Astrophysical processes around magnetized black hole

Martin Kološ, Arman Tursunov, Zdeněk Stuchlík
Silesian University in Opava, Czech Republic   martin.kolos@fpf.slu.cz

Relativistic Astrophysics Group

SLEZSKÁ UNIVERZITA V OPAVĚ

Black hole and uniform magnetic field

We study dynamics of charged test particles in vicinity of a **black hole** immersed into an asymptotically uniform external **magnetic field**. Real magnetic field generated by accretion disk around black hole will be far away from to be completely regular and uniform, uniform magnetic field is used as linear approximation.

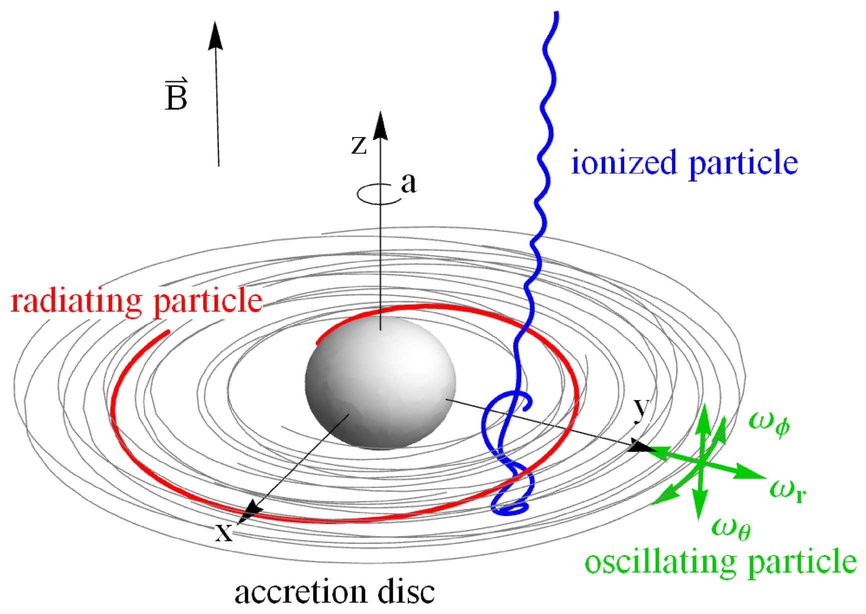
Gravity $g_{\mu\nu}$:
axially symmetric spacetime (Kerr BH)

$$\mathrm{d}s^2 = g_{tt}\mathrm{d}t^2 + 2g_{t\phi}\mathrm{d}t\mathrm{d}\phi + g_{\phi\phi}\mathrm{d}\phi^2 + g_{rr}\mathrm{d}r^2 + g_{\theta\theta}\mathrm{d}\theta^2$$

Magnetic field A_α:
external uniform magnetic field B,
electromagnetic 4-vector

$$A_\phi = \frac{B}{2}(g_{\phi\phi} + 2ag_{t\phi}) - \frac{Q}{2}g_{t\phi}$$
$$A_t = \frac{B}{2}(g_{t\phi} + 2ag_{tt}) - \frac{Q}{2}g_{tt} - \frac{Q}{2},$$

(non-charged black hole $Q = 0$ or
BH with Wald charge $Q = Q_W \equiv 2Ba$)



The motion of a charged particle with charge q and mass m in Kerr black hole spacetime with mass M and spin a in the presence of uniform magnetic field $\mathcal{B}$ can be treated by the Lorentz equation

$$\frac{\mathrm{d}u^\mu}{\mathrm{d}\tau} + \Gamma^\mu_{\alpha\beta}u^\alpha u^\beta = \frac{q}{m}g^{\mu\rho}F_{\rho\sigma}u^\sigma, \qquad g_{\mu\nu}u^\mu u^\nu = -1,$$

where $u^\mu = dx^\mu/d\tau$ is the four-velocity of the particle, $\Gamma^\mu_{\alpha\beta}$ are Christoffel symbols for Kerr black hole metric and $F_{\mu\nu}$ is tensor of electromagnetic field. The magnetic fields B is weak (it does not contribute to the metric), but magnetic field influence on the charged particles motion can be really large (specific charge). The "charged particle" can represent matter ranging from electron to some charged inhomogeneity orbiting in the innermost region of the accretion disk. The charged particle specific charges q/m for any such structures will then range from the electron maximum to zero. Dimensionless quantity $\mathcal{B}$ (magnetic parameter) can be identified as relative Lorenz force:

$$\mathcal{B} = \frac{qBGM}{2mc^4}$$

	electron	proton	Fe+	charged dust
$\mathcal{B} = 0.004$	10^{-5} Gs	0.02 Gs	1 Gs	10^9 Gs

For stellar mass black hole $M \approx 10M_\odot$, we can have one electron e- in the magnetic field $B = 10^{-5}$ Gs or charged dust grain (one electron lost, $m = 2 \times 10^{-16}$ kg) in field $B = 10^9$ Gs - the absolute value of magnetic field parameter is the same in both cases $\mathcal{B} = 0.004$.

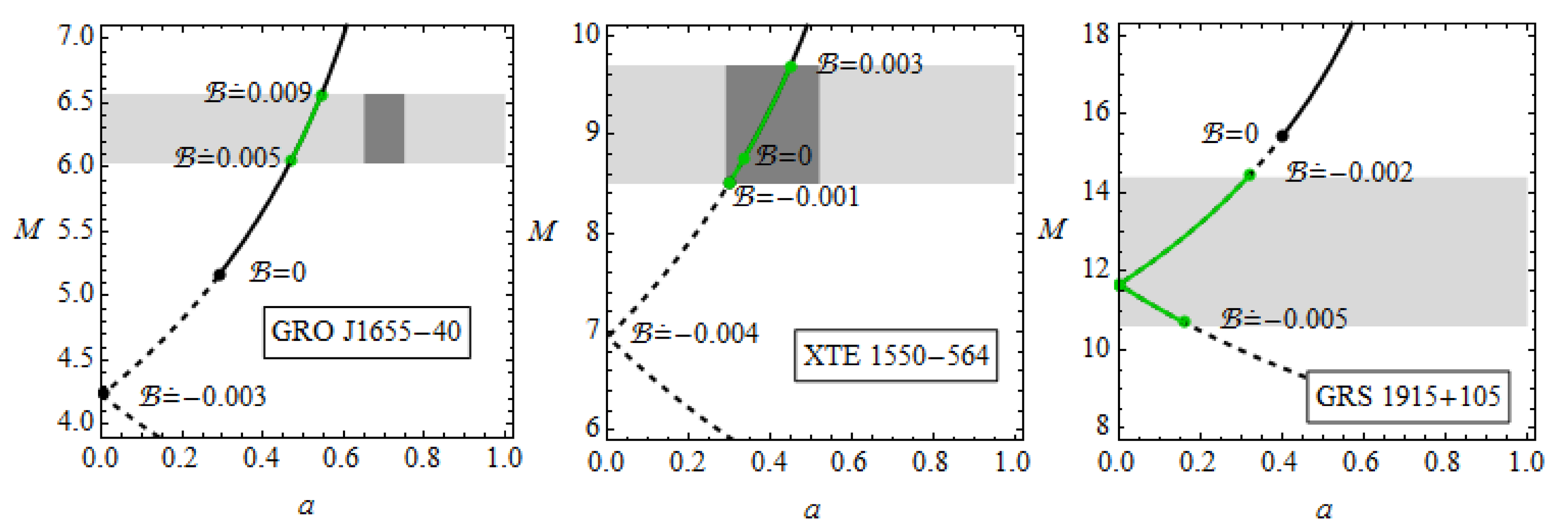
We have studied three important astrophysical processes around magnetized black hole: (1) Ionized particle acceleration as simple model of relativistic jet; (2) Charged particle oscillations and its frequencies which can be well related to the observed microquasar QPOs; (3) Radiation reaction force acting on moving charged particle.

(2) Magnetic field and microquasar QPOs

Microquasars are binary systems composed of a black hole and a companion (donor) star; the matter floats from the companion star onto the black hole trough some rotating axially symmetric structure called accretion disk. **Quasi-periodic oscillations (QPOs)** of the X-ray power density are observed in microquasars. According to the observed frequencies of QPOs, which cover the range from few mHz up to 0.5 kHz, different types of QPOs were distinguished. These are the high frequency (HF) and low frequency (LF) QPOs in the timing spectra with frequencies up to 500 Hz and up to 30 Hz, respectively. The HF QPOs are sometimes detected with the twin peaks (upper f_U and lower f_L) which have frequency ratio close to 3 : 2. In addition to HF QPOs, some sources display simultaneous existence of the low frequency (LF) QPOs f_{low} in the timing spectra. We will examine magnetic field influence on the QPOs phenomena, determining mass and spin of the black hole inside the GRS 1915+105, XTE 1550-564 and GRO 1655-40 sources.
Relativistic precession (RP) QPOs model for simultaneous HF and LF QPOs has frequencies ν_U, ν_L and ν_{low} is defined as

$$\nu_U = \nu_\phi(a, M, \mathcal{B}), \quad \nu_L = \nu_\phi(a, M, \mathcal{B}) - \nu_r(a, M, \mathcal{B}), \qquad \nu_{low} = \nu_\phi(a, M, \mathcal{B}) - \nu_\theta(a, M, \mathcal{B}).$$

One can use the observed values of HF and LF QPOs frequencies and using three equations $f_U = \nu_U$, $f_L = \nu_L$, $f_{low} = \nu_{low}$ identify the black hole mass M, spin a and magnetic parameter $\mathcal{B}$.

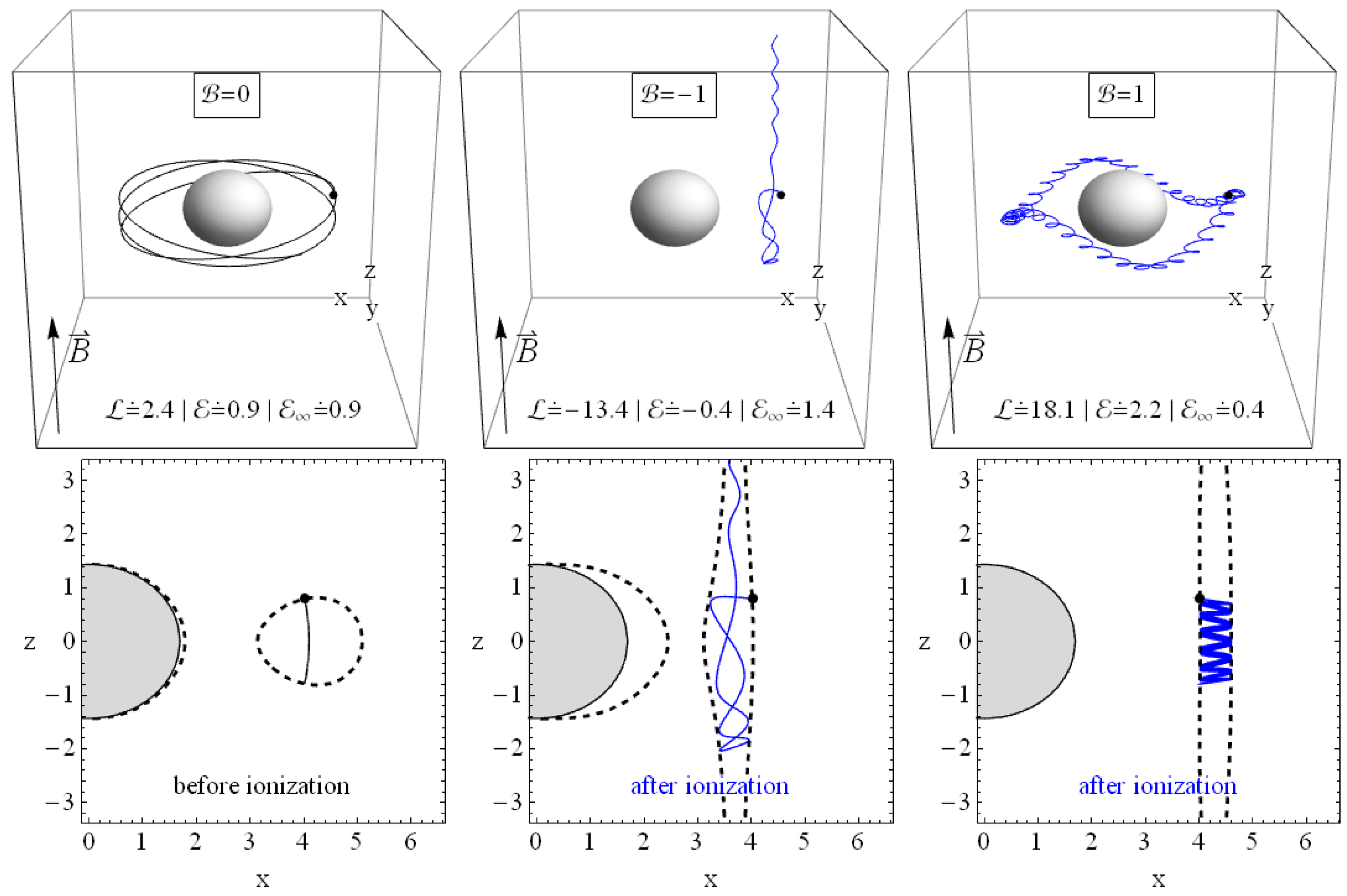


The results are presented for different strength of magnetic field $\mathcal{B}$ (thick curves) - they are compared with Kerr black hole mass M and spin a obtained by different independent method (grey rectangles).

• M. Kološ, A. Tursunov and Z. Stuchlík, *Possible signature of magnetic field in microquasar QPOs*, submitted (2017), [**arXiv:1707.02224**]

(1) Ionized particle acceleration - model of jet

Relativistic jets - collimated stream of escaping charged particles (velocities $v \sim c$); they are associated with matter accretion on to central compact object and observed in a wide variety of astrophysical systems. Many models has been proposed for relativistic **jet engine** (jets driven by accretion disk / driven by central black hole), exact mechanism still unknown, but it is generally accepted that large scale magnetic field plays fundamental role in jet formation.
The neutral particles forming accretion disk can get ionized and hence start to feel the magnetic field. **Chaotic scattering** in combined black hole gravitational and uniform magnetic field then occur and interchange between velocity around black hole u^ϕ and velocity along rotational axis u^z provides mechanism for charged particle **acceleration and escape** along the magnetic field lines. Relativistic escape velocity can be obtained even for relatively small magnitude of magnetic field.



Neutral particles from the accretion disc are located on a spherical orbit (r =cost.), external magnetic field is aligned with the rotation symmetry of the spacetime **(1)**. They get ionized and escape to the infinity along magnetic field lines with relativistic velocities **(2)**, or they can just stay and oscillate in equatorial plane **(3)** (depends on initial conditions).

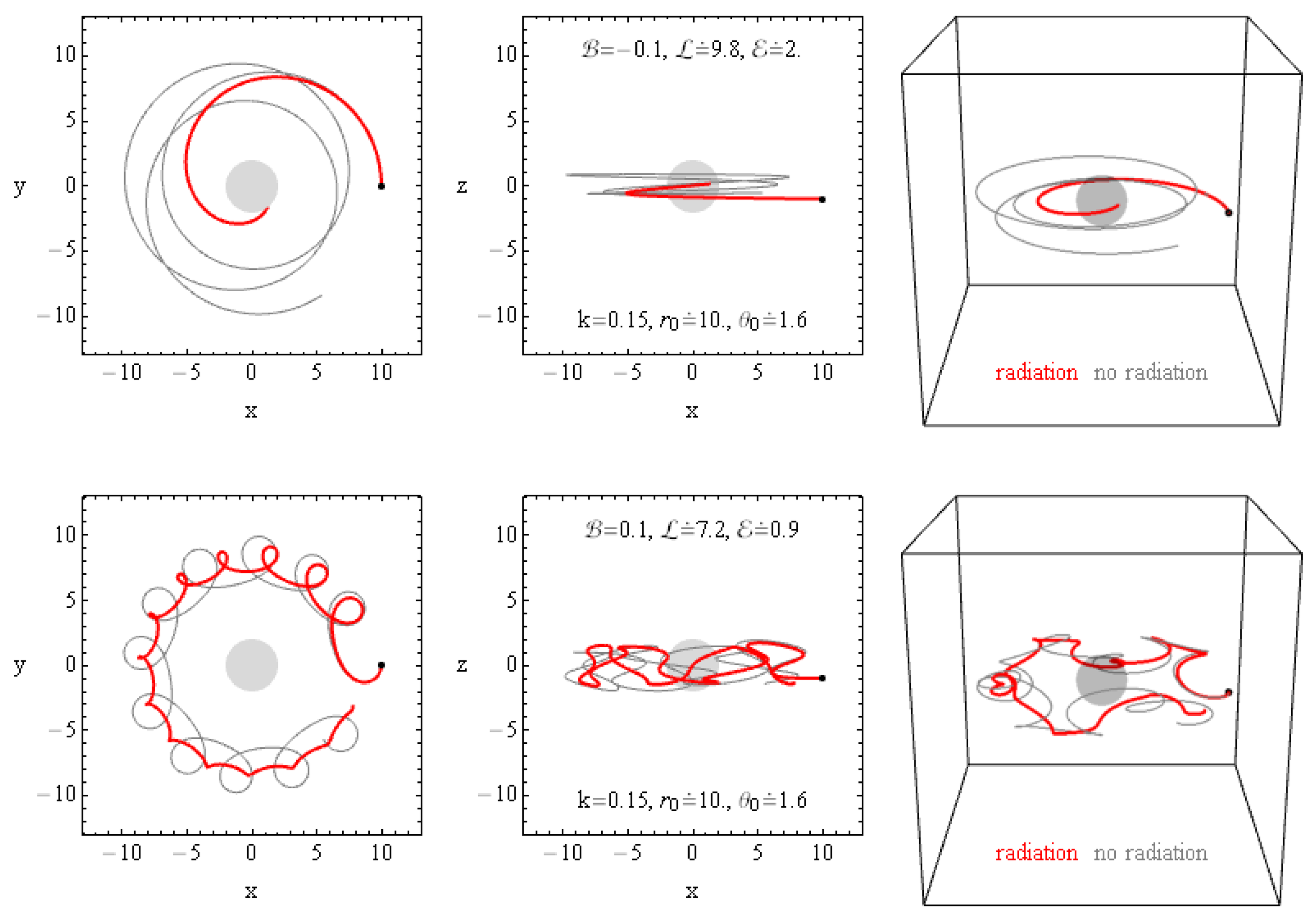
• Z. Stuchlík and M. Kološ: *Acceleration of the charged particles due to chaotic scattering in the combined black hole gravitational field and asymptotically uniform magnetic field*, The European Physical Journal C 76 (1), 1-21 (2016), [**arXiv:1511.02936**].

(3) Radiation reaction of a charged particle

Synchrotron radiation emitted by a charged particle leads to appearance of the **back-reaction force** which can significantly affect its motion. We study the dynamics of a charged particle undergoing radiation reaction force in combined Schwarzschild black hole gravitational filed and an external asymptotically uniform magnetic field

$$\frac{\mathrm{d}u^\mu}{\mathrm{d}\tau} + \Gamma^\mu_{\alpha\beta}u^\alpha u^\beta = \frac{q}{m}F^\mu{}_\nu u^\nu + \frac{q}{m}\mathcal{F}^\mu{}_\nu u^\nu,$$

where the first term on the right hand side corresponds to the Lorentz force with $F_{\mu\nu}$, while the second term with $\mathcal{F}_{\mu\nu}$ is the self-force of charged particle with the radiative field.



Depending on the orientation of the Lorentz force, the oscillating charged particle either **spirals down** to the black hole ($\mathcal{B} < 0$ - first line of figure), or stabilizes the circular orbit by **decaying its oscillations** ($\mathcal{B} > 0$ - second line of figures).

• A. Tursunov, M. Kološ, Z. Stuchlík and D. V. Gal'tsov : *Radiation reaction of a charged particle orbiting a weakly magnetized Schwarzschild black hole*, in preparation

Work supported by GAČR 14-37086G and GAČR 16-03564Y grants.