Class 14 – Active disks / Dead zones

3/17/20

Accretion equations (active disk)

Quenching of the MRI

other processes
- Photoevaporation
- winds
- other turbulence mechanisms? Gravitational turbulence?
- Disk dispersal
- Magnetospheric accretion

Viscous heating

$$2\rho\nu S^2$$

$$S = u_{i,j} + u_{j,i}$$

$$= \left(\frac{\partial u_\phi}{\partial x}\right)^2 = \Omega + r\frac{d\Omega}{dr} = \Omega(1+q) \approx \Omega q$$

$$2\rho\nu\Omega^2 q^2 = \frac{9}{4}\rho\nu\Omega^2 \quad \text{integrate in } z$$

$$\frac{9}{4}\Sigma\nu\Omega^2 \quad \text{(viscous heating}$$

half travels up and half travels down

$$\sigma T_d^4 = \frac{9}{8}\Sigma\nu\Omega^2$$

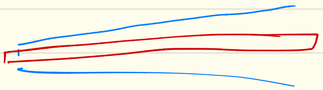
Active disk $\sigma T_d^4 = \frac{9}{8}\nu\Sigma\Omega^2$ $\quad \nu\Sigma = \frac{\dot M}{3\pi}$

$$T_d^4 = \frac{\cancel{9}^{3}}{8}\frac{\dot M \Omega^2}{\cancel{3}\pi\sigma} \qquad \boxed{T_d^4 = \frac{3\dot M\Omega^2}{8\pi\sigma}} = \frac{3GM\dot M}{8\pi\sigma r^3}$$

Concept: For accretion due to turbulence, viscosity deposits heat locally.
Show diagram of Brandenburg.

Vertical temperature structure

Discuss the process. The energy is being deposited locally on the bottom, it will either travel upwards radiatively or via convection. The entropy gradient is subadiabatic. Radiation



- Viscous heating is concentrated near midplane
- Heat is transported upward radiatively

- In an active disk the temperature is hotter in the midplane.
- In a passive disk the temperature is colder in the midplane.

$$F = -\frac{16\sigma T^3}{3\kappa_r\rho}\frac{dT}{dz}$$

$$F \cdot \rho\, dz = -\frac{16\sigma}{3\kappa_r} T^3\, dT \quad ; \quad F = \sigma T_{eff}^4 \ (\text{const})$$

$$\cancel{\sigma} T_{eff}^4 \cdot \int_0^\infty \rho\, dz = -\frac{16\cancel{\sigma}}{3\kappa_r}\int_{T_c}^{T_{eff}} T^3\, dT \Rightarrow T_{eff}^4 \cdot \frac{\Sigma}{2} = -\frac{\cancel{16}^{4}}{3\kappa_r}\left[\frac{T_{eff}^4 - T_c^4}{\cancel{4}}\right]$$

$$T_c^4 >> T_{eff}^4$$

$$T_{eff}^4 \cdot \frac{\Sigma}{2} = \frac{4}{3\kappa_r}\left[T_c^4 - T_{eff}^4\right] \qquad \tau = \frac{\Sigma\kappa}{2}$$

$$T_c^4 = \frac{3}{4}\tau \cdot T_{eff}^4$$

$$\boxed{T_c \approx \tau^{1/4} T_{eff}}$$

Usually, for an active disk $\sigma T_{eff}^4 \simeq \frac{9}{4}\nu\Sigma\Omega^2$ decreases strongly with distance. Active heating important in inner disk.

$$T_c^4 \approx \frac{3\tau}{4} T_{eff}^4 + T_{irr}^4/2$$

Only one type of disk with clear active accretion: FU Orionis disks.

Accretion outburst up to $\dot{m} \approx 10^{-4}\ M_\odot/yr$

10-100 yr

MRI dead zones

Disk evolution equations for active disk

$$\nu = \alpha c_s H$$

$$c_s^2 = \frac{kT}{\mu m_H}$$

$$\rho = \frac{1}{\sqrt{2\pi}} \frac{\Sigma}{H}$$

$$H = \frac{c_s}{\Omega}$$

$$T_c^4 = \frac{3}{4} \tau T_{eff}^4$$

$$\tau = \frac{1}{2} \Sigma \kappa_R$$

$$\nu \Sigma = \frac{\dot{M}}{3\pi}$$

$$\sigma T_{eff}^4 = \frac{9}{8} \nu \Sigma \Omega^2$$

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r} \frac{\partial}{\partial r}\left[r^{1/2} \frac{\partial}{\partial r} \left(\nu \Sigma r^{1/2}\right)\right]$$

Quenching of the MRI

Magnetic Reynolds number

$$\frac{\partial B}{\partial t} = \nabla \times \left[v \times B - \eta \nabla \times B \right] \quad ; \quad Re = \frac{v \times B}{\eta \nabla \times B} = \frac{v \cancel{B}}{\eta \cancel{B}/L} = \frac{U \cdot L}{\eta}$$

(similar to Reynolds number)

For $Re_m < 1$

$$\frac{UL}{\eta} < 1 \quad ; \quad U = v_A \ ; \ L = \lambda_{MRI} \approx H \ ;$$

$$\eta_{SPITZER} \approx 2.3 \times 10^{2} \frac{1}{x} \sqrt{T} \ \frac{cm^2}{s} \quad ; \ x \equiv \text{ionization fraction}$$

$$\eta = \frac{c^2}{4\pi\sigma_c} \qquad \sigma_c \Rightarrow \text{conductivity}$$

for $v_A \propto \sqrt{\alpha} \cdot c_s$ ($\alpha \equiv \frac{B_\phi B_r}{4\pi\rho c_s^2} \simeq \frac{v_A^2}{c_s^2}$

$$Re = \frac{v_A H}{\eta} = \frac{\alpha^{1/2} c_s^2}{\eta\Omega}$$

$$\simeq 1.4 \times 10^{12} \, x \left(\frac{\alpha}{10^{-2}}\right)^{1/2} \left(\frac{r}{1AU}\right)^{3/2} \left(\frac{T_c}{300K}\right)^{1/2} \left(\frac{M_*}{M_\odot}\right)^{-1/2}$$

$$\boxed{x_{critical} \simeq 10^{-12}}$$

very low. One ion in 10^{12} neutrals is sufficient to couple the field to the disk.

Ionization state:

Saha equation

$$\frac{n^{ion} n_e}{n} = 2\frac{g^{ion}}{g}\left(\frac{2\pi m_e k_B T}{h^2}\right)^{3/2} \exp\left(-\frac{\chi}{k_B T}\right)$$

χ is ionization energy

observations $\quad k \sim 8.6 \times 10^{-5}\ \frac{eV}{K}$

$\sim 10^{-4}\ eV/K$

$\frac{\chi}{kT} \qquad T \sim \frac{\chi}{k} = \frac{5}{10^{-4}} = 5\times10^4 K$ too high ionization.

$$\Delta V \sim \sqrt{v_{turb}^2 + \frac{2kT_{kin}}{\mu m_p}}$$

$$v_r \sim v_{visc} \Rightarrow \frac{B_z^w B_\phi^w}{\varepsilon\Omega} \sim \frac{3\nu}{2r}$$

$\nu = \alpha c_s H \qquad \alpha = B_r^c B_\phi^c$

$$\frac{v_{r,m}}{v_{r,v}} \sim \frac{B_z^s B_\phi^s}{B_z^c B_\phi^c}\left(\frac{h}{r}\right)^{-1} \qquad \text{(not needed)}$$

Wind launching

at some point above, atmosphere becomes magnetically dominated. Must have $J \times B = 0$ so that acceleration is finite. The field becomes force-free.

$\rho v^2 = \frac{B^2}{8\pi}$ mag energy = kinetic energy (Alfven surface)

Beyond Alfven surface gas inertia bends lines, rotate in spiral.

Analysis of centrifugal wind: $\frac{\partial^2 \Phi}{\partial s^2} = 0$? (why?)

Discuss turbulence and winds, with a WE DON'T KNOW

Photoevaporation