Structure of magnetized transonic accretion disks

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Accretion disc around a BH

- radiation–supported (zone a)
- gas–pressure–supported (zone b/c)
- last stable orbit
- sonic surface
- magnetic fields
- falling flow

standard disc and its inner boundary
Is there a “disk” beyond the disk?

Ballistic approximation:

\[ \Omega_z > \Omega_K \]

still small radial velocity

The shock waves are smeared due to \( \Omega_z(z) \)

Beskin & Tchekhovskoy (2005)
Density drops like
\[ \rho_{in} \simeq \rho_{disc} \times \alpha \left( \frac{H}{R} \right)^2 \]

Gas pressure
\[ P_g \propto \rho^{5/3} \]

Radiation pressure
\[ P_r \propto \rho^{4/3} \]
or stronger (radiated away)

Vertical magnetic field
\[ B_z \propto \rho \]

Azimuthal magnetic field
\[ B_\phi \propto \rho \]

Radial magnetic field (survives!)
Magnetically-supported falling flow

Cauchy problem:

\[ u'^r \frac{d}{dr} \left( u'^r \frac{dH}{dr} \right) = \text{(acceleration by MF)} - \text{(vertical gravity)} \]  

\[ \frac{a}{0.0, H/R = 0.1} \]

Abolmasov (2014)

\[ a = 0.9, H/R = 0.1 \]
Equilibrium thickness

\[
\frac{H}{R} \simeq (0.2..0.3) \left( \frac{1}{\alpha \beta} \left( \frac{H}{R} \right)_{\text{disk}} \right)^{1/3},
\]

where \( \beta = \left( \frac{p}{p_{\text{mag}}} \right)_{\text{disk}} \), \( \alpha \beta \sim 1 \)

Should we trust this?
HARM2D simulations

HARM: Gammie et al. (2003); Noble et al. (2006)

initial conditions

density (tones) and magnetic field (black contours) map
Thickesses

what's going on?
Driven current sheet!
Cylindrical and Keplerian rotation near the ISCO

\[ \omega_K = \frac{1}{r^{3/2} + a} \]
cylindrical isostrophes naturally occur in a pseudo-barotropic case: $\nabla p \parallel \nabla \rho \Leftrightarrow \nabla j \parallel \nabla \Omega$, where $j = \Omega \omega^2$ (Poincaré-Wavre theorem, aka as von Zeipel’s)

nearly Keplerian rotation is expected near the sonic surface:

$$\left( v - \frac{c_s^2}{v} \right) v' = \Omega^2 R - \frac{GM}{R} + c_s^2 \frac{d}{dR} (RH)$$ [should it hold for GR?]

magnetic fields do not spoil everything unless there is a dynamically important regular MF
**Isostrophes!**

If you want thick discs, you should consider 2D-rotation laws. Because rotation is gravity/inertia (see Abramowicz et al. (1997))

\[
\frac{\Omega_c}{\Omega_s} \sim \sin^{3/2} \theta \sim 2^{-3/4}
\]

\[
g_c/g_s \sim \sin^3 \theta \sim 2^{-3/2} \sim 3
\]

Details in Abolmasov & Chashkina (2015)
Summary:

- falling flow has a magnetically-supported component with thickness $\propto \left( \frac{h_0}{\alpha \beta} \right)^{1/3}$
- gas accretes through neutral magnetic lines in current sheets
- rotation in a thick disk is close to Keplerian and pseudo-barotropic (single barotropic gas + MF; everything can change if energy release is present!)
- everything changes when the cumulative magnetic flux becomes large

In more details: Abolmasov (2014); Abolmasov & Chashkina (2015)
Thank you for attention!
Magnetic fields

Magnetic flux conservation expressed in terms of comoving-frame-measured magnetic fields:

\[ 4\pi H r \left( u^i B^r - u^r B^i \right) = \Phi^r \]  

Poloidal magnetic fields in the disc:

\[ B^r (r) = \frac{H_0 r_0}{H r} B^r_0 \]

\[ B^\varphi (r) = \frac{H_0 r_0}{H r} \times \frac{u^\varphi - u^\varphi_0}{u^r} B^r_0 \]

\[ B^z (r) = \frac{H_0 r_0 u^r_0}{H r u^r} \times B^z_0 \]

Toroidal field in the disk:

\[ B^\varphi_{tor} = \frac{H_0 r_0}{H r} \frac{u^r_0}{u^r} B^\varphi_0 \]
Angular momenta

\[ a = 0.9 + \text{regular seed field (left) and } a = 0 + \text{multi-loop mode (right)} \]

first and second halves of the integration time domain shown separately
Two-dimensional rotation law

$\Omega(r, z)$