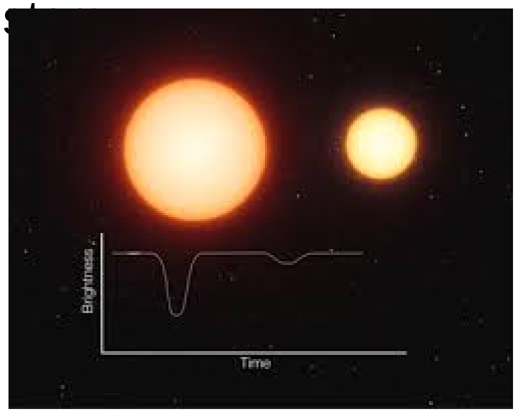
Applications: main sequence stars, white dwarfs

The last three lectures will be devoted to complementary approach to accretion: instead of concentrating on some universal physical aspects we will take observational approach. We will discuss specific classes of objects, applying there the previous knowledge, to see which aspects are well understood and which problems are still unsolved.

1. Historical comment

(after Kaitchuck 1992)
The first detection of an accretion disk was accidental, and reported only as a footnote in the paper published in the Lick Observatory Bulletine. The author, Arthur Bambridge **Wise**, studied spectroscopically the eclipsing binaries using a 3-m telescope in the Lick observatory, concentrating on Algol variables. Algol (sort period) systems consist of two main sequence stars



Algol type star – eclipses (wikipedia)

The aim was to obtain the spectrum of the secondary star, and he concentrated on the eclipse period of the primary, so the secondary could be more visible. For some of the systems, he noticed that apart from the usual stellar absorption lines, there are also weak emission lines, and their position seemed to change. For one system, RW Tau, he attempted to follow the spectral evolution during the eclipse more closely.

1. Historical comment

[9] A one-hour exposure of *RW Tau* ($8^{m}1$-$11^{m}5$, A0, period variable) was taken on 1933 Nov 21 with the 2-prism spectrograph (3½-inch camera). The predicted time of eclipse, corrected for light time, was J.D. 242 7398.870 (G.M.T.), and the time of mid-exposure was four minutes later. The plate showed an A-type spectrum, on which were superimposed the bright lines $H\beta$, $H\gamma$, $H\delta$, and probably $\lambda 4481$ of *Mg II*. The emission lines were displaced to the violet edge of the absorption lines. The star was observed to increase slightly in brightness toward the end of the exposure, and it later became evident that the absorption spectrum was caused by the light of the primary. The $11^{m}5$ secondary is without doubt fainter than the 12th magnitude photographically, and is therefore too faint to register its spectrum in one hour.

It was next proposed to take a series of short exposures during principal minimum and immediately thereafter. The desirability of making the exposures as short as possible is obvious. From the intensities of the bright lines, it was judged that $H\beta$ and $H\gamma$ would probably appear in 15 minutes. Accordingly on 1933 Dec 16 seven consecutive 15-minute exposures were made. The four plates during minimum light showed no trace of a spectrum. The three that were taken while the bright star was emerging from eclipse showed perfectly normal absorption line spectra. Incidentally, these plates furnished the material for an ephemeris correction of approximately $-0^{d}013$, or -19^{m}.

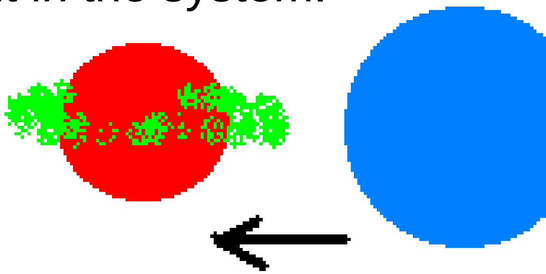
The first plate was now repeated, at the same phase and under the same conditions, 1934 Jan 10. Strangely enough, no bright lines were visible, although the absorption spectrum was present with the same intensity as before. Unfortunately there has been no opportunity to continue observations of this star.

The possibility that the star was misidentified at the time the first plate was taken is exceedingly remote. The observed star was of the brightness to be expected, and appeared to increase slightly in brightness at the time predicted by the corrected ephemeris. A search of the field on two spectrograms taken with the slitless spectrograph of the Crossley reflector on 1933 Nov 10 and 23 failed to disclose any stars with bright lines.

In the present state of affairs, the only possible conclusion is that the bright lines are variable, and that they cannot be interpreted as the flash spectrum of the bright component. The chromosphere of the secondary may vary as a whole, giving rise to variable emission lines. Further spectrographic observations of *RW Tau* should be made, and a thorough search of the field is highly desirable. Even if the bright-line spectrum should prove to belong to another star, it would be an interesting discovery.

Wyse even argued that the emission lines are unlikely to come from the chromosphere of the primary, but the data quality was not good enough to see exactly what is happening.

Now we can easily understand the origin of emission lines as comming from a faint accretion disk present in the system.



Seven years later A. Joy (1942) studied the same star with the same telescope but he collected **more spectra** during the eclipse. The pattern became clear. He saw that at the beginning of the eclipse the emission lines were redshifted by 350 km/s, they disappeared during the fulll eclipse, and then reappeared with the blueshift by 350 km/s.

Wise (1934), cited 7 times ….

1. Historical comment

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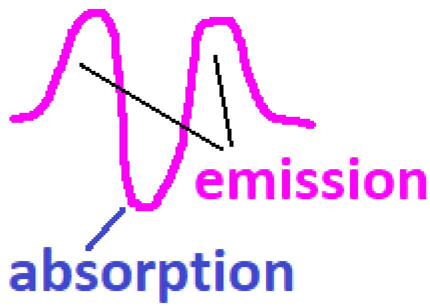
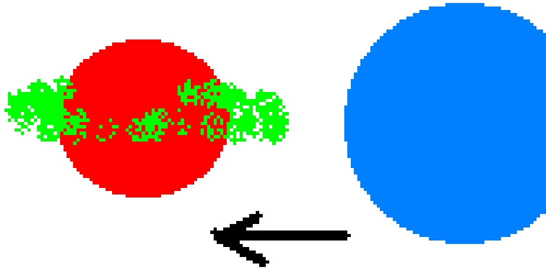
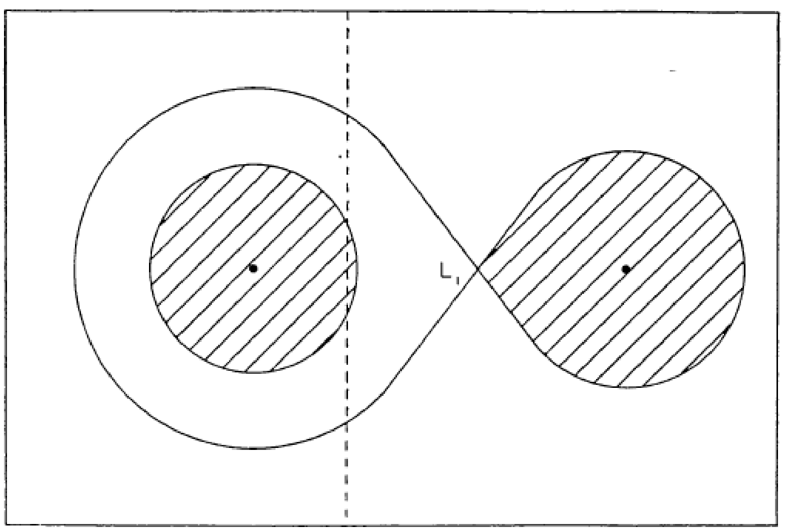




Joy also proposed an interpretation: primary is surrounded by a disk. This claim was met with a considerable interest, paper was cited 57 times. Soon many more such cases were discovered (Struve 1948, 1949, Struve and Huang 1949).

Later on the physical explanation was provided, with the introduction of the idea of the mass transfer between the stars (Crawford 1955), with now well known plot of the Roche lobe overflow.



Crawford (1955)

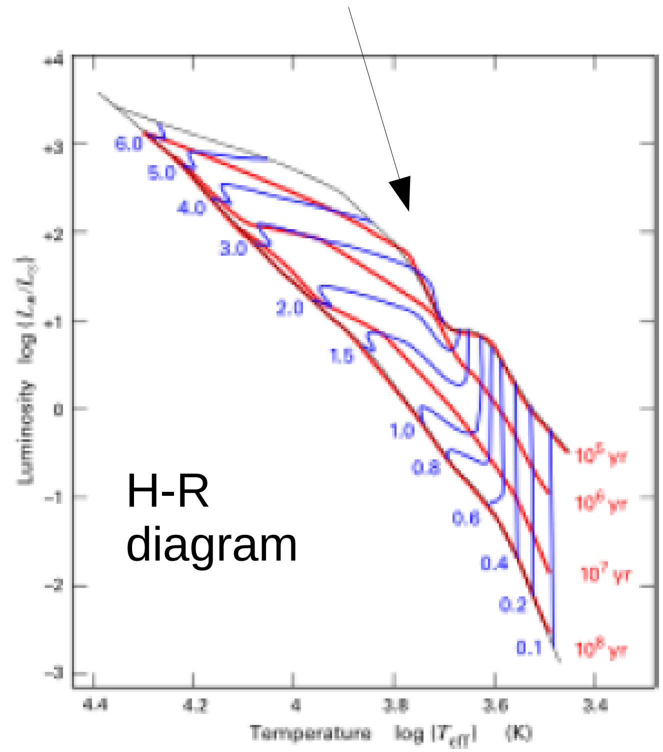
The idea of mass exhange solved two problems:

- The discrepancy between the masses and the radii in two stars
- The problem of the evolutionary stage: lower mass star of the binary is more evolved while in single stars the more massive star evolves faster.

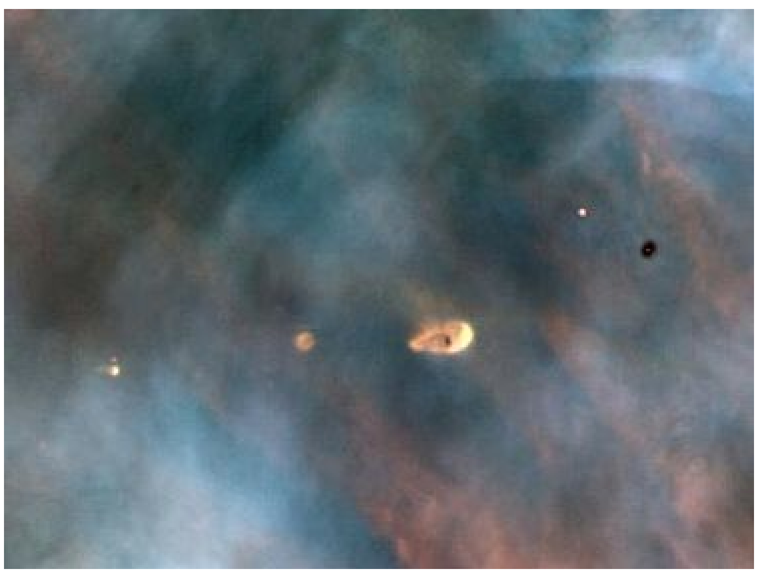
2. Accretion onto pre-main sequence stars

Formation of new stars proceeds through the contraction of the molecular cloud, and subsequent formation of a binary star or a single star with a planetary system.
T Tauri type stars are less than 10 milion years old, low mass stars (below 2 Ms), and they are still in the contraction process, move along the Hayashi track to reach the main sequence.

The star radiation is powered by contration and by buring lithium, after contraction it will start burning hydrogen and then it will settle on the main sequence.
T Tau stars are surrounded by protoplanetary disks.



Region of formation of young stars (wikipedia)
Hayashi tracks marked by mass and age (wikipedia)



Protoplanetary disks in Orion Nebula

T Tau stars belong to a larger group called Young Stellar Objects, which consists of protostars and pre-main-sequence stars.

Stars are strongly variable, and they frequently shows eruptions and jets.

2. Accretion onto pre-main sequence stars

Before high spatial resolution observations were available, we knew about the existence of the accretion disks in these systems from the broad band data.
The spectral models of accretion disks implied the flux dependence on the radius as

$$T(r) = A r^{-q}, \qquad F_\nu \propto \nu^{3-2/q}$$

with the index requested by the data

$$T(r) \propto r^{-1/2}$$

Instead of the standard $r^{-3/4}$. This indicated non-stationary character of the disk. In many disks the presence of a gap in the disk is required. In such gaps we can expect the presence of the small companion star or a large planet since the presence of the massive body inside the disk caused dynamical perturbations of the gas.

The important aspect is that these disks are additionally

- Cold
- Massive in comparison to the central star

OF GK TAU AND HK TAU L73

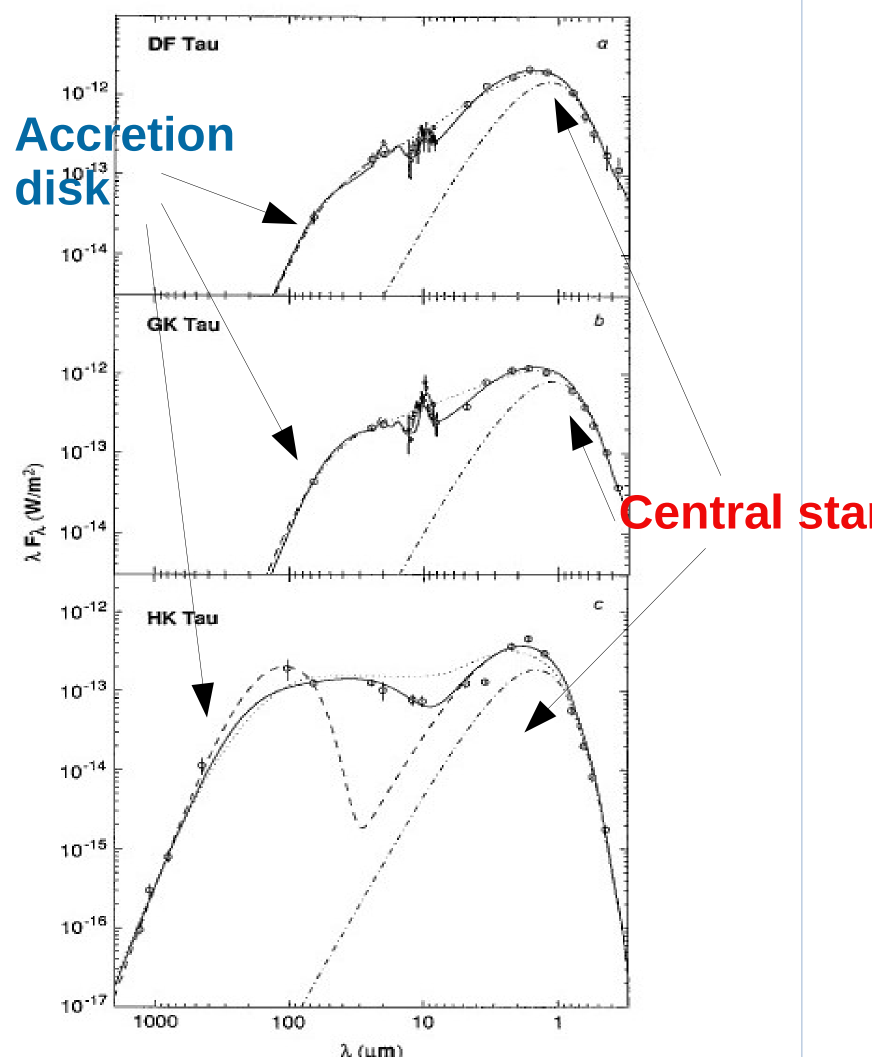
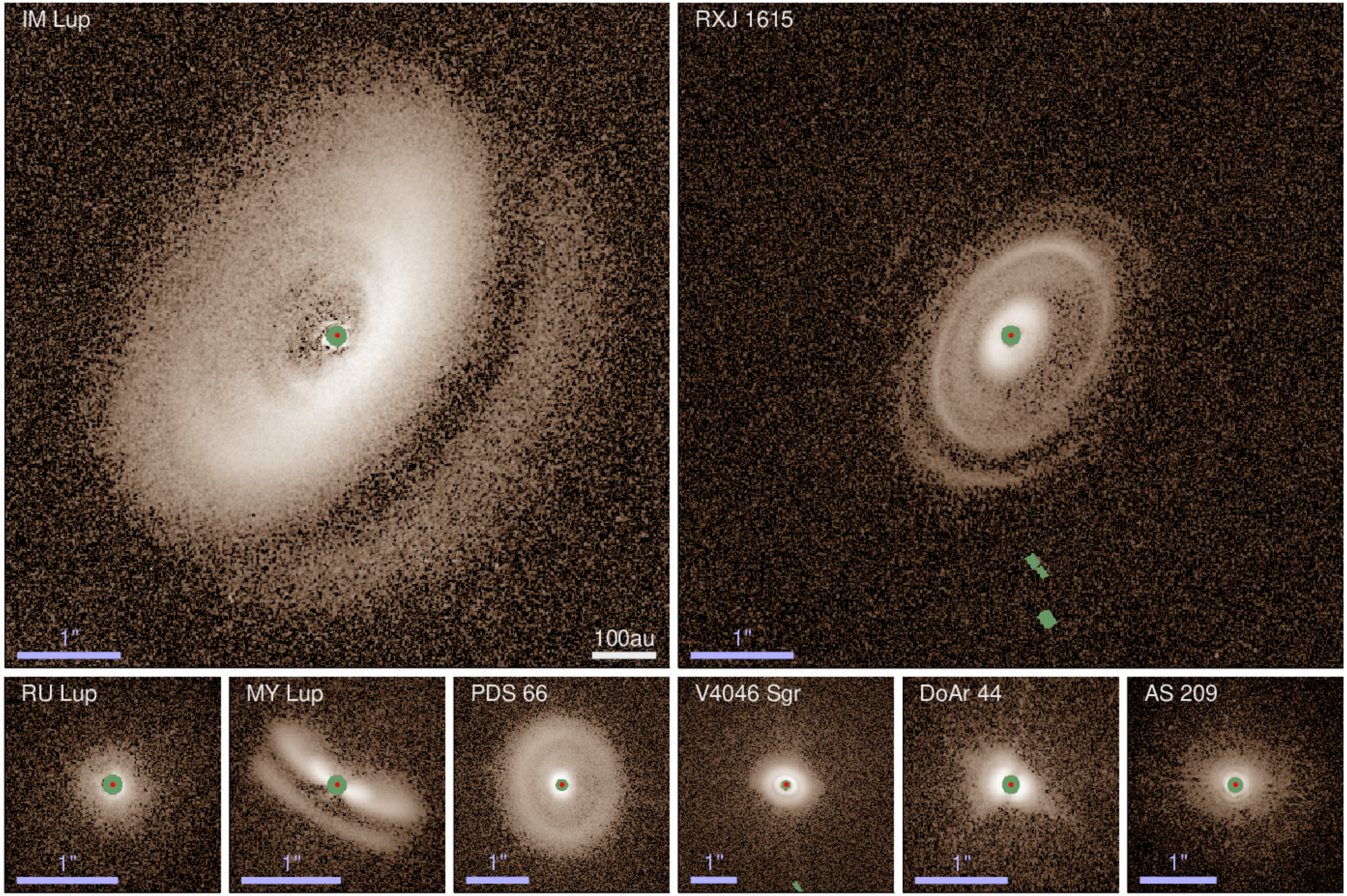


FIG. 1.—(*a*–*c*) Results of theoretical modeling of the spectral energy distributions of DF Tau, GK Tau, and HK Tau. The spectral energy, $\lambda F_\lambda = \nu F_\nu$ (where F_ν, ν, and λ represent the flux density, frequency, and wavelength) is in units of W m^{-2}. The observed data are represented by open circles with error bars. On each plot, the solid line represents the best-fit spectrum for the pure-disk model, and the dotted line represents a "gapless" pure-disk model for comparison. The dot-dashed line represents the contribution of the star + boundary layer. Also shown (*dashed line*) is the best-fit spectrum for the disk-shell model.

Marsh and Mahoney (1993)

2. Accretion onto pre-main sequence stars

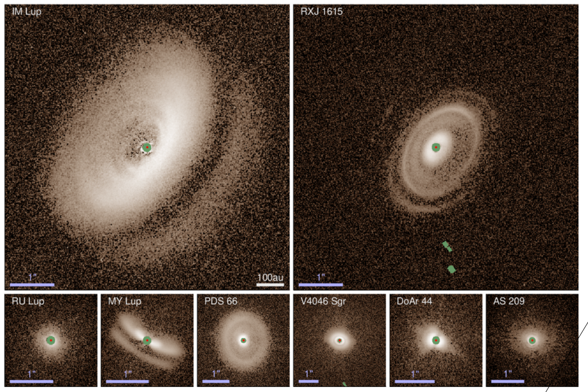


Those are actually images of the disks in T Tau stars obtained with the SPHERE/IRDIS polarimetric differential imaging in the J and H bands (Avenhaus et al. 2018). The size of the disk is of order of 80 au. It complements the previous ALMA observations in mm bands.

We see there several rings, sometimes spiral structures.

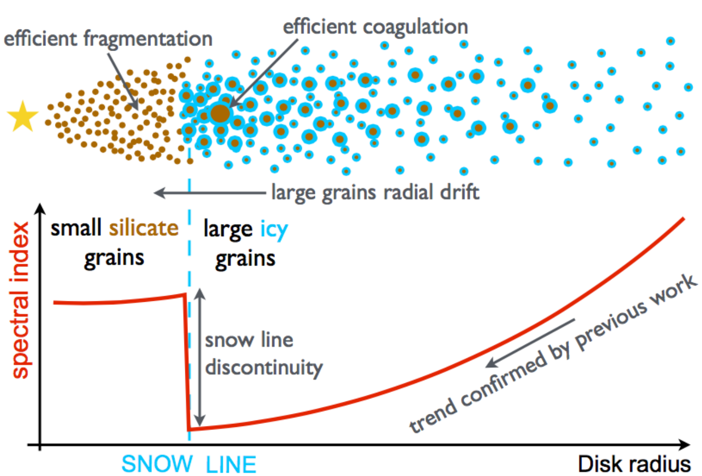
Theoretically, such disks pose a huge challenge for modelling, this is why we did not discuss the before.

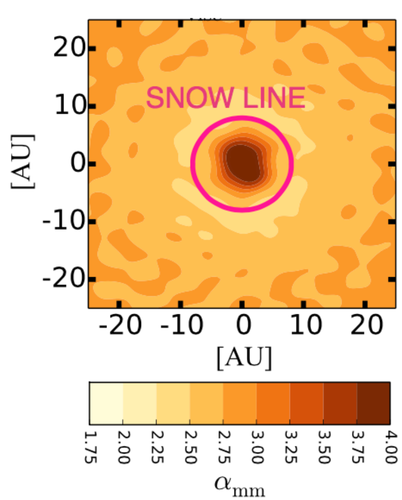
2. Accretion onto pre-main sequence stars



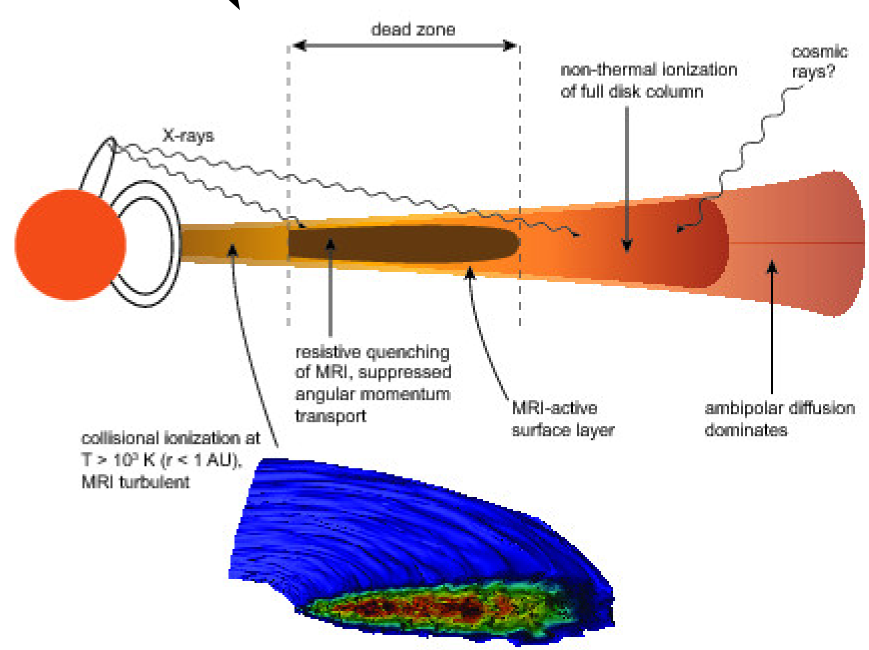
Theoretically, such disks pose a huge challenge for modelling, this is why we did not discuss them before:

- Self-gravity effects, spirals and rings
- Jets and winds
- Complex opacities dust, molecules
- Snow line
- Formation of planetesimals, subsequent formation of planets
- Gap opening by planets
- Drifting the newly formed planets toward the center
- Accretion mechanism – MRI is not operational in the full body of the disk due to too low ionization of the material and inability to froze the magnetic field lines into the (mostly neutral) plasma – dead zone problem



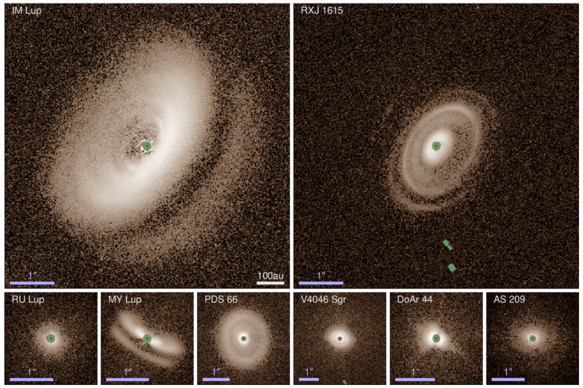


Banzatti et al. (2015)



Armitage et al. (2011)

2. Accretion onto pre-main sequence stars



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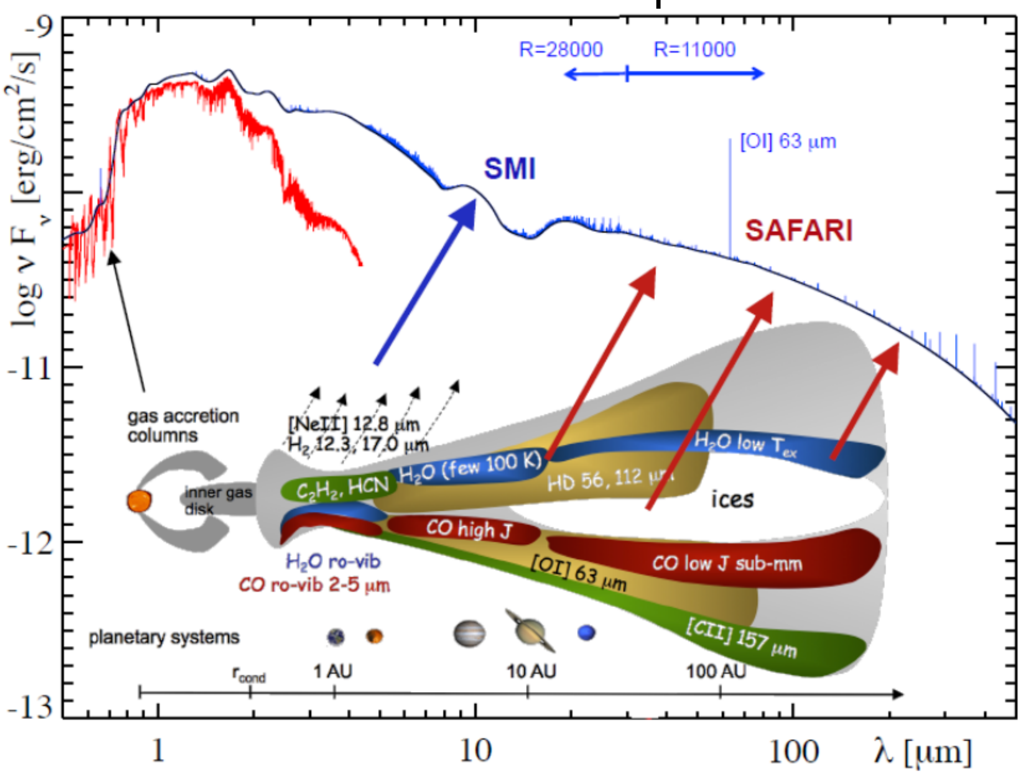


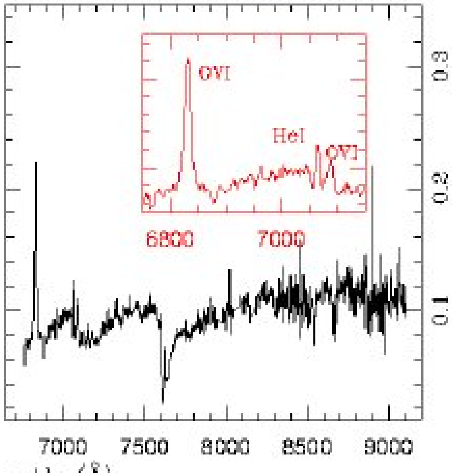
Some of these problems might aply in outer parts of AGN disks.

A plot of the disk structure made for the planned SPICA IR mission.

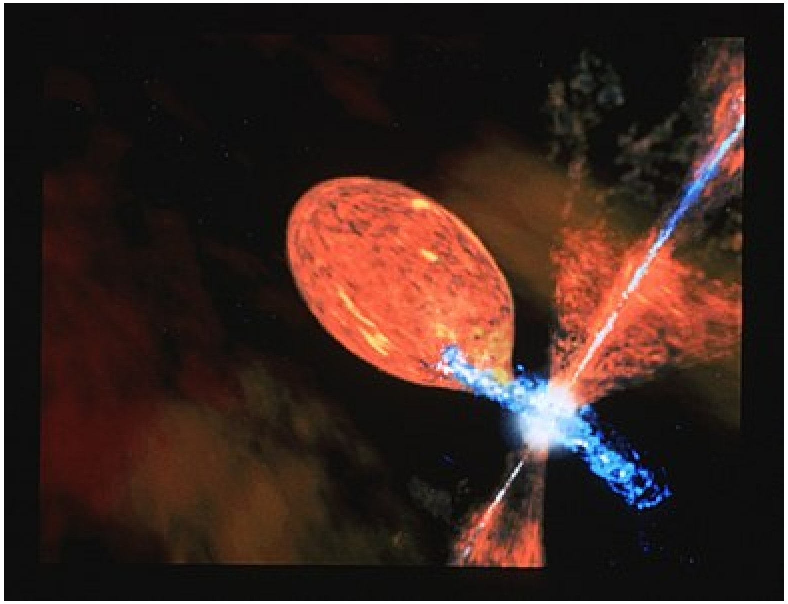
3. Symbiotic stars

In spectroscopic data these are stars show both absorption lines, typical in stars, and emission lines, typical for brigh nebulae, and they we recognized as very atypical class already by Annie Cannon. The term ‘symbiotic’ was introduced in 50’.
Those are binary stars, consisting of a evolved giant and a more compact companion, which may be white dwarf, or occasionally a neutron star, or eventually even a main sequence star (?).

Annie Cannon (1863-1941), wikipedia



An example of the spectrum of symbiotic star detected in dwarf spheroidal NGC 205 (Goncalves at al. 2014)



Artist view of a symbiotic system (wikipedia)

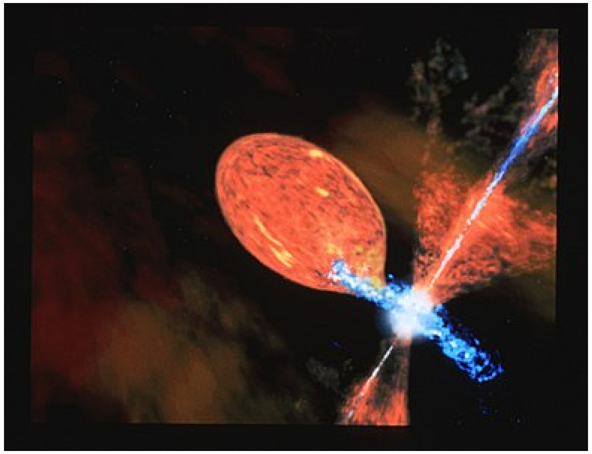
Symbiotic stars may have a jet and a disk. The flow may proceed through the inner Lagrange point or through the wind from the evolved companion.

They are additionally interesting since they are considered as possible progenitors of (some ?) SN Ia.

3. Symbiotic stars

In some symbiotic stars we see occasional eruptions of two types. One is related to a rapid increase in the mass transfer rate up to two orders of magnitude, lasting for a few years.
This might correspond to **ionization instability** which operates in X-ray novae and in cataclysmic variables.
However, a second potentially unstable process is the **burning** of hydrogen at the surface of a white dwarf.

We will discuss this burning issue more later on in this lecture, in the context of cv.



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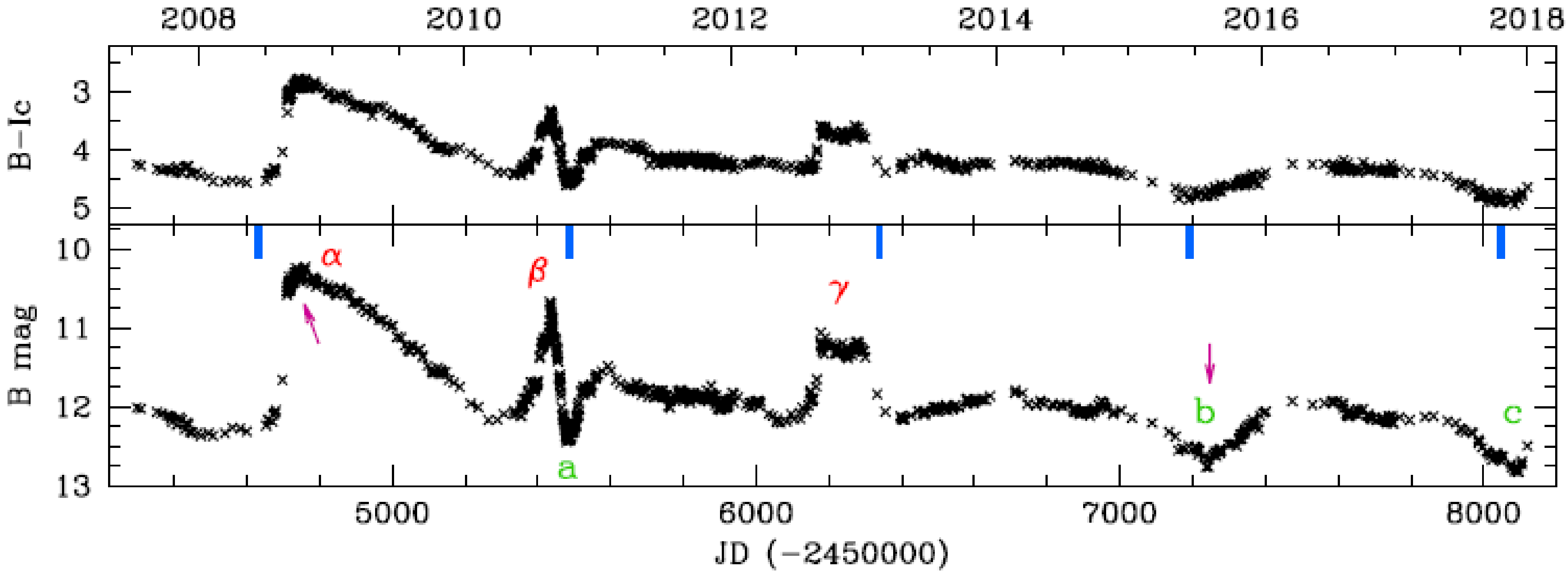
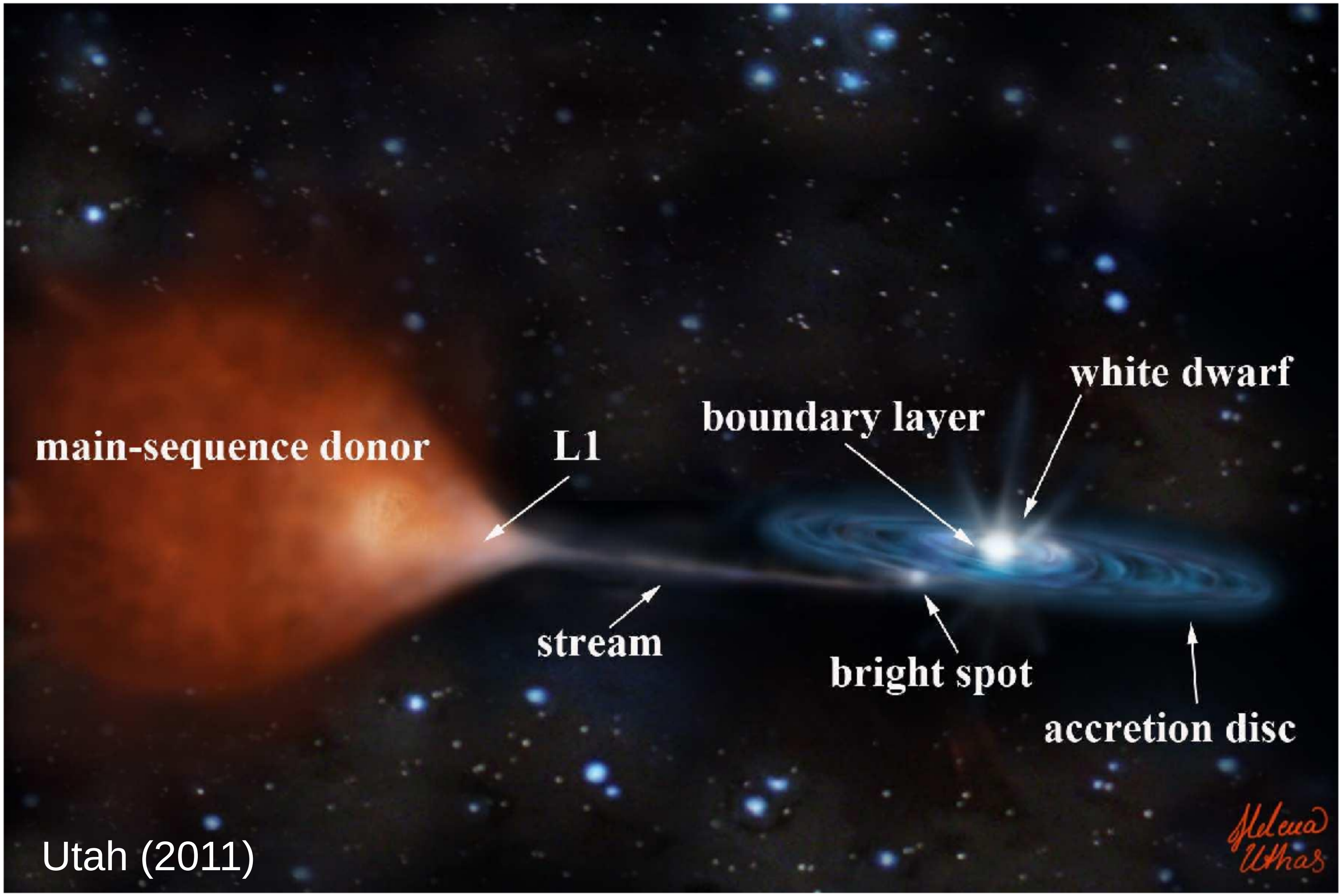


CI Cyg lightcurve from Munari (2019)

4. Cataclysmic variables

Cataclysmic variables are frequently considered as the best laboratory for studying physics of accretion disks. But before we list their advantages, we need a brief survey of this class of objects.

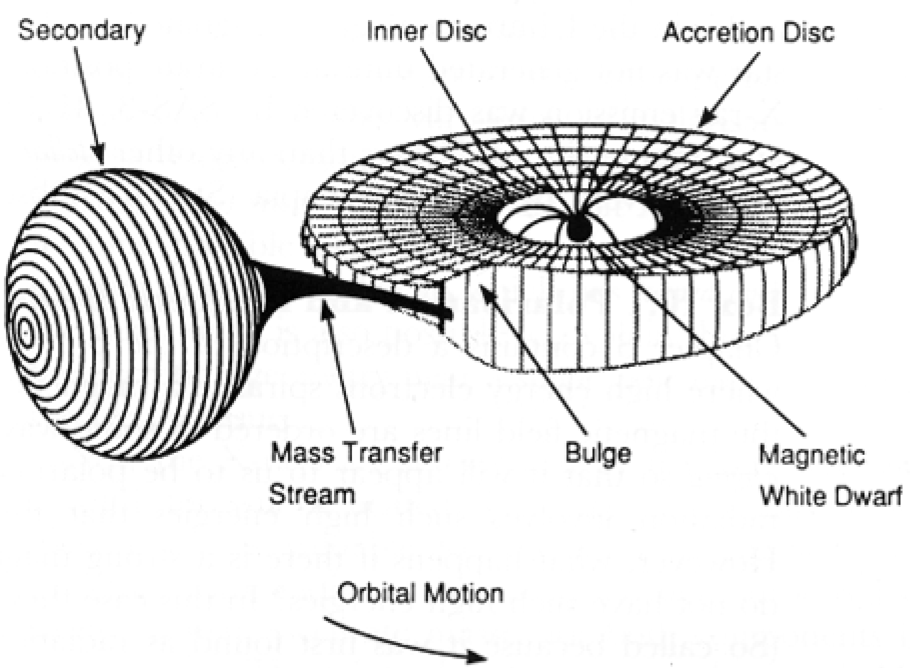


The systems always consist of a main sequence donor and white dwarf. Man sequence stars do not have strong winds, so the accretion always proceeds through the inner Lagrange point. Large angular momentum of the inflowing material frequently leads to formation of an accretion disk of the size larger than the circularization radius, so the stream hits the disk creating a bright spot (hot spot).

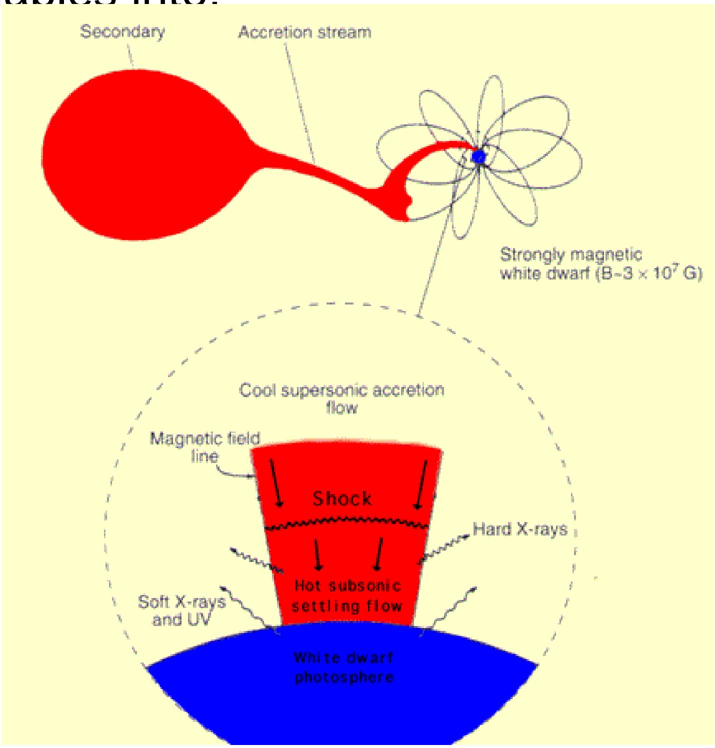
4. Cataclysmic variables

White dwarfs differ between themselves with respect to the strength of the **magnetic field.** Taking this into account, we divide cataclysmic variables into:

- Polars (AM Herculis type stars)
- Intermediate polars (DQ Herculis type stars0
- Other (U Geminorum type stars).



Intermediate polars: strong magnetic field disrupts the disk close to the accreting star (wikipedia).



Polars: strong magnetic field prevents disk formation and forces the accretion through the column along the magnetic field lines (wikipedia).

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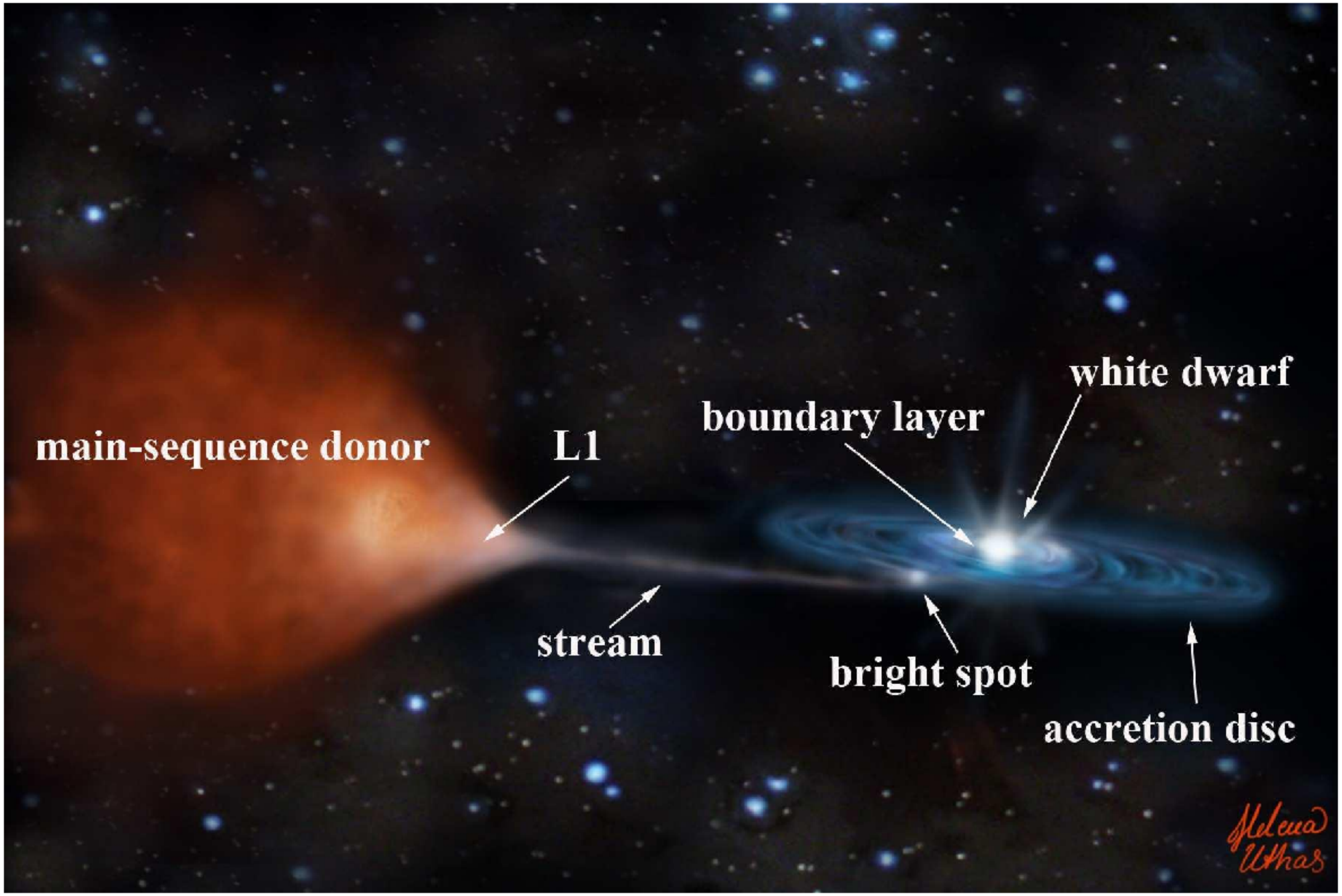
Other: magnetic field not strong enough to disrupt the disk; the disk touches the star, and the boundary layer forms which we discussed during lecture 6.



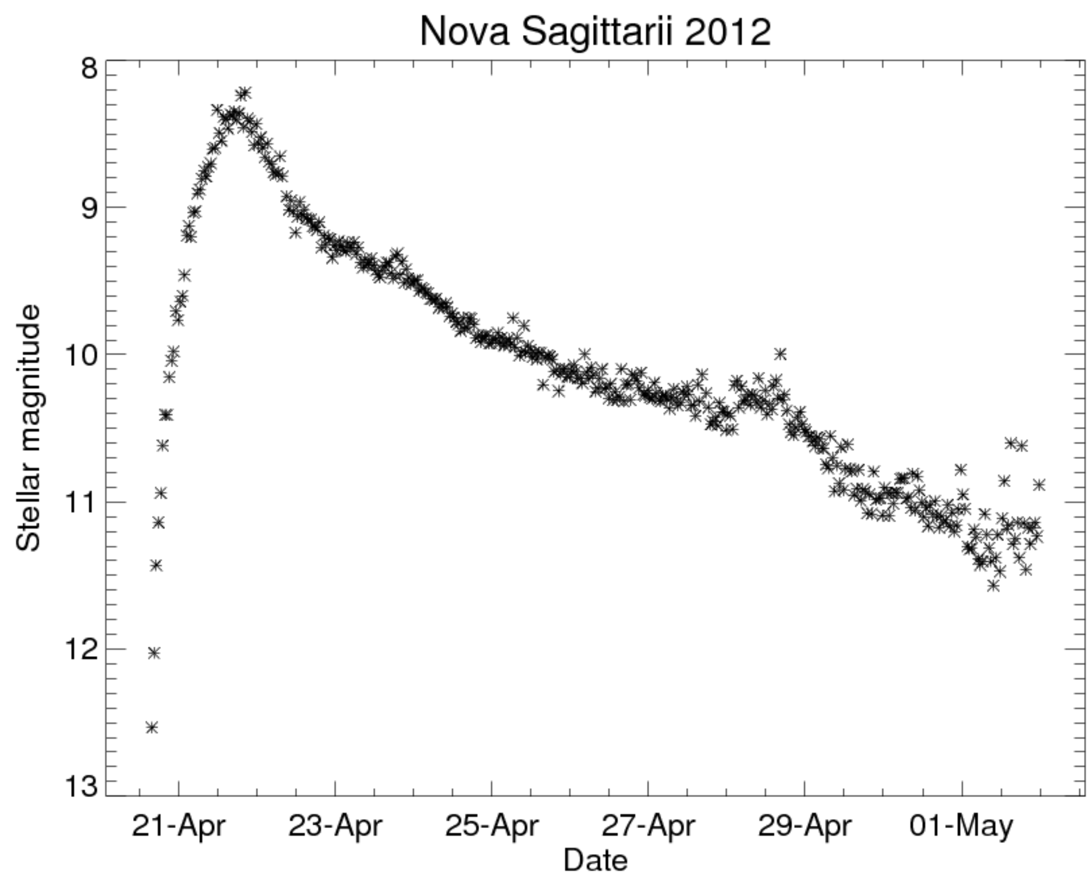
4. Cataclysmic variables

Cataclysmic variable also differ between themselves in the time-dependent behaviour. They all emerge from the binary evolution phase through a common envelope (to shrink the orbit !), later the orbit shinks further by magnetic braking and emission of gravitational waves. Thus the differences might be related to the orbital period and other details. Observationally, they are divided into

- Classical novae
- Recurrent novae
- Nova-like
- Dwarf novae

Classical novae show rapid brightening by 7 – 11 mag, and later a slow decay in the course of a few years. During this eruption the white dwarf shell is ejected, and an issue arises whether the net mass of a white dwarf is rising during its evolution or not. This is a key question from the point of view of the SN Ia progenitors.

We classify CV as a classical nova if we observed a single outburst from this star.



Thompson et al. (2012)

Classical novae are less bright than supernovae (their total energy is about 10^{44}-10^{46} erg (Orio et al. 2001), while the supernovae/hypernovae reach 10^{51} – 10^{53} erg.

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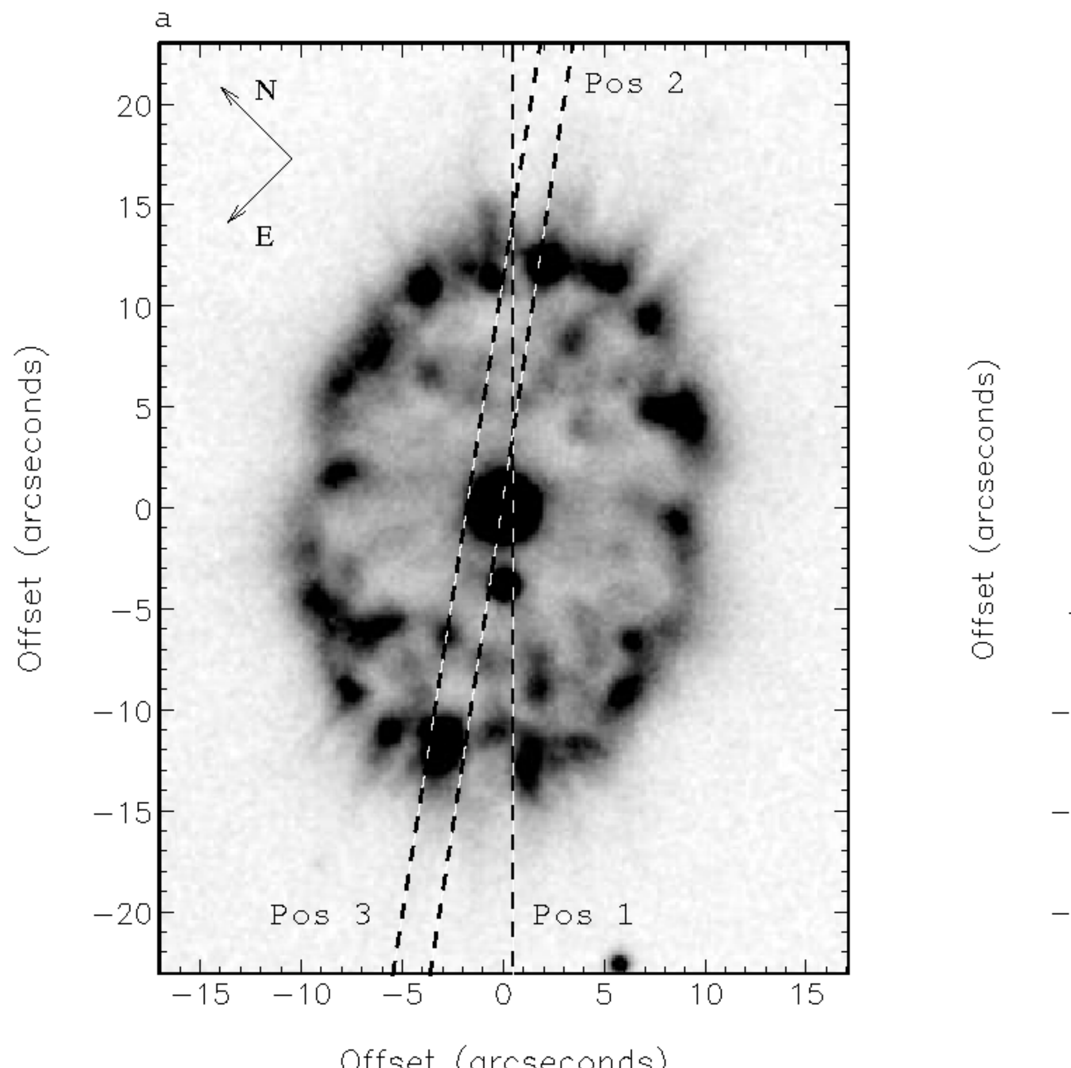
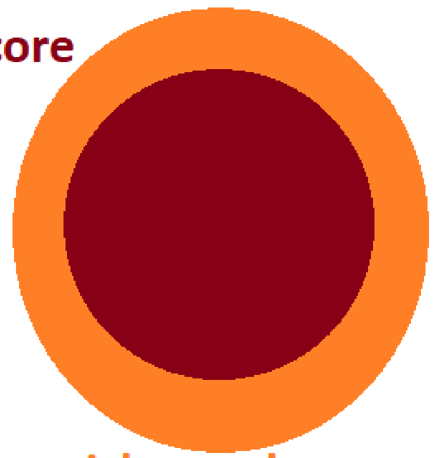


Vaytet et al. (2007), image of DQ Her shell from William Herschell telescope.

4. Cataclysmic variables: nova outburst

What is the outburst mechanism in classical novae? This is a thermonuclear flash at the surface of a white dwarf.

The hydrogen-reach material accumulates slowly at the surface of a white dwarf. As the shell increases its depth the pressure and the temperature at the bottom of the shall rises. At some point the thermonuclear reation starts.



From lecture 1:

Accretion onto a white dwarf $\quad \eta = 0.000065$
Nuclear burning $\quad \eta = 0.0075$

Material become unbound and can easily escape to infinity. What we see is an explosion.

Explosion takes place when the appropriate amount of material accumulates. If the accretion rate is higher the material accumulates faster and the eruptions should happen more frequently.

In some systems nova eruption happen frequently enough that two or more were observed from the same CV.
Those systems are classified as recurrent novae.

In other systems we just never saw an eruption but otherwise the binary looks like other novae systems well after outburst. Those systems are classified as nova-like.

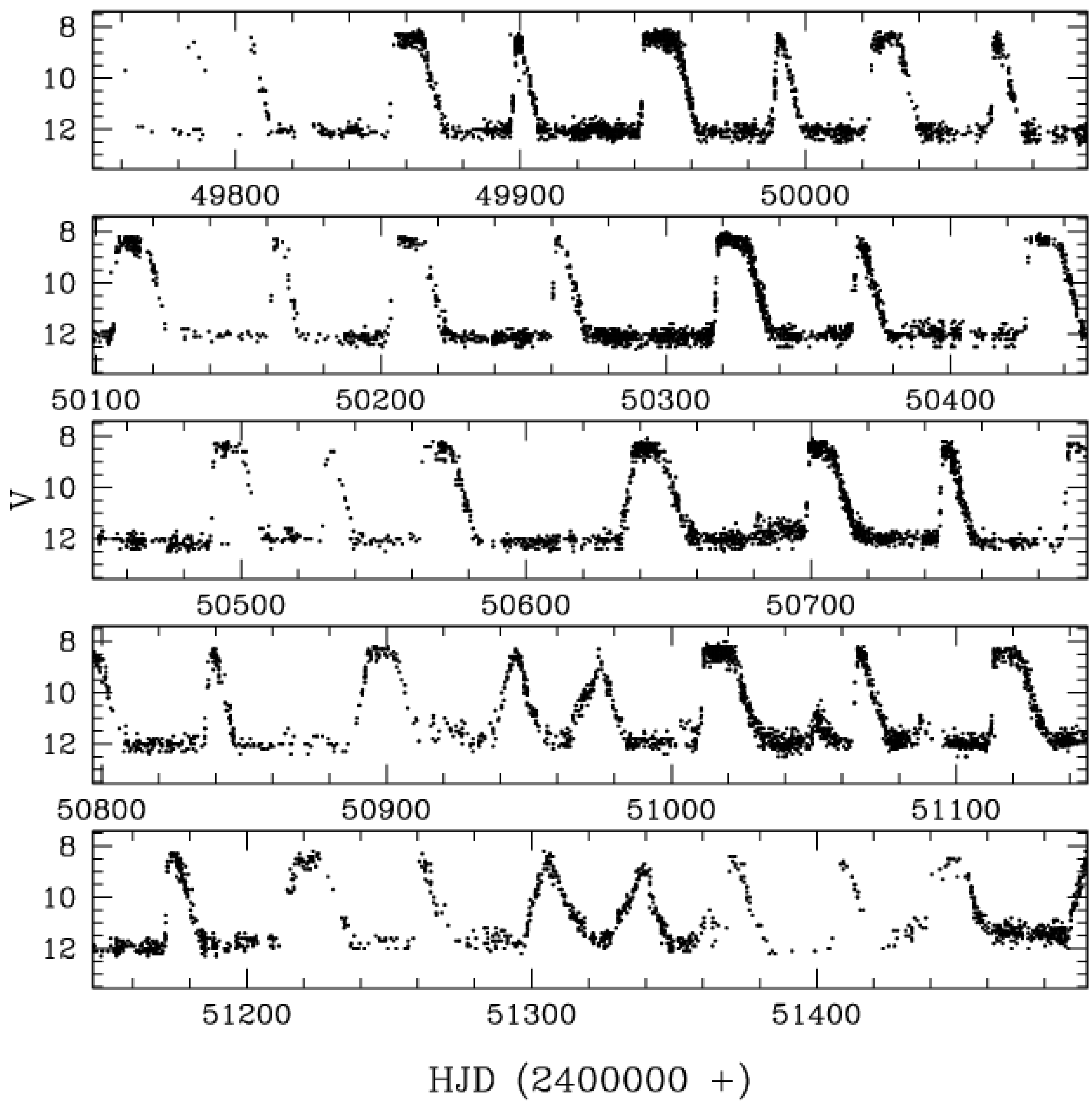
It is sometimes proposed that at special circumstances (large accretion rate ? See e.g. Starfield et al. 2016) the nuclear burning can be steady.

4. Cataclysmic variables: dwarf nova outbursts

Those outbursts are much more frequent and much less energetic than the novae outbursts.

For several years there was a discussion whether the outbursts are caused by the instabilities in the mass transfer, or instabilities in accretion disk itself.

Now it is generally agreed (starting from paper by Meyer & Meyer-Hoffmester (1981) and Smak (1982,1984) that this is ionization instability in an accretion disk.

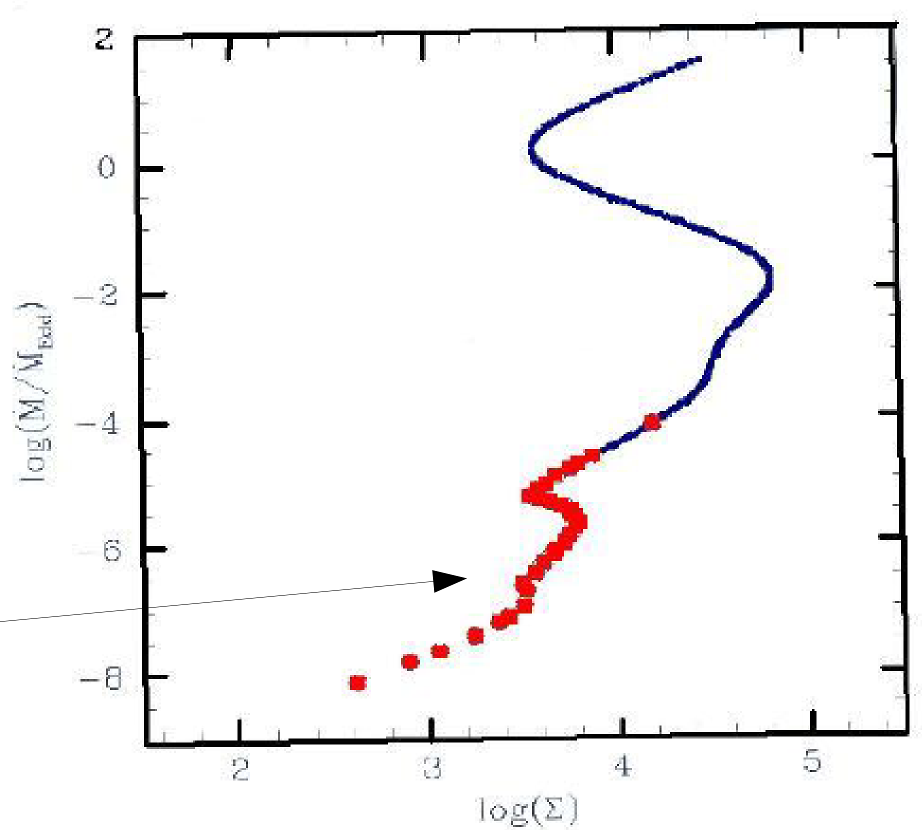


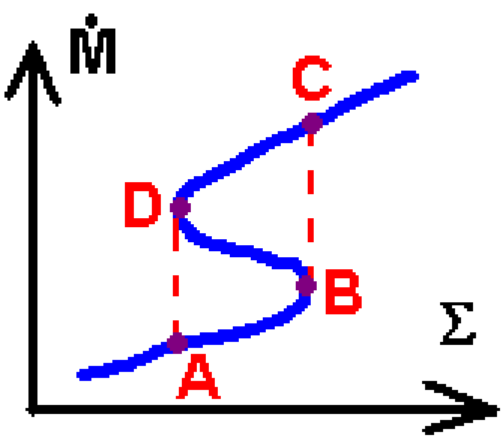
The multi-year lightcurve of SS Cyg (from Schreiber & Gänsicke 2002, collected by French observers)

4. Cataclysmic variables: dwarf nova outbursts

During lecture 9 i mentioned briefly that if the proper model of the Keplerian disk is used, you see wiggles in the surface density vs. accretion rate curve. This plot was for AGN, and at 10 R_{Schw}, but to get smaller mass, larger radius it is enough to shift this plot.

The white dwarf radius is 10 000 km, so for 1 solar mass it is 8 000 R_{Schw}. We thus never see any radiation pressure instability but the ionization instability can operate.





The arguments in favor of ionization instability in the disk:

- It well explains the division of the systems into stable and unstable; if all disk is located at upper CD branch the instability does not develop
- It well explains the observed behaviour of the hot spot and the outer disk – during the outburst disk expands and the hot spot orbital motion slows down

4. Cataclysmic variables: dwarf nova outbursts

Systems with higher accretion rates have hot stable disks (red symbols) black symbols mark unstable sources; recent compitation from Dubus et al. (2018)

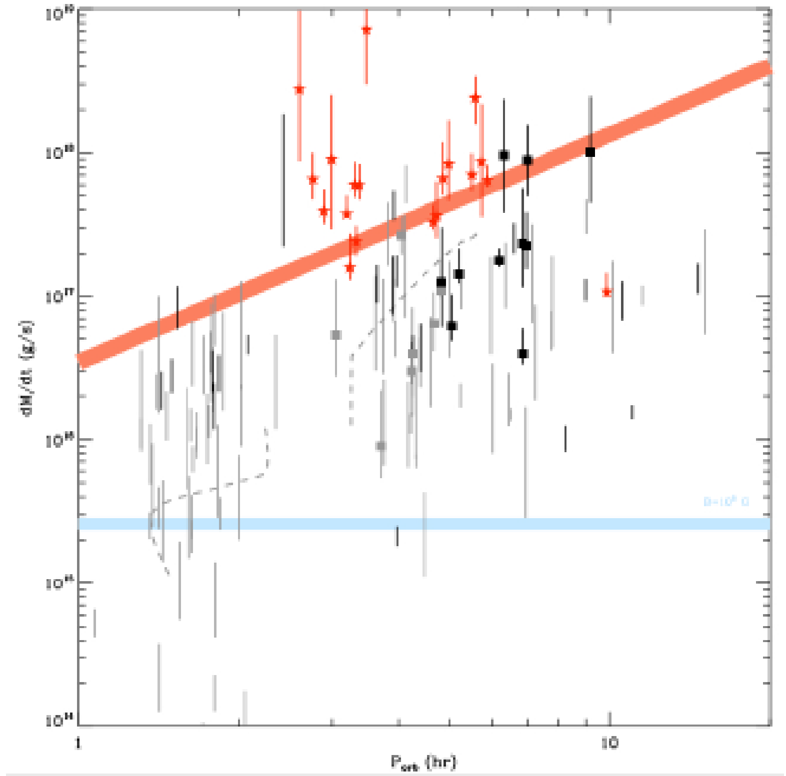


Figure 1.4: Mass transfer rates of cataclysmic variables compared to the stability criterion. Systems above the (red) upper solid line are hot and stable. Systems below the lower (blue) line will be cold, stable discs if the white dwarf magnetic field B $\geq 10^5$G. The dashed line is the expected secular mass transfer rate (Knigge et al., 2011). Square symbols indicate Z Cam type dwarf novae, (red) stars indicate nova-likes. The filling fraction, f, of each lightcurve is defined as the fraction of its bins that contain a measurement. Dwarf novae with f $\geq$ 0.5 are shown in black and those with f < 0.5 are in grey. Figure 3 from Dubus et al. (2018)

4. Cataclysmic variables: dwarf nova outbursts

Ionization instability was used to reproduce dwarf novae outbursts by many authors.

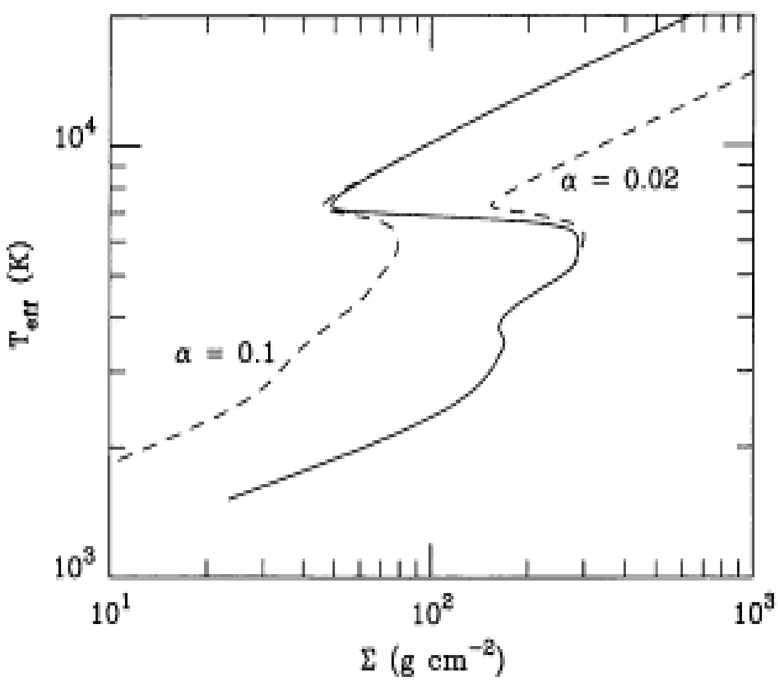


Figure 2. Modification of the $\Sigma-T_{eff}$ curves when α is no longer a constant. The dashed curves correspond to constant α, $\alpha = \alpha_{hot}$ (left) and $\alpha = \alpha_{cold}$ (right). The solid line is obtained for α given by (40). The radius of interest is 10^{10} cm, and the primary mass 1.2 $M_\odot$.

One modification has to be done in comparison to standard approach. The viscosity in the upper and in the lower branch has to be different, to get proper timescales. For example, Hameury et al. (1998) used:

$$\log\alpha = \log\alpha_{cold} + [\log\alpha_{hot} - \log\alpha_{cold}] \times \left[1 + \left(\frac{2.5\times 10^4\,K}{T_c}\right)^8\right]^{-1}$$

This is frequently explained as less efficient MRI in the lower branch where the disk becomes neutral.

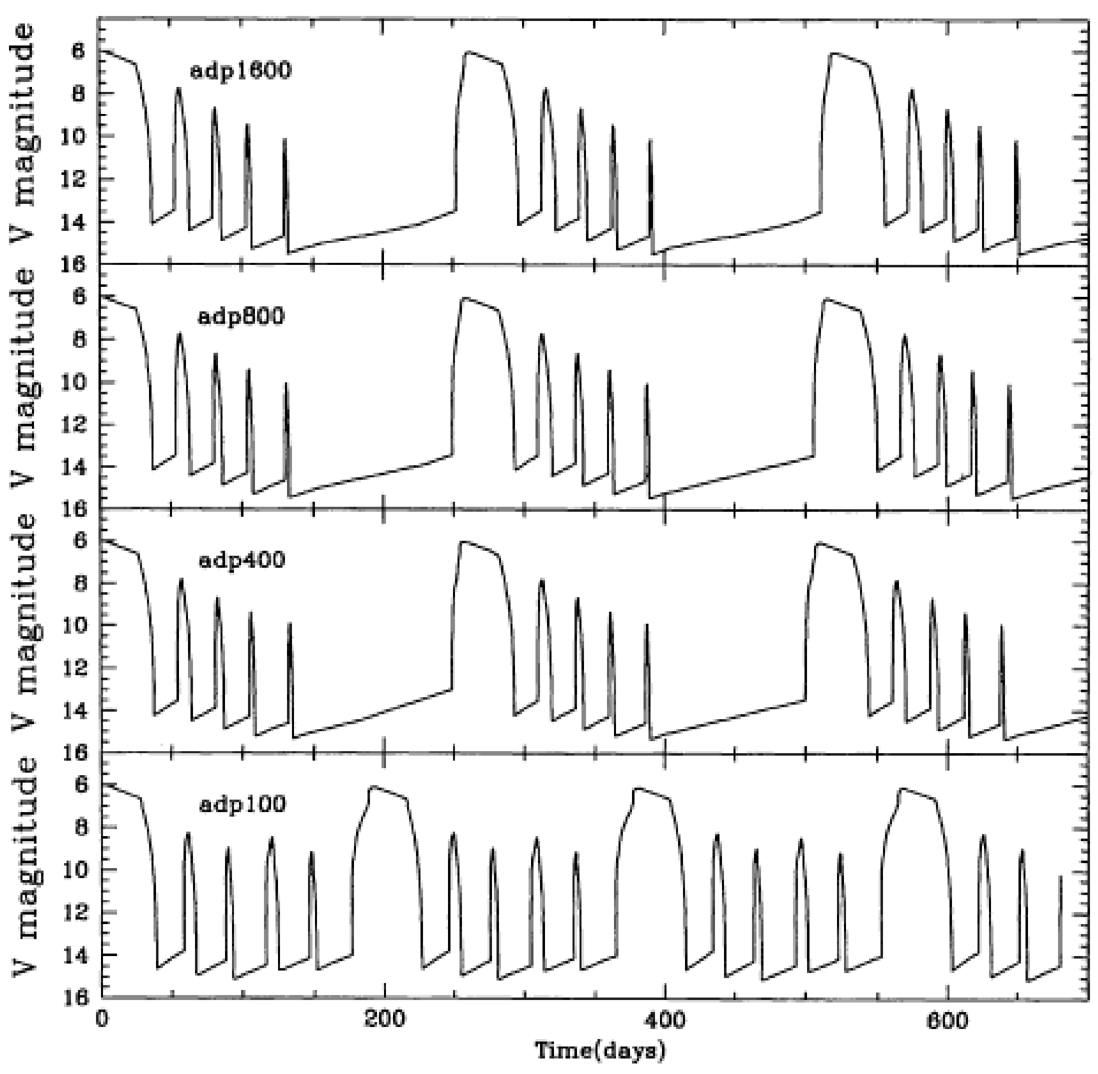
$$\frac{\partial\Sigma(R,t)}{\partial t} = \frac{1}{R}\frac{\partial}{\partial R}\left(\cdots\frac{\partial}{\partial R}\cdots\right) \qquad \frac{\partial T_{eff}(R,t)}{\partial t} = \;\ldots.$$

Equations are solved numerically, as discussed in lecture 9. The disk is assumed to be in hydrostatic equilibrium, thermal and viscous evolution is followed.

The disk vertical structure is included in the form of tables, and effectively equations are solved in 1+1 approximations (separately in the radial and in the vertical direction).

4. Cataclysmic variables: dwarf nova outbursts

Numerical models even reproduce ths fact that outbursts are not always equal, although the pattern in numerical solutions are much more regular than the observed outbursts.



Examples of dwarf novae outbursts from simulations by Hameury et al. (1998).

Some problems are however related with the grid used in computations. Here the lightcurves differ only by the radiat grid distribution...

4. Cataclysmic variables: dwarf nova outbursts

Advantages of dwarf novae outburst modelling:

- Relatively small dynamical range: Rout/Rin about 100
- Negligible role of the boundary layer (?…)
- Possibility to confront the models (e.g. temperature profiles) with disk mapping obtained for eclipsing sources; disk in outbursts well modeled by Keplerian stationary disk

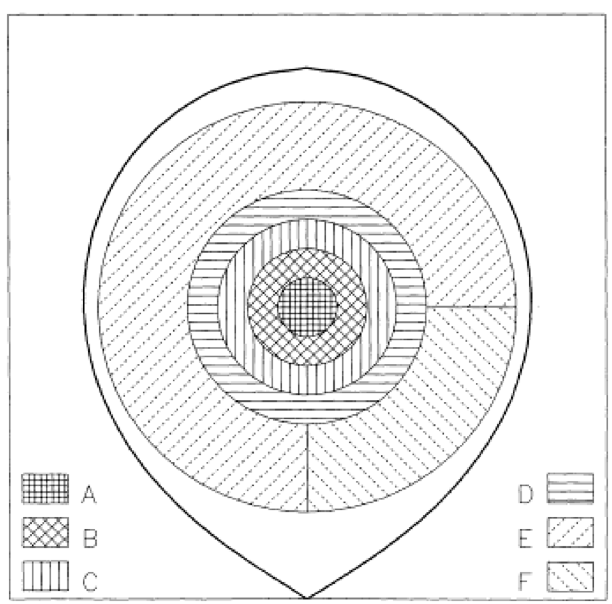


Fig. 4. Disk regions for which spectra are presented in Fig. 5 and Table 1. The bold line indicates the outline of the Roche lobe in the orbital plane

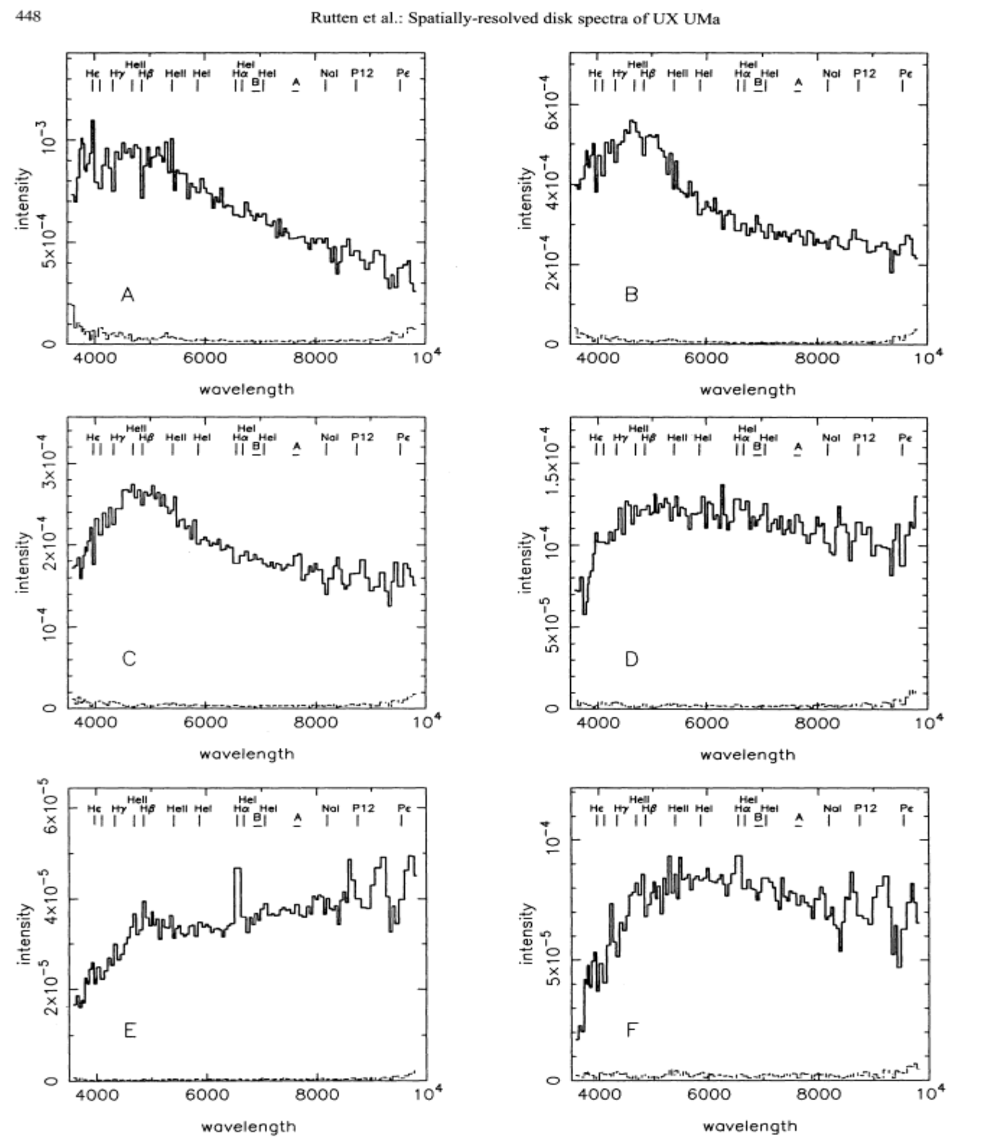
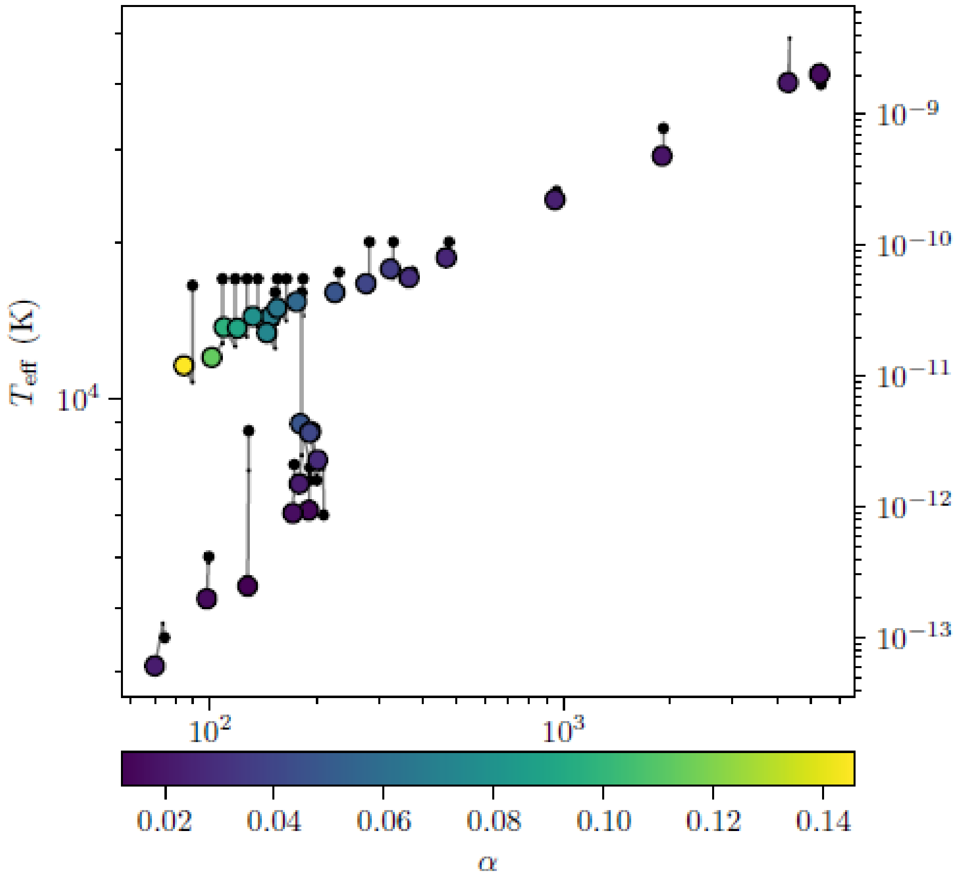
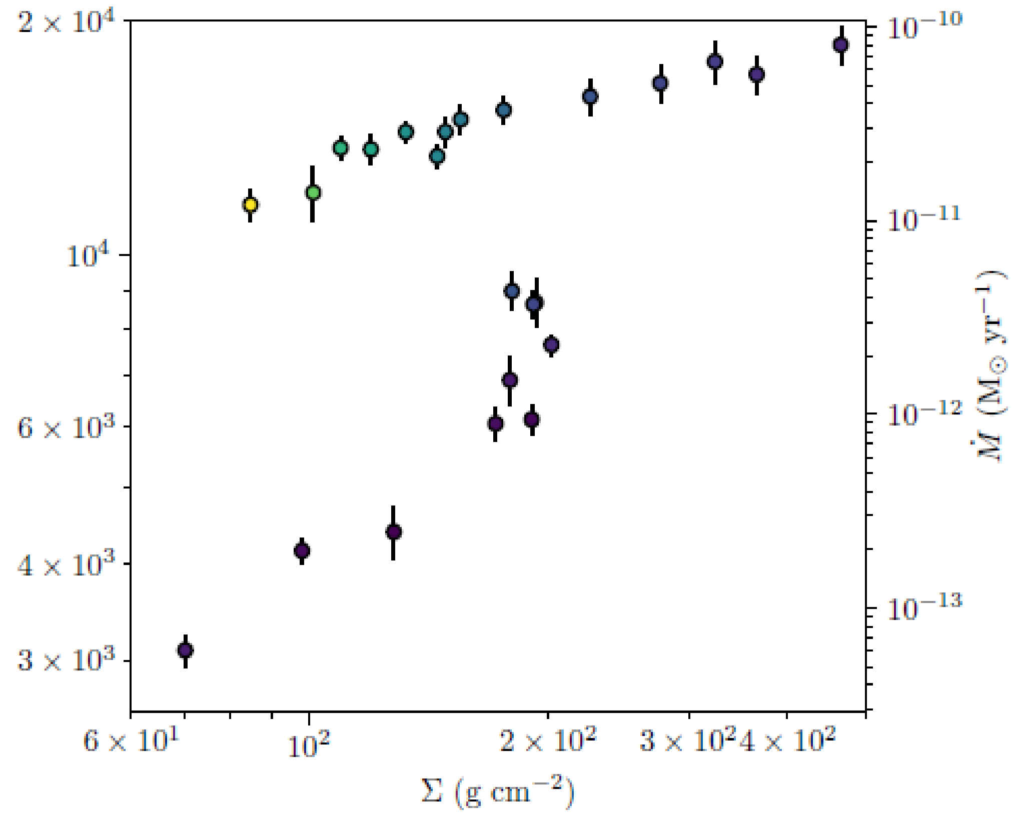


Fig. 5a–f. Specific intensities in erg cm^{-2} s^{-1} Hz^{-1} ster^{-1} as a function of wavelength for selected regions of the reconstructed accretion disk. The labels A to F correspond to the areas on the disk presented in Fig. 4. The dashed line shows the statistical uncertainty on each spectrum. The position of some of the main spectral features are indicated

4. Cataclysmic variables: dwarf nova outbursts

Recent shearing-box MHD simulations with realistic opacities recovered the strong dependence of the viscosity on the disk thermal state (Coleman et al. 2018).





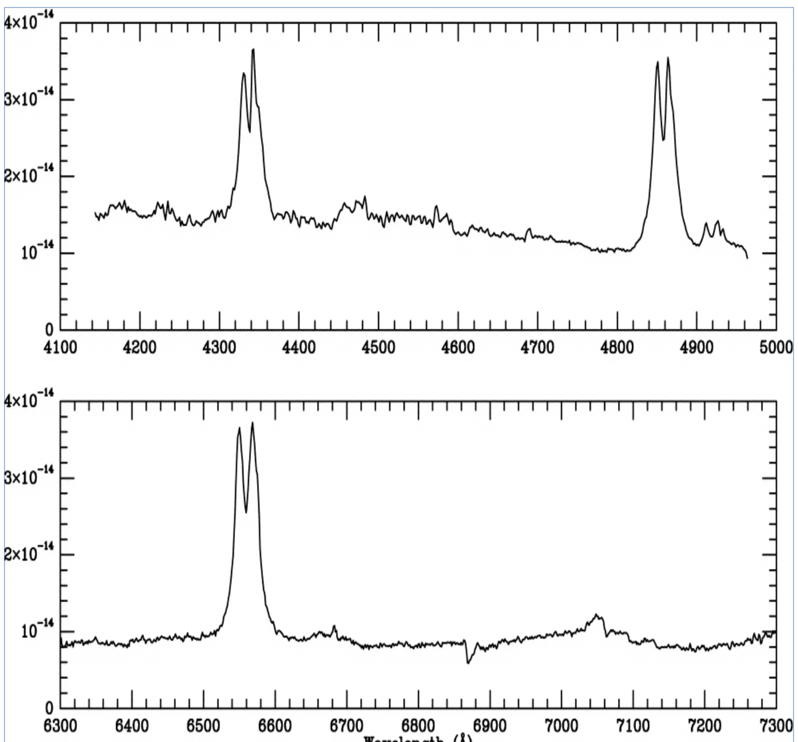
The ranges of effective alpha obtained from MHD reproducing the MRI action correspond to what is indeed required by the observational data.

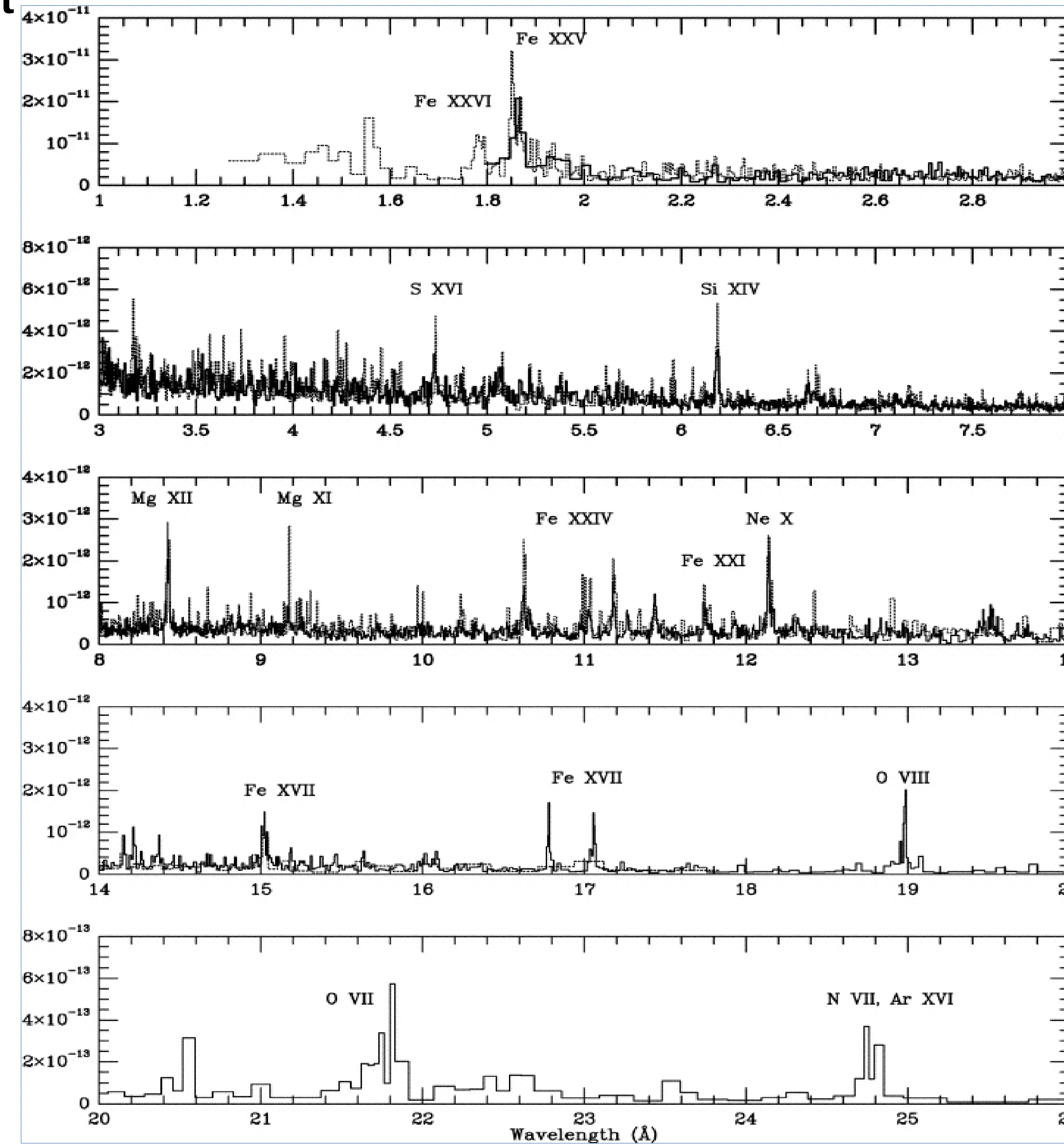
4. Cataclysmic variables: dwarf nova outbursts

Problems of the dwarf novae outburst modelling:

- Quiesent state
- Outburst trigger
- Superhamps and superoutbursts

We will concentrate on the quiescent state issue. Observations by Skody et al. (2002) with 3 m optical telescope and with Chandra telescope show the outer disk ring and a hot X-ray emitting plasma close to a white dwarf. Inner hot flow? Bounday layer?





System U Gem (Szkody et al. 2002)

4. Cataclysmic variables: dwarf nova outbursts

Problems of the dwarf novae outburst modelling:

- Quiesent state

Models predict that between the outbursts the source luminosity rises.

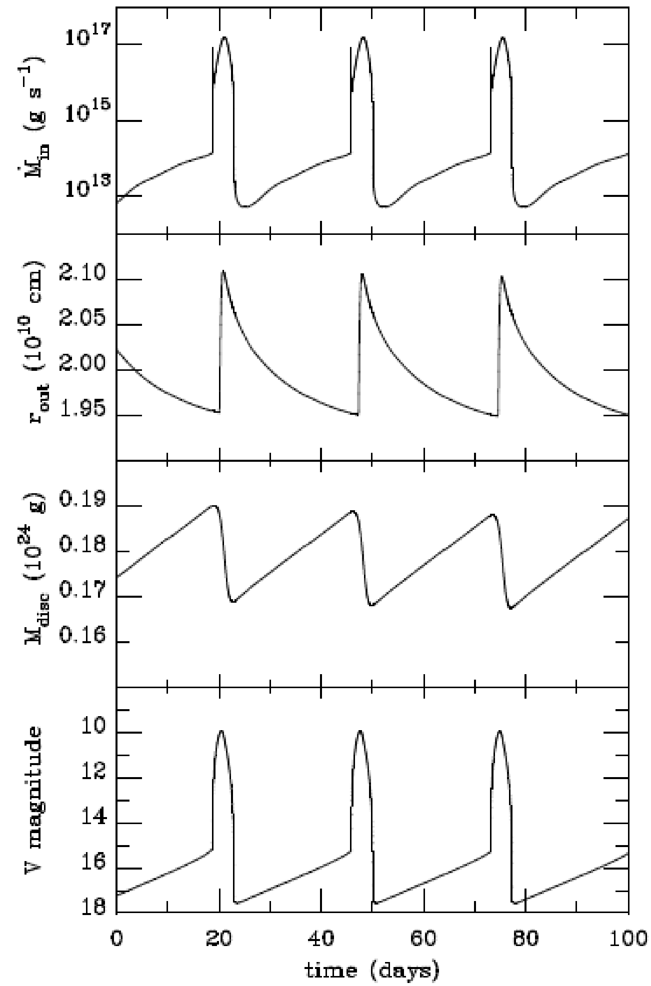
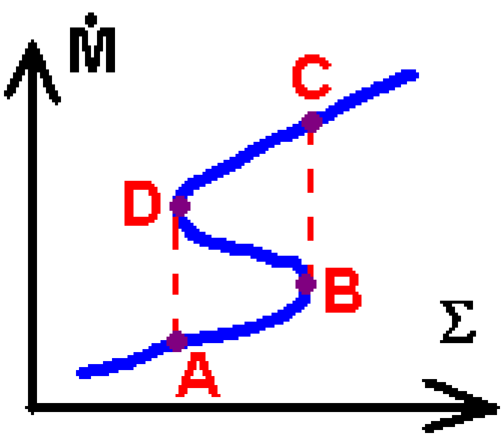


Figure 3: Outbursts properties for $M_1 = 0.6\,M_\odot$, $r_{in} = 8.5\times10^8$ cm, $\alpha_{cold} = 0.04$, $\alpha_{hot} = 0.20$, $< r_{out} >= 2\times10^{10}$ cm, and $\dot{M} = 10^{16}$ g s^{-1}. The upper panel shows the mass accretion rate onto the white dwarf, the second one the outer disc radius, the third one the disc mass, and the lower panel the visual magnitude. Note that only the disc contribution to the optical light is included. (from Hameury et al., 1998)



After review by Hameury (2019)

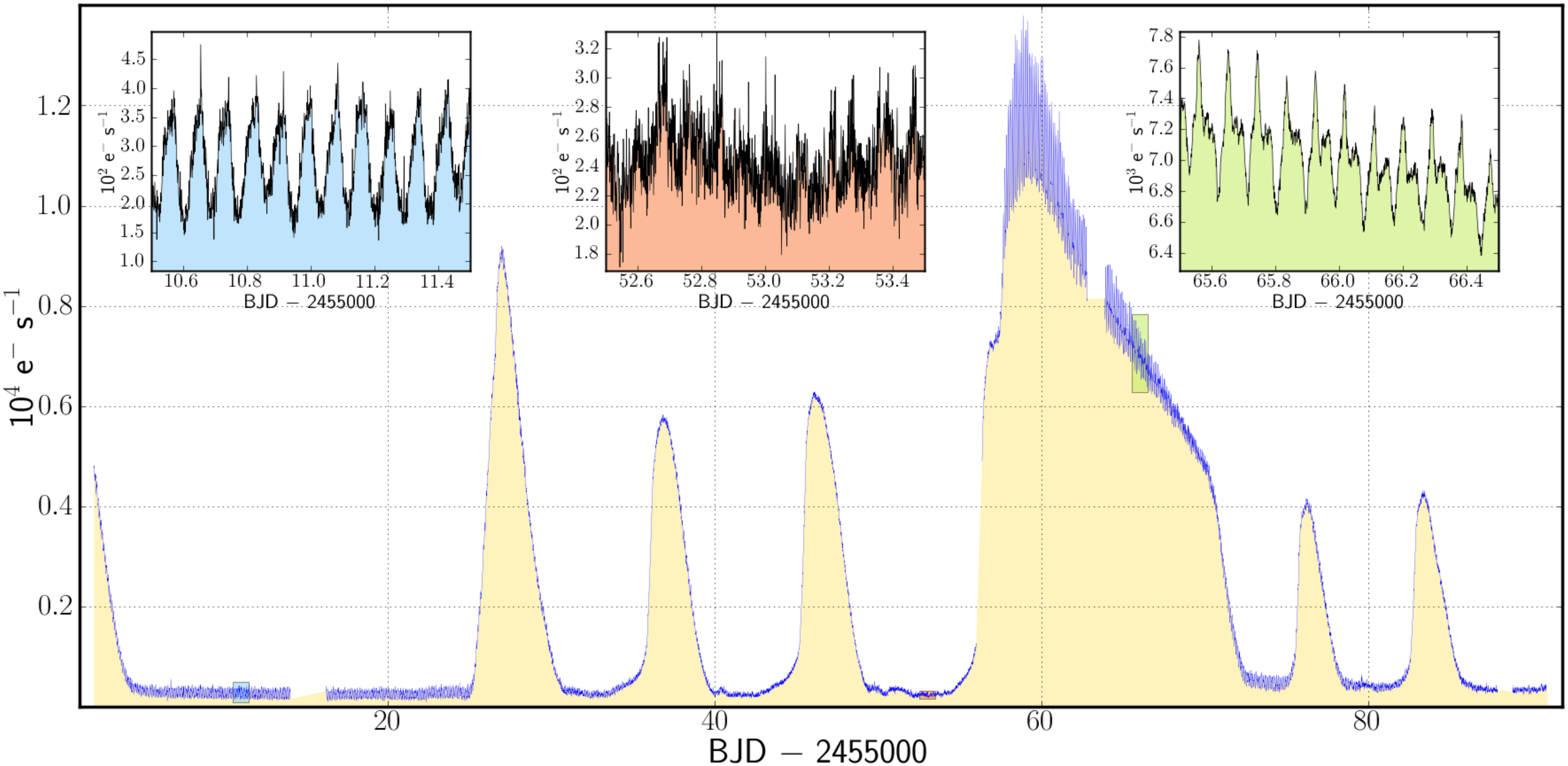
4. Cataclysmic variables: dwarf nova outbursts

Problems of the dwarf novae outburst modelling:

- Quiesent state

Models predict that between the outbursts the source luminosity rises.

The data does not show the corresponding slow increase.



http://zooniverse-resources.s3.amazonaws.com/blogs.zooniverse.org/11/files/2012/04/dwarf_novae.png

One of the few dwarf novae discovered by accident in Kepler data (Barcleys et al. 2012) providing unprecedented lightcurve quality.

4. Cataclysmic variables: dwarf nova outbursts

Problems of the dwarf novae outburst modelling:

- Quiesent state
  It must be related to the inner hot flow but we do not well understand this transition. Meyer & Meyer-Hoffmeister (1994) proposed that the hot corona forms above the disk, and subsequently the electron conduction at the disk/corona border is responsible for the transition to an optically thin flow; we need a magnetic field to get this corona
- Outburst trigger
  The matter must accumulate in the outer part, somehow without being visible in the V band ?
- Superhamps and superoutbursts

Superhumps are caused by the disk precession during the superoutburst, when the disk is considerably expanded. Superoutbursts themselves are generally considered to be caused by tidal instabilities which occasionally enhances the mass trasfer (Osaki & Kato 2013, at the basis of Kepler data). It might be still related to the presence of resonances, as earlier postulated by Whitehurst & King (1991).

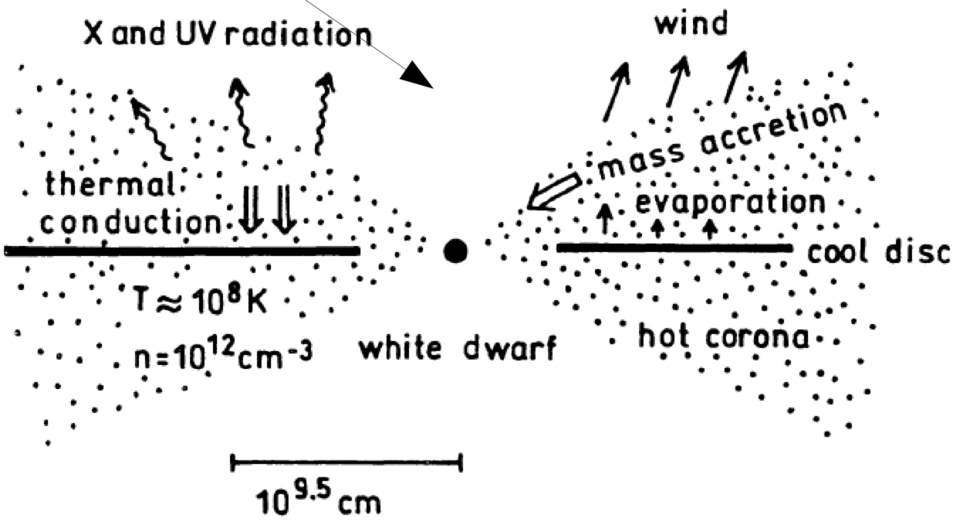


Fig. 1. Schematic description of the processes in the evaporating inner disk

Cartoon from Meyer and Meyer-Hofmeister (1994)

Homework

- Give arguments why the outer radius of the disk expands during outburst