ASTROPHYSICS OF INTERACTING BINARY STARS

Lecture 3

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Energetics of accretion (1)

- Accretion disks are important in astrophysics as they efficiently transform gravitational potential energy into radiation.

- The gas accreted in a mass transfer binary must lose the gravitational potential energy liberated as it falls toward the mass gaining star. If this energy is radiated, luminosity is:

$$L \approx \frac{GM\dot{M}}{R},$$

where M and R are the mass and radius of the accreting star, and $\dot{M}$ is the mass transfer.

Energetics of accretion (2)

- The luminosity of an accretion disk is the bigger the larger the mass flow rate is, the higher the mass of the accretor is, and the more compact the accretor is.
- Compare to the rest mass energy of the gas accreted per unit time:

$$\dot{M}c^2$$

- Efficiency of the accretion process (fraction of the rest mass energy that is radiated):

$$\varepsilon \approx \frac{GM\dot{M}}{R} \times \frac{1}{\dot{M}c^2} = \frac{GM}{Rc^2}$$

Energetics of accretion (3)

- Accretion onto **a main sequence star**: as template we take the Sun: $M=1.99 \cdot 10^{33}$g, $R=6.96 \cdot 10^{10}$cm:

$$\varepsilon \approx 2 \cdot 10^{-6}$$

- Compare to nuclear fusion of hydrogen to helium. Energy release is $6 \cdot 10^{18}$ erg per gram of hydrogen:

$$\varepsilon_{H \rightarrow He} \approx 7 \cdot 10^{-3} \qquad (0.7\%)$$

- Thus, the specific energy output of accretion onto a main sequence star is more than three orders of magnitude less efficient than the hydrogen-helium fusion.
- The absolute values of energy output, i.e., the luminosity, however, depend also on the amount of mass involved in the fusion and the accretion process.

Energetics of accretion (4)

$$\varepsilon \approx \frac{GM\dot{M}}{R} \times \frac{1}{\dot{M}c^2} = \frac{GM}{Rc^2}$$

- Accretion onto **a white dwarf**: typical mass 10^{33}g, R=10^9cm:

$$\varepsilon \approx 10^{-4}$$

- Accretion energy is still much smaller - if the accreted hydrogen burns on the surface of the white dwarf can release a lot more energy.
- However, it becomes an interesting energy source in such systems by the sheer fact that nuclear fusion does no longer happen in white dwarfs.

Energetics of accretion (5)

- **A neutron star:** typical mass $3 \cdot 10^{33}$g, R=10^6cm:

$$\varepsilon \approx \frac{GM\dot{M}}{R} \times \frac{1}{\dot{M}c^2} = \frac{GM}{Rc^2}$$

$$\varepsilon \approx 0.2$$

- **A black hole:** The radius of the horizon is given by the Schwarzschild radius: $R_{BH} = R_{Sch} = \frac{2GM}{c^2}$

  However, for a non-rotating black hole the innermost stable orbit is $R = 3R_{Sch}$ (for rotating, or Kerr black holes, $R < 3R_{Sch}$). Thus,

$$\varepsilon \approx 1/6$$

- Very high efficiency - accreting neutron stars and black holes in binaries are luminous sources, normally in X-ray radiation.

Observational Evidence for Accretion Disks (1)

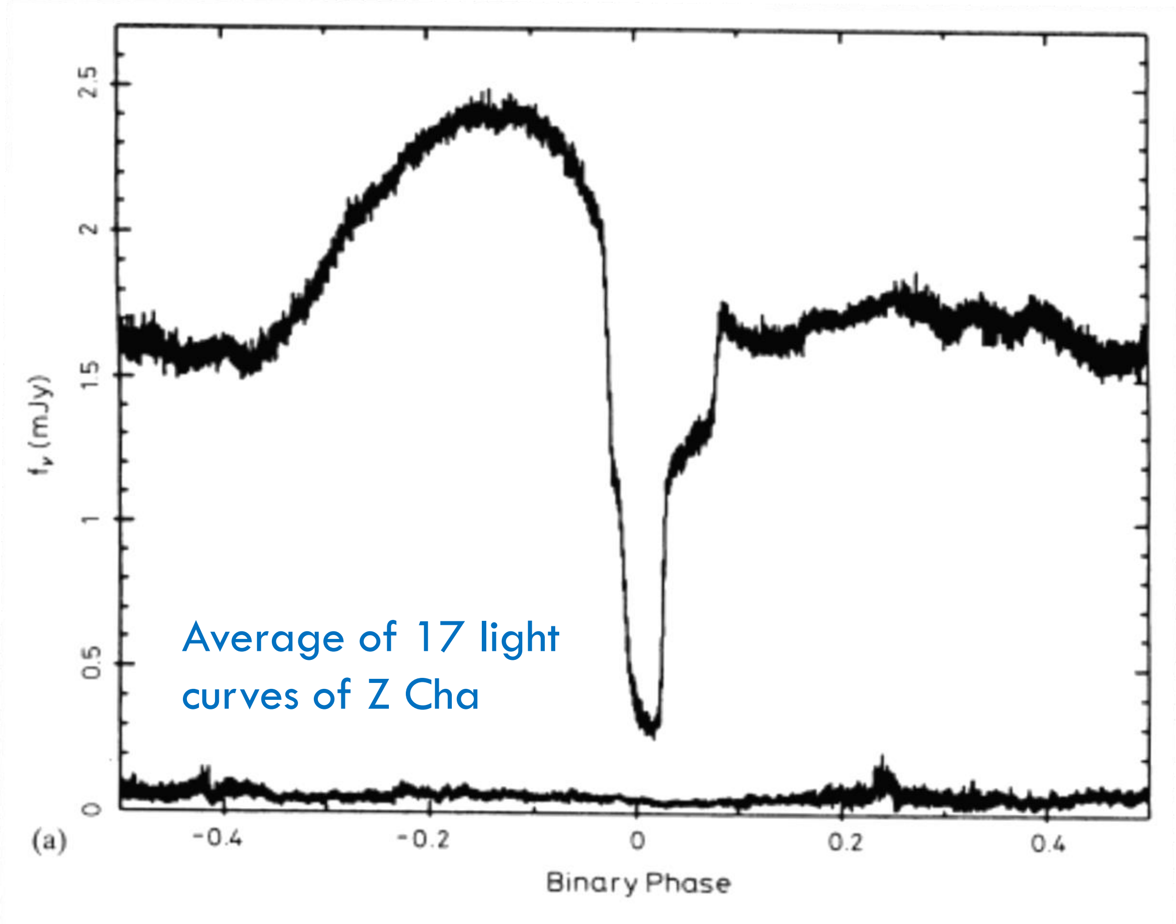
- Direct observational evidence for accretion disks in form of a spatially resolved picture of such a disk does not yet exist:
  even in the nearest disk-containing systems the angular size of the disk is far below available angular resolution.
- At a distance of $D \sim 50$pc and with a radius of $r \sim 1 R_{\odot}$, the disk subtends an angle < 0.2 mas.
- Thus all evidence for accretion disks must necessarily be indirect.

Observational Evidence for Accretion Disks (2)

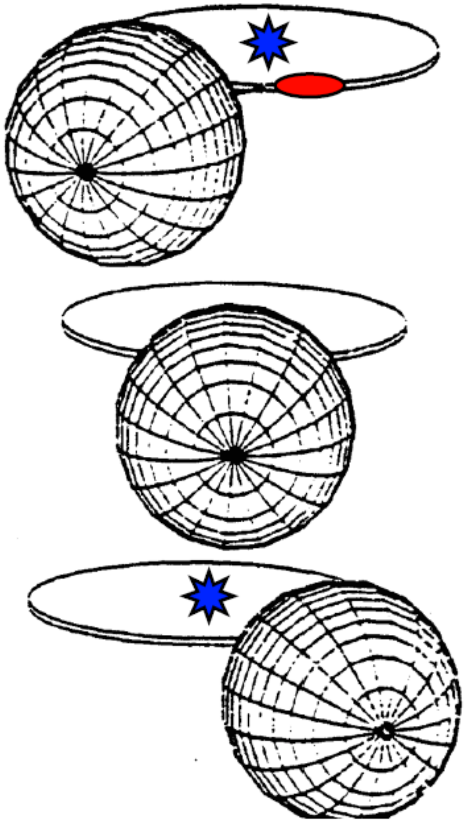
- There are two pieces of evidence:
  - the results of light curve analysis of eclipsing systems **and**
  - the interpretation of the line profiles of the observed spectra.

Light curves of eclipsing CVs

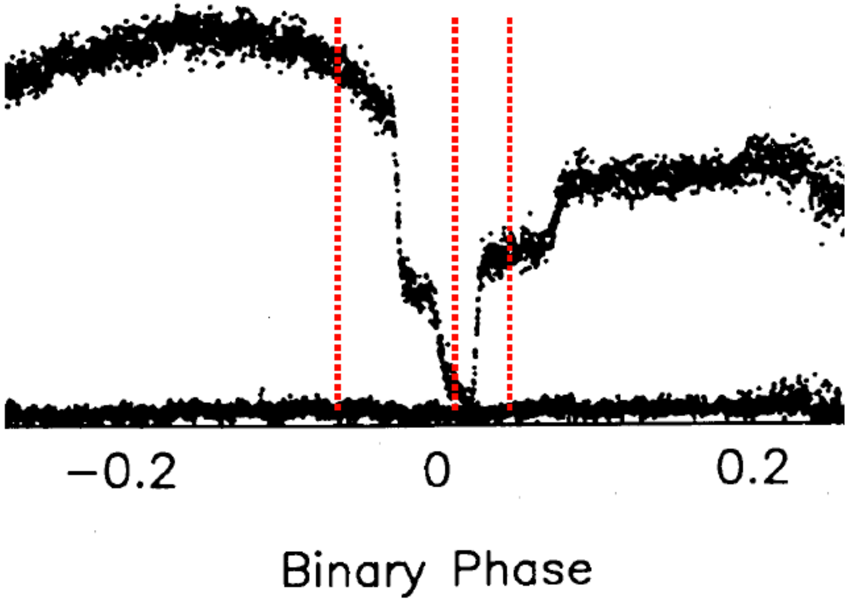
Cataclysmic variables (CVs) - binary star systems that have a white dwarf and a low-mass normal star companion. They are typically small – the entire binary system is usually the size of the Earth-Moon system – with an orbital period of 1 to 10 hours.



Light curves of eclipsing CVs



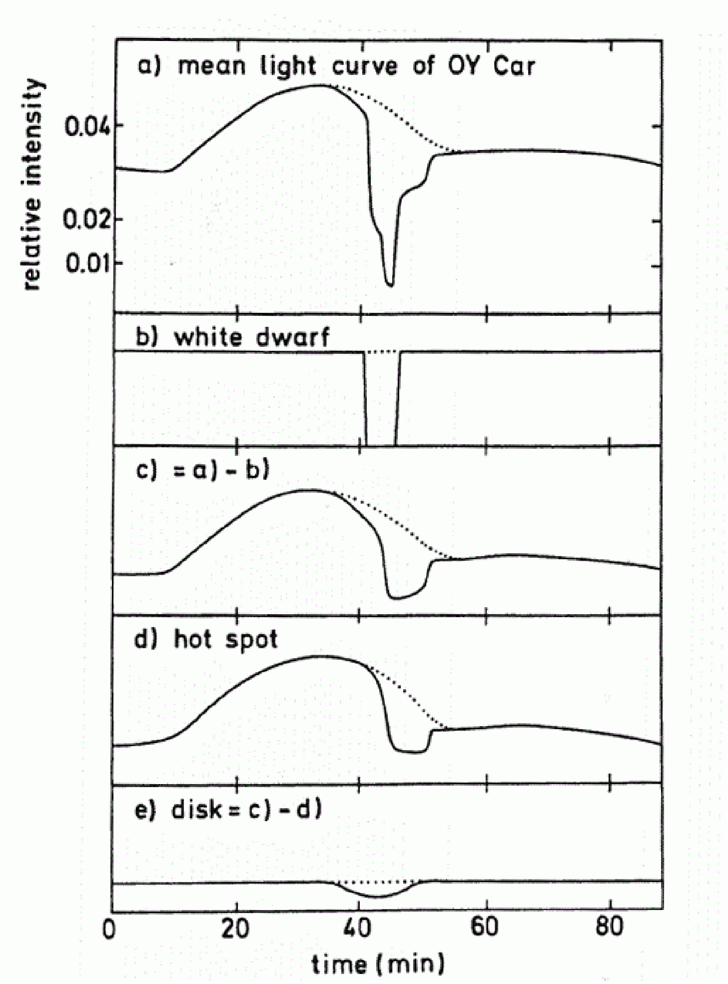
OY Car in quiescence



from Wood et al. 1989, ApJ, 341, 974

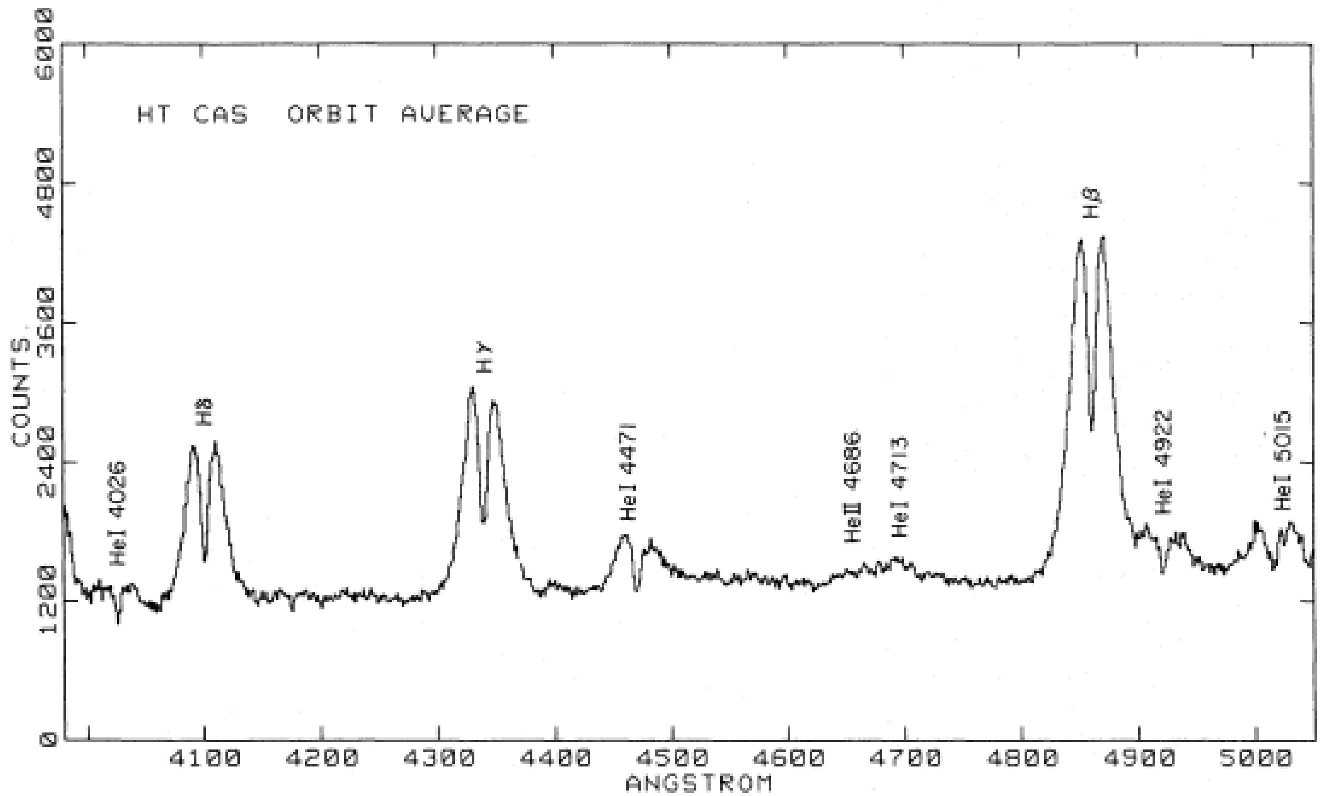
Light curves of eclipsing CVs

An observed light curve can be decomposed into the various contributions.



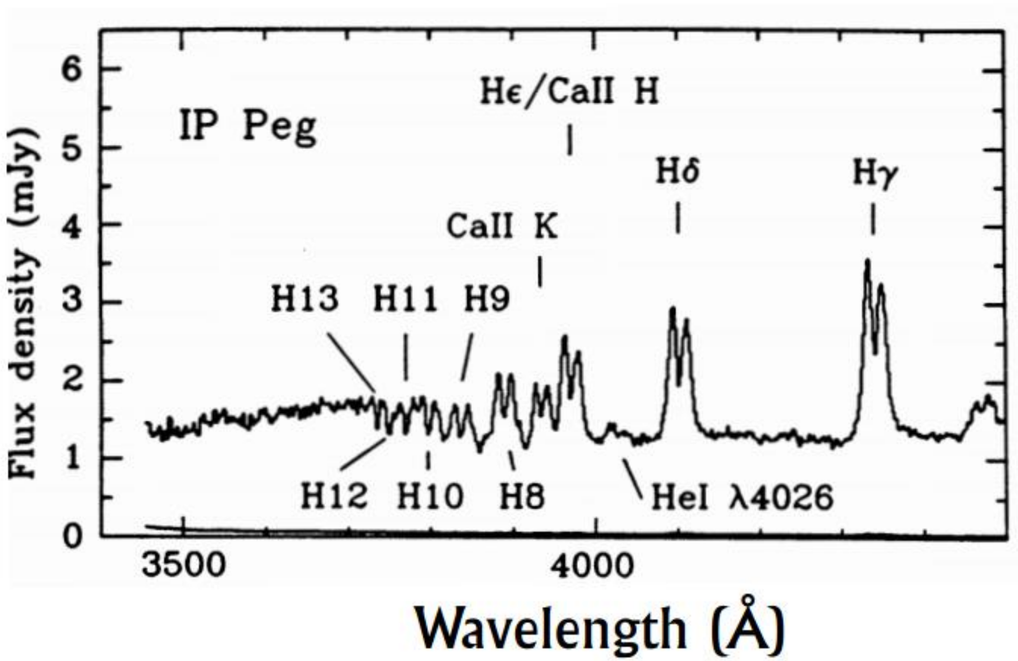
Spectroscopy: Emission line profiles

Mean spectrum of HT Cas outside eclipse

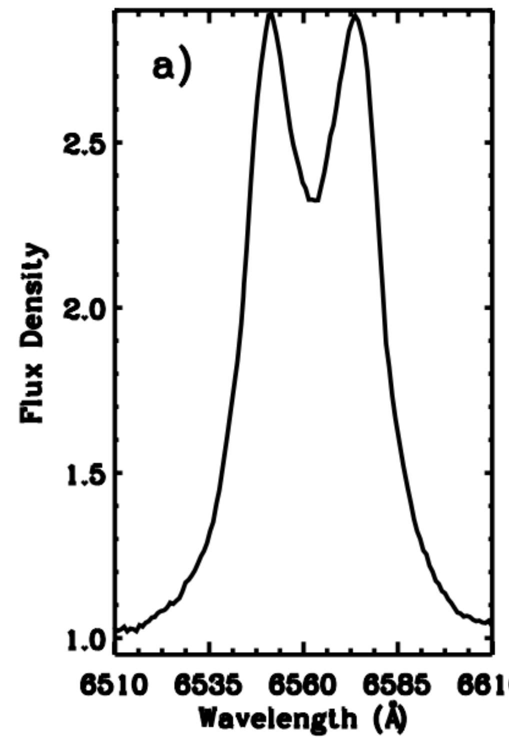


Very broad double-peaked emission lines of nearly the same width. The dominant broadening mechanism is the Doppler shift due to rotation of the accretion disk around the accretor.

Spectroscopy: Emission line profiles



IP Peg in low state
from Marsh 1988, MNRAS, 231, 1117



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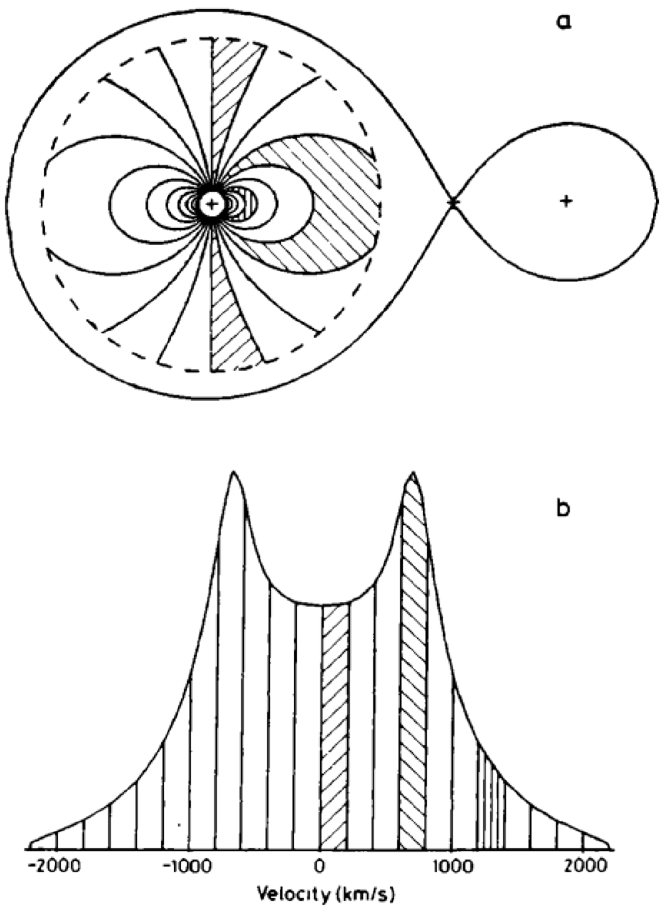
Nielsen et al. 2008, MNRAS, 384, 849

Spectroscopy: Emission line profiles

(a) Loci of constant radial velocity in a Keplerian disk in a binary of mass ratio $q = 0.15$ viewed at quadrature

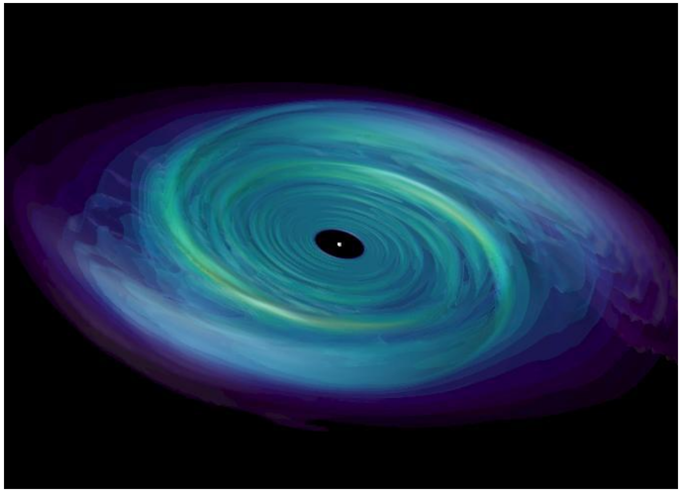
(b) Velocity profile of emission lines from the disk. Emission in the shaded velocity ranges originates in corresponding shaded regions on the disk.

(From Home & Marsh 1986).



Accretion Disks

- Accretion disks are important in astrophysics as they efficiently transform gravitational potential energy into radiation.



- **3 Classic Papers:**
  - Black hole accretion disks
    - Shakura & Sunyaev 1973, A&A, 24, 337
  - Time-dependent disks
    - Lynden-Bell & Pringle1974, MNRAS, 168, 603
  - Gas streams
    - Lubow & Shu 1975, ApJ, 198, 383

Accretion disk properties

Order-of-magnitude estimates

- **Mass flow rates in interacting close binary systems.**
  As template we take a cataclysmic variable (CV), a binary system with an orbital period of 1 to 10 hours.
  The observed disk luminosity of such systems is of order of one solar luminosity $L=3.9 \cdot 10^{33}$ erg/s. Then

$$L \approx \frac{GM\dot{M}}{R} \quad \Rightarrow \quad \dot{M} = \frac{LR_{WD}}{GM_{WD}}$$

$$= 2.0 \cdot 10^{16}\,\frac{\mathrm{g}}{\mathrm{s}} \left(\frac{L}{L_\odot}\right) \left(\frac{R_{\mathrm{WD}}}{10^{-2} R_\odot}\right) \left(\frac{M_{\mathrm{WD}}}{M_\odot}\right)^{-1} =$$

$$= \underline{3 \cdot 10^{-10}\,\frac{M_\odot}{\mathrm{yr}}} \left(\frac{L}{L_\odot}\right) \left(\frac{R_{\mathrm{WD}}}{10^{-2} R_\odot}\right) \left(\frac{M_{\mathrm{WD}}}{M_\odot}\right)^{-1}$$

Accretion disk properties

Order-of-magnitude estimates

- **Temperatures of accretion disks.**
  When one knows the outer radius of a disk and its luminosity one can estimate an average effective temperature of a disk. The luminosity is proportional the radiating area times the forth power of the (average) temperature (assuming the black body approximation):

$$L_d \approx 2\pi {R_d}^2 \sigma {T_{eff}}^4$$

The factor of 2 takes care of the two surfaces of an accretion disk ("top" and "bottom" surface).

Accretion disk properties

Order-of-magnitude estimates

- **Temperatures of accretion disks (cont).**
  With the total disk luminosity of $L \approx GM\dot{M}/R_{WD}$ we get

$$T_{eff} \approx 10^4 K \left[\frac{\left(\frac{M_{WD}}{M_\odot}\right)\left(\frac{\dot{M}}{10^{-9} M_\odot \,\mathrm{yr}^{-1}}\right)}{\left(\frac{R_{WD}}{10^{-2} R_\odot}\right)\left(\frac{R_d}{R_\odot}\right)^2} \right]^{1/4}$$

- The average temperature depends only weekly (by its forth root) on accretor's mass and size and on the accretion rate, but somewhat stronger (by its root) on the disk size

Accretion disk properties

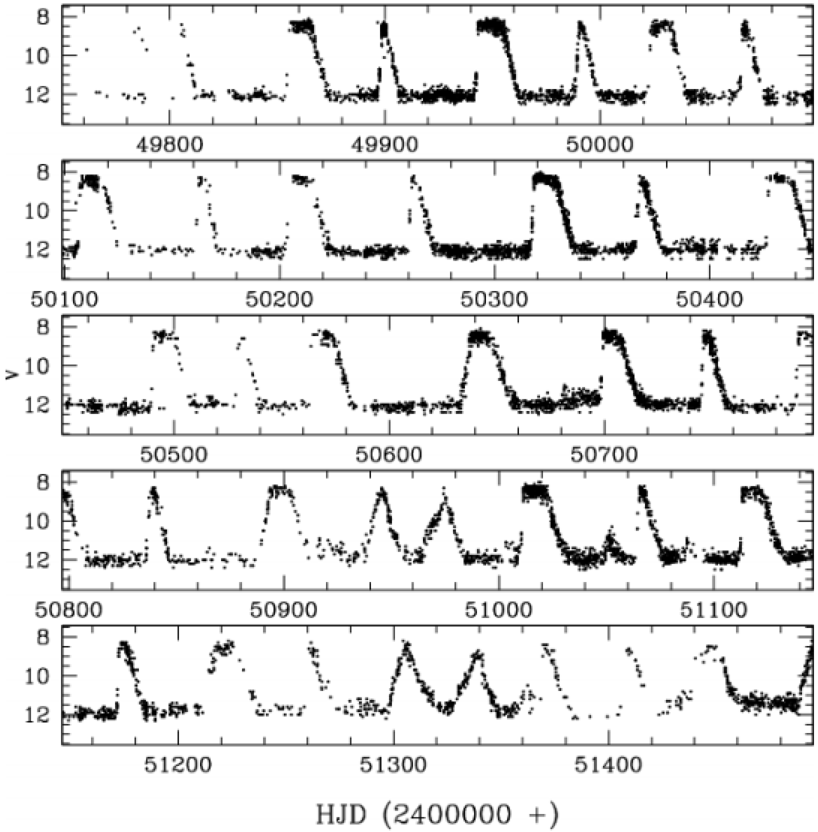
Order-of-magnitude estimates

- **Temperatures of accretion disks (cont).**
  The dependence on the available area shows that the effective temperature cannot be constant throughout the disk. As long as $R_d \gg R_{WD}$, a change of R_d does not alter the luminosity considerably while, at the same time, it strongly changes the available radiating area and thus the effective temperature.
- This leads to the suspicion that the effective temperature in accretion disks decreases with increasing radius. This is the case, indeed.

Accretion disk properties

Order-of-magnitude estimates

- **Disk masses in dwarf novae.** Dwarf novae - a subtype of CVs which exhibits outbursts with a characteristic (though not strict) repetition period of a few ten days.
- The outbursts are caused when the accretion disk reaches a critical temperature, the disk becomes unstable and the gas collapses onto the white dwarf (we will discuss it in detail later).



Accretion disk properties

Order-of-magnitude estimates

- **Disk masses in dwarf novae (cont).**
  The repetition time scale of the outbursts defines the average evolution time scale, i.e. the time scale it takes a particle on average to move through the entire extent of the disk.
- Let us assume an evolution time scale $\tau_{disk} \approx 10$ days $\approx 10^{-1.5}$ yr. Together with the mass flow rate we get a disk mass in a dwarf nova:

$$M_{disk,DN} \approx \dot{M}_{DN} \tau_{DN} \approx 10^{-9} M_{\odot} yr^{-1} 10^{-1.5} yr \approx 10^{-10.5} M_{\odot} \ll M_{WD}$$

- Dwarf nova accretion disks have a much smaller mass than the white dwarf about which they move and onto which they accrete. In this respect DN disks are practically **massless.**

Accretion disk properties

Order-of-magnitude estimates

- **Velocities in dwarf nova disks.**
  If the disk is practically massless, the particles in the disk move about the centre according to Kepler's third law as long as they move on closed orbits. The azimuthal velocity

$$V_\varphi = \sqrt{\frac{GM}{R}} = 4.4 \times 10^7 \, \frac{cm}{s} \left(\frac{M_{WD}}{M_\odot}\right)^{1/2} \left(\frac{R}{R_\odot}\right)^{-1/2}$$

- At the same time, one can estimate the radial velocity V_R through the disk with which the mass moves

$$V_R \approx \frac{R}{\tau_{\text{disk}}} \approx 7 \times 10^4 \, \frac{cm}{s} \left(\frac{R}{R_\odot}\right)$$

Accretion disk properties

Order-of-magnitude estimates

- **Velocities in dwarf nova disks (cont.).**
  Comparing the azimuthal and radial velocities, one finds
  $$\frac{V_R}{V_\varphi} = 1.6 \times 10^{-3} \left(\frac{M_{WD}}{M_\odot}\right)^{-1/2} \left(\frac{R}{R_\odot}\right)^{3/2} \ll 1$$

- This shows that in accretion disks the motion is almost that of test particles orbiting the centre of the disk in circles, superposed by a slow radial inward drift.