ASTROPHYSICS OF INTERACTING BINARY STARS

Lecture 13

Vitaly Neustroev

360

Non-magnetic Nova-like Variables

Nonmagnetic Nova-like Variables

- Non-magnetic Nova-like variables (NL) resemble novae between eruptions;
- NLs include all of the "non-eruptive" CVs.
  - However, many of them may have "low states"
  - However, some may also exhibit "stunted" outbursts

Nova-like Variables

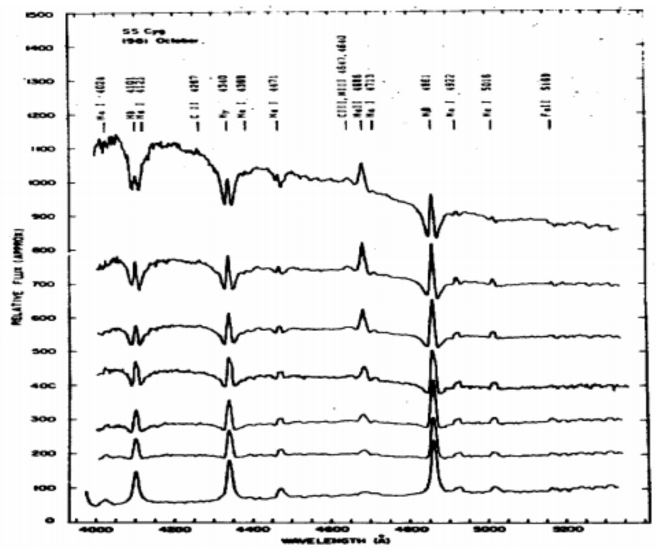
The NL class is a very heterogeneous group of stars, and the definition of the subclasses within NLs is mostly based on observational features of objects.

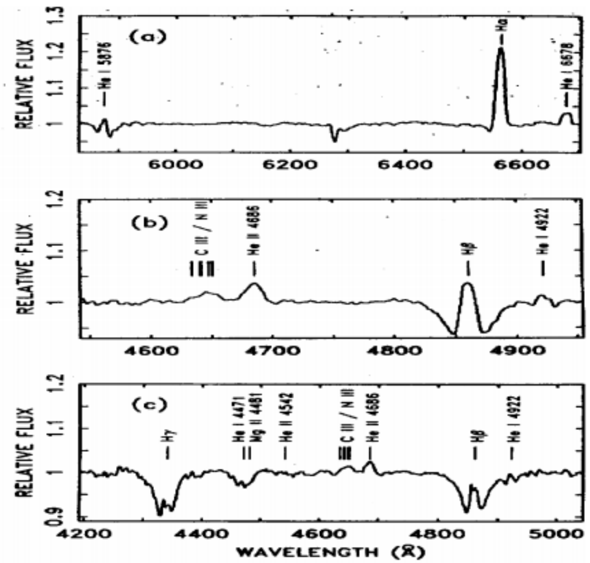
- **Classification:**
  - The UX Ursae Majoris stars (UX UMa) show persistent broad Balmer absorption lines.
  - The RW Triangulum stars (RW Tri), per contra, have pure emission-line spectra.
  - SW Sextantis stars (SW Sex) show many unusual yet consistent properties (will discuss later).
  - VY Sculptoris stars (VY Scl) show states of low luminosity (drops) exceeding 1 mag.

The absence of DN outbursts in NLs is believed to be due to their high mass transfer rates, producing ionised accretion disks in which the disk instability mechanism is suppressed.

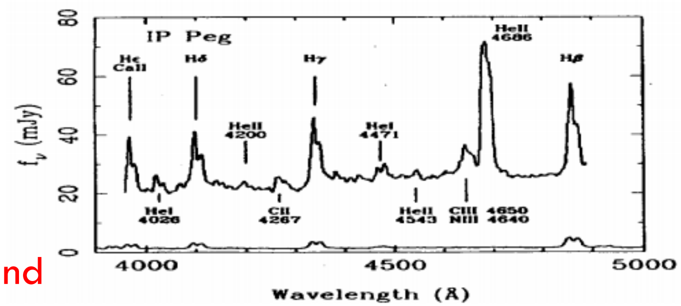
Nova-like Variables

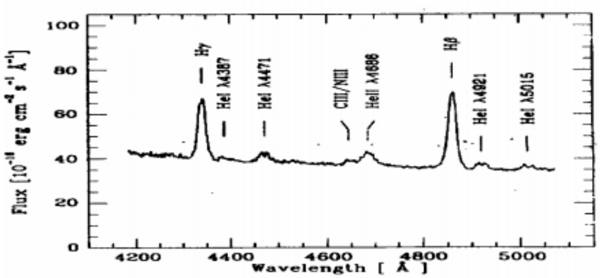
The DN
SS Cyg in
outburst and
quiescence





The UX UMa-star
IX Vel





The SW Sex-star
WX Ari

The DN
IP Peg in
outburst and
quiescence

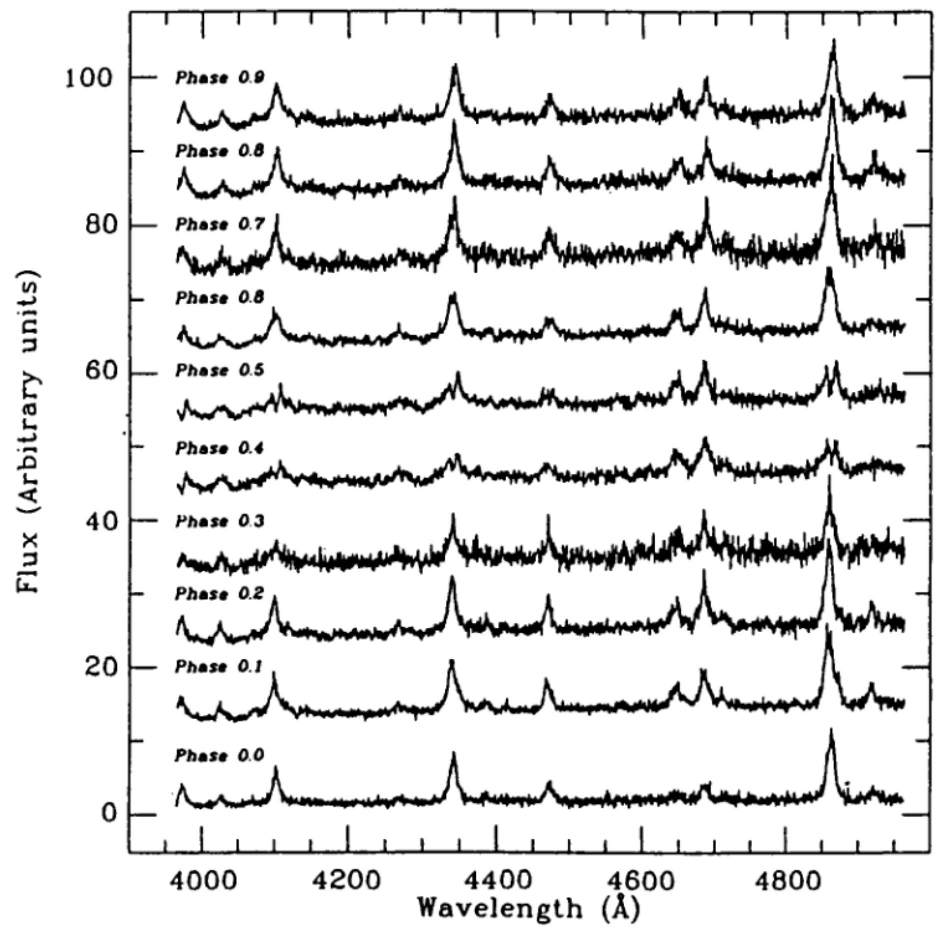
SW Sextantis stars

- Relatively large group of NLs, which was initially populated by eclipsing systems only (high inclination!);
- Largely occupy the narrow orbital period stripe between 3 and 4.5 hours;
- Single-peaked emission lines despite the high inclination;
- Strong high excitation spectral features (He II, C III/N III);
- Central absorption dips in the emission lines around phase 0.4 – 0.7;
- High-velocity emission S-waves with maximum blueshift near phase ~0.5.

SW Sextantis stars

Time-resolved spectra of V1315 Aql.

From
Dhillon, Marsh & Jones (1991).



SW Sextantis stars

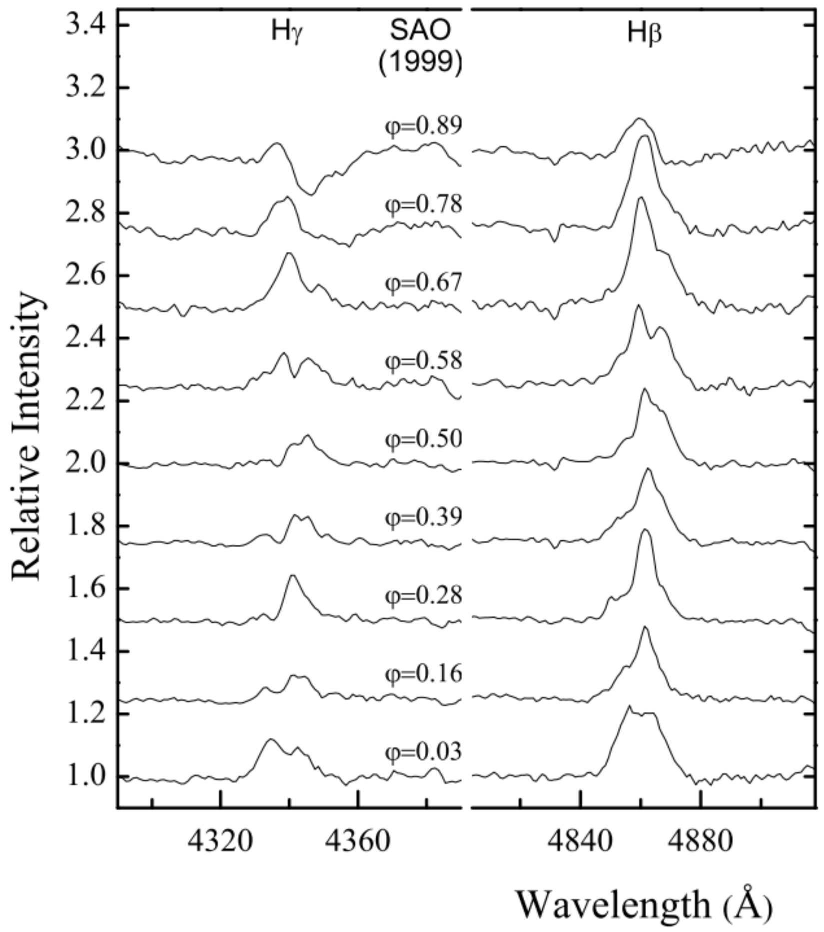
- The unusual spectroscopic behaviour of the SW Sex systems has led to their intensive studies.
- Many NLs above the 3 – 4.5 hr period interval have been found to show distinctive SW Sex behaviour;
- Even some LMXBs!
- Even the proto-typical NL UX UMa!

SW Sextantis stars

Even the proto-typical NL UX UMa has now been shown to exhibit SW Sex-like behaviour.

Time-resolved spectra of UX UMa.

From Neustroev et al. (2011).



Nova-like Variables

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We now suspect that all NLs could be classified as SW Sex stars if one looks long and hard enough.

Magnetically-Controlled Accretion

- Polars
- Intermediate Polars

Magnetically-Controlled Accretion

- In some CVs we observe interesting features:
  - Strongly polarized emission (up to 60 % circular polarisation in the optical);
  - Strong X-ray emission;
  - Unexpectedly long soft X-Ray component;
  - Highly variable light curves in optical and X-Ray;
  - In some objects: short-period coherent variability.

⇒ Strong Influence from a magnetic field on the binary system

Magnetically-Controlled Accretion

- Magnetic Field of the WD in First Approximation:
  - Both stars have a magnetic field;
  - The magnetic flux is roughly conserved during star evolution: $B \cdot R^2 \approx const$

  ⇒ **High field strengths up to 20MG near the WD;**
  - Magnetic field is usually approximated as a Dipole.

Magnetically-Controlled Accretion

- Important parameter:
  The magnetospheric radius, R_M - the distance from the WD where the magnetic pressure is equal to the ram pressure:

$$\frac{B^2}{8\pi} = \rho(r) v_{in}^2(r)$$

- For polars, $B_{wd} \sim 10^7$ G, $R_M \sim 10^{11}$ cm $\sim a$

  NO DISK!

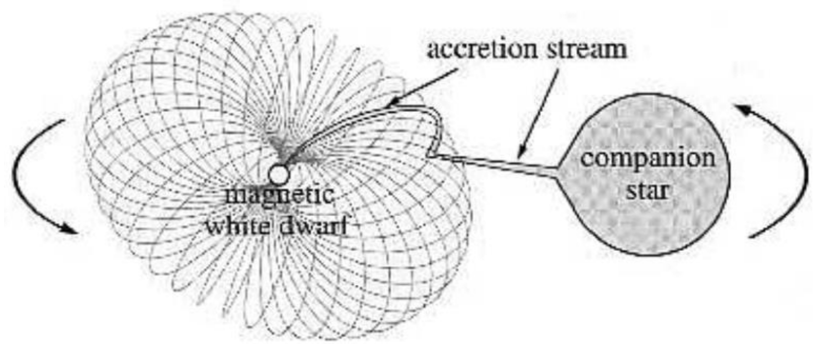
- For intermediate polars, $B_{wd} \sim 10^6$ G, $R_M \sim 10^{10}$ cm

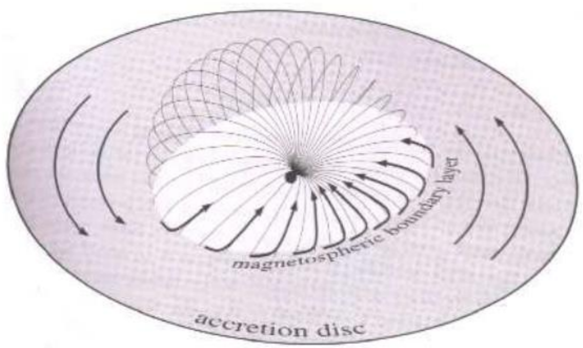
  TRUNCATED DISK

Magnetically-Controlled Accretion

- Pressure balance defines the inner edge of the accretion disk:
  - For strong magnetic fields of the WD no disk is formed, instead the accretion stream follows the field lines directly;
  - For weaker magnetic fields a truncated accretion disk will form.

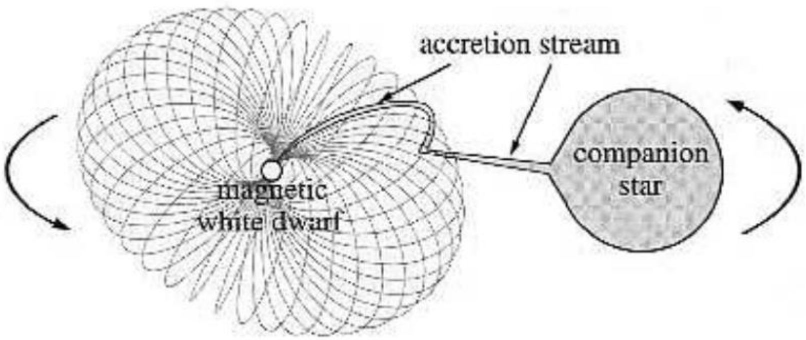
- These two scenarios are called an accretion column and an accretion curtain, respectively.

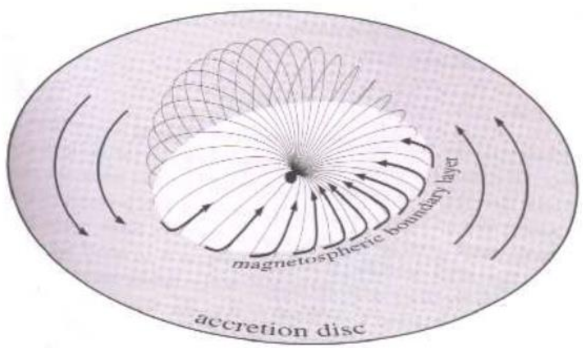




Magnetically-Controlled Accretion

- The corotation radius is the radius at which the disk corotates with the magnetic field. This is usually near the inner edge of the disk, which is the magnetospheric radius.





Magnetically-Controlled Accretion

- Spin Periods and Angular Momentum:
  - System has an orbital period P_{orb};
  - the WD has a spin period P_{spin};
  - Therefore modulations should be observed;
  - Accretion stream transfers angular momentum to WD

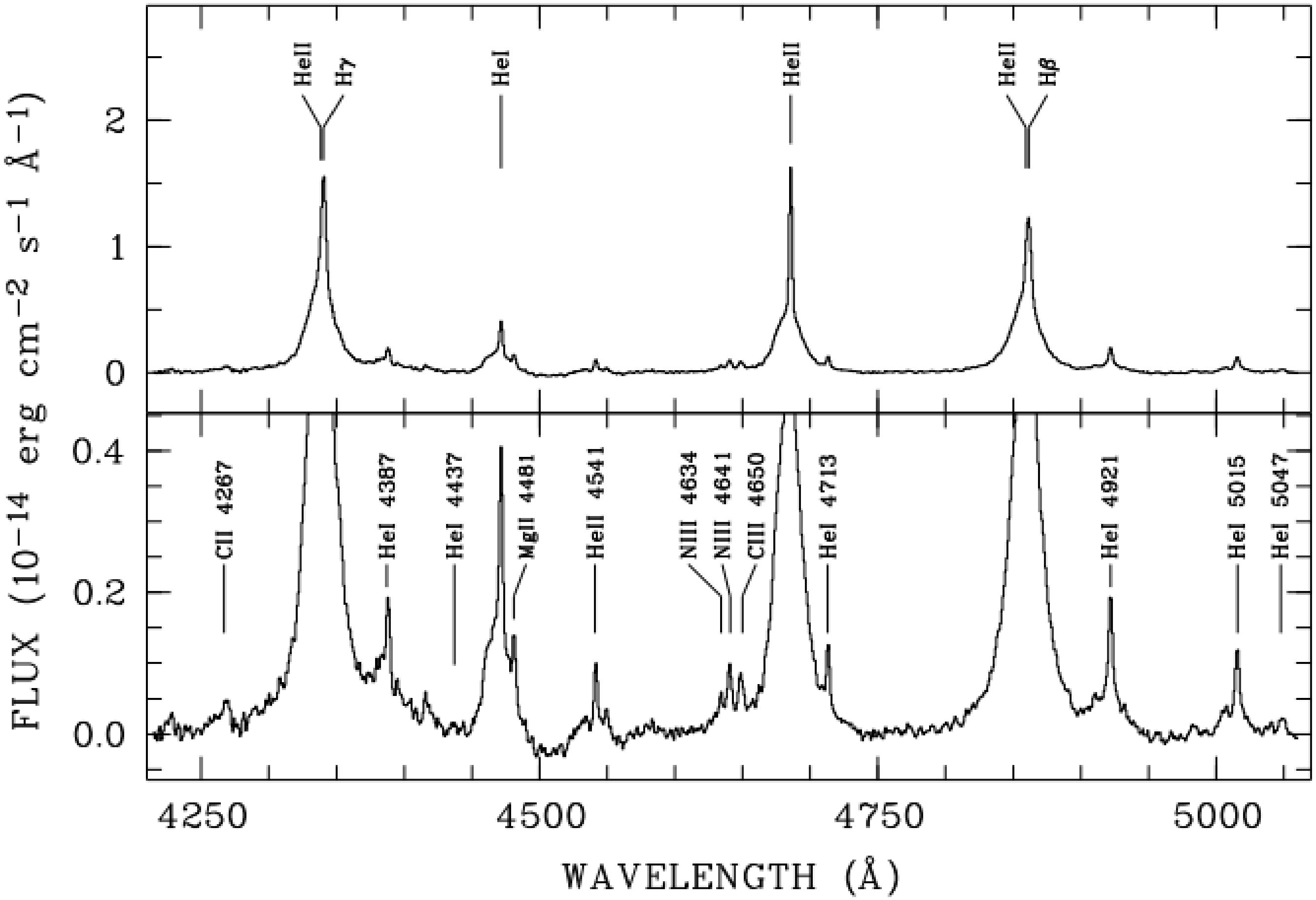
    ⇒ **Spin-up ?**
  - Consider interaction of magnetic moments of the two stars!
  - Magnetic moments can **balance** transfer of angular momentum, if interaction is strong enough

Polars

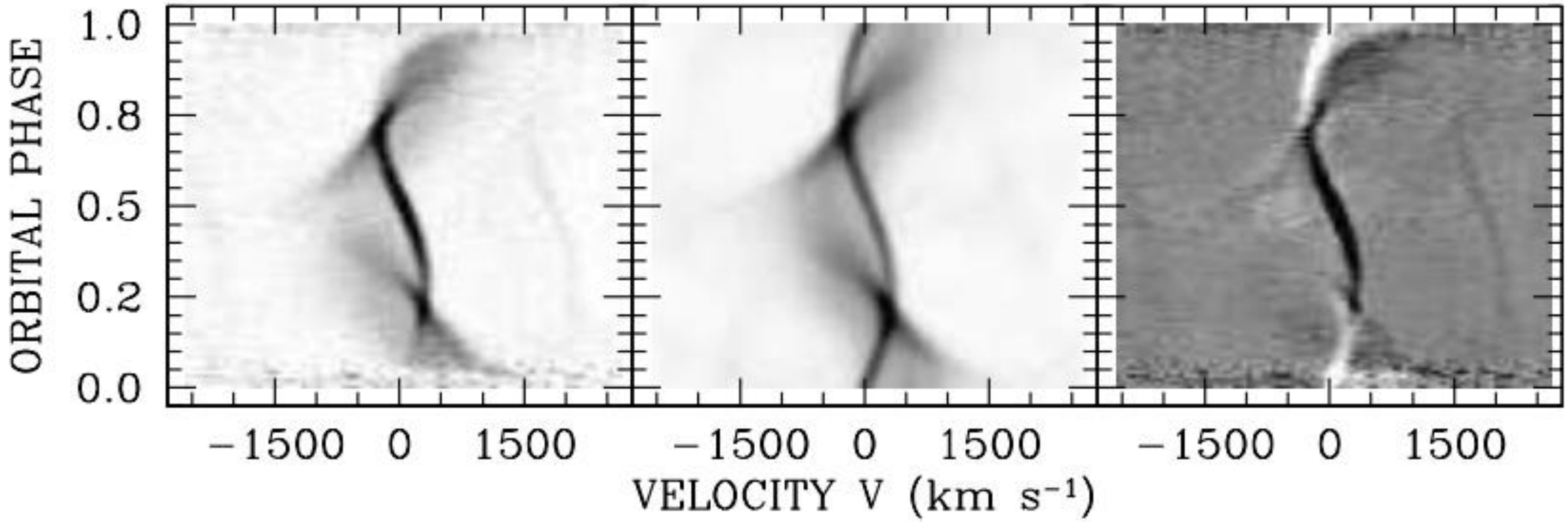
- **Polars** or **AM Her** Stars:
  Systems with Strong Magnetic Field and Strong Magnetic Interaction:
  - Synchronise orbital period and spin period of the WD, due to magnetic interaction;
  - Don't have accretion disks;
  - Can be identified through strong polarisation in optical wavelength.

Polars

Mean-orbital high-resolution spectrum of the polar HU Aqr



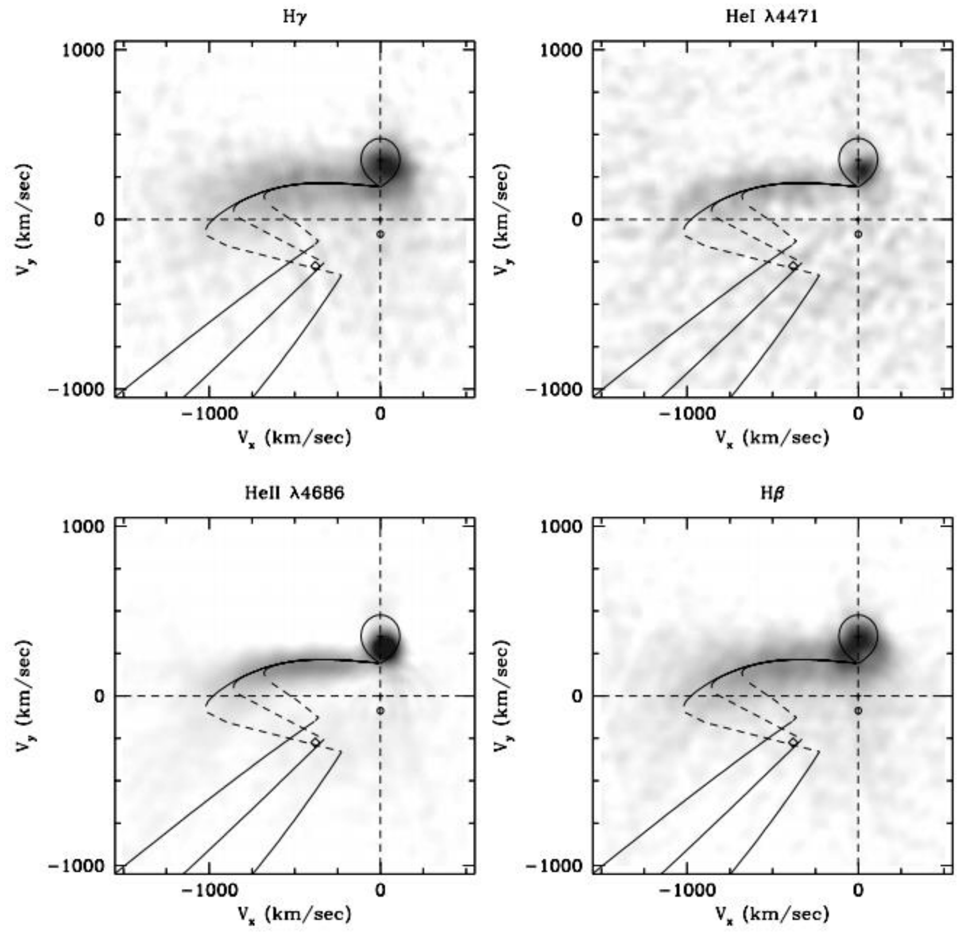
Polars



Trailed spectrogram of the He II emission line of the polar HU Aqr

Polars

Doppler maps of the four main emission lines of the polar HU Aqr

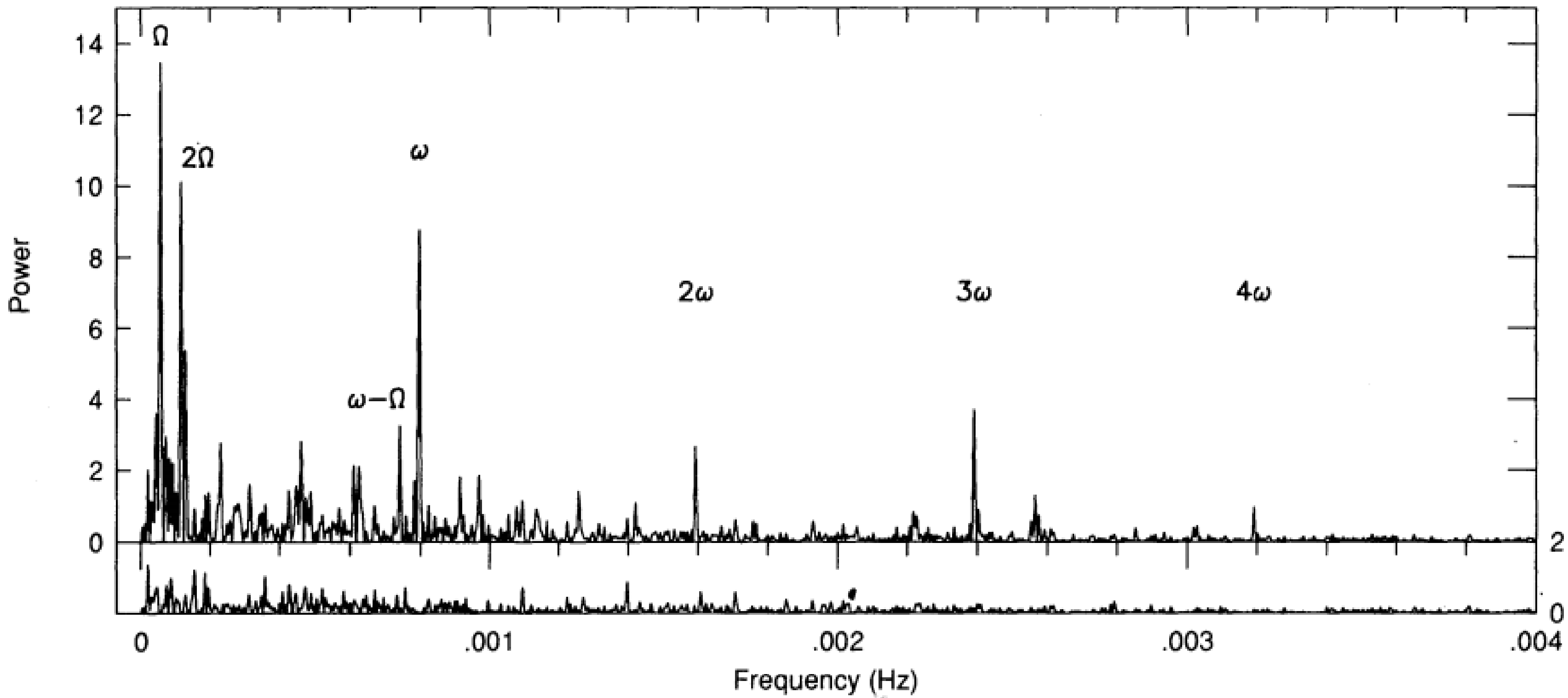


Intermediate Polars

- **Intermediate Polars** or **DQ Her** Stars:
  Systems with Weaker Magnetic Field:
  - Low Interaction between magnetic moments;
  - Spin Up, due to transfer of angular momentum;
  - No synchronised state of the rotation periods, but rotation at high velocities;
  - A truncated accretion disk, as magnetic pressure can’t control the plasma far enough.

Not always the case! **Video**

Intermediate Polars



The power spectrum of the X-ray light curve of FO Aqr: **multiple periodicities**

AM CVn Binaries

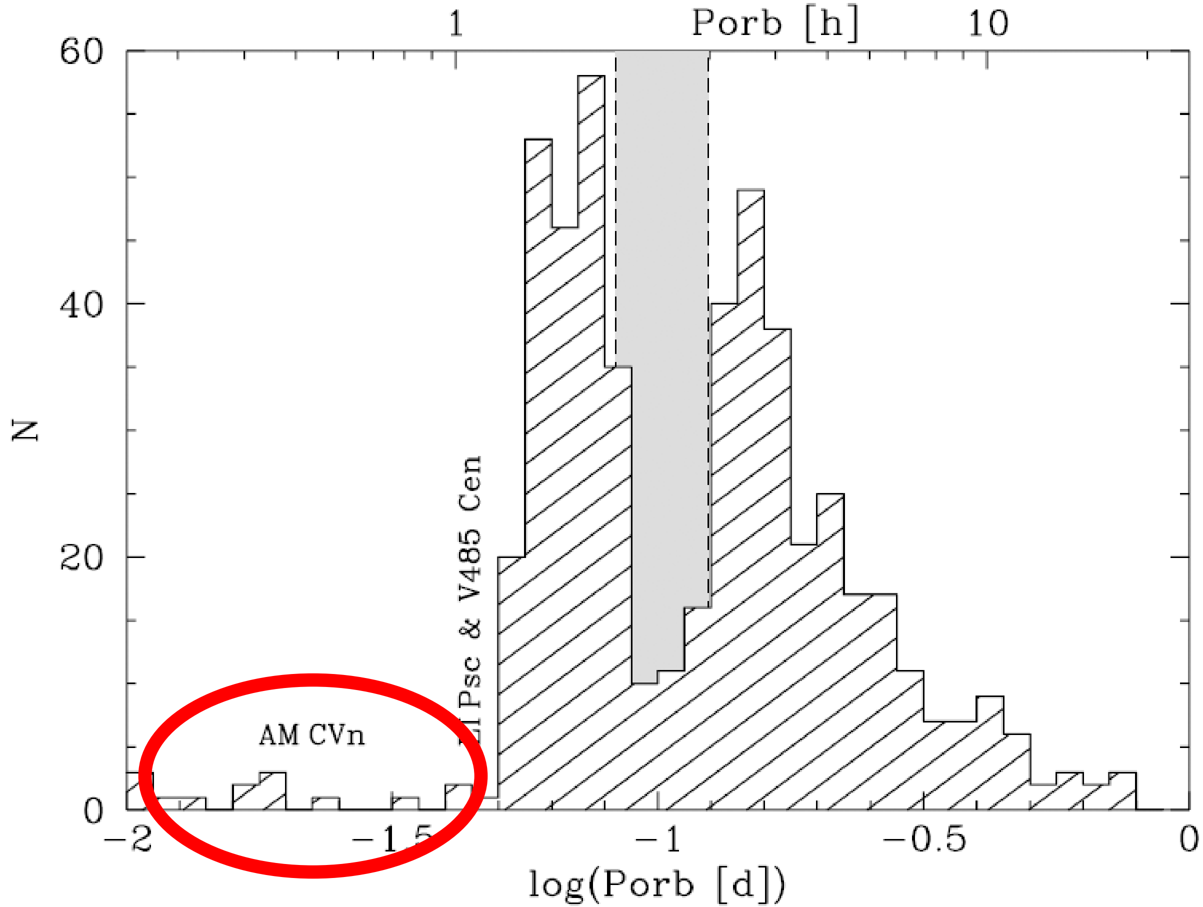
Close Binary Systems

secondary / primary	main-sequence star *)	evolved star **)	white dwarf	neutron star or black hole
main-sequence star *)	[binary T Tauri stars] [RS CVn stars] Algols (AD) (TAD) {W UMa stars = contact systems}	symbiotic stars Type I as e.g. CI Cyg, Z And, AR Pav (AD) Algols (AD), (TAD)	*) main-sequence star or slightly evolved **) evolved star, but not yet a compact star [ ] detached systems	
evolved star **)	[Wolf-Rayet binaries] [binary planetary nebulae]		(AD) evidence for an accretion disk (TAD) evidence for a transient accretion disk	
white dwarf	[pre-cataclysmic binaries] non-magnetic CVs: UX UMa stars (AD) dwarf novae (AD) DQ Her stars (AD) AM Her stars	long period CVs as GK Per (AD) recurrent nova (AD) symbiotic stars (AD) symbiotic novae (AD)	[double white dwarfs] AM CVn stars (AD)	
neutron star or black hole	massive X-ray binaries (AD) (wind accretion) low mass X-ray binaries (AD) HZ Her/Her X–1 (AD) SS 433 (AD)	long period low mass X-ray binaries (AD)	[binary pulsars] 4U1820–30 (AD)	[binary pulsars]

Comments: in semi-detached systems the mass gaining star is listed as the primary
in detached systems the more evolved star is listed as the primary

CVs: Distribution of Orbital Periods

The orbital period distribution of 531 CVs from Ritter & Kolb (2003,V7.3).



The AM Canum Venaticorum binaries

- Key properties:
  - No hydrogen
  - Very short periods (5 – 10 to 65 minutes)
  - Spectra characteristic of accretion disks
  - Weak X-ray emission

- AM CVn binaries are a class of ultracompact systems in which the donor stars are hydrogen deficient. The accretors are white dwarfs.

AM CVn stars

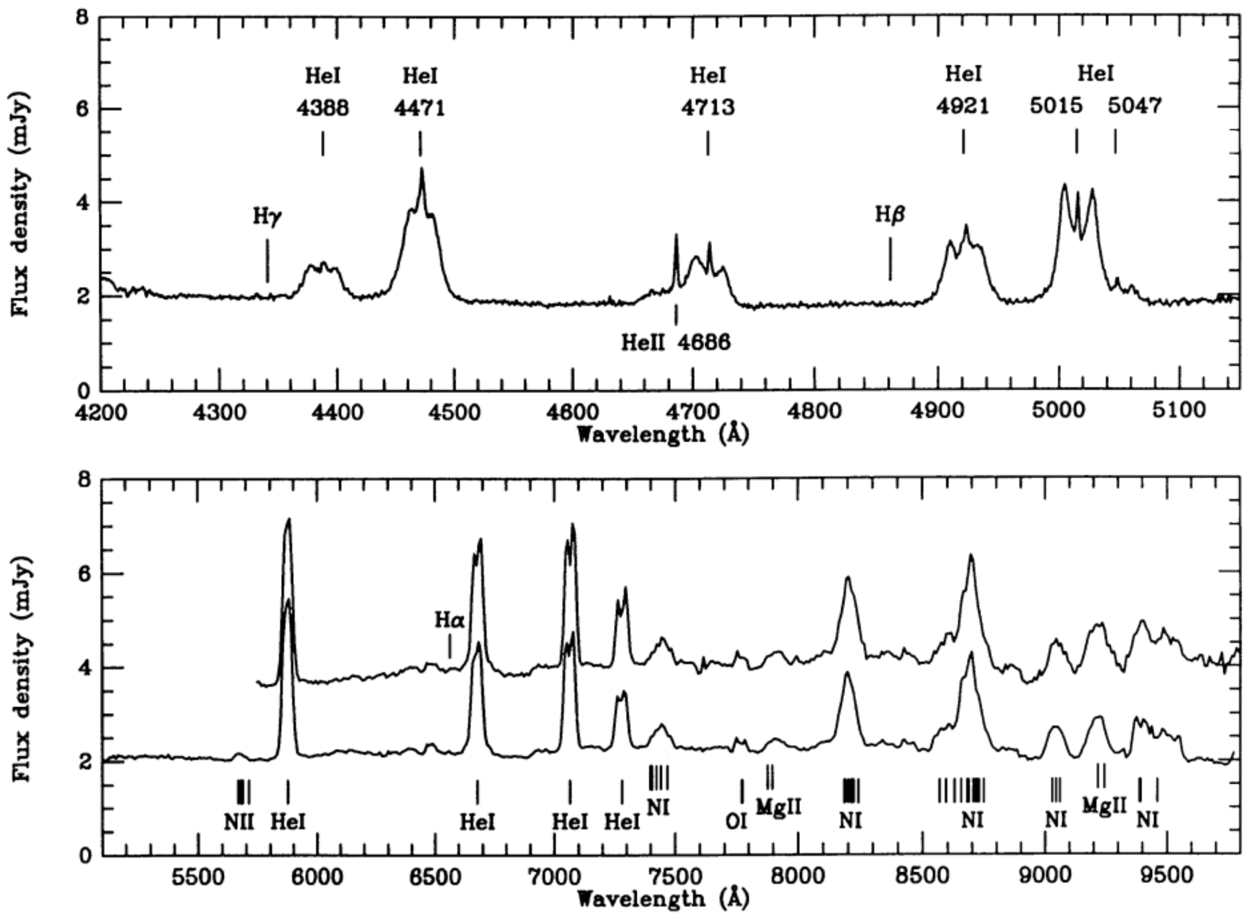
- To fit within their Roche lobes, the donor stars must be dense ($\bar{\rho}_2$= 100 – 4000 g cm^{-3}), suggesting they may be degenerate too:
  "double degenerate" (Faulkner et al 1972).

- Currently 56 known AM CVn systems.
  (Ramsay et al., 2018, A&A, 620, A141)

Spectra of AM CVn's

The most obvious observational signature is their optical spectrum - lack of hydrogen lines.

GP Com, P=46 min (Marsh et al. 1991)



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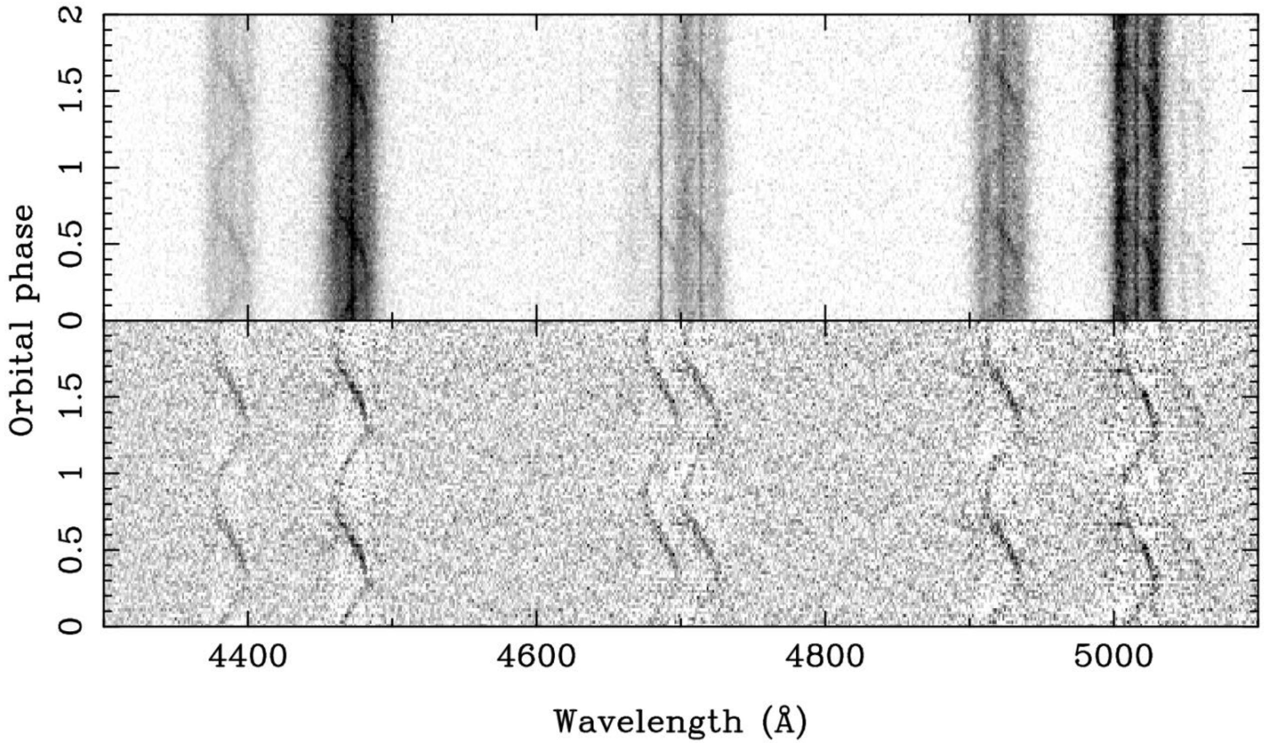
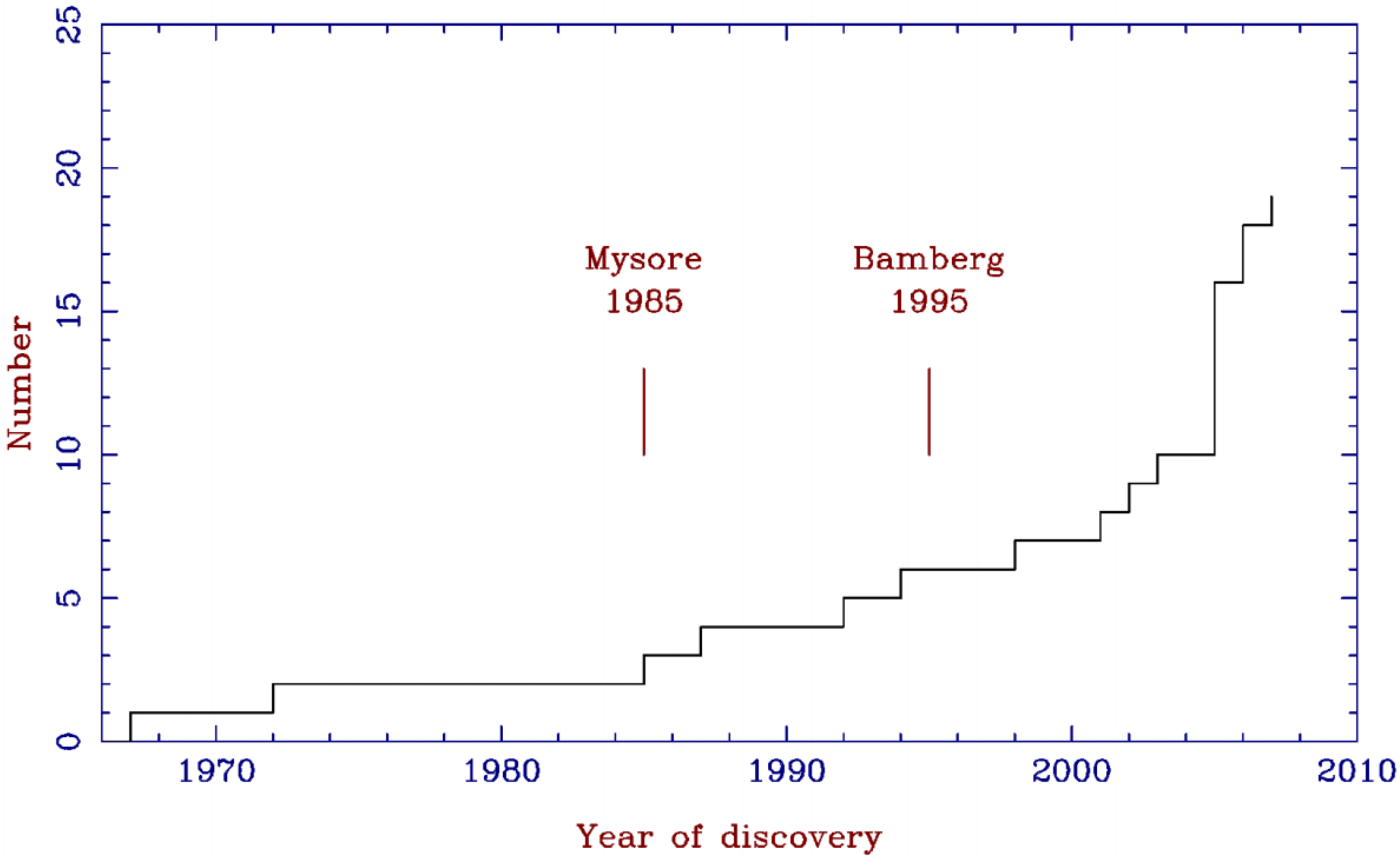


GP Com, P=46 min (Marsh et al. 1991)

AM CVn stars

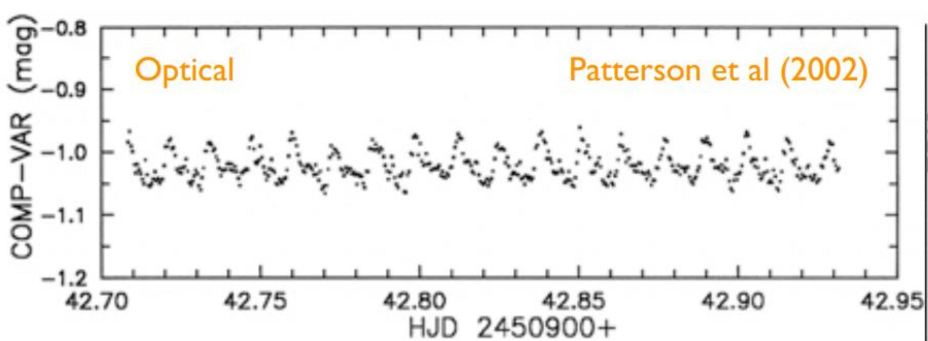
- Total number in Galaxy: $3 \times 10^5 – 3 \times 10^6$ (Roelofs et al 2007)
- Accreting white dwarfs: $M_1 \sim 0.6 M_\odot$
- Mass donors: $M_2 = 0.015 — 0.15 M_\odot$
- Orbital separations: $a = 0.1 — 0.4\ R_\odot$
- Disk size: $R_d \sim 0.35a$
- Mass transfer rates: $\dot{M} = 10^{-12} — 10^{-8}\ M_\odot/yr$
- Absolute magnitudes: $M_V = 5 — 13$

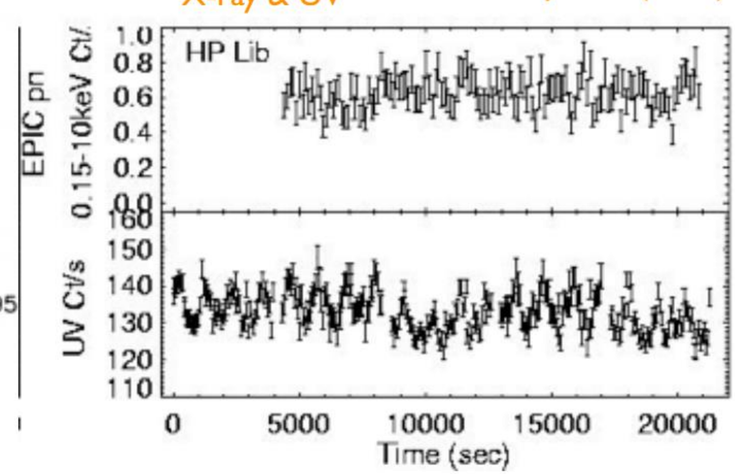
AM CVn stars: Discovery history



Light curves of AM CVn's

- Can be split into systems in low state, high state and those which undergo outbursts. Systems in outburst and in a high state show characteristic modulations in their optical light curve.



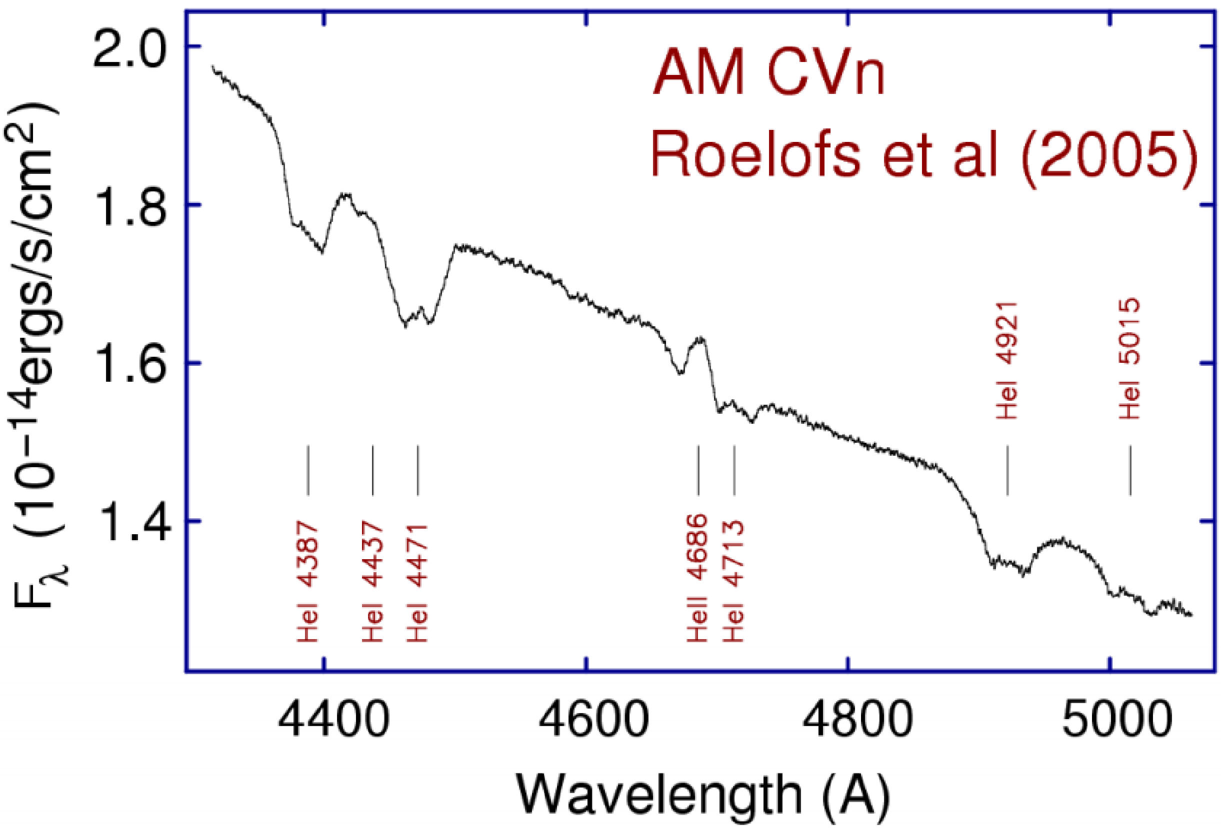


HP Lib (Porb=18.4min) Optical and UV light curves show modulation due to precession period of the accretion disc.

Three groups of AM CVn's

AM CVn stars split into three groups:

1) High $\dot{M}$, permanently bright, dominated by the accretion disk, P < 20 mins



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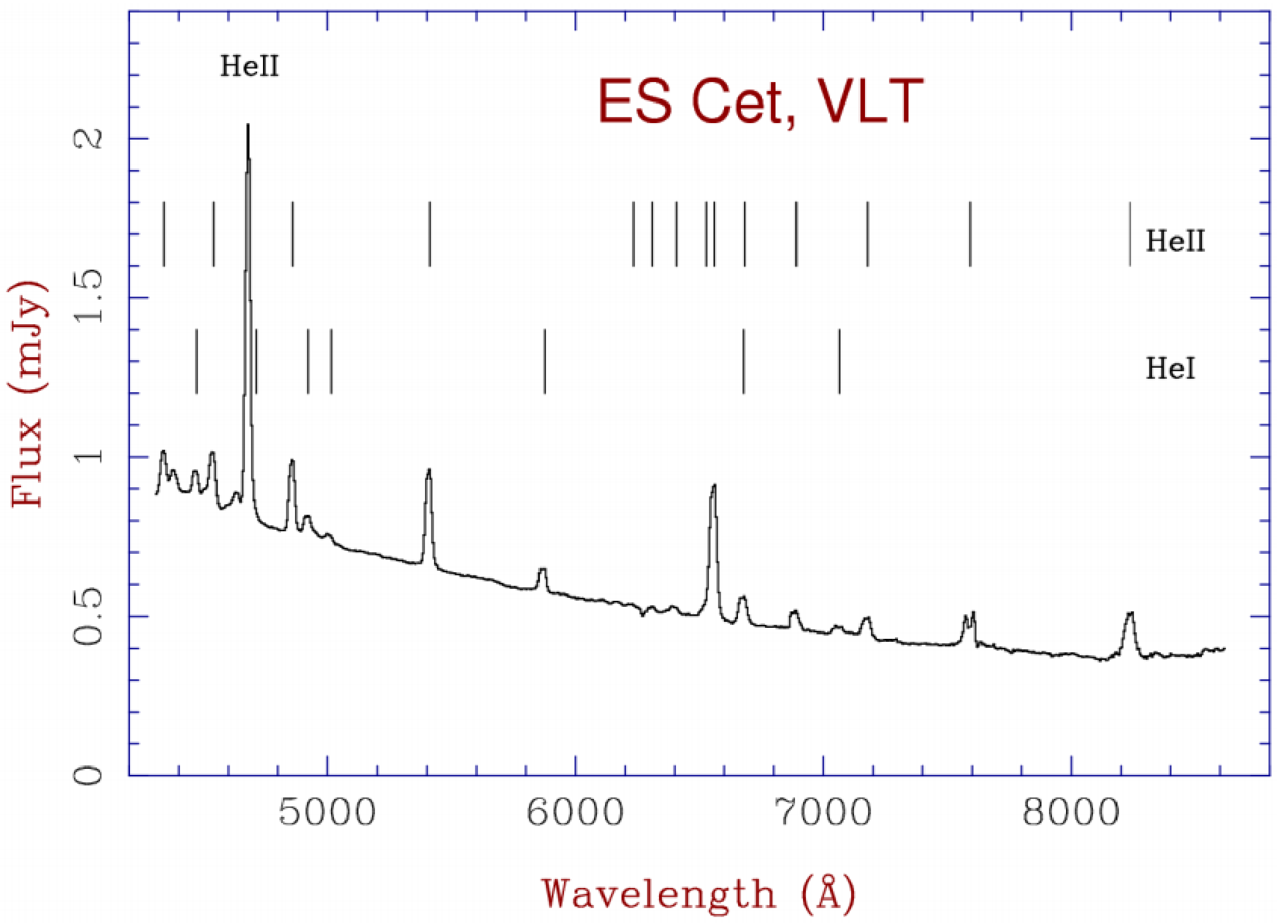
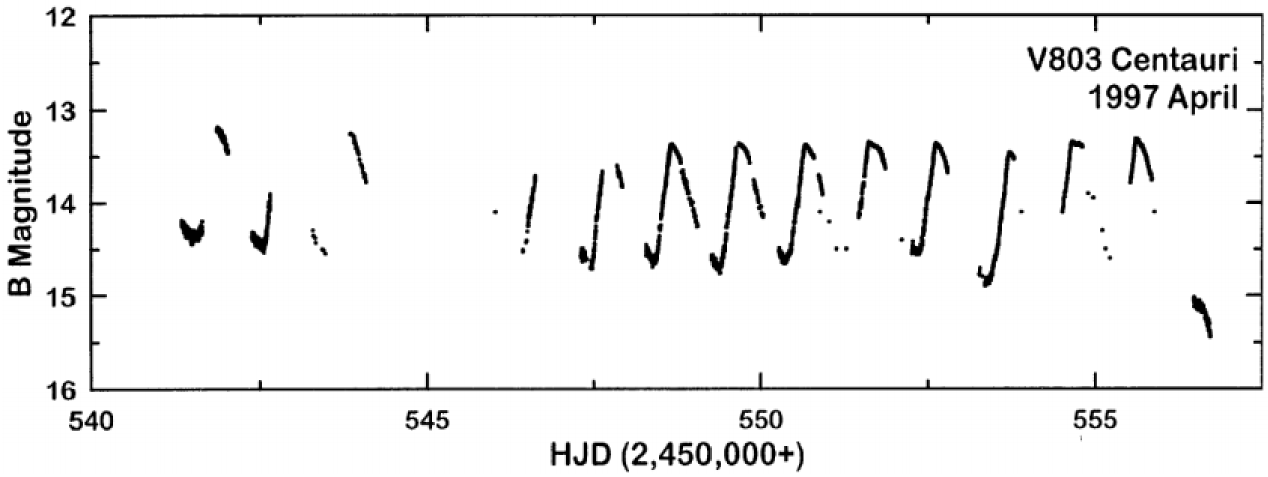


Three groups of AM CVn's

AM CVn stars split into three groups:

2) Medium $\dot{M}$, "dwarf novae", $20 < P < 40$ mins

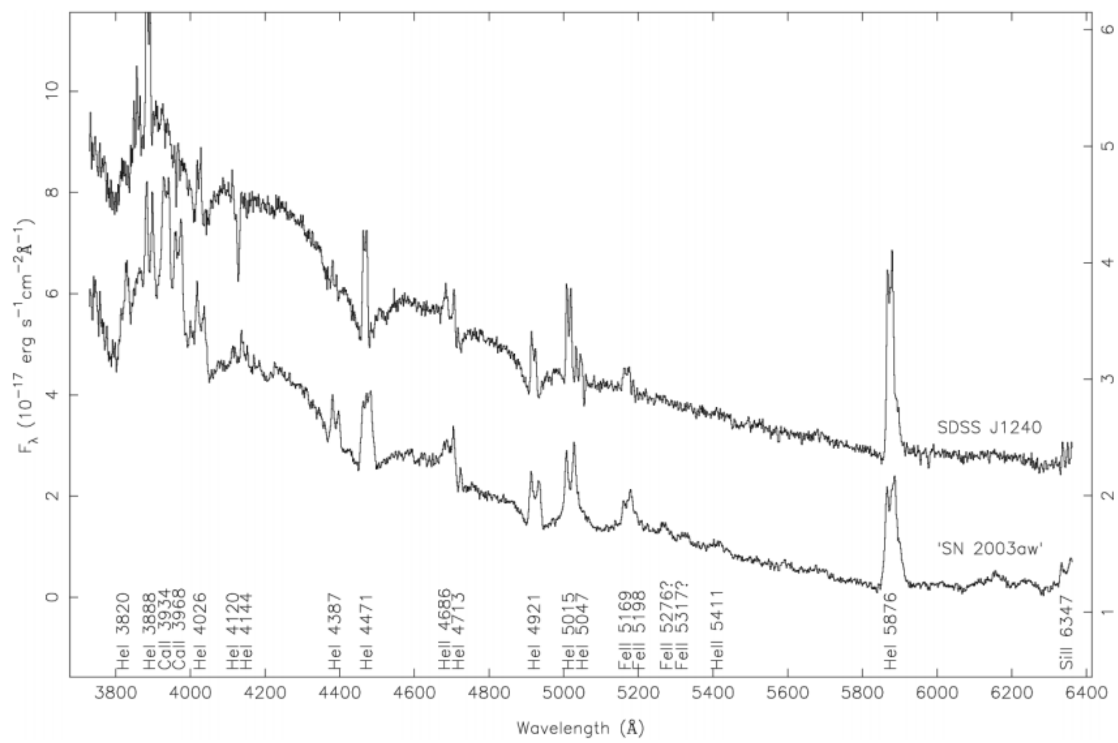


V803 Cen, Patterson et al. (2002)

Three groups of AM CVn's

AM CVn stars split into three groups:

3) Low $\dot{M}$, permanently faint. Continuum from the accreting white dwarf, emission lines from the disk, P > 40 mins



SN 2003aw, SDSS1240, Roelofs et al (2005)

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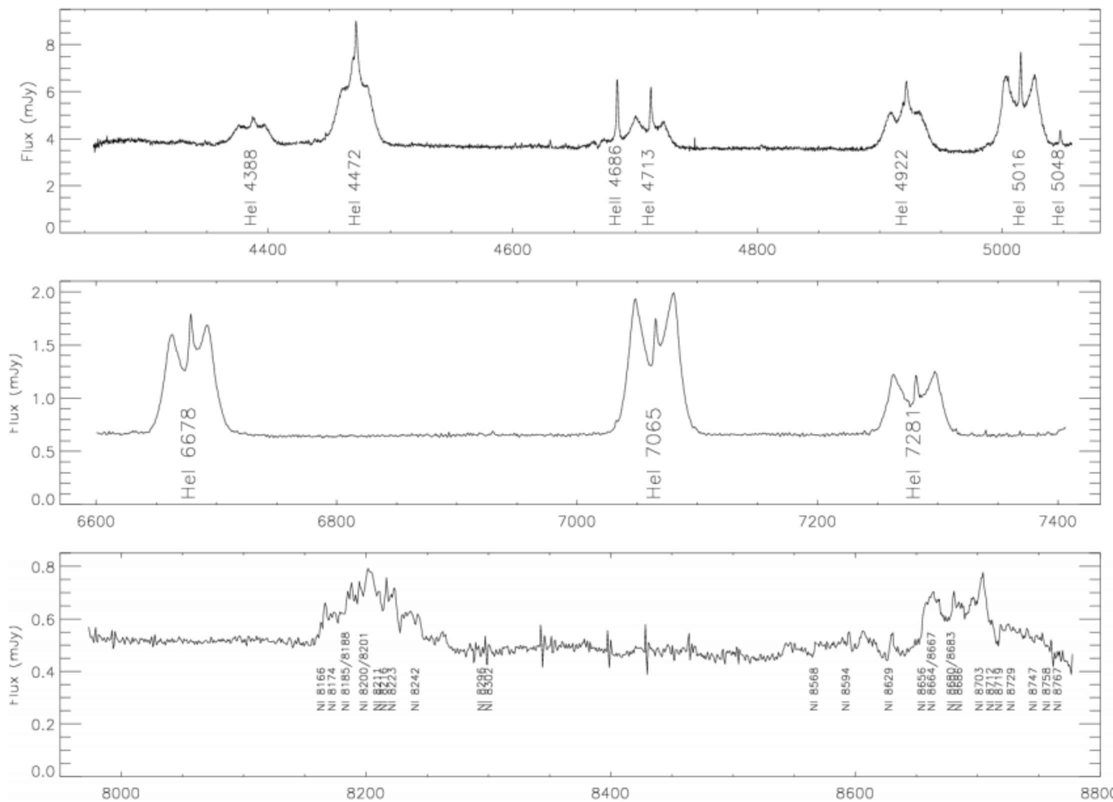


GP Com, Morales-Rueda et al (2003)

Orbital period/accretion rate relation

If

(a) the donors in AM CVn stars are degenerate,

(b) mass transfer is driven by gravitational radiation, and

(c) $M_2 << M_1$:

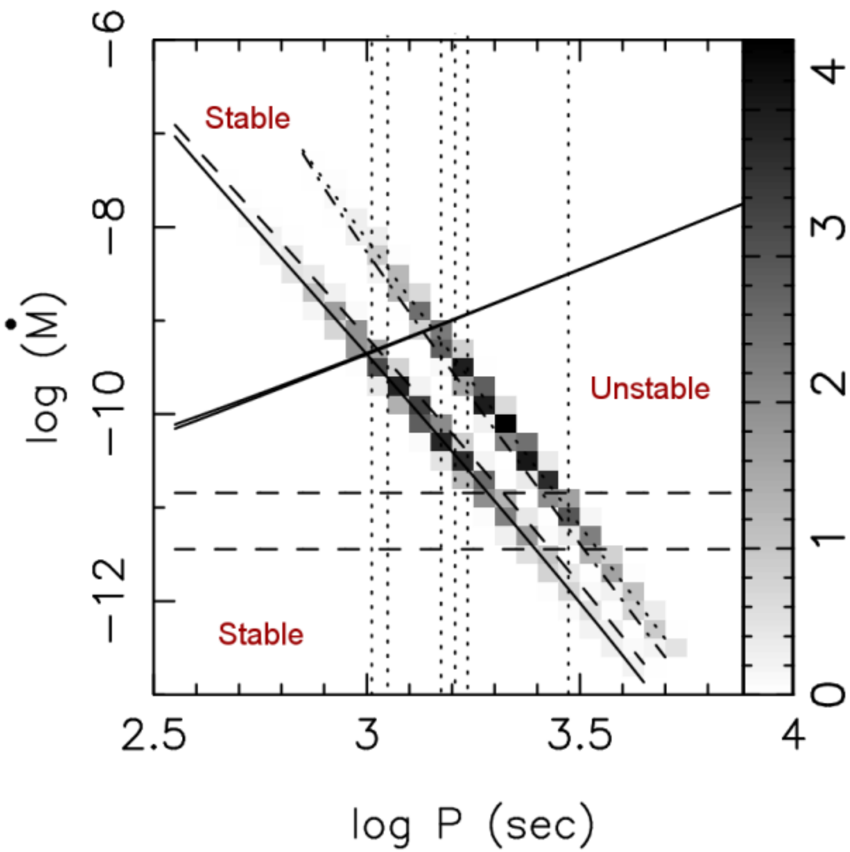
- Can eliminate a, R_2 and M_2 to show:

$$\dot{M}_{accr} \propto P^{-14/3}$$

- **⇒ AM CVn stars vary much more strongly with orbital period than their hydrogen-rich counterparts.**

The evolution of AM CVn stars – I.

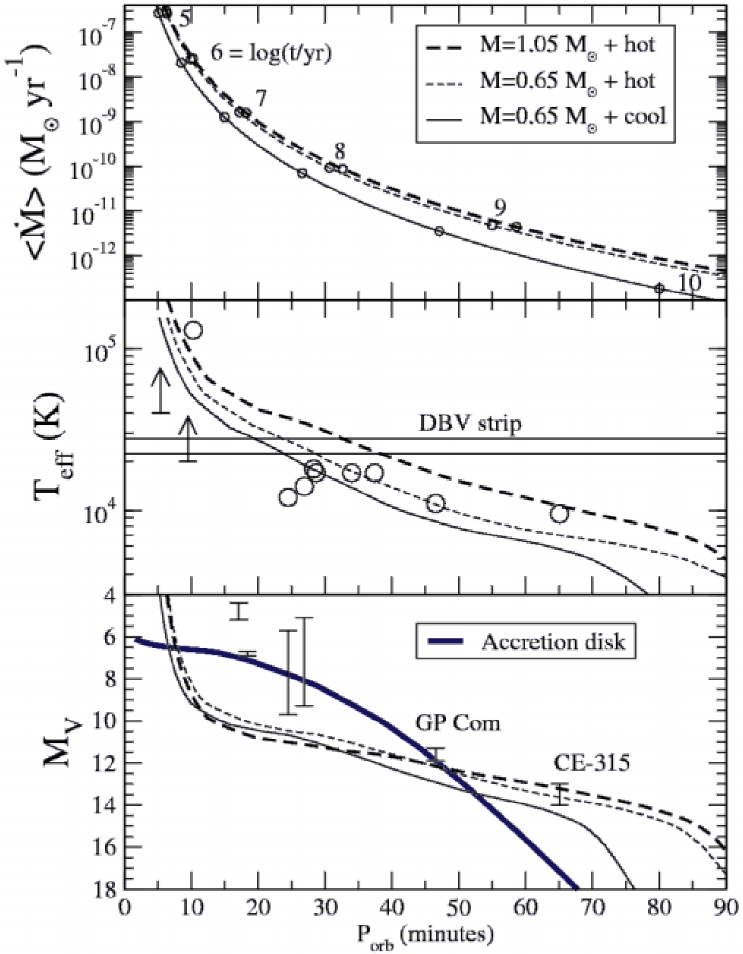
The steep drop of $\dot{M}$ with period combined with a thermal instability caused by the ionisation of helium (Tsugawa & Osaki 1997) can explain the 3 types of systems.



Nelemans et al (2001)

The evolution of AM CVn stars – II.

- The accreting white dwarf's temperature is a combination of normal evolutionary cooling and compressional heating (Bildsten et al 2006).
- It may dominate over the accretion luminosity at both short (< 10 min) and long (> 40 min) orbital periods.



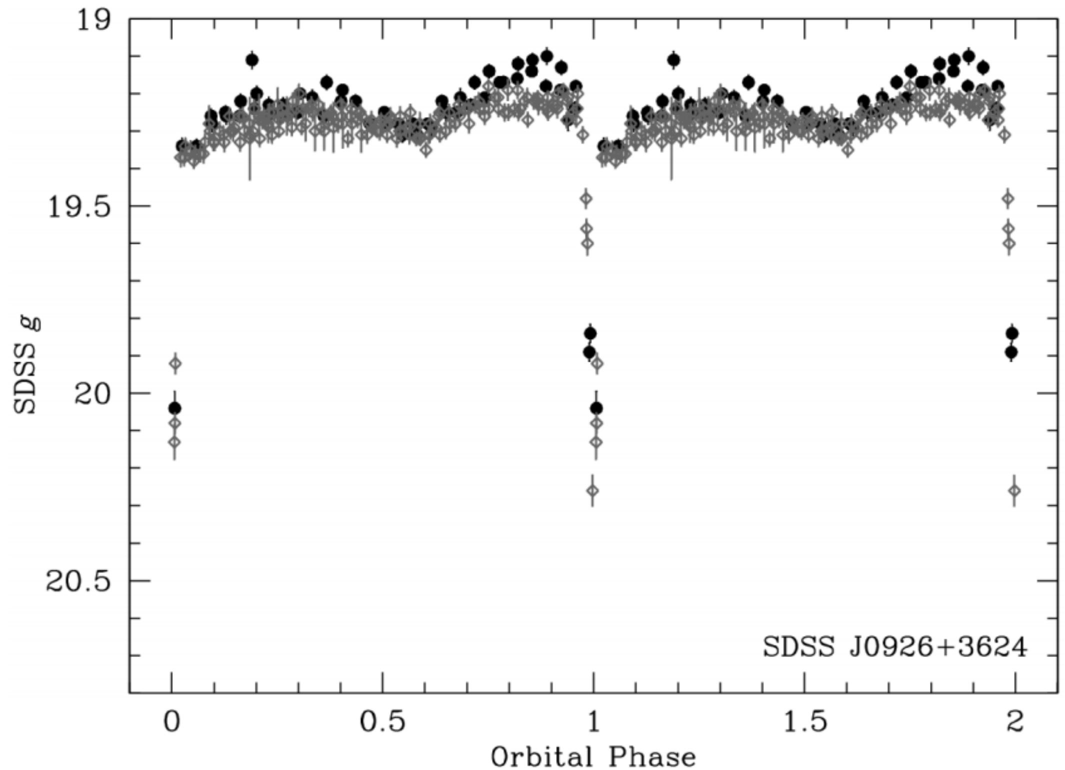
The first eclipsing AM CVn star

SDSS0926+3624

P = 28 minutes, the only eclipsing AM CVn known

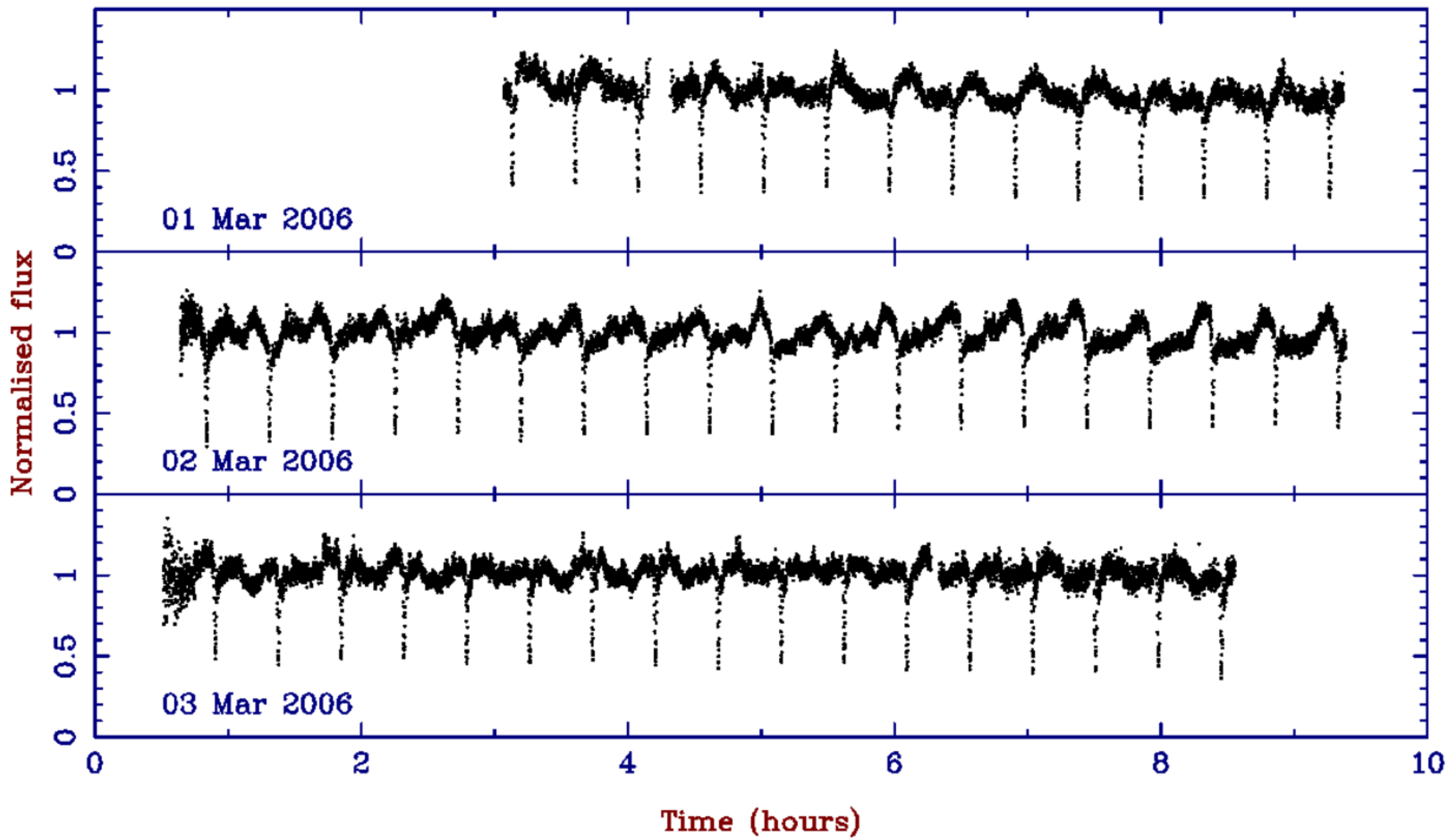
g' = 19.3 with eclipses that last 1 minute.

Our first chance to measure component masses directly.



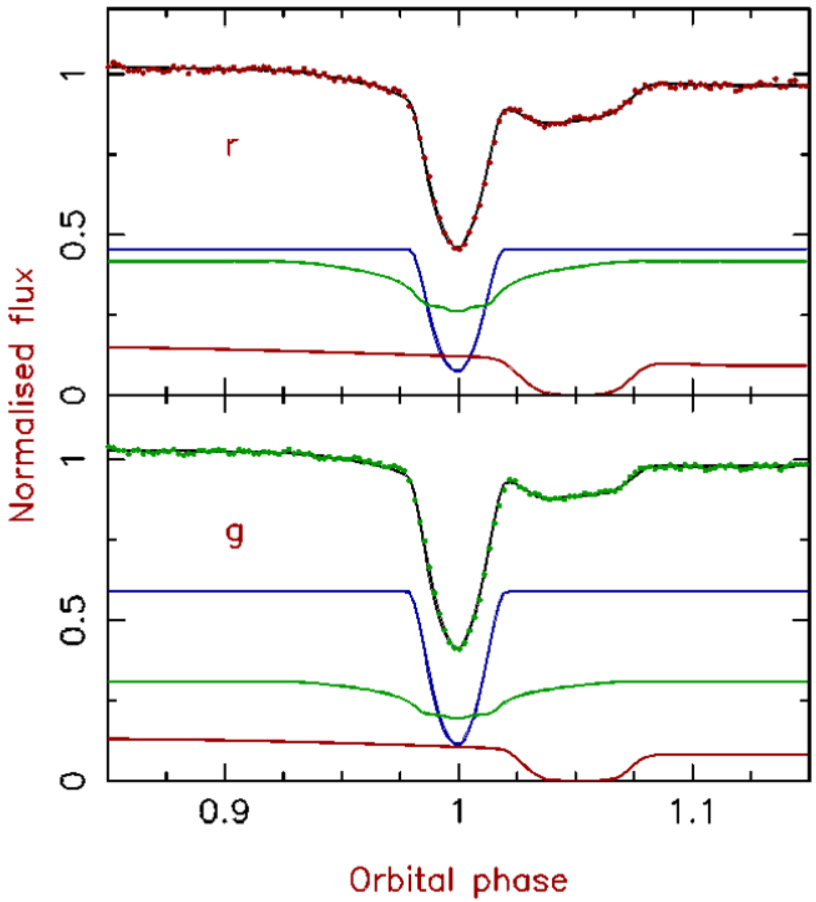
Anderson et al (2005)

SDSS0926+3624 with WHT+Ultracam



SDSS0926+3624 with WHT+Ultracam

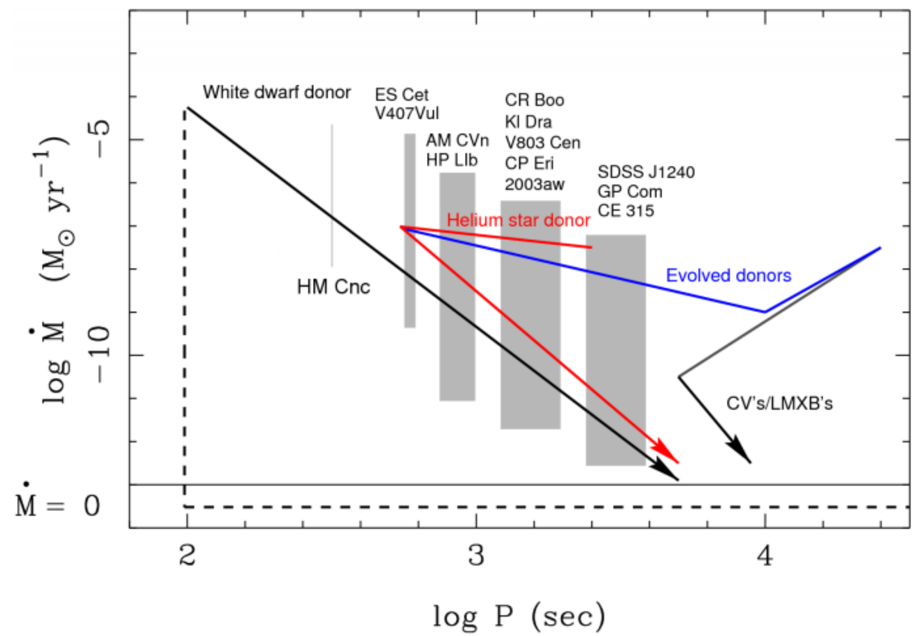
- Light curve fit ⇒ $M_2 = 0.029 \pm 0.002 M_\odot$, higher than expected for complete degeneracy ($0.019 M_\odot$).
- Indicates significant thermal energy in the donor, nevertheless it is consistent with a double white dwarf progenitor (Deloye et al 2007).



AM CVn puzzles I. – their origin

- Three possibilities:
  - 1. Double white dwarfs (Paczynski 1967; Nelemans et al 2001).
  - 2. White dwarf/helium star binaries (Iben & Tutukov 1991).
  - 3. CVs with evolved donors (Posiadlowski et al 2003).

- Other than the possible-but-disputed 5 minute binary HM Cnc, all models can explain the orbital periods.

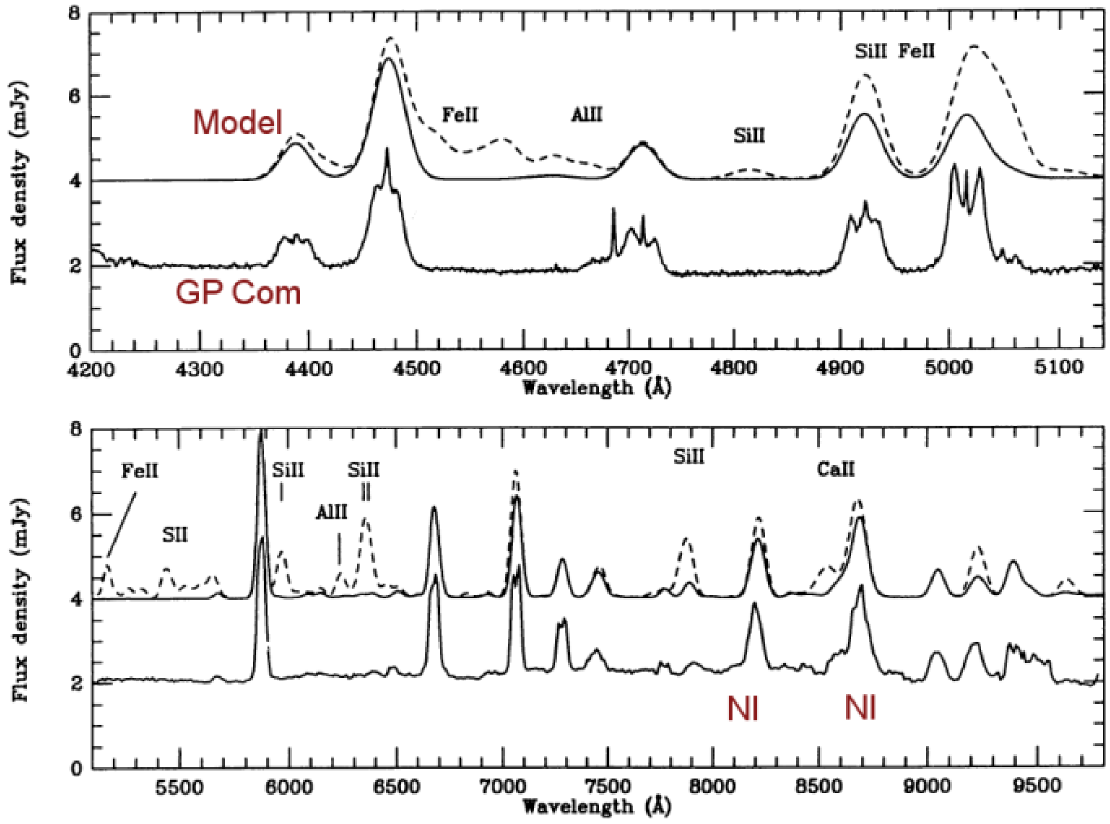


Nelemans et al (2001)

AM CVn puzzles II. – abundances

GP Com appears to have ~ solar CNO/He (mostly N), but lacks Ca, Si and Fe.

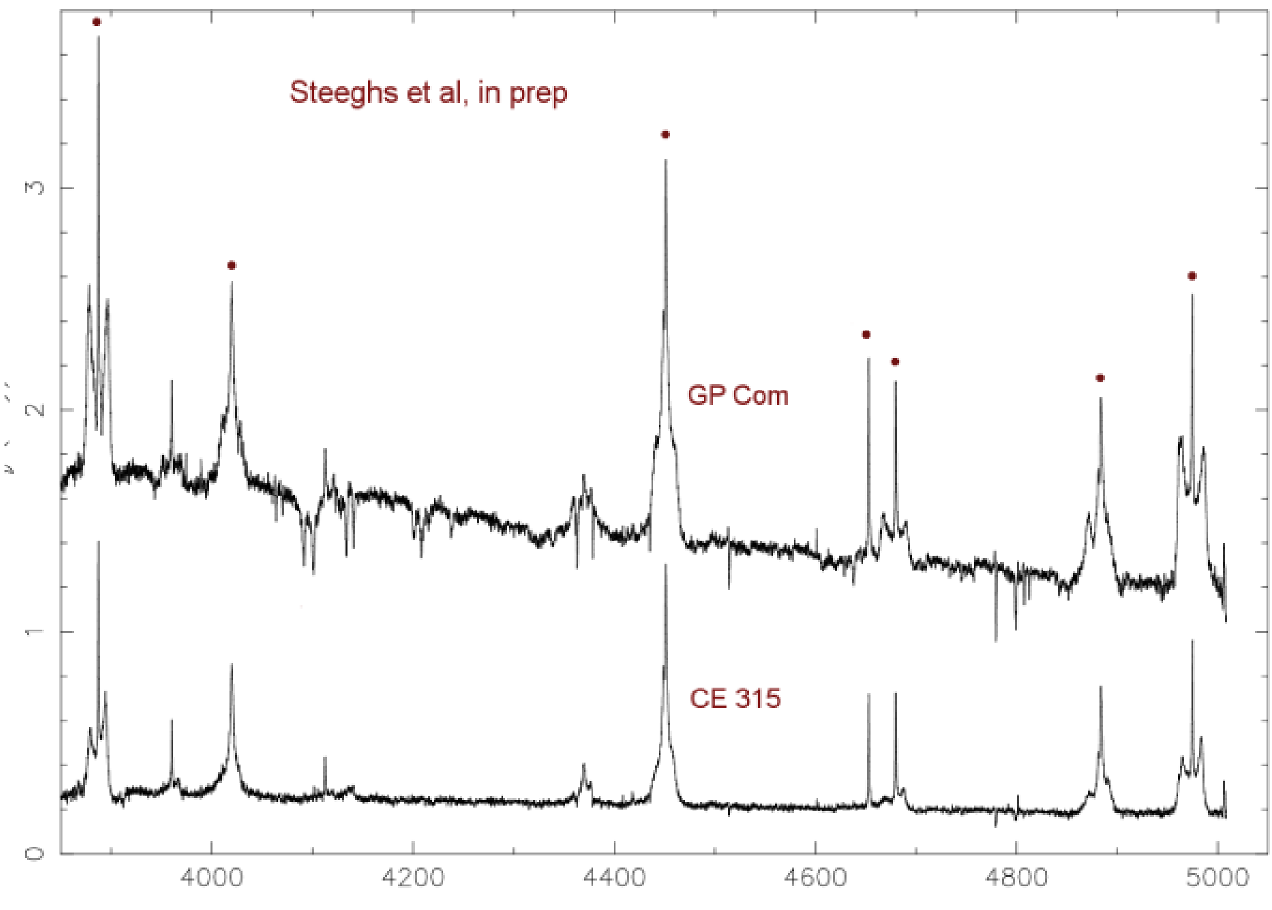
However, the model (single-temperature LTE slab) is crude.



Marsh et al (1991)

AM CVn puzzles III. – spikes

Several systems show sharp components at the centres of the double-peaked lines from the disks.



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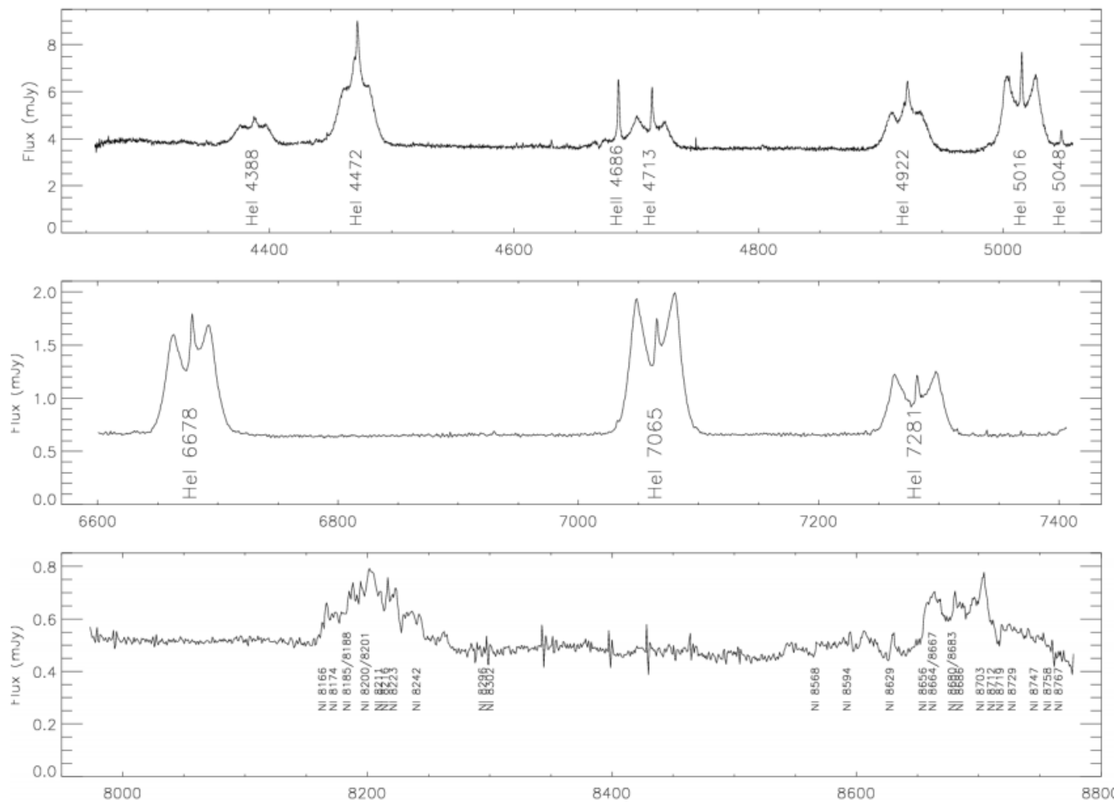
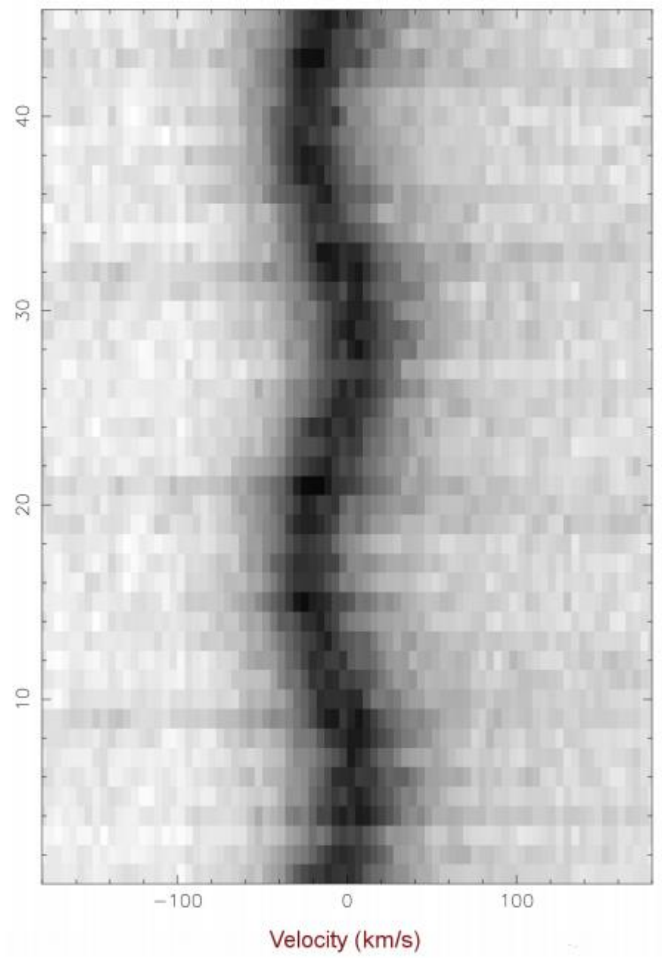


GP Com, Morales-Rueda et al (2003)

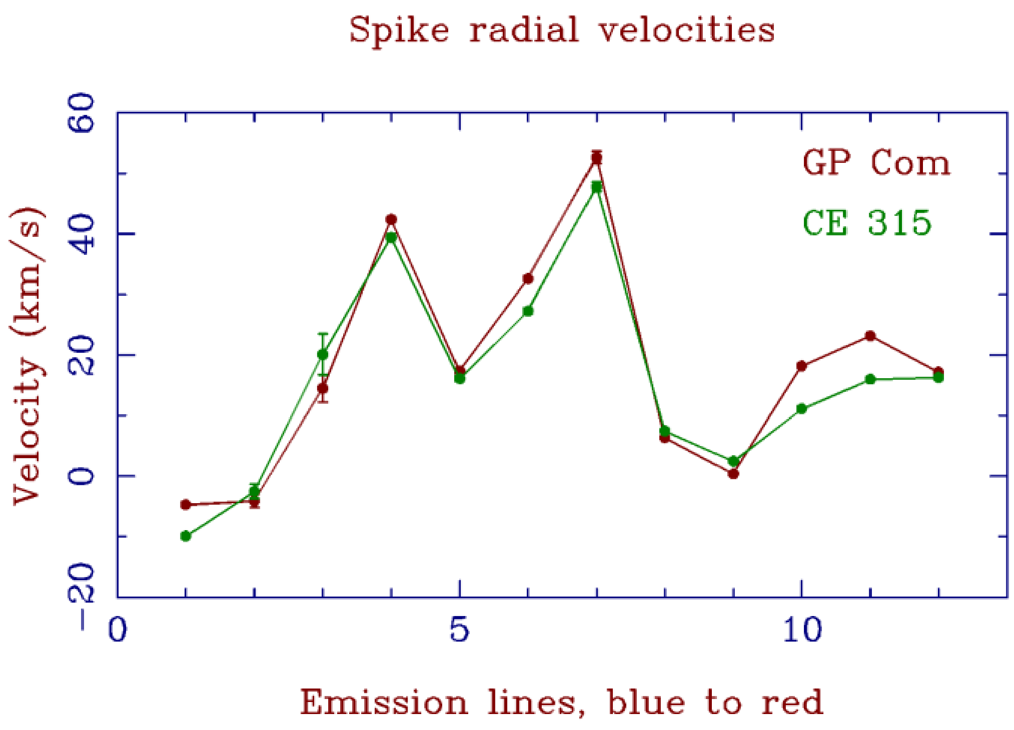
AM CVn puzzles III. – spikes

- Kinematic constraints show that they come from the accreting white dwarfs, (Marsh 1999)
  ⇒ slow rotation,
  $v \sin i < 50$ km/s,
  cf breakup ~ 5000 km/s.



AM CVn puzzles III. – spikes

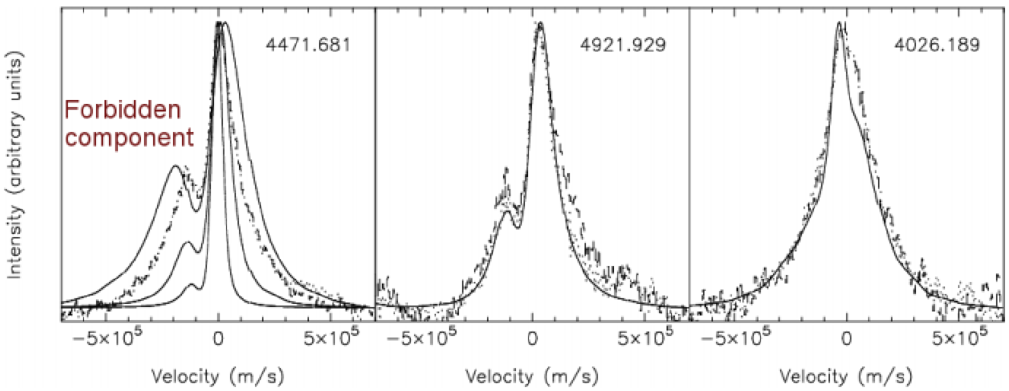
- Spikes should show a gravitational redshift, but the mean spike velocity is observed to vary from line-to-line.



AM CVn puzzles III. – spikes

- Spike shifts & profiles probably the result of Stark broadening (Morales-Rueda et al 2003)

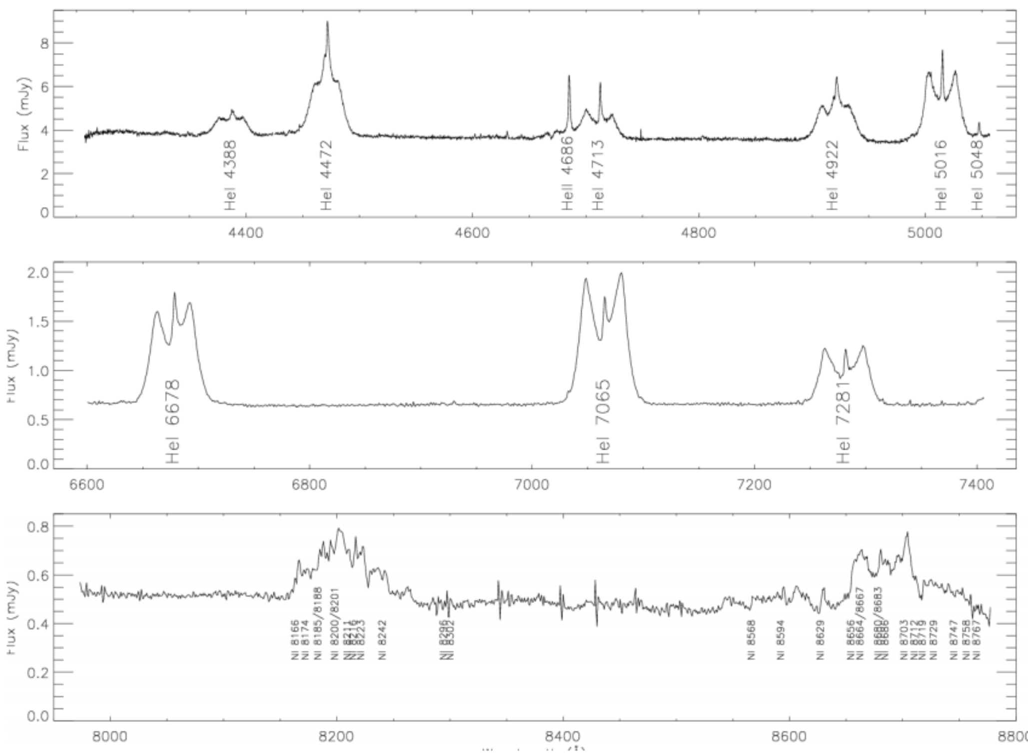
- $n_e \sim 10^{15} – 10^{16}\ cm^{-3}$



Steeghs, Roelofs et al, based on models of Beauchamp et al (1997)

AM CVn puzzles III. – spikes

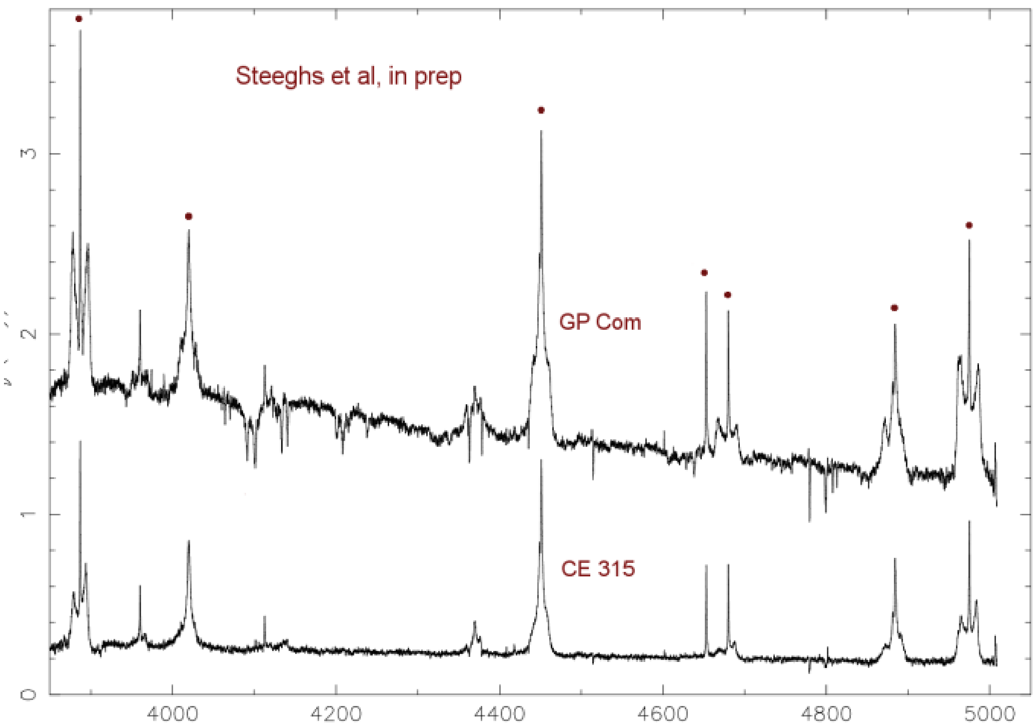
- How do the spikes form?
- Why are they seen in AM CVn stars but not in hydrogen-rich CVs?
- Why are they not always seen in AM CVn stars?
- How can the accretors rotate so slowly?



GP Com, Morales-Rueda et al (2003)

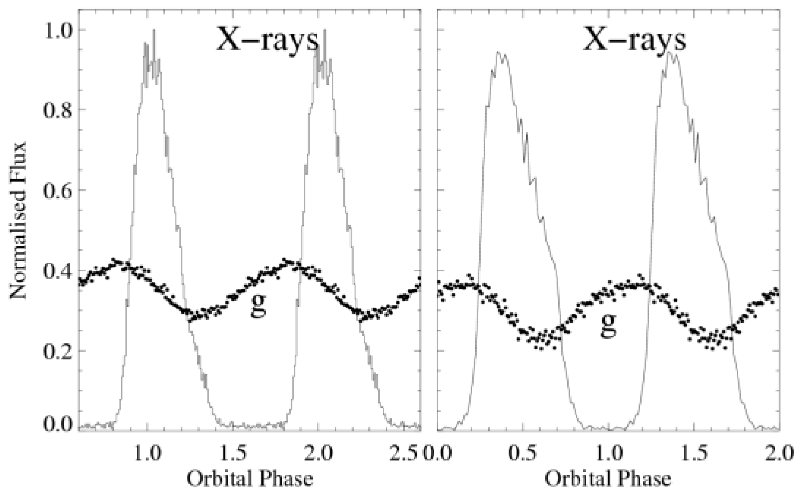
AM CVn puzzles IV. – dips

- Photosphere? If so, what element(s)?
- Time-variable? Accretion vs sedimentation. Critical $\dot{M} \sim 10^{-12}\ M_{\odot}\ yr^{-1}$ (Bildsten et al 2006).
- Request: cool white dwarf model atmospheres for 98% helium, 2% nitrogen plus heavier elements.

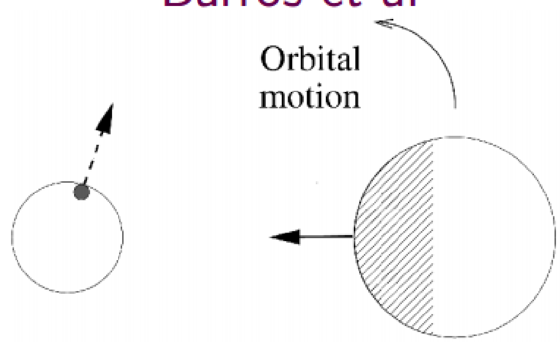


The shortest period binaries?

- Two stars, V407 Vul and RX J0806+1527, have very similar light-curves and periods of 569 and 321 seconds.
- These are thought to be orbital periods ⇒ strong emitters of gravitational waves.
- If accreting, double white dwarf avoidance of mergers will be established.



Barros et al



AM CVn stars

1. The advent of large scale surveys has lead to the discovery of many new AM CVn stars.
2. The basic semi-detached, gravitational-wave driven model has held up well under the onslaught.
3. There have been significant advances in our understanding of the stellar components.
4. These stars pose a number of fascinating evolutionary and spectroscopic problems that we have yet to solve; the accretion disks remain an area of considerable uncertainty.
5. We need more good parameter estimates. These may only come from finding a few more of the million-odd systems in our Galaxy.

X-ray Binaries

- LMXBs
- HMXBs

X-ray Binaries

- X-ray binaries are a class of binary stars that are luminous in X-rays.

- They were among the first X-ray sources to be discovered (apart from the Sun and other Solar System sources).
  - Sco X-1 and Cyg X-1 were the first X-ray sources to be discovered in the constellations of Scorpius and Cygnus respectively and they are both X-ray binaries.

Black Body Radiation (1)

- Light can be produced in many ways. The most fundamental source of radiation is a so-called "black body".
- A black body is an idealized physical body that absorbs all incident electromagnetic radiation. Because of this perfect absorptivity at all wavelengths, a black body is also the best possible emitter of thermal radiation.
- Black body radiation is thus radiation which is in thermal equilibrium and which continuous spectrum depends only on the body's temperature.

Black Body Radiation (2)

Depending on its temperature T, a black body emits radiation according to Planck's law:

$$L_\lambda(T) = \frac{2\,h\,c_0^2}{\lambda^5}\left[\exp\left(\frac{h\,c_0}{\lambda\,k_\mathrm{B}T}\right) - 1\right]^{-1}$$

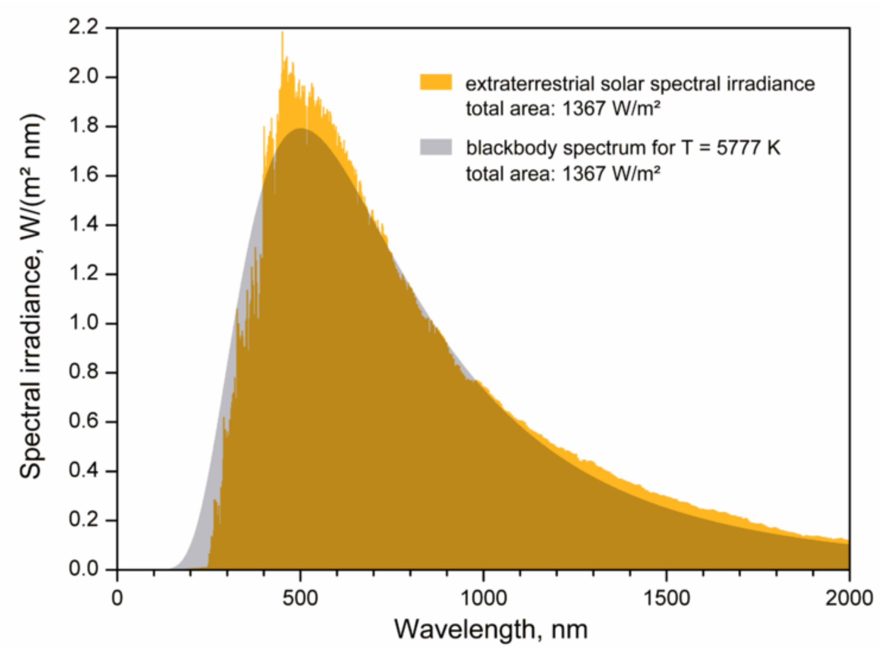
where $k_B = 1.38 \times 10^{-16}$ erg/K is the Boltzmann constant and L_λ(T) is the spectral radiance at the wavelength λ.

The corresponding formula for L_ν (T) is

$$L_\nu(T) = \frac{2\,h\,\nu^3}{c_0^2}\left[\exp\left(\frac{h\,\nu}{k_\mathrm{B}T}\right) - 1\right]^{-1}$$

Black Body Radiation (3)

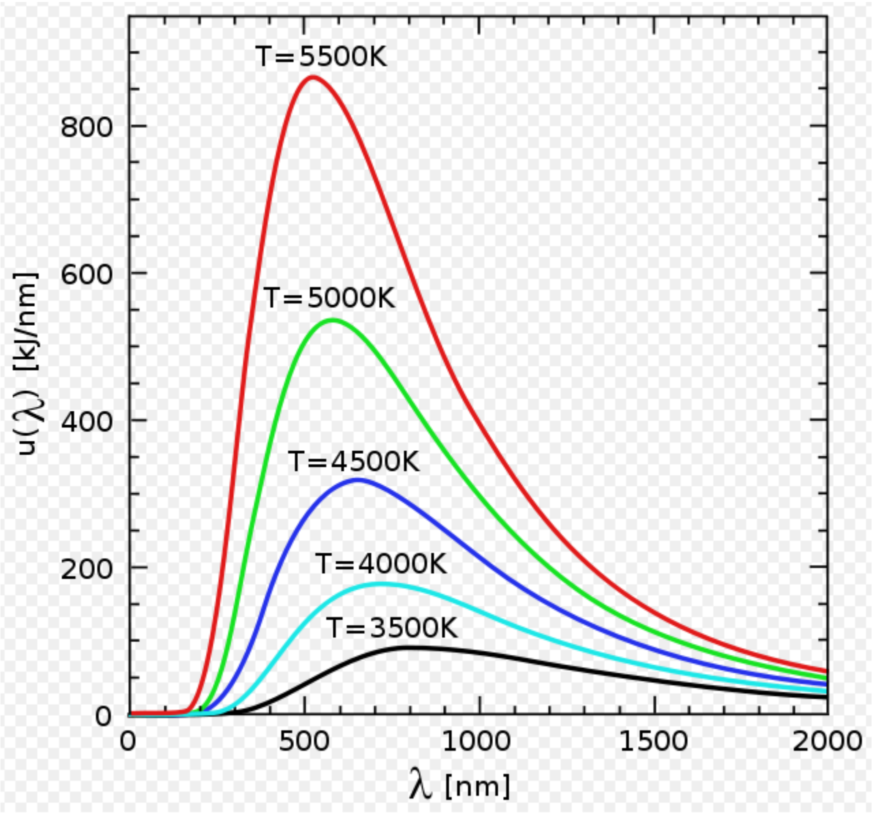
- A black body is the extreme case of an optically thick medium. In the Universe, many plasma systems emit radiation approximately according to Planck's law, at least, in certain wavelength ranges.



Properties of the blackbody spectrum

- As the temperature increases, the peak of the blackbody radiation curve moves to higher intensities and shorter wavelengths.
- Wien's displacement law:
  $\lambda_{max} \approx 0.29(\mathrm{cm})/T$
  λ_{max} is a function only of the temperature

For T=10^7 K we have $\lambda_{max} \approx 2.9$ Å
This is a typical X-ray wavelength range

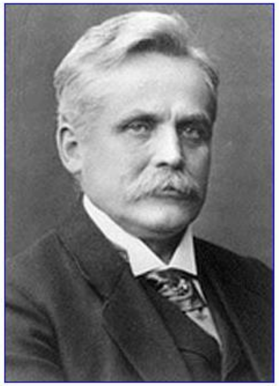


L(T+ΔT) > L(T) at all λ for positive ΔT

X-ray Photons

- **Wien's Displacement Law** (1893):

$$T = 5 \times 10^7 \ ^\circ K \ / \ \lambda_{max} \ (Angstroms)$$



→ 10 Angstroms is very hot !

Wilhelm Carl Werner Otto Fritz Franz Wien

- **X-rays:** Photons 0.6-12 Angstroms ➔ Energies 20-1 keV
  - Thermal Equivalent kT = 4 to 80 million °K
  - Heating mechanisms ➔ non-thermal processes
    - synchrotron radiation (high energy e- in B field)
    - inverse Compton (photon upscattered by high energy e-)

Energetics of accretion (1)

- The accretion of gas onto a compact object can be a very efficient way of converting gravitational potential energy into radiation.
- The amount of energy released by accreted gas is

$$E_{acc} = \frac{GM_*\dot{M}}{R_*}$$

M_* and R_* are the mass and radius of the accreting star.

- By comparison, the conversion of the hydrogen into helium would yield an energy

$$E_{H\rightarrow He} \approx 0.007\,\dot{M}c^2$$

Energetics of accretion (2)

- Efficiency of the accretion process (fraction of the nuclear fusion [hydrogen to helium] energy that is radiated) is

$$\frac{E_{acc}}{E_{H \to He}} \approx \frac{G M_* \dot{M}}{0.007\, \dot{M} R_* c^2} \approx \frac{70\, R_{Sch}}{R_*}$$

$R_{Sch} = \frac{2 G M_*}{c^2} \approx 3km \frac{M_*}{\mathrm{M}_\odot}$ → The Schwarzschild radius

- Thus, accretion on to a compact object with $R_* \leq 70\, R_{Sch}$ is a more efficient mechanism than nuclear fusion of hydrogen to helium.

Energetics of accretion (3)

- **A white dwarf:** typical mass $2{\cdot}10^{30}$g (1 $M_\odot$)

$$R = 7000\ km \gg 70\ R_{Sch}$$

- **A neutron star:** typical mass $3{\cdot}10^{33}$g (1.5 $M_\odot$)

$$R = 10\ km \ll 70\ R_{Sch}$$

- **A black hole**

Accreting neutron stars and black holes are luminous sources, normally in X-ray radiation.

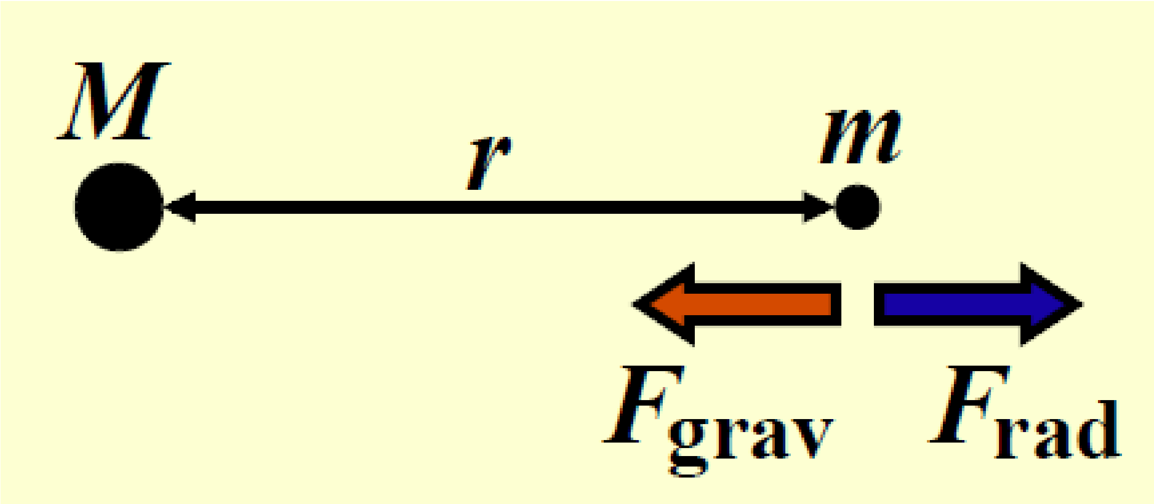
Where does accreted matter come from? ISM?

No – captured mass is too small. Companion? Yes.

The Eddington Luminosity (1)

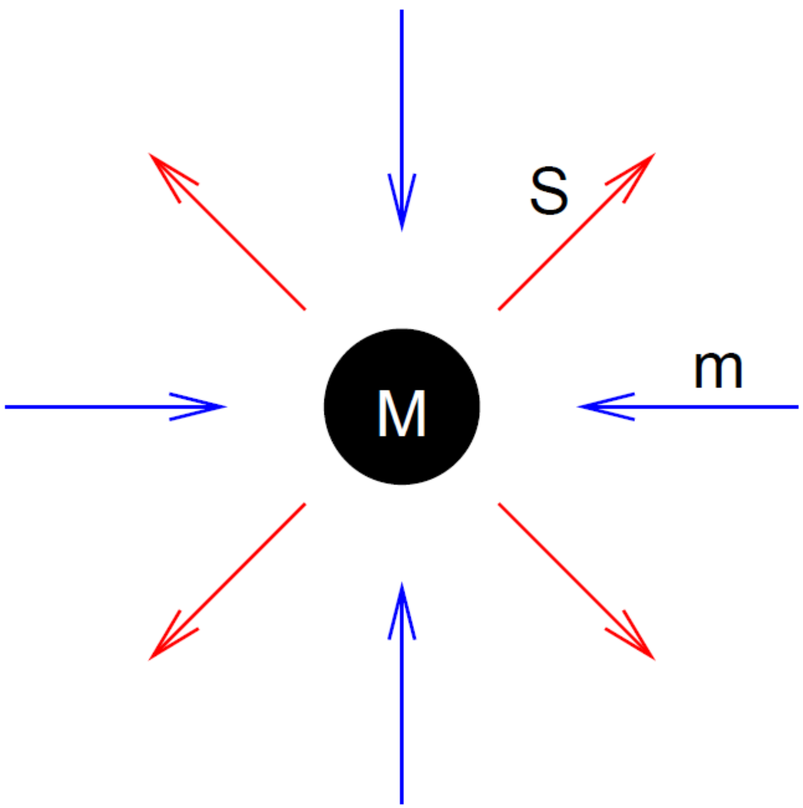
- There is a (not strict) limit to the rate $\dot{M}$ at which a compact object can accrete matter.
- Accordingly, there is a limit to the luminosity that can be produced by a steadily accreting object, known as the **Eddington luminosity**.
- Effectively it is reached when the inward gravitational force on matter is balanced by the outward transfer of momentum by radiation.

The Eddington Limit (1)



Accretion rate controlled by momentum transferred from radiation to mass

The Eddington Limit (2)



- Assume mass M spherically symmetrically accreting ionized hydrogen gas.
- Inward force: **gravitation**:

$$F_{grav} = \frac{GM_* m_p}{r^2}$$

- At radius r, accretion produces **energy flux S**:

$$S = \frac{L}{4\pi r^2}$$

- The luminosity L of the central compact object exerts a radiation force on the free electrons by **Thomson scattering**:

$$F_{rad} = \frac{\sigma_T S}{c}$$

- **Note:** the Thomson cross-section of protons is $\sim 10^6$ times smaller than that of electrons. But: electrostatic forces between electrons and protons bind them so they act as a pair: **F_{rad} also has effect on protons!**

The Eddington Limit (3)

- Accretion is only possible if gravitation dominates:

$$\frac{GM_*m_p}{r^2} > \frac{\sigma_T S}{c} = \frac{\sigma_T}{c}\frac{L}{4\pi r^2}$$

- and therefore

$$L < L_{Edd} = \frac{4\pi G M_* m_p c}{\sigma_T}$$

where L_{Edd} is called the Eddington luminosity.

- or, in astronomically meaningful units

$$L < 1.3 \times 10^{38}\ erg\ s^{-1}\ \frac{M}{M_\odot}$$

- When the luminosity of the central compact object is greater than this value, the surrounding hydrogen gas will be blown away by the radiation pressure.

The Eddington Luminosity (2)

- If the Eddington luminosity is emitted as black-body radiation, the temperature will be

$$T_{bb} = \left(\frac{L_{\rm Edd}}{4\pi R_*^2 \sigma_{SB}}\right)^{1/4} = \left(\frac{GM_* m_p c}{R_*^2 \sigma_{SB}}\right)^{1/4}$$

  where σ_{SB} is the Stefan-Boltzmann constant, and R_* is the radius of the surface from which the radiation is emitted (for a black hole, of course, this surface will be outside the Schwarzschild radius).

- For a black hole accreting at the Eddington limit, the temperature of the radiation will be $\boldsymbol{T_{bb} \sim 4\times10^7}$ **K** $\boldsymbol{(M_*/M_\odot)^{-1/4}}$, if the radiation comes from immediately outside the Schwarzschild radius.
- The spectrum of the emitted photons will then peak at a photon energy $\boldsymbol{E \sim 20}$ **keV** $\boldsymbol{(M_*/M_\odot)^{-1/4}}$.

Maximum Accretion Rate

- The existence of the Eddington luminosity implies the existence of a maximum accretion rate, $\dot{M}_{Edd}$, for an accreting compact object. If the accretion energy E_{acc} is converted entirely into radiation, then the luminosity is $L_{acc} = GM_*\dot{M}/R_*$, and the maximum possible accretion rate is

$$\dot{M}_{\rm Edd} = \frac{4\pi m_p c R_*}{\sigma_T} = 9 \times 10^{16}\,{\rm g\,sec^{-1}}\left(\frac{R_*}{1\,{\rm km}}\right) = 1 \times 10^{-3}\,{\rm M_\odot\,yr^{-1}}\left(\frac{R_*}{\rm R_\odot}\right)$$

- In reality, the conversion is not 100% efficient, the accretion is not perfectly spherically symmetrical, and the radiation is not perfectly spherically symmetrical; thus, matter can be accreted at rates somewhat greater than $\dot{M}_{Edd}$.