Models of AGN, the gas supply, black holes and accretion efficiency

Tuomo Salmi

University of Turku

thjsal@utu.fi

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Models of AGN

Proposed models for source of the energy:

- Compact star clusters (without black holes):
  - Dense cluster of massive, hence rapidly evolving, stars undergoing many supernova outbursts.
  - Problem 1: Fluctuations. Less luminous active galactic nuclei should be the more variable, contrary to observation.
  - Problem 2: Systematic motion. Evidence for increasing source separation, which is incompatible with a model involving random outbursts.
  - Problem 3: Evolutionary argument. Small stars would escape the cluster and more massive stars evolve to a central BH on a time scale of 10^7 yr.

Models of AGN

Proposed models for source of the energy:

- Supermassive stars
  - Stars with mass $\approx 10^8 \mathrm{M}_\odot$ radiating at $\leqslant 10^{46} \mathrm{ergs}^{-1}$.
  - Problem 1: General relativistically unstable: Small contraction leads to further contraction, even with "magnetoid" or "spinar" support.
- Black holes
  - "Current orthodoxy".
  - Fuel supplied either by a local star cluster or by the host galaxy globally.

The gas supply

- Mass supply rate of $1 - 100\mathrm{M}_{\odot}\mathrm{yr}^{-1}$ needed in order to power the brightest quasars.
- The origin of the gas and the mechanism to deliver it to the tiny nuclear region at the required rate?
- What makes a galaxy potentially active? What turns the activity on?

The gas supply

- "Local" model: fuelled by a local dense star cluster (< 10 pc).
  - How did the cluster form then?
  - The rate at which gas is liberated is insufficient (normal stellar evolution, tidal disruptions, ablation, and physical collisions between stars).
- "Extranuclear" models: Gas from $\geq$ 1 kpc from the main body of the host galaxy, or from infall of intergalactic gas, or from galaxy interactions.
  - Standard accretion disc with $\alpha \leq 1$ cannot steadily supply the required fuel.
  - Mechanism with effective $\alpha \gg 1$ could work: Large (galactic) scale magnetic fields and/or non-axisymmetric gravitational instabilities to power the accretion.

Black holes

Energy equation for Newtonian particle orbiting a mass M:

$$\frac{1}{2}\left(\frac{\mathrm{d}r}{\mathrm{d}t}\right)^2 + V(r) = E$$

where E = constant is the total energy of the particle per unit

$$V(r) = h^2/2r^2 - GM/r$$

is called the *effective potential* for a particle of constant angular
mass. Particles of zero angular momentum, $h = 0$, fall radially

Black holes

Same for Schwarzschild solution:

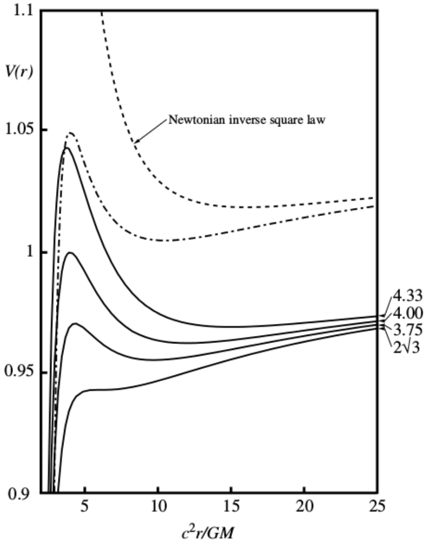
$$\frac{1}{c^2}\left(\frac{\mathrm{d}r}{\mathrm{d}s}\right)^2 + V^2(r) = E^2,$$

$$\frac{\mathrm{d}t}{\mathrm{d}s} = E(1 - 2GM/rc^2)^{-1},$$

and the effective potential is given by

$$V^2(r) = (1 - 2GM/rc^2)(1 + h^2/c^2r^2),$$

Black holes



1.1
V(r)
1.05
1
0.95
0.9
Newtonian inverse square law
4.33
4.00
3.75
2√3
5
10
15
20
25
c²r/GM

Black holes

- Circular orbits possible when $\partial V / \partial r = 0$.
- Maxima => Unstable circular orbit
- Minimum => Stable circular orbit (the innermost possible one is $r_{\min} = 6GM/c^2 = 3R_{\rm schw}$, ISCO)
- Beyond ISCO the infall time is short compared with a radiative life time, so ISCO is the surface for maximum feasible energy extraction.

Black holes

Maximum efficiency of energy generation (convertion from gravitational potential energy to radiation energy):

$$\begin{aligned}
\varepsilon_{\max} &= \text{(maximum available gravitational potential energy)/} \\
&= \text{(maximum binding energy)/(rest mass energy)} \\
&= \frac{(GMm/2r_{\min})}{mc^2} = \frac{1}{12}.
\end{aligned}$$

- Proper relativistic calculation would give 6%.
- In case of rotating BH (Kerr solution): 40% for a particle corotating with BH having the maximum allowed angular momentum.

Accretion efficiency

- High efficiency is essential requirement of a quasar model if we are to avoid an excessive accretion rate and the accumulation of an exceedingly massive black hole over a quasar lifetime.
- As seen, presents no problem in accretion discs (even for Schwarzschild BH).
- In this chapter of the book it is shown to be the case for spherical accretion too.

Accretion efficiency

- Assuming adiabatic optically thin infall (with time scale short compared with the radiative time scale due to bremsstrahlung) one gets $\eta = 9 \times 10^{-3}(L/L_{\rm Edd})^{1/2}$
- Reasonable for AGN if for $L \approx L_{\rm Edd}$. However, impossible to achieve without violating the assumptions made when deriving the estimate. For example:

$$\frac{t_{\rm rad}}{t_{\rm in}} \sim \frac{NkT}{4\pi j_{\rm br}} \left(\frac{r^3}{GM}\right)^{-1/2} \sim 10^2 T_8^{1/2} \eta \frac{L_{\rm Edd}}{L} \left(\frac{r_{\rm acc}}{r}\right)^{1/2}$$

showing that it is inconsistent, since then $t_{\rm rad} \approx t_{\rm in}$.

Accretion efficiency

- What is needed to improve the efficiency, is a source of heating of the infalling gas which is more effective than adiabatic compression (e.g. heating by dissipation of turbulent velocities in the infalling gas, reconnection of magnetic fields, acceleration in shocks).
- Rate of dissipative heating should be close to the cooling rate at the horizon $r = R_{\rm schw}$ (too strong cooling reduce the work that can be done on the gas).

The End