Plasma accretion near black holes

Jaroslav Hamerský

Astronomical Institute of the Czech Academy of Sciences

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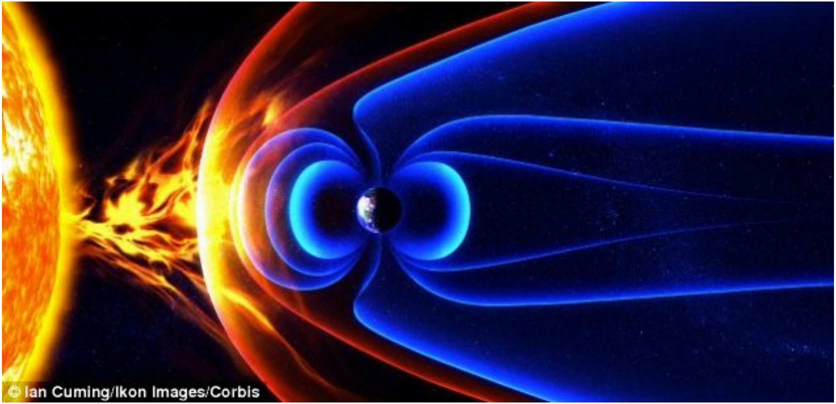
Outline

1. Plasma in the Universe
2. General relativistic MHD
3. Accretion disc

Magnetospheres of planets



Credit: Ian Cuming

Sun

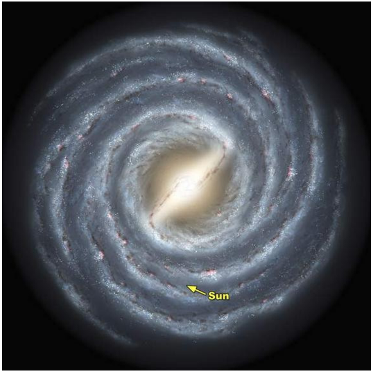
Sun

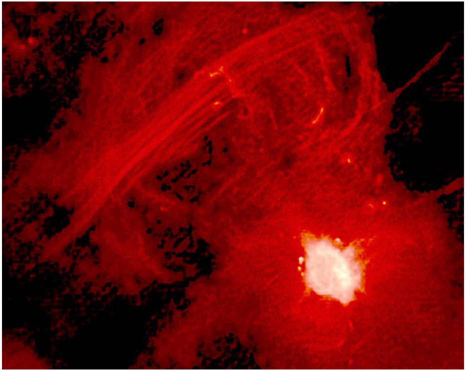
- G-type main-sequence star
- 99% of the mass of the Solar system
- Population I (heavy-element-rich star), Au, U
- Primarily from H and He, metals - less than 2%

Sun

- Core
  - $20 - 25\%$ of the Solar radius
  - Density up to $150 g \cdot cm^{-3}$
  - Temperature $T \sim 15 \cdot 10^6 K$
- Radiative zone, Tachocline, Convective zone
- Photosphere - visible surface of the Sun (5 800K)
- Chromosphere
- Corona - visible during a Solar eclipse, $T \sim 1 \cdot 10^6 - 6 \cdot 10^6 K$

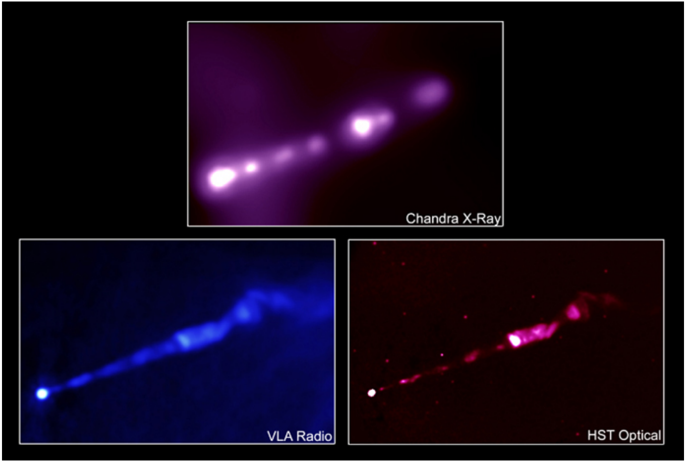
Galaxies





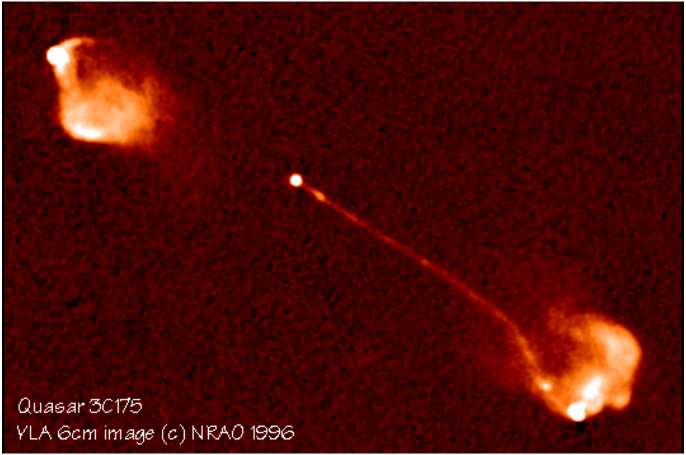
Credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech), F. Yussef-Zadeh et al., VLA, NRAO.

Galaxies



Jet from the radio galaxy Virgo A in different bands. Source: http://physweb.bgu.ac.il

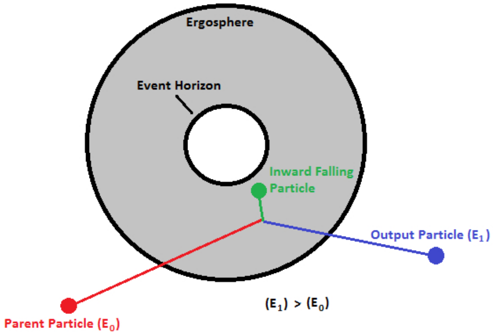
Galaxies



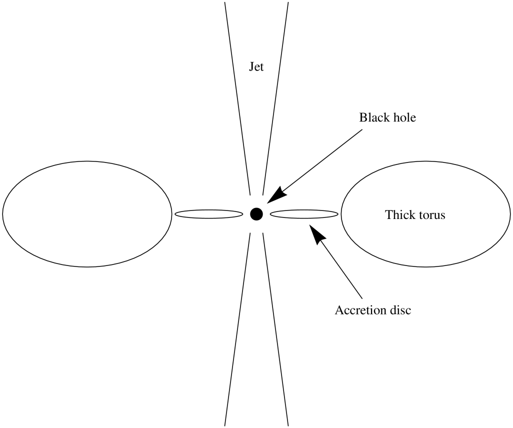
Jet from the quasar 3C175. Source: http://physweb.bgu.ac.il

Which mechanism drives jets?

- Blanford-Znajek mechanism and Penrose process

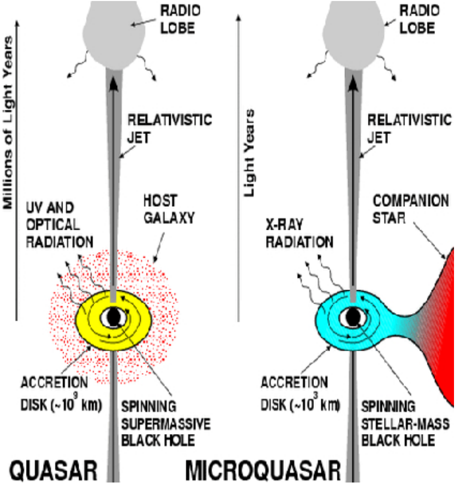


Active Galactic Nuclei



Schematic ilustration of AGN

Quasar and microquasar



Quasars and other AGN

- Supermassive BH at centres of galaxies ($M_{BH} = 10^6 - 10^9 M_{\odot}$)
- Temperature in SMBH accretion discs: $T = 10^5 - 10^2 K$
- Accretion produces radiative power that often outshines the host galaxy
- Accretion disc is surrounded by moving gas clouds and large torus of gas and dust
- Very fast jets (almost speed of light) emerge from many AGN

Quasars and other AGN

- Black hole accretion in quasars is the most powerful and efficient stationary engine in the universe
- High angular momentum of rotating matter is transported outwards by stresses
- It allows matter to move inwards
- Gravitational energy is converted to heat
- Accretion disc physics: gravity, hydrodynamics, viscosity, radiation and magnetic fields

Quasars and other AGN

- More than 200 000 quasars are known
- Redshifts between 0.06 and 7.1 $\rightarrow 6 \cdot 10^8 - 29 \cdot 10^9$ light years away
- Luminosities are typically $10^{12} L_\odot$
- Typical luminosity: $L \sim 10^{40} watts$

MHD equations

- Conductive fluids can support magnetic field
- Magnetic fields act on the fluid (plasma)
- Nonrelativistic MHD equations: conservation laws of mass, momentum and energy together with the induction equation
  - $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$
  - $\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \vec{j} \times \vec{B} + \nabla \cdot \sigma$
  - $\frac{\partial \rho}{\partial t} + \vec{v} \cdot \nabla p + \gamma p \nabla \cdot \vec{v} = Q$
  - $\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} = \nabla \times (\vec{v} \times \vec{B}) + \eta \nabla^2 \vec{B}$

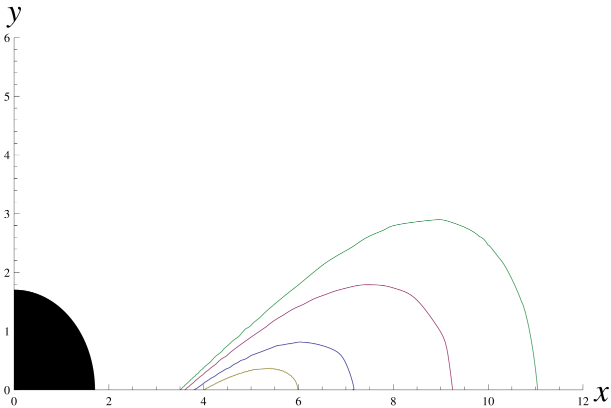
MHD in general relativity

- Conservation of mass:
  $\partial_t(\sqrt{-g}\rho_0 u^t) = -\partial_i(\sqrt{-g}\rho_0 u^i)$ $\partial_t \rho = -\nabla \cdot (\rho v)$
- Ideal MHD:
  $u_\mu F^{\mu\nu} = 0$ $E + v \times B/c = 0$
- Energy and momentum conservation:
  $\partial_t(\sqrt{-g}T^t{}_\nu) =$
  $-\partial_i(\sqrt{-g}T^i{}_\nu) + \sqrt{-g}T^\kappa_\lambda \Gamma^\lambda_{\nu\kappa}$ $\partial_t(\rho v) = -\nabla \cdot T - \rho \nabla \phi$
- Induction equation:
  $\partial_t(\sqrt{-g}B^i) =$
  $-\partial_j(\sqrt{-g}(u^j b^i - b^j u^i))$ $\partial_t B = -\nabla(vB - Bv)$
- No monopoles constraint:
  $\partial_i(\sqrt{-g}B^i) = 0$ $\nabla \cdot B = 0$

Stationary solution

- The energy-momentum tensor of an ideal fluid:
  - $T^{\mu\nu} = (\rho_0 + p + u)u^\mu u^\nu + pg^{\mu\nu}$
- Assuming a steady state and $\mathcal{L}_\xi u^\mu = 0$:
  - $T^{\mu\nu}_{\ ;\nu} = 0 \rightarrow \frac{p_{,\mu}}{p+\epsilon} = (\ln u^t)_{,\mu} - \frac{l\Omega_{,\mu}}{1-\Omega l}$ - relativistic Euler equation
- Final equation for the torus:
  - $W - W_{\mathrm{in}} \equiv \ln u_t - \ln u_{t\mathrm{in}} - \int_{l_{in}}^{l} \frac{\Omega \mathrm{d}l}{1-\Omega l} = -\int_0^p \frac{\mathrm{d}p}{p+\epsilon}$

Equipotential surfaces of the disc

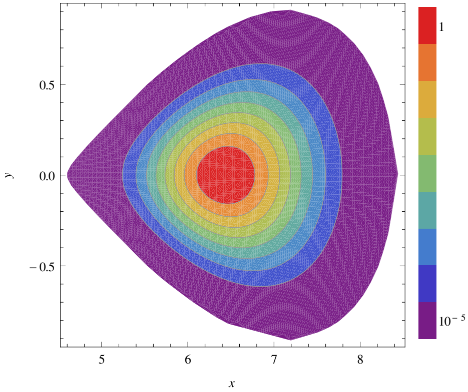


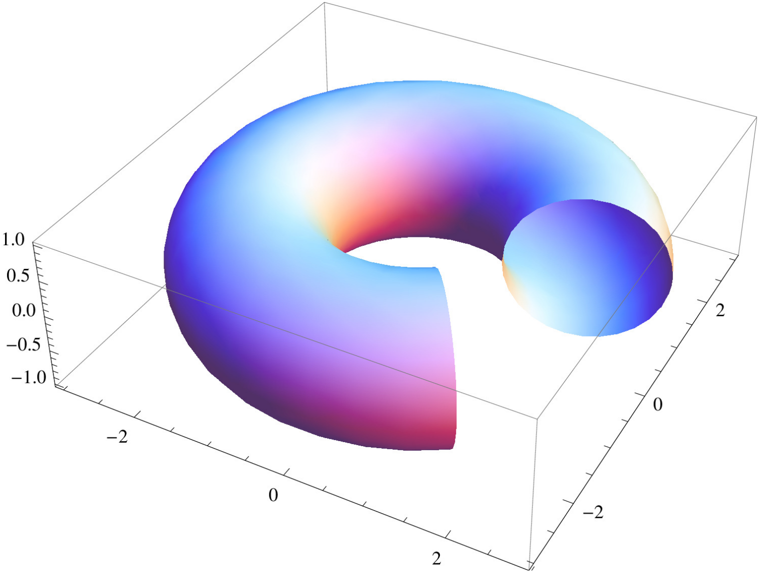
Spin $a = 0.5$. The inner edge is at $R_{\mathrm{in}} = 3.5, 3.6, 3.8, 4.0$.

Evolution equations

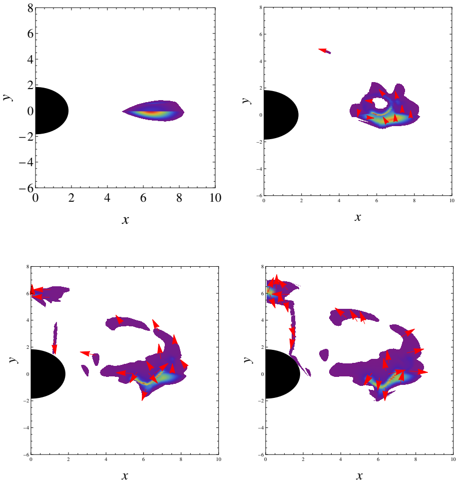
- Conservation laws
  - $T^{\mu\nu} = (\rho_0 + u + p + b^2)u^\mu u^\nu + \left(p + \frac{b^2}{2}\right) g^{\mu\nu} - b^\mu b^\nu$
  - $T^{\mu\nu}_{\ ;\nu} = 0 \rightarrow 4$ equations
  - $(\rho_0 u^\mu)_{;\mu} = 0 \rightarrow 1$ equation
  - $F^{\mu\nu}_{\ ;\nu} = 0 \rightarrow 3$ evolution equations and constraint div $B = 0$
- Force-free constraint: $F^{\mu\nu} u_\nu = 0$
- Equation of state $p = \kappa {\rho_0}^\gamma$

Stationary distribution of mass



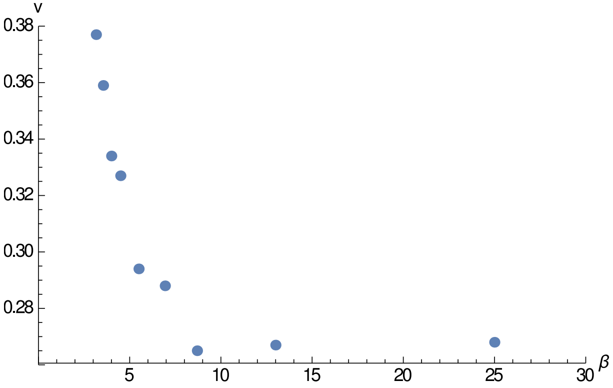

1.0
0.5
0.0
−0.5
−1.0
−2
0
2
2
0
−2

Mass accretion and ejection



$t = 0, 15, 19, 20, \beta = 5.5$

Dependence of outflow velocities on magnetization



Maximal value of vertical outflow velocity.

Thank you for your attention!