Constraints on the supermassive black hole spin from observations on the jets

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Young Researcher Conference, 2012 Budapest

Observing of the spin

Supermassive black holes can emit a pair of relativistic jets.

The jet power in all jet launching model depends very sensitively on the SMBH spin (e.g. Meier 2003).
But powerful jet $\nrightarrow$ high spin (mass of central BH? associated magnetic field?).

An option to get other *observable evidence* of the spin state is

the **low energy cutoff or LEC** seen in many jet's spectra (e.g Duschl & Lesch 1994).

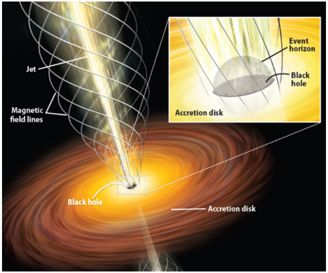

Figure : Black hole and its environment. Credit & ©: Astronomy/Roen Kelly

Possibly explanation of the LEC

π^+ decay resulting from pp collisions (e.g. Biermann et al. 1995).

$\boxed{p + p \rightarrow p + n + \pi^+}$ $\boxed{\pi^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu} + \nu_\mu}$

Process of the π^+ decay does require relativistic temperature (Mahadevan 1998).
Typical for an advection dominated accretion flow or ADAF.

Extremely high temperature → high BH spin (a$>$ 0.95)
(e.g. Gopal-Krishna et al. 2004).

Mass of the pion sets a low limit to the energy of the decay product.
→ A truncated particle population evolves in the ADAF disk and can be injected to the jet.

ADAF → high spin.
ADAF →? LEC. Does it work?

Connection between the LEC and the ADAF

Pion production. $p + p \rightarrow p + n + \pi^+$
Threshold energy demand (protons are moving with equal and opposite velocities, then total momentum is zero):
$E = 2\gamma_r m_{0,p} c^2 = m_{0,p} c^2 + m_{0,n} c^2 + m_{0,\pi^+} c^2$

Substituting the rest mass of particles the above equality yields $\gamma_r = 1.075$ and $v_r = 0.367c$ in relativistic frame.
Using relativistic velocity addition formula, it is correspond to $\gamma = 1.311$ and $v_{p,\mathrm{min}} = 0.646c$ in rest frame of one proton.

Then a required minimum kinetic energy for the protons:
$E_{\mathrm{kin}} = \gamma E_{m_{0,p}} - E_{m_{0,p}} \approx 290\mathrm{MeV} \approx 4.67 \times 10^{-11} J$.

Proton kinetic energy is a key parameter

Basic ADAF equations

Two dimensional (Rψ), steady state ($\partial/\partial t = 0$), axisymetric flow ($\partial/\partial\psi = 0$) (e.g. Narayan & Yi 1994).

$$\frac{d}{dR}(\rho R H v) = 0 \tag{1}$$

$$v\frac{dv}{dR} - \Omega^2 R = -\Omega_K^2 R - \frac{1}{\rho}\frac{d}{dR}(\rho c_s^2) \tag{2}$$

$$v\frac{d(\Omega R^2)}{dR} = \frac{1}{\rho R H}\frac{1}{dR}\left(\frac{\alpha\rho c_s^2 R^3 H}{\Omega_K}\frac{d\Omega}{dR}\right) \tag{3}$$

$$\Sigma v T\frac{ds}{dR} = \frac{3+3\epsilon}{2}2\rho H v\frac{dc_s^2}{dR} - 2c_s^2 H v\frac{d\rho}{dR} = Q^+ - Q^- \tag{4}$$

In ADAFs the heat energy is stored as entropy of the accreting gas

→ very high particle temperature can be present in the flow.

Random velocity in the ADAF

Random velocities of the protons could be adequately high to reach the minimum speed requirement.

Protons are treated as ideal gas. Proton speeds are characterized by Maxwell-Boltzmann distribution $f(v) = \frac{4}{\sqrt{\pi}} \left(\frac{m_p}{2kT}\right)^{3/2} v^2 \exp\left(-\frac{m_p v^2}{2kT}\right)$.

The most probable speed $\frac{1}{2} m_p v_{mp}^2 = kT$.

$\boxed{v_{mp} \approx v_{p,min} \rightarrow \text{strong pion production.}}$

If v_{mp} exceeds $v_{p,min}$ for pion production, then a positron population showing a LEC evolves from decays of the created pions.

Where in the ADAF? Goal: v_{mp}(T(R)) function.

Self-similar solutions - scaling laws (note, $0 < R < \infty$)

$$\rho \propto R^{-3/2}, v \propto R^{-1/2}, \Omega \propto R^{-3/2}, c_s^2 \propto R^{-1} \tag{5}$$

The isothermal sound speed (c_s) gives a connection between R and T through the relevant scaling law:

$$c_s^2 = \frac{2(5+2\epsilon')}{9\alpha^2} v_K^2 \left(\left[1 + \frac{18\alpha^2}{(5+2\epsilon')^2} \right]^{1/2} - 1 \right) \approx \frac{2}{5+2\epsilon'} \left(\frac{Gm}{R} \right). \tag{6}$$

If we assume a pure hydrogen plasma, then
$c_s = \sqrt{\frac{P}{\rho}} \rightarrow c_s^2 = \frac{1}{\rho} \frac{\rho k T}{\overline{\mu} m_H} = \frac{kT}{m_p}$
→ temperature as function of radius in the ADAF:

$$T \approx \frac{m_p}{k} \frac{2}{5+2\epsilon'} \frac{Gm}{R}. \tag{7}$$

$v_{mp}(\mathrm{T}(\mathrm{R}))$

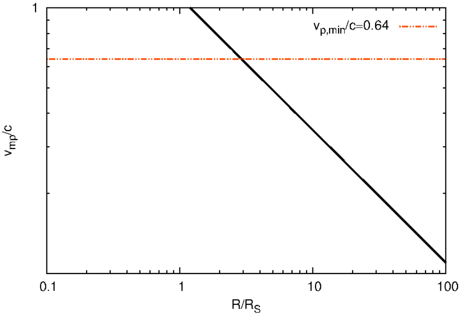

Figure : v_{mp} as function of R/R_S inside of a radiatively inefficient ADAF. R denotes the radial coordinate of the accreting particle in the Rψ plane and R_S denotes Schwarzschild radii of the central black hole. The dotted-dashed line indicates the minimum speed limit of the pion production. If the plasma is gas dominated, $\gamma \approx 5/3$ and then $\epsilon' \to 0$.

Summary and outlook

- In our toy model the pion production is a workable process to evolve of a secondary positron population in the ADAF.

- An observed LEC in the jet spectra signs existence of the ADAF at the base of the jet.

- Existence of the ADAF implies the high spin state of SMBH.
$\rightarrow$ an observed LEC is a good indicator of the high spin.

- Pion production will be strong below 3 RS. Scaling laws break down at this regime (Gammie & Popham 1998).

- We assumed thermal equilibrium for protons and a fully gas dominated disk.

- Additional work is needed to put the model assumptions on a more general basis. (general gas dynamics, 3D GR MHD).

Thank you for your attention!