Accretion in Protoplanetary Disks (conventional and transitional)
Pre-main-sequence stars accrete

Blue excess powered by accretion

Calvet & Gullbring 98
Muzerolle et al. 05
Hartmann et al. 06
Herczeg & Hillenbrand 08
Transitional Disks

\[ \tau_{10\mu m} \sim 20 - 200 \]

Calvet et al. 05
Brown et al. 08
Holes are not empty

- Mild near-IR excesses in some sources
  \[ \tau_{10\mu m} \sim 0.002 - 0.05 \]

- Many accrete
  \[ \dot{M} \sim 0.1 \times \text{median T Tauri} \]

- Inner molecular gas disks
  \[ \Sigma(H_2) > 0.1 \text{ g cm}^{-2} \text{ at } \sim 0.2\text{AU} \]
Puzzle: $1000 \times$ smaller $\tau$ but comparable $\dot{M}$

Theories:

- Grain growth
- Clearing by companion

Not mutually exclusive
Clearing by companion (Transitional = Circumbinary)

**Binary separation**
- $a_{\text{binary}} \approx 8$ AU
- $\approx$ Hole radius
- $a_{\text{rim}} \approx 10$ AU

- $\tau_{10\mu m} < 0.002$

- $\dot{M}_* < 10^{-10} M_\odot/\text{yr}$

- No CO gas out to 2 AU

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CoKu Tau/4

Ireland & Kraus 08 (Keck AO)
Artymowicz & Lubow 94

D'Alessio et al. 05
Najita et al. 07
Blake, Salyk, personal comm.
Clearing by companion (Transitional = Circumbinary)

Mass can still accrete onto star (viscosity / pressure / eccentricity / mass ratio)

Fast flow (up to radial free-fall) implies low surface density

Resolves the puzzle of similar $\dot{M}$ but 1000x lower optical depth

Hanawa et al. 06
Clearing by multiple planets

Simulation of 4-planet system in viscous disk

Right sign, too small magnitude — unless dust is also depleted
Planets inside the hole do not explain disk accretion

Outer disk must still be viscous
Magneto-rotational instability (MRI) = linear instability which drives turbulence in weakly magnetized, outwardly shearing flows

Requirements

1. Magnetic flux freezing (defeat Ohmic dissipation)
   (Fleming, Stone, & Hawley 00)

2. Good neutral-ion coupling (defeat ambipolar diffusion)
   (Blaes & Balbus 94; Hawley & Stone 98; Bai & Stone 11)

\[
Re_M \equiv \frac{c_s h}{\eta} \propto \frac{n_e}{n} > Re_M^* \approx 10^2 - 10^4
\]

\[
Am \equiv \frac{n_i \langle \sigma v \rangle_{in}}{\Omega} > Am^* \approx 1-100
\]
Surface Layer Accretion by the MRI

Sources of ionization

1. Cosmic rays
2. Stellar X-rays
3. Stellar UV

Glassgold et al. 97
Sano et al. 00
Ilgner & Nelson 06
Bai & Goodman 09
Turner et al. 10
Perez-Becker & EC 11a
Perez-Becker & EC 11b
Galactic cosmic rays blocked by stellar wind

**Fig. 1.** The omnidirectional fluxes as a function of kinetic energy of solar protons with $R_0 = 100$ MV (the dot-dashed line) and of GCR protons in the solar system (using equation (1)), for no modulation ($M = 0$) and for three levels of modulation: solar maximum ($M = 950$ MeV), the 11-year average ($M = 550$ MeV), and solar minimum ($M = 375$ MeV).

**Fig. 2.** Top curve is cosmic ray flux from the neutron monitor in Climax, Colorado (1953–1996). Middle curve is annual mean variation in cosmic ray flux as measured by ionization chambers (1937–1994). The neutron data have been normalized to May 1965, and the ionization chamber data have been normalized to 1965. Bottom curve is the relative sunspot number.

Svensmark 98
Reedy 87
Pre-main sequence stars are X-ray luminous

Preibisch et al. 05
Chandra COUP Orion survey
\[ \text{H}_2^+ + \text{H}_2 \rightarrow \text{H}_3^+ + \text{H} \]

\[ \text{H}_3^+ + \text{CO} \rightarrow [\text{HCO}^+] + \text{H}_2 \]

\( \beta_t \sim 10^{-9} \text{ cm}^3 \text{ s}^{-1} \)

\( \beta_{\text{diss}} \sim 3 \times 10^{-7} \text{ cm}^3 \text{ s}^{-1} \)

\( \beta_{\text{rec}} \sim 4 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1} \)

Oppenheimer & Dalgarno 74
Umebayashi & Nakano 83
Glassgold et al. 86
Polycyclic Aromatic Hydrocarbons (PAHs)

PAH abundance ~ 0.01-10 ppb H₂

(in diffuse ISM ~1 ppm H)

Allamandola et al. 99
Geers et al. 06
Charge Balance

\[
\text{X-rays} \Rightarrow \text{HCO}^+, \text{Mg}^+ \quad \rightarrow \quad \text{e}^- \quad \text{grain}^- (1 \, \mu\text{m}) \\
\quad \text{PAH}^- (6 \, \text{Å})
\]
Ohmic dissipation

Ambipolar diffusion

$X$-ray ionization only

Field may be frozen to plasma ✔
But ions decoupled from neutrals ✗

region allowed by PAHs

(0.01-10 ppb H$_2$)

$\alpha = 30$ AU
$x_M = 10^{-8}$

Perez-Becker & EC 11a
see also Mohanty, Ercolano, and Turner 11, in prep.
MRI with ambipolar diffusion

\[ \alpha \approx \frac{1}{2\beta} \]
and \( \beta_{\text{min}}(\text{Am}) \)

\[ \Rightarrow \alpha_{\text{max}}(\text{Am}) \]

\[ \alpha_{\text{max}}(\text{Am}) \text{ and } \text{Am}(\Sigma) \]

\[ \Rightarrow \dot{M} \]

X-rays + PAHs = weak accretion

\[ \dot{M} \text{ [M}_\odot/\text{yr}] \]

Conventional Disk

Observed Rates

X-ray

Perez-Becker & EC 11ab

Kunz & Balbus 94
Hawley et al. 95
Desch 04
Pessah 10
Bai & Stone 11
Far-Ultraviolet (FUV) Ionization

$L_{\text{FUV}} \sim 10^{30}-10^{32}$ erg/s

HST + FUSE
(Bergin et al. 03; Herczeg et al. 02)
FUV Ionization

Strömgren slab

\[ \frac{L_{\text{FUV}}}{h \nu 4\pi a^2} \cdot \frac{h}{a} \sim n_i n_e \alpha_{\text{rec}} \cdot h \]

\[ n_i = n_e = f n_{\text{H}_2} \text{ (cosmic abundance)} \]

\[ \Rightarrow \Sigma_{\text{MRI}} \sim n_{\text{H}_2} \mu h \]

\[ \sim 0.1 \left( \frac{L_{\text{FUV}}}{10^{30} \text{ erg/s}} \right)^{1/2} \left( \frac{10^{-5}}{f} \right) \text{ g/cm}^2 \]

Perez-Becker & EC 11ab
\[
\text{Am} = (x_{\text{CII}} + x_{\text{SII}}) \beta_{\text{tot}} / \Omega
\]

\[
10^{-5} \quad 10^{-3} \quad 10^{-1}
\]

\[
\Sigma [\text{g cm}^{-2}]
\]

\[
10^{12} \quad 10^{10} \quad 10^{8} \quad 10^{6} \quad 10^{4} \quad 10^{2}
\]

\[
n_{\text{tot}} [\text{cm}^{-3}]
\]

FUV ionization only

Field is frozen to plasma ✔

Good ion-neutral coupling ✔

robust against PAHs

( PAHs included at maximum abundance)

sensitive to dust-to-gas ratio

( vertical settling of dust)

\[
N_{T=1} = 10^{24} \text{ cm}^{-2} \quad [S/H] = -1
\]

\[
N_{T=1} = 10^{22} \text{ cm}^{-2} \quad [S/H] = 0
\]

\[
a = 3 \text{ AU}
\]

Perez-Becker & EC 11b
Hall effect not important

\[ \chi \]

\[ N_{VSG}^{\tau=1} = 10^{24} \text{ cm}^{-2} \]

\[ \epsilon = 1/30 \]

\[ \alpha \text{ [AU]} \]
FUV-ionized surface layers can reproduce accretion rates at large radius but not small radius.

\[ \dot{M} \sim 2 \times 3\pi \Sigma^* \nu \]

\[ \sim 6\pi \Sigma^* \alpha \frac{kT}{\mu\Omega} \]

Conventional Disk

Observed Rates

FUV

X-ray

\( \dot{M} \) [\( \text{M}_\odot/\text{yr} \)]

\( \alpha \) [AU]
Ion recombination time vs. dynamical time

Turbulent mixing of plasma to greater depths can extend MRI-active layer

Ilgner & Nelson 06b
FUV-driven MRI in Transitional Disks

Rim accretion rate reproduces observations

Transport problem at small radii could be solved by companions

Murray-Clay & EC 07
Kim et al. 09
Perez-Becker & EC 11ab
Zhu et al. 11
Extra Slides
Is the required field super-equipartition?

On the one hand, the field must be strong enough:

\[
\dot{M} \sim \langle B_r B_\phi \rangle h/\Omega
\]

\[
\Rightarrow \min B > 1 \text{ G} \left( \frac{\dot{M}}{10^{-8} M_\odot/\text{yr}} \right)^{1/2} \left( \frac{r}{\text{AU}} \right)^{-5/4}
\]

\[
\beta \equiv \frac{P_{\text{gas}}}{P_{\text{mag}}} = \frac{8\pi n k T}{B^2} < 1 \left( \frac{\Sigma}{0.1 \text{ g/cm}^2} \right) \left( \frac{10^{-8} M_\odot/\text{yr}}{\dot{M}} \right) \left( \frac{r}{1 \text{AU}} \right)
\]

On the other hand the field cannot be too strong: \( \beta > 1 \)

Possible for \( r > 1 \text{ AU} \)

e.g., Bai & Goodman 09
Inside-Out Accretion of Transitional Disks
Measuring dust layer thicknesses
(e.g., occulting circumbinary disk of KH 15D)

- Dust thickness $h/r \leq R_\odot/r \sim 10^{-2}$
- Inclination $I \sim 10^{-1}$
- Warp $\Delta I / I < 10^{-1}$ (self-gravity)
  $\Delta I / I \sim -10^{-1}$ (gas pressure)
EC & Murray-Clay 07

X-ray driven MRI

\[ \dot{M} \sim \frac{12\pi\alpha N^* a_{\text{rim}}^2 (kT^*)^{3/2}}{GM_* \mu^{1/2}} \]

For constant \( \alpha \),
\[ \Sigma_{\text{gas}} \sim 10 - 100 \, \text{g cm}^{-2} \]
@ 1 AU

- 10-100 x lower density than MMSN
- Satisfies CO lower limits
- Type II migration slower than usual

But cannot explain origin of hole

Rim controls accretion rate

For constant \( \alpha \),
\[ \Sigma_{\text{gas}} \sim 10 - 100 \, \text{g cm}^{-2} \]
@ 1 AU

- 10-100 x lower density than MMSN
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But cannot explain origin of hole

Kim et al. 09
Spitzer Cha I
Inner disk fills in

Initial profile set to analytic steady state; note robustness of inner disk

\[ \dot{M}_{\text{inner}} \approx 0.1 \dot{M}_{\text{outer}} \]

But planetary migration reduces clearing efficiency
Short-lived solution \( t_{\text{diffusion}} \sim r^2 / v \sim 10^4 \) orbits
Perhaps multiple planets can help
But deeper correlations may exist ...

Same $\dot{M}_* \propto M_*^2$

holds for non-transitional disks

How to keep the inner hole clear of dust?

Leaked dust might concentrate at $a \ll a_{\text{rim}}$,
restoring $\tau_{10\mu m} > 1$:

Gapped ("pre-transitional") disk possible

Kim et al. 09
Inside-Out MRI

\[ M_{\text{rim}} = 2\pi a_{\text{rim}} \times 2h \times N^* \mu \]

\[ t_{\text{diff}} \sim a_{\text{rim}}^2 / \nu \]

\[ \nu = \alpha c_s h \]

MRI simulations give \(10^{-4}-10^{-1}\)

\[ \dot{M} \sim \frac{M_{\text{rim}}}{t_{\text{diff}}} \sim \frac{12\pi \alpha N^* a_{\text{rim}}^2 (k T^*)^{3/2}}{G M_* \mu^{1/2}} \]

\[ L_X \sigma_X e^{-N^* \sigma_X} f_{\text{heat}} n \sim \Lambda_{\text{CO}}(T^*) \]

photo-ionization heating  CO ro-vibrational cooling

Glassgold, Najita, & Igea 04

EC & Murray-Clay 07
Keeping inner hole clear of dust

Aerodynamic filter

- $\nabla P$ points in

Gas is super-Keplerian
Dust is Keplerian $\therefore$ dragged out

Radiation pressure

$t_{\text{blow}} \sim \frac{1}{\Omega} \left( \frac{1}{\Omega t_{\text{stop}}} \right)$

Rice et al. 06
EC & Murray-Clay 07

- Filtering is inefficient
- Leaked dust might concentrate at $a \ll a_{\text{rim}}$, restoring $\tau_{10\mu m} > 1$:
  Gapped (“pre-transitional”) disk possible
“Pre-Transitional” Gapped Disks

Espaillat et al. 07

Espaillat et al. 08

LkCa 15

1600 K blackbody fit to excess

0.12 AU

< 0.15 AU

46 AU
But deeper correlations may exist ...

\[ a_{\text{rim}} \propto M_*^2 \]

Why?

And does similar relation hold for debris disks?

Same \[ \dot{M}_* \propto M_*^2 \] holds for non-transitional disks
Sustaining MRI at a \(<< a_{\text{rim}}\)

Scale to minimum temperature (blackbody)

\[
T = 50 \text{ K } a_{\text{AU}}^{-3/4} \dot{M}^{1/4} \hat{T} \quad (\hat{T} > 1)
\]

\[
N_{\perp} = 10^{25} \text{ cm}^{-2} a_{\text{AU}}^{-3/4} \alpha_{0.01}^{-1} \dot{M}^{3/4} \hat{T}^{-1}
\]

ζ (Igea & Glassgold 99)

\[
\zeta \approx 90 @ 1 \text{ AU} \quad \text{vs.} \quad \dot{A}_m^* \approx 100
\]

Am \approx 120 @ 0.1 \text{ AU}

∴ Even midplane is MRI-active
Outer disk photoevaporation starves inner disk

Evolution of surface density: $M_*=1M_\odot$, $\phi=10^{42}$ s$^{-1}$

$t=0$
$t=6$ Myr
$t=6.02$ Myr
$t=6.18$ Myr

Properties of inner hole sources

Alexander 08
Estimating \( N^* \)

\[
x_e = \frac{n_e}{n} = x_{\text{e, met, tot}} = 10^{-6}
\]

\[
N (\text{cm}^{-2})
\]

\[
\beta_{\text{gr}} + \left( \frac{\beta_{\text{t}}}{\beta_{\text{rec}}} \right) x_e^2 + \left( \frac{\zeta}{n \beta_{\text{diss}}} \right) \left( \frac{\beta_{\text{t}}}{\beta_{\text{rec}}} \right) x_e - \left( \frac{\zeta}{n \beta_{\text{diss}}} \right) \left( \frac{\beta_{\text{gr}} + x_{\text{met, tot}}}{\beta_{\text{rec}}} \right) x_e - \frac{\beta_{\text{t}}}{\beta_{\text{rec}}} \left( \frac{\zeta}{n \beta_{\text{diss}}} \right)^2 = 0
\]

\[
n = \frac{2N}{a_{\text{rim}}}
\]

\[
\zeta = \frac{L_X \sigma_X e^{-N \sigma_X \xi_{\text{secondary}}}}{4\pi E_X a_{\text{rim}}^2}
\]
Theories for transitional disks are not mutually exclusive

Planets + Grain growth + MRI + Radiative / aerodynamic blowout

smaller $\dot{M}_*$ smaller $\tau_{10\mu m}$ origin of viscosity smaller $\tau_{10\mu m}$

Multiple planets might explain factor of 10 and prolong Type II migration

Imperfect clearing can lead to gapped disks (e.g. LkCa 15)
X-ray ionized MRI-active surface layer

At 3 AU,
Am \sim 1 \ (\alpha \sim 10^{-3})

\Sigma_{\text{active}} \sim 1 \ \text{g cm}^{-2}
X-ray ionized MRI-active surface layer

At 30 AU,
\[ \text{Am} \sim 1 \left( \alpha \sim 10^{-3} \right) \]
\[ \Sigma_{\text{active}} \sim 0.1 \text{ g cm}^{-2} \]
if no cosmic rays
\[ \Sigma_{\text{active}} \sim 10 \text{ g cm}^{-2} \]
if cosmic rays
Far-UV (912-1100 Å) ionized MRI-active surface layer

- $\text{H}_2 + h\nu \rightarrow \text{H} + \text{H}$
- $\text{H} + \text{H} + \text{grain} \rightarrow \text{H}_2 + \text{grain}$
- $\text{C} + h\nu \rightleftharpoons \text{C}^+ + e^-$
- $x_{\text{CO}} = 10^{-4}$

At 3-30 AU,

- $\text{Am} > 10^2$ ($\alpha \sim 0.1$)
- $\Sigma_{\text{active}} \sim 0.01 \text{ g cm}^{-2}$
Planet Clearing

Initial $\Sigma_{\text{inner}} / \Sigma_{\text{outer}} = 0.01$

Run duration $= 100$ orbits
$\ll$ Viscous time $t_{\text{diff}} \sim 10000$ orbits

$$t_{\text{diff}} \sim \frac{a_{\text{rim}}^2}{\nu}$$

$$\nu = \alpha c_s h$$

0.004 (assumed)

$\therefore$ Hole in simulation reflects assumed initial conditions
<table>
<thead>
<tr>
<th></th>
<th>( \Sigma_{\text{active}} ) (g/cm(^2))</th>
<th>( \alpha )</th>
<th>( T ) (K)</th>
<th>( \dot{M} ) (M(\odot)/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 AU X-ray</td>
<td>1</td>
<td>10(^{-3})</td>
<td>80</td>
<td>10(^{-11})</td>
</tr>
<tr>
<td>3 AU Far-UV</td>
<td>0.01</td>
<td>0.1</td>
<td>300</td>
<td>4 \times 10(^{-11})</td>
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<tr>
<td>30 AU X-ray+CR</td>
<td>0.1-10</td>
<td>10(^{-3})</td>
<td>30</td>
<td>10(^{-11})-10(^{-9})</td>
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<tr>
<td>30 AU Far-UV</td>
<td>0.01</td>
<td>0.1</td>
<td>300</td>
<td>10(^{-9})</td>
</tr>
</tbody>
</table>
Protoplanetary Disks

disk mass $\sim 0.001-0.1$ stellar mass