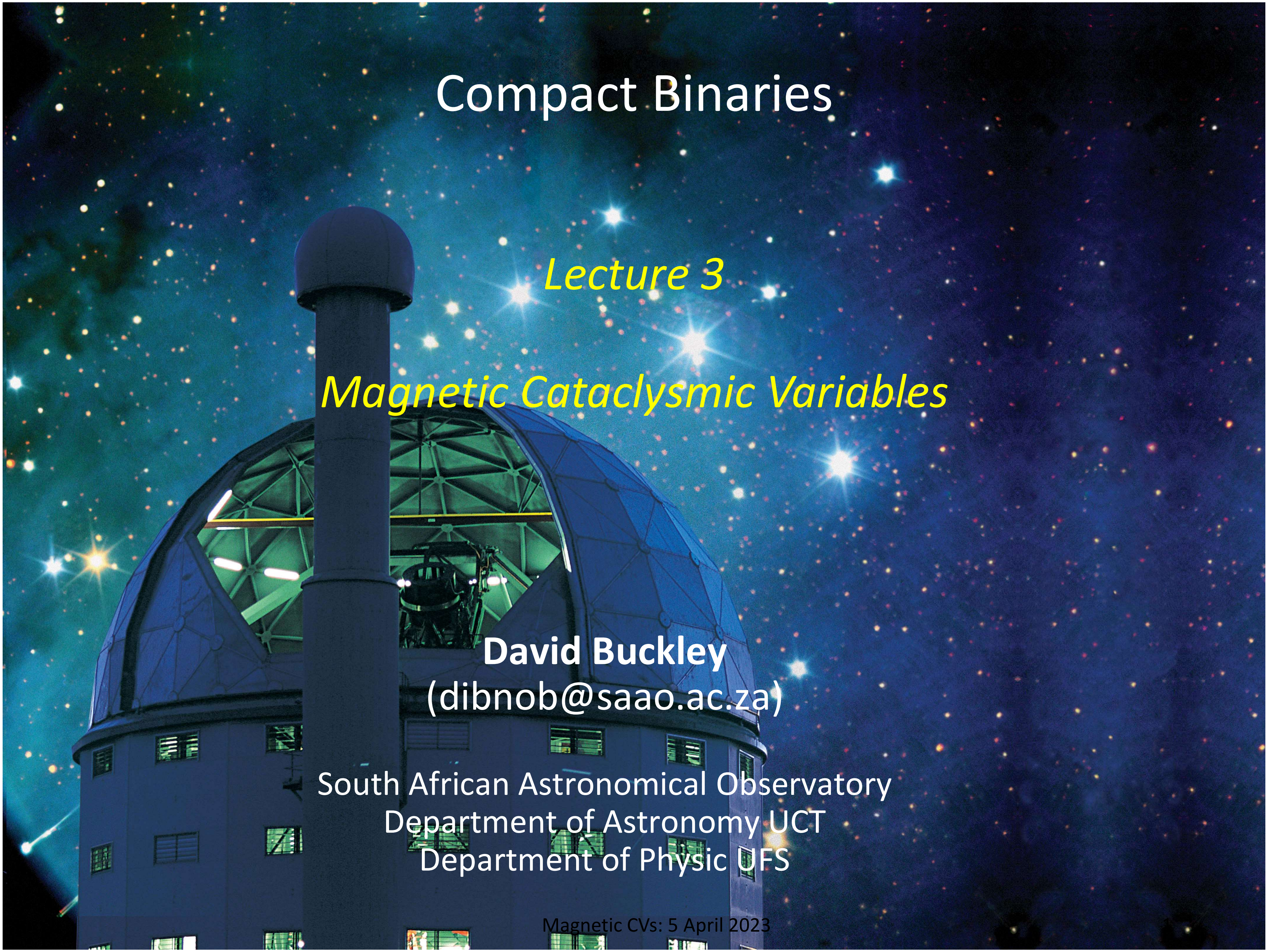

Compact Binaries

Lecture 3

Magnetic Cataclysmic Variables

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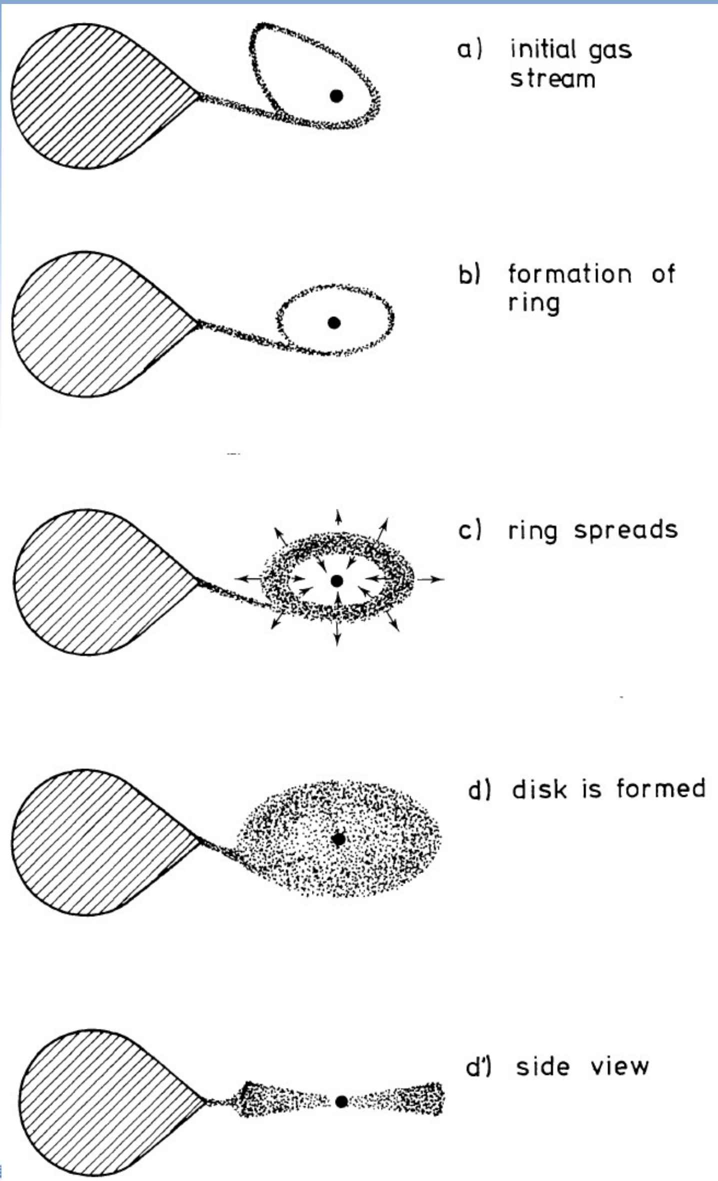
Department of Astronomy UCT
Department of Physic UFS

Formation of an accretion disc



transport of
- M inwards/outwards
- L outwards

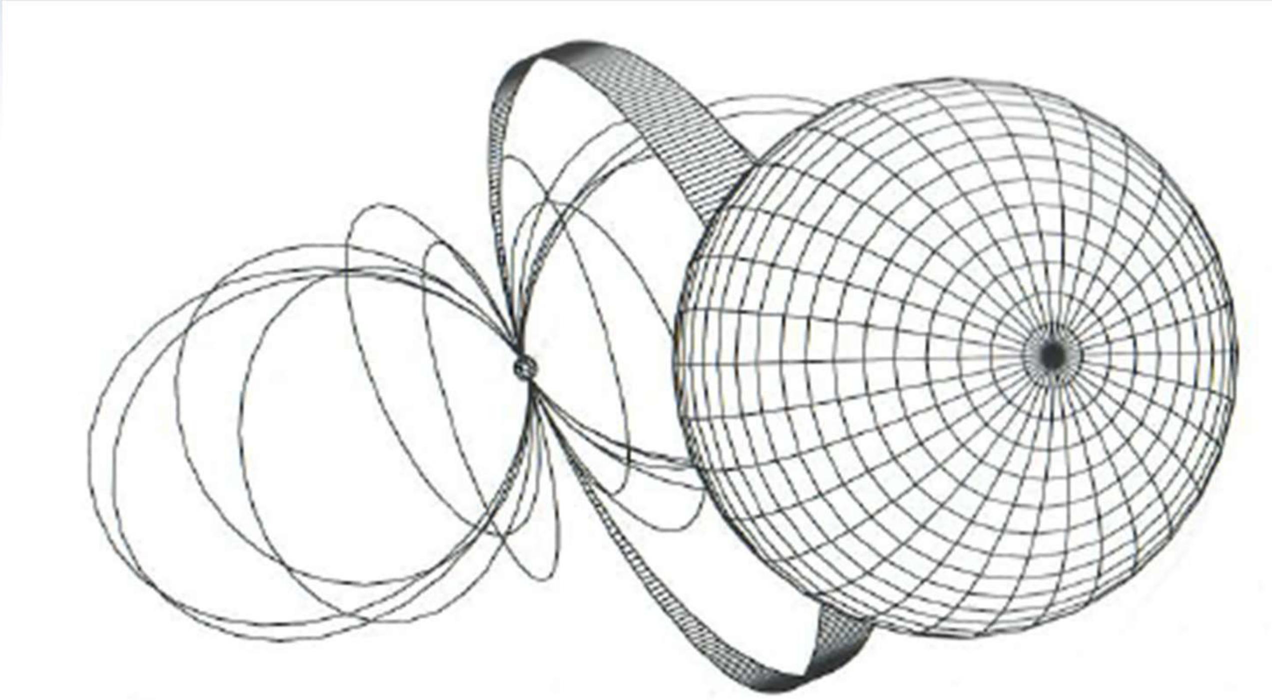
$$E_{tot} = -\frac{GMm}{r} + \frac{1}{2}mv^2$$
$$= -\frac{GMm}{r} + \frac{1}{2}\frac{GMm}{r}$$
$$= -\frac{1}{2}\frac{GMm}{r}$$

$$L_{disc} = \frac{1}{2}\frac{GM\dot{m}}{R} = \frac{1}{2}L_{acc}$$

(the other half: boundary layer between disc and star)

Magnetic CVs

- *Accretion disk formation prevented (polars)*
- *Accretion disks are partially disrupted (intermediate polars)*
- *Crucial fact is that a magnetic dipole's strength varies as* $B \propto r^{-3}$

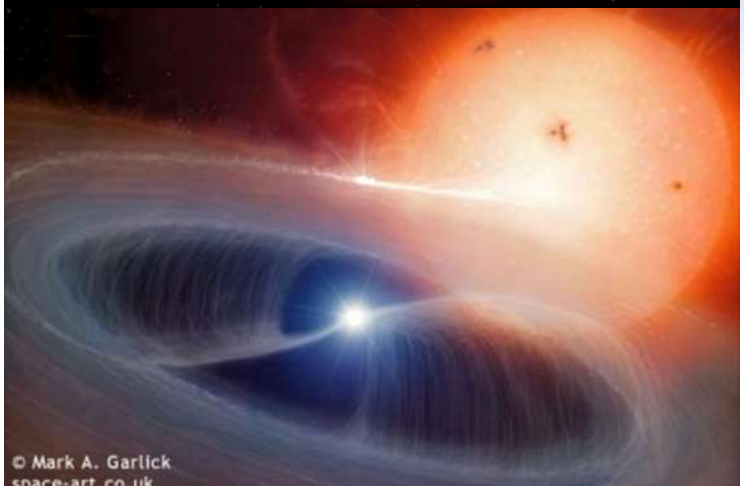


Magnetism in CVs

nova-like
dwarf nova

$$\mu \leq 10^{33}\ Gcm^3$$
$$R_* \approx R_M << a$$

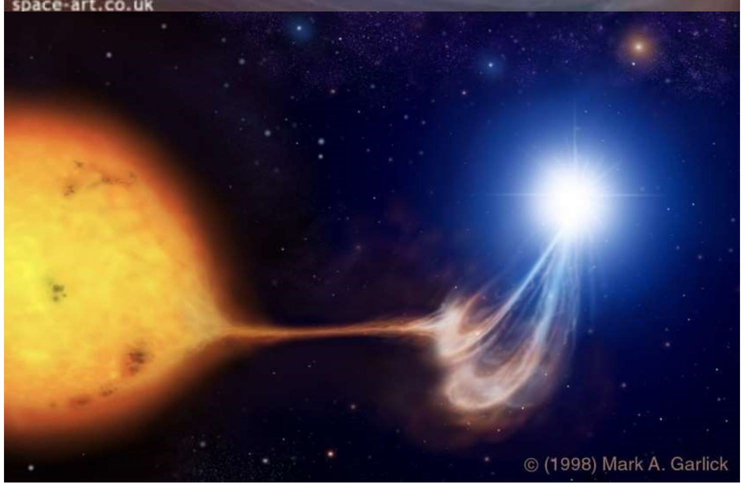
$P_{spin} << P_{orb}$



Intermediate Polar

$$\mu \leq 10^{34}\ Gcm^3$$
$$R_* << R_M < a$$

$P_{spin} \sim 0.1\ P_{orb}$

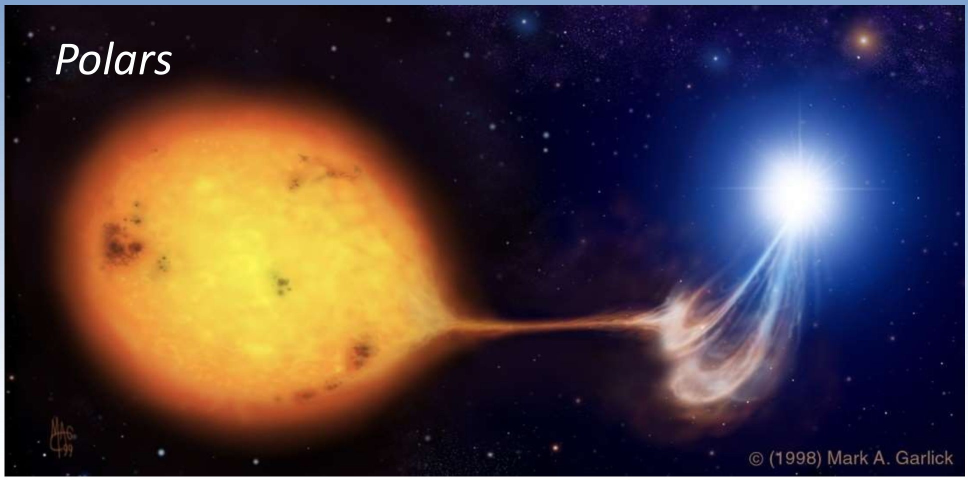


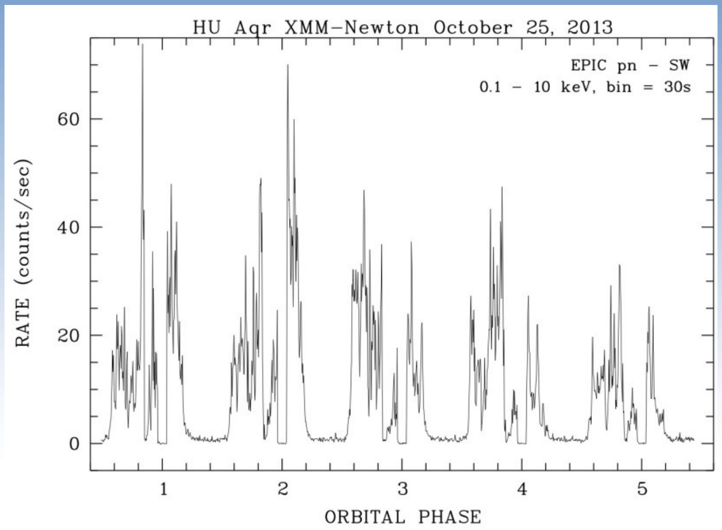
Polar
(AM Herculis star)

$$\mu \geq 10^{34}\ Gcm^3$$
$$R_* << R_M \approx a$$

$P_{spin} = P_{orb}$

Flavours of Magnetic CVs: Polars





- *Discovered through their X-ray emission*
  - *Both hard (bremsstrahlung) and soft (black body)*
- *Prototype: AM Herculis (polars often called AM Her stars)*
- *Show optical polarization and cyclotron emission*
- *Spin period and orbital period are synchronized (to < few %)*
  - *B is > 10 MG and enough to apply spin-down torque on WD*
- *No accretion disks and emission lines can show high free-fall velocities (few 1000 km/s)*

Polars: Spectral Energy Distributions

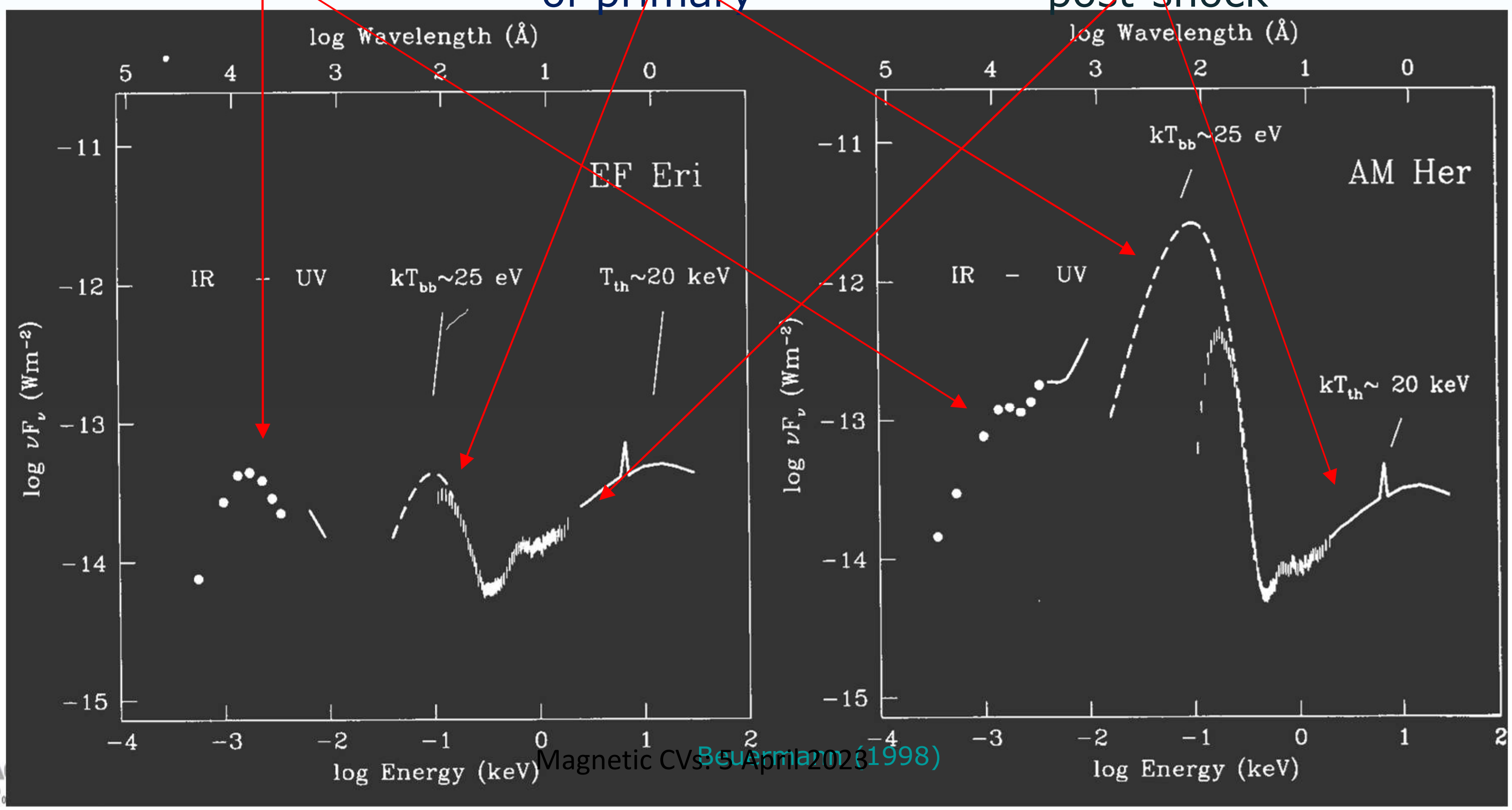
Most of the energy from these systems is a result of accretion

3 main components:

cyclotron radiation from accretion column

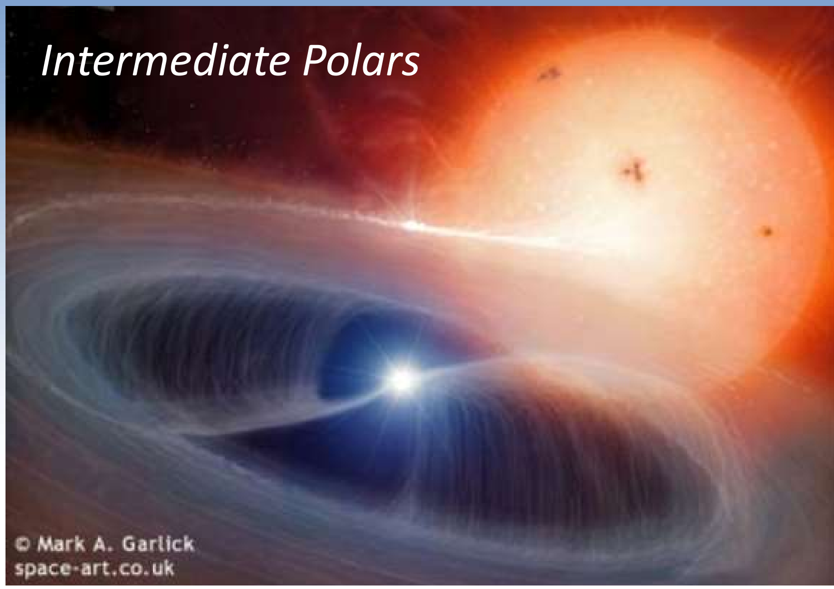
soft X-ray emission, from heated surface of primary

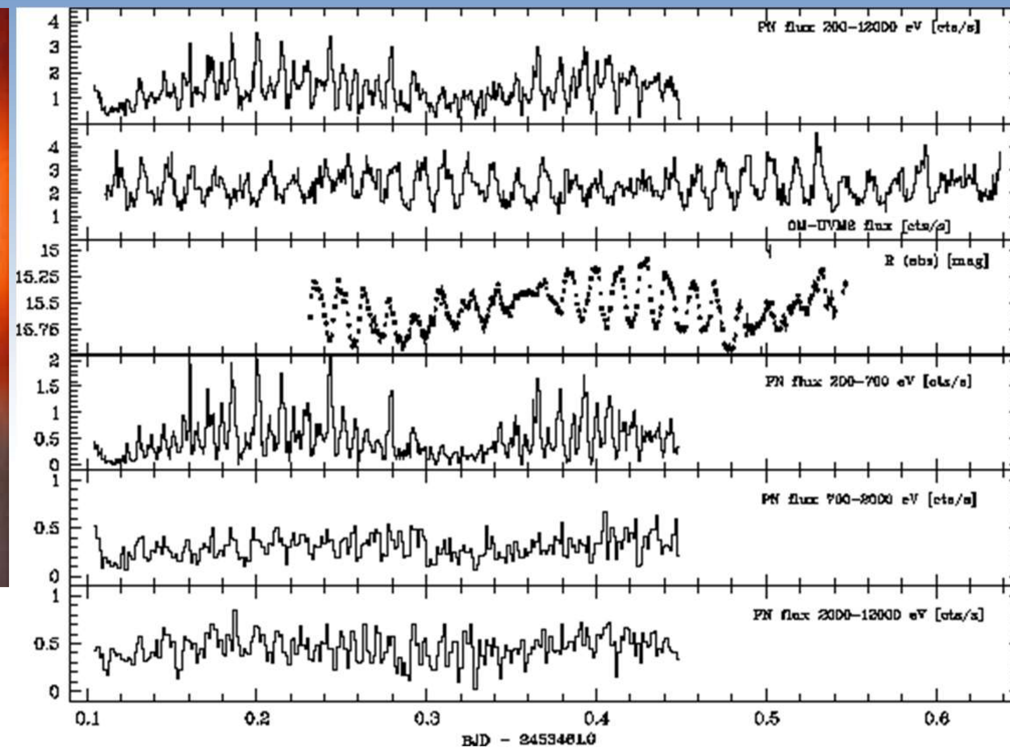
hard X-ray emission, also from accretion column post-shock



Beuermann (1998)

Flavours of Magnetic CVs: intermediate polars

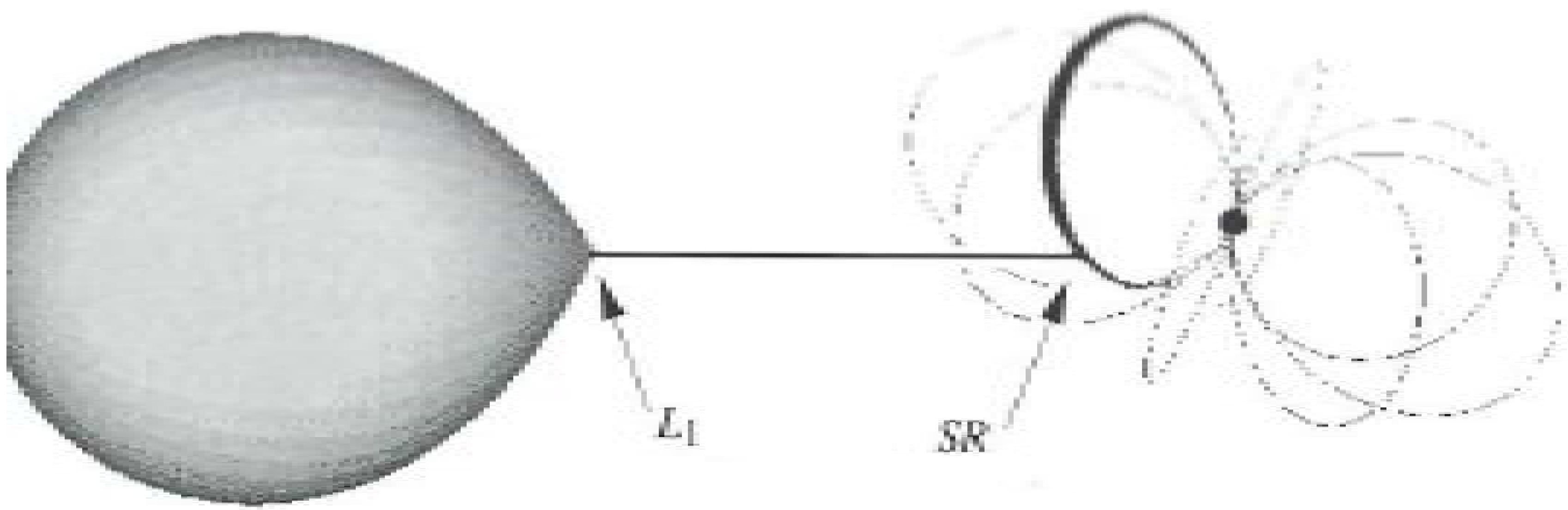




- *Also X-ray sources*
  - *mostly hard (bremsstrahlung)*
- *Sometimes called DQ Herculis (but these are usually considered a small subclass)*
- *Show spin modulated emission (across all λ) typically at 10% orbital period*
  - *So asynchronous and weaker B (< 10 MG)*
- *Most have accretion disks disrupted at $R_{mag} \sim R_{inner}$ (one known discless IP)*
- *Some show polarization*

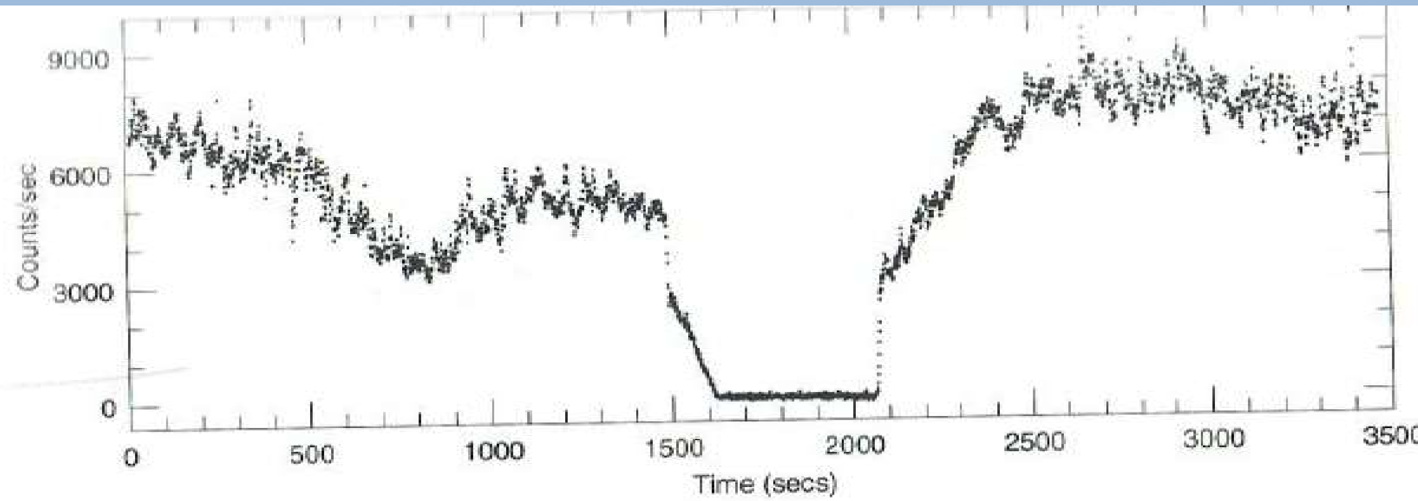
Polars

- *Accretion stream from L_1 penetrates to ~R_{mag} (stagnation region)*
- *Plasma "threads" onto B field lines and accretes onto one or both magnetic polar regions (~ 0.01 R_{WD})*
- *Forms an accretion`column*
    - *Most of luminosity comes from this region*
    - *Stream is fragmented (turbulence) and can have diamagnetic "blobs"*



Polars

- *Eclipse light curves can provide a probe into accretion hot-spot (& sometimes stream) geometries:*



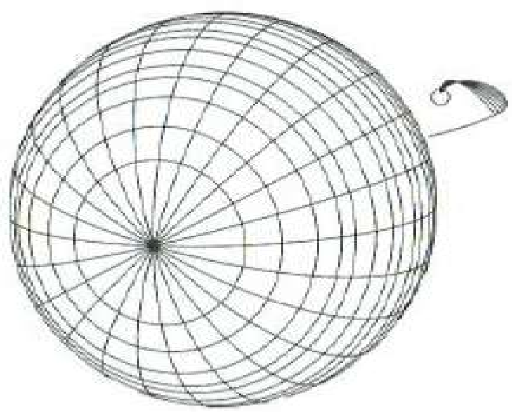
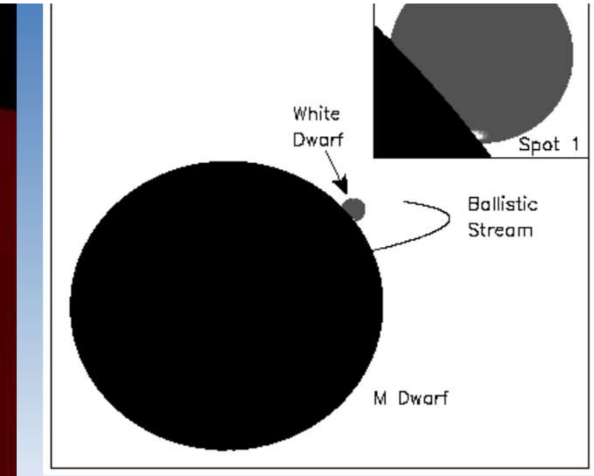
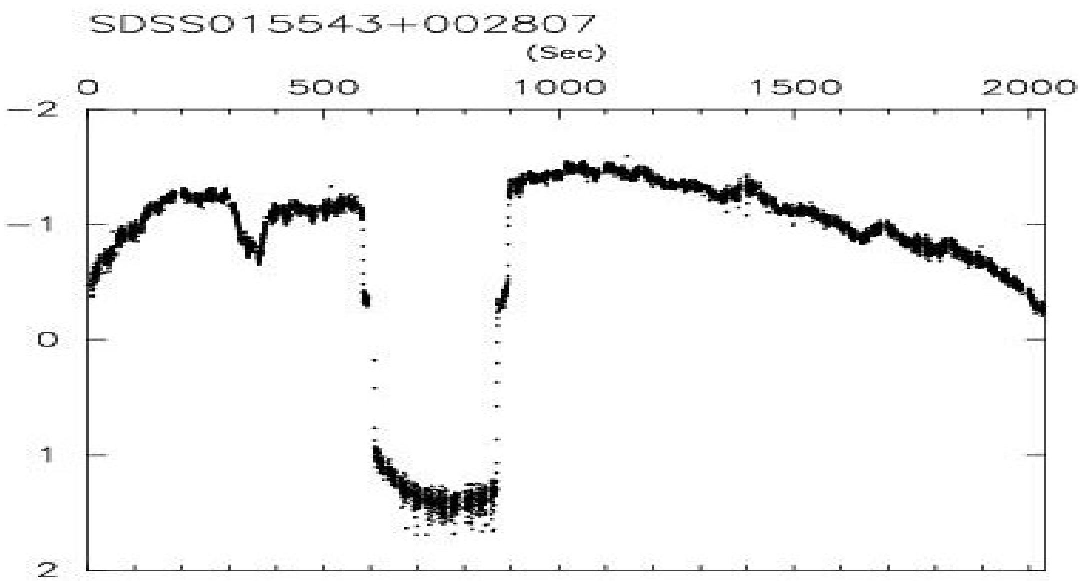
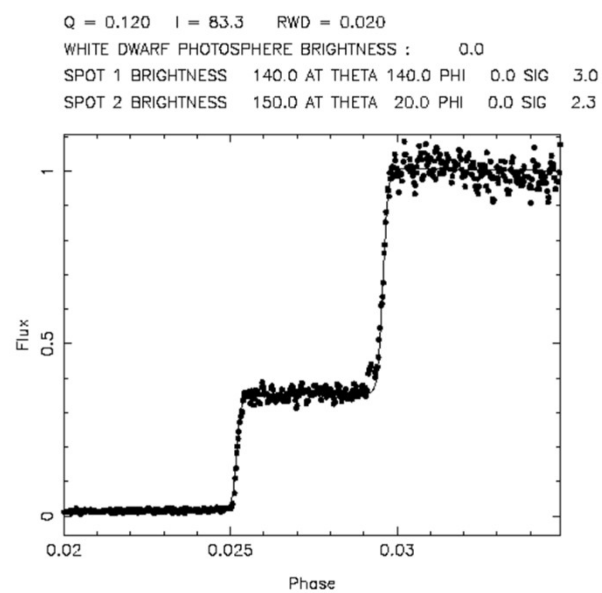


Fig. 8.3: An optical lightcurve of the AM Her star HU Aqr (*above*) and an illustration of the system approaching eclipse (*left*), corresponding to 1300 sec in the above plot.[4] At 1490 sec the tiny accretion spot is eclipsed, and the light drops dramatically. The bright stream enters eclipse over the next 130 sec. At the end of the eclipse the accretion spot suddenly emerges from behind the red dwarf (2075 sec), followed by the stream (2075–2300 sec). Earlier, at around 800 sec, the stream had been in front of the accretion spot, absorbing some of its light and causing a dip in the lightcurve.


White Dwarf
Spot 1
Ballistic Stream
M Dwarf


SDSS015543+002807
(Sec)
0
500
1000
1500
2000
−2
−1
0
1
2


Q = 0.120 I = 83.3 RWD = 0.020
WHITE DWARF PHOTOSPHERE BRIGHTNESS : 0.0
SPOT 1 BRIGHTNESS 140.0 AT THETA 140.0 PHI 0.0 SIG 3.0
SPOT 2 BRIGHTNESS 150.0 AT THETA 20.0 PHI 0.0 SIG 2.3
Flux
0
0.5
1
0.02
0.025
0.03
Phase

Finding New Polars from Optical Photometry

- Most polars are found by virtue of their X-ray emission
  - Many new discoveries followed from ROSAT
  - Good sensitivity to soft X-ray component

- Intermediate polars are also often discovered through X-ray emission
  - Important class of hard X-ray sources found from INTEGRAL

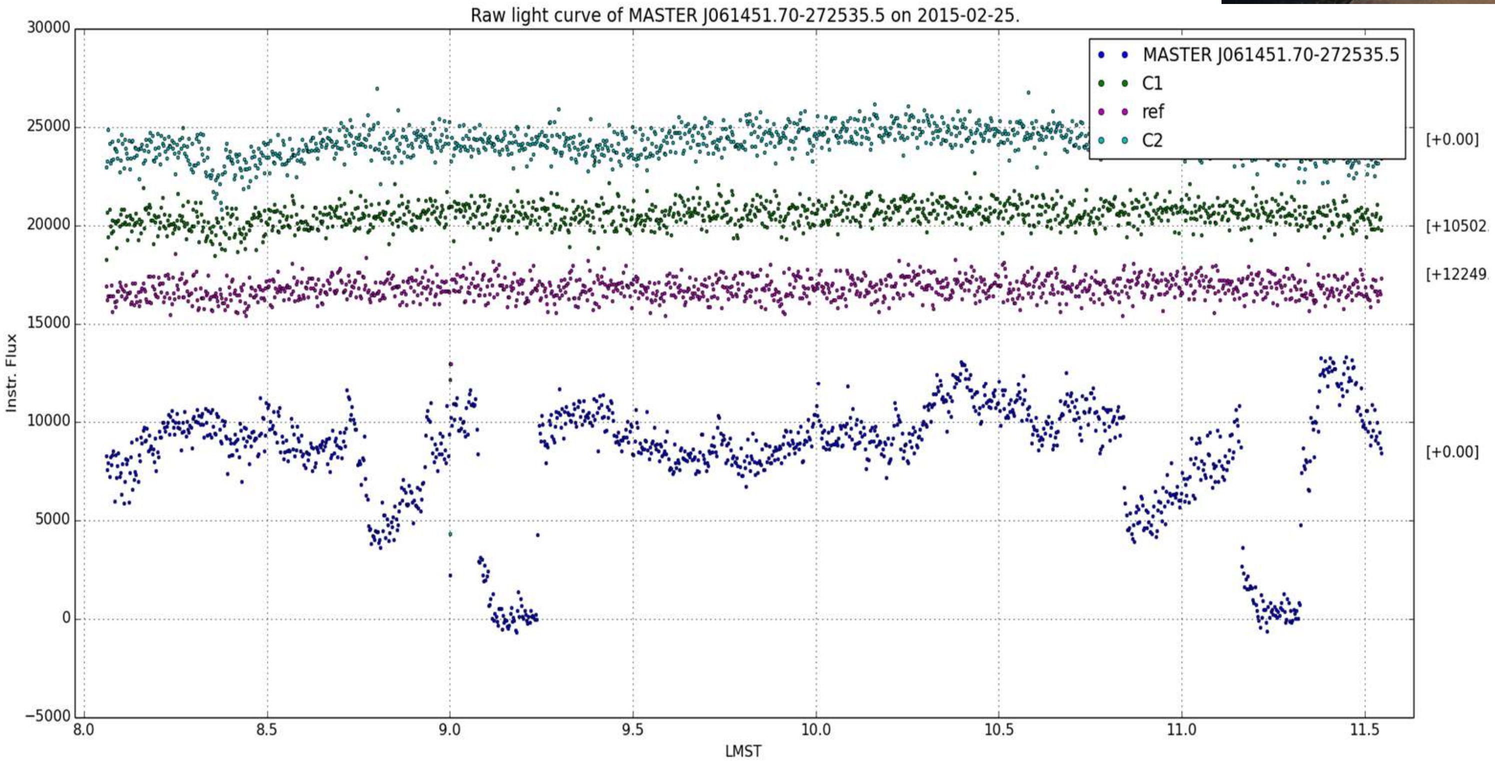
- Time resolved optical photometry can identify new mCV candidates
  - From surveys of transients/variable objects (e.g. MASTER, ASAS-SN, CRTS)
  - Look for tell-tale features
    - "bright phase/faint phase" orbital modulations (polars)
    - spin-modulated variations (intermediate polars)
    - sharp eclipse ingress/egress rather than gradual accretion disk eclipses
    - high/low accretion states from long time base photometry (~years)

Compact Binaries

MASTER OT J061451.70-272535.5: a new eclipsing polar

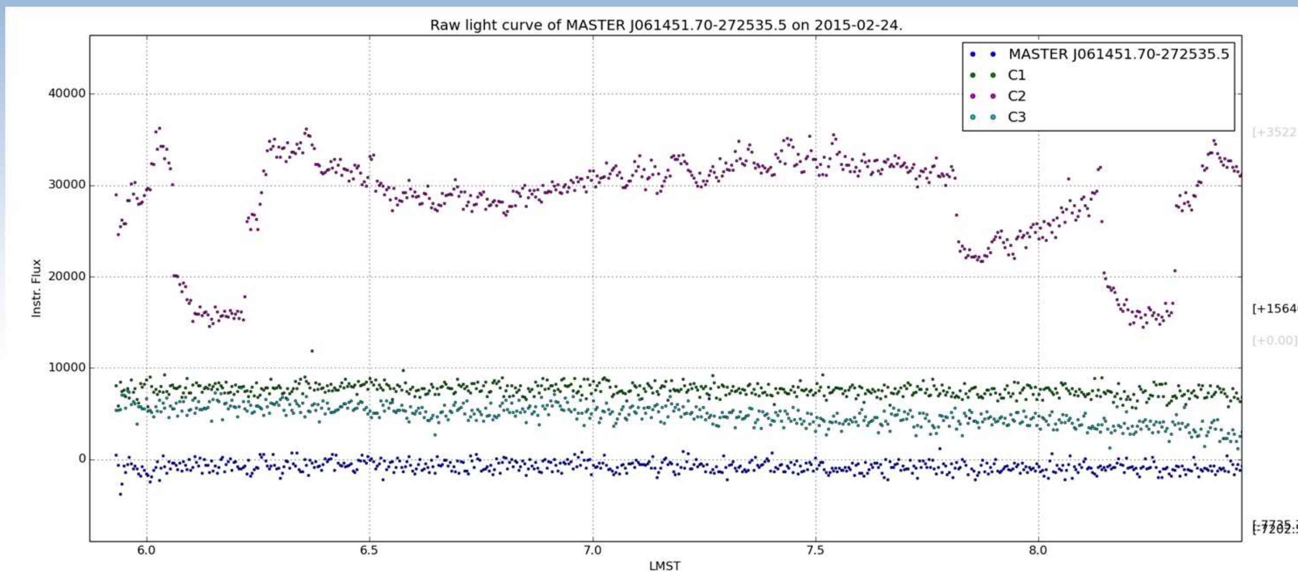
- Discovered as m = 18 transient from MASTER-SAAO
- Followed up photometrically
- Light curves show eclipses and stream obscuration, typical of Polar (e.g. HU Aqr)
- Orbital period = 2.1 h

(Breytenbach et al. 2018)



Compact Binaries

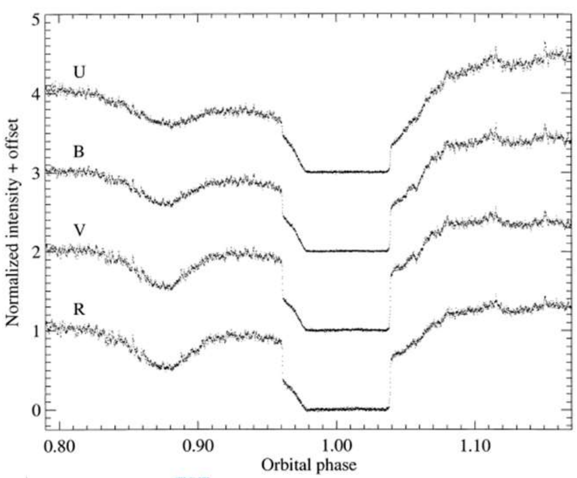
MASTER OT J061451.70-272535.5

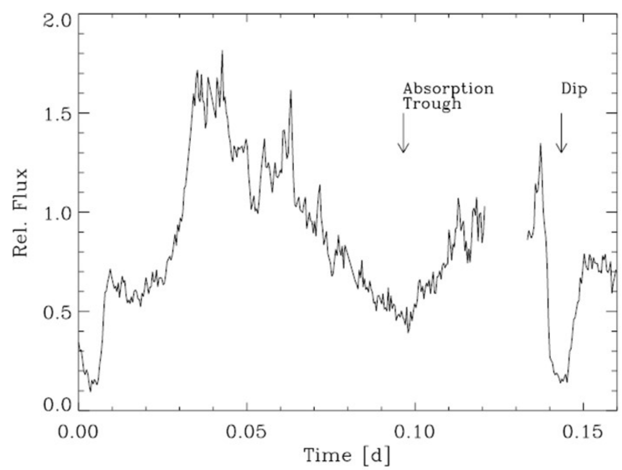


Pre-eclipse dips caused by stream obscuration of hot-spot.

As in HU Aqr (Harrop-Allin et al. 1999).

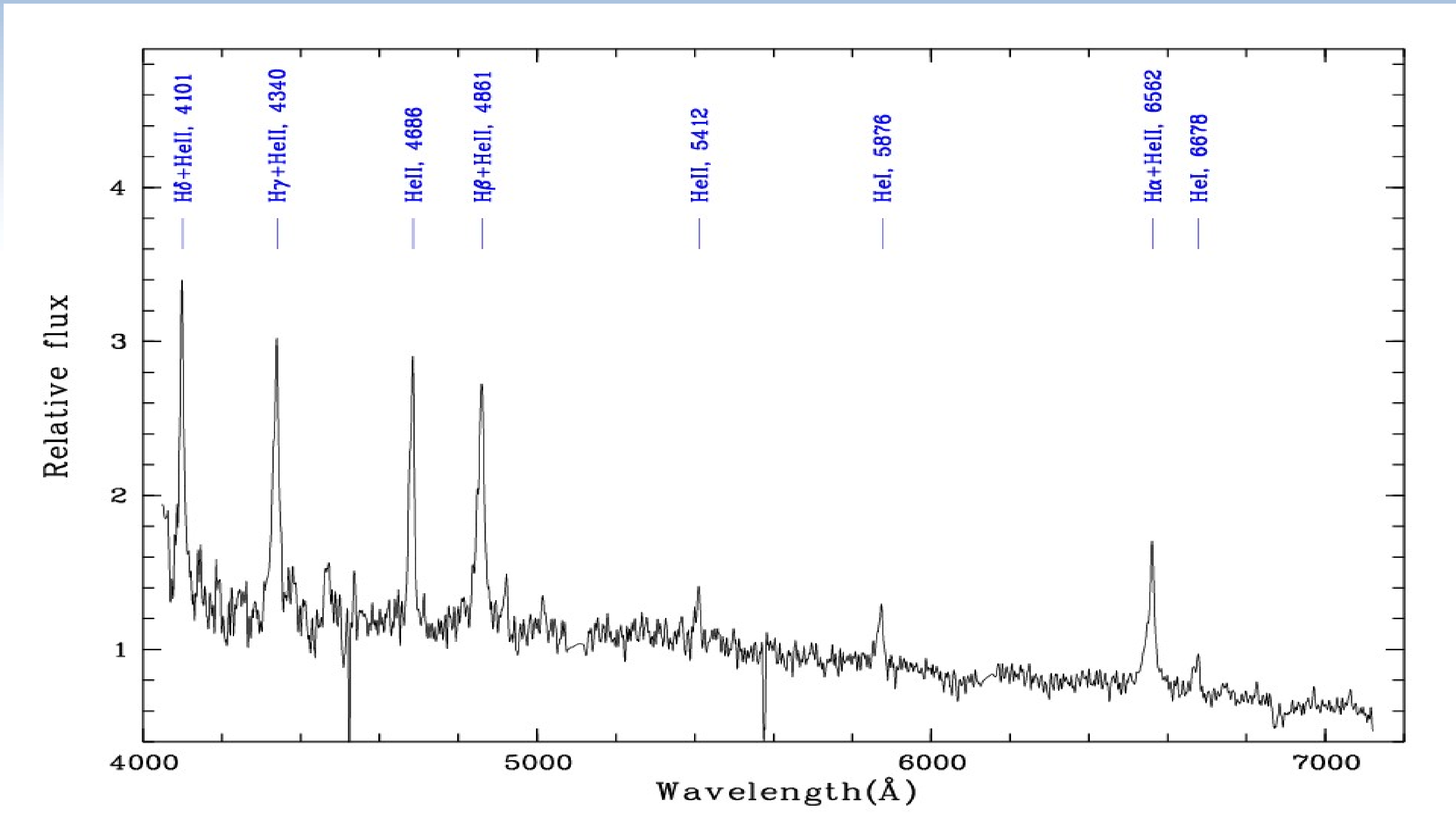
Possibly also in asynchronous polar V1432 Aql (Watson et al. 1995, Staubert et al. 2003)?





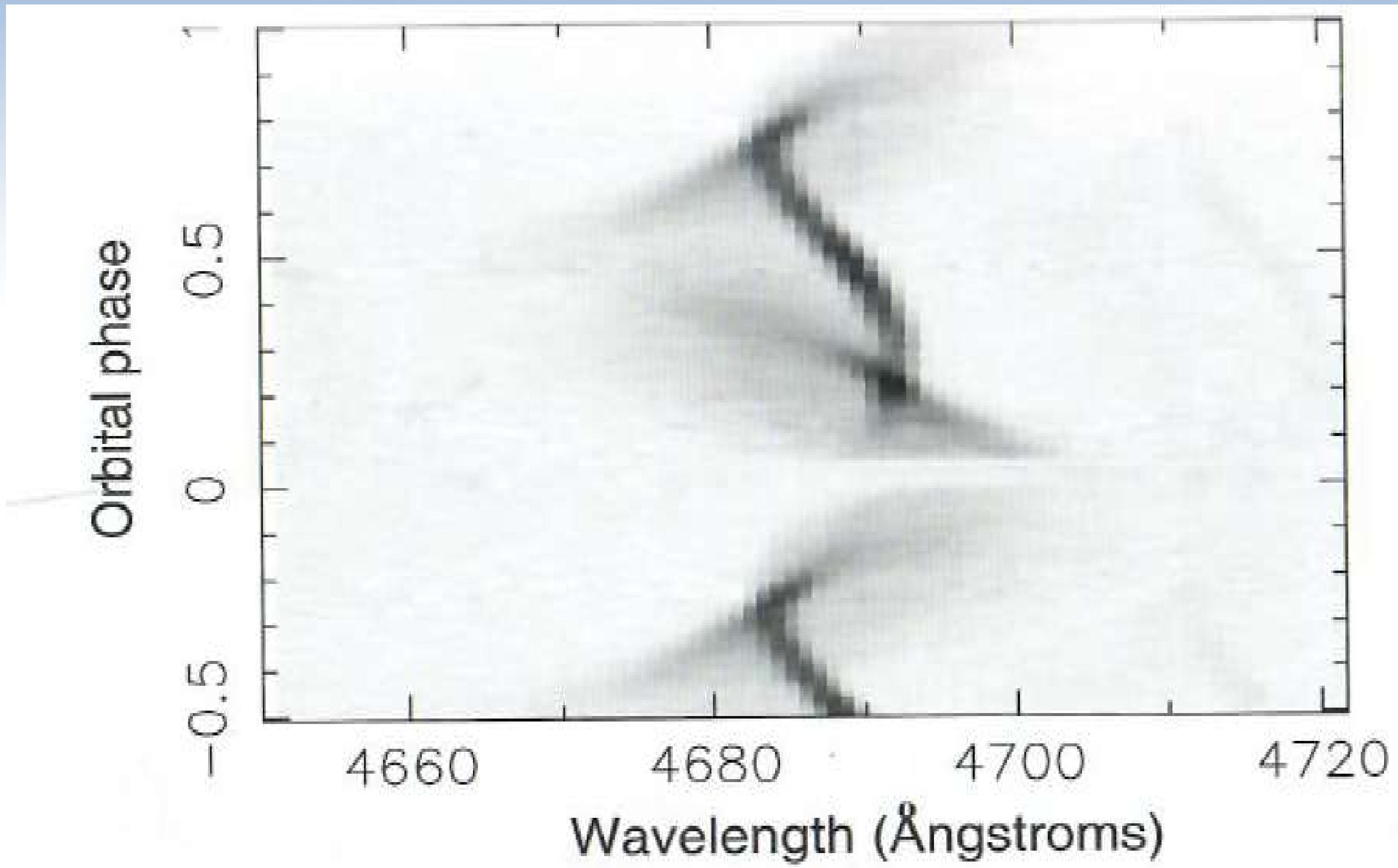
MASTER OT J061451.70-272535.5

- SALT observation confirms mCV spectrum (strong HeII):



Polars: spectroscopy

- *Spectroscopy can probe stream flow, magnetic connection and irradiation*



Doppler Tomography

- What does it do?
  - Maps spectral line information to emission regions in binary frame
- Doppler tomography of polars
  - Standard projection (Marsh & Horne 1988)
  - Inside-out projection (Kotze et al. 2015, 2016)
- Examples:
  - CTCV J1928-5001
  - HU Aqr
  - V834 Cen
- SALT/SAAO observations
  - Long-slit spectroscopy with the Robert Stobie Spectrograph
- Standard and inside-out Doppler tomography

Doppler Tomography

- Takes radial velocity information and maps the emission to a Doppler “map”
- Used on any system with a periodic changing emission line position
  - Orbital
  - Spin

- Used for disk accreting CVs to probe accretion disk
- Used on magnetic CVs to probe interaction of stream with the magnetic field
- Psuedo free-fall velocities of stream are “stopped” by magnetic field and redirected along field lines

Doppler Tomography

- An accretion disk velocity profile (Chapter 3 Hellier)

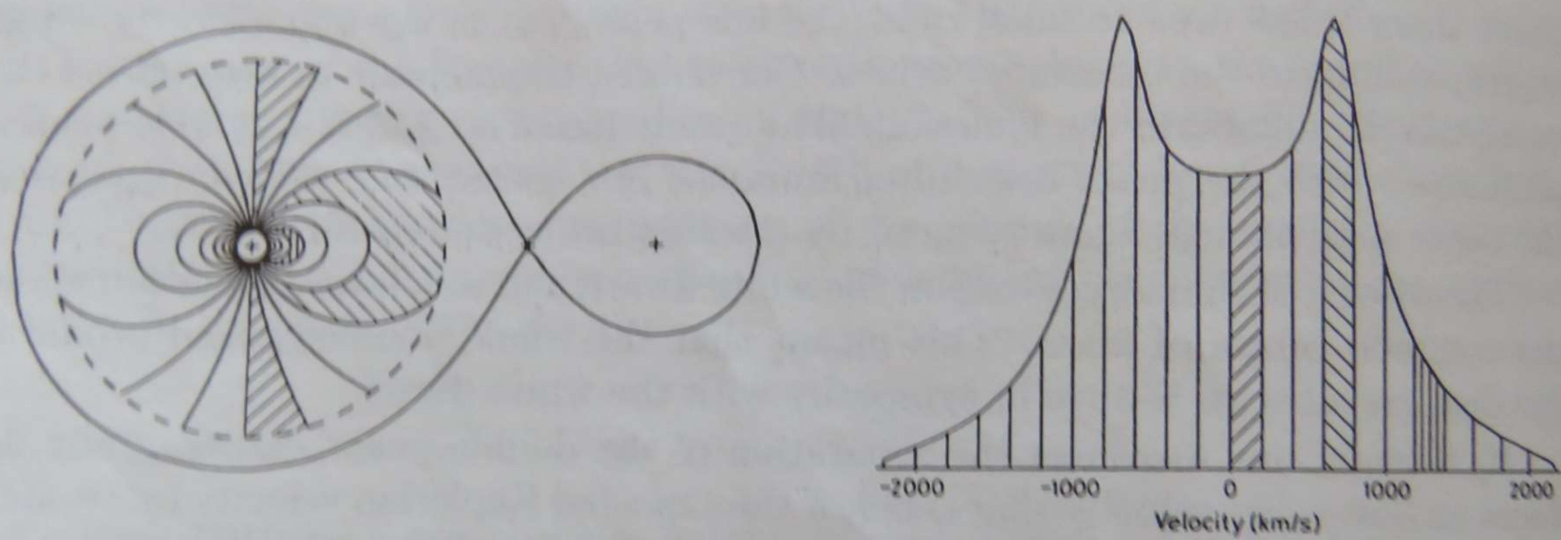
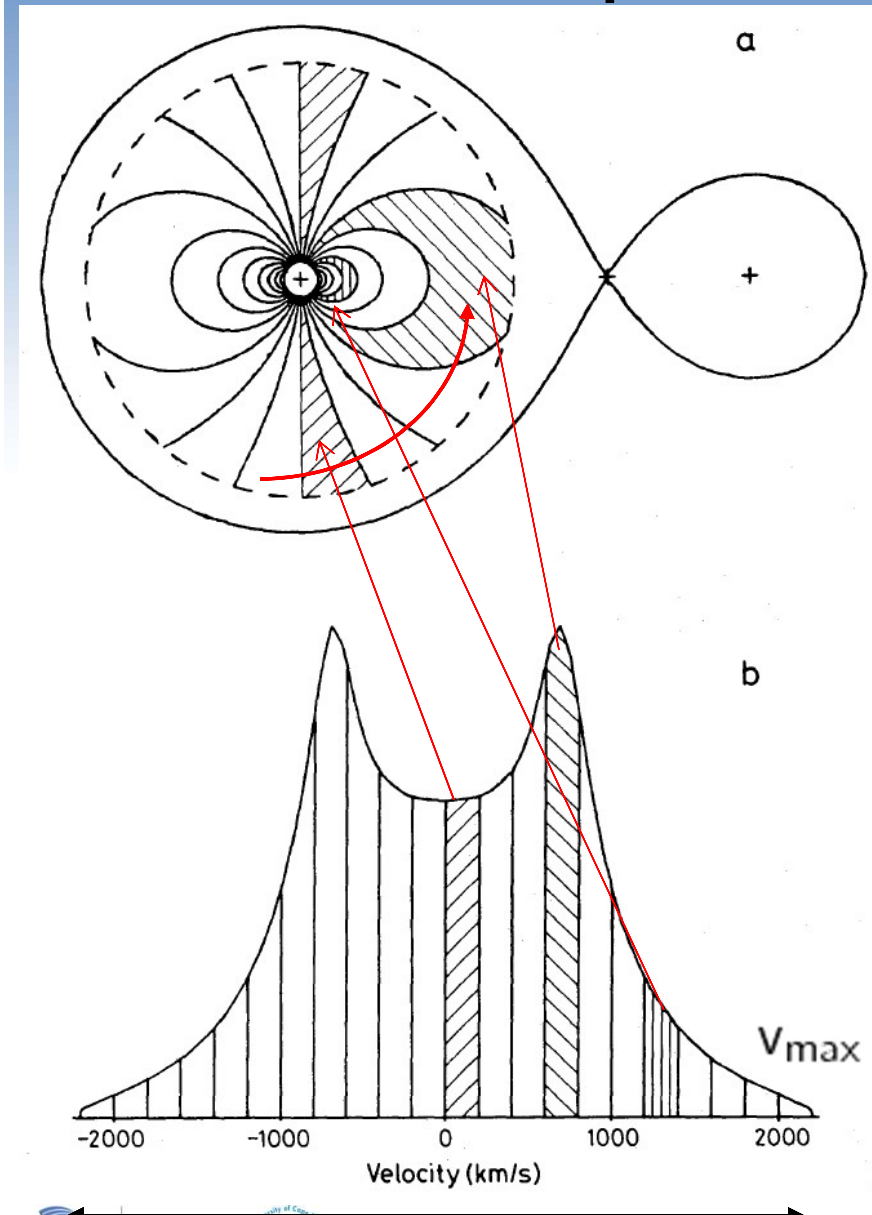
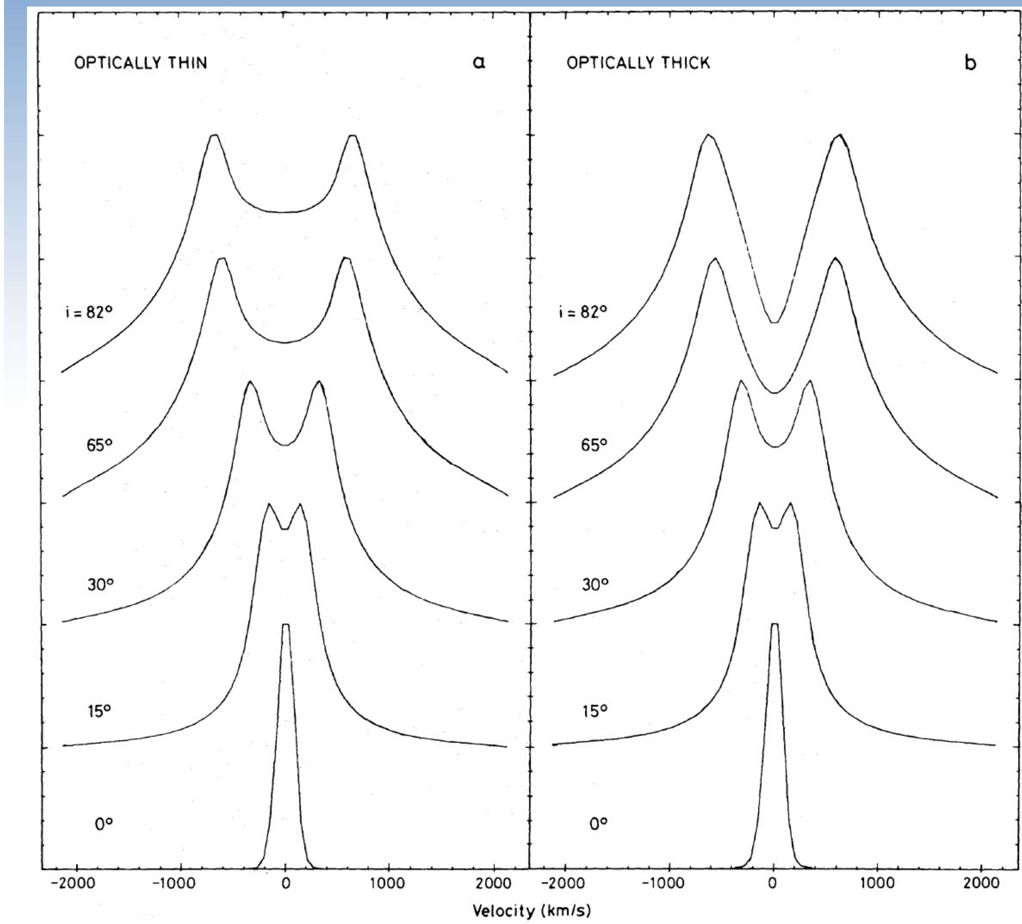


Fig. 3.9: *Left:* A Keplerian disc with contours of the different velocities as projected onto the line of sight (the viewer is below the plot). *Right:* The resulting double-peaked profile. The different shadings match corresponding regions in the two plots. (Figures by Keith Horne and Tom Marsh.[10])

Line profiles from accretion discs



FWZI



$$\sin i \, v_{max} = \sqrt{\frac{GM_*}{R_*}}$$

Doppler Tomography

- An accretion disk velocity profile (Chapter 3 Hellier)

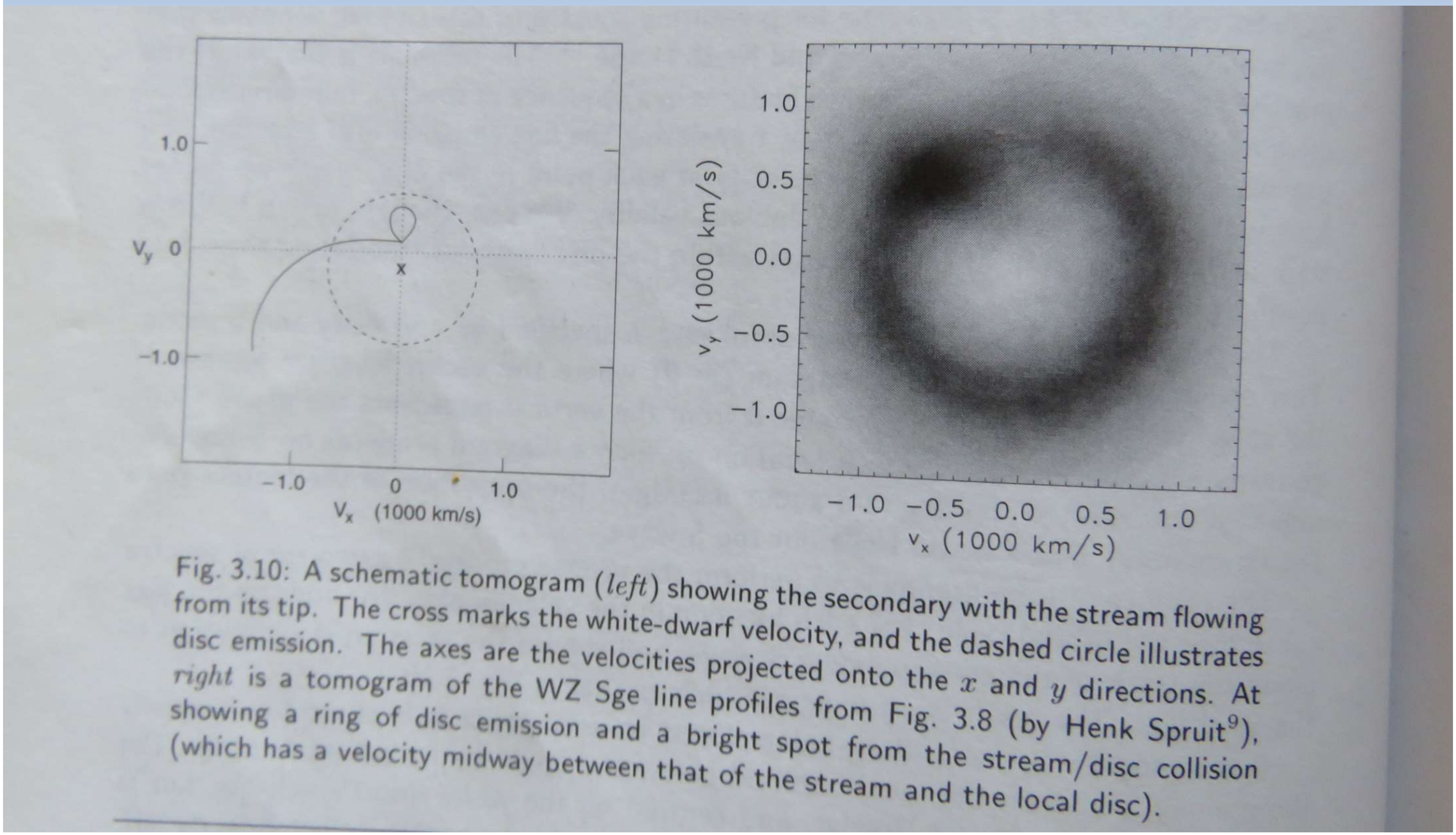
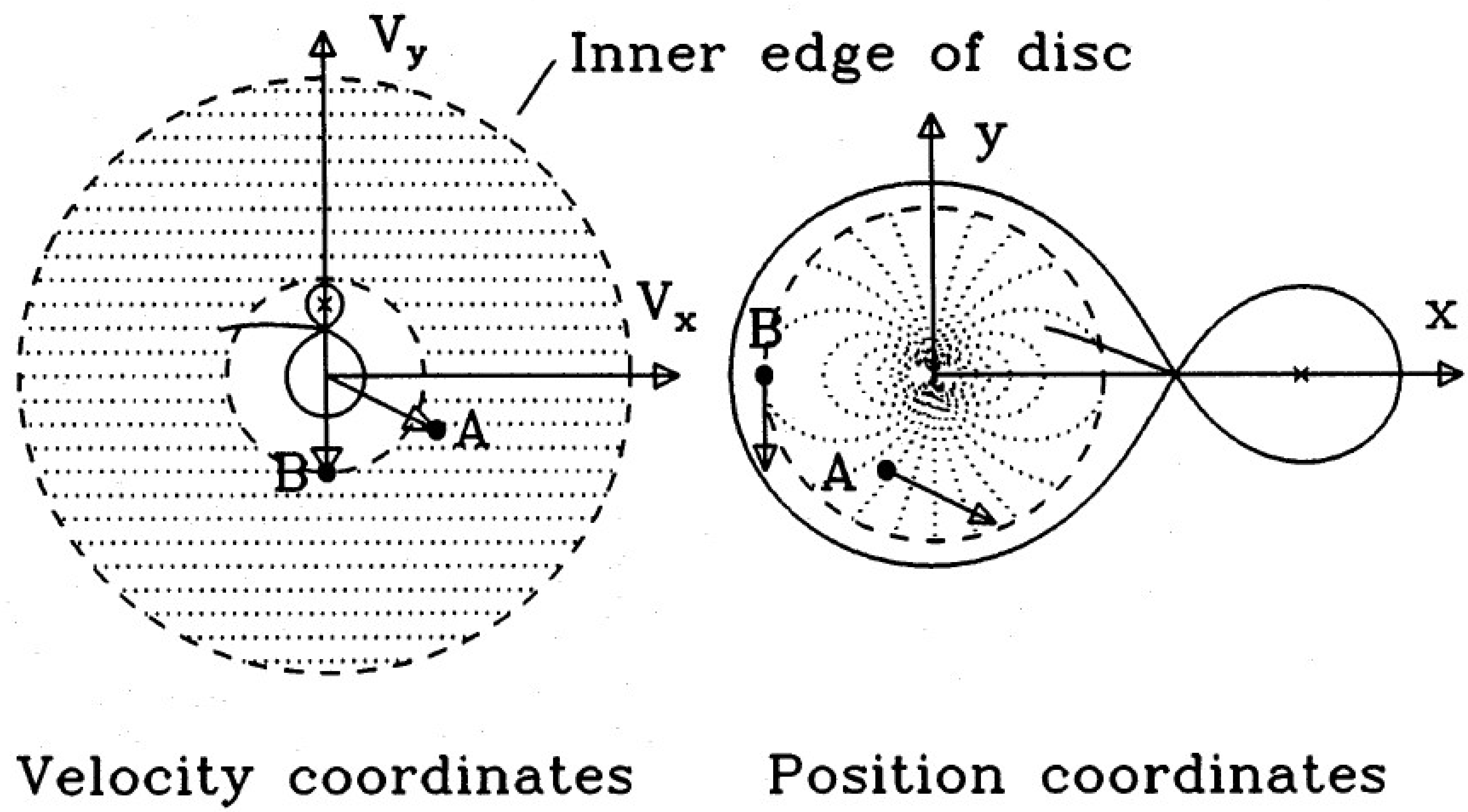
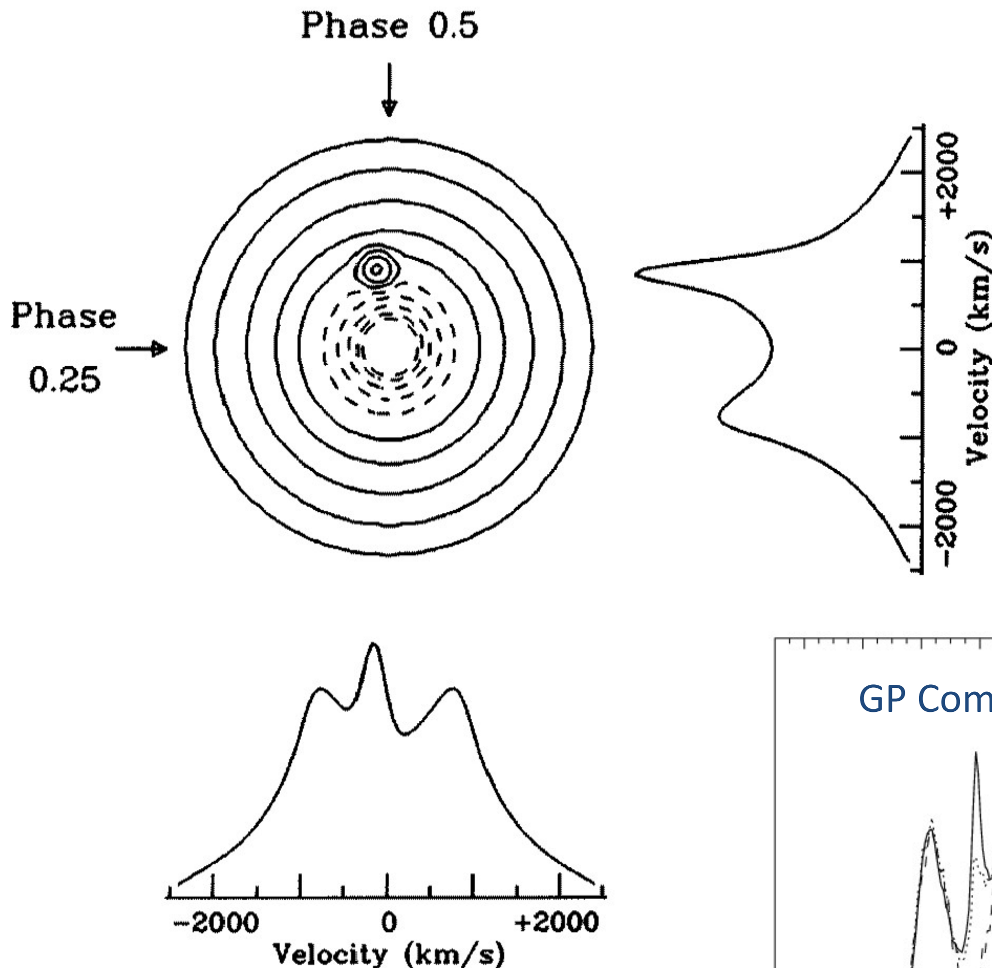


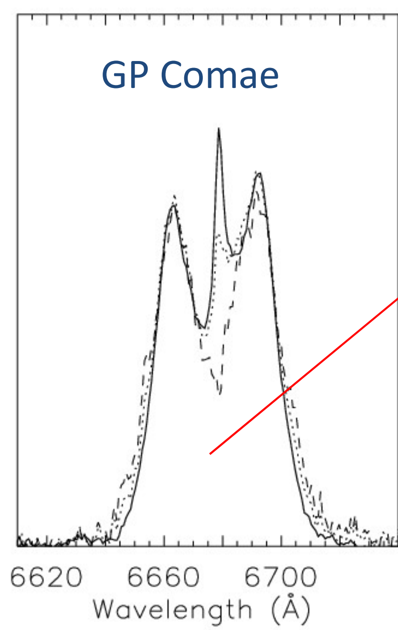
Fig. 3.10: A schematic tomogram (*left*) showing the secondary with the stream flowing from its tip. The cross marks the white-dwarf velocity, and the dashed circle illustrates disc emission. The axes are the velocities projected onto the x and y directions. At *right* is a tomogram of the WZ Sge line profiles from Fig. 3.8 (by Henk Spruit[9]), showing a ring of disc emission and a bright spot from the stream/disc collision (which has a velocity midway between that of the stream and the local disc).

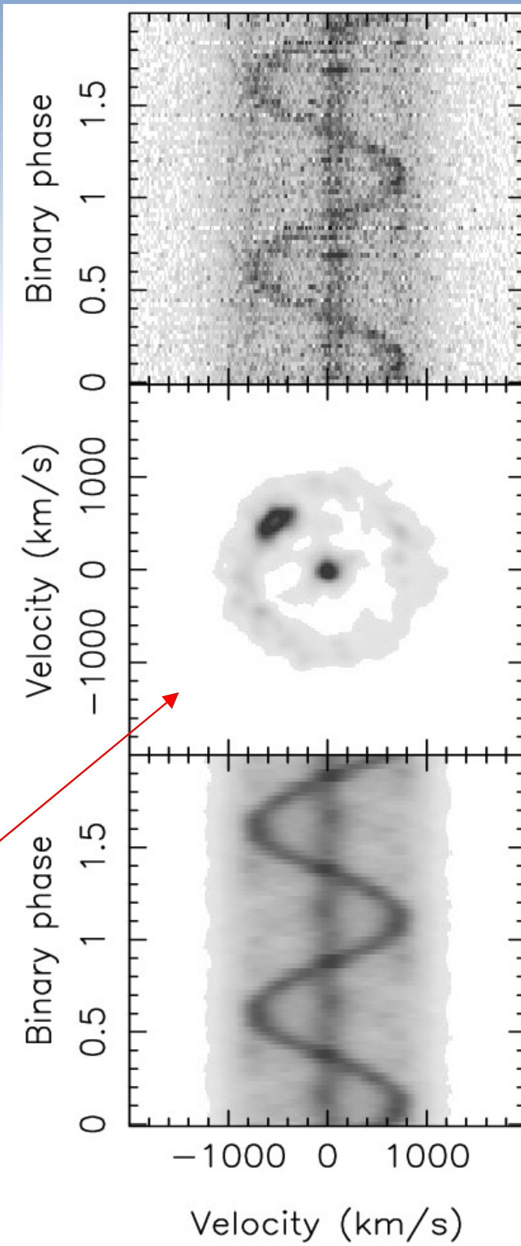
Doppler imaging: an image in velocity space



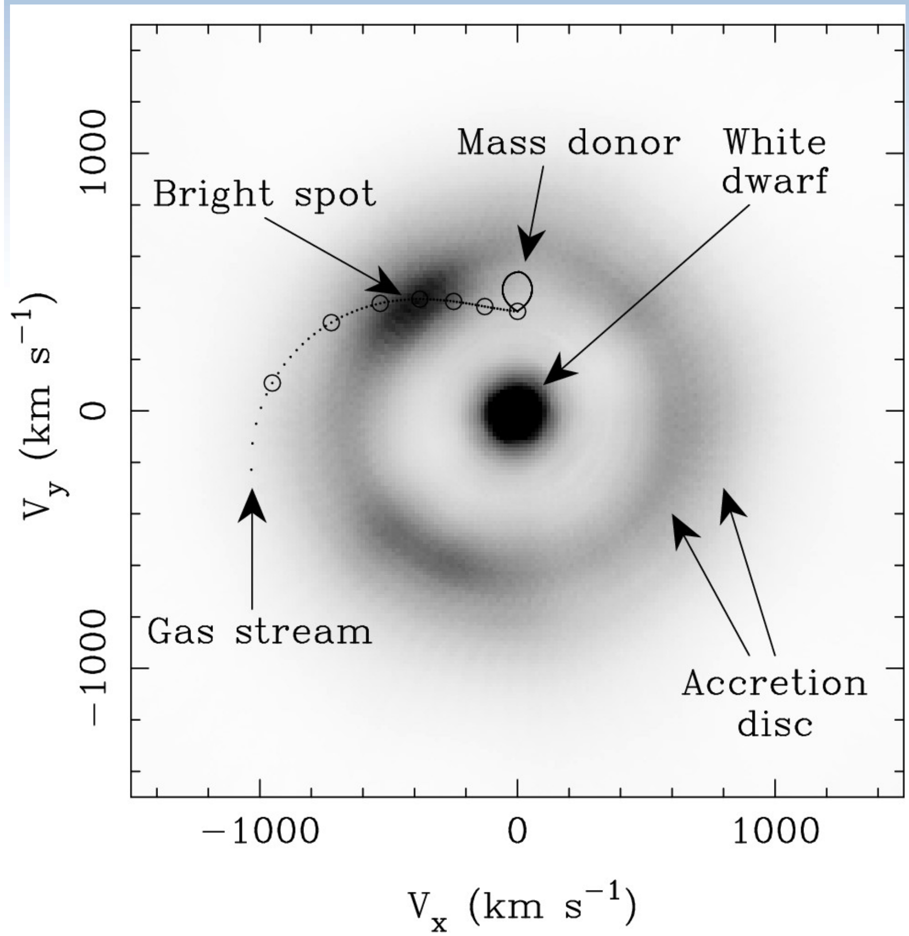
“point sources” in Doppler maps

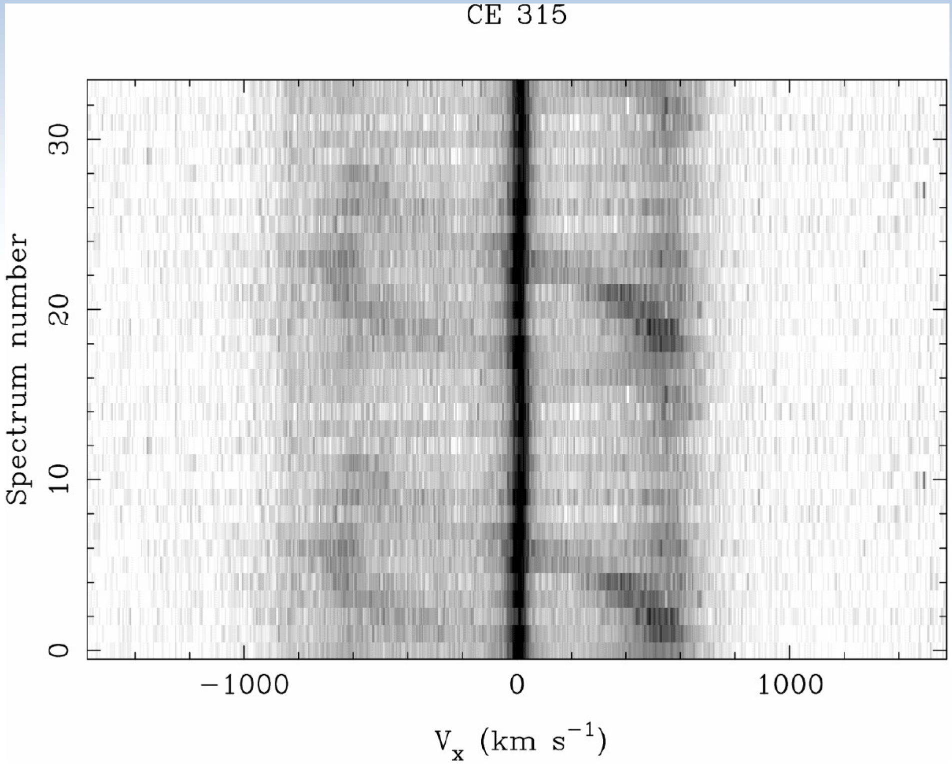




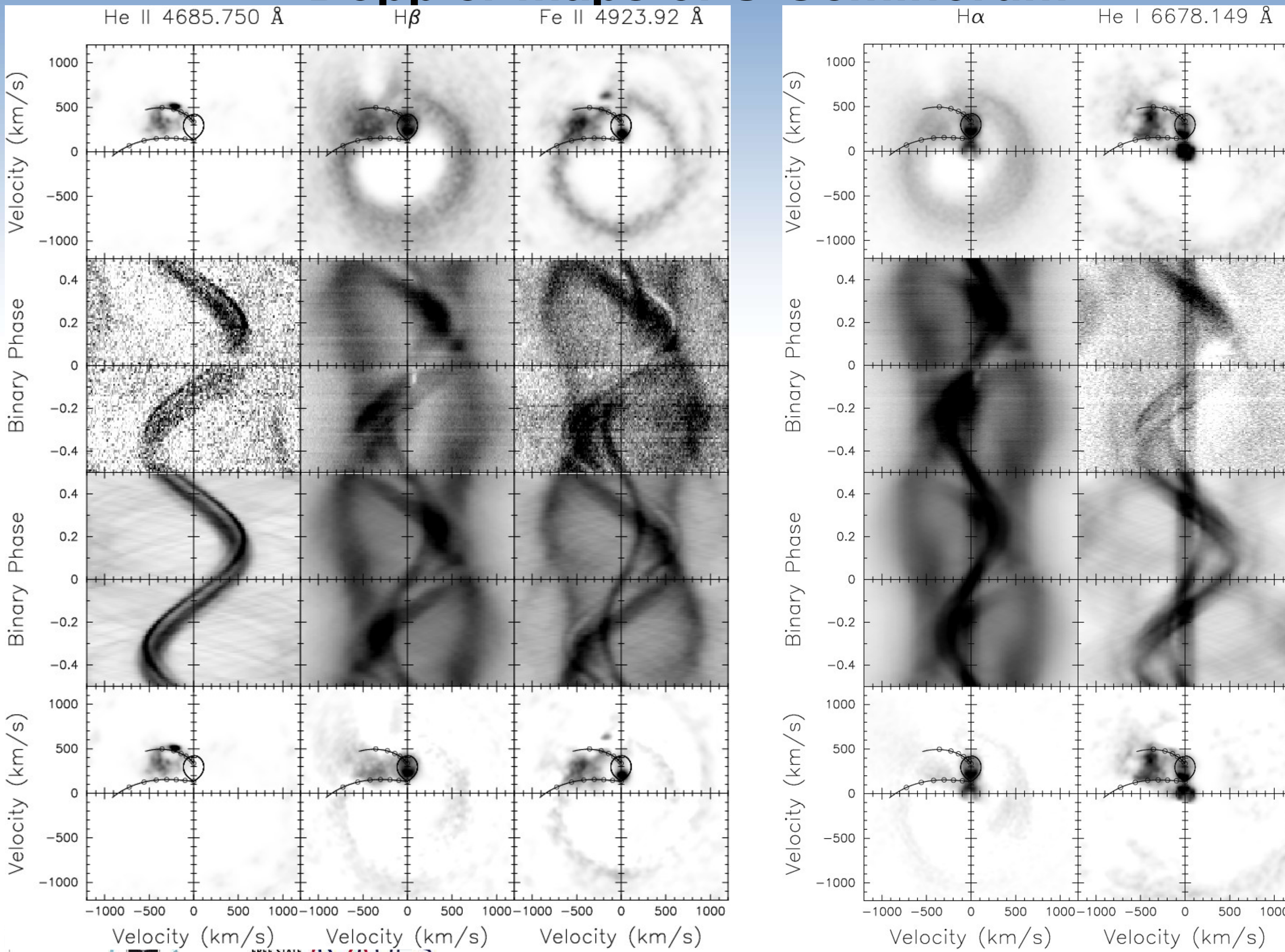


The components of a binary star in velocity space

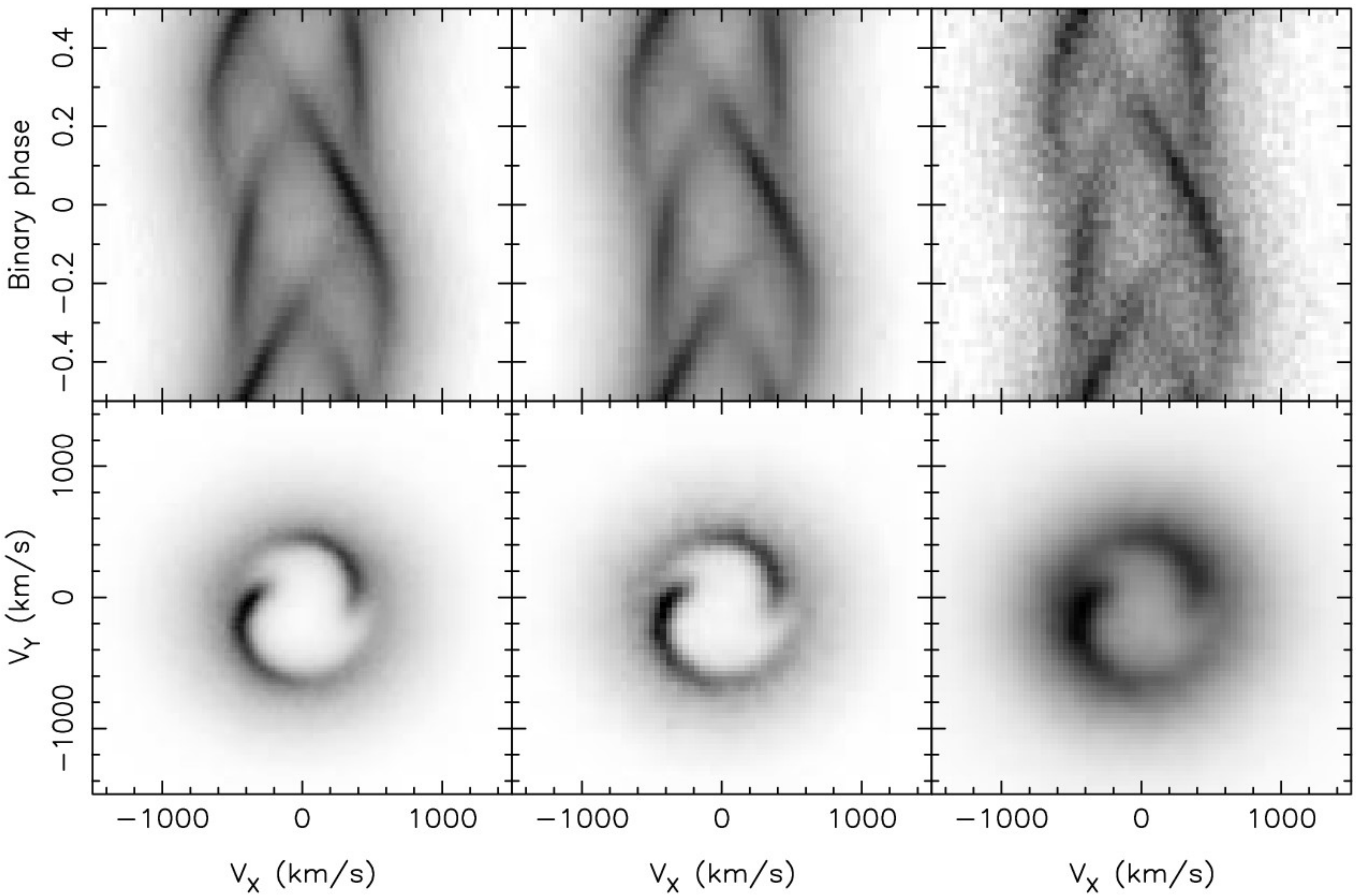




Doppler maps of U Geminorum

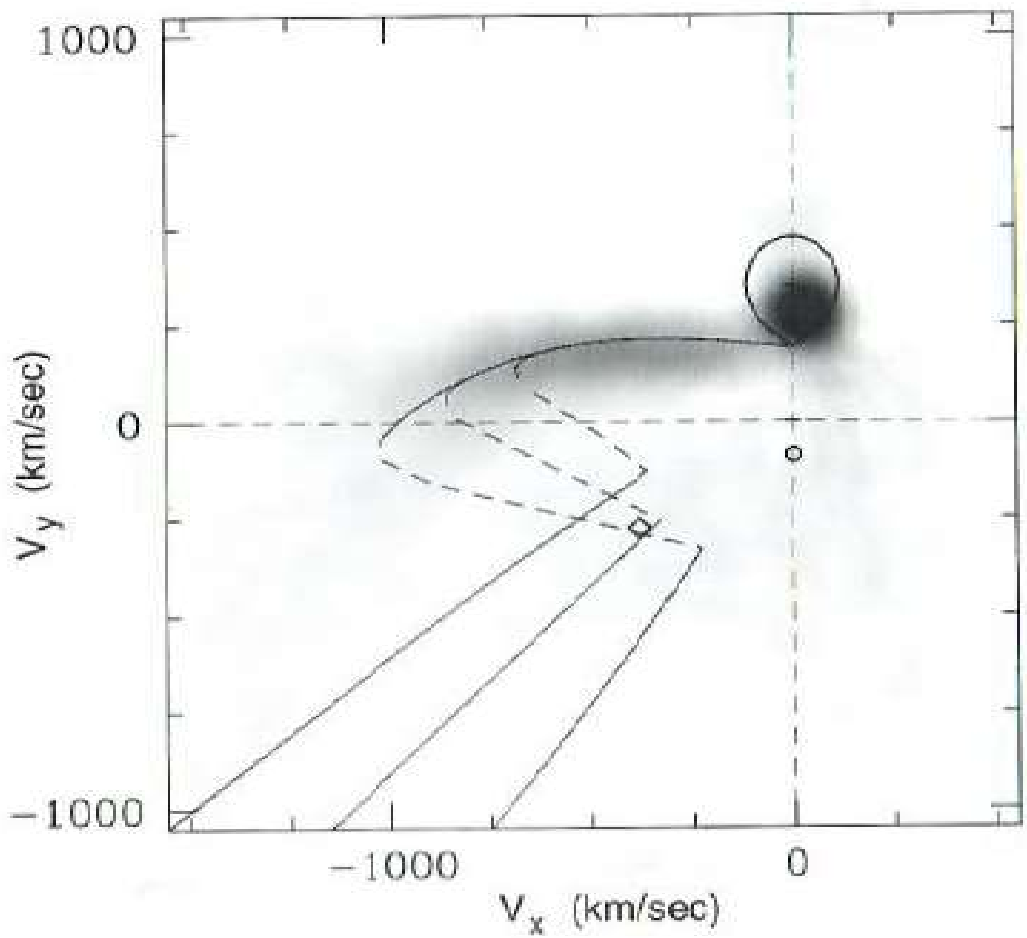


Simulations: spiral shocks in the discs of binary stars



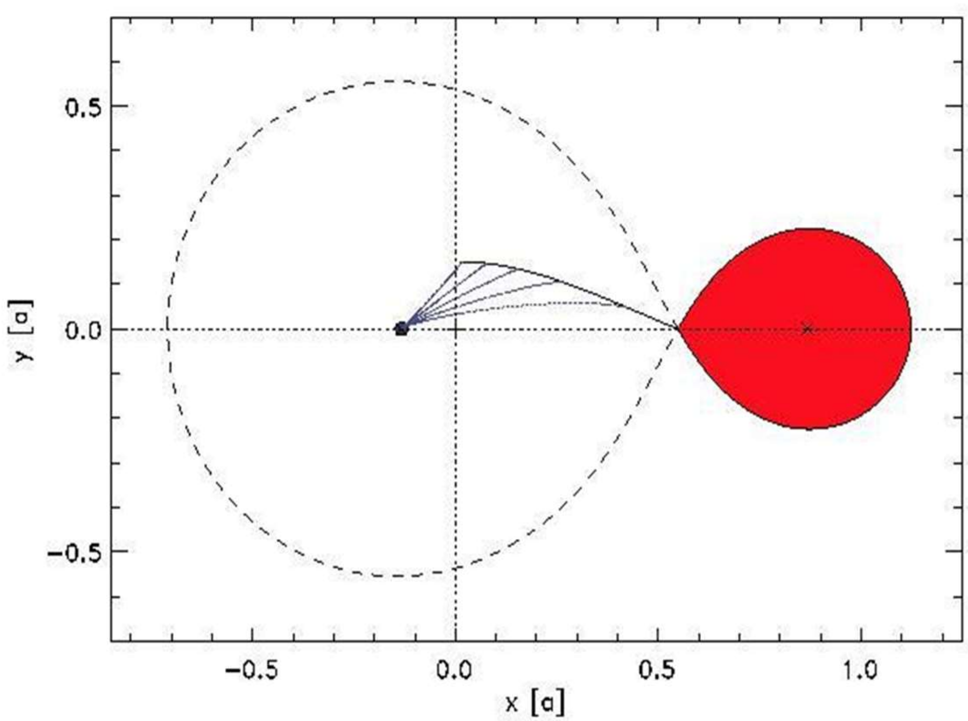
Polars

- *Doppler tomogram*



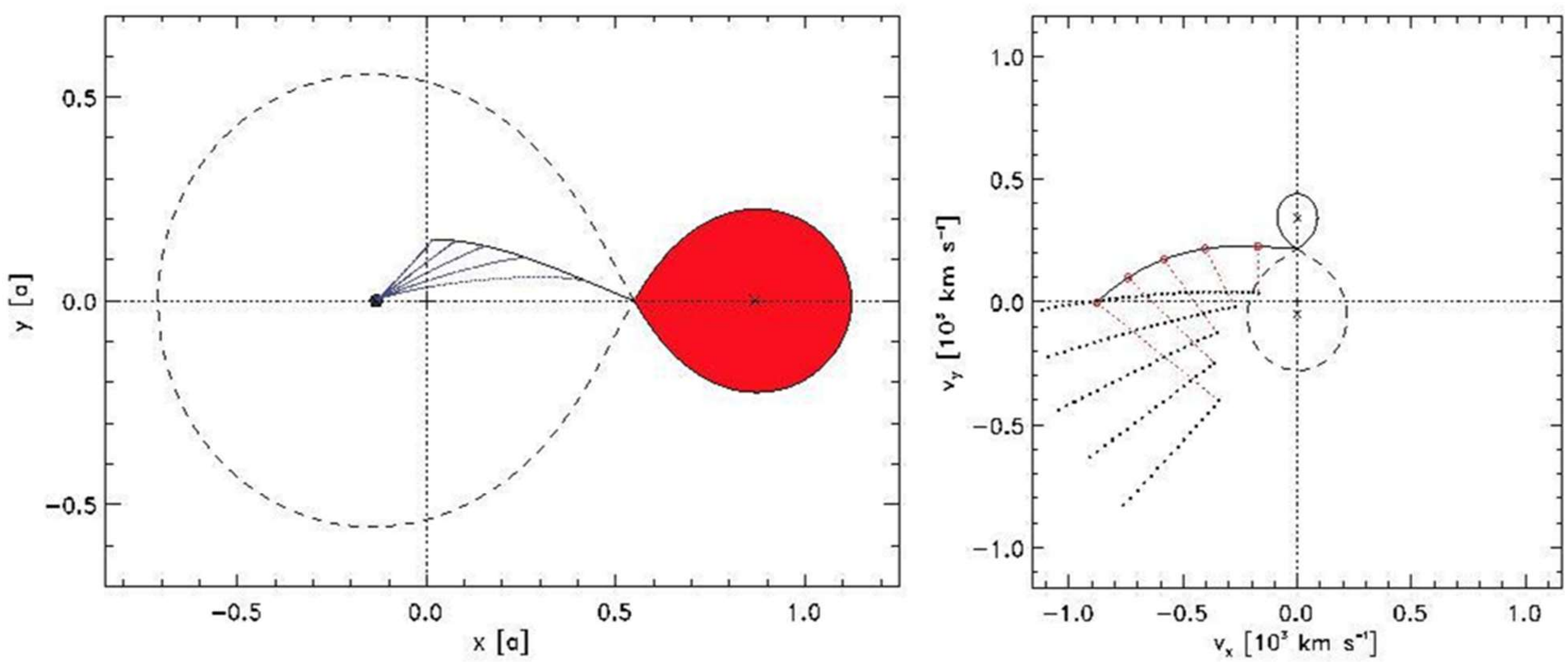
Doppler tomography of polars

- Construct a spatial model of a polar based on the known (or assumed) system parameters



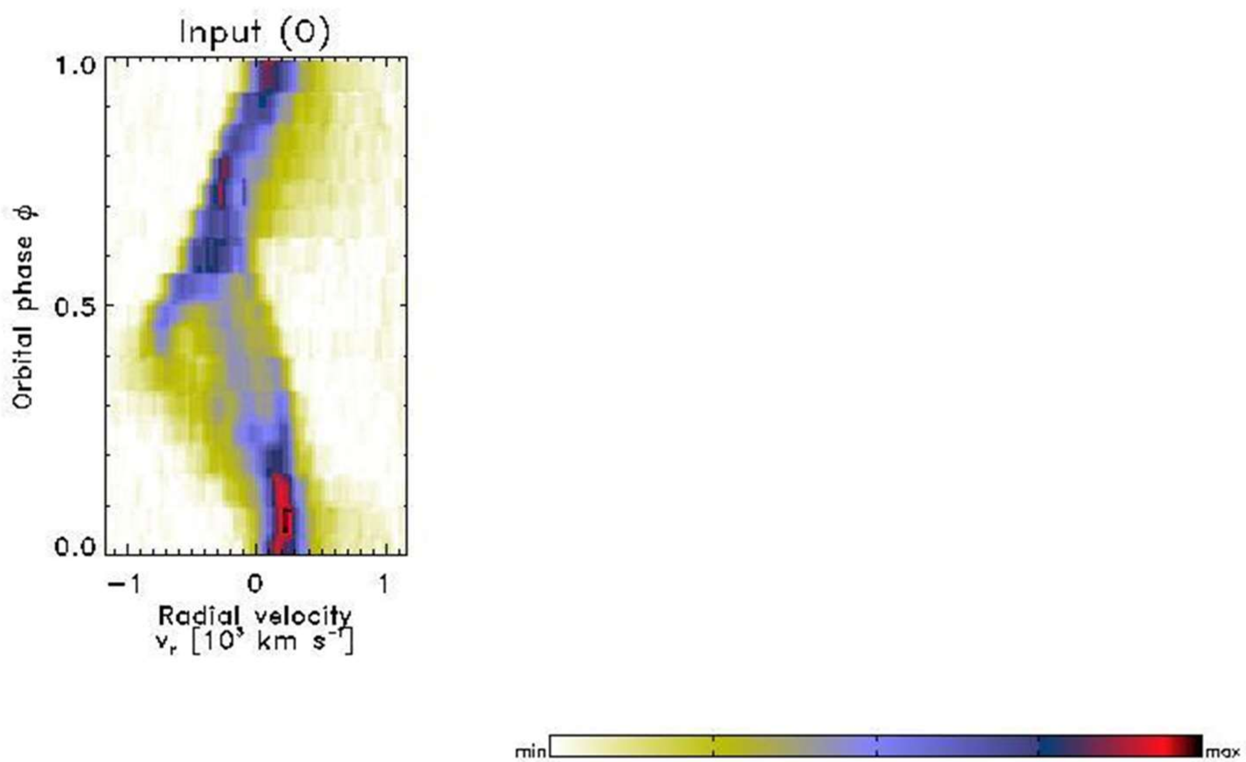
Doppler tomography of polars

- From the spatial model determine the corresponding model velocity profile taking into account the inclination of the system



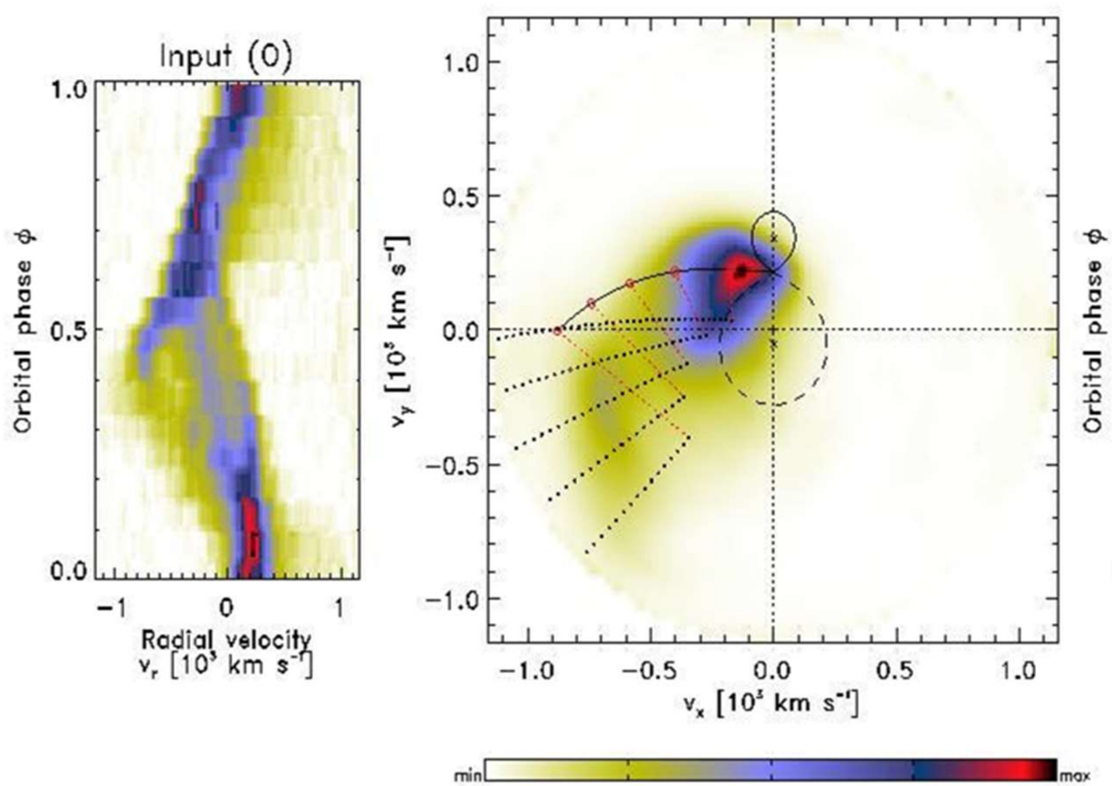
Doppler tomography of polars

- Doppler tomography uses phase-resolved spectra to construct a 2D image in velocity coordinates of the emission distribution in an interacting binary
- Example CTCV J1928-5001



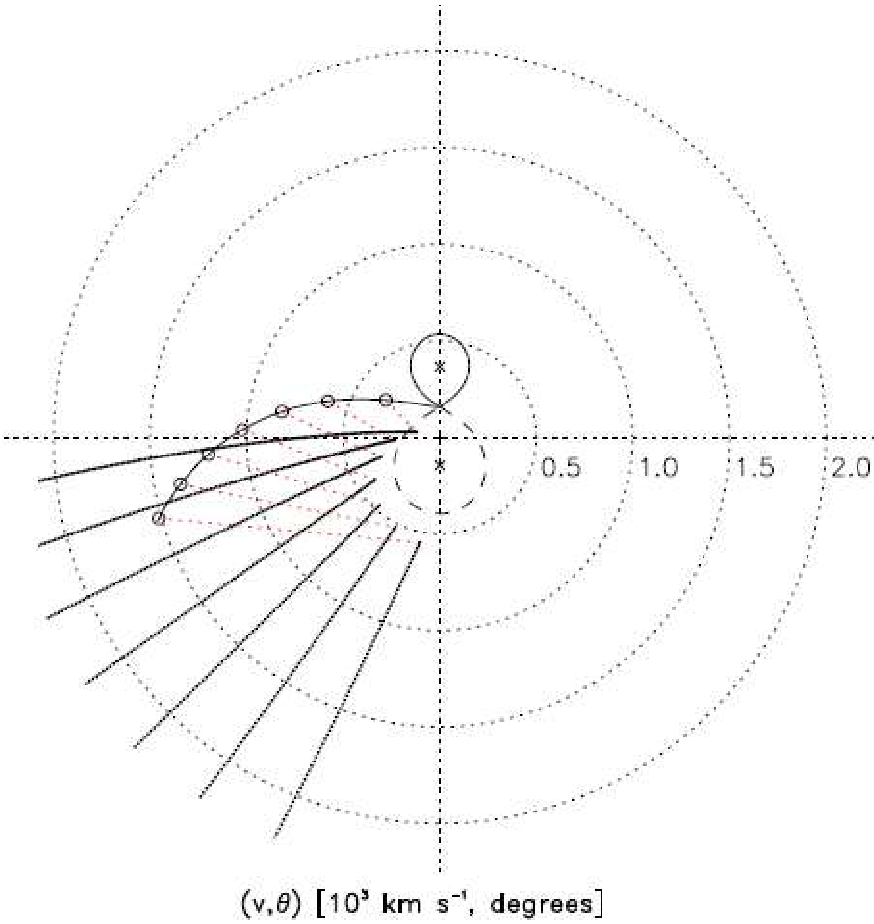
Doppler tomography of polars

- Compare the model velocity profile on the Doppler tomogram to aid the interpretation of the emission distribution
- CTCV J1928-5001

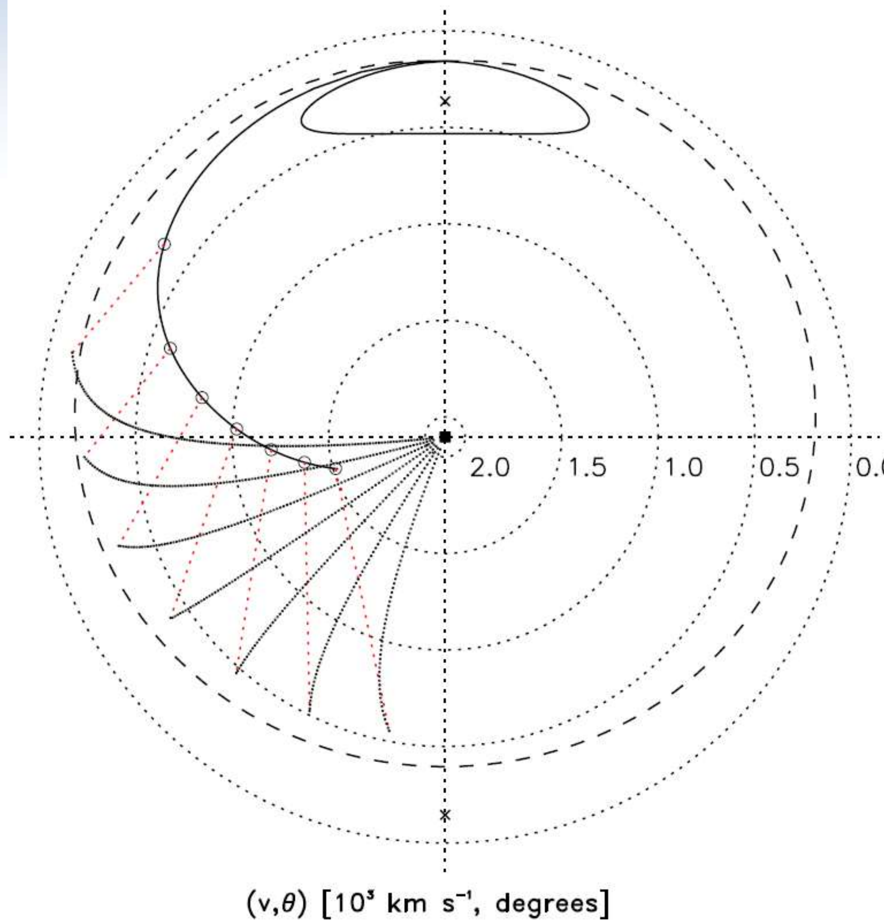


Tomograms

Standard velocity space



Inside-out velocity space

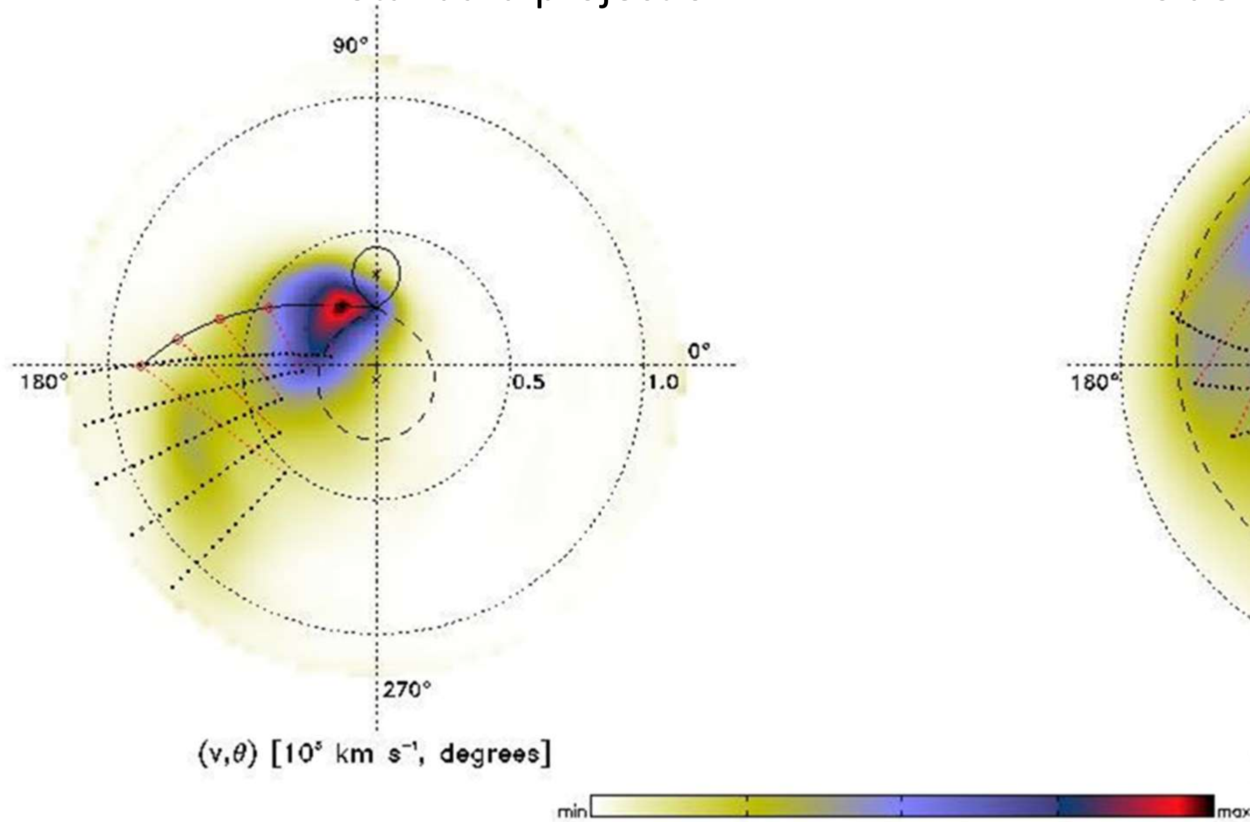


Doppler tomography of polars

- Doppler tomograms
- CTCV J1928-5001

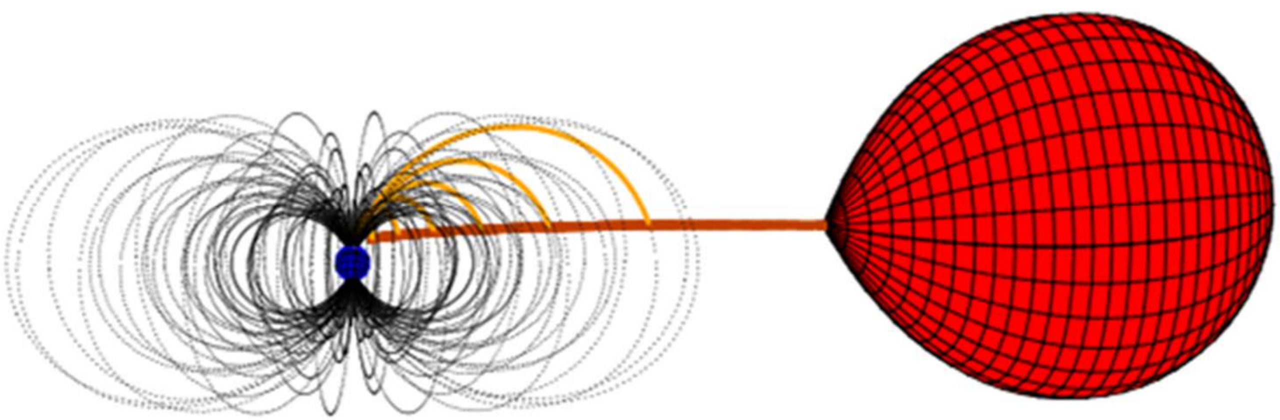
Standard projection

Inside-out projection



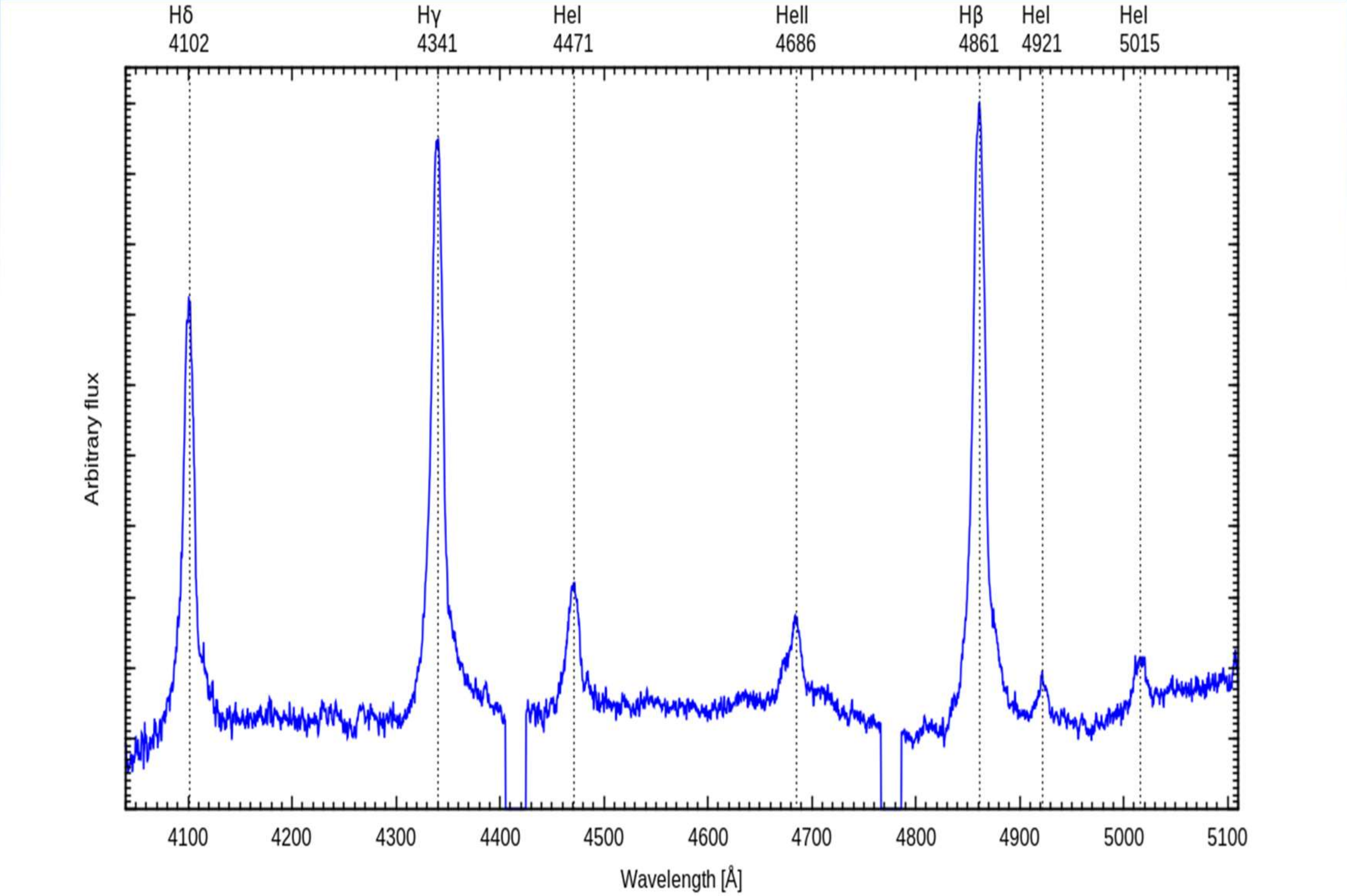
Example 1: CTCV J1928-5001: an eclipsing polar

- Identified as a polar candidate by Tappert et al. (2004) in the Calán-Tololo Survey
- Confirmed as a polar by Potter et al. (2005) with high time-resolved photo-polarimetry
- System parameters
  - Inclination i = 78°
  - Orbital period P_{orb} = 0.070162312 d (~101 min)
  - Primary mass M_1 = 0.5 $M_{\odot}$, mass ratio $q = M_2 / M_1$ = 0.2
  - Primary magnetic axis: azimuth = 72°, co-latitude = 15°



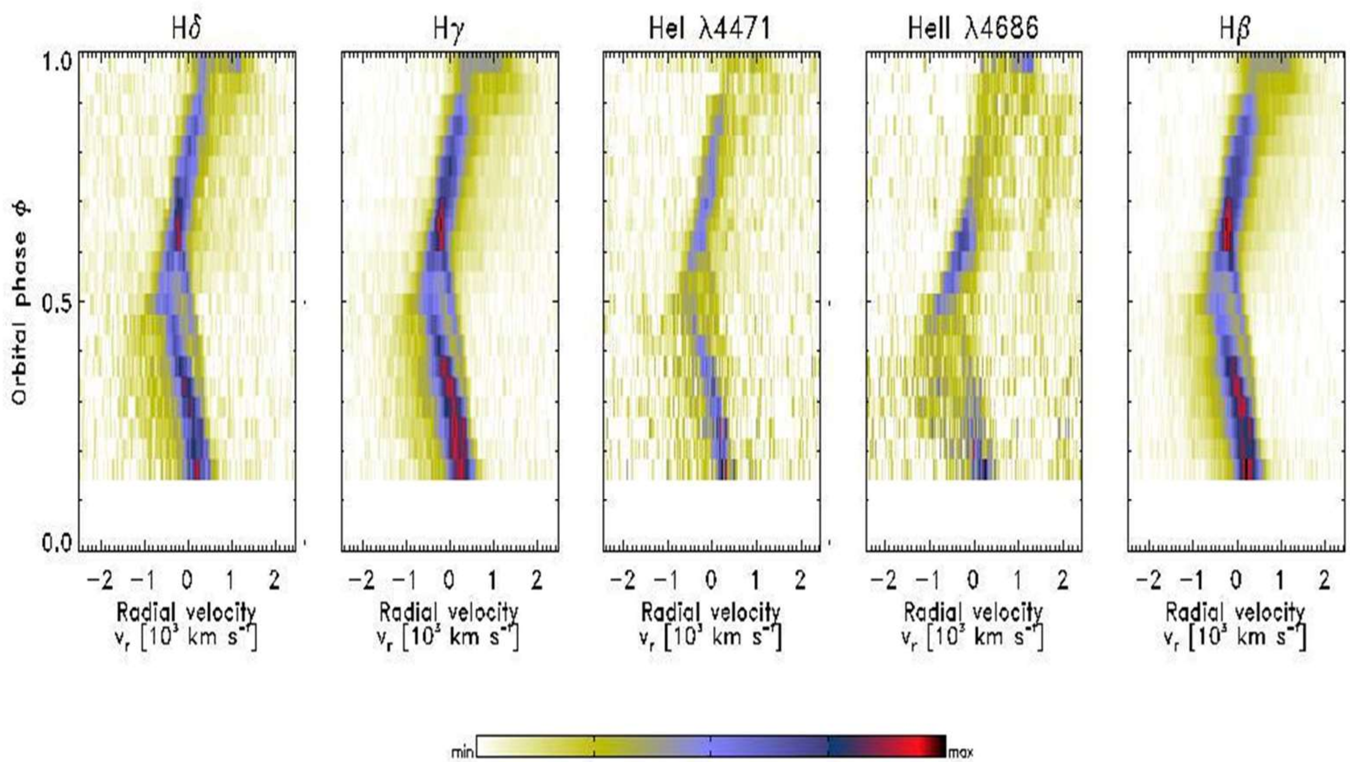
SALT observations

- Mean orbital spectrum



SALT observations

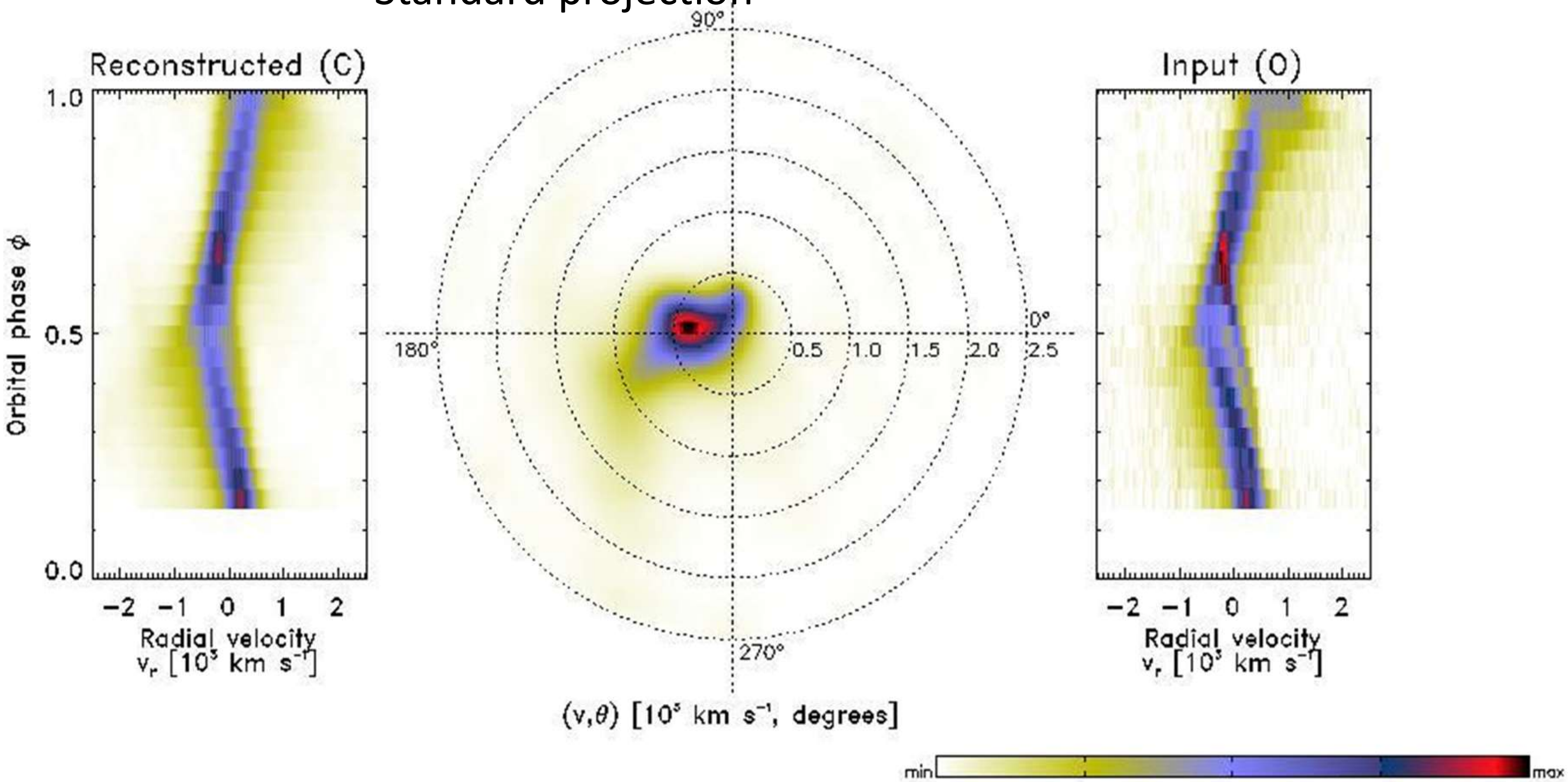
- Trailed spectra of prominent emission lines



Standard and inside-out Doppler tomography

- Hβ emission line

Standard projection

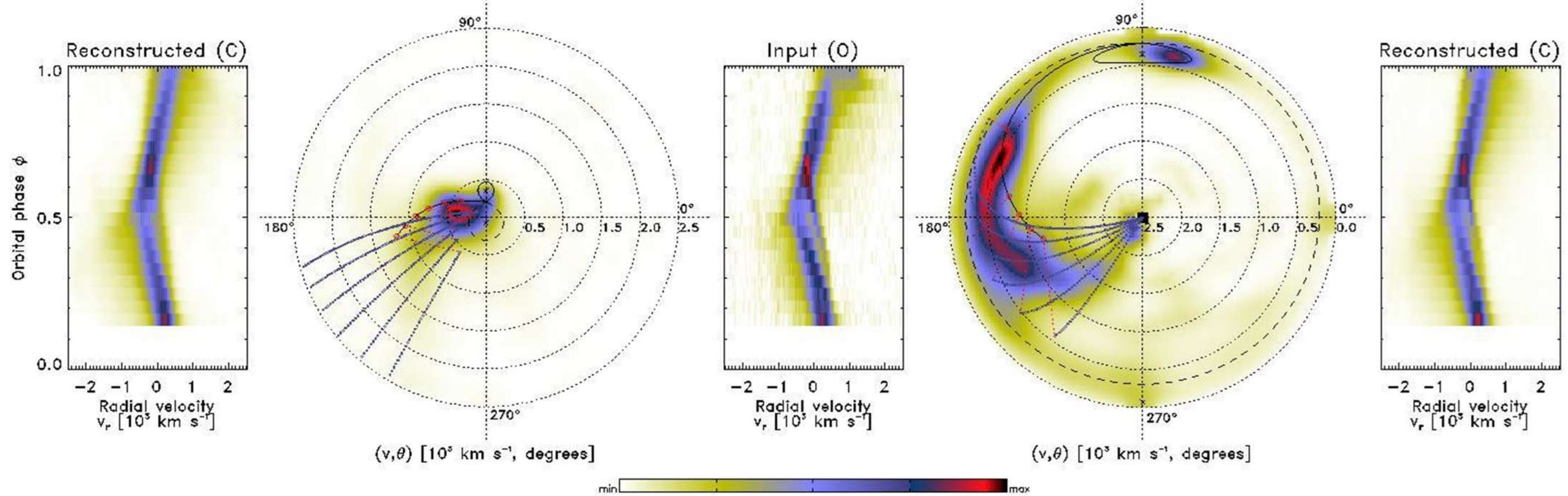


Compact Binaries

Standard and inside-out Doppler tomography (CTCV J1928-5000)

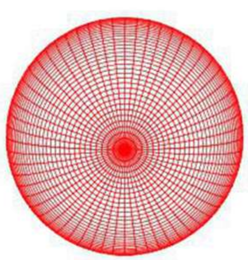
- Hβ emission line

Standard projection　　Inside-out projection



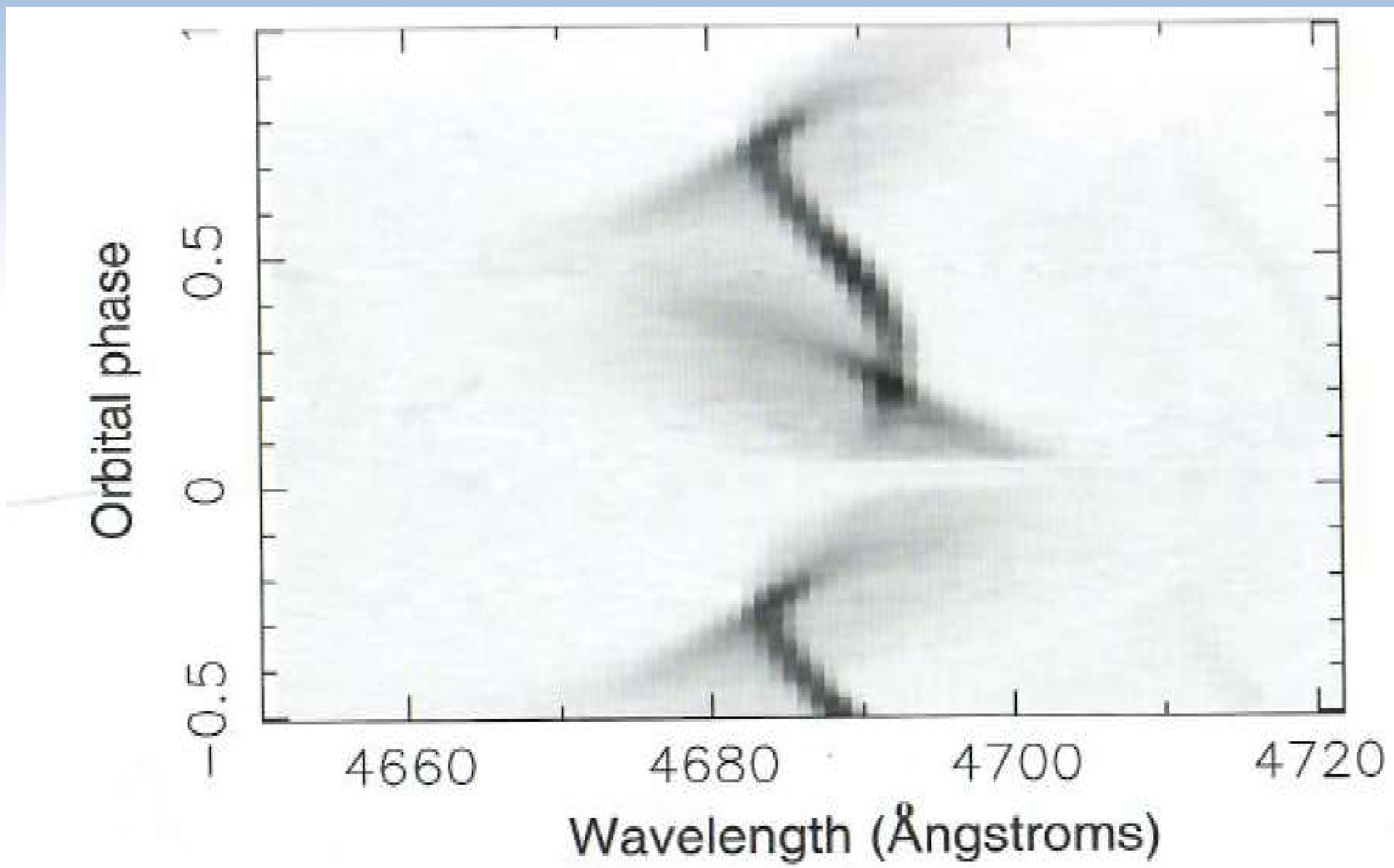
Other Examples

- HU Aqr
  - Ballistic accretion flow (Schwope et al . 1997)
  - Model parameters (Heerlein et al. 1999, Schwope et al . 1997):
    - $i = 84^0$, $M_1 = 0.875 M_{Sun}$, $q = 0.40$, $P_{orb} = 0.086820$ d (~125 min), magnetic dipole axis co-latitude 12^0 and azimuth 38^0



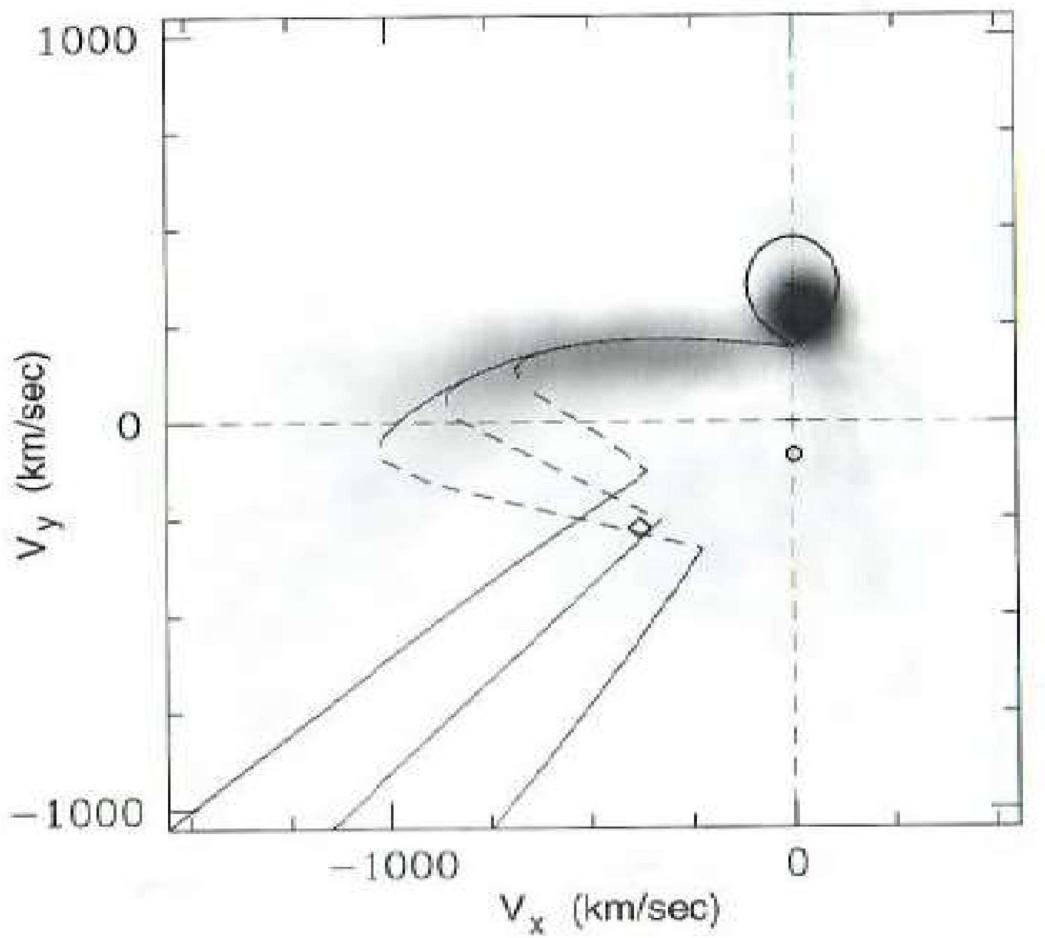
Polars: spectroscopy

- *Previous HU Aqr observations (Schwope et al.)*



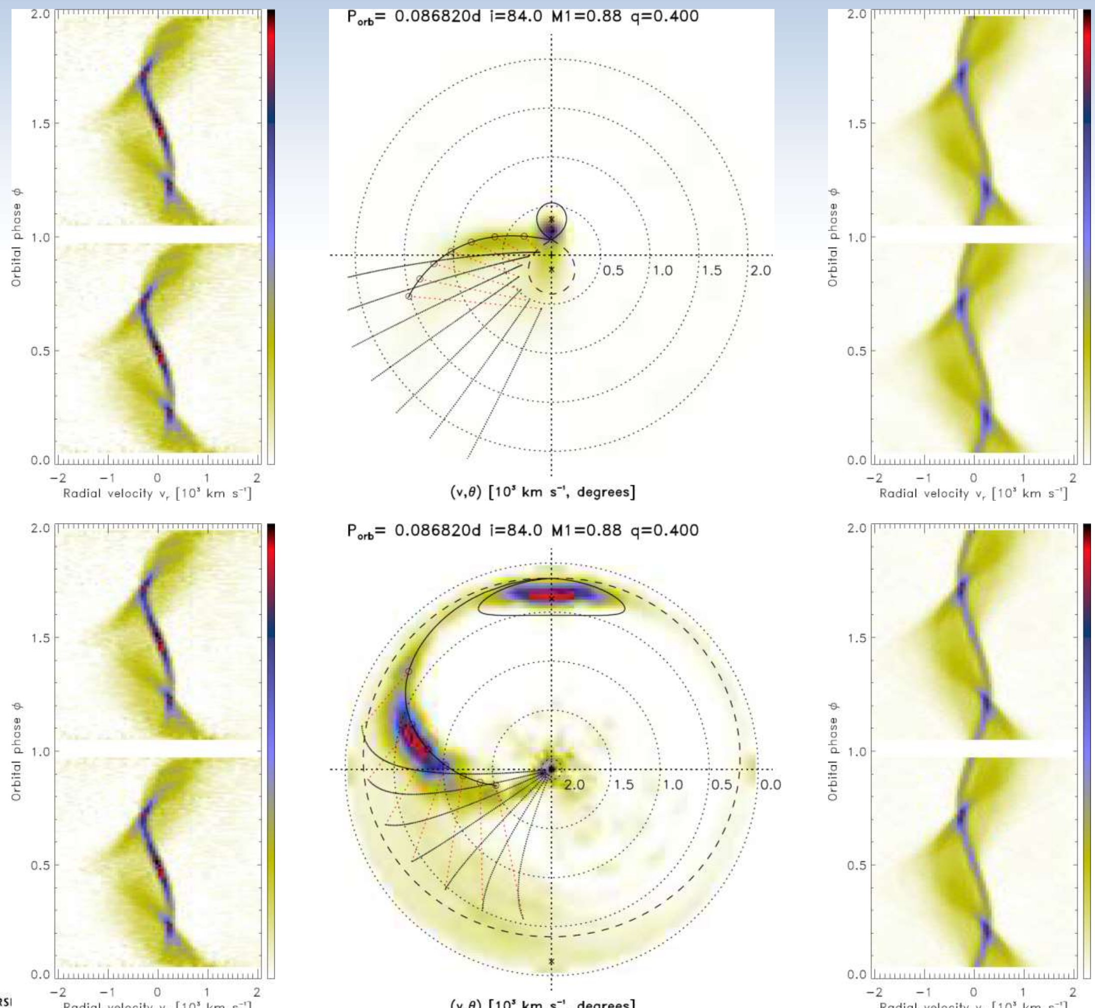
Polars

- *Doppler tomogram*



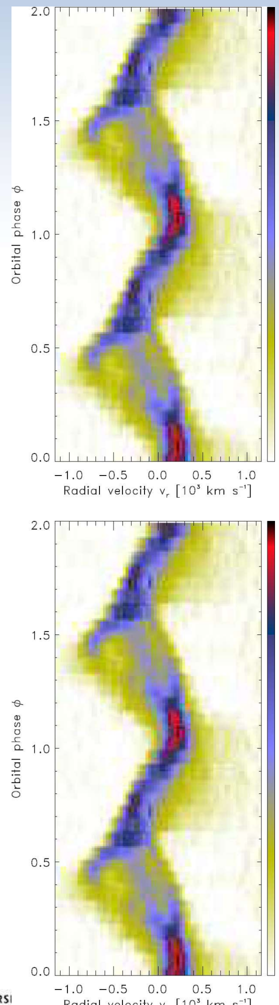
Doppler tomography:
SAAO observations of HU Aqr (HeII 4686Å) with inside-out

Observed spectra: Doppler tomogram: Reconstructed spectra:

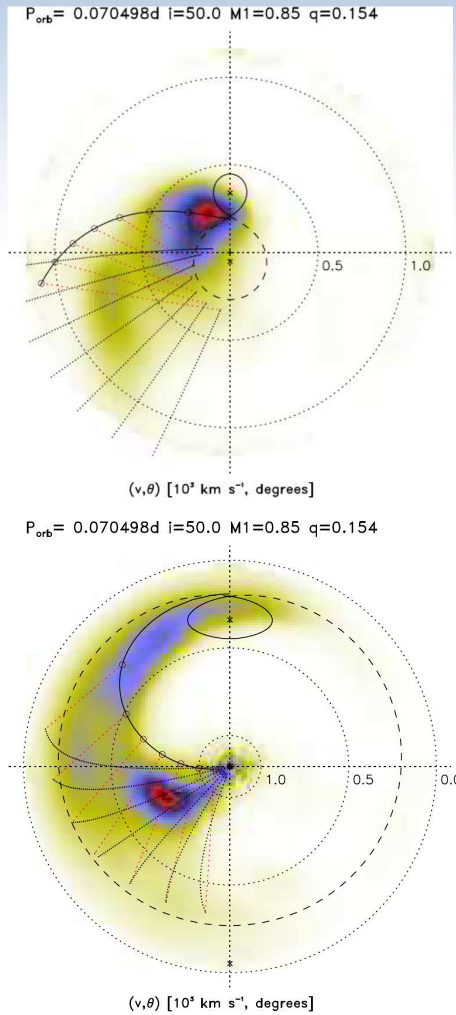


Doppler tomography
V834 Cen (HeII 4686Å)

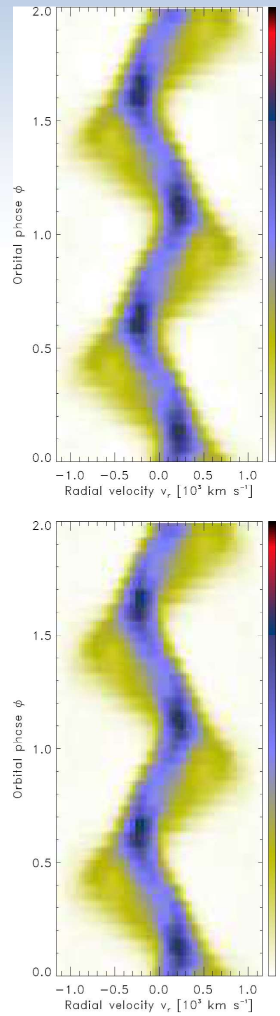
Observed spectra:



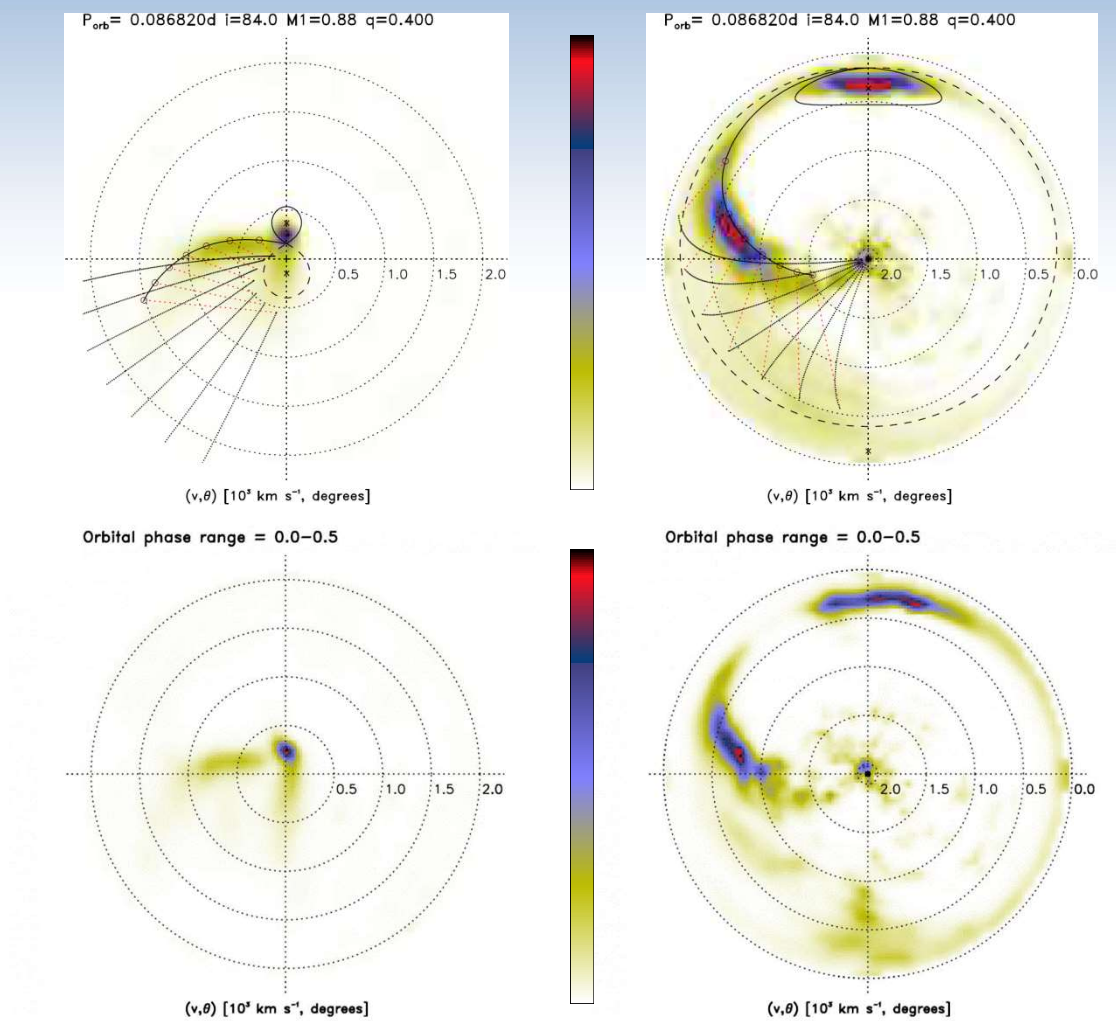
Doppler tomogram:



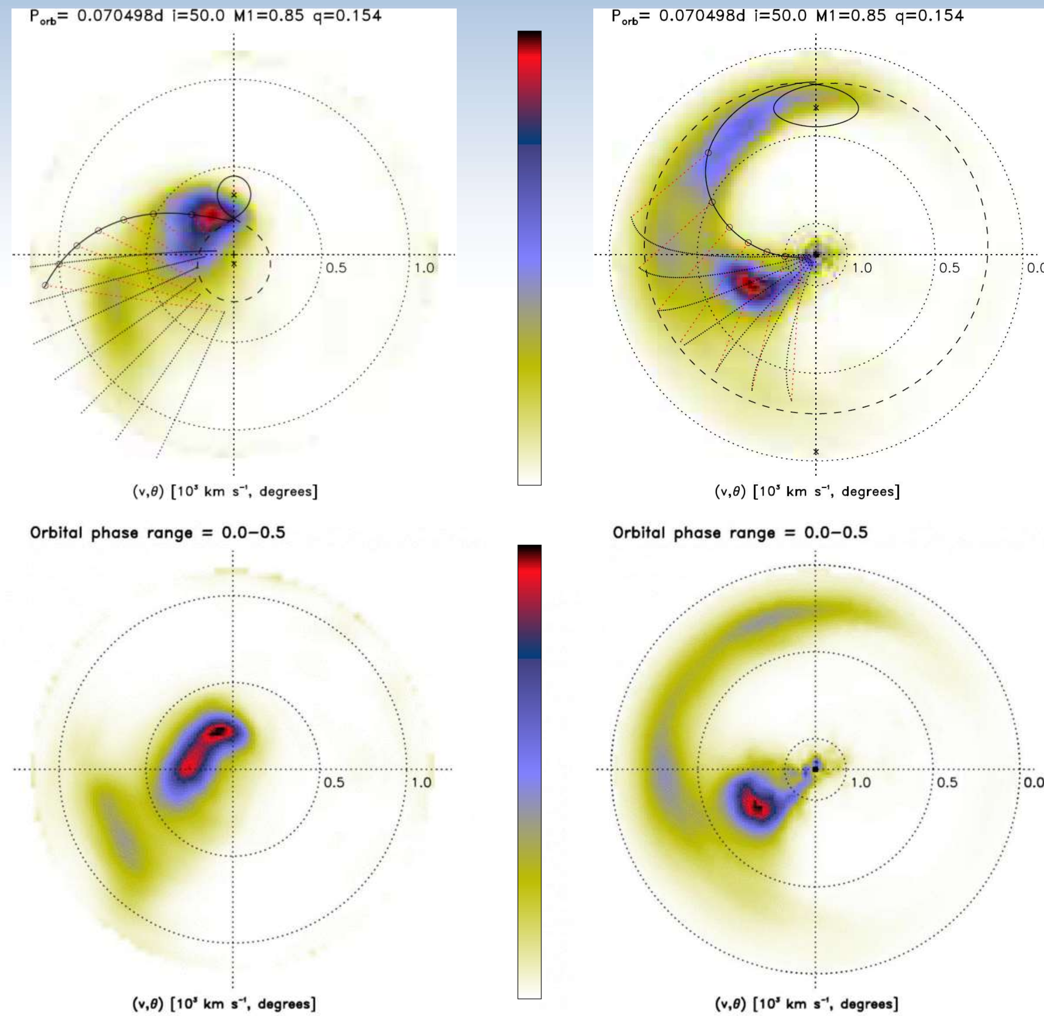
Reconstructed spectra:



Summary
HU Aqr: Ballistic accretion flow

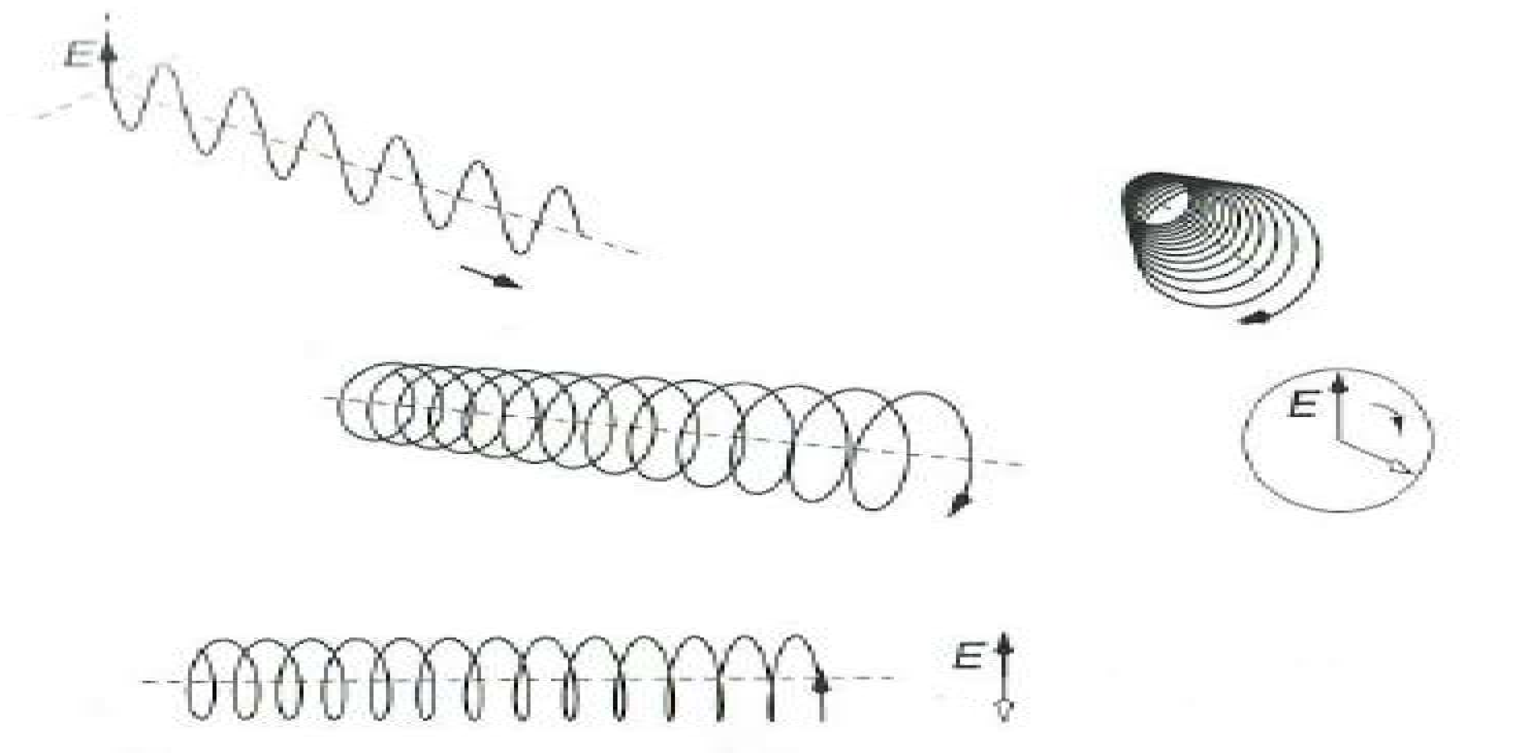


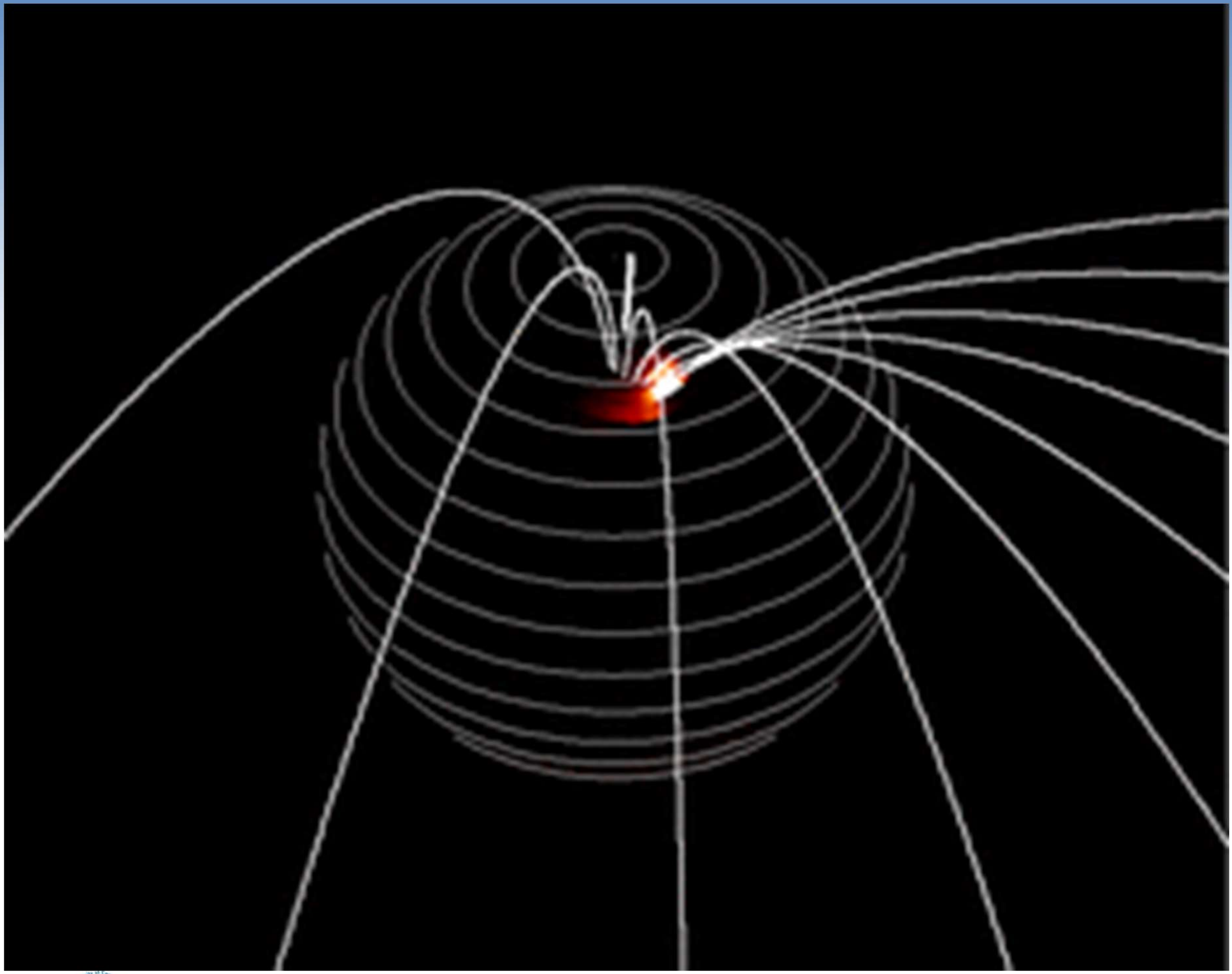
Summary
V834 Cen: Magnetic accretion flow



Polars: Polarized optical/IR emission

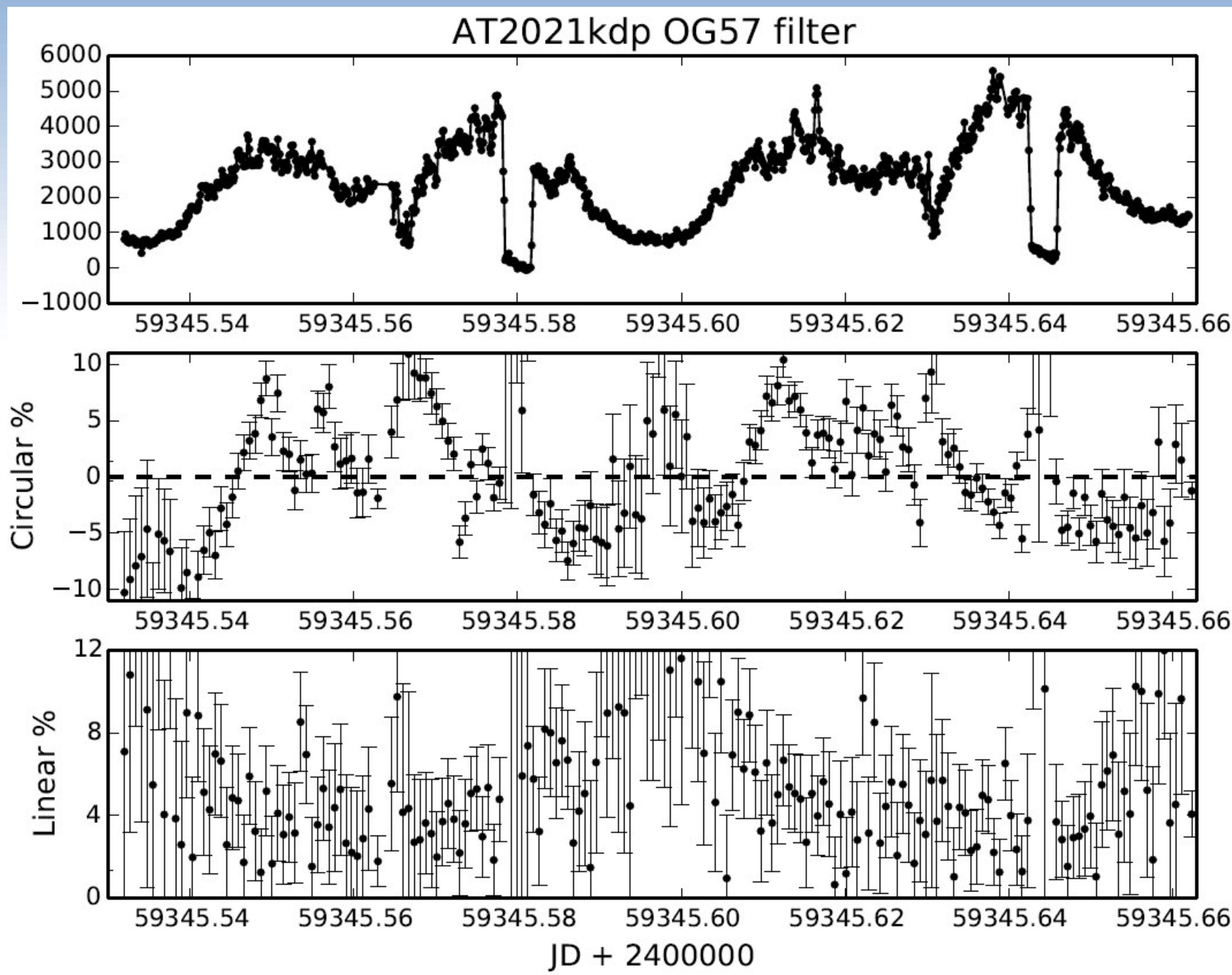
- Electrons in a strong magnetic field emit polarized cyclotron emission
- Both linear and circular polarization is seen, depending on the orientation of the fields lines
- Polarimetry is a powerful tool to determine the accretion geometry and magnetic field topology



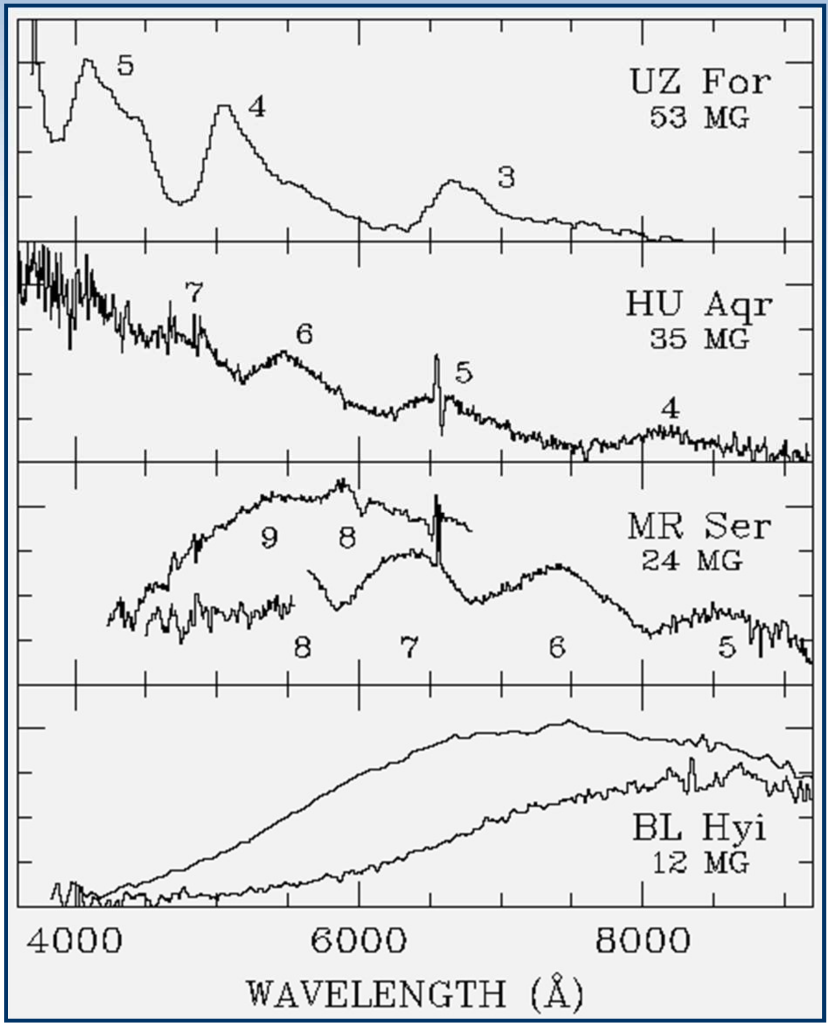


Polarized optical/IR emission

- Example: new discovery of AT2021kpd (HIPPO)



Optical cyclotron spectra

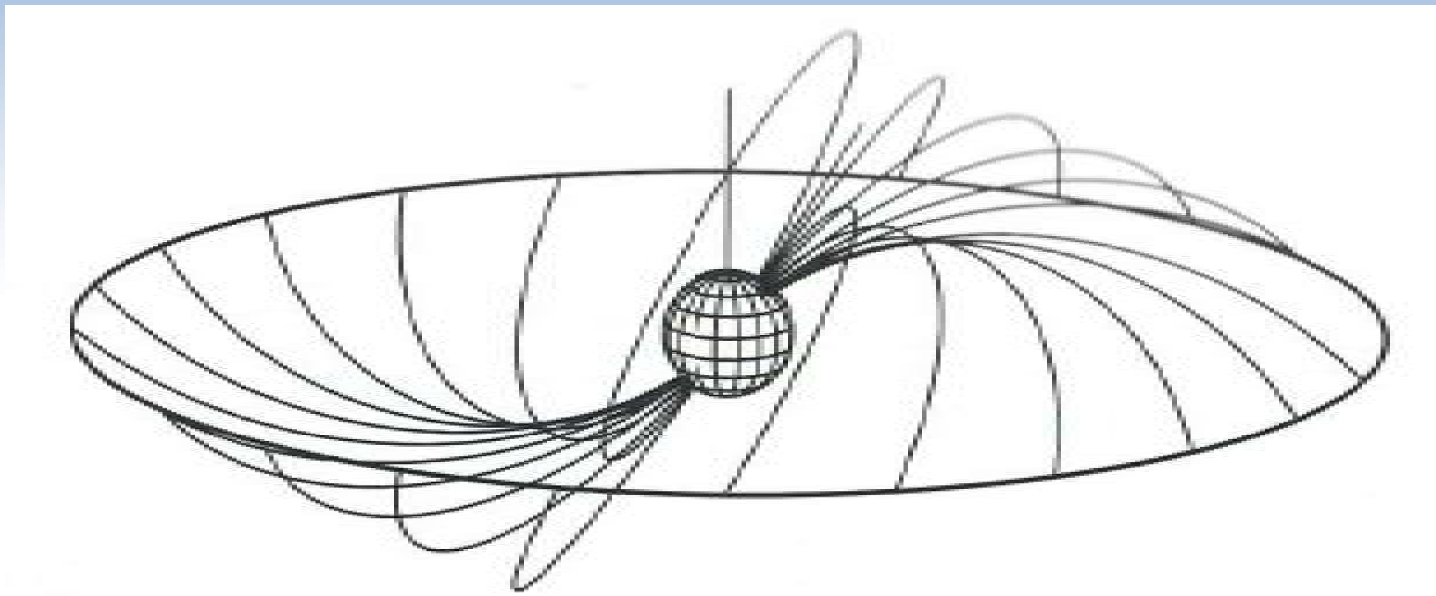


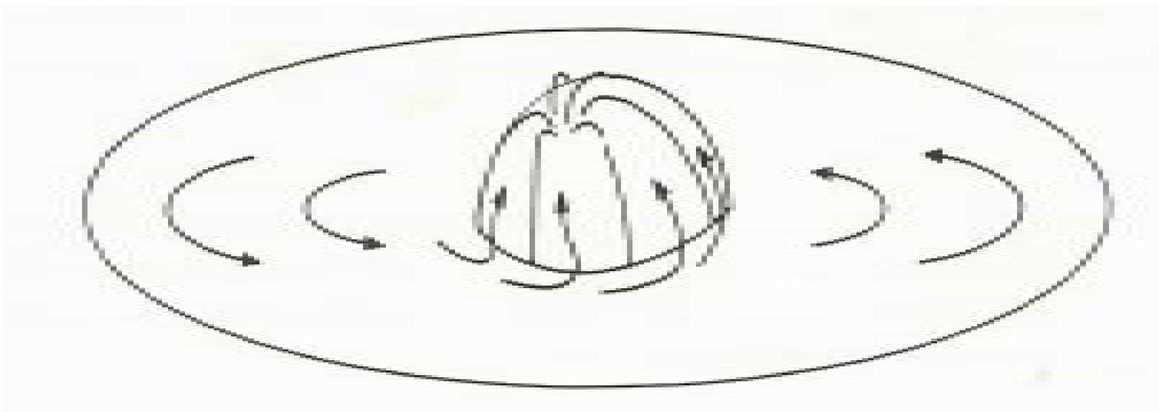
Cyclotron = mildly or non-relativistic synchrotron

- 140 Polars known
- ~50 with measured field strength
- 40 via cyclotron harmonics
- B = 12 – 230 MG

Intermediate Polars

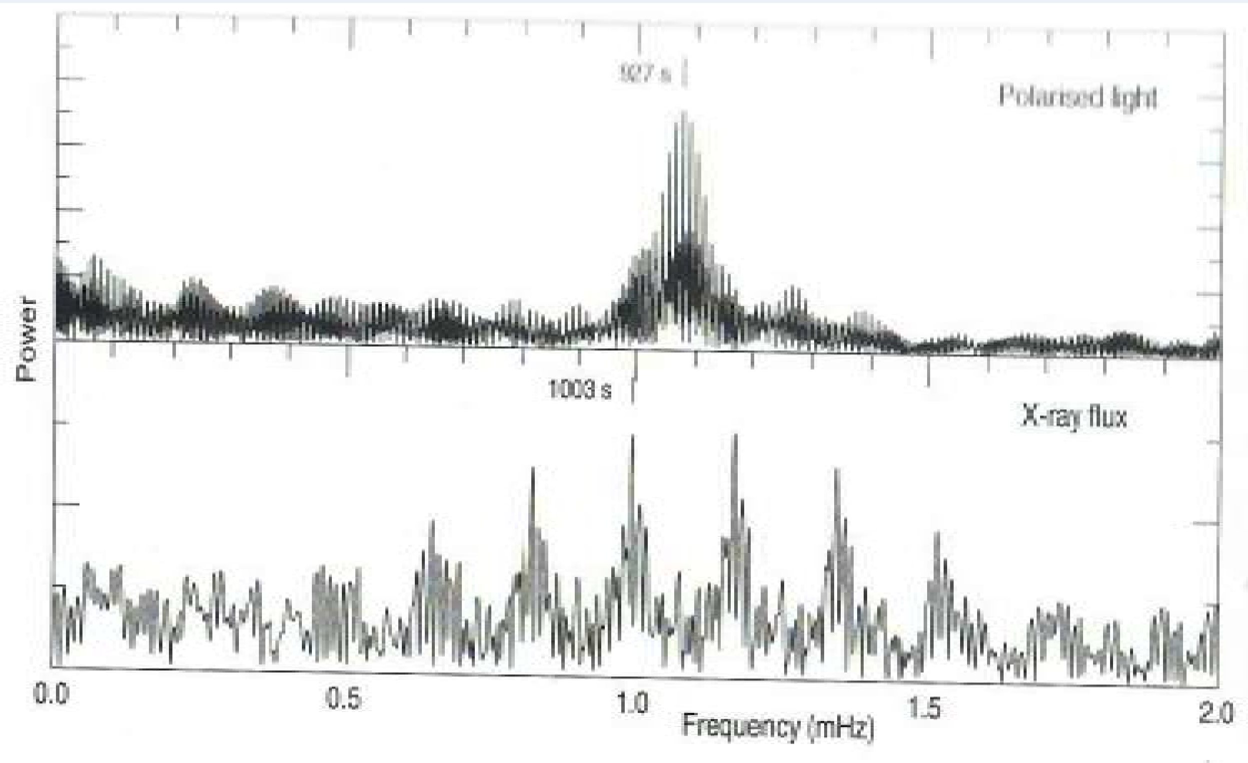
- Accretion mainly from inner regions of accretion disk
- Creation of accretion curtains

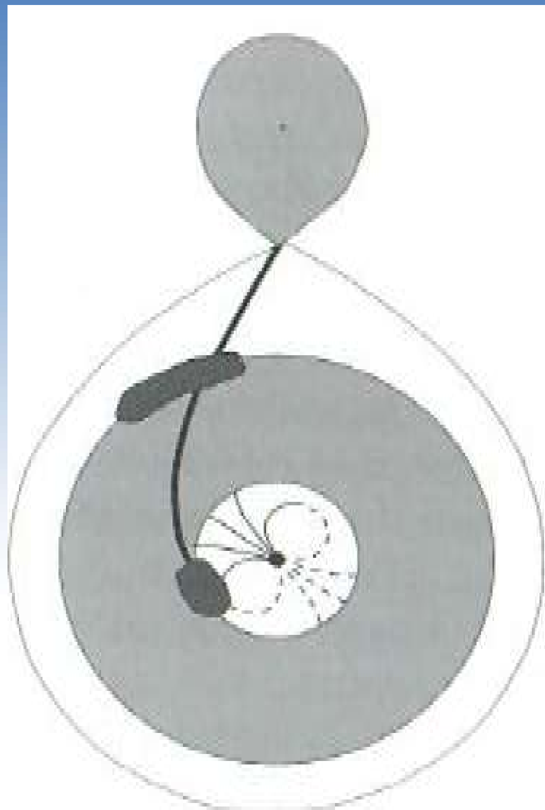


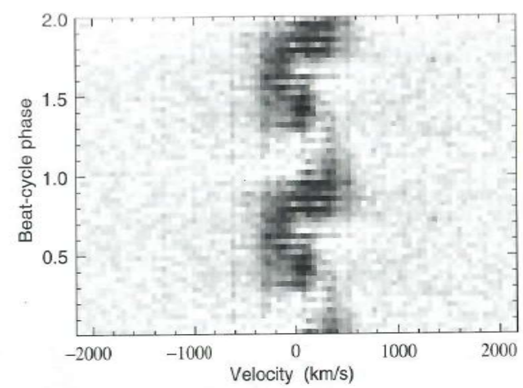


Intermediate Polars

- Sometimes direct stream-fed accretion
- One case (V2400 Oph) of *diskless* accretion
  - From polarimetry and X-rays
- Confirmed by Doppler tomography (spin tomograms)

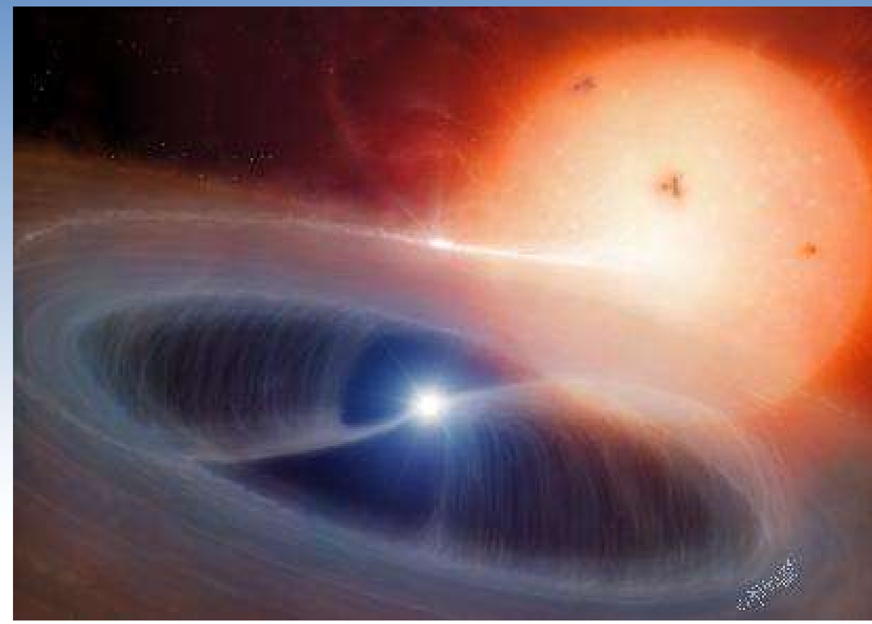


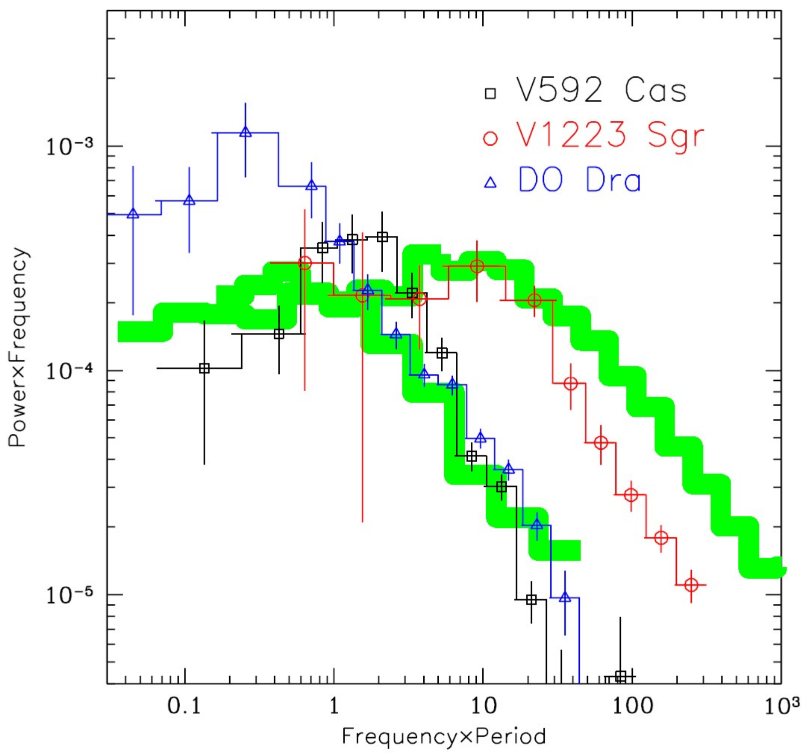


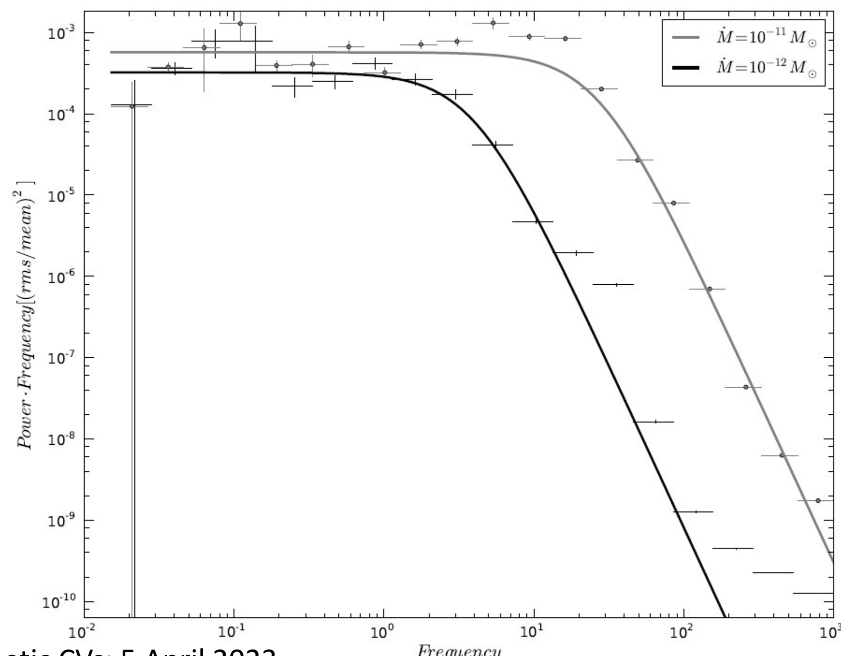


High Speed Photometry of Intermediate Polars

- Investigation of flickering & aperiodic behaviour of Ips
  - Power spectra clues to missing inner disk?
  - Disrupted power law
  - QPOs

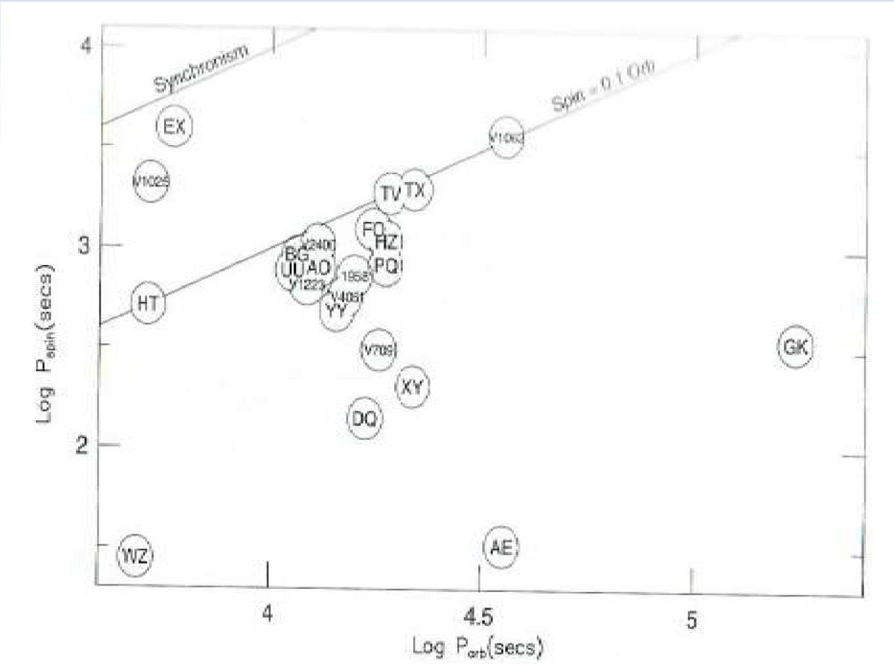


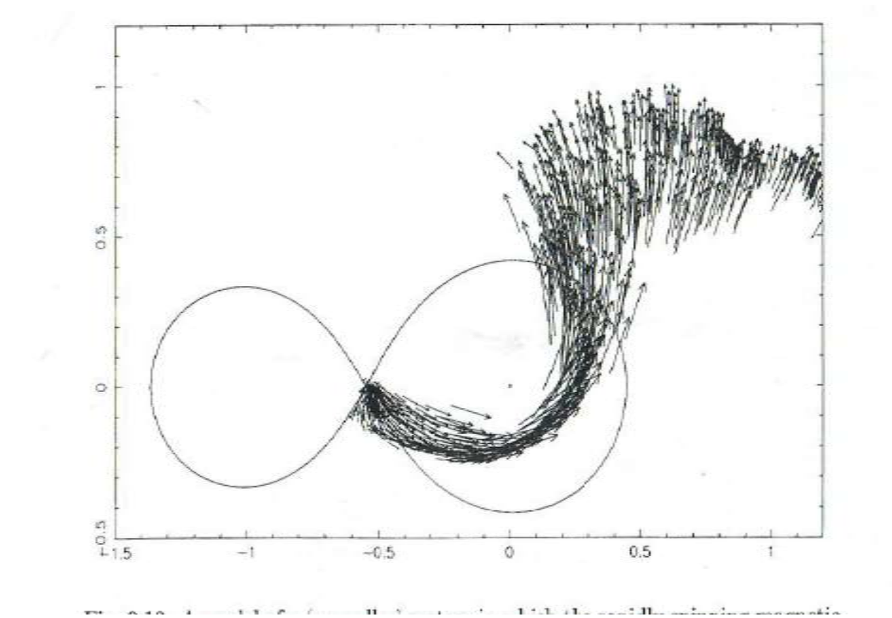




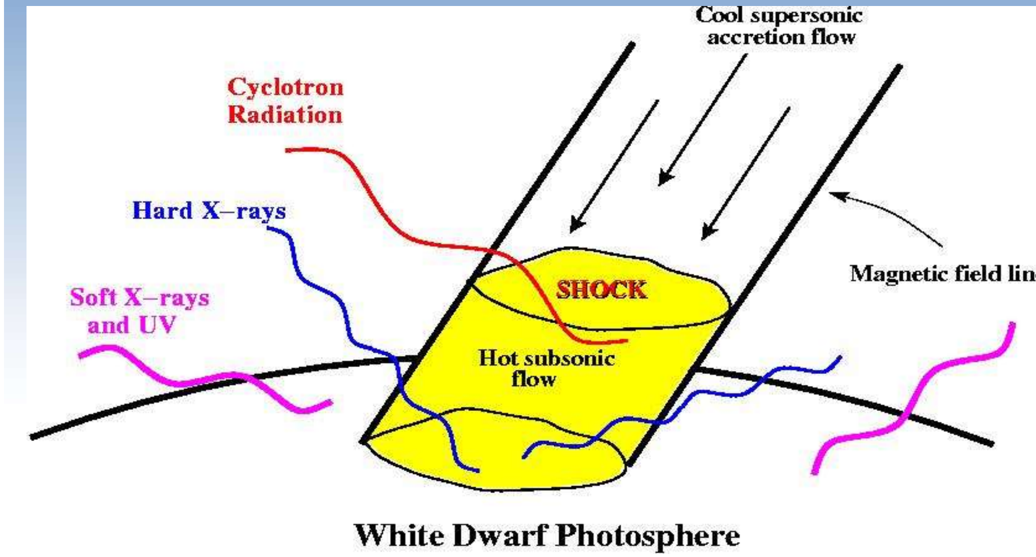
Periods of IPs

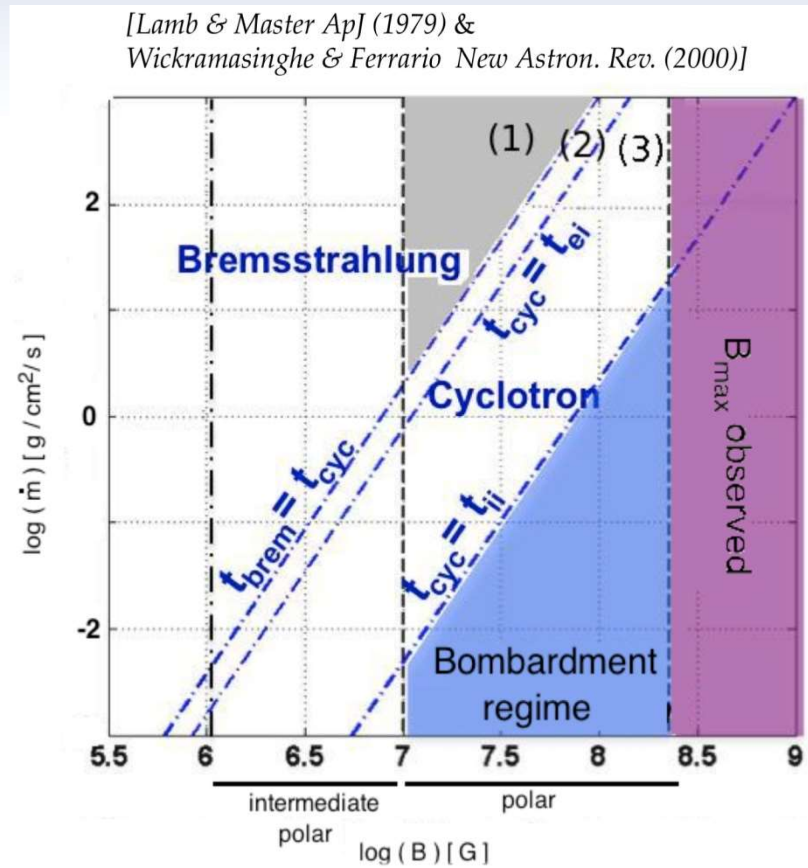
- Some moving to synchronize
- Fast spinners show episodic ejection from propeller (e.g. AE Aqr)



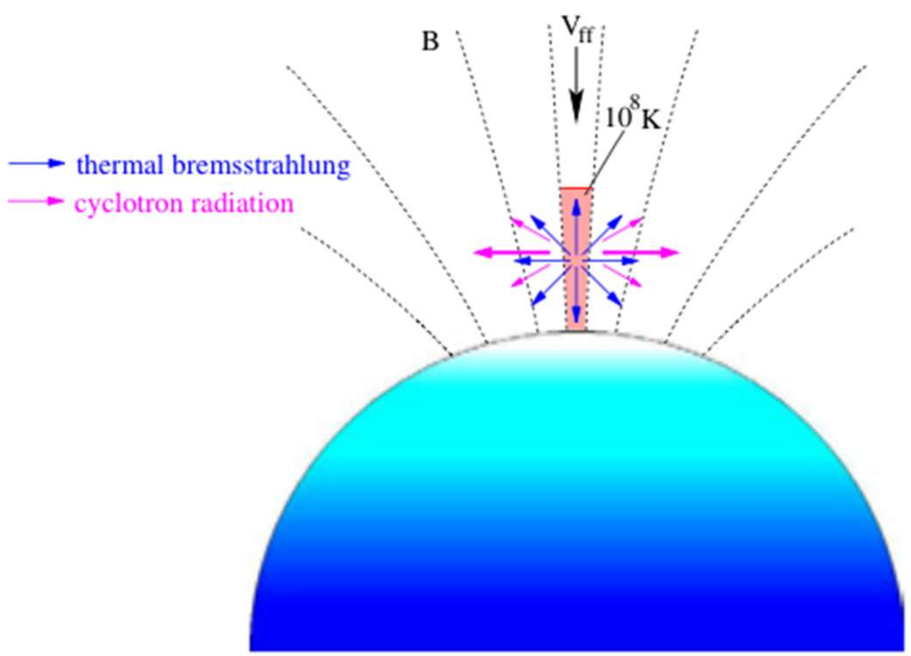


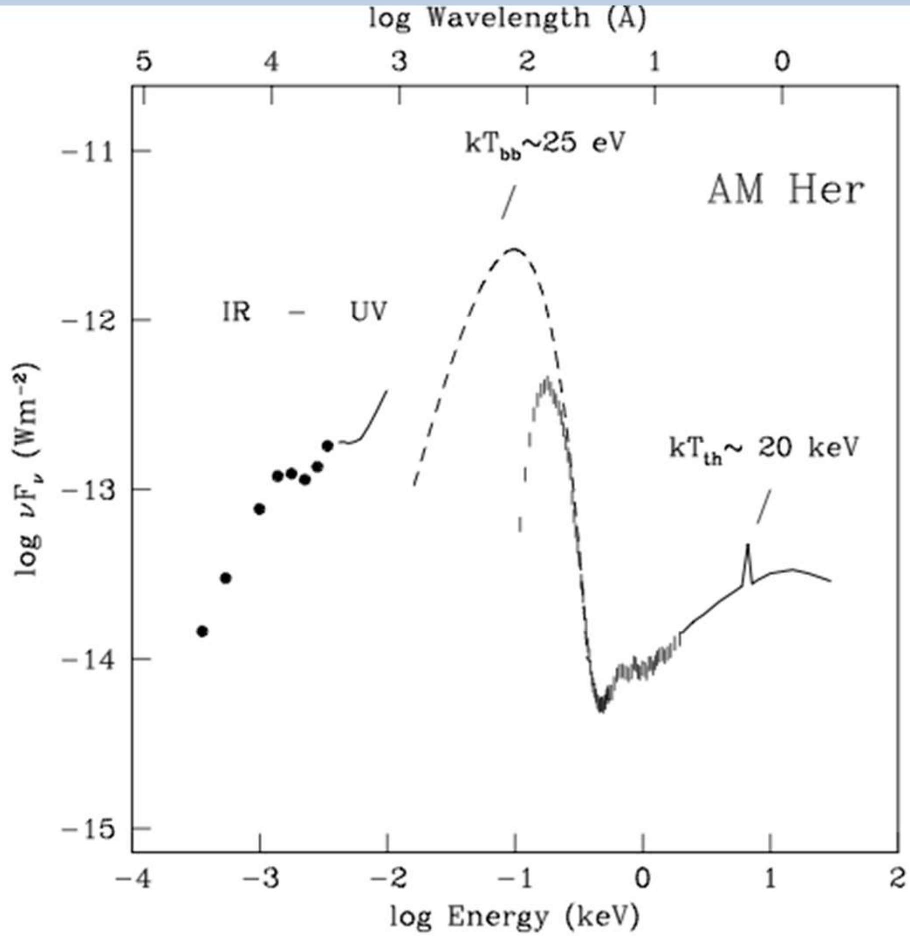
Accretion Columns





Accretion column and SED





Magnetic accretion

- Quasi-radial accretion
- Accretion columns
- Need HD or better MHD to understand the structure of columns and the concept of hydrodynamic shocks
  - Assume radial accretion with $v=v_{ff} > c_s$
  - Strong adiabatic shock
    → heating
    → subsonic settling flow
  - Cooling via thermal plasma and cyclotron radiation till T → T*
  - Kinetic energy $0.5mv^2$ → $E_{p+} >> E_{e-}$
    → consider protons and make sure that equipartition justifies one-fluid treatment
  - Stopping of ions:
    - NS: below Photosphere, complex MHD
    - WD: above photosphere → analytic solution

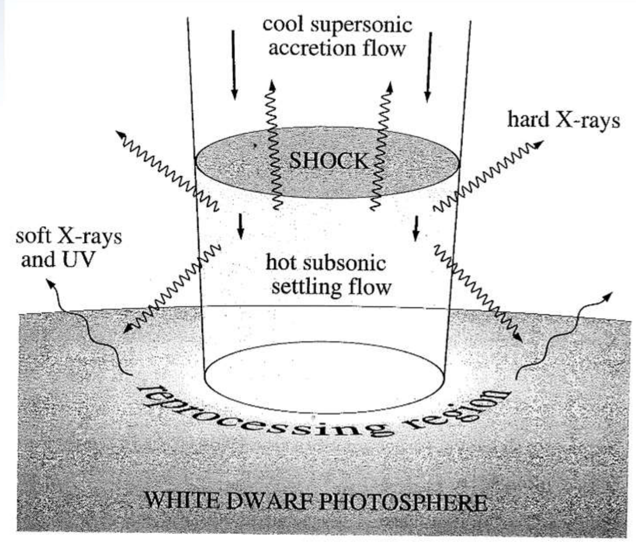
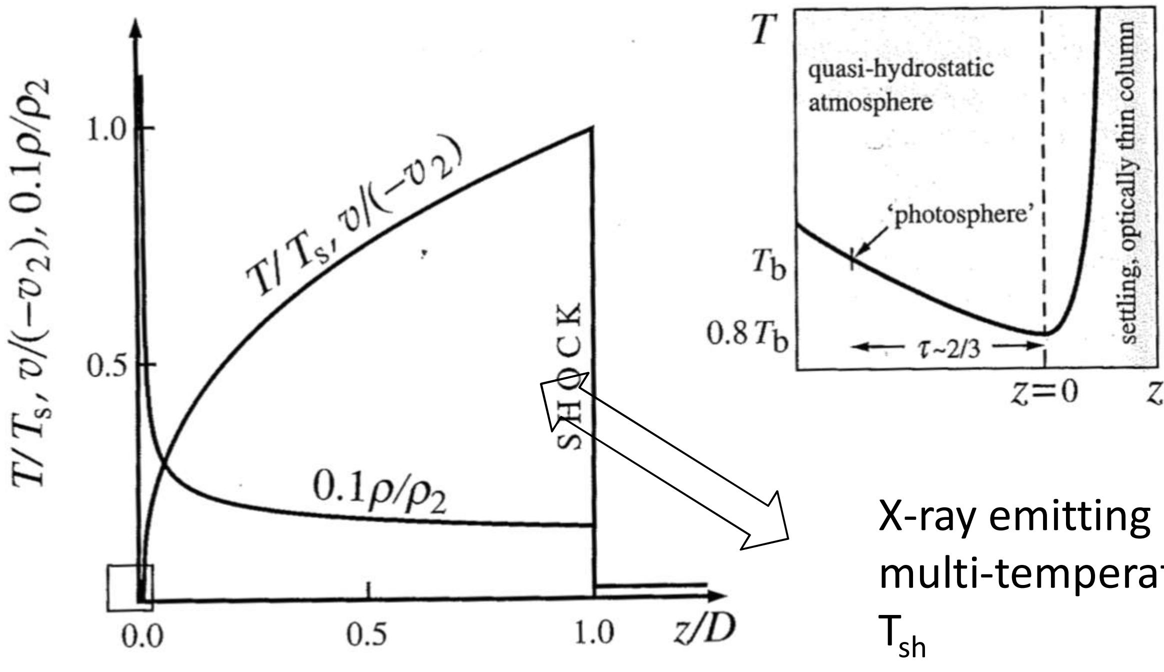


Fig. 6.11. Accretion column geometry for a magnetized white dwarf. The accretion column shown here is circular in cross-section and the accreting plasma is assumed uniform across the column.

Analytical solution for one-fluid plasma (Aizu 1973)
Electrons and protons are always in equilibrium



X-ray emitting cooling multi-temperature plasma $T_{max,e}$ · T_{sh}

Fig. 6.13. Simple radiative accretion column as discussed in the text. Inset: the base of the column near $z = 0$, showing how the column solution matches to a quasi-hydrostatic 'atmosphere' solution having effective temperature T_b at the point where $T = 0.8T_b$.

Cooling time scale & shock height

Cooling time scale t_{cool} = energy content / energy loss rate (cooling rate)

$$t_{\rm cool} = \frac{3}{2}\frac{n_e kT}{\varepsilon_{\rm ff}} = 0.6\,s\,\sqrt{\frac{kT}{16\,{\rm keV}}}\,\frac{4.4\times10^{15}{\rm cm}^{-3}}{n_e}$$

Shock height h

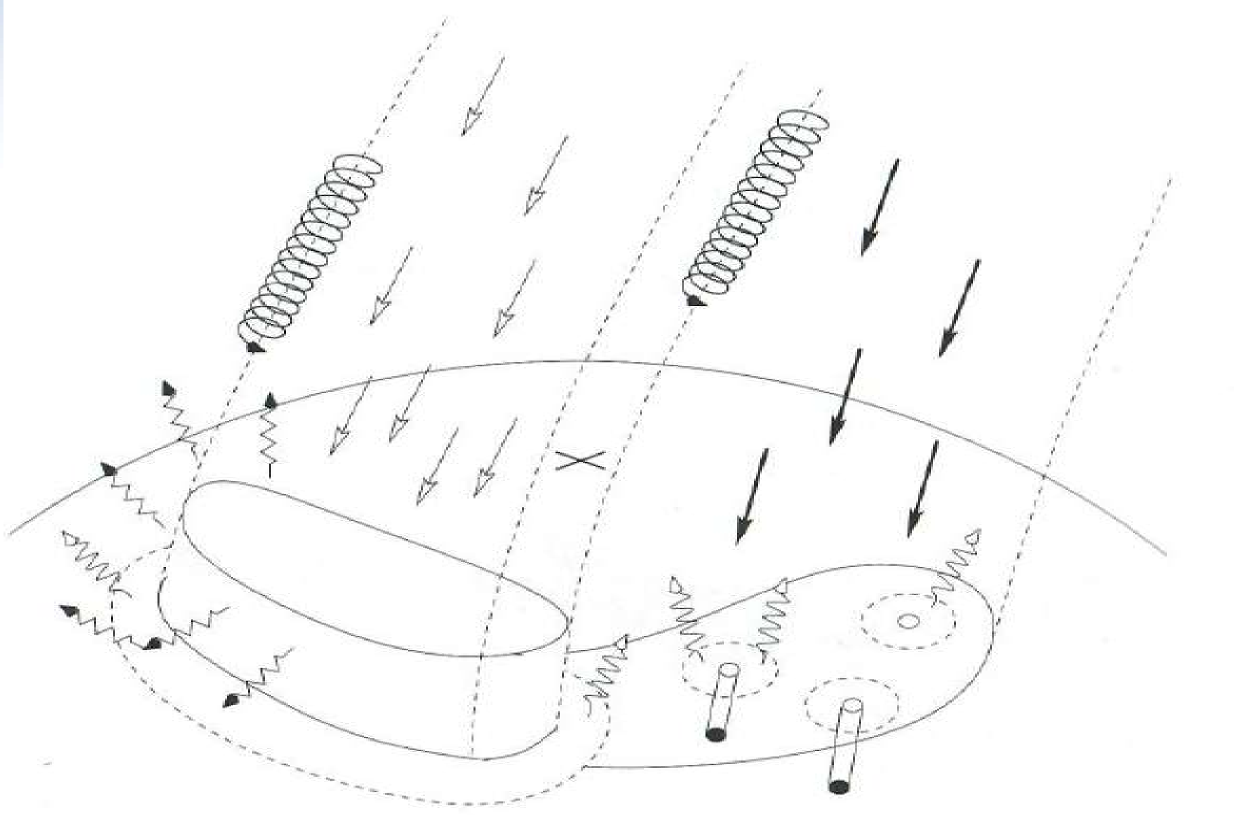
$$h = 0.605\,v_{\rm ff}\,t_{\rm cool} = 3\times10^5\,m \quad \dot{M}_{16}^{-1}\,\frac{f}{0.001}\,M_{0.5}^{3/2}\,R_9^{1/2}$$

$\dot{M}_{16}$: mass accretion rate in units of 10^{16} g s^{-1}
f: surface fraction that is accreting
$M_{0.5}$: mass of WD in solar units
R_9: radius of WD in units of 10^9 cm

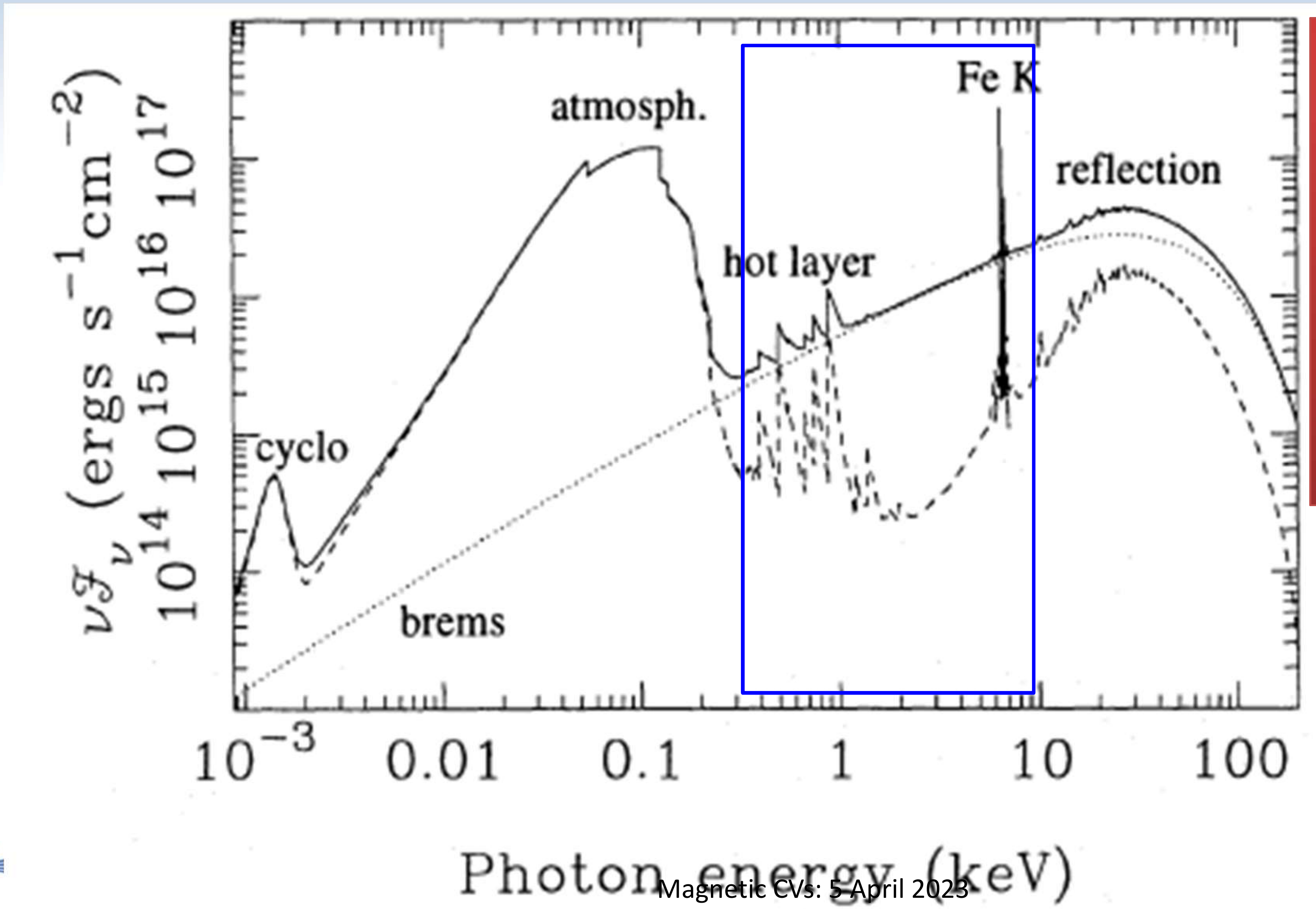
One can show: equilibrium time scale << cooling time
→ $T_e = T_i$ one fluid treatment is good approximation

Magnetic accretion: blobs

- Diamagnetic (unthreaded) blobs can penetrate the WD photosphere and thermalize
- Raises the WD photospheric temperture contributing to the soft X-ray black body emission



Column environment: Emission, reprocession, Fe fluorescence and Compton reflection



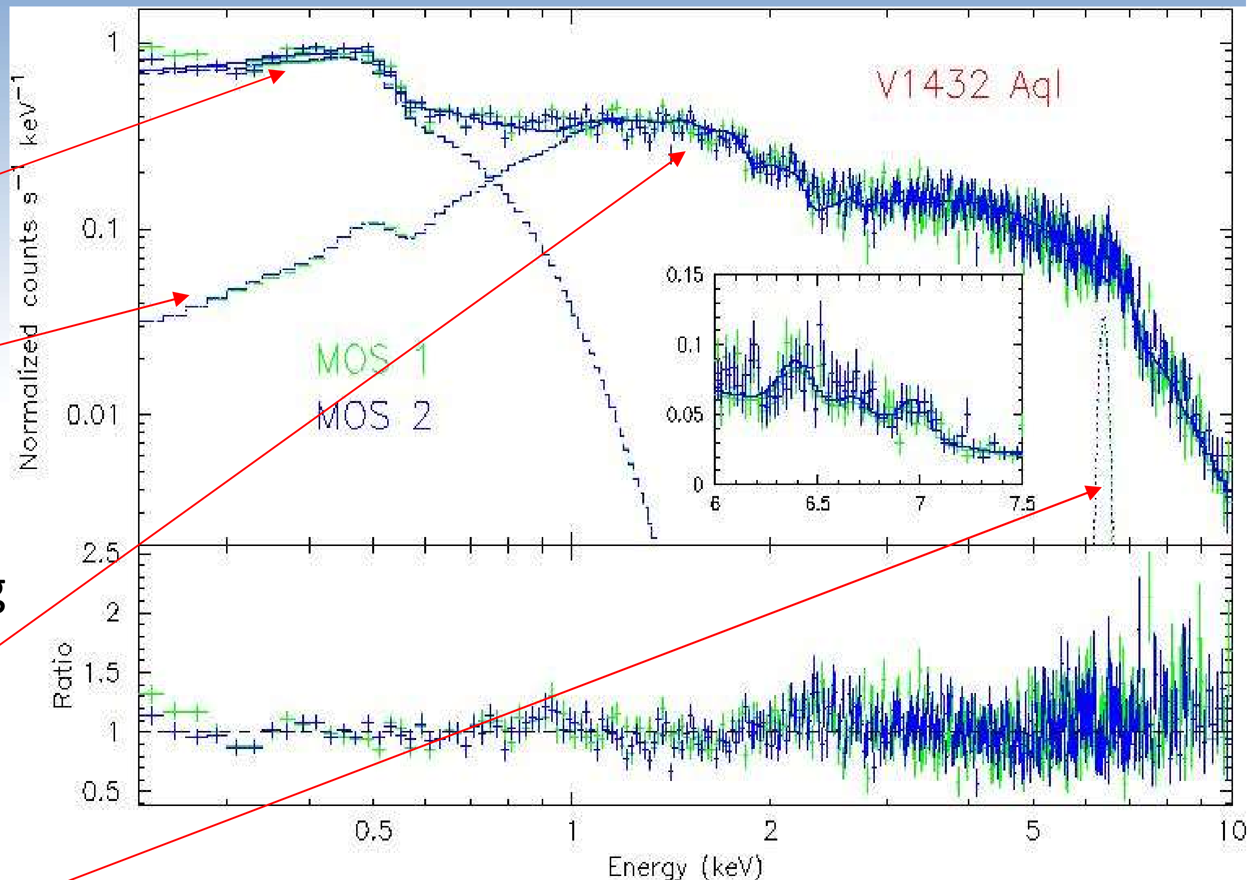
Multi-T thermal spectra aka cooling flow

Cold & warm absorbers

Compton reflection hump

SED example: XMM-Newton Spectrum of V1432 Aql

Rana, Singh, Buckley & Barrett 2005, ApJ



Model Components:

Black body emission (88±2 eV)

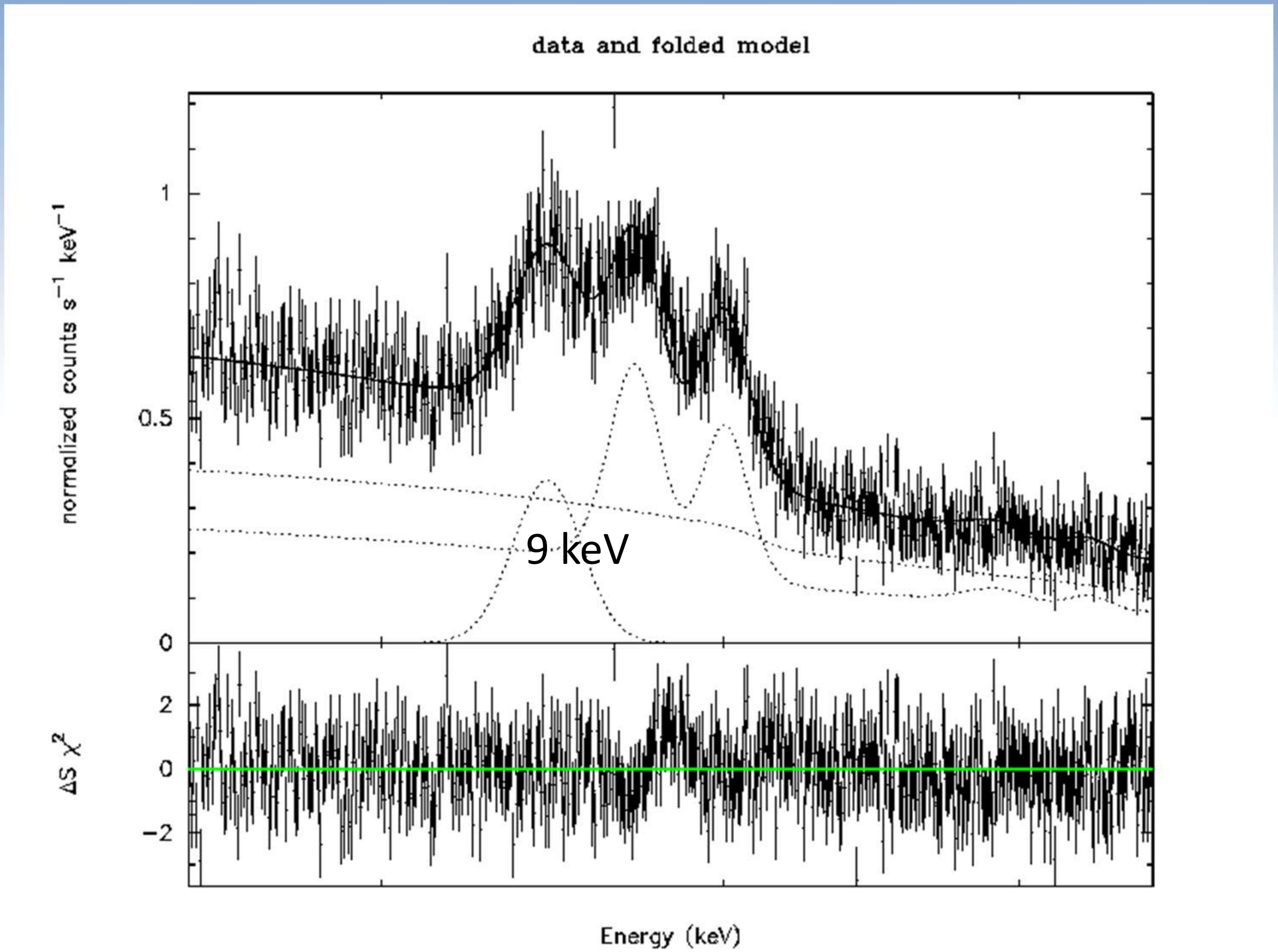
Absorbers: $1.7\pm0.3 \times 10^{21}$ cm^{-2}, fully covering the source & $1.3 \pm0.2 \times 10^{23}$ cm^{-2}, covering 65%

Multi-temperature plasma model (kT > 10 keV)

Gaussian for 6.4 keV line emission

Compact Binaries

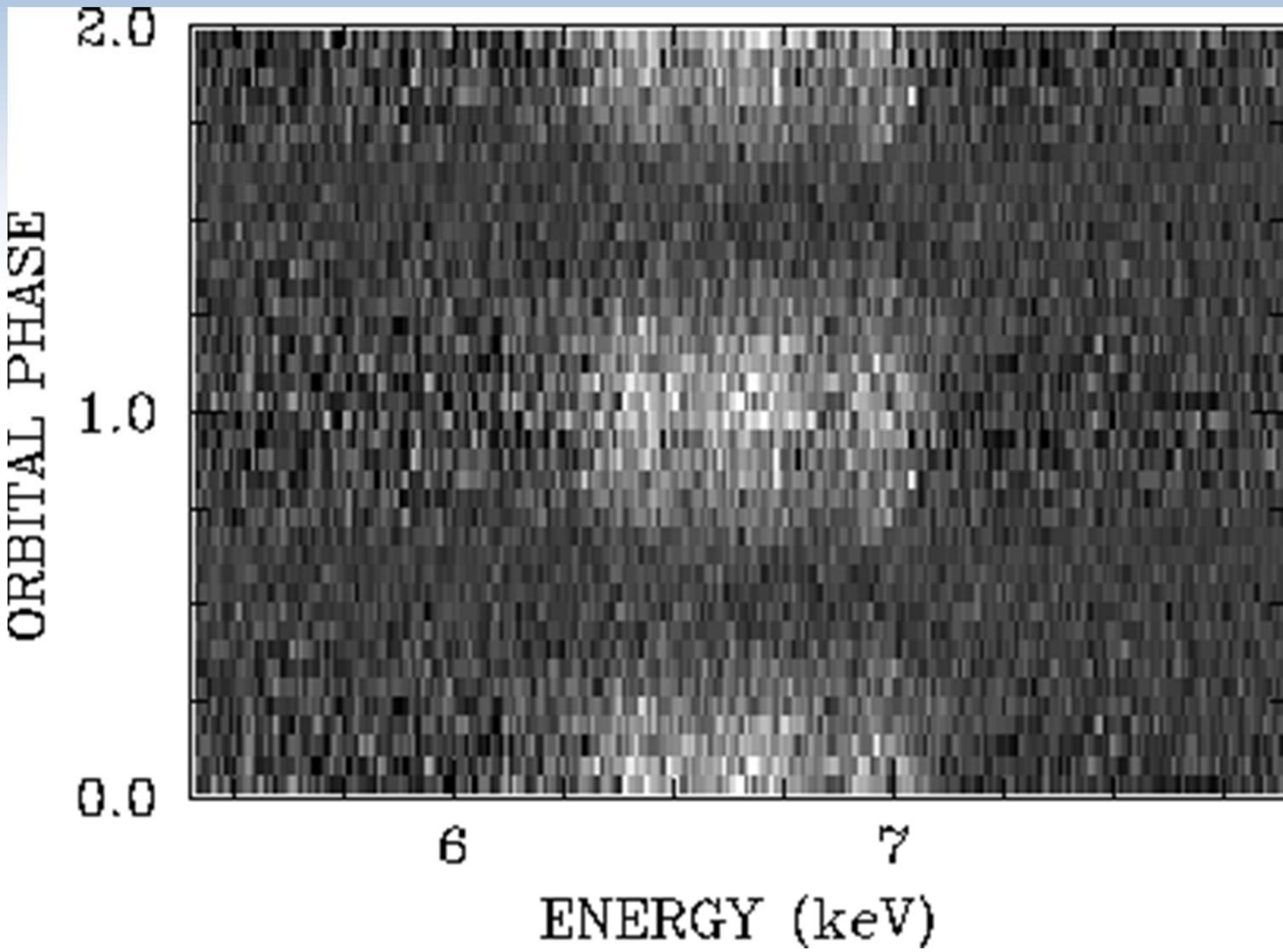
AM Her: The Fe-line complex with XMM-Newton



H-like and He-like Fe line ratio as bolometer for top of the column

Kα line due to reflection of primary photons at WD surface

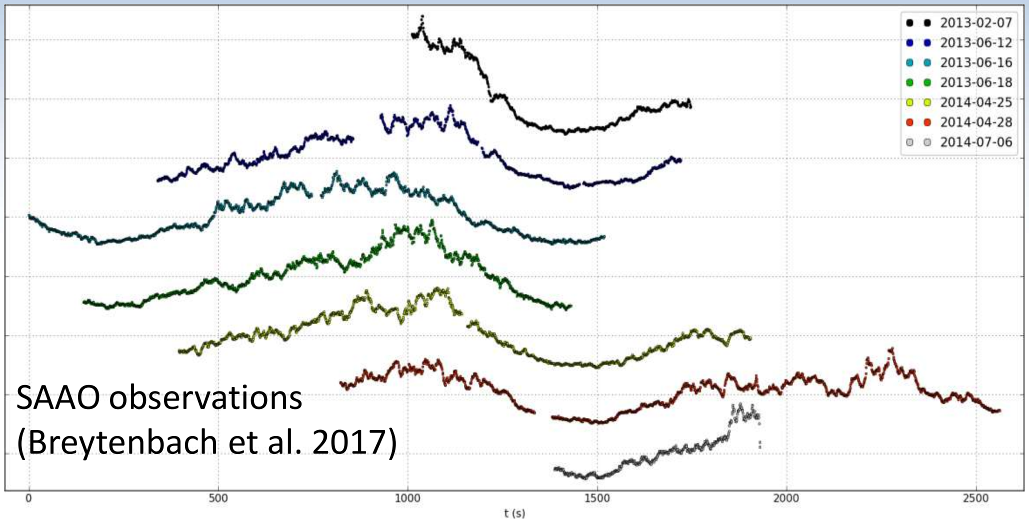
AM Her Fe triplet phase-resolved XMM-Newton



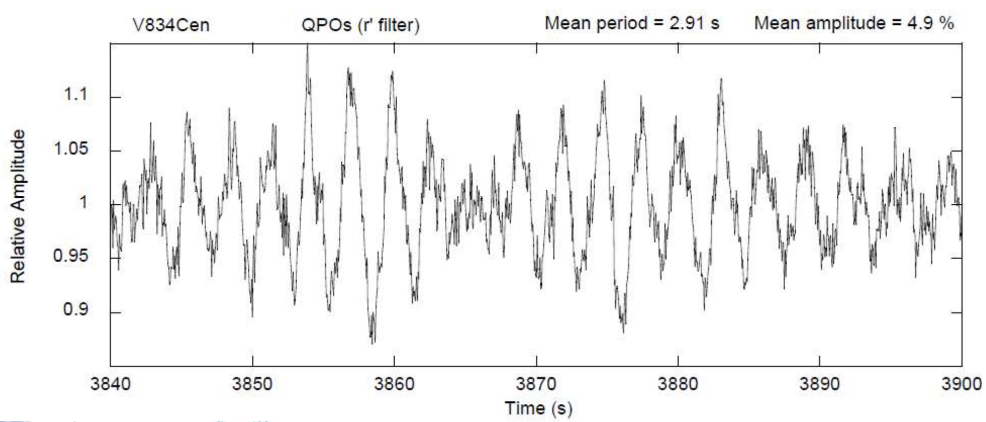
Compact Binaries

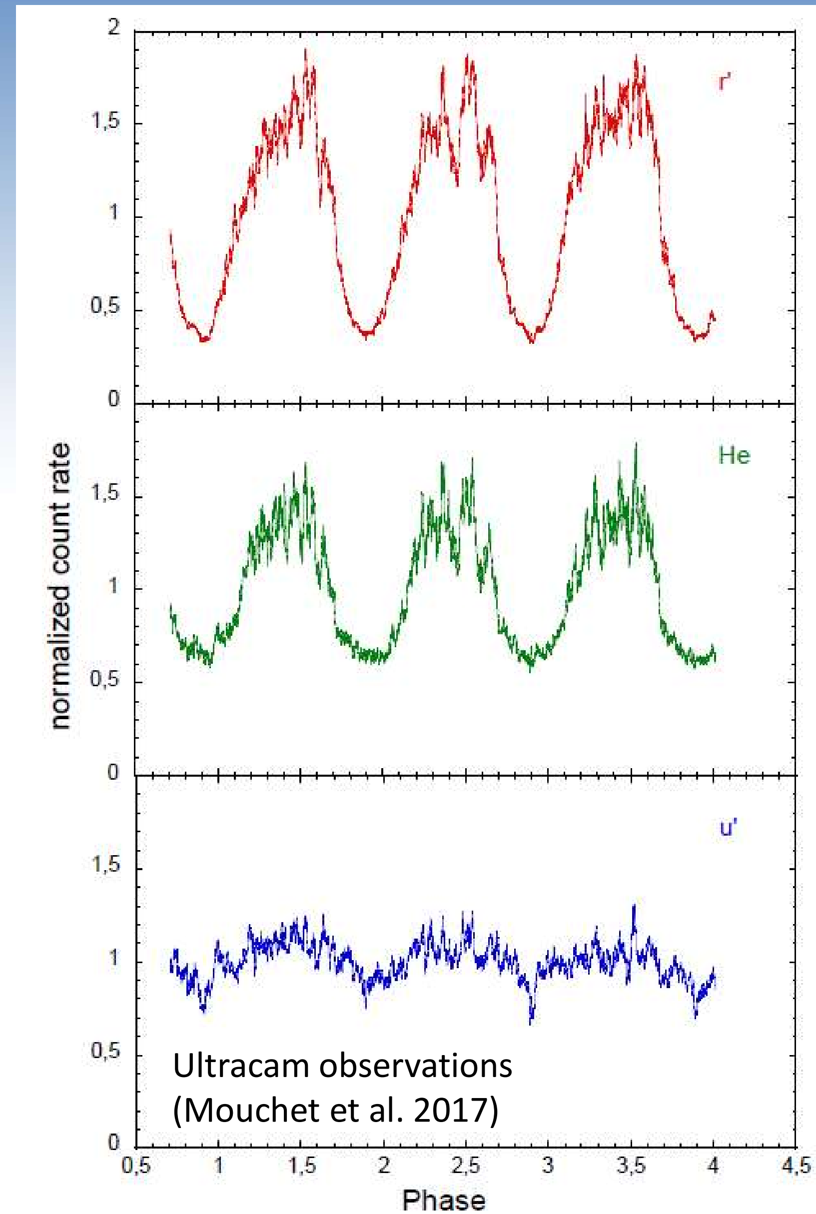
Quasi-Periodic Oscillations

- High frequency "ringing" produced in accretion columns (few sec period)
- E.g. V834 Cen
  - Orbital period = 101.5 min (1.69 h)
  - QPO at ~3 sec



SAAO observations (Breytenbach et al. 2017)

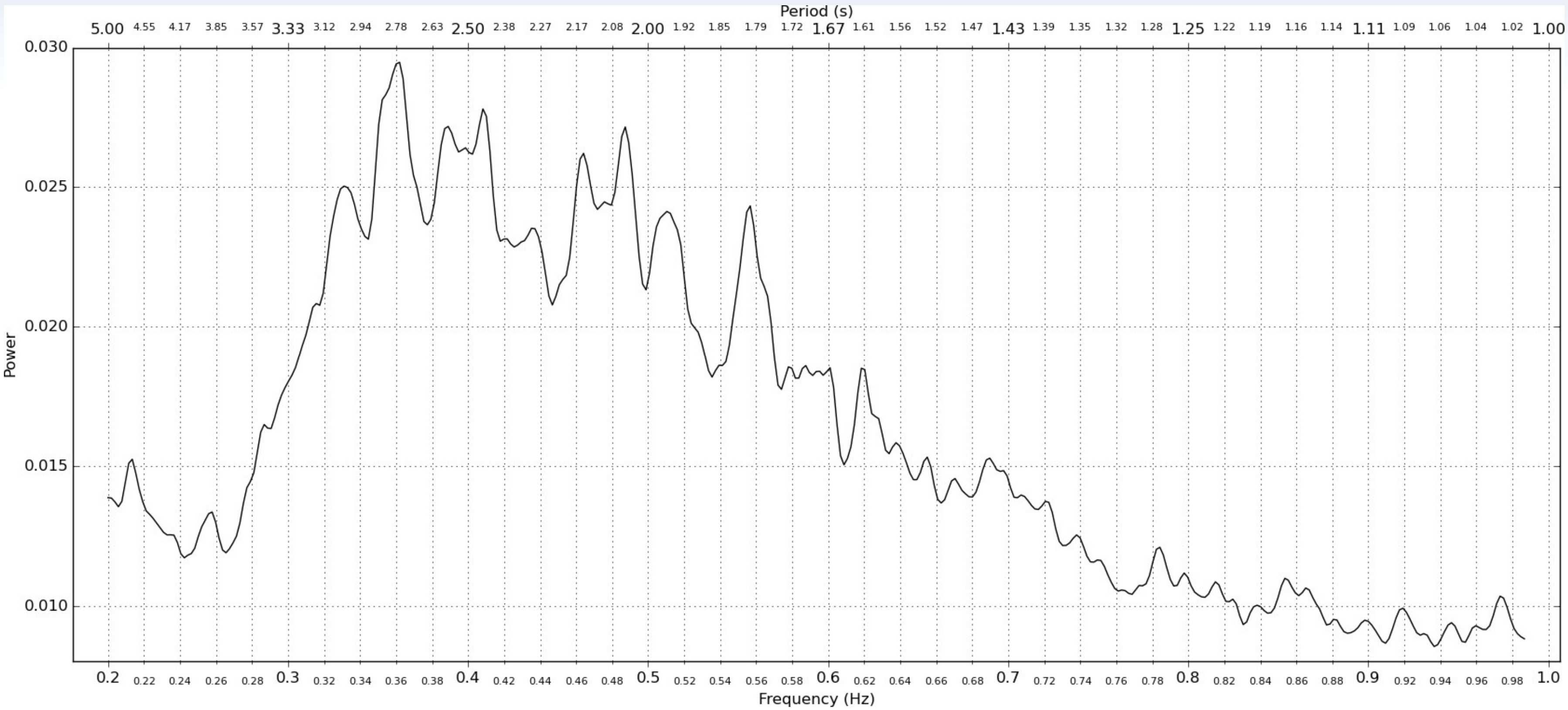




Ultracam observations (Mouchet et al. 2017)

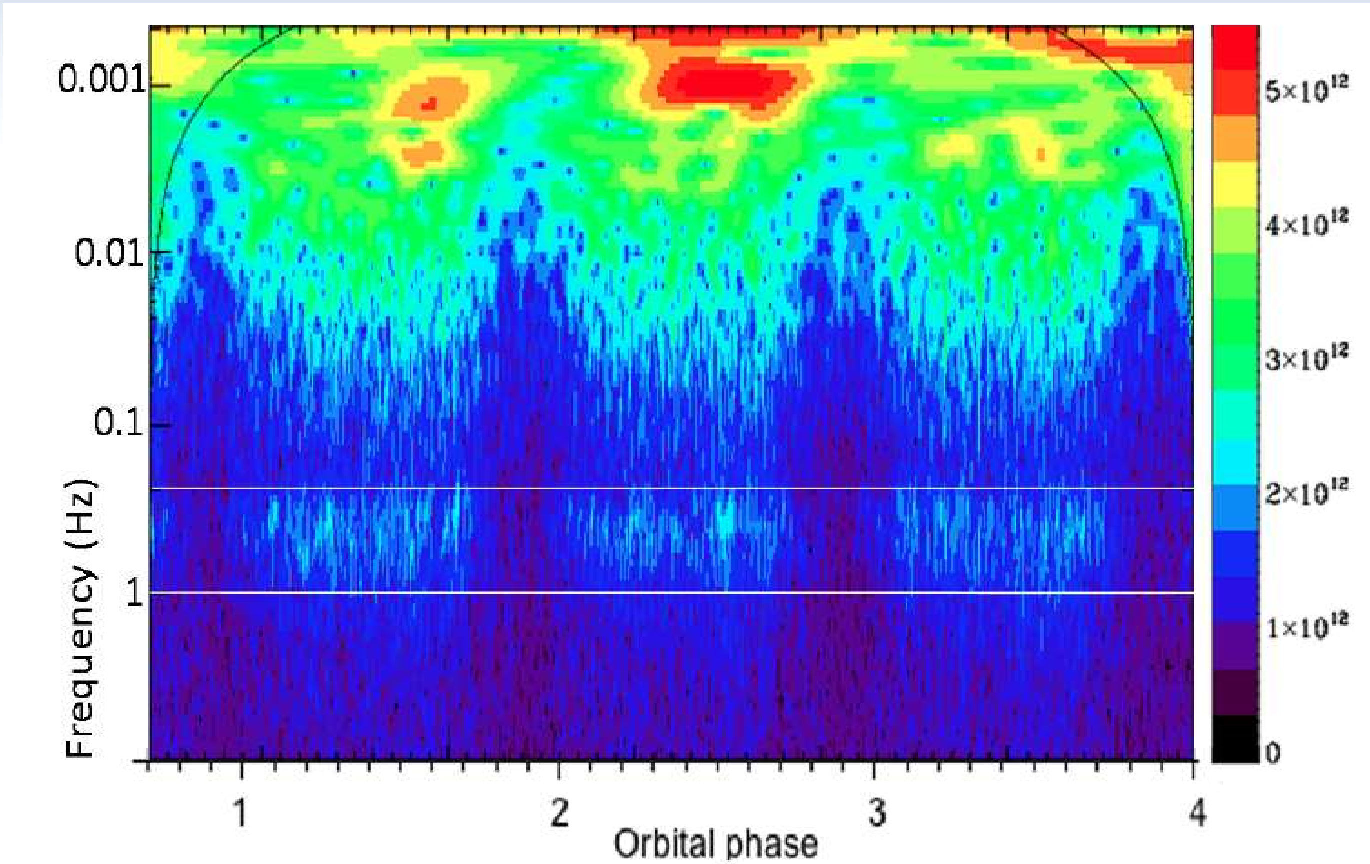
V834 Cen QPOs

- Power seen at a range of frequencies that come & go
- Thought to be due to instabilities in accretion flow within isolated magnetic flux tubes
- Still uncertain



V834 Cen QPOs

- Wavelet analysis shows lower frequency power too
  - Periods of ~100s



Modelling the Accretion column

Hydrodynamical equations:

$$\frac{\partial \rho}{\partial t} = -\frac{\partial \rho v}{\partial r}$$

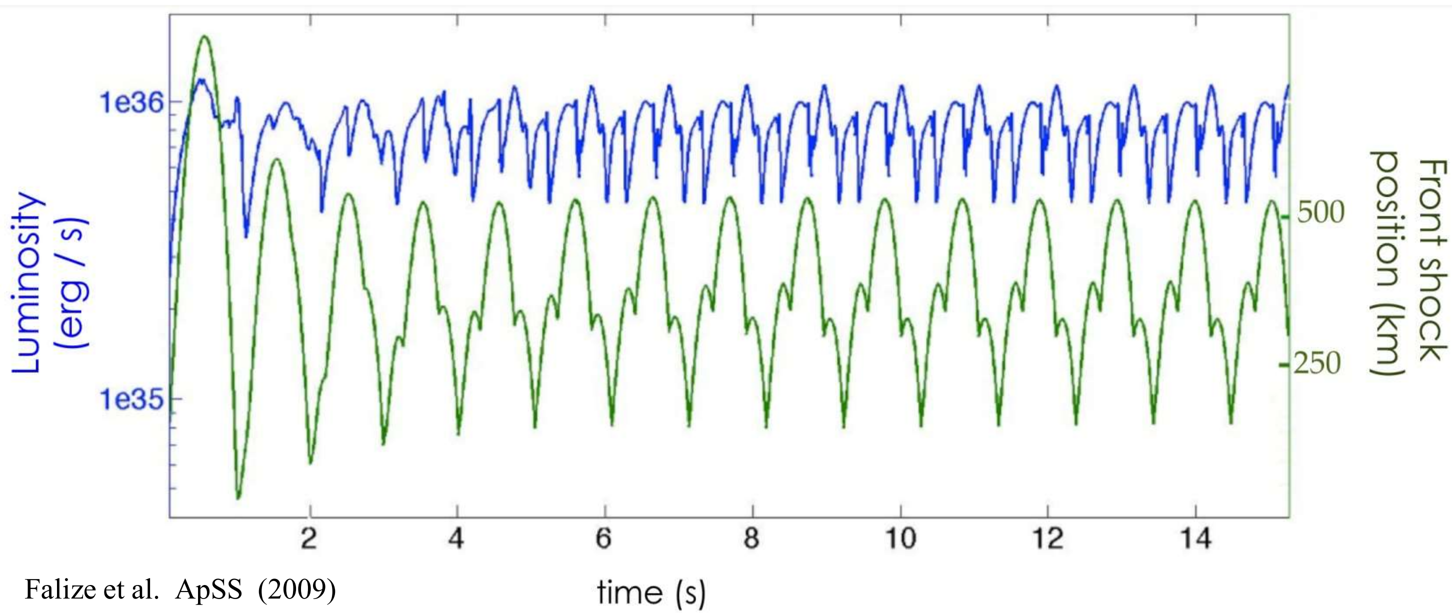
$$\frac{\partial v}{\partial t} = -v\frac{\partial v}{\partial r} - \frac{1}{\rho}\frac{\partial P}{\partial r} - \frac{\partial \phi}{\partial r}$$

$$\frac{\partial P}{\partial t} = -v\frac{\partial P}{\partial r} - \gamma P\frac{\partial v}{\partial r} - (\gamma - 1)(\Lambda_{bremss} + \Lambda_{cyc})$$

Cyclotron cooling:

Brehmsstrahlung cooling:

Langer S. et al. (1981)



MHD simulations

Falize et al. ApSS (2009)

Understanding the QPOs

- Current MHD predictions (e.g. RAMSES) are at variance with observations
  - X-ray QPOs are expected, but none detected from XMM-Newton survey of 24 brighter polars (Bonnet-Bidaud et al 2015)
  - Only for higher fractional area can amplitude limits be reconciled, but then the expected frequencies are much higher than observed

- X-ray
- optical

References/Acknowledgements

- *Accretion Power in Astrophysics :* J. Frank, A.R. King, D.J. Raine (Cambridge University Press, 1985)
- *Cataclysmic Variable Stars*: Coel Hellier (Springer 2001)

Some of these slides were provided courtesy of Axel Schwope (IAP)