Rotating Black Hole Energy Mechanisms

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Talk Overview

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- Kerr Metric and Negative Energy Region
- Standard Penrose Process
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Motivation

- What mechanisms can explain high-energy cosmic events? (relativistic jets in active galactic nuclei, binaries)
- Aren't black holes cold and dead?
- How can we get any energy out of them?
- One answer: spin.
- We consider mechanisms powered by black hole rotation.

(artist's conception)
Kerr Metric

• The extreme-spin Kerr metric in the equatorial plane:

\[ d\tau^2 = \left(1 - \frac{2M}{r}\right) dt^2 + \frac{4M^2}{r} dt d\phi - \frac{dr^2}{\left(1 - \frac{M}{r}\right)^2} - R^2 d\phi^2 \]

\[ R = \sqrt{r^2 + M^2 + \frac{2M^3}{r}} \]

• The energy constant of motion:

\[ \frac{E}{m} = \left(1 - \frac{2M}{r}\right) \frac{dt}{d\tau} + \frac{2M^2}{r} \frac{d\phi}{d\tau} \]

• The formal condition for negative energy is:

\[ R \frac{d\phi}{dt} < R \frac{2M - r}{2M^2} \]
Negative Energy Region

- When is this radial velocity achievable?

- Light: $R \frac{d\phi}{dt} = \frac{2M^2}{rR} \pm \frac{r - M}{R}$
Penrose Process

- Take two particles to a region of negative energy.
- One is captured by the black hole.
- The other escapes to infinity.
- A loss in rotational energy provides for the increase in energy.
- How efficient is this process?

(Gravitational Collapse: The Role of General Relativity, R. Penrose)

Figure 5. Rotating “black hole” (Kerr-Newman solution with \(m^2 > a^2 + \lambda^2\)). The inhabitants of the structures \(\delta\) and \(\delta^*\) are extracting rotational energy from the “black hole.”
Penrose Process Efficiency

• Take the “practical process” presented in EBH.
• Energy of the counter-rotational radiation is

\[
\frac{(r - M) - (2M^2)/r}{\sqrt{r^2 + M^2 + \frac{2M^3}{r}}}
\]

• Maximum efficiency ~50%.
• More realistic calculations show 20.7%
• (1983 S. Chandrasekhar)
Kerr-Newman Penrose Process

- M. Bhat et. al. (1985) ask: *What if there was residual charge?*

- **Problem:** Astrophysical objects are not known to have significant net charge.

- **Justification:** Even a “small” charge gives rise to an appreciable Lorentz force felt by a particle in the area.

- Thus, include electromagnetic interaction in effective potential.

- Since \( Q/M \ll 1 \), ignore effects of charge in the metric.

("Energetics of the Kerr-Newman black hole by the Penrose process" Bhat, M.; Dhurandhar, S.; Dadhich, N.)
Above, $l$ is the reduced angular momentum of the incoming electron (L/m), and $\lambda$ is the product of the charge (eQ).
Kerr-Newman Penrose Process

- **Result #1:** NE Region has a greater extent.
- **Result #2:** Energy can be more negative.
- Same fundamental mechanism as Penrose.
- *Theoretically,* we can choose trajectories and parameters to obtain any value of the efficiency!
- *Practically,* this is limited by the residual charge and the angular momentum of incoming charged matter.

(Next, move the charge *outside* the black hole...
Blandford-Znajek Mechanism

Three ingredients:
- angular momentum
- massive black hole
- magnetic field

(Electromagnetic extraction of energy from Kerr black holes, Blandford, R. D.; Znajek, R. L.)
**Blandford-Znajek Mechanism**

- Magnetized accretion disk creates magnetic field lines threaded through the horizon.
- Induces EMF on neighboring charged particles (plasma) and accelerates them away.
- Bits of plasma spiral out in either direction, as if in a synchrotron.
- Shown to be equivalent to a circuit.
- *Spin* of the hole powers the mechanism.

*(Black Holes and Time Warps, Thorne, K.)*
Blandford-Znajek Mechanism

But the devil is in the details!

- Very little observational evidence.
- What order of magnetic fields can be expected in the universe?
- Interactions between magnetosphere and surrounding disk?
- What effect does an extensive, magnetized accretion disk have?
- Many models assume infinitely thin disks. Size and height of accretion disks?
- What's the power throughput? How high of a Lorentz factor?
Discussion

We have presented three mechanisms. Which can give rise to relativistic jet phenomena?

- **Penrose Process**: Inefficient. Requires spontaneous relativistic breakup of particles.

- **Kerr-Newman Penrose Process**: Not a favored mechanism due to feasibility concerns.

- **Blandford-Znajek Process**: Some models give good results. Some present complications.

The Blanford-Znajek Mechanism is one of our best contemporary attempts to explain high-energy galactic events. But much research remains to be done!