Non-planet mechanisms for clearing and sculpting discs

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- Barbara Ercolano (IOA -> LMU)

Hope to convince you:

- (Xray) photoevaporation now well understood
- Significant factor in disc evolution
- (Probably) responsible for ultimate clear out of protoplanetary discs
- En route, produces structures with properties overlapping those produced by planets

Are observed structures (gaps, holes) pure dust phenomena?

Probably not….

- Sharp edge due to radiation pressure?

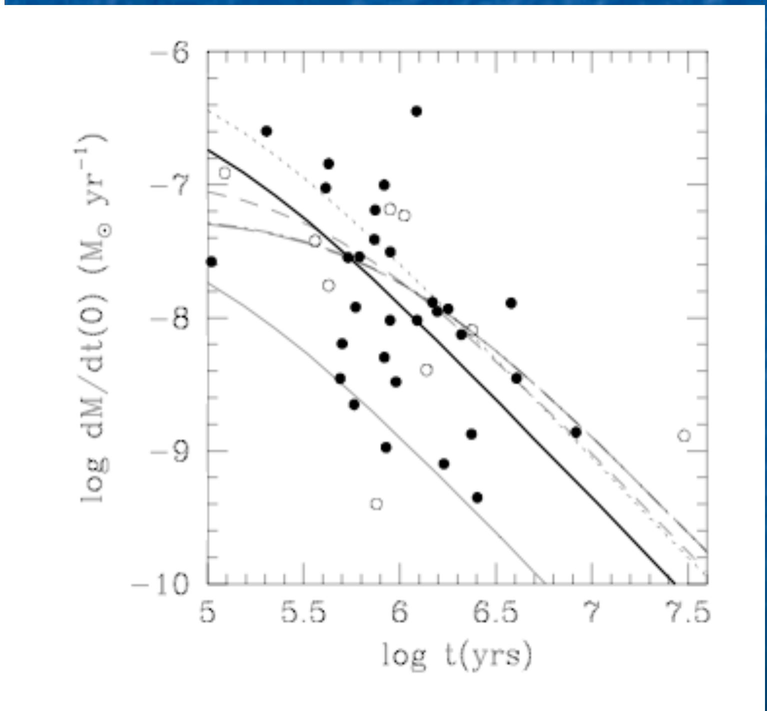
See Dominik & Dullemond 2011

- Sharp edge due to photophoresis (Krauss et al 2007)?

Hard to suppress small dust production

Do disccs clear via viscous accretion?

- UV excess => do accrete at rates ~ M_disc/age ✔



(Lynden-Bell & Pringle 1974,
Hartmann et al 1998)

Phenomenological description as due to action of (pseudo) viscosity e.g for $\nu \sim R$ (=> $\Sigma \sim 1/R$) get similarity solution:

$$M = M_{in} \left(1 + t / t_{\nu in} \right)^{-1.5}$$

- Far too slow decline at late times….

Need extra gas clearing mechanism

To clear discs within ~ 5 Myr, to make observed hole/gap structures…

- Planets ?
- Photoevaporation ?
- Clearing by MRI driven winds?

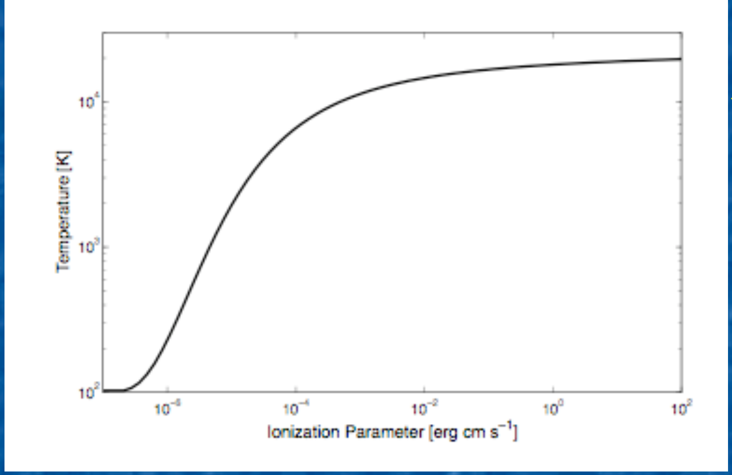
Suzuki et al 2010: inner hole forms very early (0.1 A.U. @ 10^5 years, 1 A.U. @ 10^6 years)

← Halts accretion onto star from very early times also….

Actually destination of `wind' unclear (doesn't attain escape velocity….)

Key facts for understanding Xray photoevaporation

- Temperature of Xray heated gas set by $\xi = Lx/nr^2$,



←←←← max T is 1-2 x 10^ 4 K

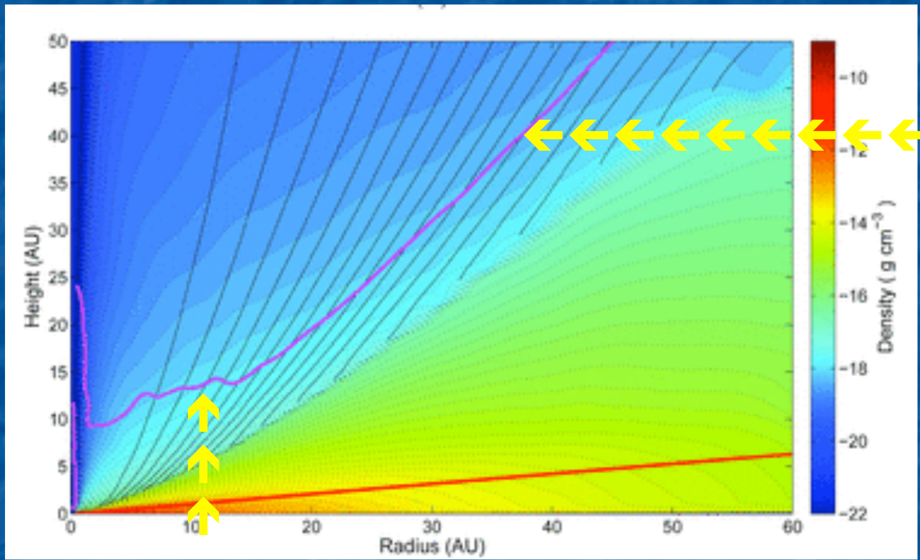
- In a Parker✪ wind, sonic transition occurs at radius where

$$c_s^2 \approx \frac{GM_*}{2R}$$

✪ = isothermal , spherical

Results of radiation hydrodynamical modeling of Xray photoevaporation (Owen et al 2010, 2011b)

T ~ 2000 K



sonic surface where

$$c_s^2 \approx \frac{GM_*}{2R}$$

still holds approximately

T ~ 10,000 K

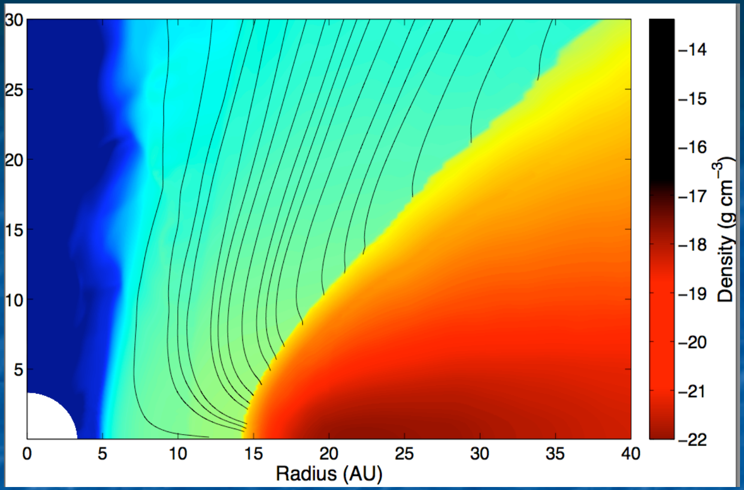
- R => T and (beyond 10 A.U.) $\xi = Lx/nr^2$ fixes n and hence mass flux

Result:

$$\dot{M}_w(M_*, L_X) = L_X \sqrt{\frac{8k_B\pi^2}{\mu m_h}} \int_0^\infty \mathrm{d}T_{\rm esc} \frac{T_{\rm esc}^{-1/2}}{f^{-1}(T_{\rm esc}/2)}$$
$$\approx \quad 8 \times 10^{-9} \left(\frac{L_X}{1 \times 10^{30}\,\mathrm{erg\ s^{-1}}} \right) \mathrm{M_\odot\ yr^{-1}}$$

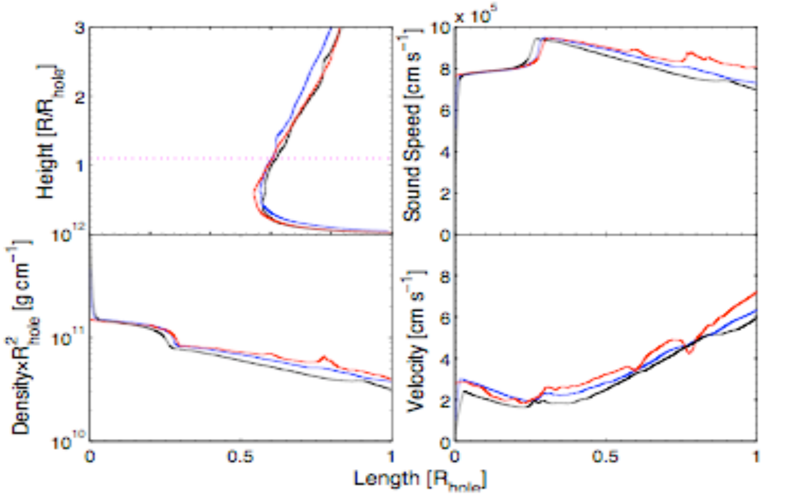
- Proportional to L_x
- Independent of M_*
- Doesn’t depend on properties of underlying disc!

Discs with inner holes



Owen et al 2010

As vary R_hole , topology of innermost streamline and variation of c_s and u with scaled distance along streamline is invariant

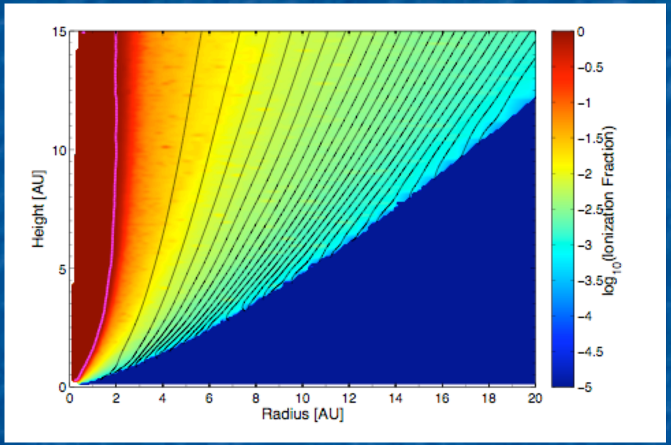


===> photoevaporation rate INDEPENDENT of inner hole size (~ 10^{-8} solar mass/yr for L_X - 10^30 erg/s)

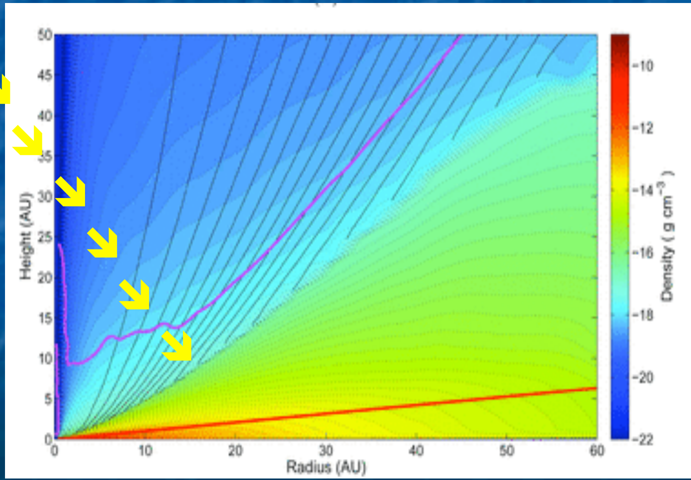
Owen et al 2011b)

What about other radiation sources?

- EUV? Can’t penetrate Xray wind



- FUV? Within 100 A.U. only heats below Xray sonic surface - doesn’t change mass loss rates



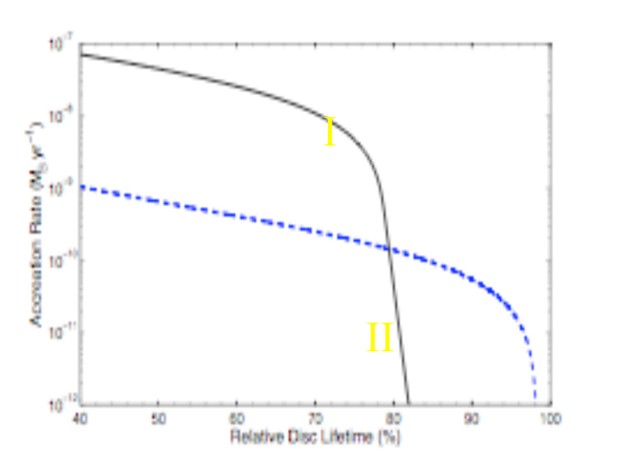
Owen et al 2011 b)

(But may affect structure of subsonic region: See Gorti & Hollenbach 2004,2008,2009)

ALSO MAY BE IMPORTANT MASS LOSS MECHANISM AT > 100 A.U.

Combining photoevaporation with viscous evolution:

↖ Constant L_X



Owen et al 2011a)

Initial →

75% total lifetime →

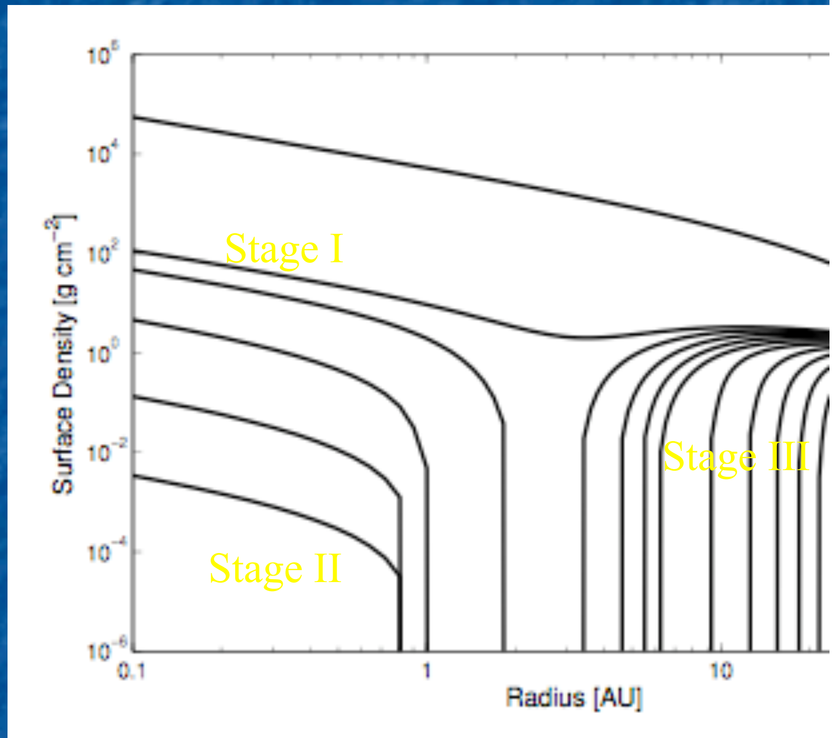
76% total lifetime →

77% total lifetime →

78 % total lifetime →

79 % total lifetime →

Etc.



↑ 76 % total lifetime ↑ 80%

Four stage evolution:

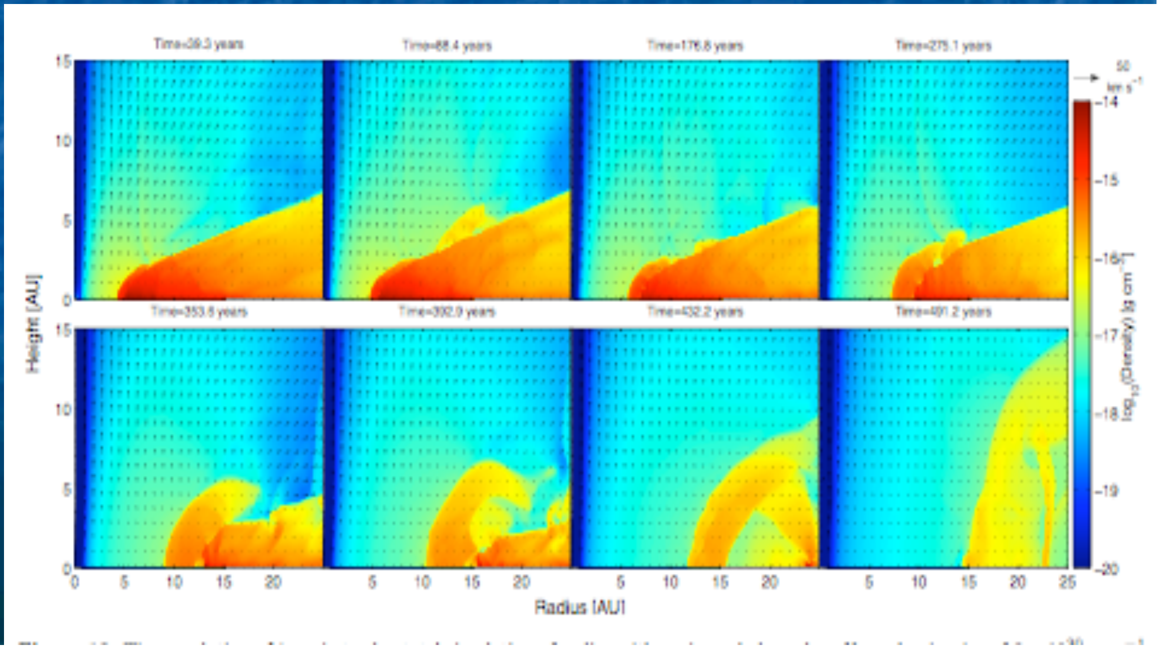
- I Viscous dominated
- II Draining inner hole ← Accreting, dust poor (migration), <10 AU
- III Outer disc clearing ← Empty inner hole, > 10 AU
- IV Thermal sweeping ← NEW

Stage IV: thermal sweeping

- Once Xrays penetrate a radial distance ~ H into disc, heated gas evaporates vertically in `plume flow'
- Residual disc clears on ~ dynamical time of inner rim (~ 10s of A.U.)

Sets in when column density at inner rim is ~ 0.5 g/cm^2

Remove few -> 10 Jupiter masses of gas



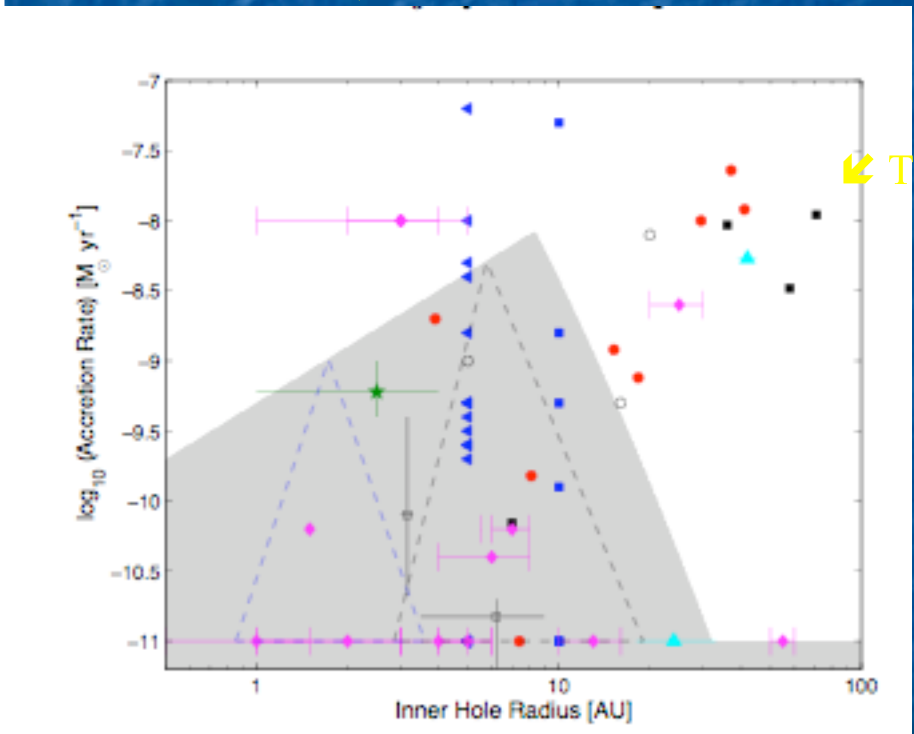
Thermal sweeping limits lifetime of non-accreting hole stage (stage III)

- Fraction of lifetime spent with hole (stage II + III) ~ 10%
- Fraction of lifetime spent with `transparent accreting' hole (stage II) ~ 5%
- Fraction of lifetime spent with non-accreting hole (stage III) ~ 5%

Which inner hole sources could be due to photoevaporation?

Around half (those in shaded region)

Owen et al 2011b)



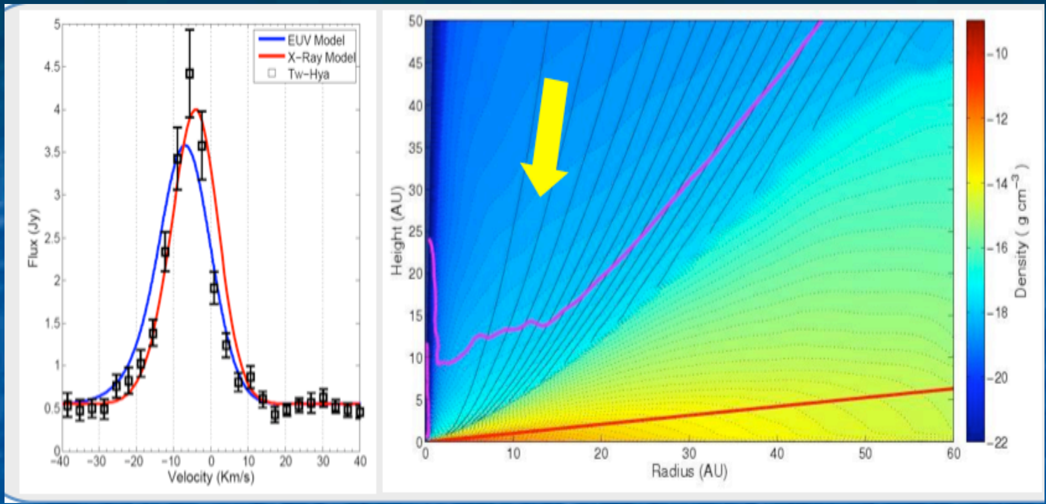
↙ These can't

↓ These are upper limits

- Systems evolve ↘ as inner holes drain
- Initial Mdot depends on L_X
- Initial radius depends on M_*

Cyan = Brown et al 09, blue = Cieza et al 10, Black open - Ercolano et al 09, Black filled = Espaillat et al 08,09, red= Kim et al 09, magenta - Merin et al 10, green = Najita et al 10

Evidence for Xray photoevaporation



Xray:Ercolano & Owen 2010
EUV: Alexander 2008

- Both Xray and EUV photoevaporation explain line profiles of NeII 12.8 μm

Cf observed profiles for TW Hydra, Pascucci & Sterzik 2009

Pascucci et al 2011

- Only Xray photoevaporation explains low velocity (~ 5 km/s) component of OI 6300 in T Tauri stars (cf EUV models: Font et al 2004)

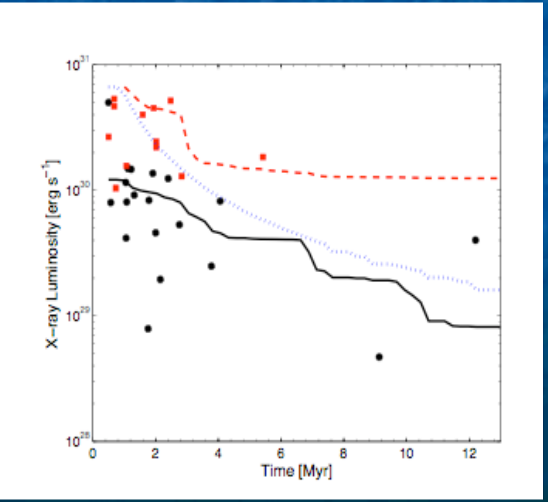
…….but note lack of blueshifted OI 6300 in TW Hyda ……Pascucci et al 2011

Evidence for Xray photoevaporation?

- High L_X stars lose discs earlier - implies WTTs should have higher L_X on average.

Preibisch et al 2005, Greogory et al 2007

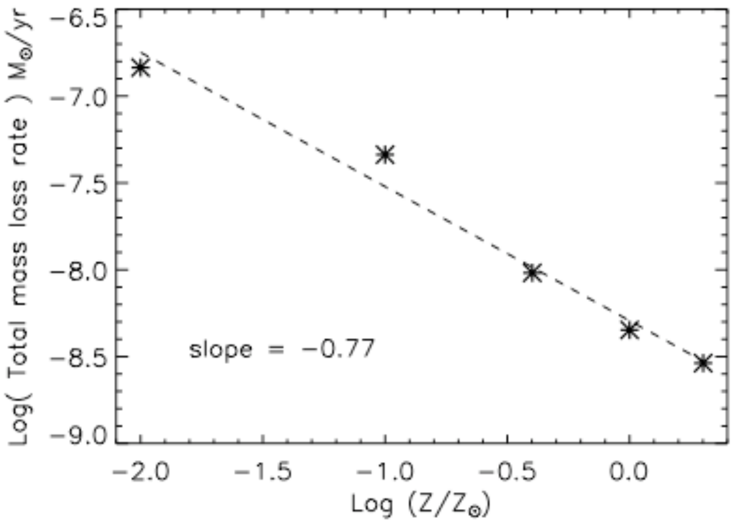
Well known observational correlation. Usually argued that Xrays suppressed/absorbed by accretion: perhaps instead accretion suppressed by Xrays……

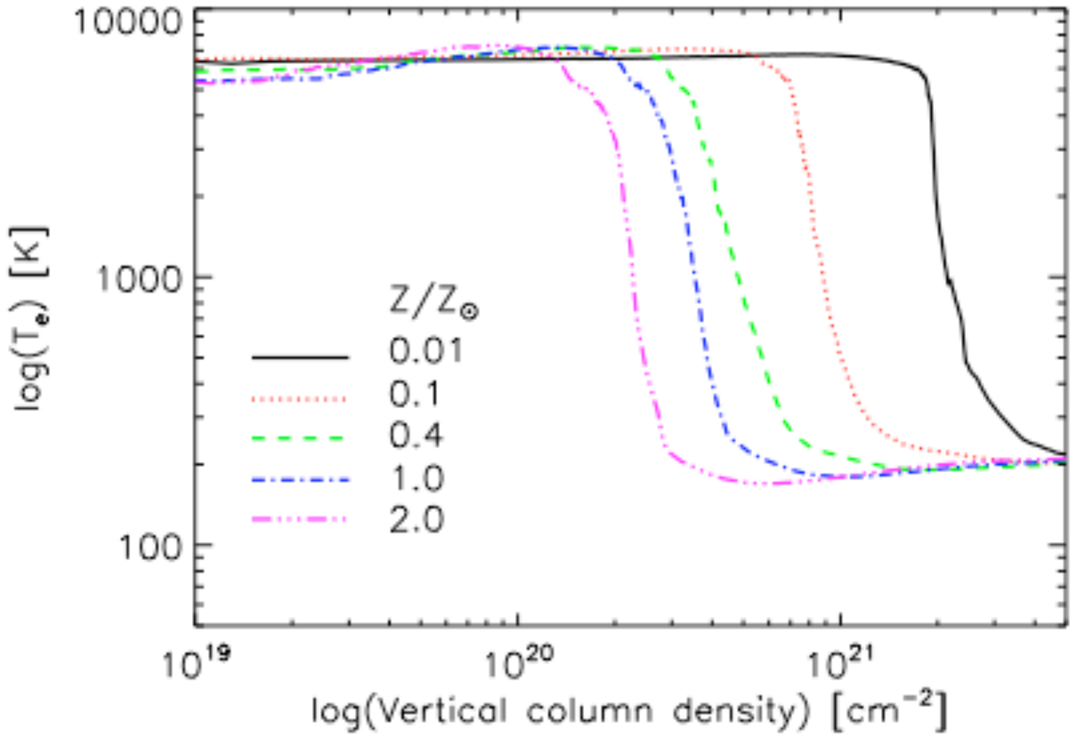


Population synthesis: Owen et al 2011a

✔

Dependence on metallicity:





Photoevaporation more efficient at low Z: lower dust extinction => Xrays heat to higher column

EXPECT SHORTER DISC LIFETIMES AT LOW Z

Disc lifetime **increases* strongly with decreasing Z if it's instead set by time required for planet formation

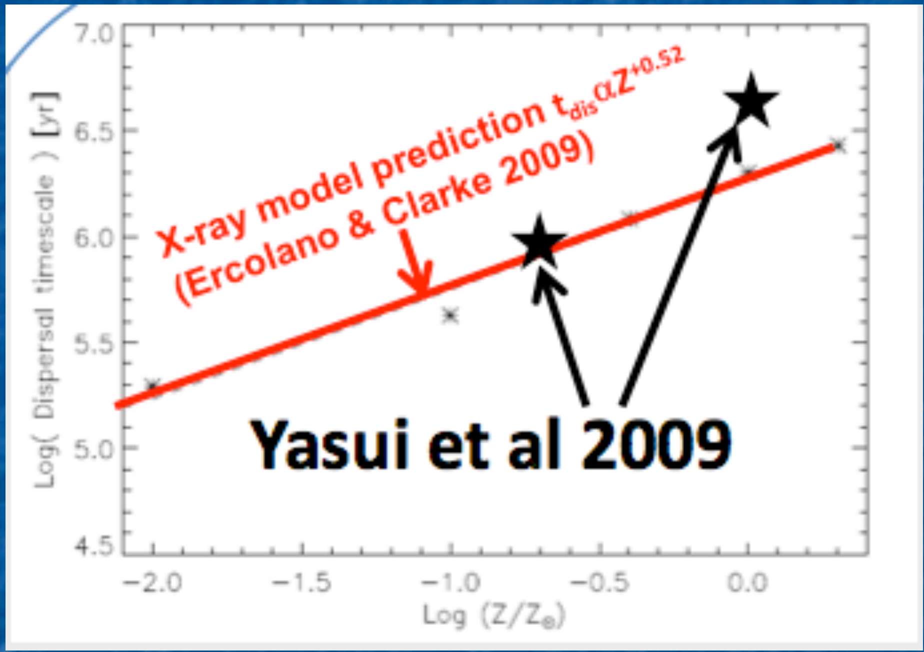
$$t_{form_{min}} \propto \left(Z^{-5} M_{g0}^{-7} r_{d0}^{(9-5p)}\right)^{(2-p)/(5-3p)} \qquad \propto \qquad Z^{-5/2}$$

(see Ercolano & Clarke 2009)

$$t_{form_{min}} \propto \left(Z^{(-13+2p)} M_{g0}^{-17} r_{d0}^{(4-2p)(6+p)}\right)^{1/(5-3p)} \qquad \propto \qquad Z^{-11/2}$$

- A possible observational discriminant?

- Recent claim of shorter disc lifetimes in lower Z environment



…further studies at low Z may hold the key to discriminating between photoevaporation and planet formation

CONCLUSIONS

Xrays can drive photoevaporative winds of 10^-8 M_sun/yr at upper end of XLF: like EUV winds, these produce a RAPID clearing phase but the Xray wind cuts in at much higher accretion rate.

Produce small holes at range of accretion rates but no accreting holes beyond ~ 20 A.U.; expect accreting and non-accreting holes to have similar frequency.

- Xray photoevaporation ==> line diagnostics ([Ne II] 12.8 μm and [OI] 6300 lines)
- Xray photoevaporation: shorter disc lifetimes at low Z (opposite to clearing by planet formation)