Magnetic null points in the magnetosphere of a plunging neutron star

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Outline

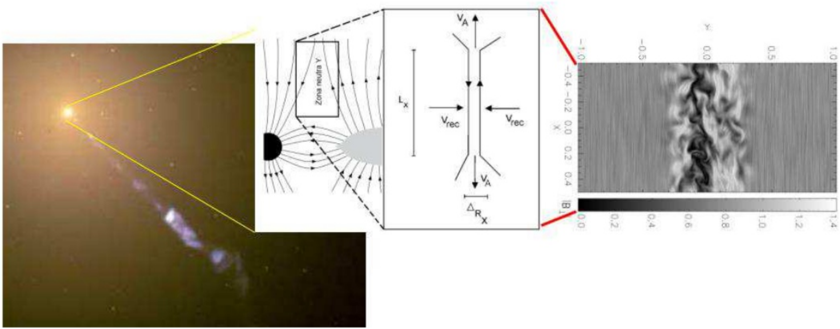


Figure: From left to right: HST image of the M87 with the astrophysical jet emerging from AGN; sketch of the magnetic field structure at the inner edge of the accretion disk with the reconnection zone; 3D MHD simulation of magnetic reconnection. Credit: Elisabete M. de Gouveia Dal Pino and Grzegorz Kowal (2013).

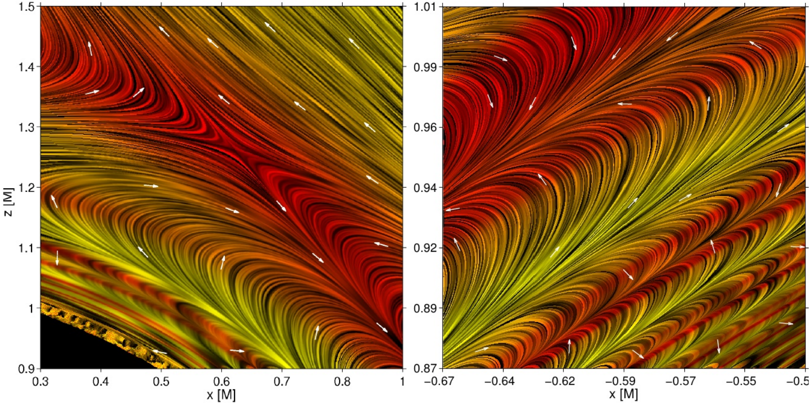


Figure: X-type magnetic null point in the vacuum magnetosphere of a rotating (Kerr) black hole immersed into asymptotically uniform magnetic field inclined with respect to the spin axis (left) and detail of the complex field structure just above the horizon (right).

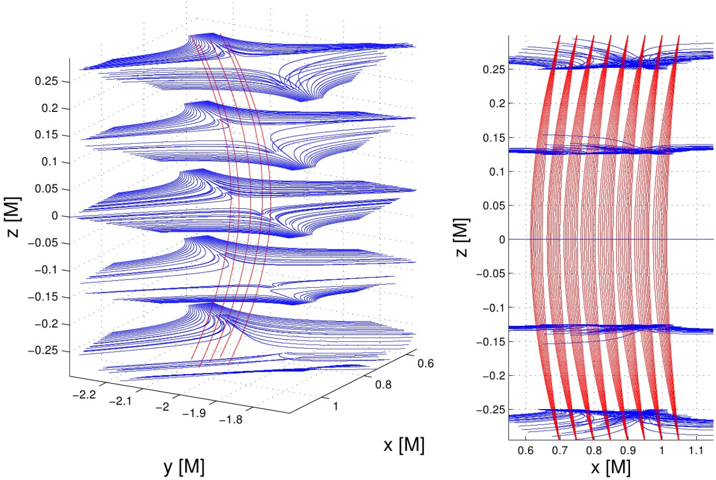
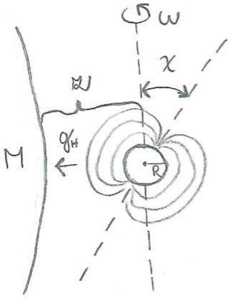


Figure: Behaviour of the electric field (red lines) in the vicinity of the magnetic null point located in the equatorial plane (blue lines). Charged matter injected to the separator site would be accelerated outside the equatorial plane.

Magnetosphere of a plunging neutron star



- idealized electro-vacuum magnetosphere of a neutron star (superconducting sphere with radius R) plunging into static supermassive black hole (of mass M)
- source of the EM field is modeled as an inclined (angle χ) rotating (frequency ω) magnetic dipole

Magnetosphere of a plunging neutron star

- we employ Rindler approximation of the Schwarzschild metric: no curvature, just acceleration (horizon surface gravity g_H)
- approximation is valid only in the vicinity of the horizon (D'Orazio & Levin, 2013, Macdonald & Suen, 1985)
- Minkowski and Rindler metric (acceleration along z-axis)

$$\begin{aligned} ds^2 &= -dT^2 + dX^2 + dY^2 + dZ^2 \\ &= -\alpha^2 dt^2 + dx^2 + dy^2 + dz^2, \end{aligned}$$

with lapse function $\alpha = g_H z$ and coordinate transformation:

$$T = z \sinh(g_H t),\;\; X = x,\;\; Y = y,\;\; Z = z \cosh(g_H t).$$

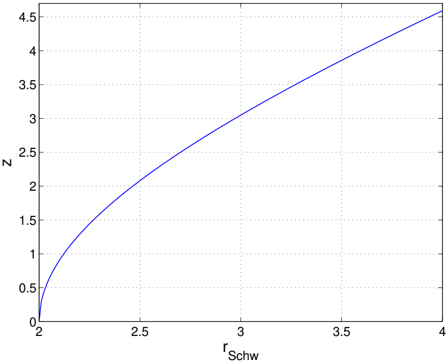


Figure: Rindler coordinate z, measuring the proper distance from the event horizon of the black hole, as a function of the Schwarzschild radial coordinate r_s.

$$z = \int_2^{r_s} \frac{\mathrm{d}r}{\sqrt{1-2/r}} = \log\left(\frac{\sqrt{1-2/r_s}+1}{|\sqrt{1-2/r_s}-1|}\right) + r_s\sqrt{1-2/r_s}$$

Spatial distance from the dipole is expressed in Rindler coordinates as follows:

$$r = \sqrt{x^2 + y^2 + (z\,\cosh(g_H t) - Z_s)^2},$$

and retarded time τ is given as:

$$\tau = T - r = z\,\sinh(g_H t) - \sqrt{x^2 + y^2 + (z\,\cosh(g_H t) - Z_s)^2}\,.$$

resulting in the magnetic field given in near zone as:

$$\begin{aligned}
B_x &= \frac{m}{r^5}\left\{\cosh(g_H t)\left[\sin(\chi)\left\{3\,x\,[x\,\cos(\omega\tau) + y\,\sin(\omega\tau)] - r^2\,\cos(\omega\tau)\right\} + 3\,(z\,\cosh(g_H t) - Z_s)\,x\,\cos(\chi)\right]\right.\\
&\quad -\omega\,\sinh(g_H t)\left[(z\,\cosh(g_H t) - Z_s)\sin(\chi)\left\{\frac{5\,R^2\,y}{r^2}(x\,\cos(\omega\tau) + y\,\sin(\omega\tau)) + (r^2 - R^2)\,\sin(\omega\tau)\right\}\right.\\
&\quad \left.\left. + R^2\,y\,\cos(\chi)\left(\frac{5\,(z\,\cosh(g_H t) - Z_s)^2}{r^2} - 1\right)\right]\right\},\\
B_y &= \frac{m}{r^5}\left\{\cosh(g_H t)\left[\sin(\chi)\left\{3\,y\,[x\,\cos(\omega\tau) + y\,\sin(\omega\tau)] - r^2\,\sin(\omega\tau)\right\} + 3\,(z\,\cosh(g_H t) - Z_s)\,y\,\cos(\chi)\right]\right.\\
&\quad +\omega\,\sinh(g_H t)\left[(z\,\cosh(g_H t) - Z_s)\sin(\chi)\left\{\frac{5\,x\,R^2}{r^2}(x\,\cos(\omega\tau) + y\,\sin(\omega\tau)) + (r^2 - R^2)\,\cos(\omega\tau)\right\}\right.\\
&\quad \left.\left. + R^2\,x\,\cos(\chi)\left(\frac{5\,(z\,\cosh(g_H t) - Z_s)^2}{r^2} - 1\right)\right]\right\},\\
B_z &= \frac{m}{r^5}\left[3\,(z\,\cosh(g_H t) - Z_s)\,\sin(\chi)\,[x\,\cos(\omega\tau) + y\,\sin(\omega\tau)] + \cos(\chi)\left(3\,(z\,\cosh(g_H t) - Z_s)^2 - r^2\right)\right],
\end{aligned}$$

where the radiative terms are dropped.

Magnetic null points near plunging neutron star

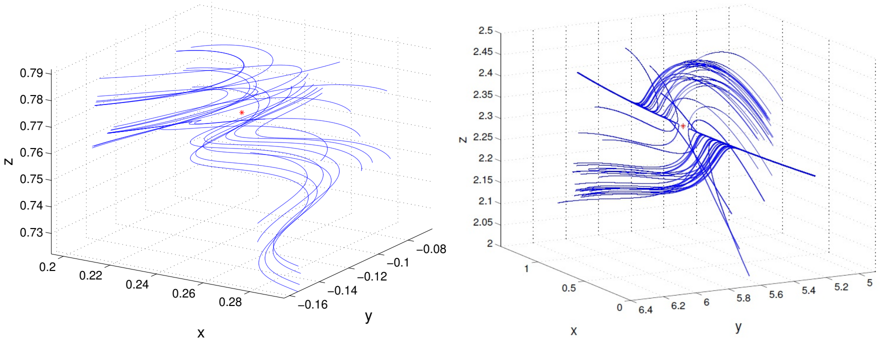


Figure: Structure of the magnetic field lines in the vicinity of the numerically located null points (red mark).

Magnetic null points near plunging neutron star

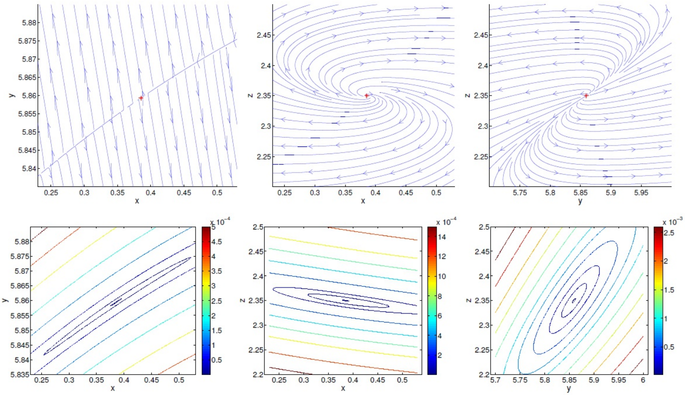
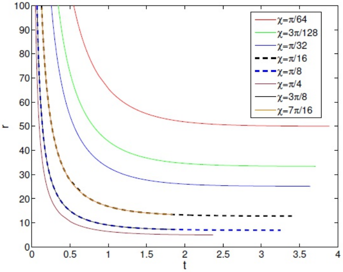


Figure: Two-dimensional sections of the magnetic field lines and iso-contours of the field strength in the vicinity of the null point (red mark) located at $x_0 = 0.39$, $y_0 = 5.86$ and $z_0 = 2.35$.

Magnetic null points near plunging neutron star



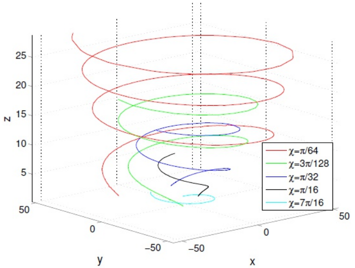


Figure: Location of the magnetic null points with respect to Rindler coordinate time t for different inclination angles χ.

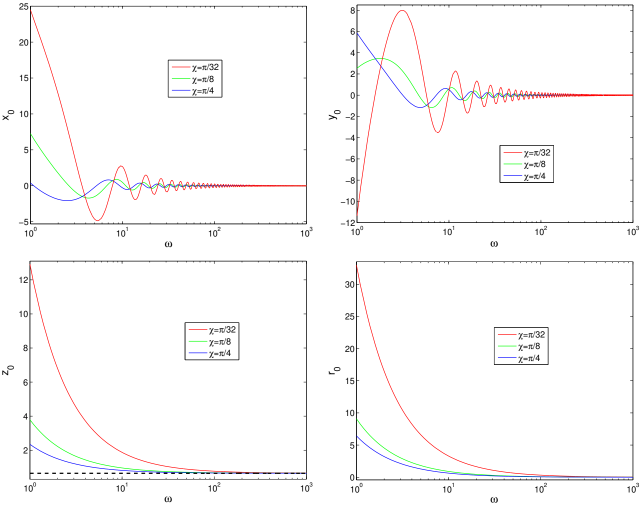


Figure: Rindler coordinates x_0, y_0, z_0 and the distance from the dipole r_0 of the magnetic null point as a function of the rotation frequency ω for several values of the inclination angle χ. Dashed line in the bottom left panel indicates the current location of the plunging neutron star at $z = 0.648$. Remaining parameters of the model are fixed as: $Z_s = 1$, $g_H t = 1$ and $R = 10^{-5}$.

Conclusions

- **magnetic null points** may emerge near plunging neutron star even without presence of any charged matter or currents
- **essential** ingredients **for the formation of null points**: (i) **non-axisymmetry** (inclination of the dipole), (ii) **rotation** of the dipole and (iii) **strong gravity**
- in the presence of plasma, **gravity** could actively **support** the process of **magnetic reconnection and particle acceleration** in the magnetospheres of compact objects
- the model is **compatible** with the conditions encountered in **realistic systems**
- neutron star plunging into a supermassive black hole - **EMRI** scenario of gravitational wave source detectable by **LISA**
- more details in Kopáček et al. 2018, 2019