Accretion on to magnetized neutron stars and white dwarfs

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Introduction

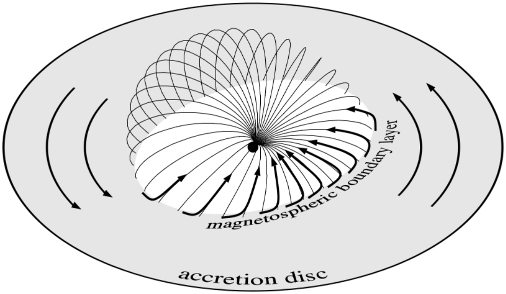

Fig. 6.3. Accretion disc around a magnetized neutron star or white dwarf. The magnetic dipole lines shown represent schematically the boundary of the magnetosphere.

Introduction

- Interaction of the disc and magnetic field.
- Stellar magnetic field disrupts an accretion flow.
- Disc not extending right down to the surface of the accreting star (no boundary layer).

Magnetospheric boundary layer

For a dipole-like magnetic field, the field strength B varies roughly as

$$B \sim \frac{\mu}{r^3} \tag{6.16}$$

at radial distance r from the star of radius R_*; here $\mu = B_* R_*^3$ is a constant (the magnetic moment) specified by the surface field strength B_* at $r = R_*$. Thus from (3.51) there is a magnetic pressure

$$P_{\mathrm{mag}} = \left[\frac{4\pi}{\mu_0}\right] \frac{B^2}{8\pi} = \left[\frac{4\pi}{\mu_0}\right] \frac{\mu^2}{8\pi r^6} \tag{6.17}$$

increasing steeply as the matter approaches the stellar surface. This magnetic pressure will begin to control the matter flow and thus disrupt the spherically symmetric infall at a radius r_M where it first exceeds the ram and gas pressures of the matter (cf. equation (3.52)). For highly supersonic accretion, as expected on the basis of our discussion in Section 2.5, it is the ram pressure term ρv^2 which is important, with the velocity v close to the free-fall value $v_{\mathrm{ff}} = (2GM/r)^{1/2}$ and $|\rho v|$ given in terms of the accretion rate $\dot{M}$ by (2.23):

$$|\rho v| = \frac{\dot{M}}{4\pi r^2}.$$

Thus setting $P_{\mathrm{mag}}(r_M) = \rho v^2|_{r_M}$ we find

$$\left[\frac{4\pi}{\mu_0}\right] \frac{\mu^2}{8\pi r_M^6} = \frac{(2GM)^{1/2}\dot{M}}{4\pi r_M^{5/2}}$$

or

$$r_M = 5.1 \times 10^8 \dot{M}_{16}^{-2/7} m_1^{-1/7} \mu_{30}^{4/7}\,\mathrm{cm} \tag{6.18}$$

where μ_{30} is μ in units of 10^{30} G cm^3. We note that a neutron star with $B* \cong 10^{12}$ G, $R_* = 10^6$ cm has $\mu_{30} \cong 1$, as does a white dwarf with $B_* \cong 10^4$ G, $R_* \cong 5 \times 10^8$ cm.

Magnetospheric boundary layer

- For a dipole like magnetic field and spherical accretion:

$$r_{\mathrm{m}} = 5.1 \times 10^{8} \dot{M}_{16}^{-2/7} m_{1}^{-1/7} \mu_{30}^{4/7} \mathrm{cm} \tag{1}$$

- Or in terms of X-ray luminosity

$$r_M = \left\{ \begin{array}{l} 5.5 \times 10^{8} m_1^{1/7} R_9^{-2/7} L_{33}^{-2/7} \mu_{30}^{4/7} \,\mathrm{cm} \\ 2.9 \times 10^{8} m_1^{1/7} R_6^{-2/7} L_{37}^{-2/7} \mu_{30}^{4/7} \,\mathrm{cm} \end{array} \right\}$$

- r_{m} is known as Alfvén radius.
- Biggest uncertainty from instabilities, which could allow matter to slip through the field lines before being channelled on to the stellar surface.

Magnetospheric boundary layer

- In case of disc accretion (cylindrical accretion disc R_{M}) by equating viscous and magnetic torques:

$$R_{\mathrm{M}} \backsim 0.5 r_{\mathrm{m}} \tag{2}$$

- Main difficulty to find an expression for the magnetic torque, because of azimuthal component of B and its dependence on instabilities and distortions from dipole-like configuration by the interaction with the disc.
- Other estimates give $R_{\mathrm{M}} \backsim 2 r_{\mathrm{m}}$, depending also on the inclination of the dipole axis.

Magnetospheric radius

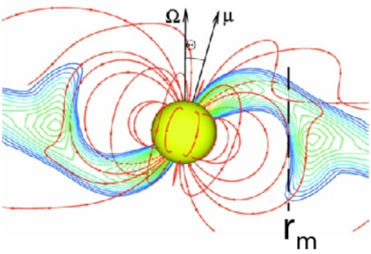

Fig. 3 Slice of the density distribution and selected field lines resulting from 3D MHD simulations of accretion onto a star with a tilted dipole magnetic field. The dashed line shows the position of the magnetospheric radius. From Romanova et al. (2004).

Magnetospheric radius

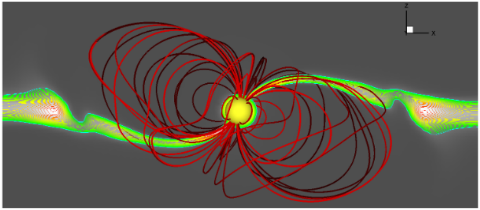

Fig. 18 An XZ-slice in the density distribution in the case of accretion onto a star with a large magnetosphere ($r_m \approx 12R_\star$). The lines are sample magnetic field lines. From Romanova et al. (2014).

Propeller effect

- If the rotation of the star is faster at R_{M}, than the Keplerian velocity, particles are repelled by the 'centrifugal barrier' at R_{M}.
- This does not happen if the "fastness parameter" $\omega_* = \Omega_* / \Omega_{\mathrm{K}}(R_{\mathrm{M}}) < 1$.
- For Roche Lobe accreting NS, R_{M} is expected to be $\backsim 10^8 \mathrm{cm}$, which is above the NS surface $\backsim 10^6 \mathrm{cm}$ (if $B_* > 10^9 \mathrm{G}$) and below R_{circ} (lower limit to the size of any accretion disc).

Area of the accreting polecap

- The area of the accreting polecaps can be estimated using dipole geometry (as a fraction from the total area):

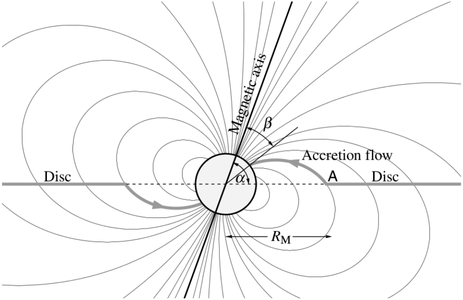

Fig. 6.4. Accretion from a disc to the polecaps of a magnetized neutron star or white dwarf.

- The result: $f_{disc} \approxeq R_* \sin^2 \alpha / 4 R_{\rm M}$ (for 2 caps $\backsim R_*/2R_{\rm M} \backsim 10^{-1} - 10^{-4}$)

Spin periods

Because most of the accretion luminosity must be released close to the stellar surface and, as we have seen, only over a fraction of it, any rotation of the accreting star will produce a periodic modulation in the observed flux from such a system. The effect will be enhanced if the radiation from the accreting polecap is beamed (see Section 6.4). Spin periods $P_{\rm spin}$ of this kind are observed in many X-ray binaries and intermediate polar systems, generally in X-rays, but sometimes optically, in the range

$$1 \text{ s} \lesssim P_{\rm spin} \lesssim 10^3 \text{ s}.$$

Spin periods

- Changes observed in the spin periods:
- 1) Modulation due to the orbital period of the binary system.
- 2) Systematic change in spin periods.
- Systematic spin-up in many X-ray binaries (torques induced by the accretion process).
- Also, occasional spin-downs caused either by fluctuations in the accretion torque or possibly by changes in the internal structure of the neutron star.

Spin periods

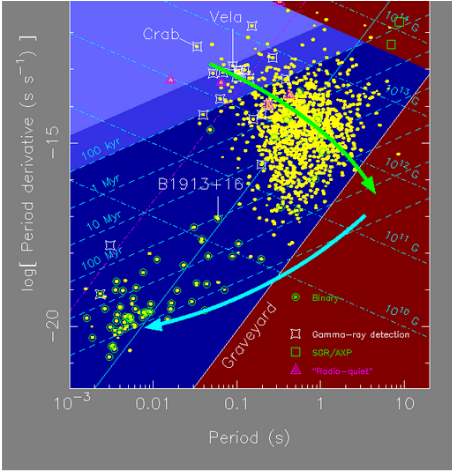

Figure 3. This P-Pdot diagram includes arrows showing the evolution of pulsars with all pulsars discovered since 1999 in the Parkes Multibeam survey as yellow dots.

Spin-up rate

- For "slow rotator" ($\omega_* \ll 1$):

$$\dot{\nu} \simeq 5 \times 10^{-12} m_1^{-3/7} R_6^{6/7} L_{37}^{6/7} \mu_{30}^{2/7} I_{45}^{-1} \mathrm{Hz s}^{-1} \tag{3}$$

- The spin-up is harder for WD than for NS, because of larger moment of inertia ($I \backsim MR_*^2$).
- Dependence mainly on $L^{6/7}$
- When/if fast rotation regime $\omega_* \backsim 1$ reached (e.g. WDs in intermediate polars), P_{spin} attains an equilibrium value, where corotation radius $R_{\mathrm{co}} = R_{\mathrm{M}}$

$$\left.\begin{aligned} P_{\mathrm{eq}} &\sim 3 m_1^{-2/7} R_9^{-3/7} L_{33}^{-3/7} \mu_{30}^{6/7}\,\mathrm{s} \\ &\sim 3 m_1^{-2/7} R_6^{-3/7} L_{37}^{-3/7} \mu_{30}^{6/7}\,\mathrm{s}. \end{aligned}\right\}$$

Spin-up rate

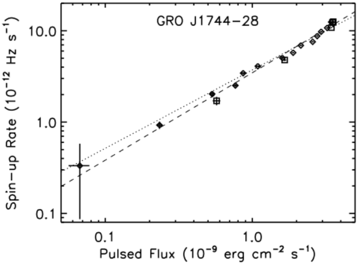

Fig. 6.5. The spinup rate of GRO J1744-28 during the December 1995 – March 1996 outburst versus the 20–50 keV r.m.s. pulsed flux. The square symbols are from the the outburst rise, and the diamond symbols are from the outburst decline. The dotted curve is the power-law with the expected index of 6/7, while the dashed curve is the best fit power-law of index 0.957 (reproduced with permission from Bildsten *et al.* (1997)).

Spin-up rate

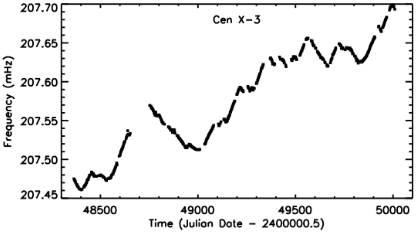

Fig. 6.6. High resolution BATSE measurements of the intrinsic spin frequencies for Cen X-3 (reproduced with permission from Bildsten *et al.* (1997)).

SAX J1808.4−3658

- Soft X-ray transient with 2.49 ms spin period found in 1998.
- X-ray pulsing with intensities differing many orders of magnitude -> Constraints to magnetic field ($\backsim 10^9\mathrm{G}$).
- Support for recycling scenario and a weakened magnetic field (perhaps because of accretion).
- Origin of the observed QPOs regarded as unknown (beat between the neutron star spin and the Kepler frequency of the blobs in the inner accretion disc orbiting at some preferred radius).

Accreting magnetic White Dwarfs

- Cyclotron emission in the $\backsim 10^7$ G magnetic field in "AM Herculis systems", or polars.
- Hard to see how an accretion disc could form in this case (with high μ, $r_{\rm m} > a$).
- Appears instead that the accretion stream couples directly to the white dwarf magnetic field at some point, the flow being along field lines down to the surface thereafter.
- For weaker magnetic fields (intermediate polars) situation more complicated. Formation of accretion disc probably still only for systems with highest orbital periods (except for AE Aquarii with the shortest spin periods).
- Intermediate polars (high orbital periods + accretion disc) as the progenitors of the AM Herculis systems (small orbital periods + no disc)?

Accreting magnetic White Dwarfs

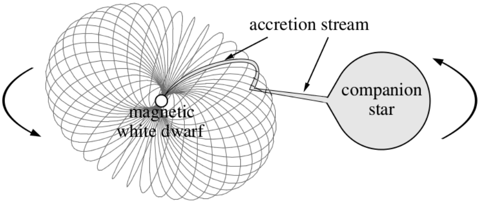

Fig. 6.7. Schematic view of an AM Herculis system. The rotation of the strongly magnetic ($\gtrsim 10^7$ G) white dwarf is locked to that of the binary ($P \lesssim 4$ h). No accretion disc forms, matter impinging directly on the magnetosphere, threading and following fieldlines down to the white dwarf surface.

Accreting magnetic White Dwarfs

Fig. 6.8. Computer simulation of the magnetic propeller system AE Aquarii. Matter in the form of diamagnetic blobs flows through the secondary star's L_1 point towards the rapidly-rotating magnetic white dwarf primary (small black dot labelled WD) and is centrifugally expelled by the strong magnetic torque. (Image supplied by Dr. G.A. Wynn. The calculations were performed on the UK Astrophysical Fluids Facility (UKAFF) supercomputer at the University of Leicester.)

Spectrum of cyclotron line

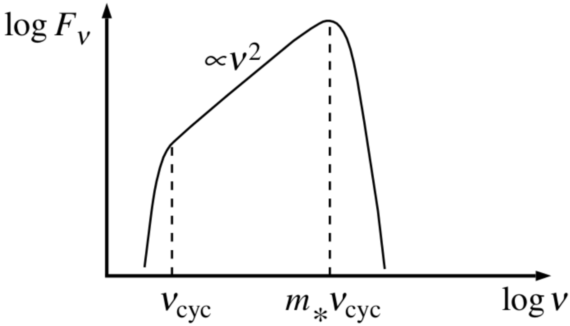

Fig. 6.9. Spectrum of a cyclotron 'line'.

Cyclotron lines in one X-ray source

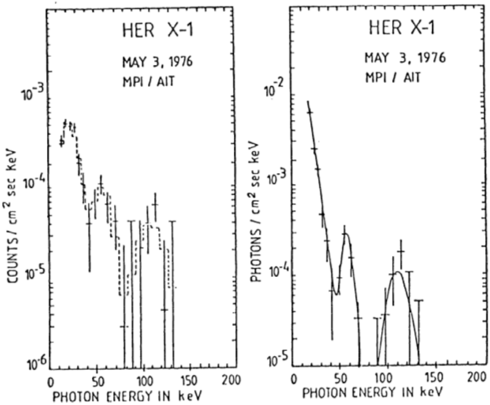

Fig. 6.10. Hard X-ray spectrum of Her X-1 obtained during the pulse phase of the 1.24 s pulsation. The left-hand figure shows a raw count-rate spectrum. The right-hand figure shows a spectrum deconvolved from the instrumental response, assuming cyclotron lines in emission at 58 and 110 keV. (Reproduced from Kirk & Trumper in *Accretion-Driven Stellar*

Conclusions

- Interaction with accretion disc and magnetosphere of NS or WD leads sometimes to channelled accretion to polar caps of the star.
- In some cases strong magnetic field or fast rotation of the star prevents accretion of the matter at R_{M}, or prevents the accretion disc to form at all.
- Spin periods may change due to accretion.
- The emission of cyclotron radiation by electrons gyrating around the field lines gives independent idea of the likely strength of the magnetic field.

The End