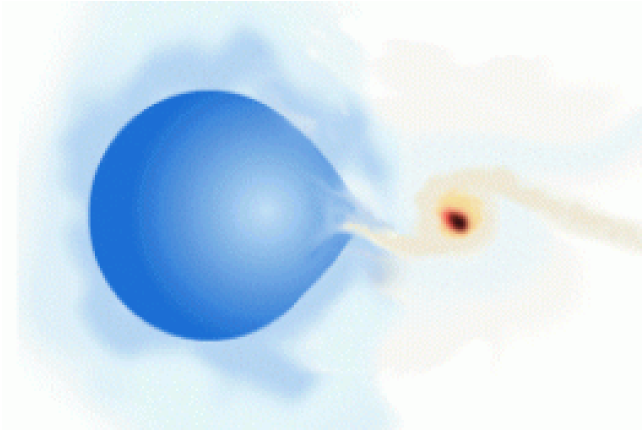
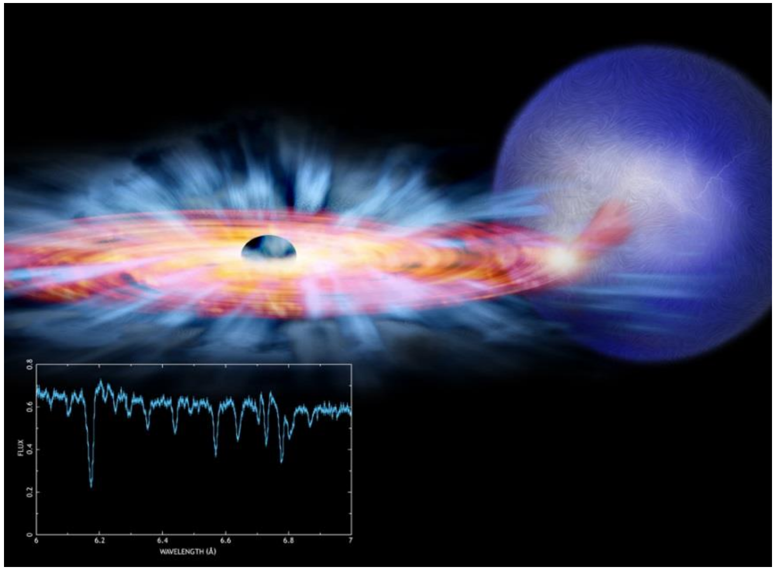
ASTROPHYSICS OF INTERACTING BINARY STARS

Lecture 14

Vitaly Neustroev

X-ray Binaries





Scenario 1: Stellar Wind Accretion

- More massive star dies first
- Stellar wind captured
  (with possible inner accretion disk)

Common for High-Mass (Companion) X-ray Binaries **(HMXB)**

Scenario 2: Roche Lobe overflow

- More massive star dies first
- Binary separation can shrink
  (magnetic braking and/or grav. radiation)
- Companion may evolve and grow

Common for Low-Mass (Companion) X-ray Binaries **(LMXB)**

High-mass X-ray Binaries

- **HMXBs** are binary systems, in which the normal stellar component is a massive star: usually an O or B star, a Be star, or a blue supergiant. The compact, X-ray emitting, component is generally a neutron star or black hole.
- A fraction of the stellar wind of the massive normal star is captured by the compact object, and produces X-rays as it falls onto the compact object.
- In a HMXB, the massive star dominates the emission of optical light, while the compact object is the dominant source of X-rays. The massive stars are very luminous and therefore easily detected.

High-mass X-ray Binaries

- Because of the large mass ratio, mass transfer generally becomes unstable, leading to a common-envelope and spiral-in phase
- Mass transfer is either due to atmospheric Roche-lobe overflow (short-lived) or wind accretion (relatively low luminosity)
- Massive stars have very strong radiation-driven stellar winds - the steady loss of mass from the surface of a star into interstellar space
- Stellar wind from OB stars: $\dot{M}_w = 10^{-5} - 10^{-8}\ \mathrm{M}_{\odot}/\mathrm{year}$
  Compare with the Sun: $\dot{M}_{\odot} = 3 \times\ 10^{-14}\ \mathrm{M}_{\odot}/\mathrm{year}$

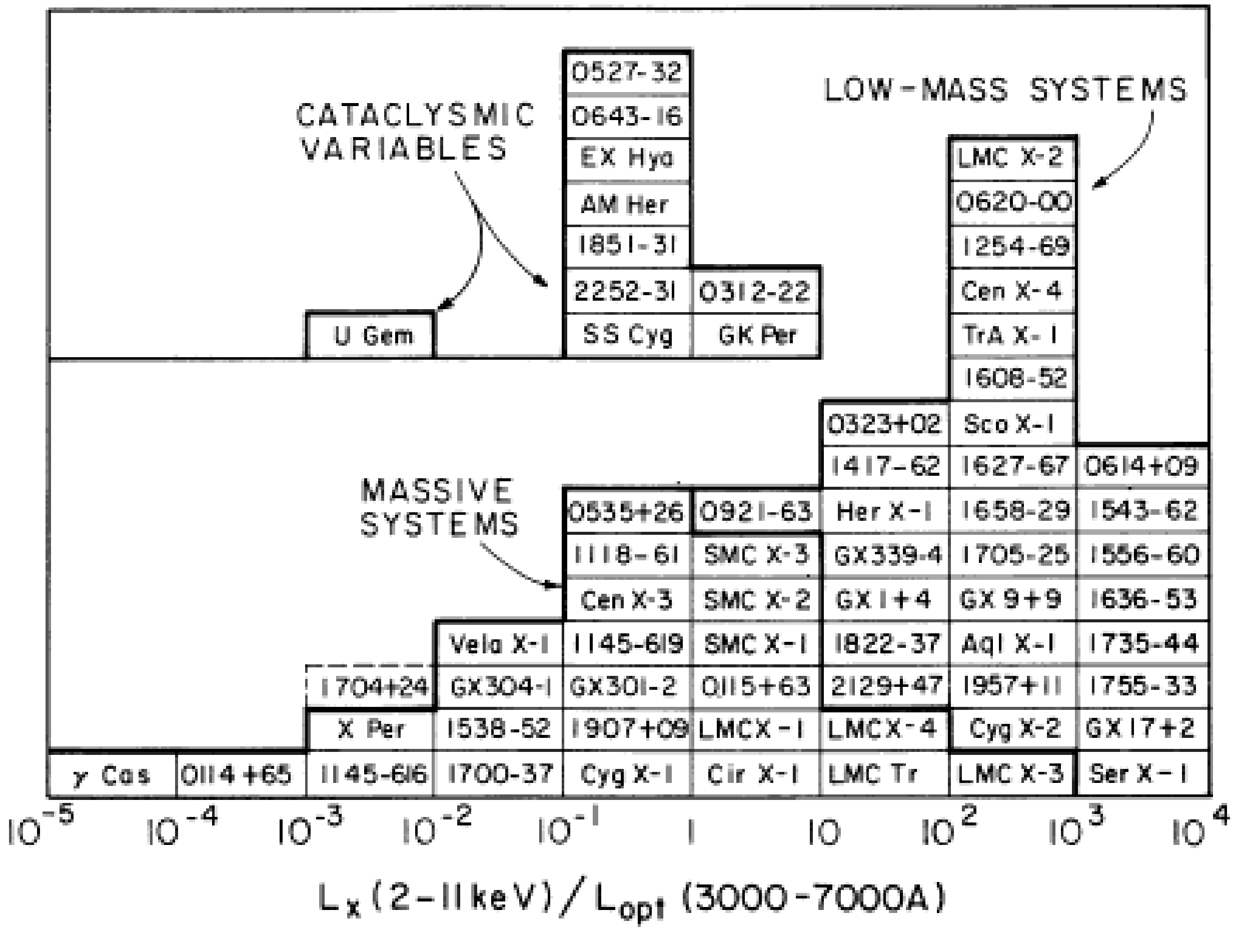
Low-mass X-ray Binaries

- **LMXB** is a binary star where one of the components is either a black hole or neutron star. The other, donor, component usually fills its Roche lobe and therefore transfers mass to the compact star.
- The donor is less massive than the compact object, and can be on the main sequence, a degenerate dwarf (white dwarf), or an evolved star (red giant).
- A typical LMXB emits almost all of its radiation in X-rays, and typically less than one percent in visible light, so they are among the brightest objects in the X-ray sky, but relatively faint in visible light. The brightest part of the system is the accretion disk around the compact object. The orbital periods of LMXBs range from ten minutes to hundreds of days.
- A couple of hundred LMXBs have been detected in the Milky Way.

X-ray Binaries

Distribution of the ratio of X-ray to optical luminocities for the binary systems containing compact objects

(Bradt & McClintock, 1983)



Properties of X-ray Binaries

Properties	HMXBs	LMXBs
Donor star	O-B (M> 5 M$\odot$)	K-M (M< 1 M$\odot$
Population	I (10^7 yr)	II (5-15 x10^9 yr)
L_X/L_{opt}	0.001-10	100-1000
Optical spectrum	stellar like	reprocessing
Orbital Period	1-100 d	10 min-10 d
Accretion disc	yes, small	yes
X-ray Eclipses	common	rare

Bondi-Hoyle wind accretion

- Massive stars have very strong radiation-driven stellar winds.

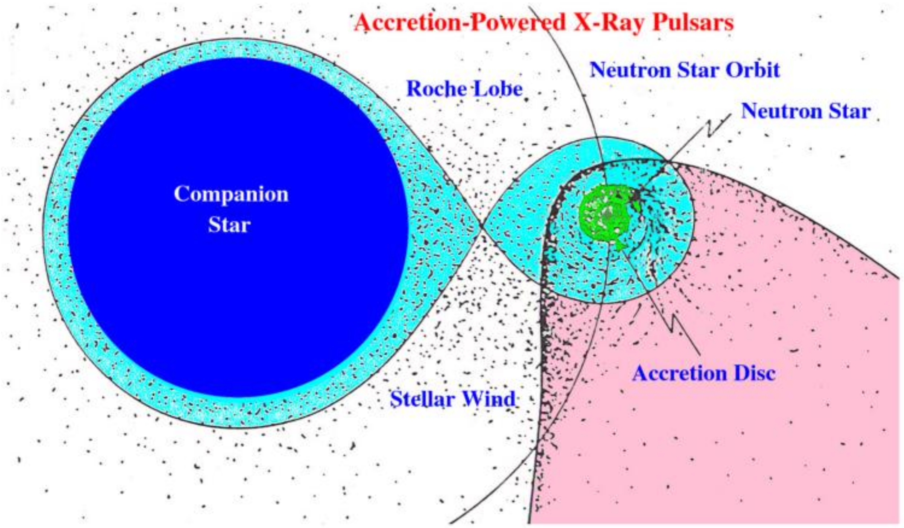
$$V_w \sim V_{esc} = \sqrt{\frac{2GM_d}{R_d}}$$

where M_d and R_d are the mass and radius of the primary star and V_{esc} is the escape velocity at its surface.

For typical parameters V_{esc} is generally a few thousand km/s which greatly exceeds the sound speed c_s. As a consequence the accreting gas is far to be in hydrostatic equilibrium.

Bondi-Hoyle wind accretion

A compact object with mass M_x moving with velocity V_{rel} through a medium will gravitationally capture matter from a roughly cylindrical region with axis along the relative wind direction which represents the volume where wind particle kinetic energy is less than the gravitational potential one.



Bondi-Hoyle wind accretion

- The material in the wind is captured once

$$\frac{mV_{rel}^{\ 2}}{2} \cong \frac{GmM_x}{R_{acc}}$$

  - V_{rel} -relative velocity of a compact object and a stellar wind

$$V_{rel}^{\ 2} = V_{orb}^{\ 2} + V_w^{\ 2}$$

  - V_{orb} -orbital velocity of a compact object around a companion

$$V_{orb}^{\ 2} = \frac{G(M_d+M_x)}{a}$$

  - a – binary separation

- The radius of the cylinder, called the accretion radius or gravitational capture radius, is given by:

$$R_{acc} = \frac{2GM_x}{V_{rel}^{\ 2}}$$

Bondi-Hoyle wind accretion

- The mass loss rate is

$$\dot{M}_w = 4\pi a^2 \rho_w(a) V_w(a)$$

- The mass accretion rate is

$$\dot{M}_{acc} = \pi {R_{acc}}^2 \rho_w(a) V_{rel}$$

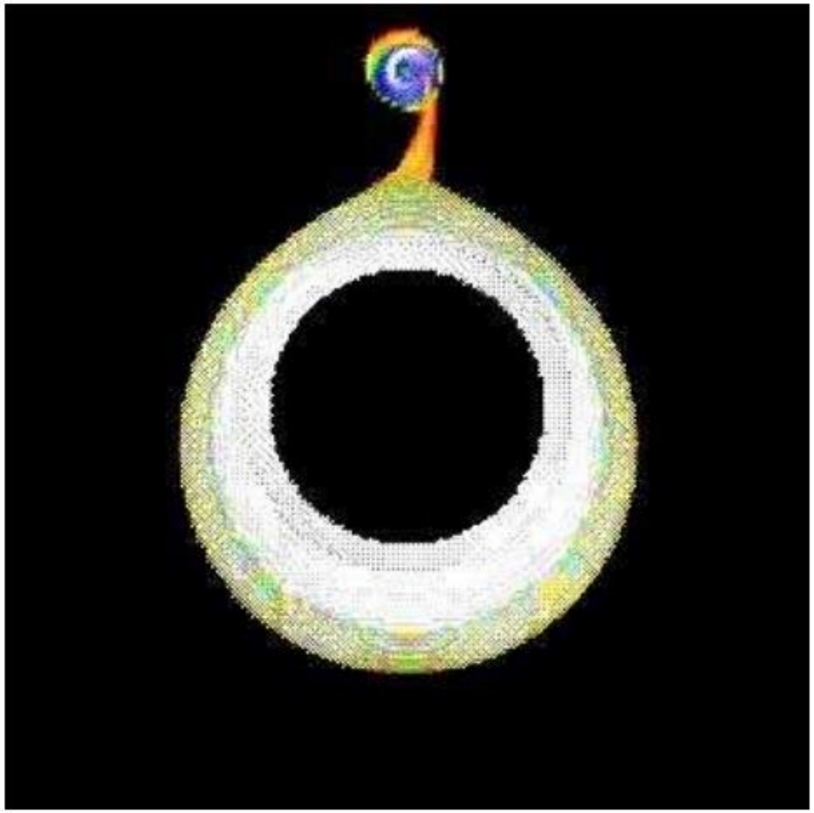
- Therefore, the fraction of the stellar wind captured by the compact star is

$$\frac{\dot{M}_{acc}}{\dot{M}_w} = \frac{1}{(1 + M_w/M_x)^2} \left(\frac{V_{orb}}{V_w}\right)^4 \frac{1}{(1 + (V_{orb}/V_w)^2)^{3/2}}$$

which is of order 10^{-5}-10^{-3} for typical parameters of HMXBs. The accretion luminosity can be as high as 10^{36} -10^{38} erg/s depending on the orbital periods.

Bondi-Hoyle wind accretion

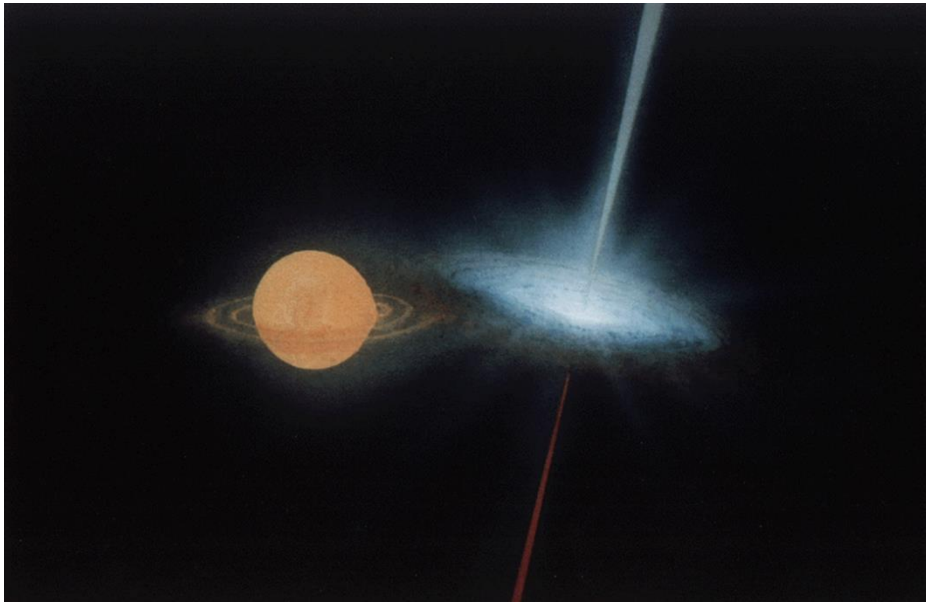
- In realistic HMXB, because the accreted material still has some angular momentum, a small accretion disk still forms.



courtesy J. Blondin

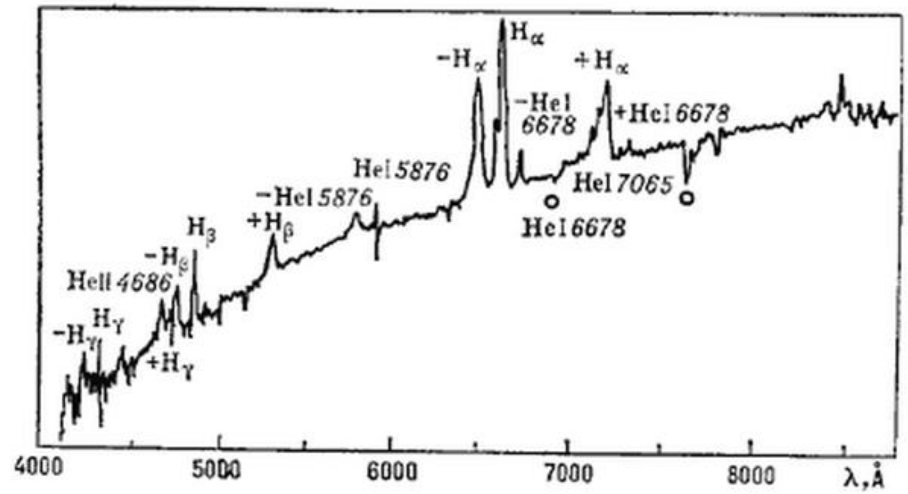
SS 433

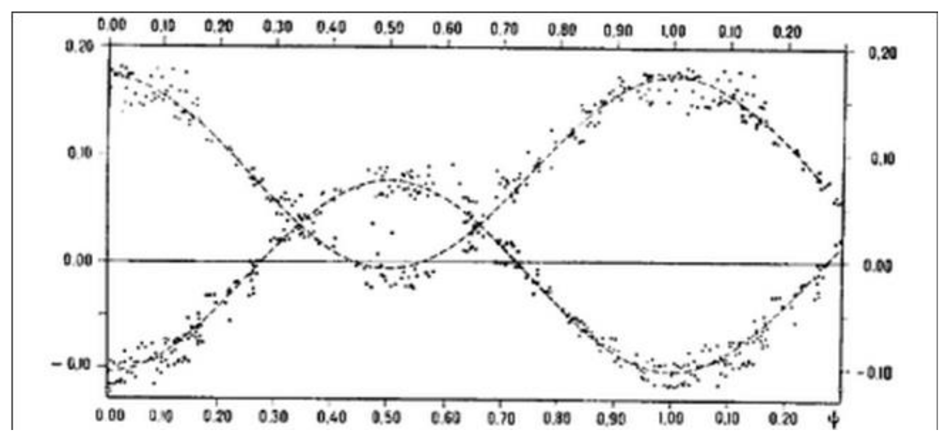
- An eclipsing X-ray binary system, with the primary most likely a black hole, or possibly a neutron star. The spectrum of the secondary companion star suggests that it is a late A-type star.



SS 433

- The jets from the primary are emitted perpendicular to its accretion disk.
- The jets and disk precess around an axis inclined about 79° to a line between us and SS 433.
- The angle between the jets and the axis is around 20°, and the precessional period is around 162.5 days
- The spectrum of SS 433 is affected not just by Doppler shifts but also by relativity: when the effects of the Doppler shift are subtracted, there is a residual redshift which corresponds to a velocity of about 12000 km/s.
- Material of jets moves with the velocity of ~80000 km/s (0.27 c).





Standard α-disk model

Properties of the thin, Steady-State AD

- **From lecture 6:**
  - Thickness: $\frac{h}{R} \cong \frac{c_S}{V_{rot}}$
  - Surface density (g/cm²): $\Sigma = \int_{-\infty}^{+\infty} \rho \, dz = \sqrt{2\pi}\rho_0 h$
  - Viscosity (alpha model – hides uncertain physics): $\nu \equiv \alpha c_S h$
  - Temperature: $T(R) = T_*(R/R_*)^{-3/4}$
  - The radial velocity is highly subsonic:

$$V_R = \frac{\dot{M}}{2\pi R\Sigma} = \frac{3\nu}{2R\left[1-\left(\frac{R_*}{R}\right)^{1/2}\right]} \sim \frac{\nu}{R} \sim \alpha c_S \frac{h}{R} \ll c_S$$

$$\nu\Sigma = \frac{\dot{M}}{3\pi}\left[1-\left(\frac{R_*}{R}\right)^{1/2}\right]$$

- It would be useful to perform slightly more elaborate modeling of α-disks, to find its properties as a function of the radius *R*, the mass M of the central object, the accretion rate $\dot{M}$, and the assumed value of *α*.

Structure of the standard α-disk (1)

- Let's combine all the equations of the steady disk:

$$c_S^2 = \frac{P}{\rho}$$

where in general the pressure *P* is the sum of gas and radiation pressures:

$$P = \frac{\rho k T_c}{\mu m_p} + \frac{4\sigma}{3c} T_c^4$$

μm_p is the mean molecular weight of the gas, σ is the Stefan Boltzmann constant , and the temperature $T(R, z)$ is close to the central temperature $T_C(R) = T(R, 0)$ (assumption).

- As in stars, the vertical energy transport mechanism may be either radiative or convective. We assume that the transport is radiative, and the disk is optically thick, i.e. $\tau = \rho h \kappa_R(\rho, T_c) = \Sigma \kappa_R >> 1$

where k_R is the Rosseland mean opacity.

- Then, the radiation field is locally very close to the blackbody.

Structure of the standard α-disk (2)

Because of the thin disc approximation, the disc medium is essentially 'plane-parallel' at each radius, so that the temperature gradient is effectively in the z-direction.

Then, the flux of radiant energy through a surface z=constant is given by

$$F(z) = -\frac{16\sigma T^3}{3\kappa_R \rho}\frac{\partial T}{\partial z} \sim \frac{4\sigma}{3\tau} T^4(z)$$

Recall from Stellar Atmospheres:

Temperature structure of the grey atmosphere

In LTE, the source function is the Planck function, $S(\tau)=B(\tau)=\sigma T^4/\pi$

$$B(\tau) = \frac{\sigma}{\pi} T^4(\tau) = \frac{3}{4\pi}(\tau + \frac{2}{3})F(0)$$

Recall that $F(0)=\sigma T^4_{\mathrm{eff}}$ by definition, so

$$\frac{1}{\pi}\sigma T^4(\tau) = \frac{3}{4\pi}(\tau + \frac{2}{3})\sigma T^4_{eff} \quad \text{or} \quad T^4(\tau) = \frac{3}{4}(\tau + \frac{2}{3})T^4_{eff}$$

We derived the **temperature dependence on optical depth.**

Note $T(\tau=2/3)=T_{\mathrm{eff}}$ as we obtained earlier, and $T^4(\tau=0)=T_{\mathrm{eff}}^4/2$

A complete solution of the grey case, using accurate boundary conditions, without Eddington approximation, leads to a solution only slightly different from this, usually expressed as

$$T^4(\tau) = \frac{3}{4}(\tau + q(\tau))T^4_{eff}$$

Here $q(\tau)$ is a slowly varying function (Hopf function), with $q = 1/\sqrt{3} = 0.577$ at $\tau=0$ to $q=0.710$ at $\tau=\infty$.

Rosseland mean opacity

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$$\frac{1}{\alpha_R} = \frac{\int \frac{1}{\alpha_\lambda}\frac{dB_\lambda}{ds}d\lambda}{\frac{dB}{ds}}$$

$$\frac{dB}{ds} = \frac{dB}{dT}\frac{dT}{ds} \quad \text{and} \quad \frac{dB}{dT} = \frac{d}{dT}\left(\frac{\sigma}{\pi}T^4\right) = \frac{4\sigma}{\pi}T^3$$

$$\frac{1}{\alpha_R} = \frac{\int_0^\infty \frac{1}{\alpha_\lambda}\frac{dB_\lambda}{dT}d\lambda}{\frac{4\sigma}{\pi}T^3}$$

Definition of Rosseland mean opacity

The Rosseland mean $1/\alpha_R$ is a weighted (harmonic) mean of opacity, for which there is a corresponding optical depth (Rosseland depth): $\tau_{Ross}(s) = \int_0^s \alpha_R(z)dz$

We hoped for the temperature structure: $T^4(\tau) = \frac{3}{4}(\tau + \frac{2}{3})T^4_{eff} = \frac{3}{4}(\tau_{Ross} + \frac{2}{3})T^4_{eff}$

Eddington approximation

The grey approximation is very good for $\tau_{Ross} \gg 1$.

Structure of the standard α-disk (3)

The energy balance equation is

$$\frac{\partial F}{\partial z} = Q^+$$

or

$$F(H) - F(0) = \int_0^H Q^+(z)\mathrm{d}z = D(R)$$

If $T_c^4 >> T^4(H)$, it becomes approximately

$$\frac{4\sigma}{3\tau} T_c^4 = D(R)$$

or, for the effective temperature of the disk:

$$T(R) = \left\{ \frac{3GM\dot{M}}{8\pi R^3 \sigma} \left[1 - \left(\frac{R_*}{R} \right)^{1/2} \right] \right\}^{1/4}$$

Structure of the standard α-disk (4)

The basic set of equations governing the accretion disk:

$$\Sigma = \rho H$$

$$H = c_s R^{3/2} / (GM)^{1/2}$$

$$P = \rho c_s^2$$

$$P = \frac{\rho k T_c}{\mu m_p} + \frac{4\sigma}{3c} T_c^4$$

$$\frac{4\sigma T_c^4}{3\tau} = \frac{3GM\dot{M}}{8\pi R^3}[1 - (\frac{R_*}{R})^{1/2}]$$

$$\tau = \Sigma \kappa_R (\rho, T_c)$$

$$\nu\Sigma = \frac{\dot{M}}{3\pi}[1 - (\frac{R_*}{R})^{1/2}]$$

$$\nu = \alpha c_s H$$

We can solve it for the eight unknowns $\rho, \Sigma, H, c_S, P, T, \tau, \nu$ as a function of the radius R, the mass M of the central object, the accretion rate $\dot{M}$, and the assumed value of α. Then the radial drift velocity v_R can also be obtained.

Structure of the standard α-disk (5)

- The above set of equations cannot be solved in a general fashion, because:
  - The pressure has two contributors
  - Different forms of opacity dominate at different locations
- The simplest procedure is to use the most dominant process at each location.
  - When the dominant source of opacity in the disk is free-free absorption, the Rosseland mean opacity $\kappa_R(\rho, T)$ is well approximated by Kramers' law:

$$\kappa_R = 6.6\,\mathrm{cm}^2\,\mathrm{g}^{-1}\left(\frac{\rho}{10^{-8}\,\mathrm{g\,cm}^{-3}}\right)\left(\frac{T}{10^4\,\mathrm{K}}\right)^{-7/2}$$

  - At higher temperatures and lower densities, the main source of opacity is Thomson scattering of photons by free electrons, with $\kappa_R = 0.40$ cm^2 g^{-1}.
- Then, the set of equations has an algebraic solution.

Structure of the standard α-disk (6)

- The disk may be composed of a number of distinct regions:
  - Outer disk (P_{rad}~0, and the dominant source of opacity is free-free absorption):

$$H\ (\mathrm{cm}) = 1.27\times10^{8}\alpha^{-1/10}\dot{M}_{16}^{3/20}M_1^{-3/8}R_{10}^{9/8}f^{3/20}$$

$$\rho\ (\mathrm{gcm^{-3}}) = 4.6\times10^{-8}\alpha^{-7/10}\dot{M}_{16}^{11/20}M_1^{5/8}R_{10}^{-15/8}f^{11/20}$$

$$v_R\ (\mathrm{cms^{-1}}) = 2.7\times10^{4}\alpha^{4/5}\dot{M}_{16}^{3/10}M_1^{-1/4}R_{10}^{-1/4}f^{-7/10}$$

$$T\ (\mathrm{K}) = 1.4\times10^{4}\alpha^{-1/5}\dot{M}_{16}^{3/10}M_1^{1/4}R_{10}^{-3/4}f^{3/10}$$

The boundaries between regions

$$R_{bc}\ (\mathrm{cm}) = 2.9\times10^{8}\dot{M}_{16}^{2/3}M_1^{1/3}f^{2/3}$$

  - Middle disk (P_{gas} >> P_{rad}, but the opacity is dominated by electron scattering)

$$H\ (\mathrm{cm}) = 8.0\times10^{5}\alpha^{-1/10}\dot{M}_{16}^{1/5}M_1^{-7/20}R_8^{21/20}f^{1/5}$$

$$\rho\ (\mathrm{gcm^{-3}}) = 1.9\times10^{-4}\alpha^{-7/10}\dot{M}_{16}^{2/5}M_1^{11/20}R_8^{-33/20}f^{2/5}$$

$$v_R\ (\mathrm{cms^{-1}}) = 1.0\times10^{5}\alpha^{4/5}\dot{M}_{16}^{2/5}M_1^{-1/5}R_8^{-2/5}f^{-3/5}$$

$$T\ (\mathrm{K}) = 5.9\times10^{5}\alpha^{-1/5}\dot{M}_{16}^{2/5}M_1^{3/10}R_8^{-9/10}f^{2/5}$$

$$R_{ab}\ (\mathrm{cm}) = 2.5\times10^{6}\alpha^{2/21}\dot{M}_{16}^{16/21}M_1^{7/21}f^{16/21}$$

  - Inner disk (P_{rad} >> P_{gas}, the opacity is dominated by electron scattering)

$$H\ (\mathrm{cm}) = \frac{3\sigma_T\dot{M}}{8\pi c}f = 1.6\times10^{4}\dot{M}_{16}f$$

$$\rho\ (\mathrm{gcm^{-3}}) = 23\alpha^{-1}\dot{M}_{16}^{-2}M_1^{-1/2}R_8^{3/2}f^{-2}$$

$$v_R\ (\mathrm{cms^{-1}}) = 44\alpha\dot{M}_{16}^{2}M_1^{1/2}R_8^{-5/2}f$$

$$T\ (\mathrm{K}) = 4.2\times10^{6}\alpha^{-1/4}M_1^{1/8}R_8^{-3/8}$$

$$f = 1-(R_*/R)^{1/2}$$

Structure of the standard α-disk (7)

The three distinct regions of the accretion disk