $R_{\text{core}} \sim 0.1 \text{ pc}$
6. The disk does not significantly expand in the accretion phase
7. $T_{\text{core}} \sim 10 \text{ K}$
8. Density profile between $\rho=c$ and $\rho \propto r^{-2}$
9. The core collapse is not influenced by B , or B is negligible.

We derive specific angular momenta:

$$j = J / M = 3 \times 10^{-4} - 3 \times 10^{-3} \text{ km/s pc}$$

Which are similar to what measured by Goodman et al. (1993)

$$j = 2 - 8 \times 10^{-3} \text{ km/s pc}$$

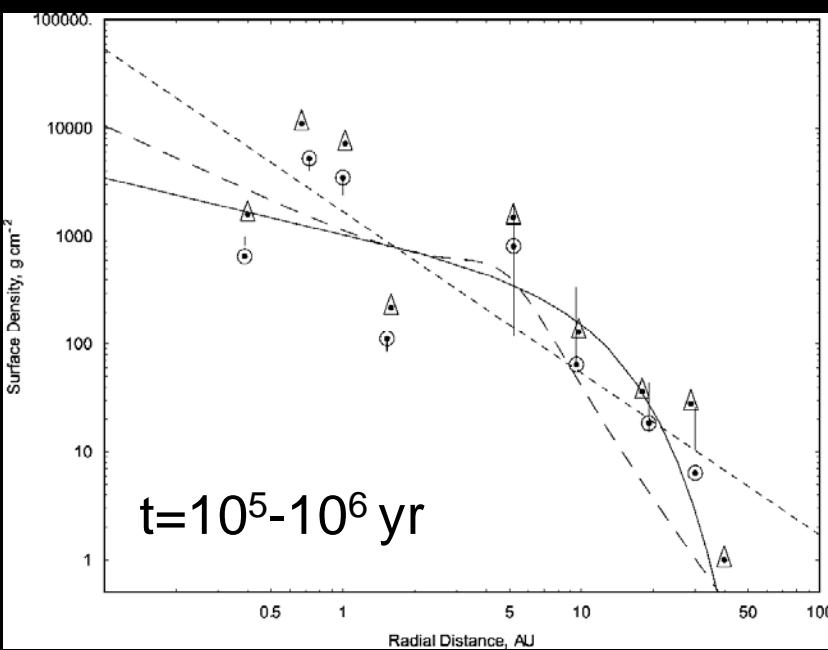
Similarity with the solar nebula

Davis (2005)

$$\Sigma(R) \cong 1.14 \times 10^3 \left(\frac{R}{1\text{AU}} \right)^{-1/2} \exp(-0.024 R^{3/2})$$

$j = 8.6 \times 10^{-6}$ km/spc Cox (2000)

$M = 0.02 M_{\text{sun}}$ Kusaka (1970)



$$\Sigma(R, t) = \Sigma_t \left(\frac{R_t}{R} \right)^\gamma \times \exp \left\{ -\frac{1}{2(2-\gamma)} \left[\left(\frac{R}{R_t} \right)^{(2-\gamma)} - 1 \right] \right\}$$

Solar nebula

$$\begin{aligned} \gamma &= 0.5 \\ R_t &= 6 \text{ AU} \\ \Sigma_t &= 340 \text{ g/cm}^2 \\ M &= 0.02 M_{\text{sun}} \\ j &= 8.6 \times 10^{-6} \text{ km/s pc} \\ F1mm &\sim 80 \text{ mJy} \end{aligned}$$

Obs. disk

$$\begin{aligned} \gamma &= -0.8 - 0.8 \\ R_t &= 18 - 110 \\ M &= 0.015 - 0.15 \\ j &= 3 \times 10^{-4} - 3 \times 10^{-3} \end{aligned}$$

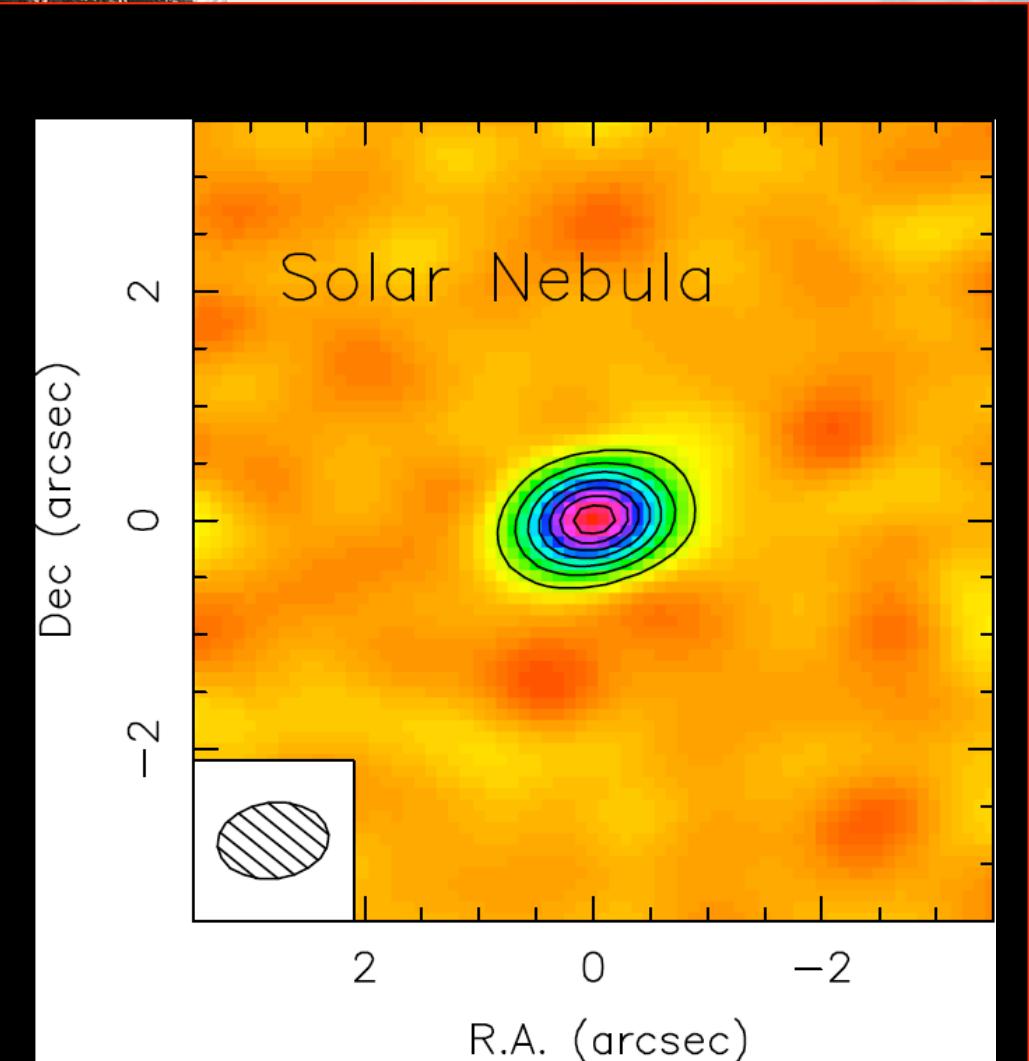
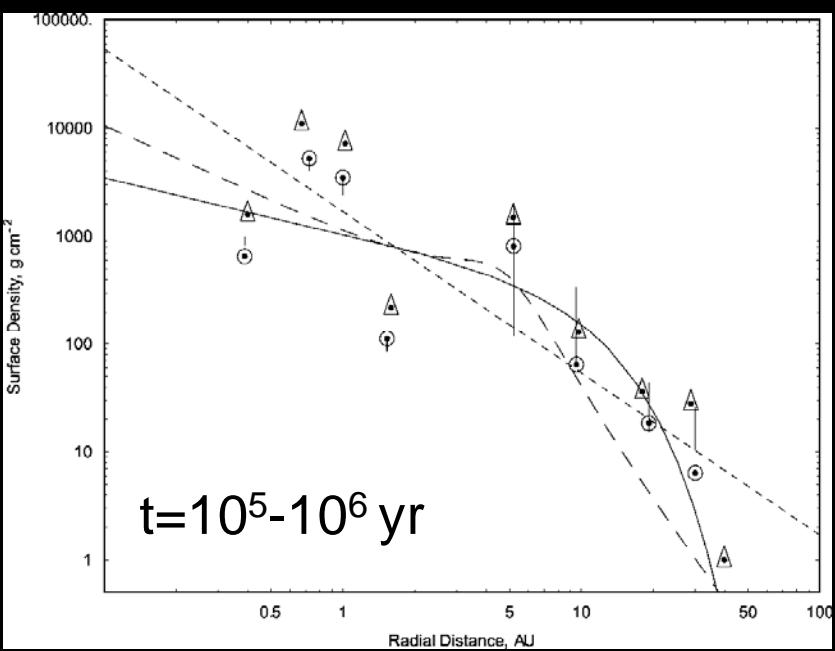
Similarity with the solar nebula

Davis (2005)

$$\Sigma(R) \cong 1.14 \times 10^3 \left(\frac{R}{1\text{AU}} \right)^{-1/2} \exp(-0.024 R^{3/2})$$

$j = 8.6 \times 10^{-6}$ km/spc Cox (2000)

$M = 0.02M_{\text{sun}}$ Kusaka (1970)



Conclusions

1. The observed disks lay on an evolutionary sequence and expand from 20 to 100 AU in about 10 Myr
2. The initial disk radius is between 20-60 AU
3. The viscous time scale is 0.1-1 Myr
4. The initial disk radius leads to angular momenta similar with the observations of low mass core
5. The solar nebula has a radius and an angular momentum at least a factor 3 and a factor 100 smaller than the observed disks.

Thank you !