Magnetically arrrested disk around a black hole, and jet formation

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THE ACCRETION OF MATTER BY A COLLAPSING STAR IN THE PRESENCE OF A MAGNETIC FIELD

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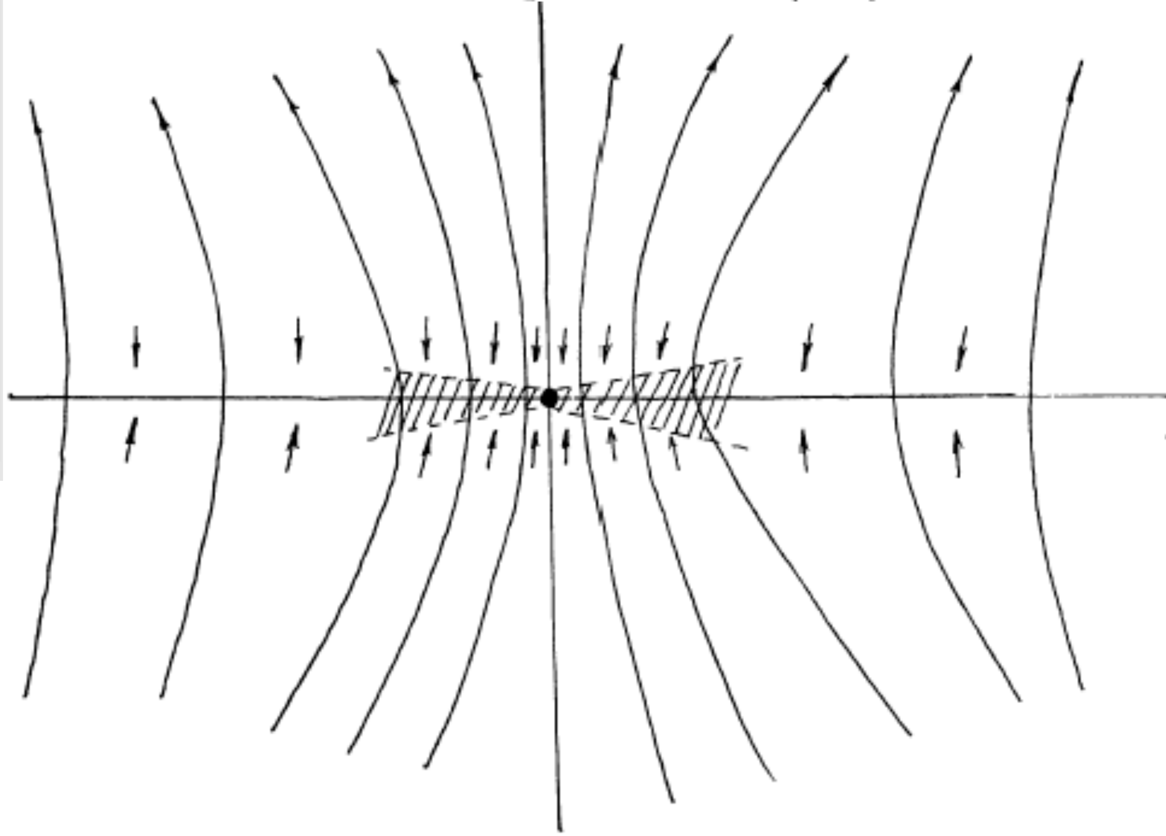


Fig. 1. A qualitative picture of the accretion of matter on to a c.s. with a frozen, regular magnetic field. Arrows indicate the direction of motion of the matter. The magnetic field far from the star lies in the direction of the z-axis and its sense is indicated by arrows on the lines of force. The infalling matter forms a disk in the plane $\theta = \pi/2$, which slowly settles to the star. In the flow region $E_B \sim E_{\rm kin}$, and rotation is entirely absent.

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\sqrt{-g}\,u_0^{-1}B^r\right)=0$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\sqrt{-g}\,u^r B^\theta\right)=0\,,$$

$$\frac{\mathrm{d}}{\mathrm{d}t}=\frac{\partial}{\partial t}+c\,\frac{u^r}{u^0}\,\frac{\partial}{\partial r}\,.$$

the Newtonian region

$$_R B=\left(1+\frac{3}{2}\,\frac{ct\sqrt{r_g}}{r^{3/2}}\right)^{4/3}B_0\cos\theta\,,$$

$$_\eta B=-\left(1+\frac{3}{2}\,\frac{ct\sqrt{r_g}}{r^{3/2}}\right)^{1/3}B_0\sin\theta\,.$$

$$\varepsilon_{ff} + \varepsilon_{fb} \approx 2 \cdot 10^{22} \, \rho T^{1/2} \text{ эрг г}^{-1}\text{с}^{-1}.$$

$$\varepsilon_{ff} \approx 2 \cdot 10^{16} \, \rho T \ln \frac{kT}{mc^2} \text{ erg g}^{-1}\text{s}^{-1}.$$

$$L_{ff} + L_{fb} = 4\pi \int_{r_{in}}^{\infty} \rho(\varepsilon_{ff} + \varepsilon_{ff}) r^2 dr \text{ erg s}^{-1}, \; r_{in} \approx 1.5 \, r_g.$$

e ~10^{-8}

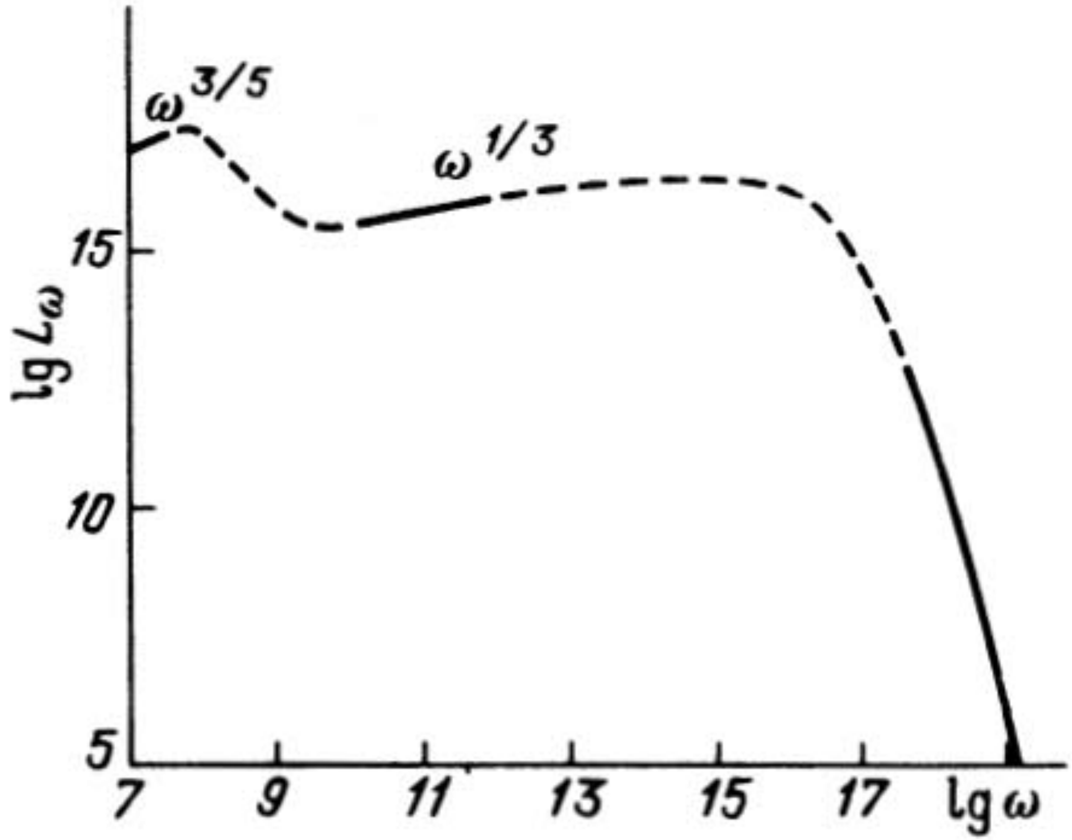
$$\rho = -\frac{\dot{M}}{4\pi r^2 v} = \frac{\dot{M}}{4\pi r^{3/2}\sqrt{GM}}, \quad T\frac{dS}{dr} = \frac{dE}{dr} - \frac{P}{\rho^2}\frac{d\rho}{dr} = \frac{Q_+ - Q_-}{v}.$$

Magnetic field, equipartition: $\frac{B^2}{8\pi} = \frac{1}{2}\rho v_r^2, \quad v_r = \alpha v_{ff} = \alpha\sqrt{\frac{2GM}{r}}, \quad \overline{B_\perp^2} = \frac{2}{3}\overline{B^2},$

$$\varepsilon_B = 2\frac{e^2}{m_p c}\left(\frac{eB_\perp}{m_e c}\right)^2 \frac{kT}{m_e c^2} \approx 0.46 \, T B_\perp^2 \text{ эрг г}^{-1}\text{с}^{-1} \text{ для } kT \ll m_e c^2 \quad (NR)$$

$$\varepsilon_B = 8\,\frac{e^2}{m_p c}\left(\frac{eB_\perp}{m_e c}\right)^2\left(\frac{kT}{m_e c^2}\right)^2$$
$$\approx 3.2 \times 10^{-10} \, T^2 B_\perp^2 \text{ erg g}^{-1}\text{s}^{-1} \text{ для } kT \gg m_e c^2 \quad (UR)$$

e ~ 0.1 (0.3 with heating at magnetic field annihilation)



Magneto-bremsstrahlung spectrum of a black hole of M = 10 Solar M, for a spherically symmetric accretion and random magnetic field, at

$$\rho_\infty = 10^{-24} \text{ g} \cdot \text{cm}^{-3},\ T_\infty = 10^4 \text{ K},\ \alpha^2 = 1/3.$$

The solid lines represent asymptotic dependencies, dashed lines give extrapolations.

THE ACCRETION OF MATTER BY A COLLAPSING STAR IN THE PRESENCE OF A MAGNETIC FIELD. II. SELFCONSISTENT STATIONARY PICTURE

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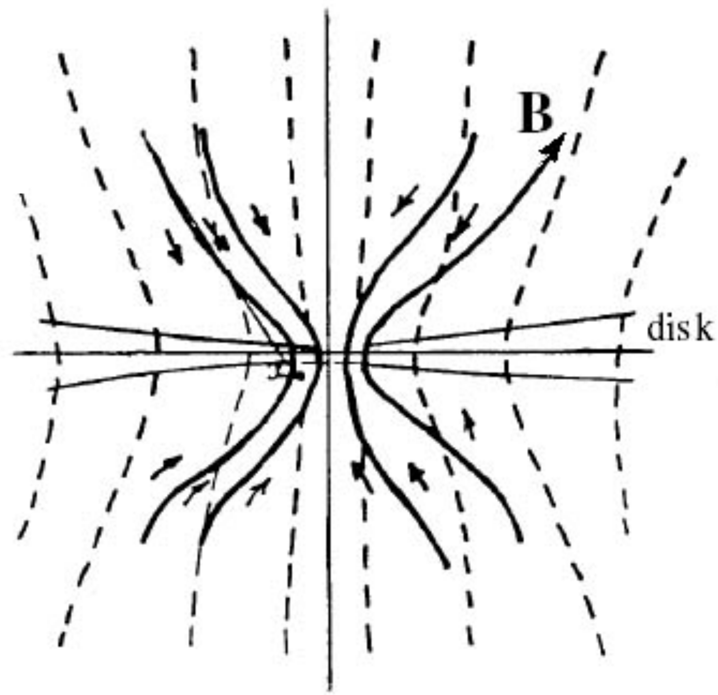


Sketch of the magnetic field threading an accretion disk.
Shown increase of the field owing to flux freezing in the accreting disk matter

At presence of large-scale magnetic field the efficiency of accretion is alvays large (0.3-0.5) of the rest mass energyflux

Self-similar solution for the stationary flow outside the symmetry plane

$$\upsilon_r \frac{\partial \upsilon_r}{\partial r} + \frac{\upsilon_\theta}{r}\frac{\partial \upsilon_r}{\partial \theta} - \frac{\upsilon_\theta^2}{r} = -\frac{GM}{r^2} - \frac{B_\theta}{4\pi\rho r}\left[\frac{\partial(rB_\theta)}{\partial r} - \frac{\partial B_r}{\partial \theta}\right],$$

$$\upsilon_r \frac{\partial \upsilon_\theta}{\partial r} + \frac{\upsilon_\theta}{r}\frac{\partial \upsilon_\theta}{\partial \theta} + \frac{\upsilon_r \upsilon_\theta}{r} = \frac{B_r}{4\pi\rho r}\left[\frac{\partial(rB_\theta)}{\partial r} - \frac{\partial B_r}{\partial \theta}\right],$$

$$\frac{1}{r}\frac{\partial}{\partial r}(r^2\rho\upsilon_r) + \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta\rho\upsilon_\theta) = 0\,,$$

$$\frac{1}{r}\frac{\partial}{\partial r}(r^2 B_r) + \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta\, B_\theta) = 0\,,$$

$$\upsilon_r B_\theta - \upsilon_\theta B_r = 0.$$

$$v_r = -\sqrt{2GM/r}\, f(\theta), \quad v_\theta = \sqrt{2GM/r}\, g(\theta), \quad \rho = \rho(\theta), \quad \mathbf{B} = a\rho\mathbf{v}, \;\; a = \text{const}.$$

$$f^2 + g^2 = 1.$$

$$f = \cos z, \quad g = \sin z \quad y = \frac{a^2}{4\pi}\rho = \frac{B^2}{4\pi\rho v^2}.$$

$$\frac{dy}{d\theta} = y(1-y)\frac{\cot z - \cot\theta}{\sin^2 z - y} \cdot \sin^2 z,$$

$$\frac{dz}{d\theta} = \frac{1}{2} - \frac{\sin z \cos z(\cot z - \cot\theta)}{\sin z - y} y$$

The only physically relevant solution: y=1

$$v_\theta = \pm \frac{B}{\sqrt{4\pi\rho}}.$$

$$\frac{dz}{d\theta} = \frac{3}{2} - \tan z \cdot \cot\theta; \quad \text{with the boundary condition} \quad z(0) = 0,$$

Accretion disk around BH with large scale magnetic field (non-rotating disk)

The Basic Equations for the Stationary Disc Structure in the Plane $\theta = \pi/2$

$$\frac{GM\Sigma}{r^2} \simeq \frac{1}{c} B_\theta I_\varphi \simeq \frac{2\pi}{c^2} I_\varphi^2, \qquad B_\theta \simeq B_r \simeq \frac{2\pi}{c} I_\varphi .$$

$$\frac{\mathrm{d}p}{\mathrm{d}z} \simeq \frac{\varrho GM}{r^2} \frac{z}{r}; \qquad h \simeq \left(\frac{r^3}{GM} \frac{p}{\varrho} \right)^{1/2} .$$

$$F = \frac{GM\dot{M}}{4\pi r^3} \left[1 + \frac{1}{2} \left(\frac{r}{R} \right)^{3/2} \right] \cdot \qquad 2F \simeq \frac{I_\varphi^2}{2h\sigma},$$

$$cCT^4 \simeq \kappa \Sigma F, \qquad 2F = \Sigma(\varepsilon_{ff} + \varepsilon_B),$$

Equation of state

Gas: $P = P_g = \rho \mathcal{R} T$ ($\mathcal{R}$ - Gas constant)

Radiation: $P = P_r = aT^4/3,$

Opacity, electron scattering $\kappa_e \approx 0.2(1+X)$

Krammers opasity: *ff+fb:* $\kappa_k \approx 2 \cdot 10^{24}\, \rho / T^{7/2}$

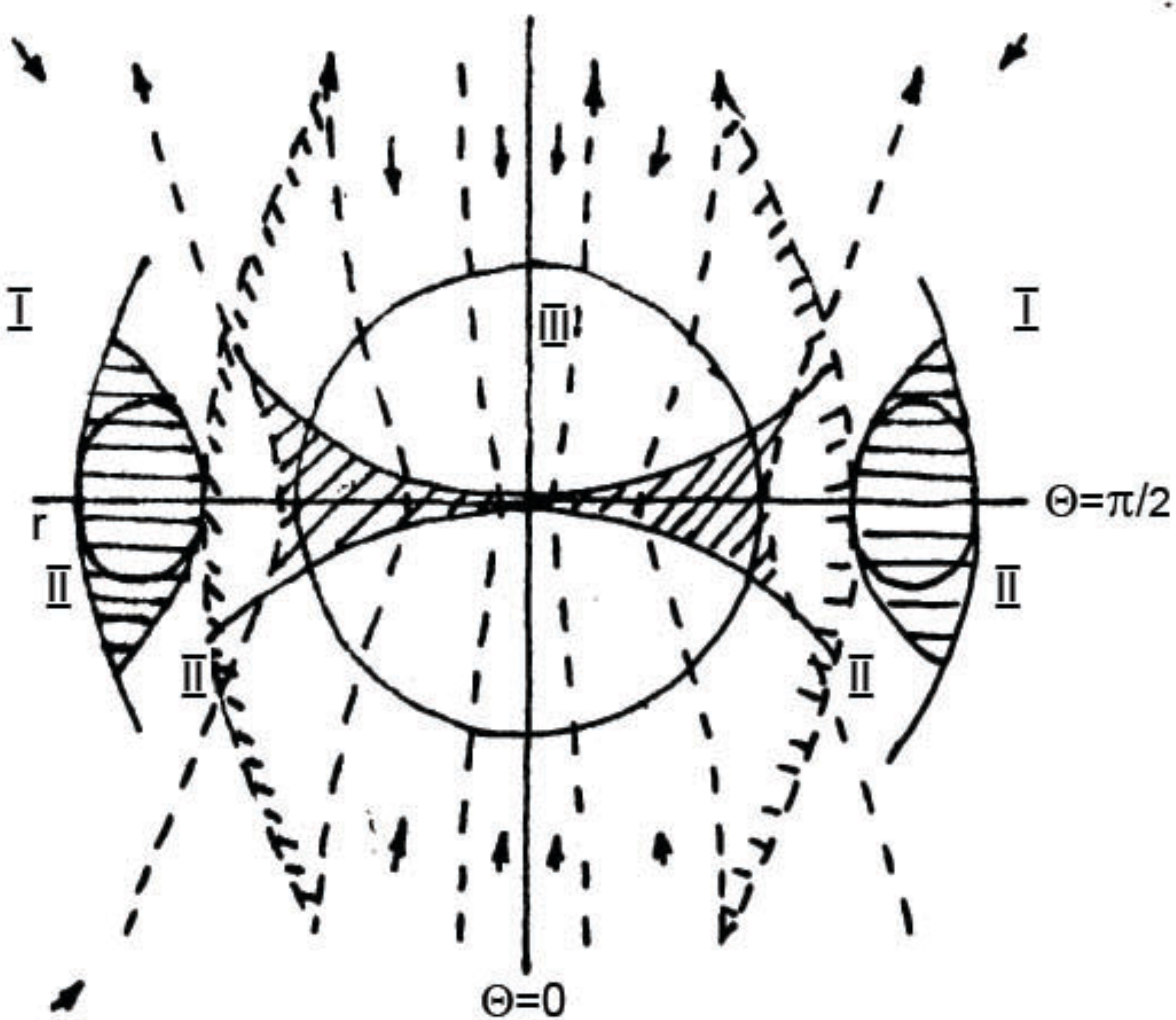
Turbulent electrical conductivity, analog of alpha viscosity

$$\sigma_t = \frac{c^2}{\tilde{\alpha} 4\pi h \sqrt{P/\varrho}},$$

$$L \simeq \tfrac{1}{2}\dot{M}c^2 \simeq 5 \times 10^{31}\ m^2\xi$$

$$\xi = \left(\frac{\varrho_\infty}{10^{-14}\ \mathrm{g\ cm^{-3}}}\right)\left(\frac{T_\infty}{10^4\ \mathrm{K}}\right)^{3/2}$$

$$B = 10^9\ \mathrm{Gs}\ m^{-1/2} x^{3/4} \alpha^{-1/2},$$



I
I
III
Θ=π/2
r
II
II
II
II
Θ=0

Magnetically Arrested Disk: an Energetically Efficient Accretion Flow

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Lucky name for the old model

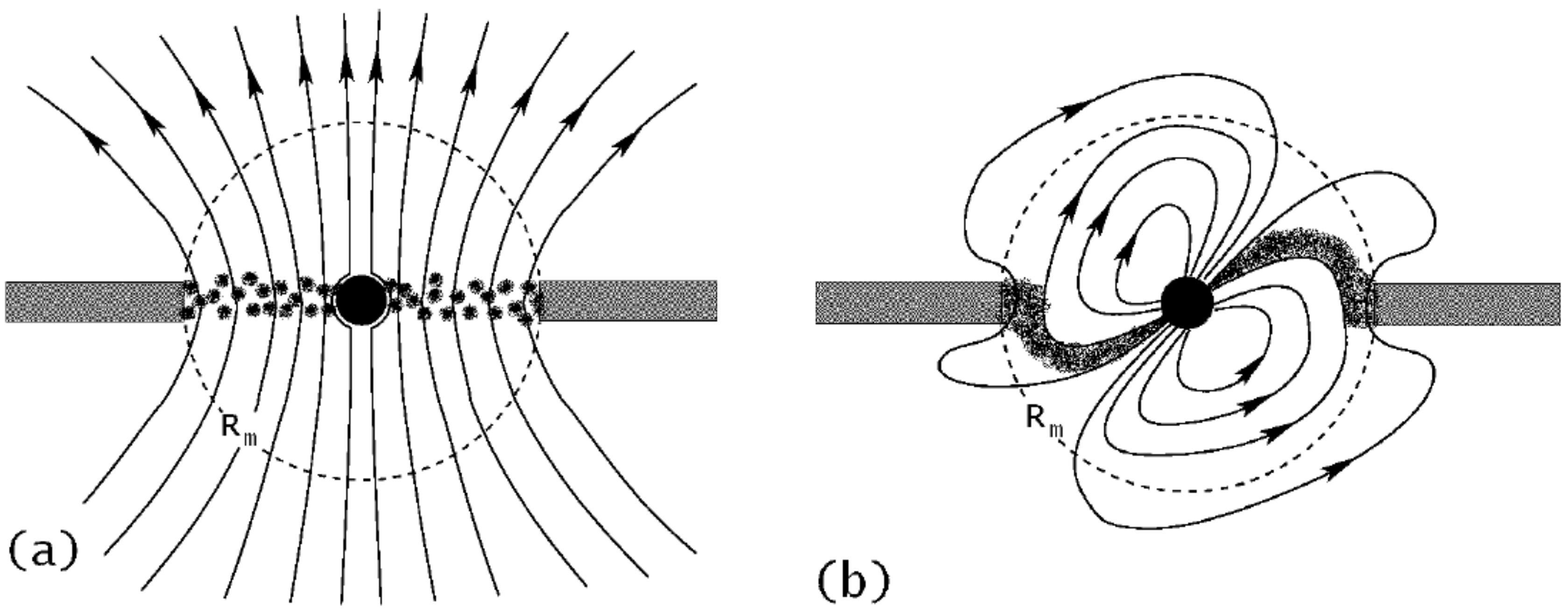
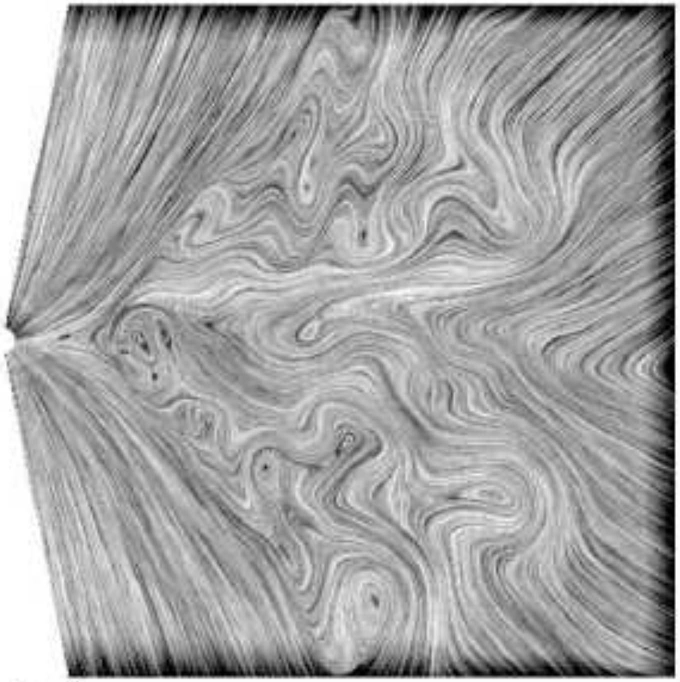


Fig. 1. (a) The basic elements of the proposed accretion model. An axisymmetric accretion disk is disrupted at a magnetospheric radius R_{m} by a strong poloidal magnetic field which has accumulated at the center. Inside R_{m} the gas accretes as magnetically confined blobs which diffuse through the field with a relatively low velocity. Surrounding the blobs is a hot low-density corona. (b) The accretion flow around a magnetized compact star. An axisymmetric disk is disrupted at the magnetospheric radius R_{m} by the strong stellar field. Inside R_{m} the gas follows the magnetic field lines and free-falls on the polar caps of the star.

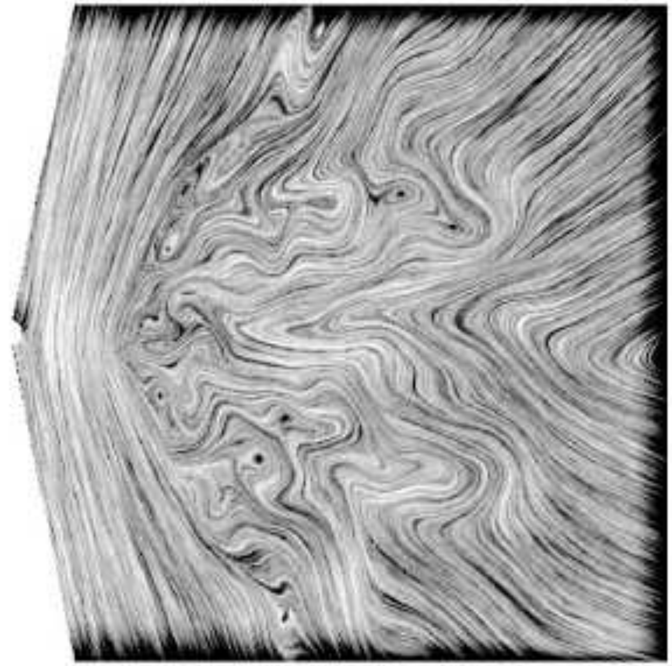
Numerical simulations of MAD

Igumenshchev, I.V. Astrophys. J. 2008,524 677, 317-326.

MAGNETICALLY ARRESTED DISKS AND THE ORIGIN OF POYNTING JETS: A NUMERICAL STUDY



(b)



(a)

Snapshot of magnetic lines in model with $\beta_{ing} = 100$, at two subsequent moments. The BH is located on the left, and the small open circle corresponds to the inner boundary around the black hole at $R_{in} = 2\,R_g$. The axis of rotation is in the vertical direction. The domain in the figure has a radial size $100\,R_g$ along the equatorial plane and represents a fraction of the full computational domain with $R_{out} = 220\,R_g$. The poloidal field lines lying in the meridional plane are shown. The accretion disk transports the vertical magnetic flux inward, which accumulates in the vicinity of the black hole. Small-scale magnetic loops are the result of turbulent motions in the disk and disk corona. (a) Period of accretion, in which most of the accumulated magnetic flux is outside the black hole horizon. (b) Accretion period, in which all the accumulated flux goes through the horizon, [30].

Two-temperature, Magnetically Arrested Disc simulations of the jet from the supermassive black hole in M87

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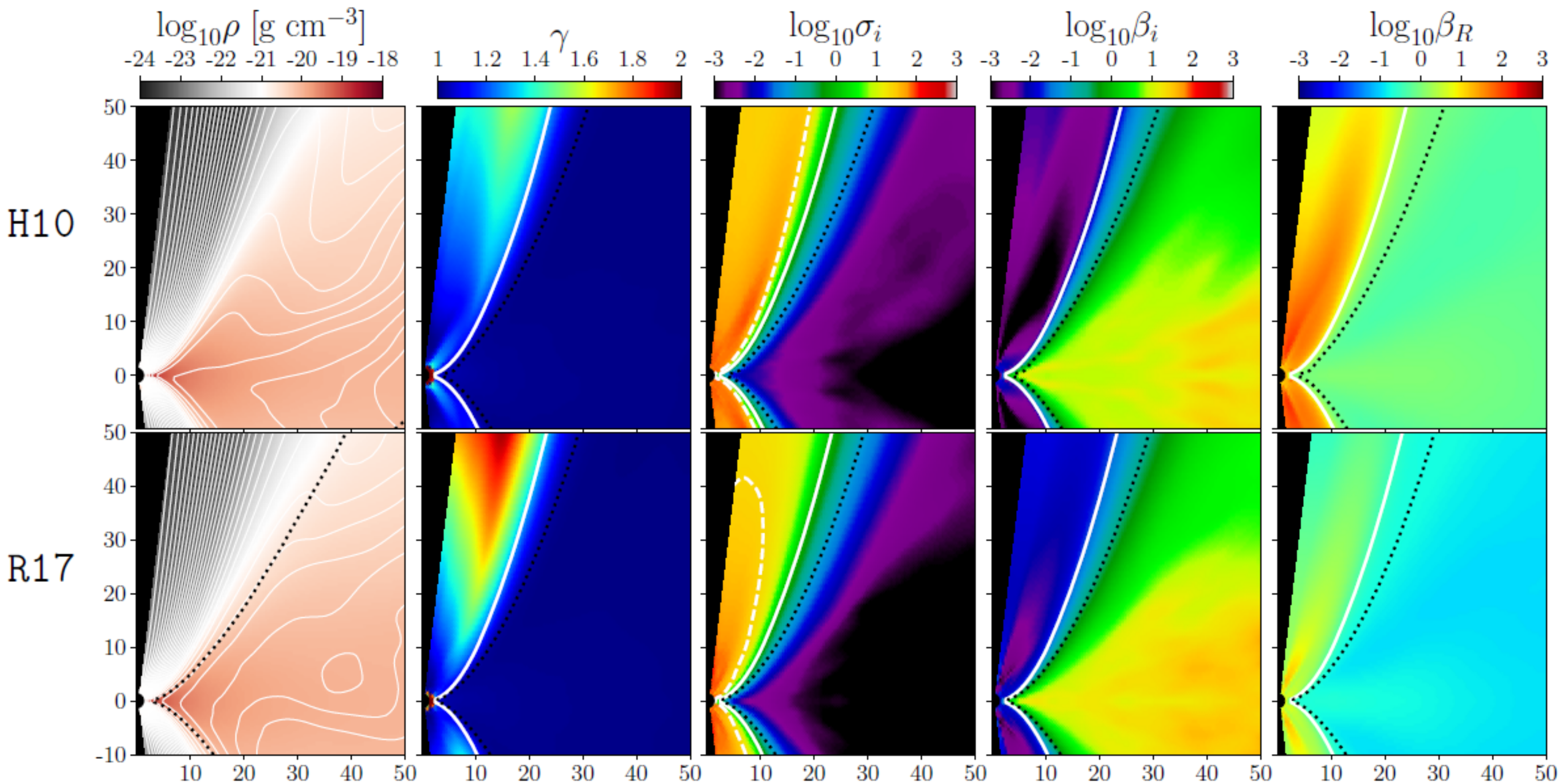

Figure 4. Additional time- and azimuth-averaged properties of the two simulations. From left to right, the quantities displayed are the density ρ in g cm^{-3}, the bulk Lorentz factor γ, the plasma magnetization $\sigma_{\rm i}$, the ratio of ion thermal pressure to magnetic pressure $\beta_{\rm i}$, and the ratio of radiation pressure to thermal pressure β_R. In the first column, white contours show the poloidal magnetic field in the averaged data. In the remaining columns, the solid white contour denotes the $\sigma_{\rm i}$=1 surface. The dashed black contour shows the Be = 0.05 surface defining the jet boundary. The dashed white contour in the third panel shows the $\sigma_{\rm i}$=25 surface; this is the maximum $\sigma_{\rm i}$ included in the radiative transfer (see Section 3.3).

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MDPI

Review

Accretion into Black Hole, and Formation of Magnetically Arrested Accretion Disks

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Quasars and AGN contain supermassive black holes

About 10 HMXR - stellar mass black holes in the Galaxy: microquasars.

Jets are observed in objects with black holes: collimated ejection from accretion disks.

Jet in M87:

radio, 14GHz, **VLA**, 0.2”

HST (F814W)

Chandra image, 0.2”,

0.2-8 keV

Adaptively smoothed

Chandra image

From

Marshall et al. (2001)

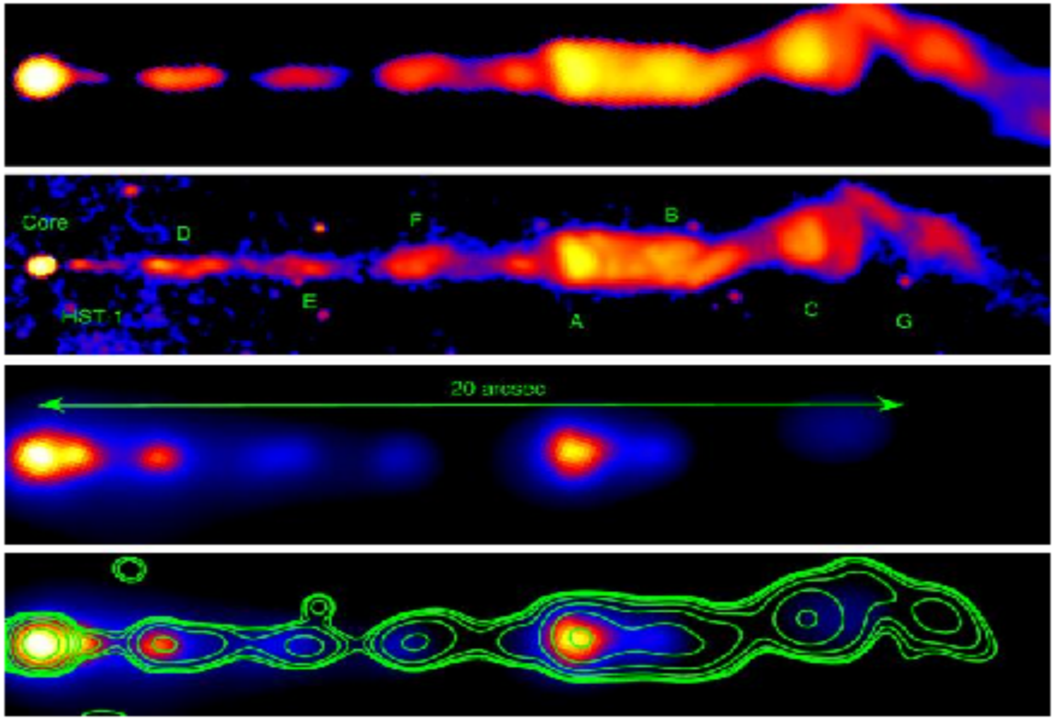


Fig. 1.— Images of the jet in M 87 in three different bands, rotated to be horizontal, and an overlay of optical contours over the X-ray image. *Top:* Image at 14.435 GHz using the VLA. The spatial resolution is about 0.2″. *Second panel:* The *Hubble* Space Telescope Planetary Camera image in the F814W filter from Perlman et al. (2001a). The brightest knots are labelled according to the nomenclature used by Perlman et al. (2001a) and others. *Third panel:* Adaptively smoothed *Chandra* image of the X-ray emission from the jet of M 87 in 0.20″ pixels. The X-ray and optical images have been registered to each other to about 0.05″ using the position of the core. *Fourth panel:* Smoothed *Chandra* image overlaid with contours of a Gaussian smoothed version of the HST image, designed to match the *Chandra* point response function. The X-ray and optical images have been registered to each other to about 0.05″ using the position of the core. The HST and VLA images are displayed using a logarithmic stretch to bring out faint features while the X-ray image scaling is linear.

3C 273

Left:

MERLIN, 1.647 GHz.

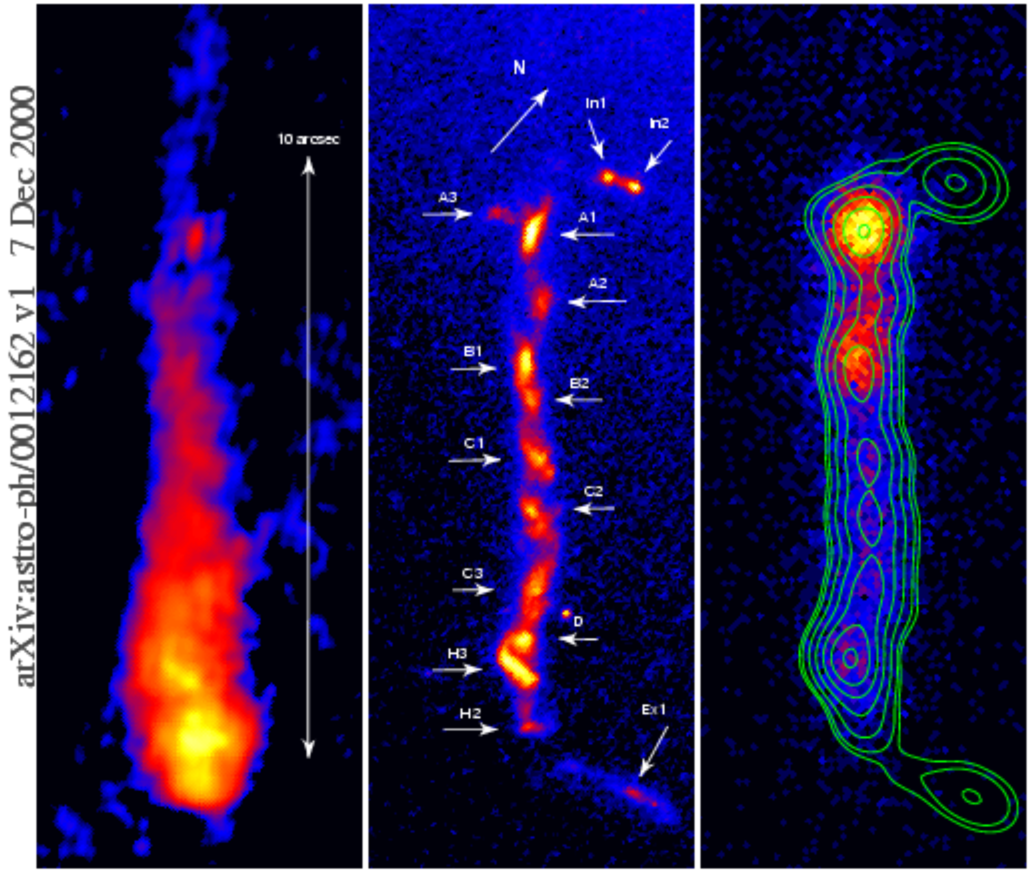
Middle:

HST(F622W), 6170A.

Right:

Chandra, 0.1 “

Marshall et al. (2000)



The end