Thermal Sweeping: A Rapid Disc Dispersal Mechanism

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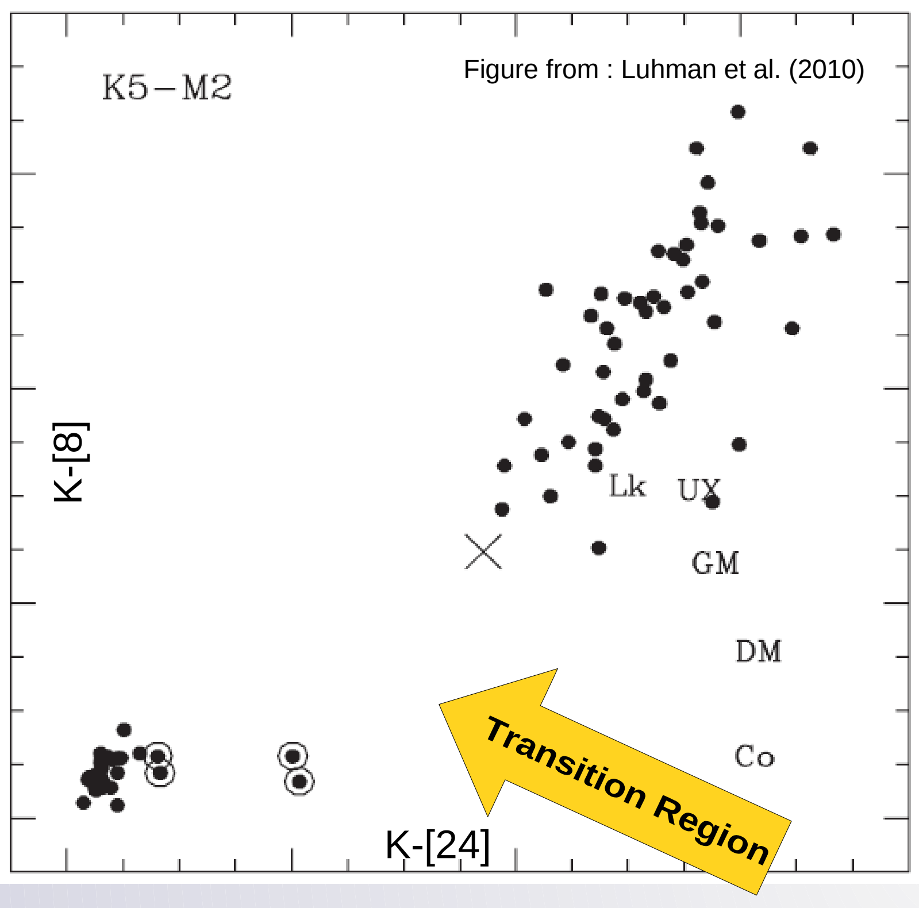
Background



Discs are observed to surround a large percentage of all young stars at an age of ~1Myr and by 10Myr they are mostly gone (Haisch et al. 2001). Very few solar type YSOs have been detected as 'transition' objects at an intermediate evolutionary stage between disc bearing class II sources and discless class III sources. Hence the time for disc destruction occurs on a much shorter timescale than the disc's lifetime. This 'transitional' timescale has been estimated to be ~10^5yr i.e. an order of magnitude shorter than the disc's lifetime (Kenyon & Hartmann 1995; Duvert et al. 2000). Several of these 'transition' objects show inner holes in their (dust) discs with hole radii between 5-50AU. Several mechanisms for the creation of these inner-hole objects have been proposed. Dust trapping by tidal interactions with a formed/forming planet embedded in the disc (Rice et al. 2003). Or inner disc clearing via photoevaporation from high energy radiation (Clarke et al. 2001). While both mechanisms can naturally explain individual objects neither mechanism is able to explain the entire population of these objects. Given these two mechanisms compete with each other to remove gas from the disc it is expected both are at work. However, photoevaporation is the only mechanism that can self-consistently produce inner-hole sources while dispersing the disc in the required timescale (Alexander et al. 2006a,b). X-ray photoevaporation models Owen et al. (2010,2011,2012) have had good success in explaining the general lifetimes of discs, the accretion rate evolution and other disc evolution diagnostics as well as explaining a large fraction of the observed transition disc population. However, the pure photoevaporation model also predicts a significant population of 'relic' discs. Since, as disc clearing proceeds it takes longer and longer to remove disc material at ever increasing radii, as there is more mass.

Thermal Sweeping

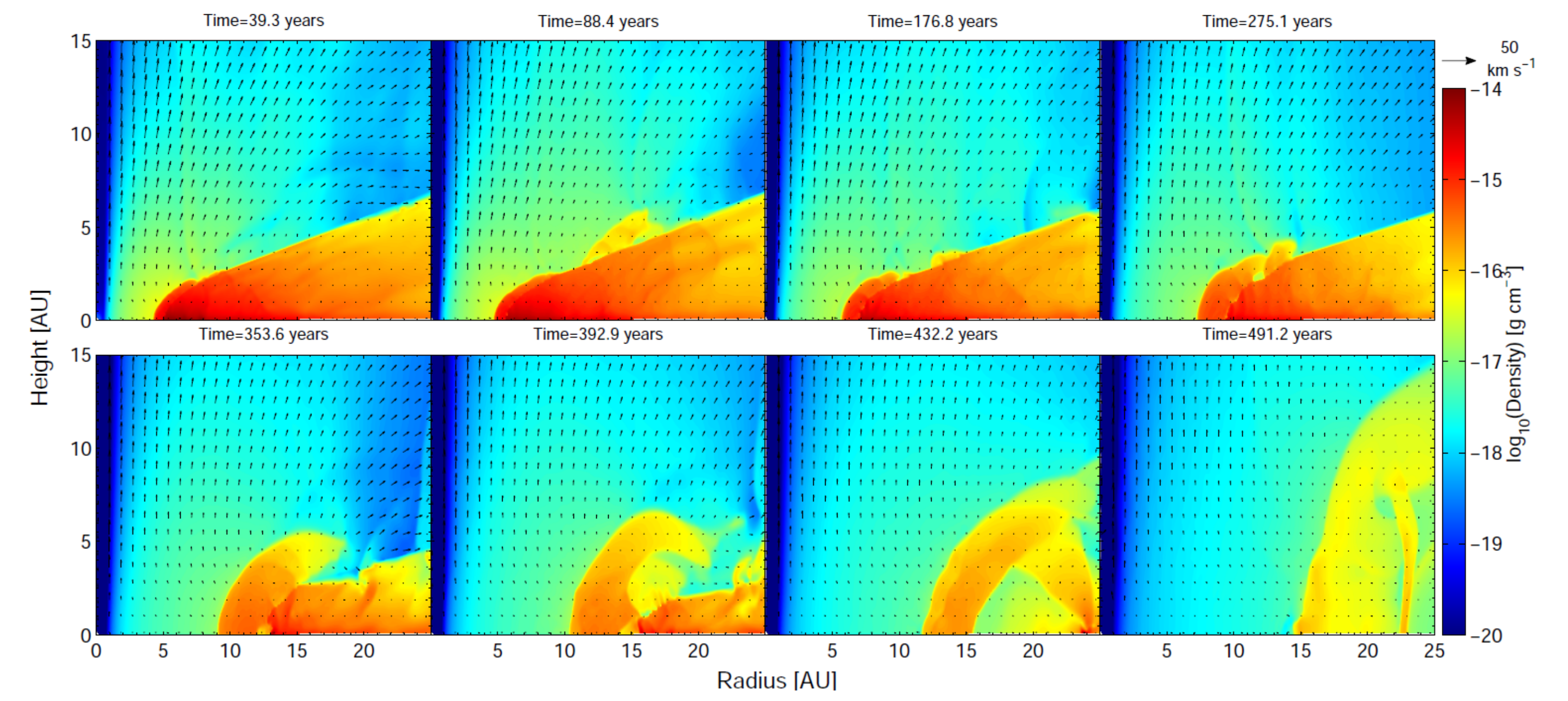


FIGURE: Time evolution of a simulation of a disc with an eroding inner hole and an X-ray luminosity of 10^{30} erg/s. The colour map shows the density structure and the arrows indicate the velocity structure. Each panel indicates a snapshot of the flow structure.

The 1D viscous models commonly used to model disc evolution under the influence of photoevaporation (Clarke et al. 2001; Alexander et al. 2006b,Owen et al. 2011) assume that mass-loss is steady. However, when discs with an inner holes reach low-surface densities, such that the inner rim can be significantly penetrated by the X-rays, the steady state photoevaporative flow structure is no longer applicable. At high surface densities applicable to steady-state mass-loss the streamlines leave the discs rim radially before being bend vertically by pressure gradients. However, at low surface densities the X-ray heated rim is able to expand vertically under pressure gradients. This vertical flow leads to run-away penetration of the disc and it's rapid dispersal as shown in the Figure above, taken from a simulation performed by Owen et al. (2012).

Characterising Thermal Sweeping

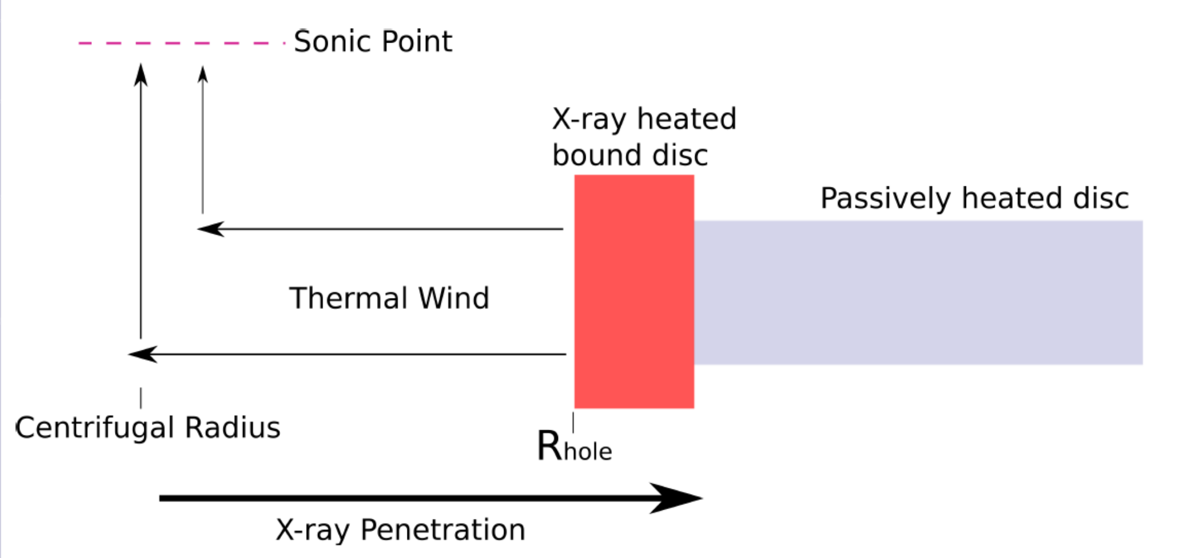


FIGURE: Schematic diagram of the flow/disc structure resulting from X-ray irradiation of a disc with a cleared inner hole.

The flow topology resulting from an X-ray irradiated inner holes, necessarily results in a bound, X-ray warm heated inner rim. The streamlines then radially flow inwards to the centrifugal radius ($R_{hole}/2$), where pressure gradients drive the flow vertically outwards. It is the X-ray heated, bound inner rim that is the origin of the thermal sweeping mechanism, and proceeds as follows: At high surface densities the X-rays do not penetrate far into the bound disc and result in a X-ray bound layer with a narrow width (Δ), as the inner hole is eroded (or the surface density drops), the X-rays can penetrate further and Δ grows. Once Δ becomes comparable to the vertical scale height (H) the layer is now unstable to run-away penetration. Since the dynamical time-scales vertically and horizontally are comparable, any vertical expansion cannot be balanced radially. This reduces the mid-plane column to the X-rays, increasing the mid-plane temperature and enhanced X-ray penetration. This processes is runaway as it leads to further vertical expansion and eventually the complete penetration of the disc's mid-plane to the X-rays.

We use 1D hydrodynamical simulations to model the mid-plane structure of an evaporating disc with an inner hole as a function of X-ray luminosity, stellar mass and inner hole radius using the ZEUS code (Stone et al. 1992, Hayes et al. 2006). These simulations allow us to calculate the surface density at which thermal sweeping will proceed in destroying the disc (shown in Figure), and derive an analytic model of the process (shown in Equation) Owen, Hudoba de Badyn & Clarke (submm.)

$$\Sigma_{TS} = \sqrt{2\pi}\mu c_c \left(\frac{L_X T_X}{\Omega \xi_{\rm min} R_{\rm hole}^2 T_c}\right) \exp\left(\frac{T_X}{2T_c}\right)$$

Tx-Temperature of X-ray heated gas, Tc-Dust temperature, Cc-sound speed in dust heated region.

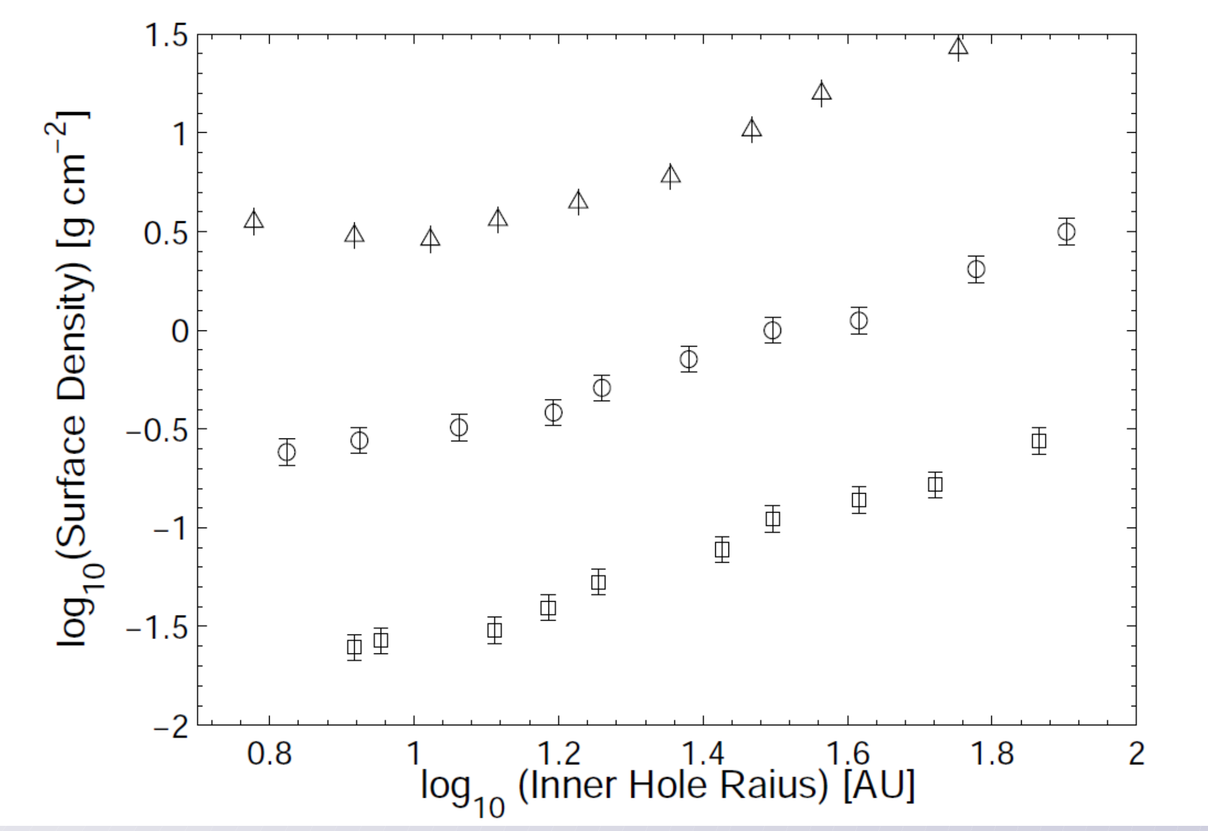


FIGURE: Surface density for thermal sweeping shown as a function of inner hole radius, for X-ray luminosities of 10^{29}(⊡), 10^{30}(O), 10^{31}(Δ) erg/s.

Evolutionary Implications

Given the surface density for thermal sweeping increases with radius, a disc that is clearing from inside-out will reach this threshold at some radius and be dynamically cleared. Assuming all discs are cleared from inside out by X-ray photoevaporation (using the Owen et al. 2011 population synthesis model). The equation for thermal sweeping allows us to predict the maximum inner hole radius a clearing disc may reach. This is shown in the figure below, where all discs are destroyed when their holes reach 20-40 AU. This means most clearing discs caused by X-ray photoevaporation spent their life as accreting transition discs rather than non-accreting transition discs, consistent with observations (Owen, Hudoba de Badyn, Clarke submm).

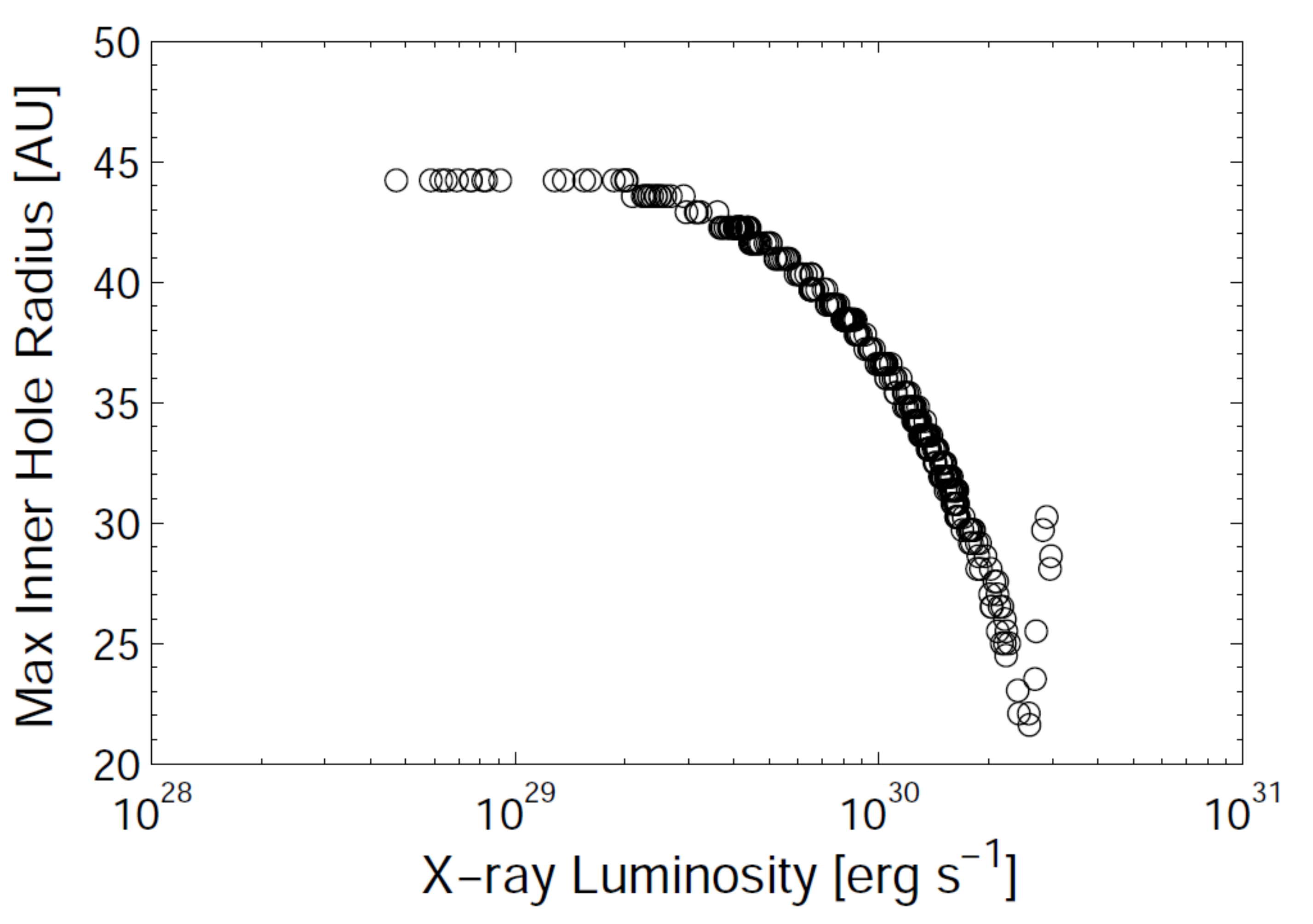


FIGURE: Maximum inner hole radii reached by clearing discs before thermal sweeping takes over. Each point represents an individual disc model, with X-ray luminosities randomly drawn from the observed X-ray luminosity function.

Summary & Inferences

Thermal sweeping is the final stage in the disc dispersal scenario and takes places once an cleared inner hole (that is optically thin to the X-rays) has developed, and the disc has fallen to significantly low surface densities. Thus can be triggered by disc clearing, either by forming planets or photoevaporation.

In the case of disc clearing triggered by photoevaporation, we find that clearing discs are destroyed by thermal sweeping when their inner holes reach radii of 20-40 AU. This means that the photoevaporation + thermal sweeping scenario predicts that transition discs spend most of their lifetime in an accreting phase in agreement with current observations. Due to the limitations of the Owen et al. (2012) simulations of thermal sweeping, while the time-scale for thermal sweeping to be triggered is understood, the time-scale for the entire disc to be dispersed in unclear. Energy-limited arguments suggest the time-scale should be of order:

$$\tau_{\rm clear} = 2\times10^3\,{\rm years}\left(\frac{L_X}{10^{30}\,{\rm erg\,s^{-1}}}\right)^{-1}\left(\frac{\epsilon}{0.25}\right)^{-1} \times\left(\frac{R_{\rm hole}}{10\,{\rm AU}}\right)\left(\frac{M_*}{0.7\,{\rm M_\odot}}\right)\left(\frac{\Sigma_{\rm hole}}{0.14\,{\rm g\,cm^{-2}}}\right)$$

Due to the rapid nature of the final stage of disc dispersal, thermal sweeping will have important dynamical consequences on any nearby planets or belts of planetesimals.

Further Reading

Owen, Ercolano & Clarke 2011, MNRAS 412, 13

Owen, Clarke & Ercolano 2012, MNRAS 422, 1880

Owen, Hudoba de Badyn, Clarke, MNRAS submitted