Stellar and dynamical evolution in AGN discs

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1 Intro

Gravitational interactions between massive bodies in their nascent discs lead to net energy change and migration, and were stidued extensively in planetary science [see review by Paardekooper et al., 2022]. In the standard picture, the gravitational interaction raises two spiral density waves excited at various resonances (corotation, inner and outer Lindblad), and their imbalance leads to net migration. Low mass object don't form a gap and migrate as type I migrate, where the net torque is $T_I \propto m_p^2$, where m_p is the mass of the planet. Massive planets open a gap and their migration rate is independent of the mass of the planet.

The type I torque is

$$\Gamma_0 \sim \frac{q^2}{h^2} \Sigma r^4 \Omega^2$$

where $q = m/M$ is the mass ratio, $h = H/r$ is the aspect ratio and $\Omega = (GM/r^3)^{1/2}$ is the Keplerian frequency.

The migration timescale is

$$\tau_0 = \frac{L}{2\Gamma_0} = \frac{mr^2\Omega}{2\Gamma_0} = \frac{1}{2\Omega}\frac{h^2}{q}\frac{M}{\Sigma r^2}$$

For type II, the timescale is the viscous timescale of the disc, $\tau_\nu = \Omega^{-1} \times (\alpha h^2)^{-1}$. This could be fast, unless the planet is massive than the disc, than it will slow down by a factor is $m/4\pi\Sigma r^2$.

What is the gap opening criterion? Currently the gap opening criterion had been revised to Kanagawa et al. [2015]

$$q \geq 5\sqrt{\alpha h^5} \approx 10^{-4} \alpha_{0.01}^{1/2} h_{0.04}^{5/2},$$

and widely used. We can define $K = q^2/\alpha h^5$. The migration is type II if $K > 25$. The gap depth is generally parametrised by $\Sigma/\Sigma_0 \approx 1/(1 + 0.04K)$. In order to make the migration continuous, the type I/II migration torque is

$$\Gamma_{I/II} = \Gamma_0 \frac{1}{1 + K'}$$

where $K' = K/25$. The gap is also formed for $K' > 1$.

1.1 How migration can be reversed?

Accretion may result in feedback and imbalance the vicinity of the planet. For gas accretion, it is expected to accelerate the migration [Lega et al., 2014], but accretion of pebbles could stall, or even reverse it [Benítez-Llambay et al., 2015]. Local simulations had shown that the heating torque can be important for wide range of configurations in accretion discs [Hankla et al., 2020].

Masset [2017] studies analytically the responce of a disc to a thermal torque. The additional variables are the thermal conductivity χ which enter into the heat transport part of the diffusion equation: The heat flux is $\boldsymbol{F}_H = -\chi\rho\nabla(e/\rho)$ (eq. 4), where e is the energy density and ρ is the gas density. Without and sources, $\partial_t e = \boldsymbol{\nabla} \cdot \boldsymbol{F}_H$, which looks like diffusion if the density gradient is small.

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The other length scale is the heat deposition scale is $\lambda = \sqrt{\chi/q\Omega\gamma}$ (eq. 120) where γ is the adiabatic index, Ω is the Keplerian frequency and $q = -d\ln\Omega/d\ln r = 3/2$ is the shear strength. Usually, the heat deposition scale is small compared to the scale height, $\lambda/H \ll 1$.

Radiative diffusion is usually the main source of diffesion, thus

$$\chi = \frac{16\gamma(\gamma-1)\sigma_{\rm SB}T^4}{3\kappa\rho_0^2H^2\Omega^2}$$

Eq. 146 of Masset [2017] for the total thermal torque reads

$$\Gamma_{\rm th}^{\rm tot} = 1.61\frac{\gamma-1}{\gamma}\eta\frac{H^2}{\lambda r}\left(\frac{L}{L_c}-1\right)\Gamma_0$$

where $\Gamma_0 = \Sigma r^4\Omega^2(m/M_\star)^2(H/r)^{-2}$ is the nominal type I torque (eq. 134), $L_c = 4\pi Gm\chi\rho_0/\gamma$ is the heat release from the planet (eq. 132), L is the luminosity and $\eta = \alpha/3 + (\beta+3)/6$ is related to the gradients of the surface density ($\Sigma \propto r^{-\alpha}$) and the temperature ($T \propto r^{-\beta}$) gradients, and usually is of order unity. It is valid for planets of mass less than $m < m_c = \chi c_s/G$, othewise the heat is deposited beyond the Bondi radius and the effect is greatly reduced.

Fromenteau and Masset [2019] also found that the eccentricity and inclination grow if $L/L_c > 1$ or dampen when $L/L_c < 1$ exponentially.

1.2 AGNS

Migration traps had been involved in AGN discs as fruitful locations for BH accumulation [Bellovary et al., 2016].

Hankla et al. [2020] looked on both AGNS and protoplanetary discs: corotation torque is complex.

They investigate the validity of the liner approach of Masset and directly apply to AGN disc. The accretion disc equations read

$$T^4 = \frac{3\tau\Omega^2}{8\pi\sigma_{\rm SB}}\dot{M} = \frac{3\tau\Omega^2}{8\pi\sigma_{\rm SB}}3\pi\Sigma\nu = \frac{3\tau\Omega^2}{8\pi\sigma_{\rm SB}}3\pi\Sigma\alpha c_s H$$
$$H = c_s/\Omega = \Sigma/\sqrt{2\pi}\rho_0;\ \tau = \kappa\Sigma$$

For the conductivity we have

$$\begin{aligned}\chi = \frac{16\gamma(\gamma-1)\sigma T^4}{3\kappa\rho_0^2H^2\Omega^2} &= 12\pi\gamma(\gamma-1)\alpha H^2\Omega \\ &= 12\pi\gamma(\gamma-1)\alpha H^2\Omega \sim 1.67\frac{\alpha}{0.1}H^2\Omega\end{aligned}$$

checking length scales:

$$\frac{\lambda}{H} = \sqrt{24\pi^3\gamma(\gamma-1)\alpha} = 1.8$$

Which is not really valid in the assumption. But this guarantees that $\lambda \gg x_c$, which is really what's important.

The ratio between the torques is

$$\frac{\Gamma_{\rm heat}}{\Gamma_0} = 0.07\frac{c}{v_k}\frac{1}{\alpha^{3/2}\tau}$$

so for optically thick, but not too thick ($\tau \lesssim 2000$), the thermal torque can possible dominate.

Li et al. [2020] numerically studies the Gruzinov negative DFs and find it's consistent.

Kaaz+2022 studies jet launching mechanisms from magnetised gas in BHL accretion. $\gamma = 5/3$ launches nice jets and reduces (or even) reversed the drag force, while $\gamma = 4/3$ doesn't really do much.

Tagawa et al. [2022] studies the role of mechanical feedback of rapidly accreting BHs. Winds can be launched for super-eddington accretion, but it doesn't hamper the flow too much. Jet feedback mechanism (JFM) causes episodic accretion and reduces rates by a factor of $10-100$.

Derdzinski+2022 discuss the birth and evolution of stars from gravitationally-unstable AGN discs. The IMF is probably top heavy. The initial stars are small, below $M_\odot$, but could rapidly accrete and grow.

2 Future work (?)

The birth, growth and dynamical evolution of stars anf BH in AGN discs is intriguing. Binary BH could also be interesting. The direction of the torque is circumbinary discs is also debated (Refs). I'd be happy to work/understand hte following:

- Incorporate the feedback from thermal conductivity and outflows into migration models. Identify the sign and magnitude of the total torque in $m - R$ space (star/stellar BH mass - radial separation). Take some prescriptoin for gas accretion (Eddington limited, super-Edd Bondi accretion, but maybe reduced) and initial conditions of a population (SF rate, mass function etc) and estimate how many mergers and EMRIs could be. Potential showcase could be unequal mass merger of two BH - the least massive could go outward while the outward one might go inward.

- More detailed evolution could be N-body + prescriptions for the migration torques. At super-Eddington accretion rates, allows winds and outflows and invoke the Gruzinov negative DF when the Mach number is > 1. Maybe add routines for resolving binaries?!

- Extend the outflow studies Gruzinov+19,Li et al. [2020] for sheared medium to mimic a disc and get a torque formula.

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