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The role of spin and charge in black hole astrophysics

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Astronomický ústav AV ČR

MUNI SCI

Some historical remarks

John Michell (1784): Phil. Trans. Roy. Soc. Lond. LXXIV, 35

If there should really exist in nature any bodies whose density is not less than that of the sun, and whose diameters are more than 500 times the diameter of the sun, since their light could not arrive at us … we could have no information from sight; yet if any other luminous bodies should happen to revolve about them, we might still perhaps from the motions of these revolving bodies infer the existence of the central ones …

Pierre S. Laplace (1796): “Exposition du Systēme du Monde”

… the attractive force of a heavenly body could be so large that light could not flow out of it.

(see W. Israel, in “300 Years of Gravitation”)

VII. *On the Means of discovering the Distance, Magnitude, &c. of the Fixed Stars, in consequence of the Diminution of the Velocity of their Light, in case such a Diminution should be found to take place in any of them, and such other Data should be procured from Observations, as would be farther necessary for that Purpose. By the Rev.* John Michell, *B. D. F. R. S. In a Letter to* Henry Cavendish, *Esq. F. R. S. and A. S.*

Read November 27, 1783.

DEAR SIR, Thornhill, May 26, 1783.

THE method, which I mentioned to you when I was last in London, by which it might perhaps be possible to find the distance, magnitude, and weight of some of the fixed

On the maximum mass

S. Chandrasekhar (1931): "The maximum mass of ideal white dwarfs", Astrophysical Journal 74, 81

... *there is no cause in the quantum theory that could prevent collapse of a body of the mass M > M_0 in a point* …

Limiting mass:

white dwarfs ≈ 1.4 M_S, neutron stars ≈ 2 M_S

S. Eddington (1935): "Relativistic degeneracy", Observatory 58, 37

W. Baade & F. Zwicky (1934): "On supernovae; Cosmic rays from supernovae", Proc. Nat. Acad. Sci. 20, 254

J. R. Oppenheimer & H. Snyder (1939): "On continued gravitational contraction", Phys. Rev. 56, 455

	Non-rotating ($J = 0$)	Rotating ($J \neq 0$)
Uncharged ($Q = 0$)	Schwarzschild	Kerr
Charged ($Q \neq 0$)	Reissner–Nordström	Kerr–Newman

$$R_g = GM_{BH}/c^2$$
$$\cong 1.5 \times 10^5 \left(M_{BH}/M_S\right) \text{ cm}$$

- ✓ Super-massive black holes (~ 10^6 – 10^9 M_S)
  - In cores of most galaxies (including the Milky Way)
  - Prime movers of Active Galactic Nuclei
- ✓ Intermediate black holes (~ 10^3 M_S)
  - Possibly in collapsed cores of stellar clusters

$$ds^2 = (1 - 2m/r)dt^2 - (1 - 2m/r)^{-1}dr^2 - r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)$$

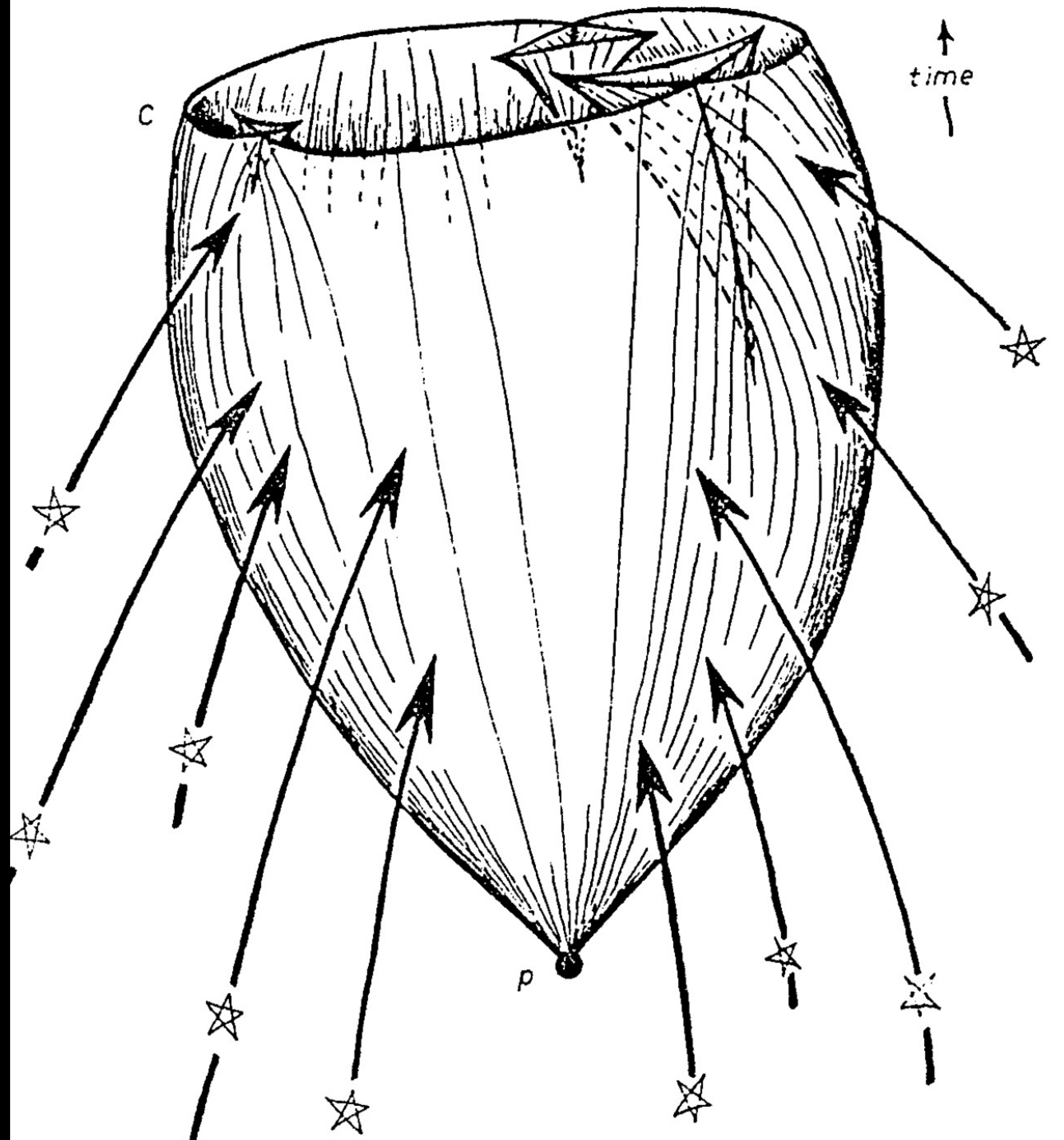

Figure 3. The future light cone of p is caused to reconverge by the falling stars.

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Black hole in a uniform magnetic field*

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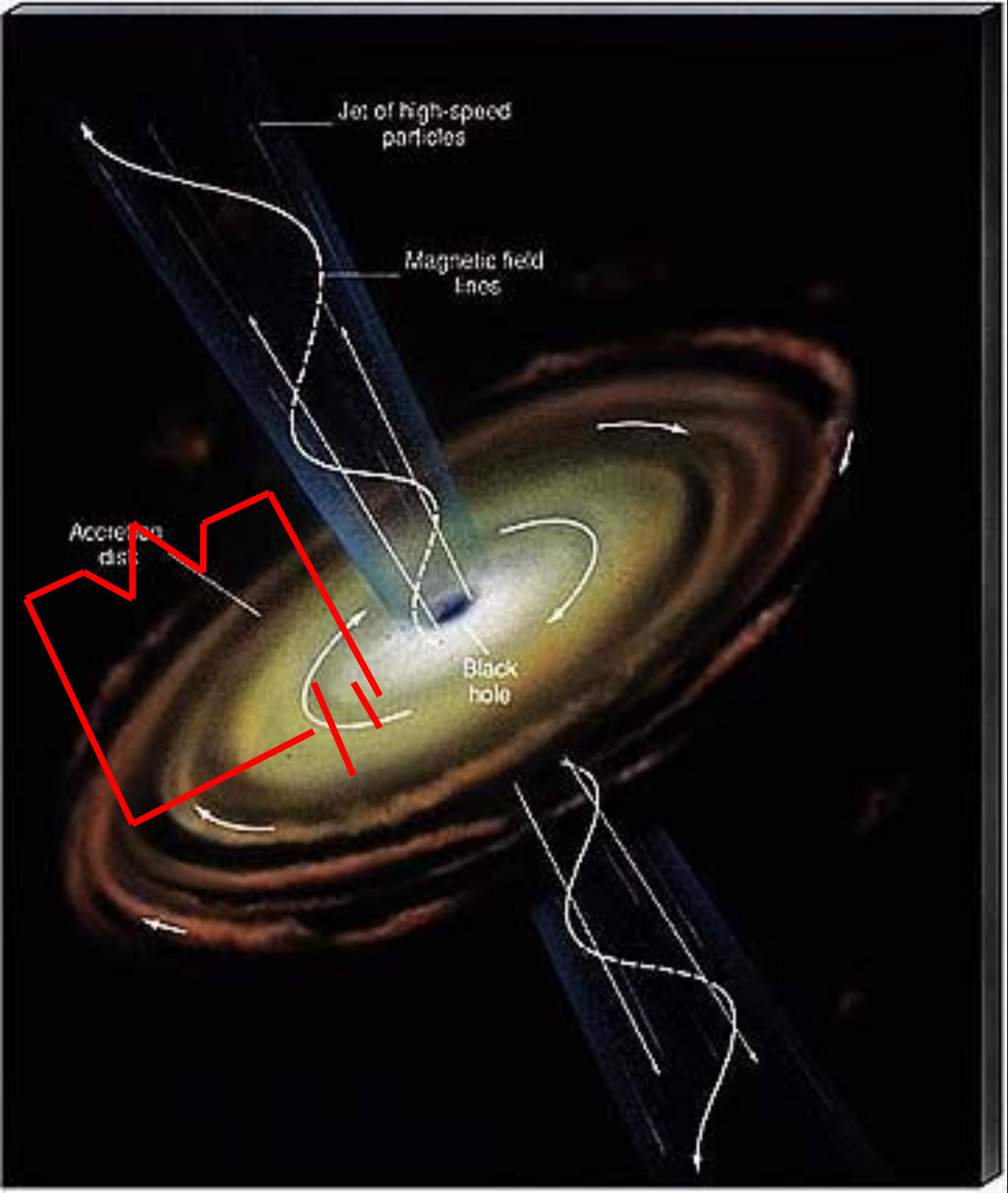
Using the fact that a Killing vector in a vacuum spacetime serves as a vector potential for a Maxwell test field, we derive the solution for the electromagnetic field occurring when a stationary, axisymmetric black hole is placed in an originally uniform magnetic field aligned along the symmetry axis of the black hole. It is shown that a black hole in a magnetic field will selectively accrete charges until its charge becomes $Q=2B_0J$, where B_0 is the strength of the magnetic field and J is the angular momentum of the black hole. As a by-product of the analysis given here, we prove that the gyromagnetic ratio of a slightly charged, stationary, axisymmetric black hole (not assumed to be Kerr) must have the value $g=2$.

I. INTRODUCTION

From the results on black-hole uniqueness which have been proved during the last several years (particularly the theorems of Israel,[1] Carter,[2] Hawking,[3] and Robinson[4]), it is now well established that an isolated black hole cannot have an electromagnetic field unless it is endowed with a net electric charge. Thus, an isolated black hole can participate in electromagnetic effects only if there is a mechanism for charging it up. However, if the black hole is not isolated, electromagnetic fields produced by external sources (e.g., plasma accreting onto the black hole) may be present.

Electromagnetic formation of jets

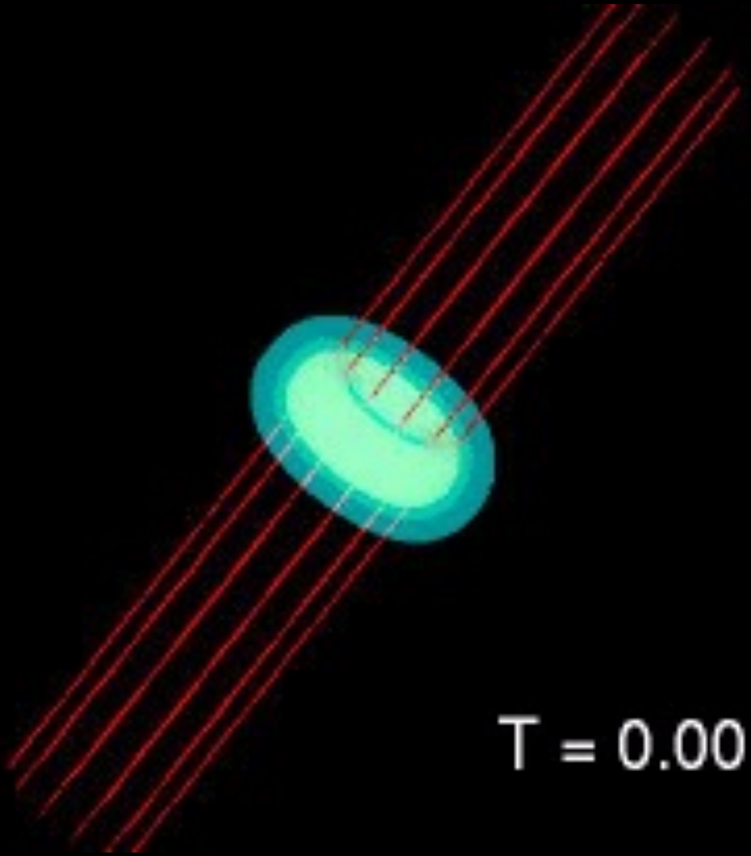


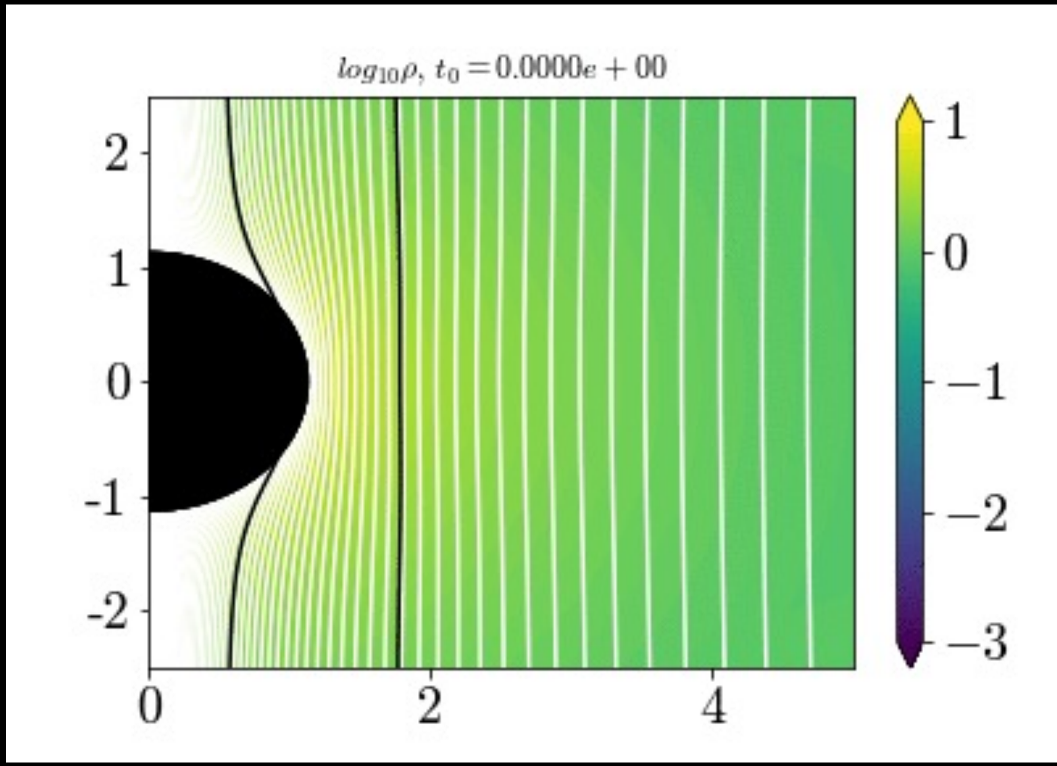
For a quasar jet:

B ~ 10^4 G;
U ~10^{20} V
I ~ 10^{18} A
P ~ 10^{38} W

Blandford & Znajek

Magnetized black holes: accretion, jets and outflows





Matsumoto

Karas, Janiuk, & Sapountzis

Magnetized Kerr-Newman (MKN) black hole:

$$ds^2 = -\mathrm{e}^{2\nu}\,\mathrm{d}t^2 + \mathrm{e}^{2\psi}(\mathrm{d}\varphi - \omega\,\mathrm{d}t)^2 + \mathrm{e}^{2\lambda}\,\mathrm{d}r^2 + \mathrm{e}^{2\mu}\,\mathrm{d}\theta^2$$

$$\mathrm{e}^{2\nu} = |\Lambda|^2\,\Sigma\,\Delta A^{-1}, \qquad \mathrm{e}^{2\psi} = |\Lambda|^{-2} A\Sigma^{-1}\sin^2\theta\,,$$

$$\mathrm{e}^{2\lambda} = |\Lambda|^2\,\Sigma\,\Delta^{-1}, \qquad \mathrm{e}^{2\mu} = |\Lambda|^2\,\Sigma\,,$$

$$\Sigma = r^2 + a^2\cos^2\theta\,, \qquad \Delta = r^2 - 2Mr + a^2 + e^2,$$

$$A = (r^2 + a^2) - \Delta a^2\sin^2\theta\,, \qquad \Lambda = 1 + B_0\,\Phi - \frac{1}{4}B_0^2\,\mathcal{E}\,.$$

…exact solution of Einstein-Maxwell eqs.

Garcia Díaz; Ernst & Wild

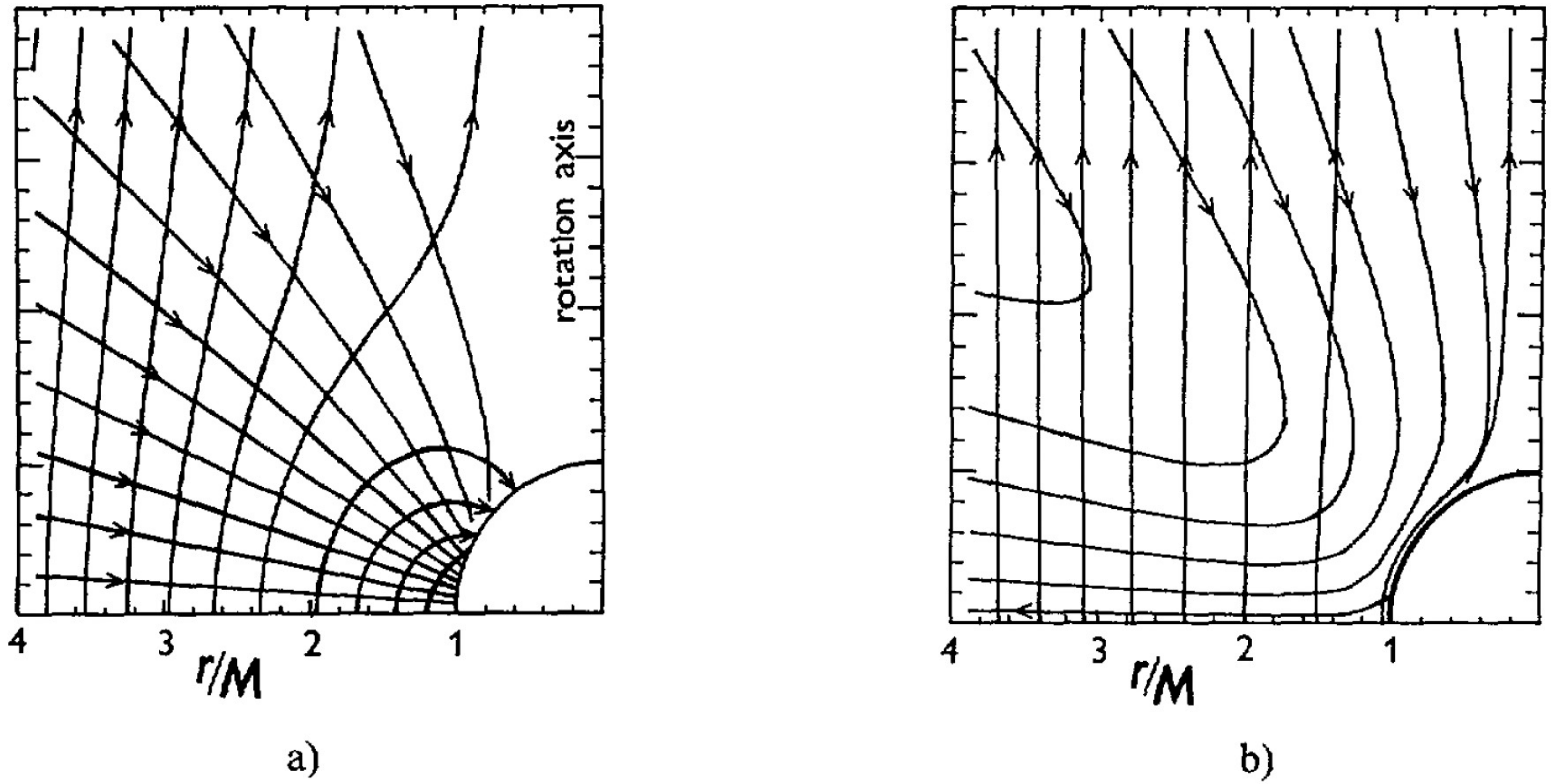


Fig. 1. — Two typical configurations of the magnetic and electric lines of force near an extreme [$e = -(M^2 - a^2)^{1/2}$], magnetised Kerr-Newman black hole with $\beta = 0.018$, $a/M = 0.99$ (a), and $\beta = 0.071$, $a/M = 0.99$ (b). The latter case corresponds to an uncharged configuration, $e + 2 B_0 Ma = 0$. Far from the hole the magnetic lines of force become uniform and parallel to the rotation axis, which goes vertically in the figure. Figures are symmetric with respect to the equatorial plane and axially symmetric about the rotation axis. Near the horizon (denoted by the quadrant $r/M = 1$) they obviously have a dipole-like structure (a), but in an uncharged extreme configuration (b) the magnetic field lines are expelled out of the horizon completely. Electric lines of force are in both cases asymptotically radial. In (b) their shape, unexpected on the basis of our experience with an analogous problem from the classical electrodynamics of rotating magnetised spheres (cf. Thorne *et al.* [23]), is produced by the effects of the gravitomagnetic interaction.

Plasma horizon: $|\boldsymbol{E} \times \boldsymbol{B}| = E^2$ (Ruffini, Damour)

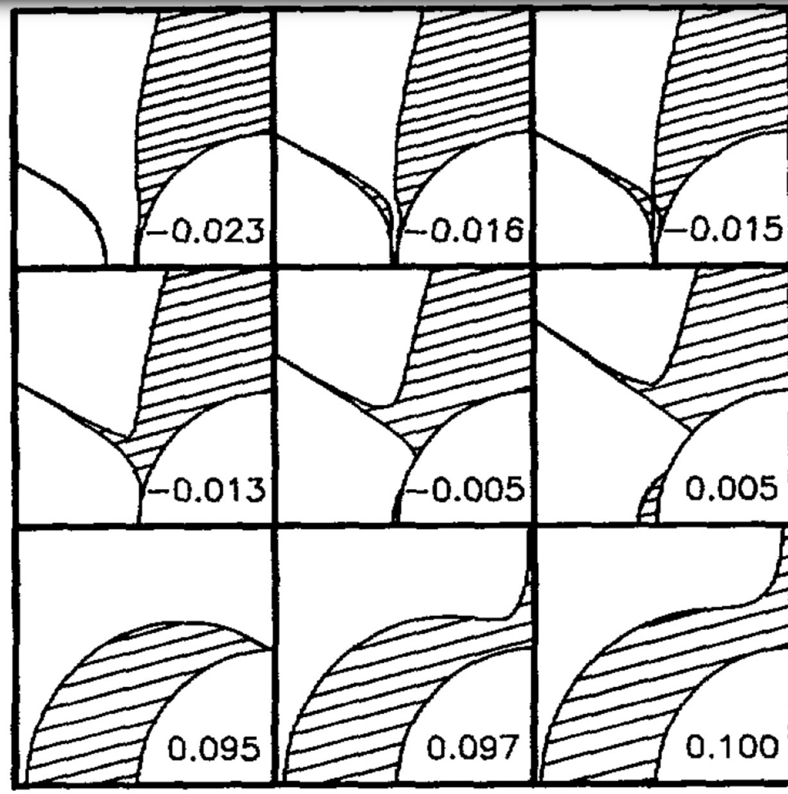


Fig. 2. — Plasma horizons in the MKN space-time with $\beta = 0.05$ and $a/M = 0.95$. Hatching denotes the unstable regions with $V_\alpha V^\alpha < 0$ as defined by equation (7). The black hole horizon is denoted by a quadrant in each figure. The values of e/M are shown with figures : $e/M > 0.095$ corresponds to the positive total charge of the black hole ; this case was discussed by Hanni [14] in detail.

Karas & Vokrouhlický

Plasma flow lines: guiding center approximation

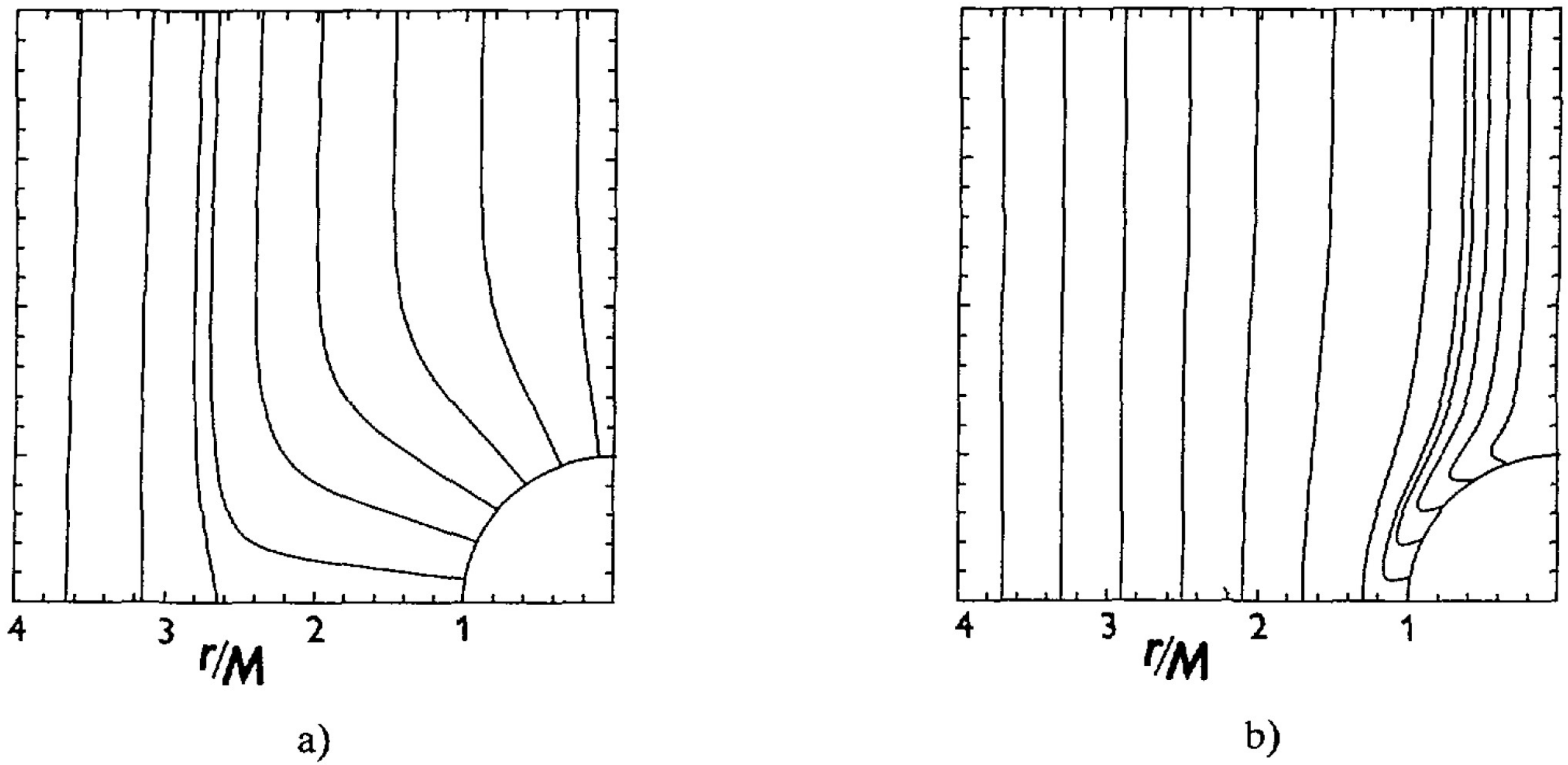


Fig. 3. — Typical configurations of the plasma flow lines near an extreme MKN black hole with $\beta = 0.018$, $a/M = 0.090$ (a), and $\beta = 0.05$, $a/M = 0.933$ (b).

…in asymptotically non-flat BH spacetimes

Conclusion

Vanishing cross section for plasma capture in asymptotically non-flat BH spacetimes

An important configuration is that with the vanishing cross section, $\mathcal{A} = 0$, because the accretion rate then goes to zero as well. One can verify that this is the case of an extreme black hole with a zero total electric charge or, in the limit of a weak magnetic field, $e = -2B_0 Ma$ ….. One obtains $\mathrm{d}r/\mathrm{d}\lambda = 0$, $\mathrm{d}\theta/\mathrm{d}\lambda \neq 0$ at $r = r_+$ just for the uncharged extreme configurations, in which the flow lines do not cross the horizon. This is in agreement with Wald's [25] results about selective accretion onto a black hole in the test field approximation. Analogous results can be obtained with exact expressions of reference [12] (nonlinearized in the magnetic field parameter); in this case the effective cross section vanishes for $e = -2B_0 Ma/(1 - B_0^2 e^2/4)$.

Thank you for attention