PHYC 581: High Energy Astrophysics
Fall 2014

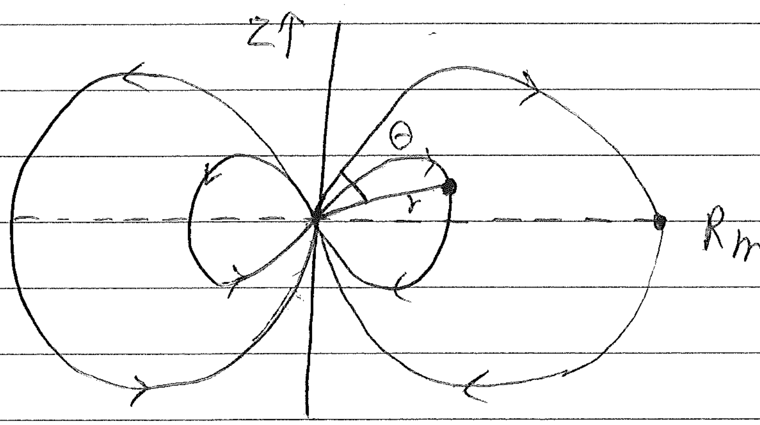
Lec 24: 11/10/2014

Accretion Columns (Cont'd):

Accretion Columns in Magnetic Cataclysmic Variables:

In these systems the primary is a magnetized white dwarf. As mentioned, it is sufficient to keep the magnetic dipole term at sufficiently large distances from the star's center. A dipole field line is described by the following relation:

$$r = \text{Const.} \times \sin^2\theta$$



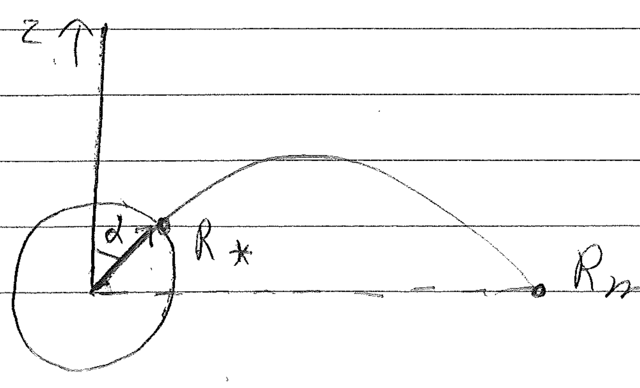
$$\theta = \frac{\pi}{2} \Rightarrow r = R_m$$

Thus:

$$\text{Const.} = R_m \Rightarrow r = R_m \sin^2\theta$$

The outer angle of impact at the white dwarf's surface is:

$$\delta = \sin^{-1}\left(\frac{R_*}{R_m}\right)^{\frac{1}{2}}$$



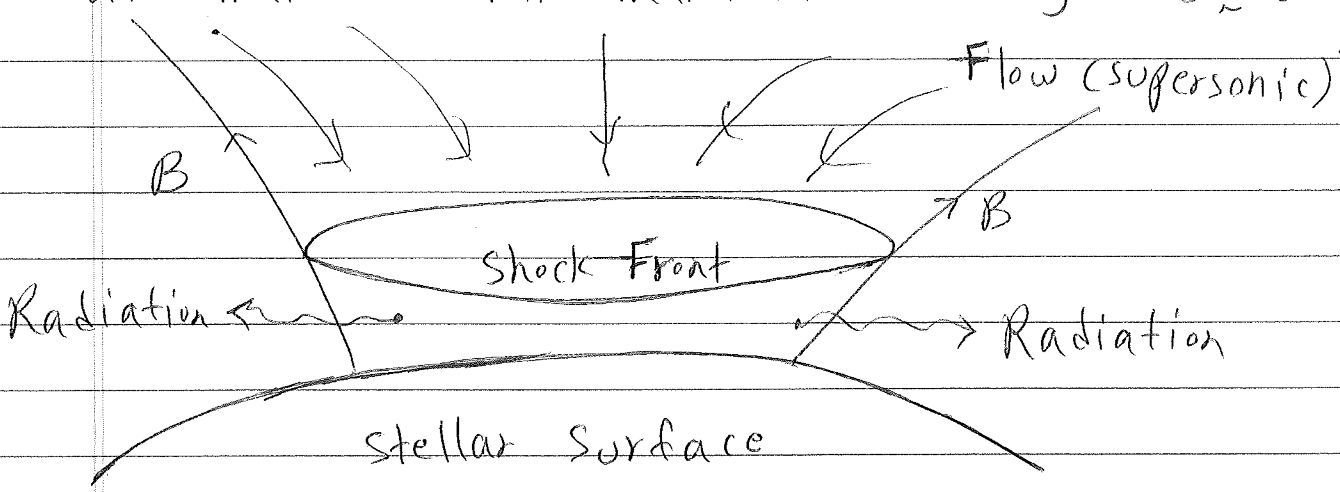
For a white dwarf:

$R_* \sim 10^9$ cm , $B_* \sim 2 \times 10^7$ G , $T \sim 10^5$ K

The latter result in:

$R_m \sim 10^{10}$ cm

Hence $\delta \sim 20^\circ$ for a white dwarf primary. We note that the magnetic field lines thread the disk beyond R_m and feed the termination funnel at smaller δ. This makes the entire region $\theta \lesssim \delta$ full.



For $\delta \sim 20^\circ$, the polar cap area beneath the flow is $\sim \frac{1}{40}$ of the total stellar surface area. Since both polar caps can be active, a fraction $f \sim \frac{1}{20}$ of the entire white dwarf's surface participates in the accretion.

Inside the funnel, the falling matter reaches the free-fall velocity,

$$v_{ff} = \left(\frac{2GM}{R_*}\right)^{1/2} \sim 5\times 10^8 \text{ cm s}^{-1}$$

The thermal velocity of electrons at temperatures relevant for a white dwarf is $v_{th} \sim \left(\frac{kT}{m_e}\right)^{1/2} \sim 10^8 \text{ cm s}^{-1}$ (and much smaller than this for protons). This is roughly the speed of sound in the medium, which implies that the inflow is supersonic. As a result, it produces a shock that heats up the material in the region behind the shock.

We recall that across a strong shock the relative velocity of the gas drops by a factor of 4. Conservation of the mass then implies that the density should increase by the same factor. The density in the shocked region will therefore be,

$$\rho_{shock} \simeq 4 \frac{\dot{M}}{4\pi f R_*^2} \left(\frac{2GM}{R_*}\right)^{-1/2} \sim 10^{-10} \text{ g cm}^{-3}$$

The corresponding temperature is:

$$T_{shock} \sim \frac{m_H}{3k}\left(\frac{3 v_{ff}}{4}\right)^2 \sim 6 \times 10^8 \, K$$

The plasma is thus heated up by the shock quite considerably. It the cools off quickly as photons leave the system without being trapped. This can be seen by finding the optical depth in the transverse direction:

$$\tau_{\perp} \sim \left(\frac{\rho_{shock}}{\nu m_H}\right) \sigma_T \, f^{\frac{1}{2}} R_* \sim 0,03$$

This confirms that the medium is optically thin.

The overall spectrum from accretion columns of a white dwarf has various components. The dominant one is Bremsstrahlung radiation in the hard X-ray. There is also cyclotron emission in the UV (since there is a magnetic field), as well as a soft blackbody X-ray radiation that comes from reprocessing of hard X-rays that penetrate below the stellar surface.

Accretion Columns in X-ray Pulsars:

The main complication arising in the case of X-ray pulsars is the larger radiation pressure in this case. Since the accreted plasma is funneled onto smaller polar cap regions, "f" will be much smaller (at least by an order of magnitude) in this case. The radiative flux will therefore be larger than an isotropically emitting source by a factor of $\frac{1}{f}$. This implies that even with an accretion rate $L_{acc} \sim 0.1 L_{edd}$, the effective luminosity out of the funnel can be comparable to L_{edd}. Once this happens, radiation process significantly affects the accretion.

A second complication is that the transverse optical depth $\tau_{\perp}$ is much larger in the case of X-ray pulsars. Since $\tau \propto n_e R_*$ while $n_e \propto R_*^{-2}$, then $\tau_{\perp} \propto R_*^{-1}$. Hence $\tau_{\perp}$ in the case of a neutron star is larger than that for a white dwarf by a factor of $\sim 10^3$, which results in $\tau_\perp \sim 30$, and hence an optically thick medium.

With an Eddington flux being produced within the funnel, and the medium being optically thick, one may expect to have instabilities. Numerical simulations confirm the view that the accretion column in these circumstances must be unstable.