Rotating Black Hole Energy Mechanisms

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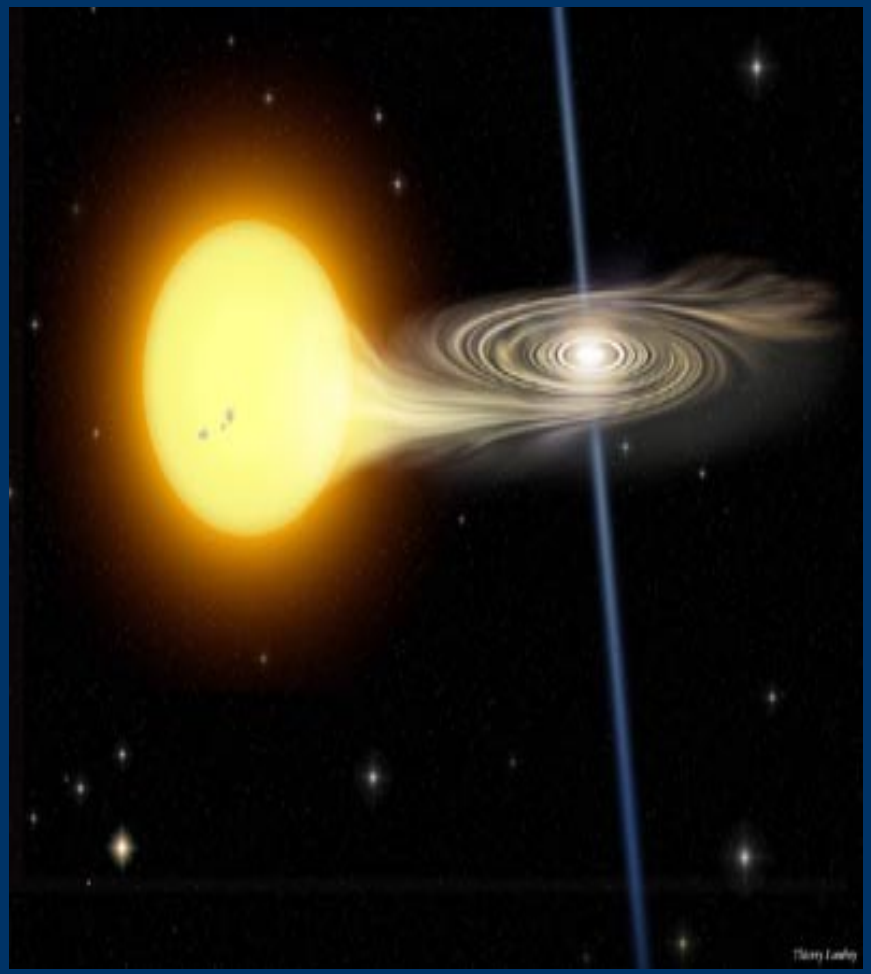
Talk Overview

- Motivation
- Kerr Metric and Negative Energy Region
- Standard Penrose Process
- Kerr-Newman Penrose Process
- Blandford-Znajek Process
- Discussion

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:

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

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

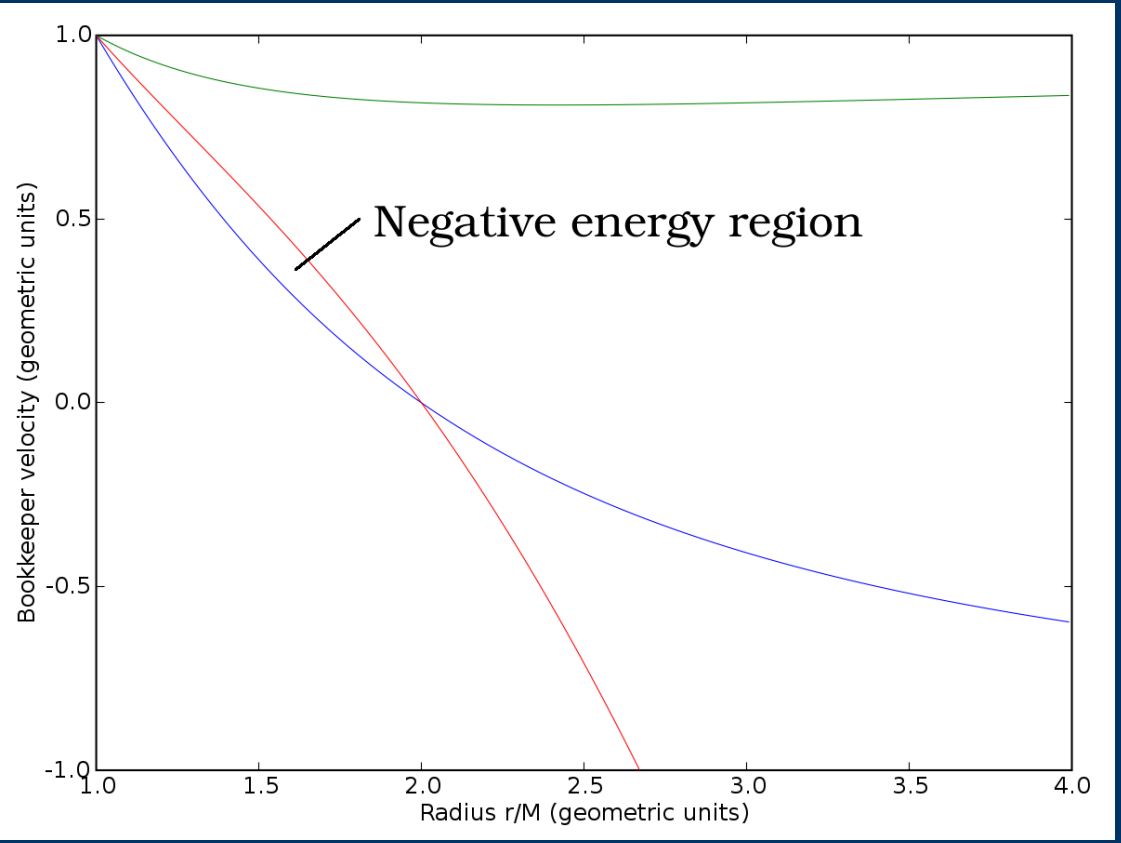
- The energy constant of motion:

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

- 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)

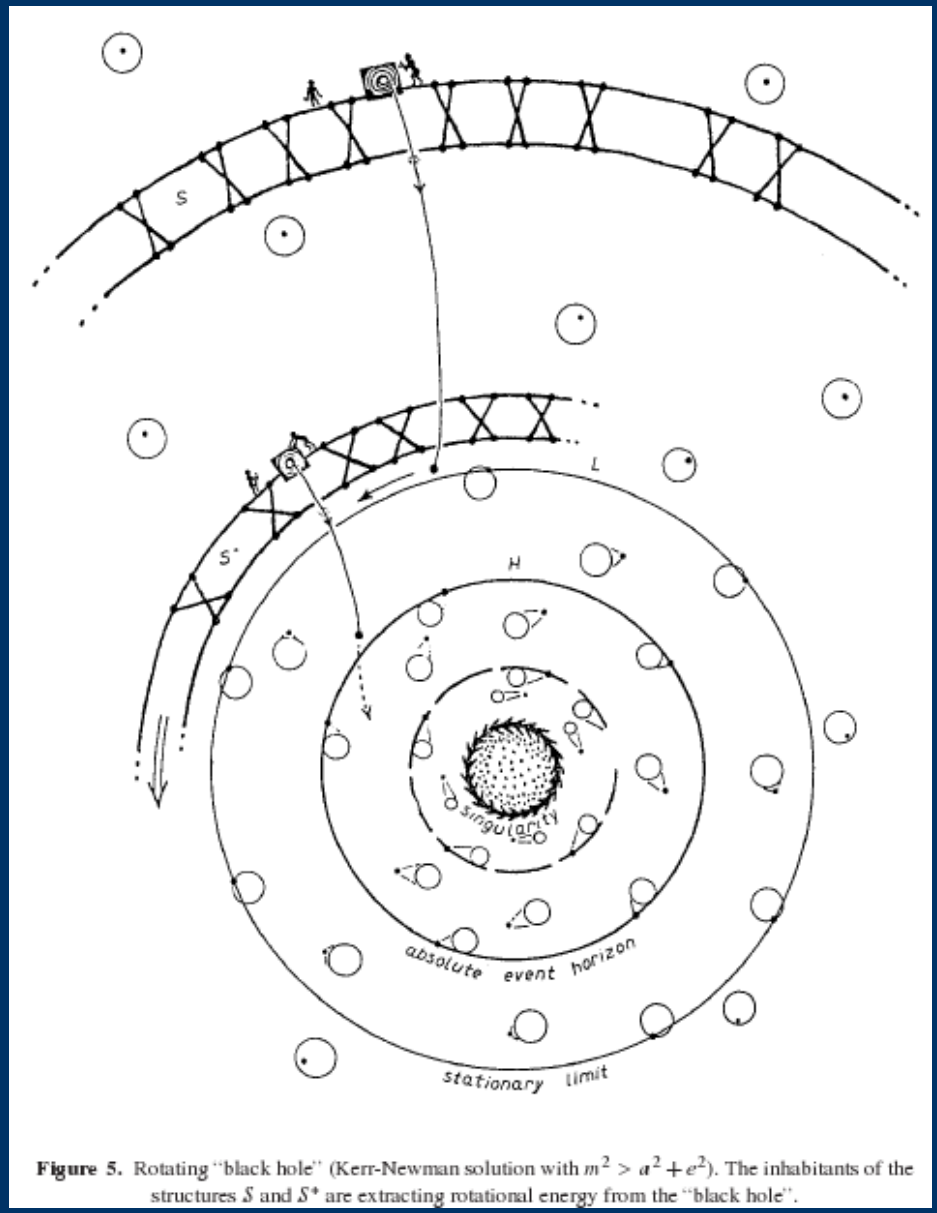
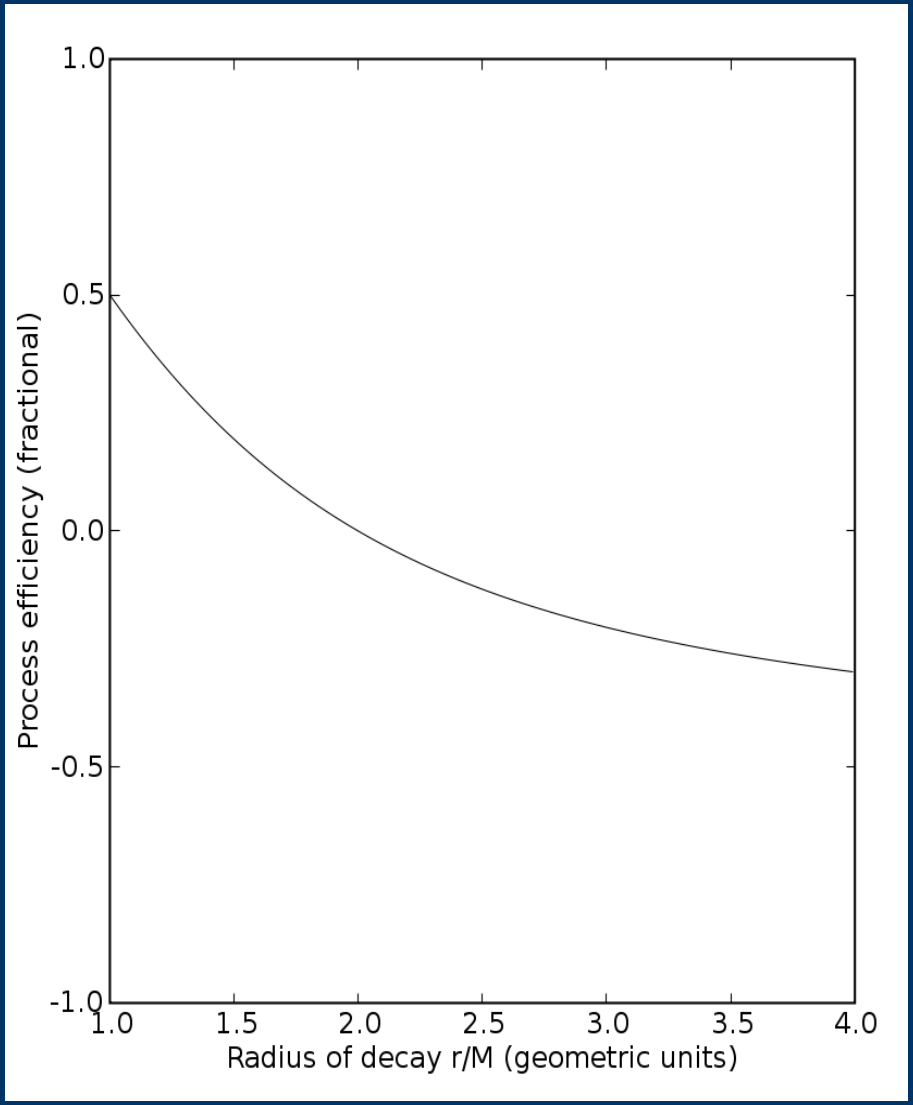


Figure 5. Rotating "black hole" (Kerr-Newman solution with $m^2 > a^2 + e^2$). The inhabitants of the structures S and S^* are extracting rotational energy from the "black hole".

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 << 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.)

Kerr-Newman Penrose Process

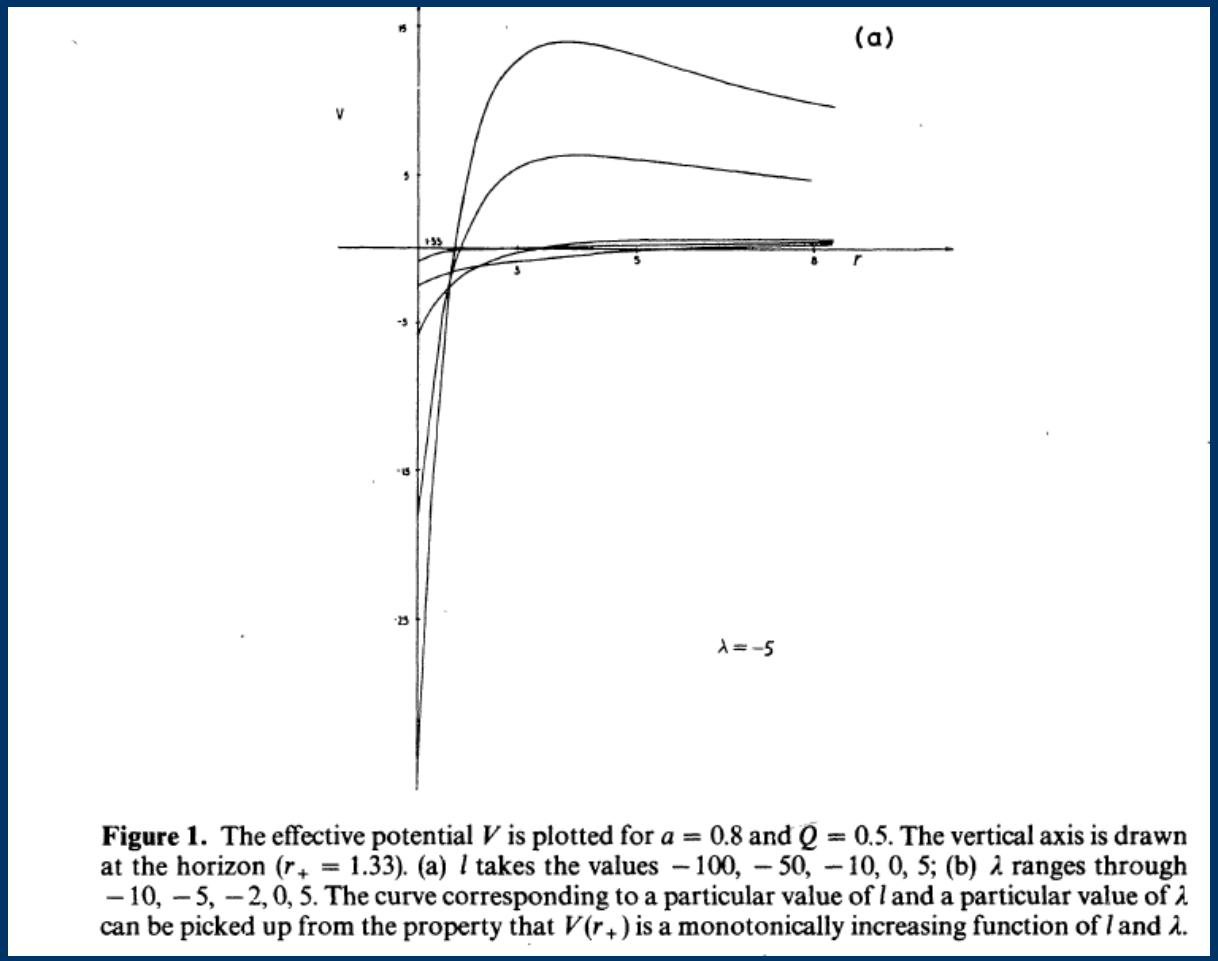


Figure 1. The effective potential V is plotted for $a = 0.8$ and $Q = 0.5$. The vertical axis is drawn at the horizon ($r_+ = 1.33$). (a) l takes the values -100, -50, -10, 0, 5; (b) λ ranges through -10, -5, -2, 0, 5. The curve corresponding to a particular value of l and a particular value of λ can be picked up from the property that $V(r_+)$ is a monotonically increasing function of l and λ.

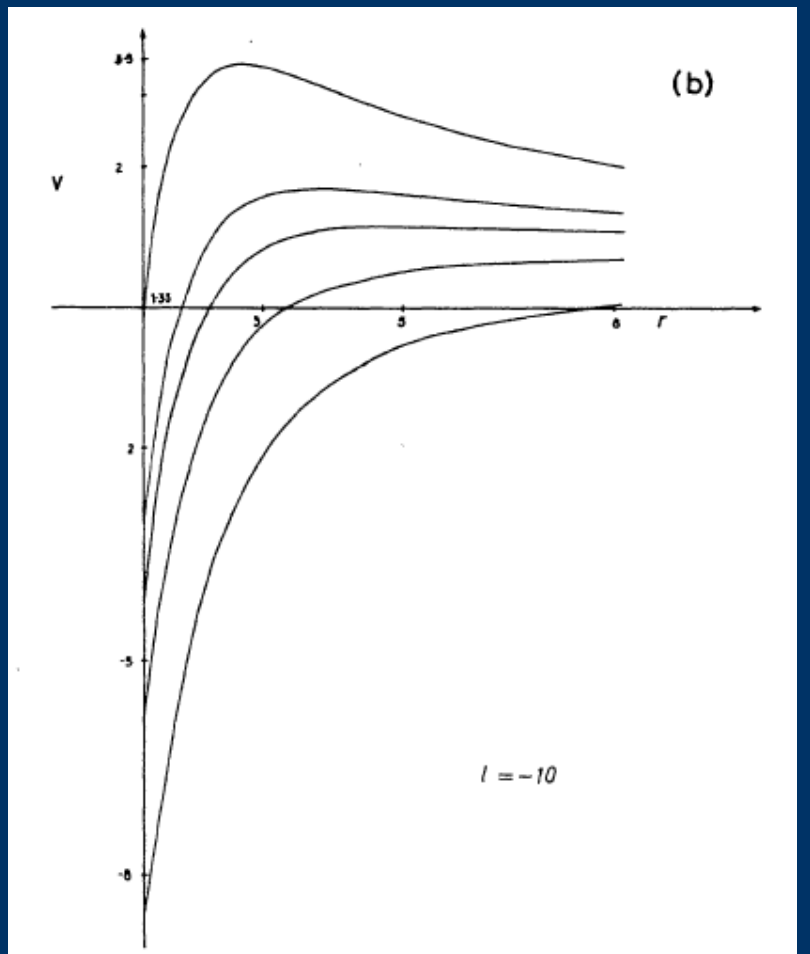


Figure 1. Continued.

Above, *l* is the reduced angular momentum of the incoming electron (L/m), and λ is the product of the charge (eQ).

Kerr-Newman Penrose Process

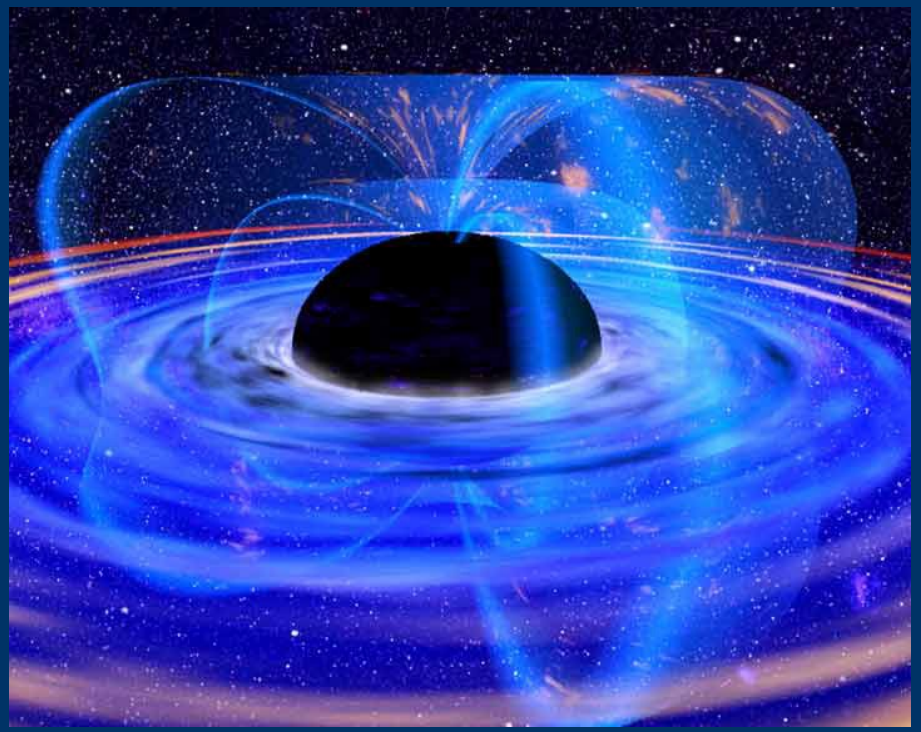
- **Result #1:** NE Region has a greater extent.
- **Result #2:** Energy can be more negative.
- Same fundamental mechanism as Penrose.
- *Theoretically*, we can choose trajectories and parameters to obtain any value of the efficiency!
- *Practically,* this is limited by the residual charge and the angular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

(Next, move the charge *outside* the black hole...)

Blandford-Znajek Mechanism

Three ingredients:

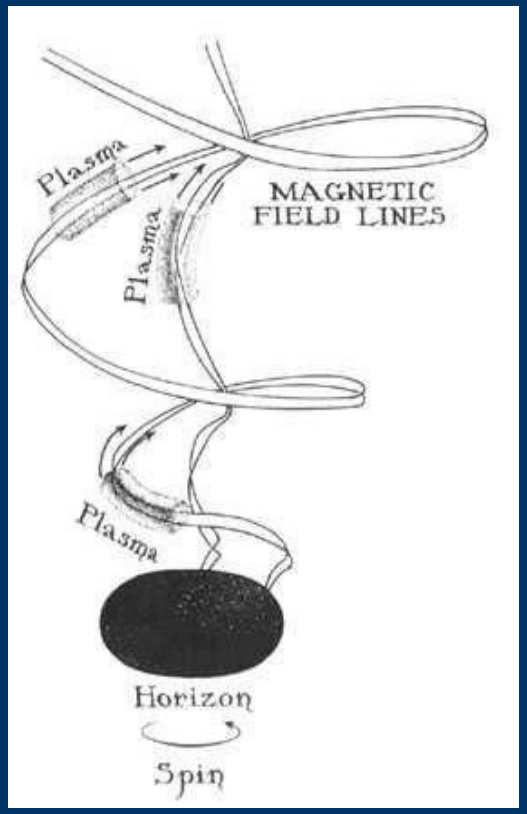
- *angular momentum*
- *massive black hole*
- *magnetic field*



(artist's conception)

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

Blandford-Znajek Mechanism



(*Black Holes and Time Warps*, Thorne, K.)

- 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.

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!