L8: AGN's and Accretion Disks

Mass and Angular Momentum Flow

Specific energy Recall: $\frac{1}{2}\left(\frac{dr}{dt}\right)^2 + \underbrace{\left[\frac{\ell^2}{2r^2} + \psi\right]}_{V_{eff}}$ where $\psi_{kep} = \frac{-GM_*}{r}$

For circular orbit, $\frac{dr}{dt} = 0$ and $dV_{eff}/dr = 0 \rightarrow \boxed{\frac{d}{dr}\left[\frac{\ell^2}{2r^2} + \psi\right] = 0}$ gives $r_0(\ell)$

(equivalent to $\frac{d\psi}{dr} = \frac{V_\varphi^2}{r}$) (for kep. $r_0 = \frac{\ell^2}{GM_*}$)

So $\mathcal{E}$ in an orbit is

$$\mathcal{E} = \ell^2/2r_0^2 + \psi(r_0) \quad \text{where } r_0 = r_0(\ell) \longrightarrow \text{so } \mathcal{E} = \mathcal{E}(\ell)$$

> Q: How does $\mathcal{E}$ vary with ℓ? Careful: r_0 is itself a function of ℓ!

$$\frac{d\mathcal{E}}{d\ell} = \left(\frac{\partial \mathcal{E}}{\partial \ell}\right)_{r_0} + \cancel{\left(\frac{\partial \mathcal{E}}{\partial r_0}\right)_\ell}\frac{\partial r_0}{\partial \ell} = \left(\frac{\partial \mathcal{E}}{\partial \ell}\right)_{r_0}$$

since $\left(\frac{\partial \mathcal{E}}{\partial r_0}\right)_\ell = 0$ by definition of r_0

$$\boxed{\frac{d\mathcal{E}}{d\ell} = \frac{\ell}{r_0^2} = \Omega}$$

This will be useful.

$m_2 \quad \mathcal{E}_2(\ell_2)$

$m_1 \quad \mathcal{E}_1(\ell_1)$

Consider 2 particles on orbits. They can exchange mass and angular momentum, keeping the totals fixed.

> Q: How can E_{tot} be lowered?

$$E_{tot} = m_1\mathcal{E}_1(\ell_1) + m_2\mathcal{E}_2(\ell_2)$$

$$M_{tot} = m_1 + m_2 \qquad dM_{tot} = 0 = dm_1 + dm_2$$

$$L_{tot} = L_1 + L_2 = m_1\ell_1 + m_2\ell_2 \qquad dL_{tot} = 0 = dL_1 + dL_2$$

$$= dm_1\ell_1 + m_1 d\ell_1 + dm_2\ell_2 + m_2 d\ell_2$$

$$dE_{tot} = dm_1\mathcal{E}_1 + m_1\overbrace{\frac{d\mathcal{E}_1}{d\ell_1}}^{\Omega_1}d\ell_1 + dm_2\mathcal{E}_2 + m_2\overbrace{\frac{d\mathcal{E}_2}{d\ell_2}}^{\Omega_2}d\ell_2$$

invoke $dM_{tot} = 0$:

$$= dm_1(\mathcal{E}_1 - \mathcal{E}_2) + m_1\Omega_1 d\ell_1 + m_2\Omega_2 d\ell_2$$

add + subtract terms:

$$= dm_1(\mathcal{E}_1 - \mathcal{E}_2) + m_1\Omega_1 d\ell_1 + dm_1\Omega_1\ell_1 - dm_1\Omega_1\ell_1$$
$$+ m_2\Omega_2 d\ell_2 + dm_2\Omega_2\ell_2 - dm_2\Omega_2\ell_2$$

$$= dm_1(\mathcal{E}_1 - \mathcal{E}_2) + \Omega_1 dL_1 - dm_1\Omega_1\ell_1 + \Omega_2 dL_2 - dm_2\Omega_2\ell_2$$

using also $dL_{tot} = 0$:

$$= dm_1(\mathcal{E}_1 - \mathcal{E}_2) + dL_1(\Omega_1 - \Omega_2) - dm_1(\Omega_1\ell_1 - \Omega_2\ell_2)$$

$$\boxed{dE_{tot} = dm_1\left[(\mathcal{E}_1 - \Omega_1\ell_1) - (\mathcal{E}_2 - \Omega_2\ell_2)\right] + dL_1(\Omega_1 - \Omega_2)}$$

Now $\mathcal{E} - \Omega\ell = \frac{1}{2}V_\varphi^2 + \psi - \frac{V_\varphi}{r}V_\varphi r = -\frac{1}{2}V_\varphi^2 + \psi$

so $\frac{d(\mathcal{E} - \Omega\ell)}{dr} = -V_\varphi\frac{dV_\varphi}{dr} + \frac{d\psi}{dr} = -V_\varphi\frac{dV_\varphi}{dr} + \frac{V_\varphi^2}{r} = -V_\varphi r\frac{d}{dr}\left(\frac{V_\varphi}{r}\right) = -V_\varphi r\frac{d\Omega}{dr}$

In all astrophysical systems, $\frac{d\Omega}{dr} < 0$. So $\frac{d(\mathcal{E} - \Omega\ell)}{dr} > 0$

$$dE_{tot} = dm_1 \underbrace{\left[(\varepsilon_1 - \Omega L_1) - (\varepsilon_2 - \Omega L_2)\right]}_{<0} + dL_1 \underbrace{(\Omega_1 - \Omega_2)}_{>0}$$

Conclusion: To decrease E_{tot}, need $dm_1 > 0$ (move mass inward)
$dL_1 < 0$ (move L outward)

The minimum energy state (never attained) has a tiny mass carrying all the L in a very large radius, while all the mass collects at the center.

AGN Phenomenology

"Active" galaxies, which are a small minority in the field, have very bright nuclei often show emission lines, as opposed to usual absorption lines from stars. Now thought to harbor BH's fed by accretion disks. There are several types:

> Seyfert Galaxies Discovered in 1940's. About 10% of Sa + Sb galaxies (bulgy spirals) harbor Seyfert nuclei. Not found in ellipticals.

Seyfert 1's – $\boxed{\text{broad}}$ emission lines of allowed transitions (eg $H\alpha$)
$V \lesssim 10^4$ km/s, much higher than stars in Galaxy (~ 100 km/s)

Seyfert 2's – $\boxed{\text{narrow}}$ emission lines (500 km s^{-1}) of both forbidden and permitted lines. Forbidden – eg. [OIII] at 5007 Å

broad continuum

Both types, and indeed most AGN's, exhibit a very broad continuum emission, extending over 8-10 decades in λ. Seyferts have $L \lesssim 10^{11} L_\odot$

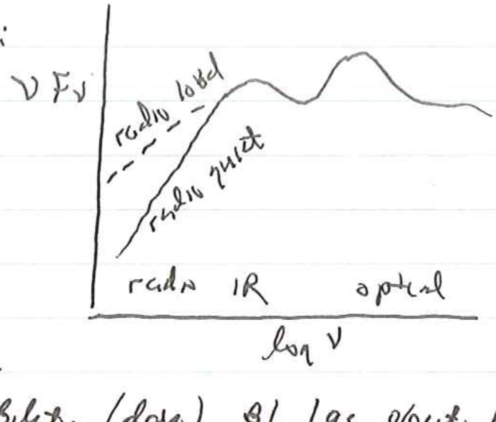
> Radio Galaxies – These are bright nuclei within elliptical galaxies. The (optical) core has emission lines, like Seyferts. But has much more radio emission, which can extend into enormous "lobes" up to a Mpc in size! The lobe is connected to the core by a jet. Eg M87 jet in the Virgo cluster.

highly variable

All types are highly variable.

> Quasars – The most luminous objects known. The brightest have 10^5 x the luminosity of the Milky Way ($\sim 3 \times 10^{10} L_\odot$) The 1st found were "quasi-stellar" (eg point-like) radio sources. But most, it turns out, are radio-quiet. Technically, these are called QSO's, but people use "quasar" for both. Variable optical + UV emission lines (broad). $\boxed{\text{Galaxies: ellipticals or bulgy spirals}}$

Quasars, again, have a very broad continuum: the "SED" plots log νF_ν vs. log ν.
In this way $\int \nu F_\nu \, d\log\nu$ gives energy emitted in each decade of ν.



> Blazars — often considered a subset of quasars; have strong continuum, but little or no emission lines. Most extreme variability (days). BL Lac objects have no emission lines at all. The most extreme form of AGN; highly variable & strongly polarized radio & optical emission.

Evidence for BH's

> Argument from radiation pressure

The very high L of AGN's sets a lower limit on the mass of the galactic nuclei. If they were less massive, their gravity would be unable to prevent matter from exploding as a result of radiation pressure.

Ledd

Radiation pressure acts mainly on electrons. The "classical radius" of the electron is defined by $m_e c^2 = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_0} \longrightarrow r_0 = \frac{e^2}{4\pi\epsilon_0 m_e c^2}$

The "Thompson cross section" for radiation is $\sigma_T = \frac{8\pi}{3} r_0^2 = \frac{e^4}{6\pi\epsilon_0^2 m_e^2 c^4}$

$= 6.65 \times 10^{-25}\ cm^2$

Radiation carries L energy/time
and thus L/c momentum/time $(\equiv F)$
The radiation pressure at a point is $\frac{L}{4\pi r^2 c}$ $\left(\frac{\text{force}}{\text{area}}\right)$

Each electron feels a force $\frac{\sigma_T L}{4\pi r^2 c}$. This is also the force on the whole atom. Counterbalancing this must be the gravity of the nucleus, of mass M:

$$\frac{G M m_p}{r^2} > \frac{\sigma_T L}{4\pi r^2 c}$$

Thus $\boxed{L < L_{edd} \equiv \frac{4\pi G m_p c M}{\sigma_T} = 3\times10^4 L_\odot \left(\frac{M}{M_\odot}\right)}$

[NB – The textbook writes –
$L_{edd} = \frac{4\pi G c}{\kappa_{es}} M$
where κ_{es} is the e-s opacity. We have approximately $\kappa_{es} \doteq \frac{\sigma_T}{m_p}$ for a pure H gas]

For a given, observed L, the requirement $L_{edd} > L$ gives a minimum mass.
The typical quasar luminosity is $L \doteq 10^{13} L_\odot$ [for comparison $L_{MW} \simeq 3 \times 10^{10} L_\odot$]
So the mass of the nucleus is at least $\boxed{M = \frac{10^{13}}{3 \times 10^4} M_\odot = 3 \times 10^8 M_\odot (!)}$

> Time variability. If changes occur over a time Δt, the size of the emitting region can be no larger than $c\Delta t$. [actually, $c\Delta t/\gamma$ for receding source].
Take a typical $\Delta t \sim 1$ hour and let $\gamma \sim 1$; $\boxed{R \sim c\Delta t = 10^{12}\ m = 7\ AU}$

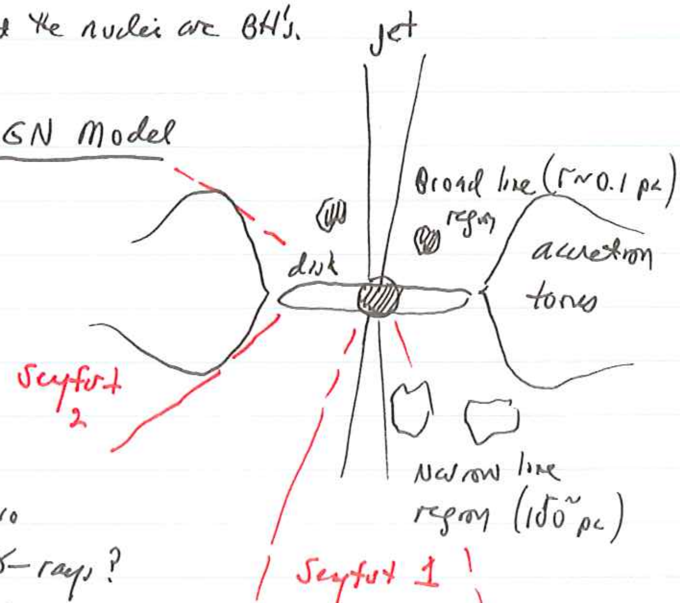
> Schwarzschild radius. If M is confined to this R, is the object a BH?

$R_s = \frac{2GM}{c^2} = 6\ AU$ for $M = 3 \times 10^8 M_\odot$

This agreement supports the view that the nuclei are BH's.

Unified AGN Model

It is now agreed that all the AGN types are the same basic system viewed at different angles.



> The broad continuum emission comes from the accretion disk. Since M is so huge, why is the continuum not all γ-rays?
Actually, the inner-edge T of a disk declines with mass:

$$T = \left(\frac{GM\dot{M}}{8\pi\sigma R^3}\right)^{1/4}$$

But the inner edge of the disk is the last stable orbit of a BH $\rightarrow R \propto M$

The high L comes from matter spiraling through the disk. $\boxed{L = \eta \dot{M} c^2}$
Here η varies from 0.06 (Sch. BH) to 0.42 (maximally rotating BH) & is usually assumed to be ~ 0.1. If $L \propto L_{edd}$, then $\dot{M} \propto M$ and

$$T \propto \left(\frac{M^2}{R^3}\right)^{1/4} \propto \left(\frac{1}{M}\right)^{1/4}$$

The T actually declines with M.

B-lines are twisted in the disk & create a relativistic jet. This powers radio lobes.

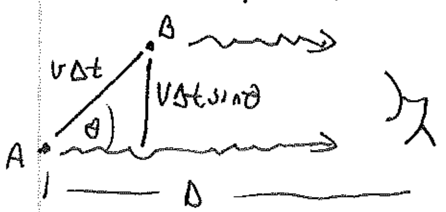
In Seyfert 1's, we see both fast-moving clouds (broad lines) + slower ones (narrow forbidden lines). Forbidden lines are formed at lower density (farther out).
In Seyfert 2's, we only see only narrow lines, since the fast-moving clouds are blocked from view.
In Blazar's, we may be seeing straight down the jet; only continuum emission.
The radiation from the jet is narrowed to a cone by relativistic beaming, so we see it as much brighter than in the rest frame.

> Reverberation mapping Measure Δt, the time delay between a brightness change in the continuum (disk) and the broad-line emission region. Then $c\Delta t$ is r, the distance of these fast-moving clouds from the nucleus.
Measure also σ, the width of the (broad) lines. Set $\sigma \sim \sqrt{\frac{GM}{r}}$

We have a mass measure $\boxed{M = \frac{f c \Delta t \, \sigma^2}{G}}$ Comparing to other methods used for nearby galaxies, $f \simeq 5$

Superluminal Jets

Radio blobs often appear to move faster than c (proper motion). Easily explained:



$t=0$: Blob at A emits light
$t=\Delta t$: Blob at B emits light

Light from A received at $t_A = D/c$

Light from B received at $\Delta t + \frac{D - v\Delta t\cos\theta}{c} = t_B$

$\Delta t_{rec} = t_B - t_A = \Delta t - \frac{v\Delta t\cos\theta}{c} = \Delta t\left(1 - \frac{v}{c}\cos\theta\right)$

During that time blob has traveled across the sky a distance $v\Delta t\sin\theta$

So the apparent $V_\perp = \frac{v\sin\theta}{\left(1 - \frac{v}{c}\cos\theta\right)}$ $\quad \beta_\perp = \frac{\beta\sin\theta}{1-\beta\cos\theta}$

For superluminal jets, $\beta_\perp > 1 \longrightarrow \beta\sin\theta > 1 - \beta\cos\theta$

$\beta > \frac{1}{\sin\theta + \cos\theta}$ But $f(\theta) \equiv \sin\theta + \cos\theta$ has a maximum value of $\sqrt{2}$ $\left(\theta = \frac{\pi}{4}\right)$

$\beta > \frac{1}{\sin\theta + \cos\theta} > \frac{1}{f_{max}} \longrightarrow \boxed{\beta > \frac{1}{\sqrt{2}}}$