Multi-Wavelength & Time Resolved Studies of Cataclysmic Variables

[With an emphasis on current & future work involving the Southern African Large Telescope (SALT)]

David Buckley

SALT Science Director & Astronomy Operations Manager

In collaboration with

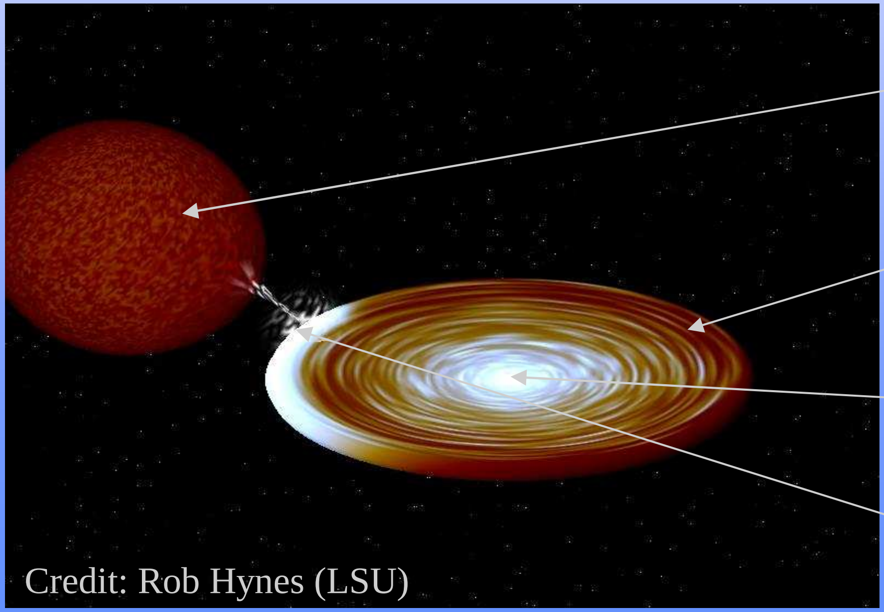
Janus Brink, Phil Charles, Marissa Kotze, Darragh O'Donoghue, Steve Potter, Encarni Romero Colmenero, Mellony Spark, & Ewald Zietsman (SAAO)

Brian Warner & Patrick Woudt (UCT)

Oswald Siegmund, Barry Welsh & Jason McPhate (UC Berekeley Space Science Lab)

What are Cataclysmic Variables (CVs)?

- Close binary stars involving (at some stage) mass transfer through Roche lobe overflow
- Orbital periods >80 min to many hours (for non-degenerate secondaries, at least)
- Accreting object is a White Dwarf
- Donor object is typically a low mass red dwarf (K-M)
- Accreting material typically form an accretion disc



Donor star

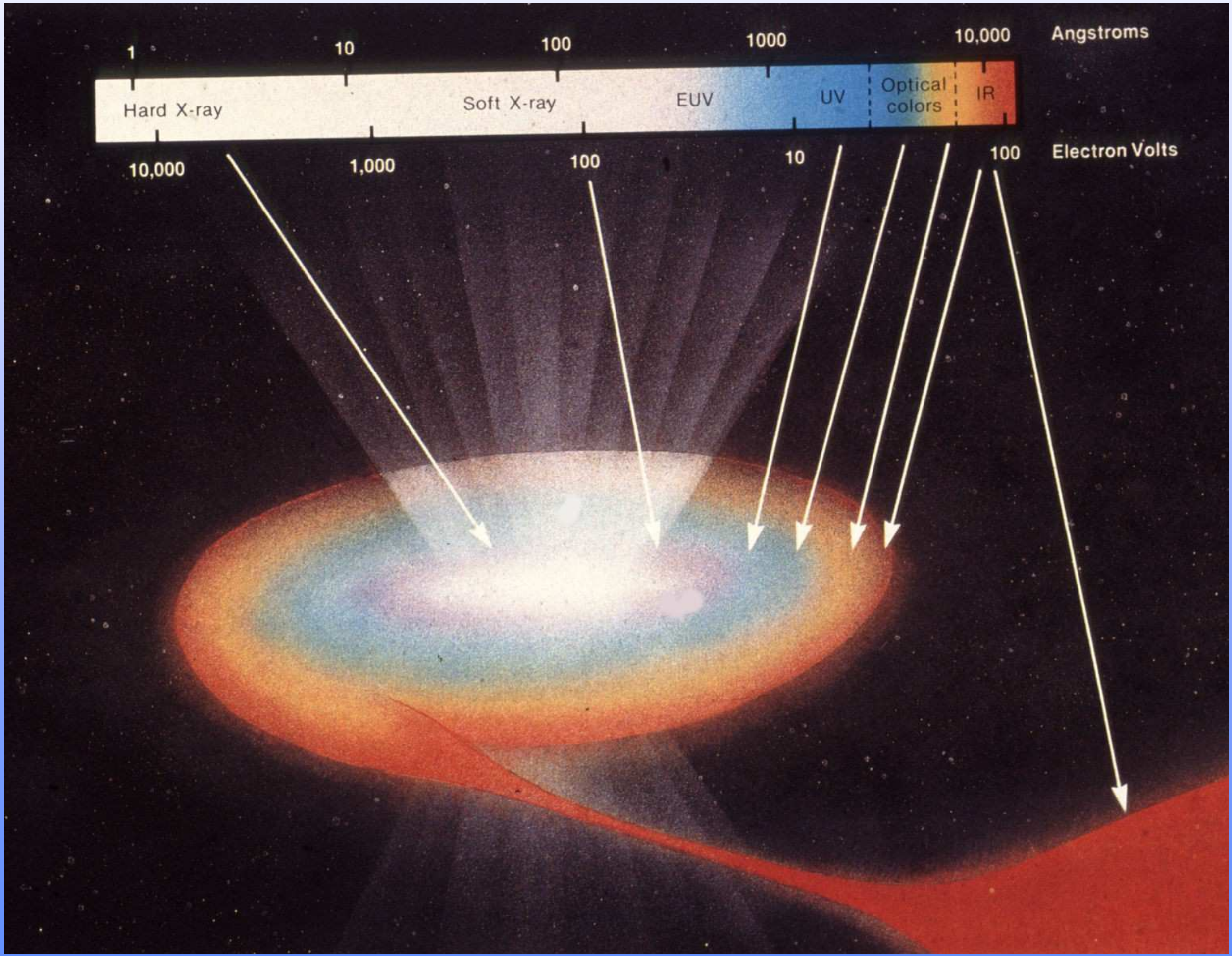
Accretion disc

White dwarf

Bright spot

What are Cataclysmic Variables (CVs)?

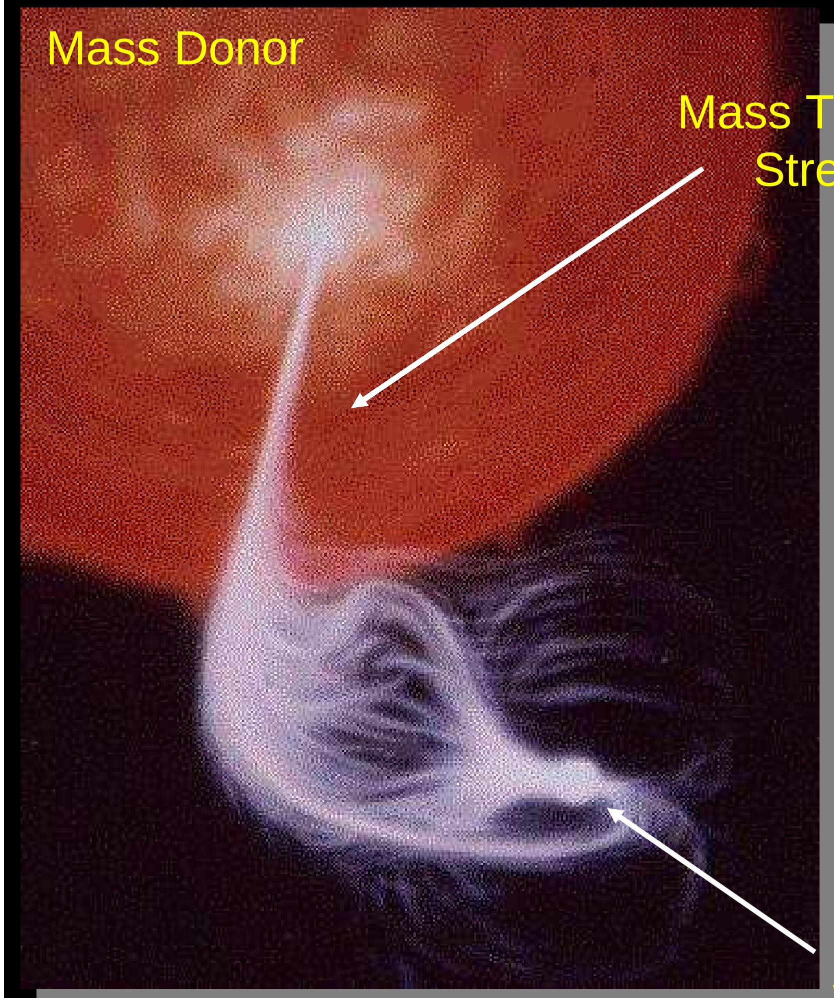
- **Variability is observed over all timescales (sub-sec to centuries)**
- **Emission over the whole E-M spectrum and from different regions**



What are Cataclysmic Variables (CVs)?

- **Accretion process determines the evolution and observational properties and accretion luminosity often dominates**
- **‘Outbursts’ can occur, due to accretion disk instability (Dwarf Novae) or thermonuclear reactions (Novae & Super Soft Sources)**
- **Many “flavours” of CVs, with observational characteristics determined by**
  - **Accretion rate**
  - **WD mass**
  - **Orbital period/binary separation**
  - **Disc viscosity**
  - **Magnetism**
- **CVs are also potential precursors to Supernova Ia**

Magnetic CVs: a wealth of Multi-λ emission



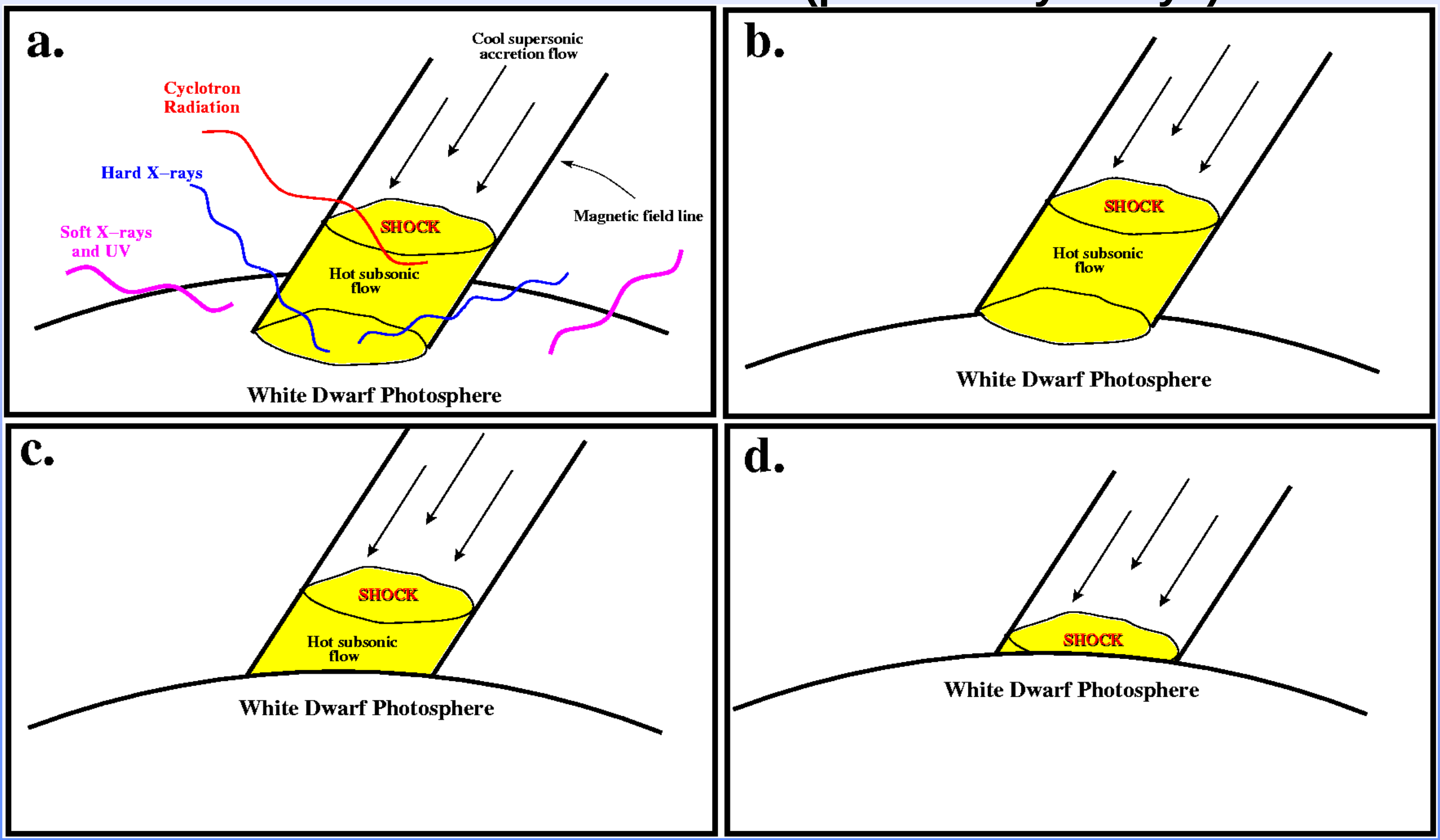
- Strongly magnetic white dwarf (10^1 – 10^2 G) inhibits accretion disc formation, or disrupts it
- Magnetic field channels accretion directly to magnetic poles of white dwarf
  - diskless systems: Polars
  - disrupted disc systems: Intermediate Polars
- Multi-λ emissionsites (X-rays, EUV, UV, optical, IR, radio), sites & mechanisms (thermal & non-thermal)
- Often discovered by virtue of X-ray emission from cooling shock

Probing Accretion Shocks

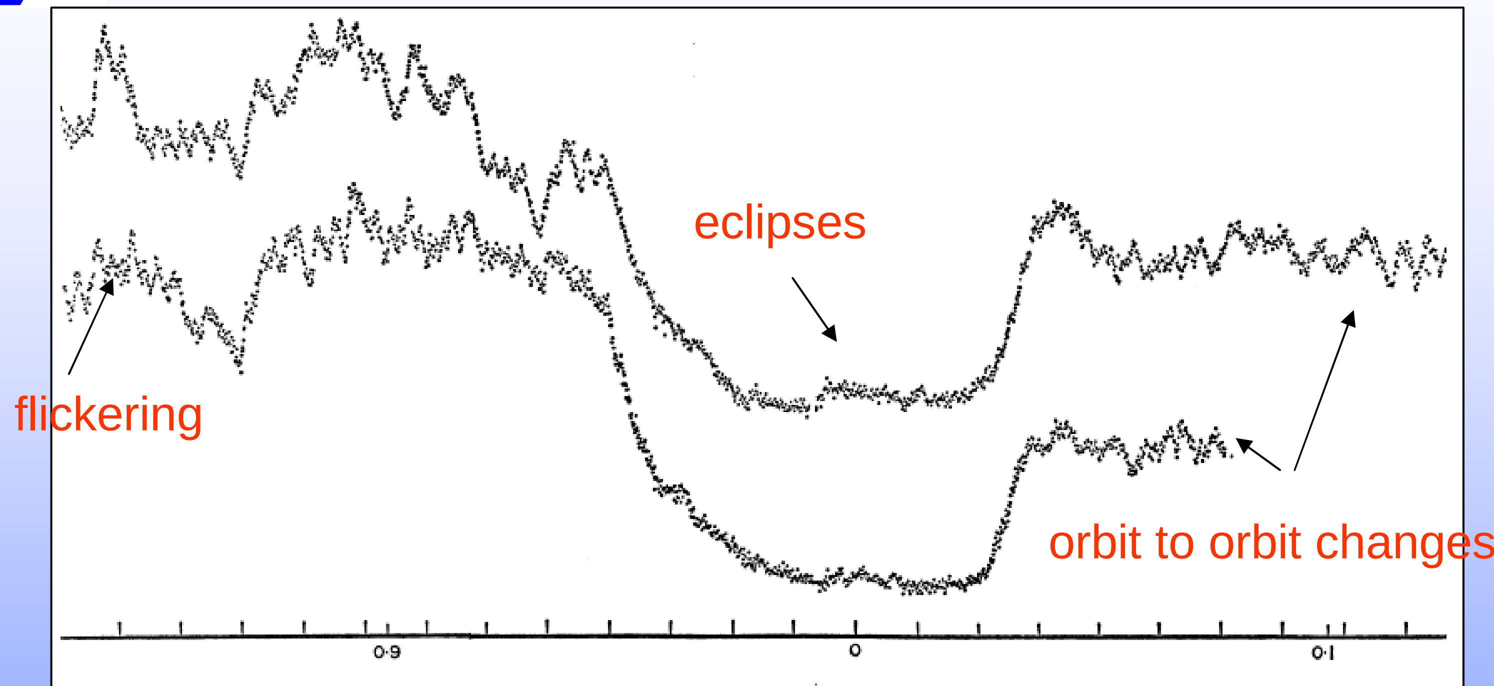
Self-occulting of accretion columns as WD rotates allows shock regions to be sampled. Resolve stratified temp profile?

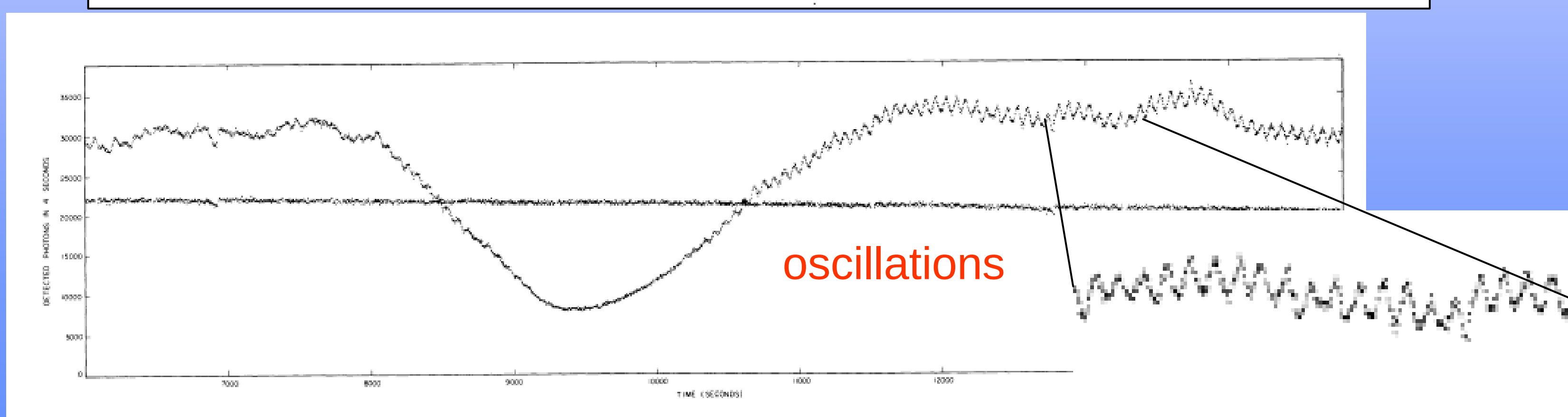
Needs:

- **time resolution (fast observations & readouts)**
- **signal-to-noise (large collecting area, *like SALT*)**
- **simultaneous obs at other λ (particularly X-rays)**



Optical Intensity Variability in CVs: typical example





What science can we do?

- **Binary Evolution**
  - Measure M_2, R_2 as a function of period
  - Evolution theory invokes stellar models (atmospheres and evolution), angular momentum loss (GR, dynamos and wind loss) and common envelope evolution

- **White Dwarfs**
  - Asteroseismology, compressional heating

- **MHD**
  - Potential to measure
    - » Dynamics of gas stream/B-field interactions
    - » Warping and Precession of Discs
    - » Location and energetics of flickering

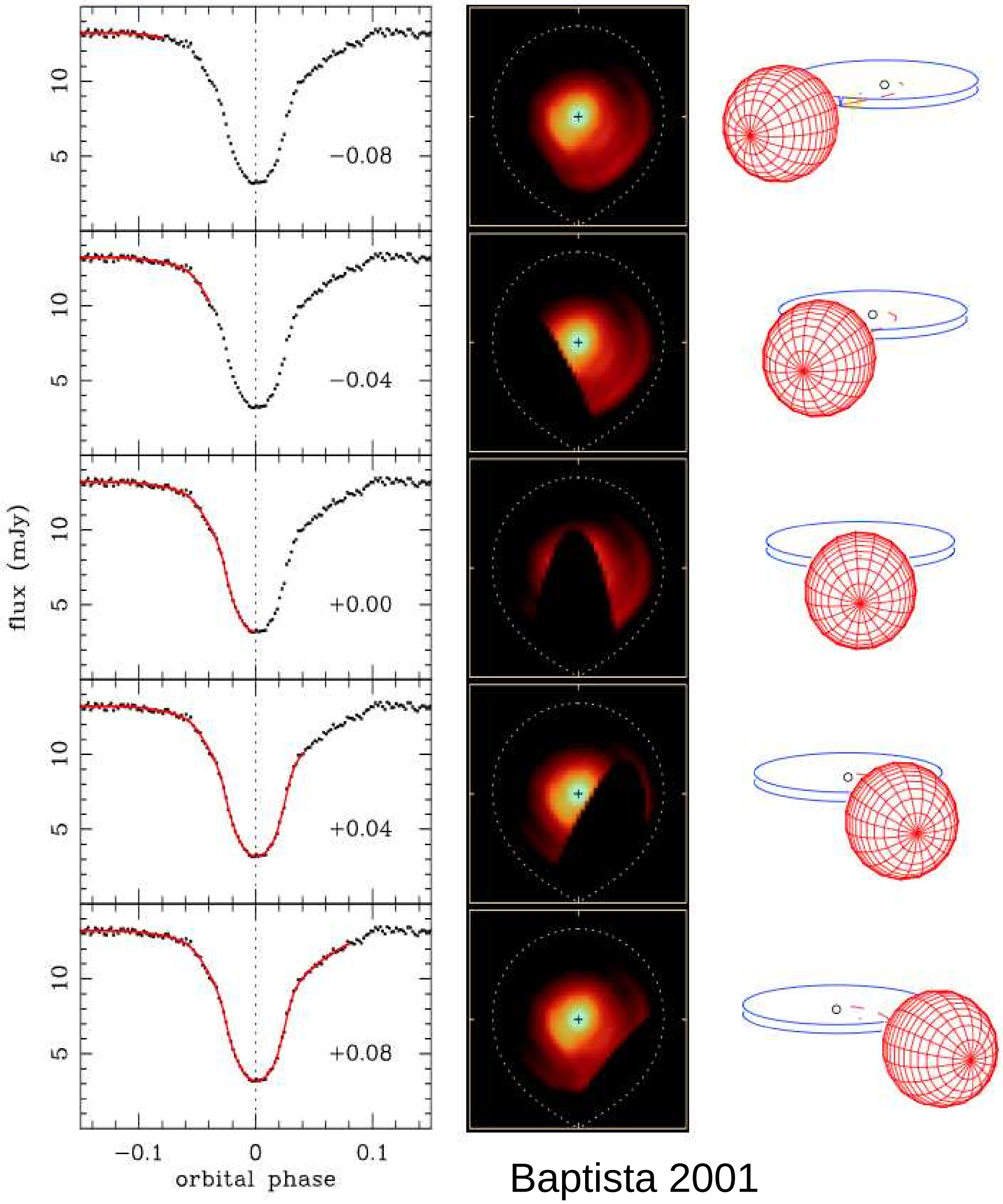
  - CVs are excellent test-beds for top-end MHD codes

Examples of analysis tools

- Eclipse mapping: **eclipses by the Roche lobe of the companion**
- Doppler tomography: **Doppler motions of up to 10^3 -10^4 km/s**
- Echo mapping: **light travel time delays (seconds), for flares etc**

<u>Eclipse Mapping:</u>

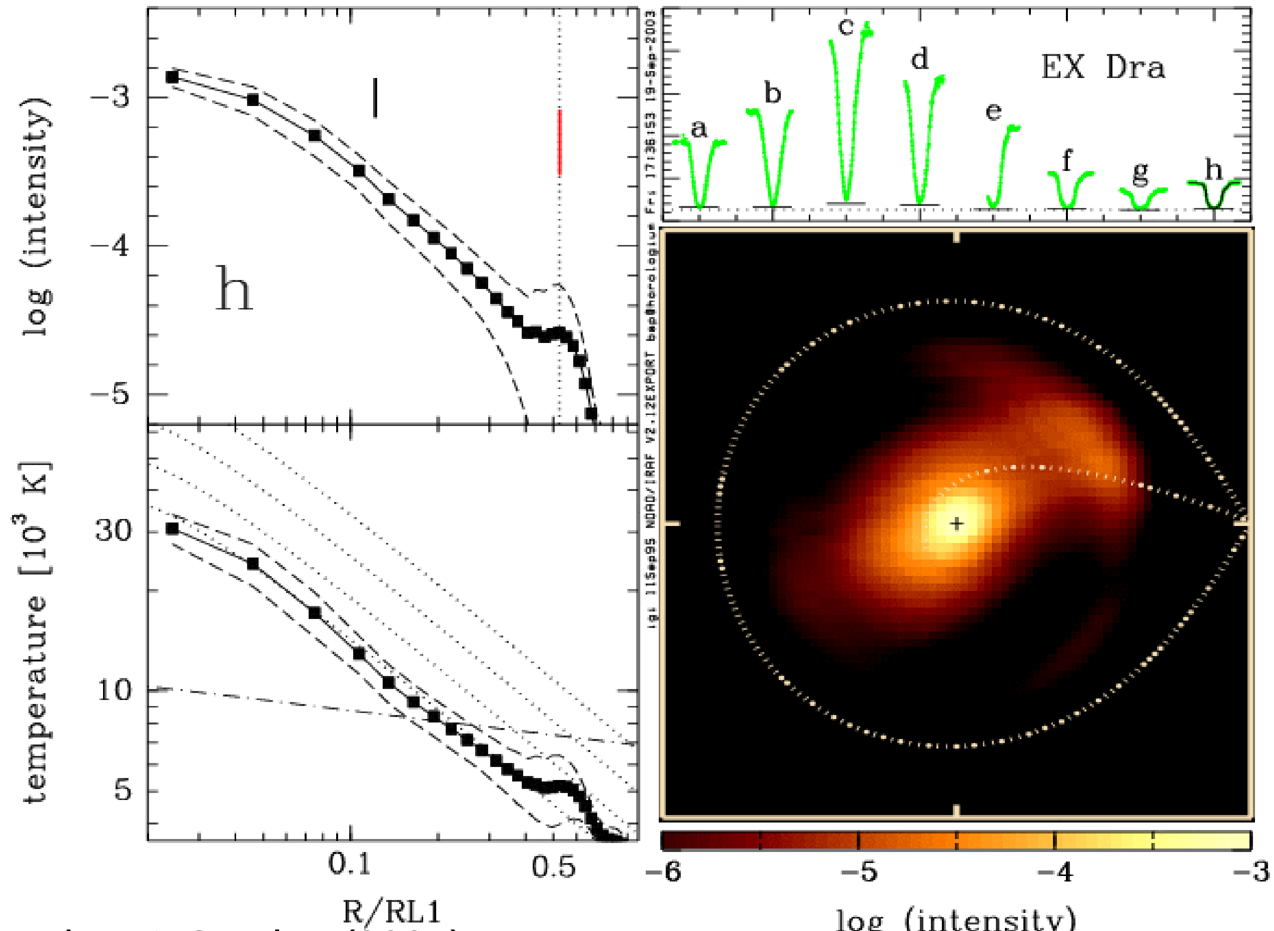
- **Flux through eclipse is given by a series of slices across the accretion disc**
- **As in medical tomography, the slices can be used to reconstruct the original brightness distribution**



Baptista 2001

Eclipse Mapping Movies

- **Construct eclipse maps at different points in the outburst cycle**
- **“Movie” of disc evolution over time**

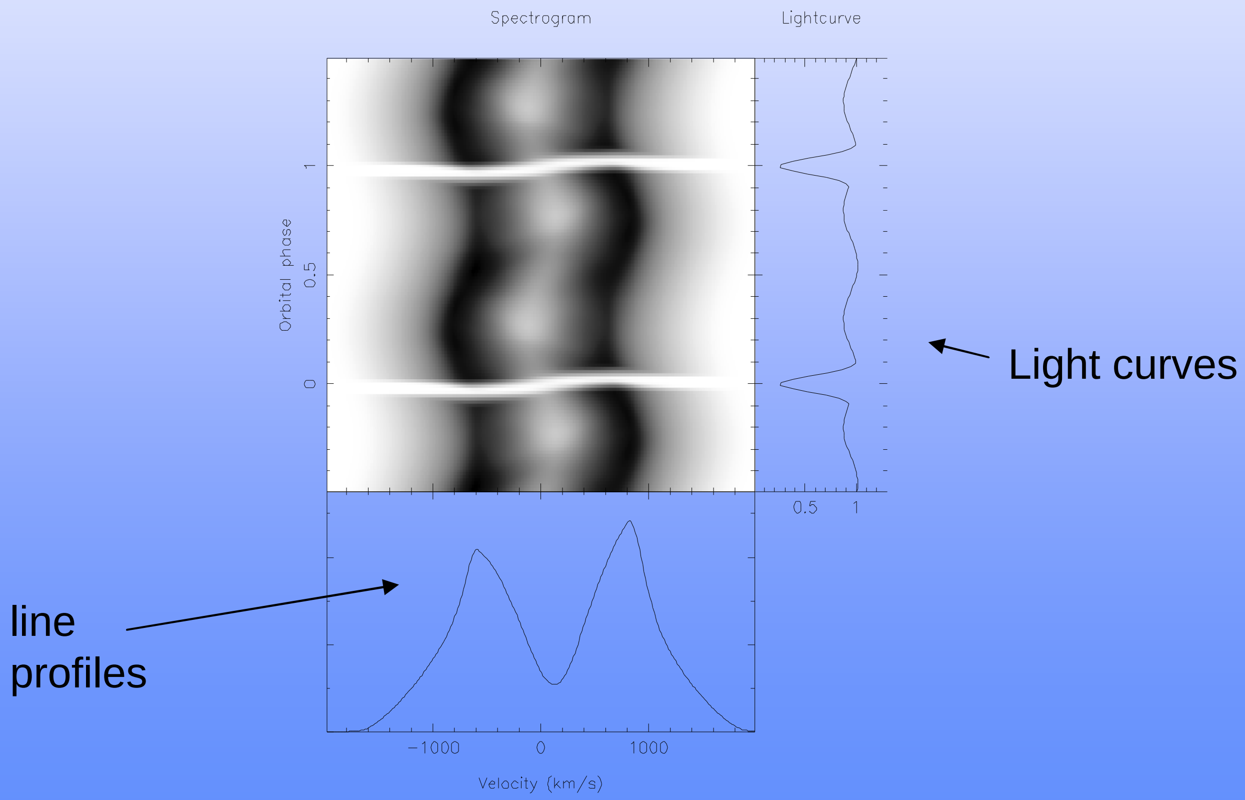


Baptista & Catalan (2001)

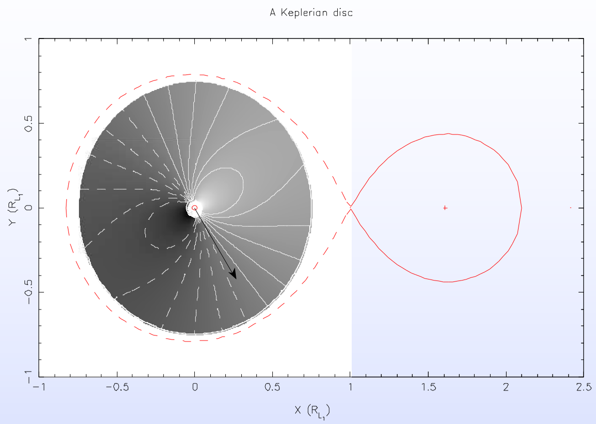
Doppler Tomography

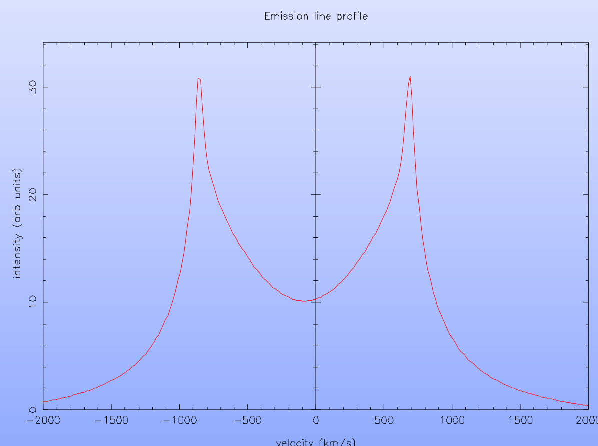
- **Angular extent of typical CV (binary separation ~ few $R_{\odot}$, d ~ 100 pc) is ~10^{-6} arc second**
  - **Will never get direct images!**

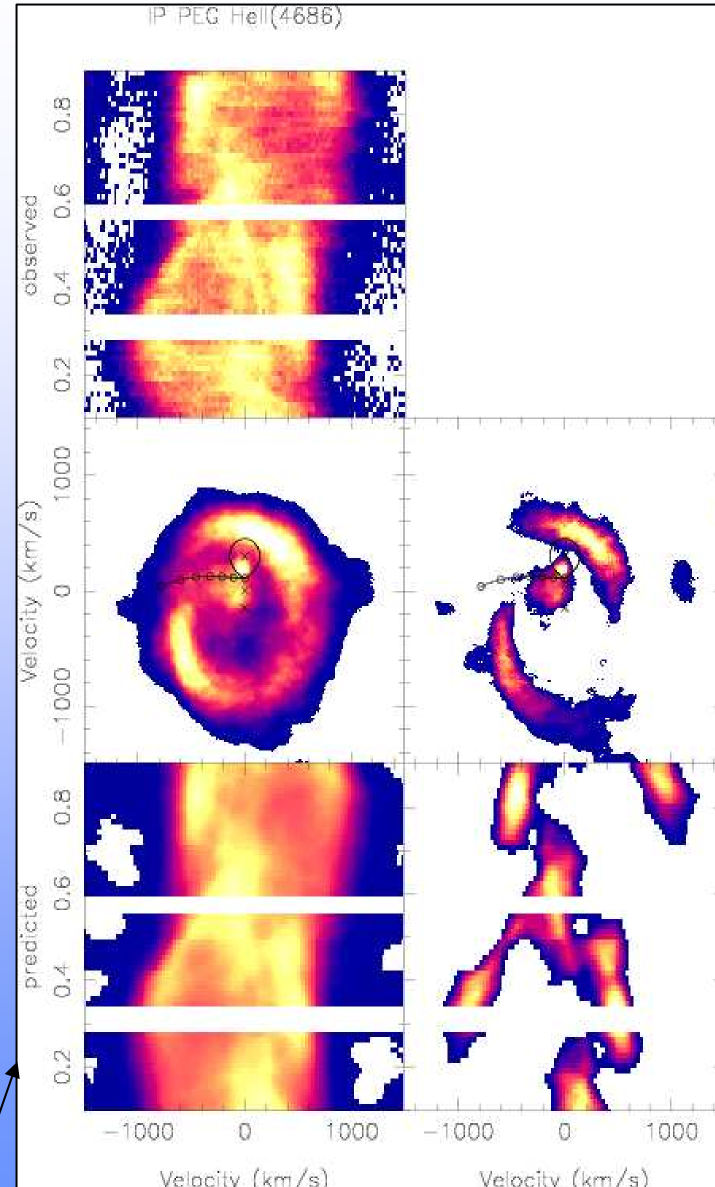
- **Indirect image reconstructions exploit the changing view that is provided across the binary orbit**



Doppler Tomography







Broad emission lines from the supersonic disc flow

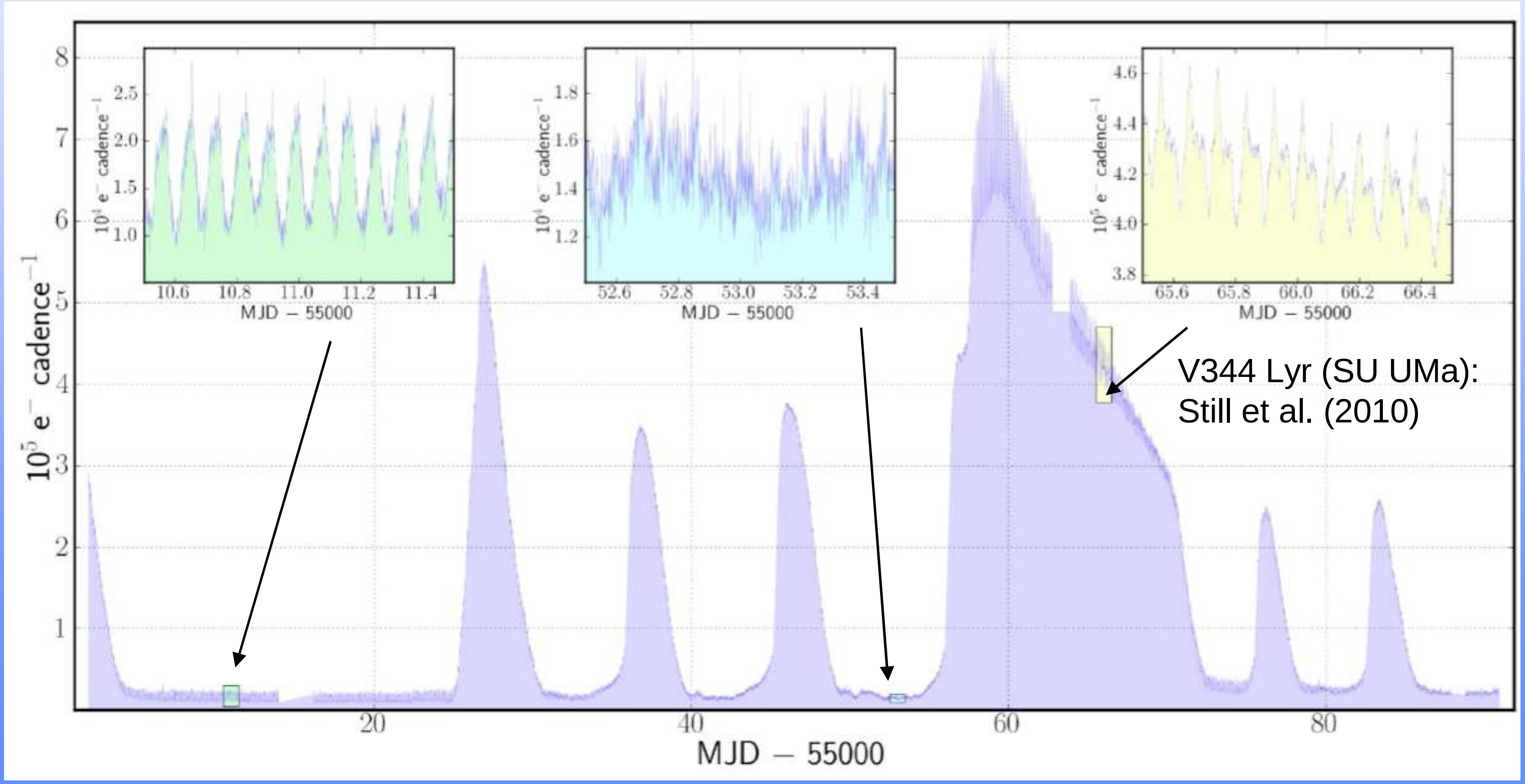
- **standard method to map the velocity structure of accretion discs**
- **need to have good phase coverage and ideally many consecutive orbital cycles**

Spiral waves in the accretion disc of IP Pegasi

Synoptic Monitoring Observations

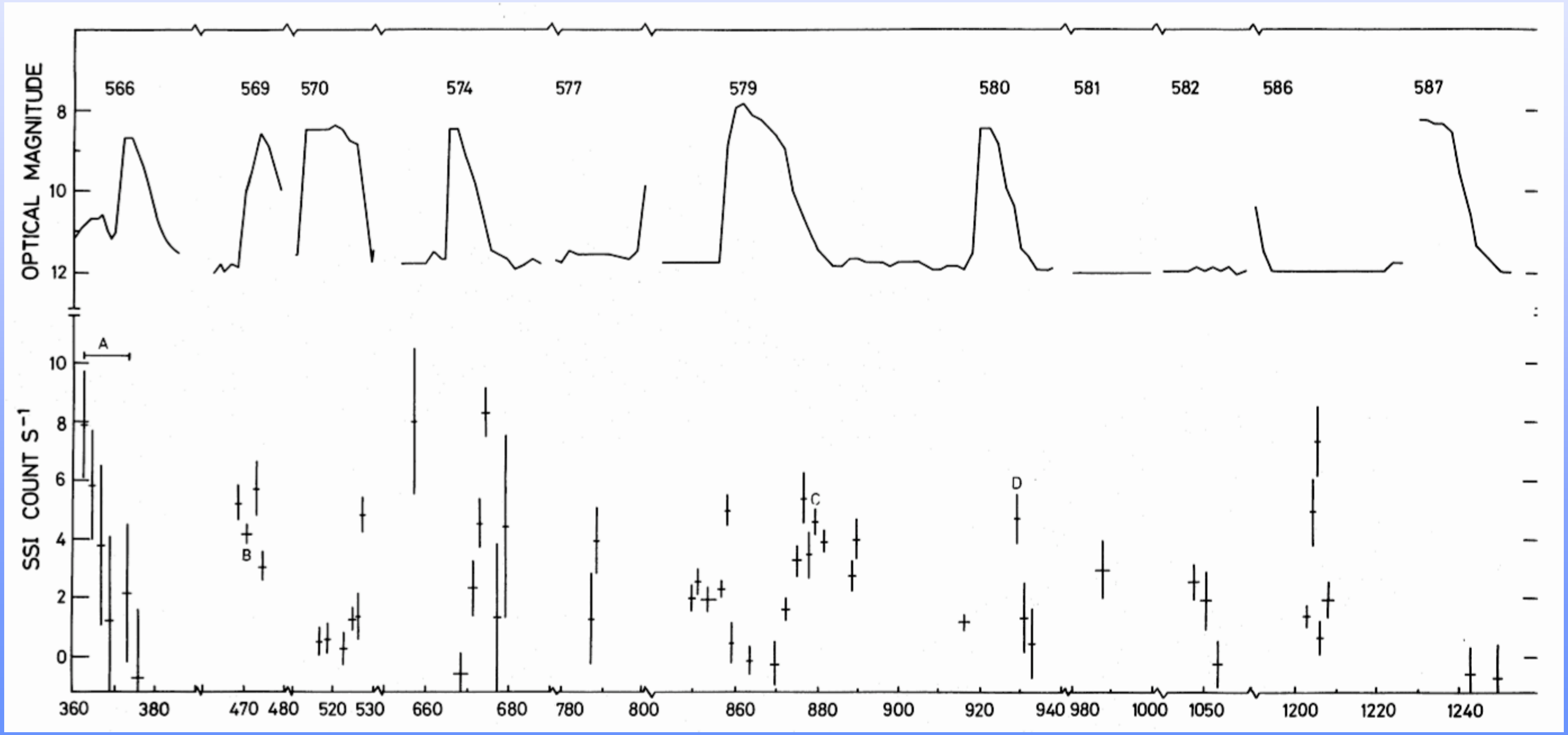
- **Because many CVs are *variable* in luminosity over many timescales (days, weeks, months, years), a true picture of a given system requires regular monitoring**

- **Amateur astronomers (e.g. AAVSO) have, for along time, been the mainstay of monitoring state changes in CVs**
- **Now many robotic ground-based telescopes and satellites are assisting in this (e.g. CBA, RXTE ASM, Kepler)**



Simultaneous Multi-wavelength Observations

- **Because of stochastic changes, even over short timescales (several orbital cycles), simultaneous observations at different wavelengths are most useful.**
- **First pioneered by X-ray-UV-optical observations (e.g.SS Cyg with Ariel V)**



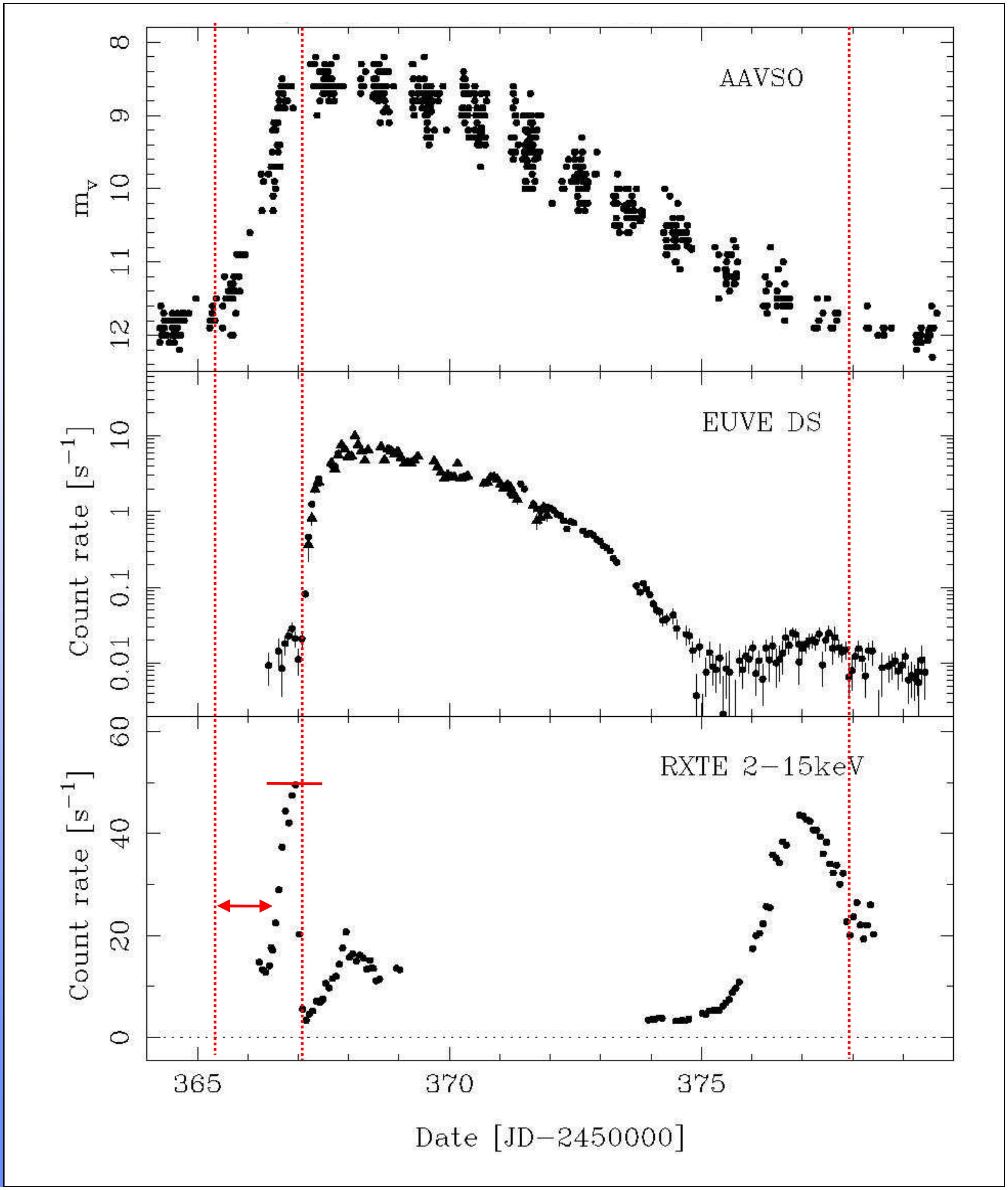
Ricketts, King & Raine 1979

More recent SS Cyg example:

- **Optical (AAVSO), EUVE & RXTE observations of SS Cyg (Wheatley, Mauche & Mattei 2003)**

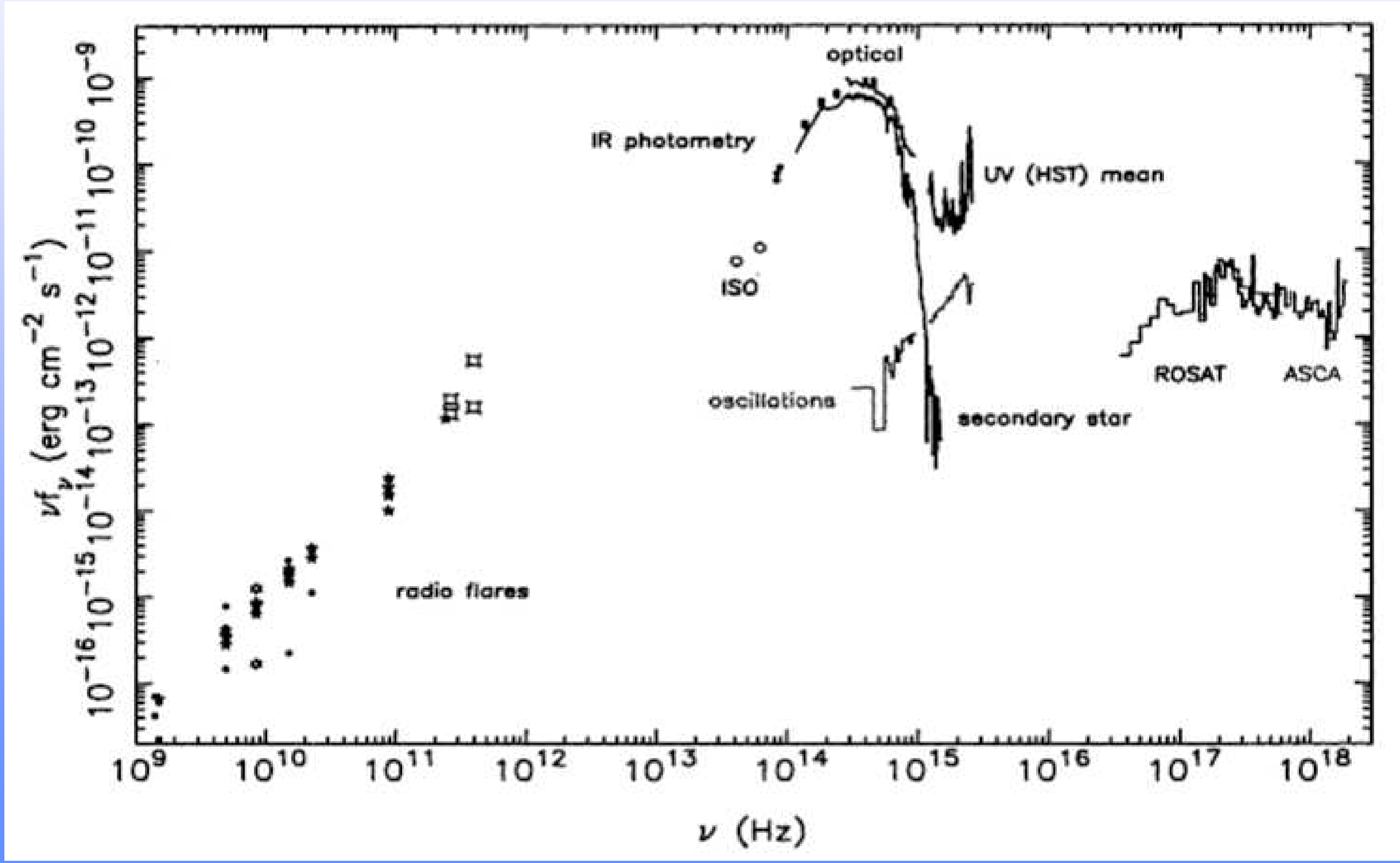
- **Time delay shows the time taken for heating wave to travel through disc.**

- **Peak flux tells us accretion rate at which BL becomes optically thick.**



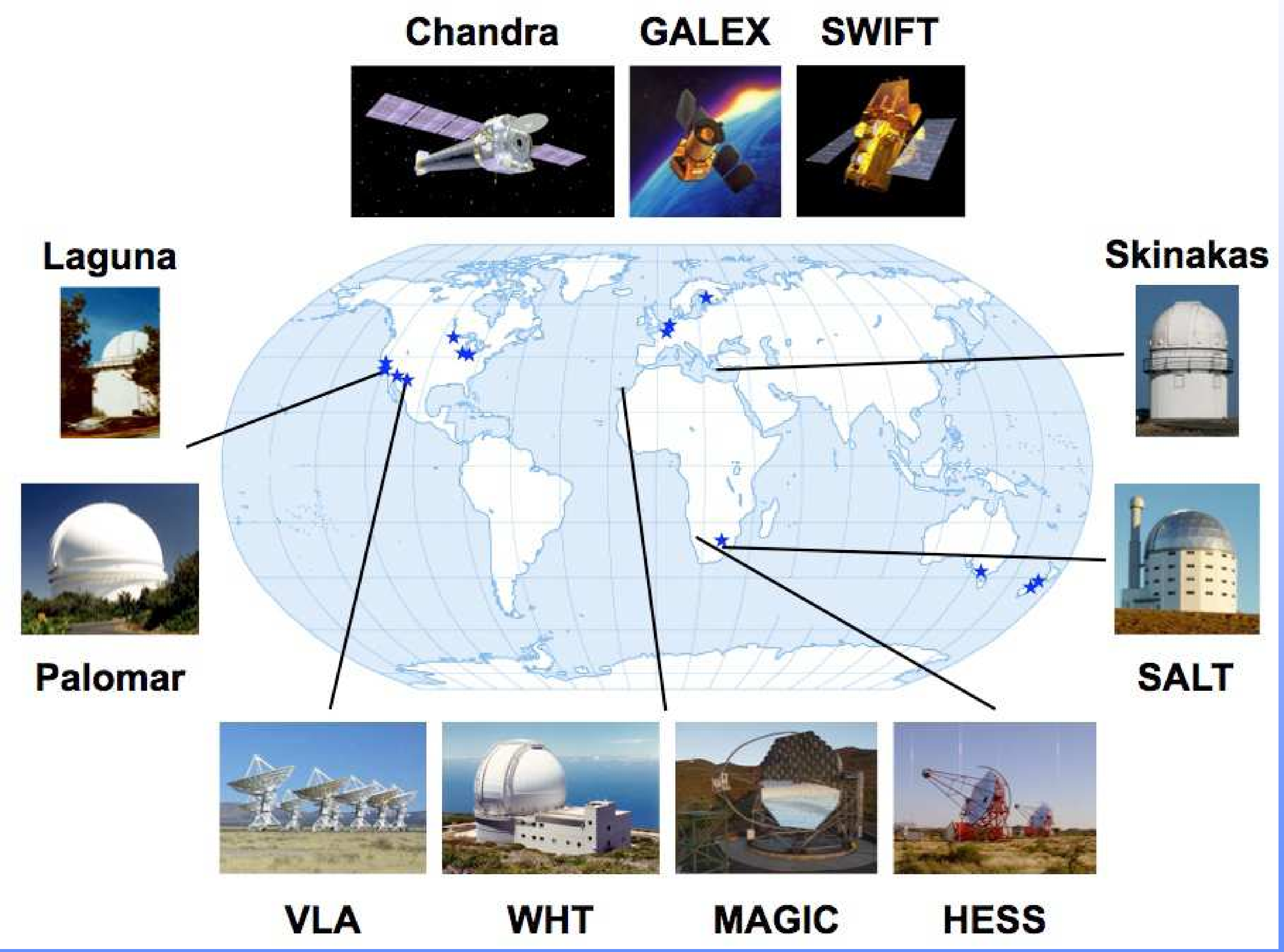
Simultaneous Multi-wavelength Observations

- **Multi-wavelength / multi-telescope / multi-site observations are extremely productive**
- **Recent example was the 2005 campaign on AE Aqr (Mauche 2009)**
- **Not really a typical CV, but a good example of a multi-λ campaign**



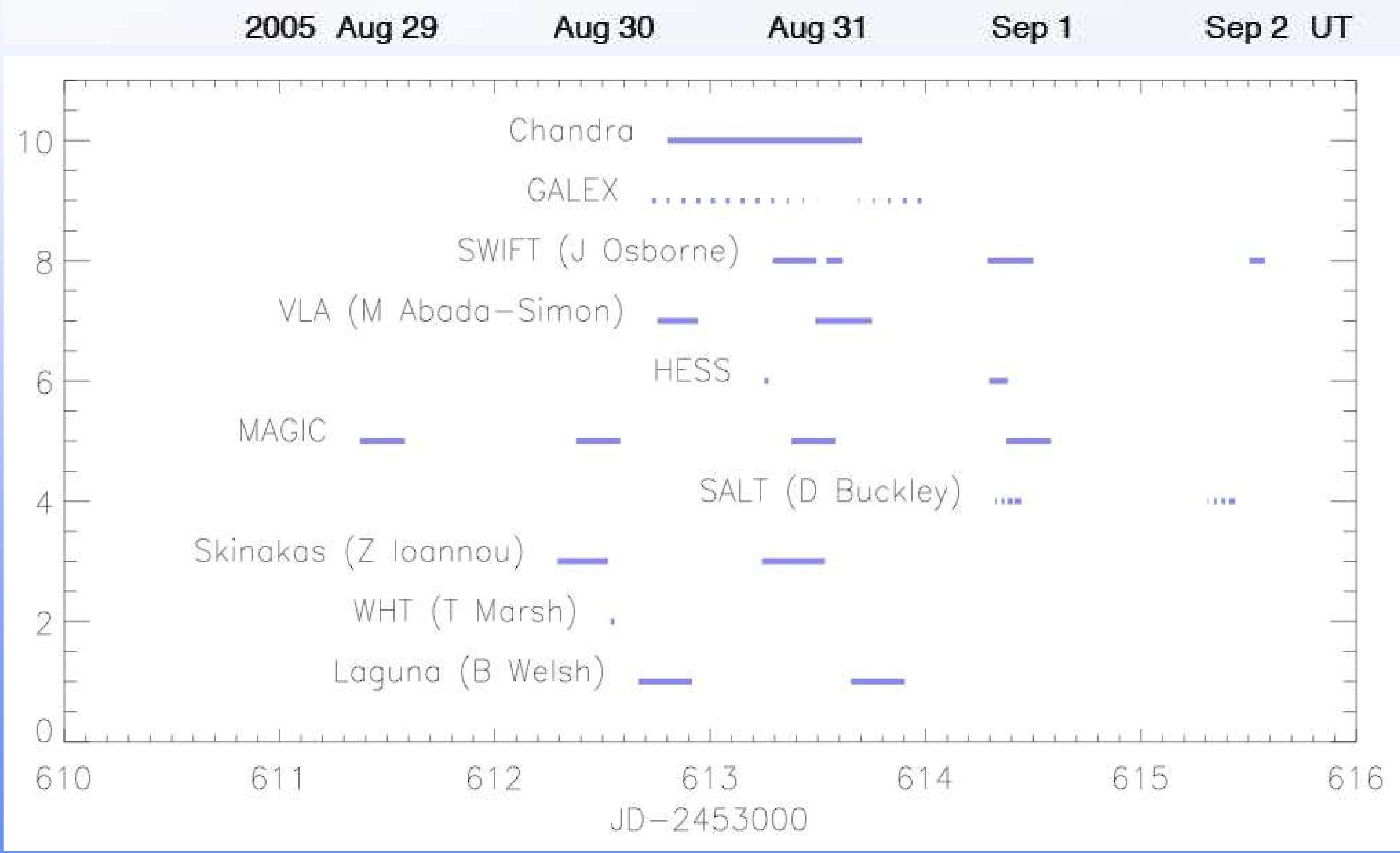
Simultaneous Multi-wavelength Observations

- **Campaign involved 3 satellites and 8 ground-based telescopes**



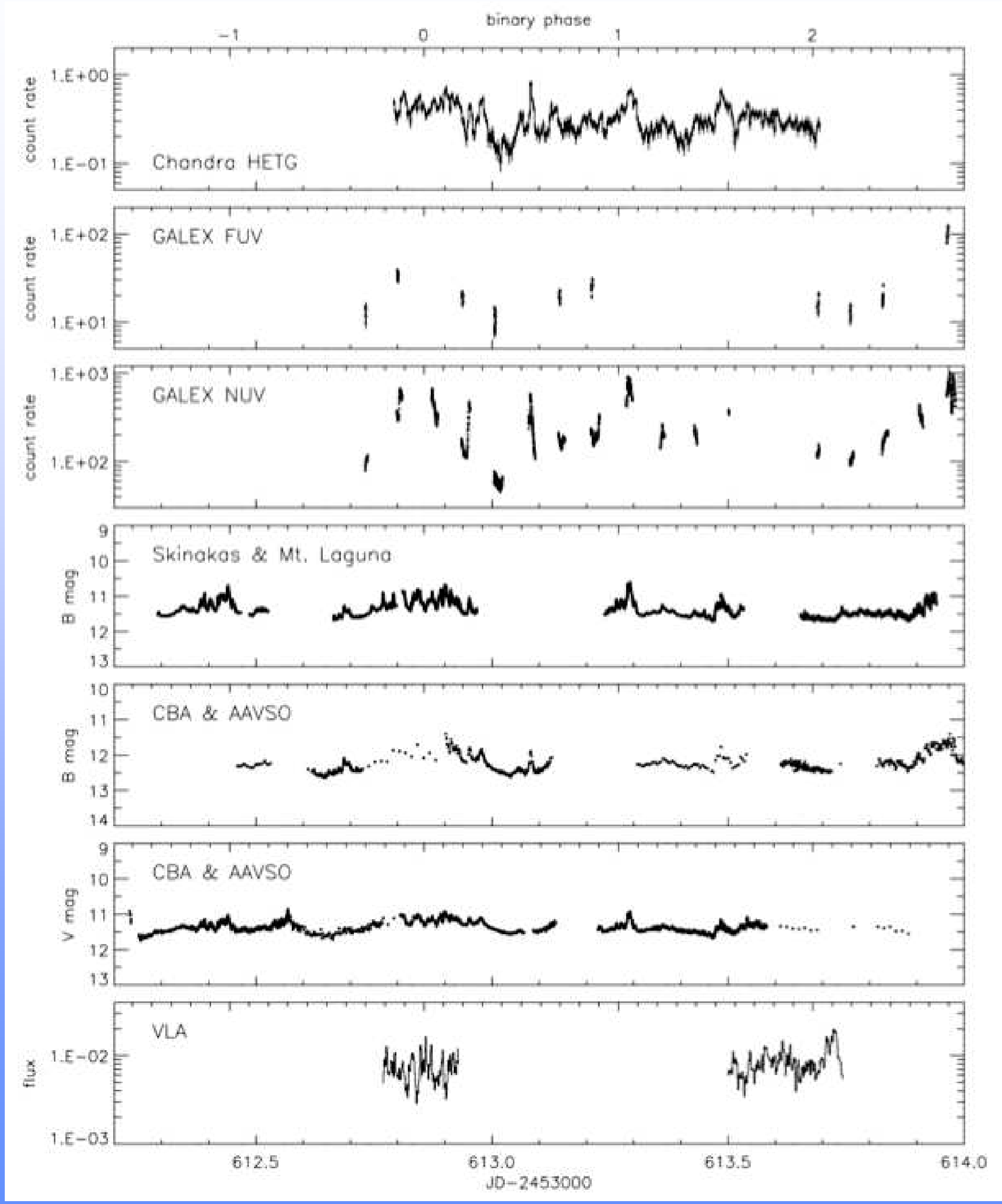
Simultaneous Multi-wavelength Observations

- **2005 AE Aqr campaign covered radio, optical, UV, X-ray & γ-ray**



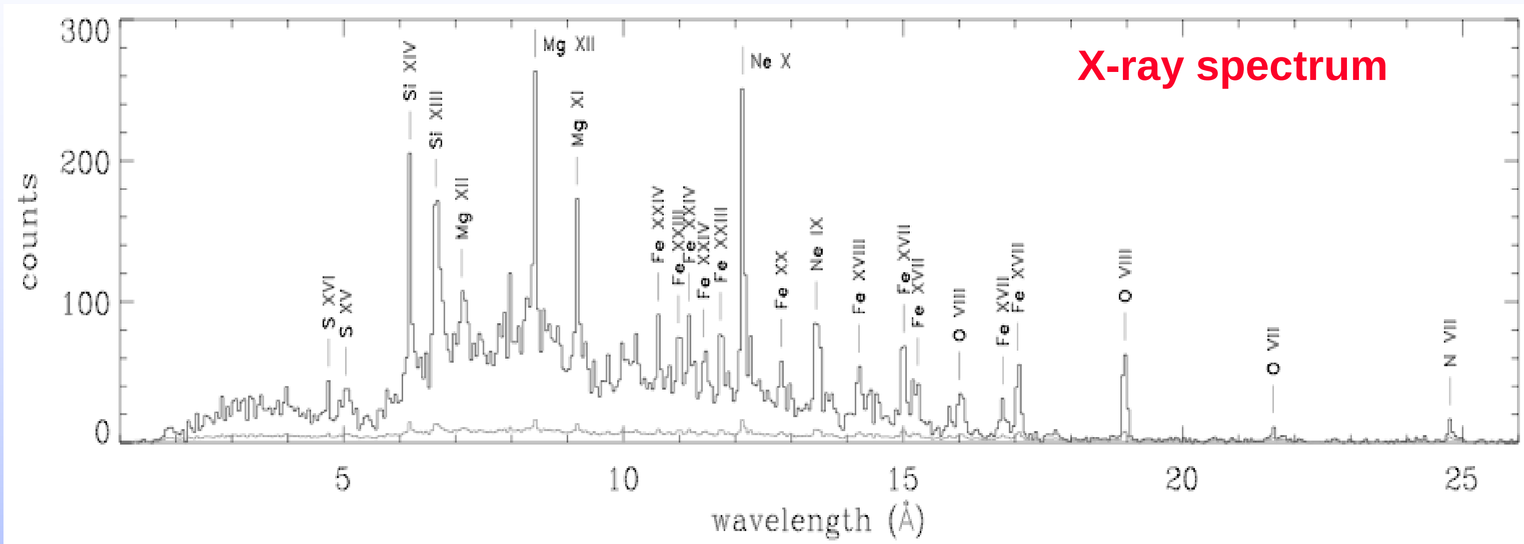
Simultaneous Multi-wavelength Observations

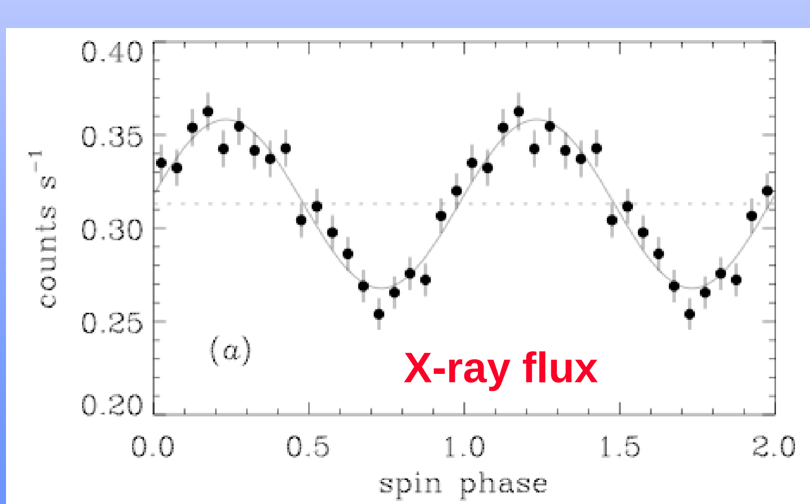
- **Correlated flares and spin modulation (33 sec) observed in optical & X-rays**
- **No correlation with radio**
- **No detection at TeV wavelengths (MAGIC or HESS)**
- **Mauche concludes that AE Aqr is *not* a TeV source**

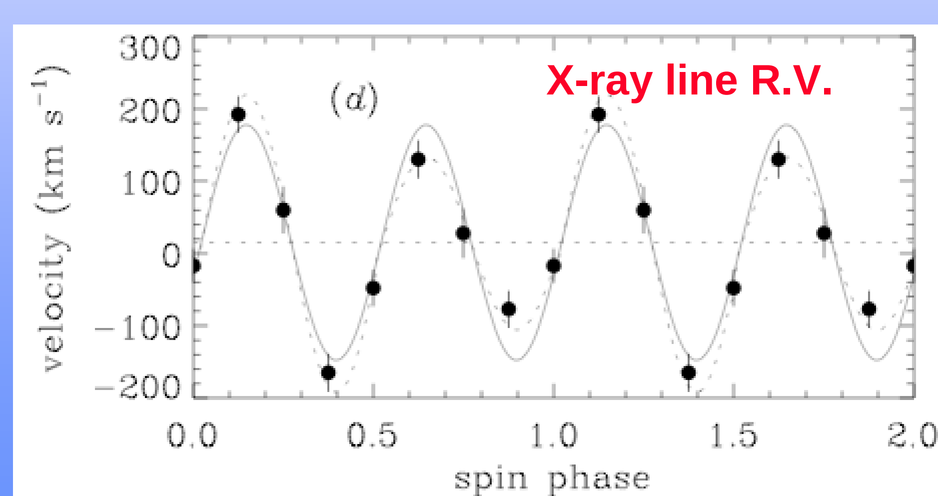


Simultaneous Multi-wavelength Observations

X-ray spectral observations (Chandra HETG) of AE Aqr



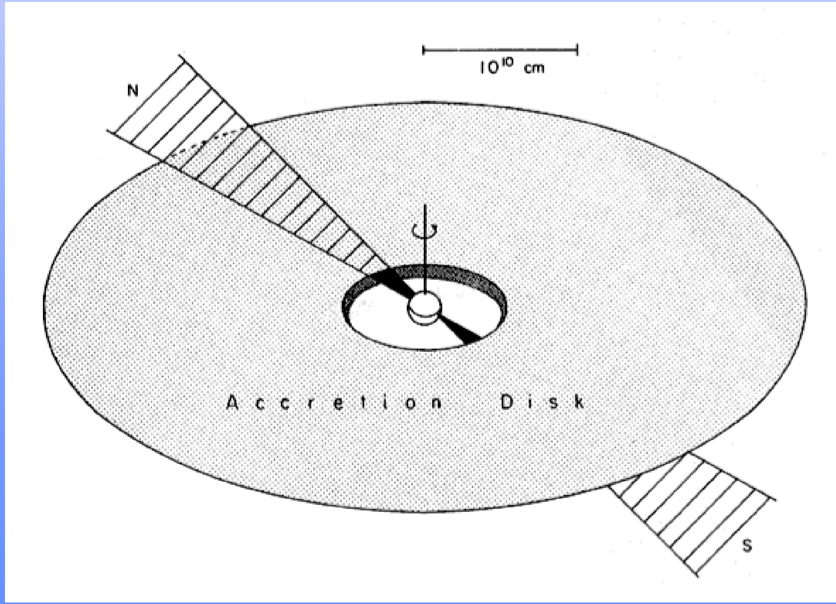


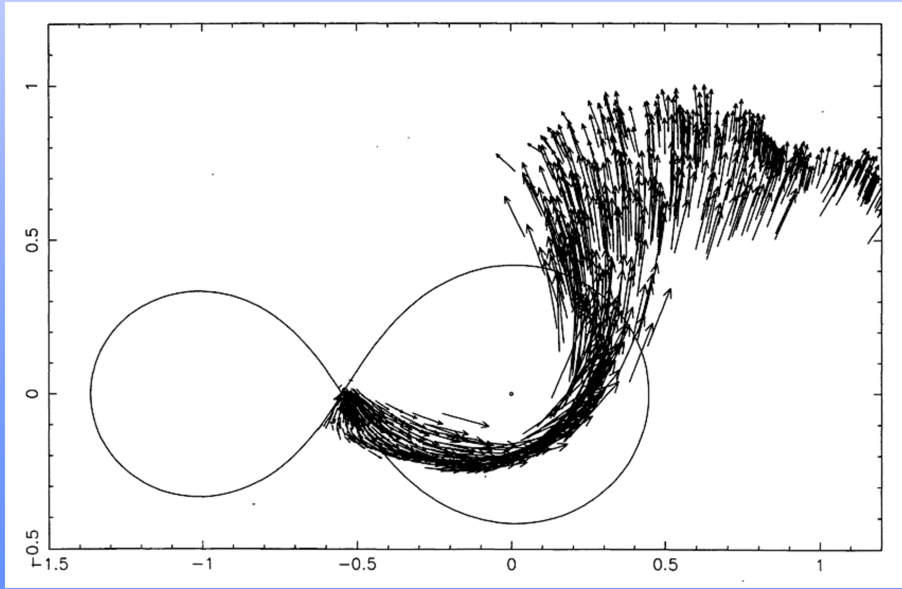


Simultaneous Multi-wavelength Observations

Conclusions from the 2005 AE Aqr campaign

- The pulsating component of the X-rays follows the motion of the white dwarf around the binary center of mass.
- The X-ray emitting plasma in AE Aqr has a *much* smaller spatial extent than previous estimates (more localized)
- The radial velocity of the X-ray emission lines varies on the white dwarf 33 s spin phase, with two oscillations cycle, broadly consistent with plasma trapped, and rotating with, the white dwarf's dipolar magnetic field.
- This is consistent with the originally postulated oblique rotator model (e.g. Patterson 1979) rather than the more recent propeller model (Wynn, King &Horne 1997).

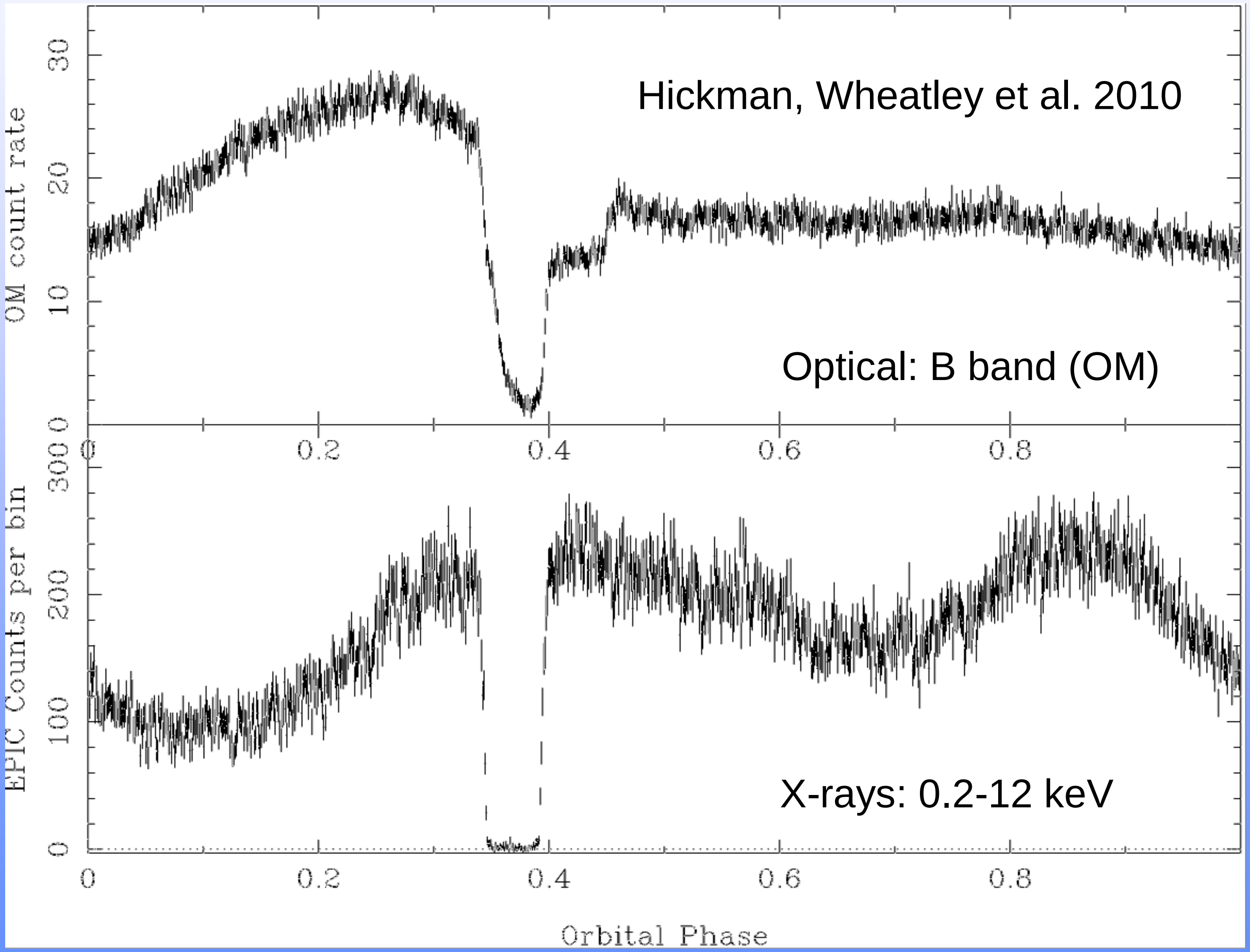




Simultaneous Multi-wavelength Observations

Other examples:

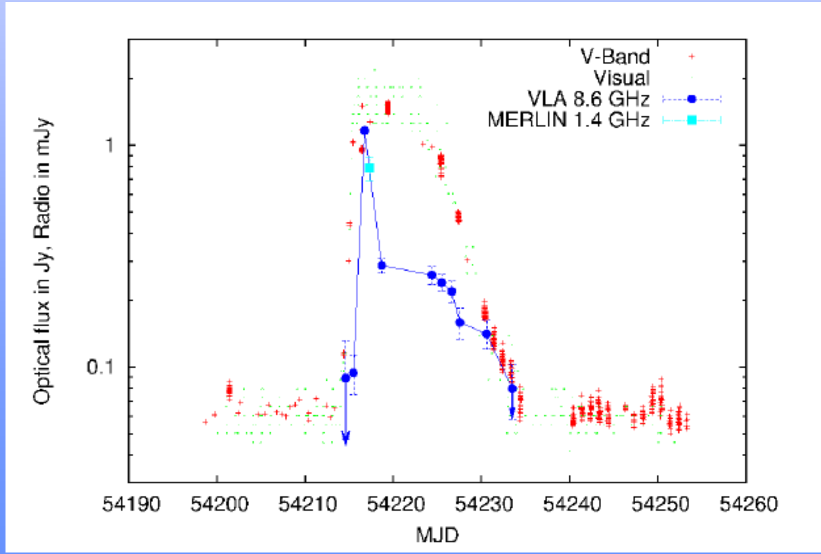
- **Z Cha observed with XMM-Newton**



Multi-wavelength Observations

Other wavelengths:

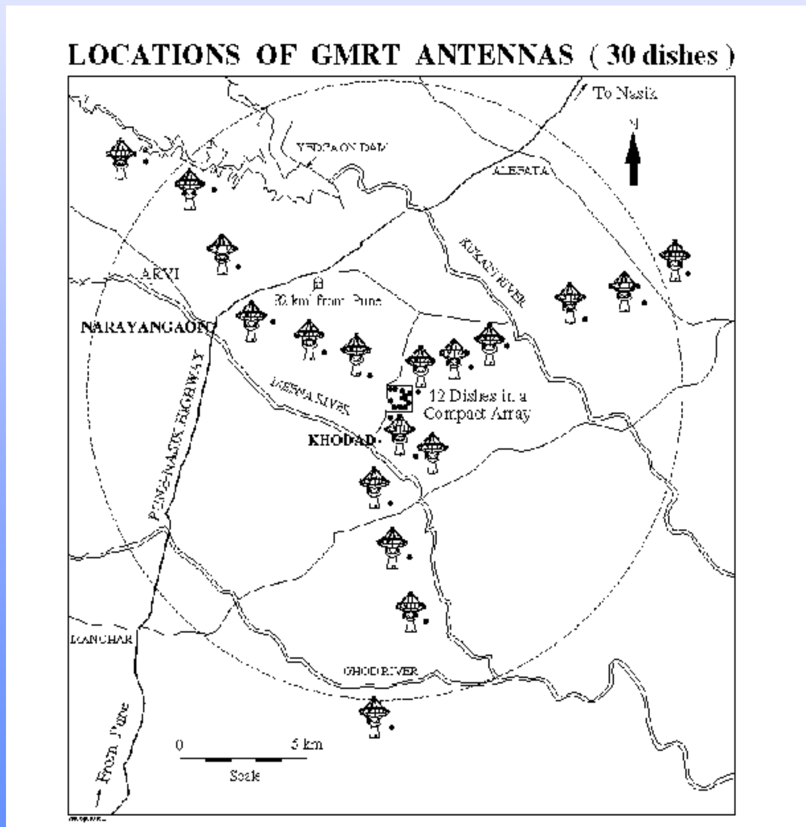
- **UV-FUV-EUV region**
  - **Hot thermal sources (e.g. disc boundary layer)**
  - **Disc winds**
- **Near IR region**
  - **Probes cool thermal sources (e.g. secondary star photospheres)**
  - **Non-thermal sources (e.g. cyclotron emission in magnetic CVs**
- **Radio region**
  - **Only 3 CVs have been detected as *persistent* radio sources (plus 1 pre-mCV, V471 Tau)**
  - **All are magnetic CVs (AM Her, AE Aqr & AR UMa)**
  - **Synchrotron emission from magnetospheric interactions (secondary & WD) and generation of electric fields (dynamo)**
  - **SS Cyg has been detected in a radio flare event**



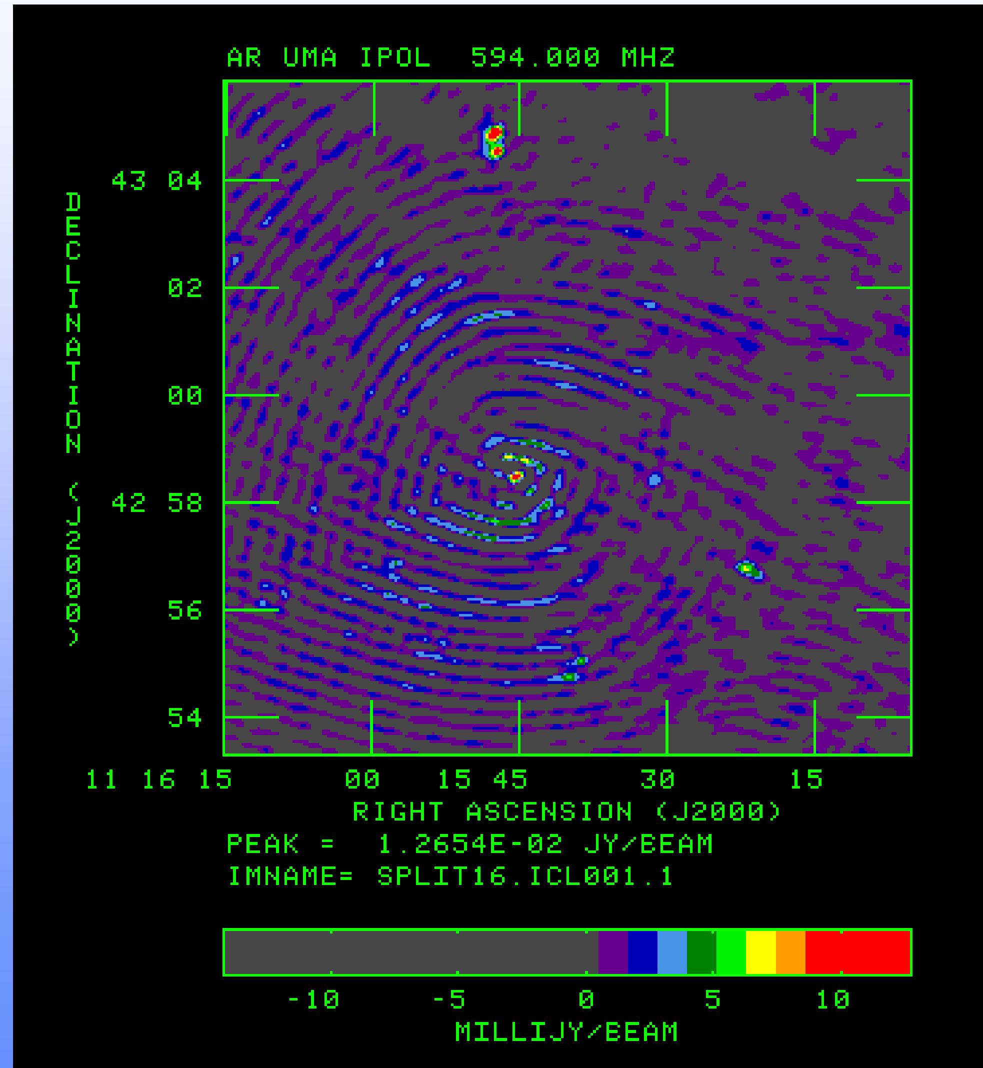
Multi-wavelength Observations

Other wavelengths:

- **Radio region**
  - **AR UMa observed by GMRT (Mason et al. 2009)**



GMRT 50 cm map during low accretion state

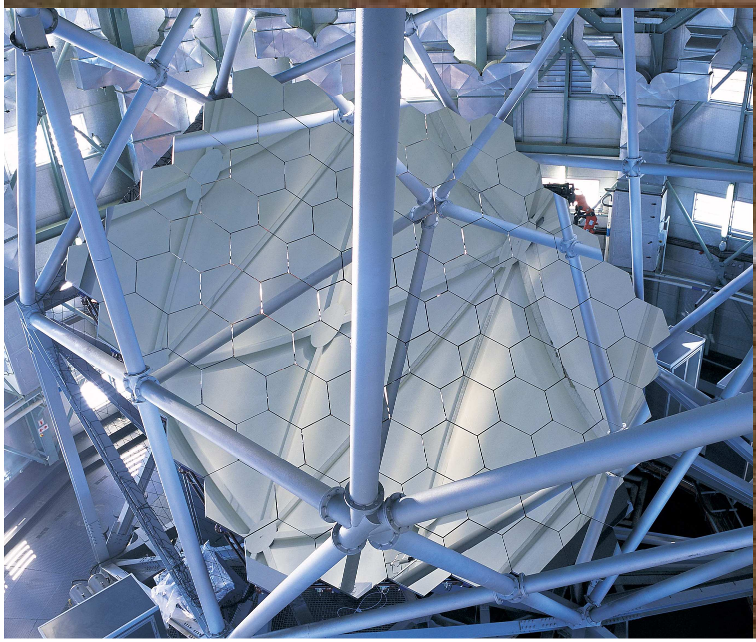


High Time Resolution Astronomy

- **Used to probe rapid variability: excellent tool for multi-λ CV research**
- **Can be used to better constrain the dimensions or geometry of compact emitters**
- **HTRA has become an new frontier in many branches of astronomy**
  - **Observations of compact objects (WDs, NS, BH)**
  - **Studies of compact accretion powered objects, like CVs & X-ray binaries**
  - **Non radial oscillations in stars**
  - **Planetary astronomy (occultations, transits)**
  - **Transients (e.g. Novae, SNe, GRBs)**
- **Powerful tool, particularly when combined with simultaneous multi-λ observations**
- **Requires high-speed detectors with little or no deadtime**
  - **Ideally photon counting detectors (for time res), but QE better with CCDs (EM-CCDs now offer best of both)**
- **HTRA & multi-λ astronomy are major science drivers for SALT**

The Southern African Large Telescope: ‘sister’ of the HET, but with improvements

- currently the single largest optical telescope in the southern hemisphere
- 10 m x 11 m array of 91 of 1.2-m segments (78 m^2 glass)
- SALT Construction Phase phase completed in Nov 2005
- Commissioning & Performance Verification & early science since then
- Early science has exploited HTRA
- SALT has some rare capabilities (λ down to 320nm, polarimetry, F-P, fibre-fed hi-res vacuum spectrograph)
- After a period of solving engineering problems, SALT is in final stages of commissioning and full science operations will begin mid-2011

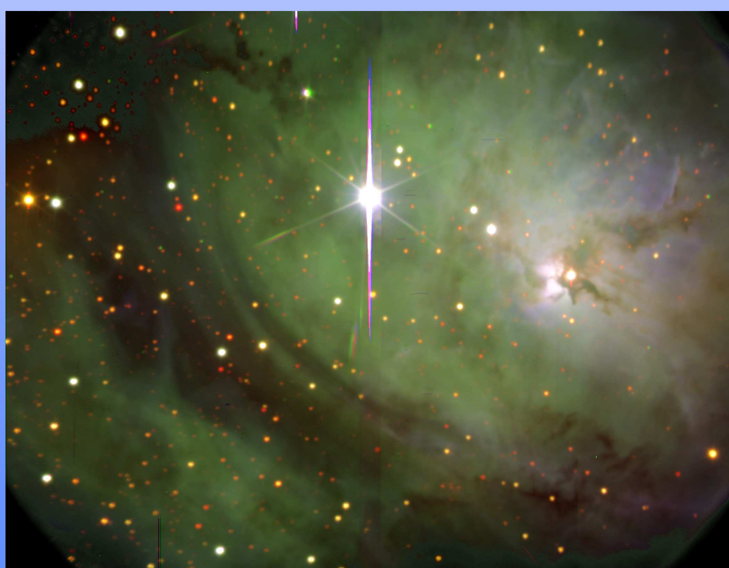


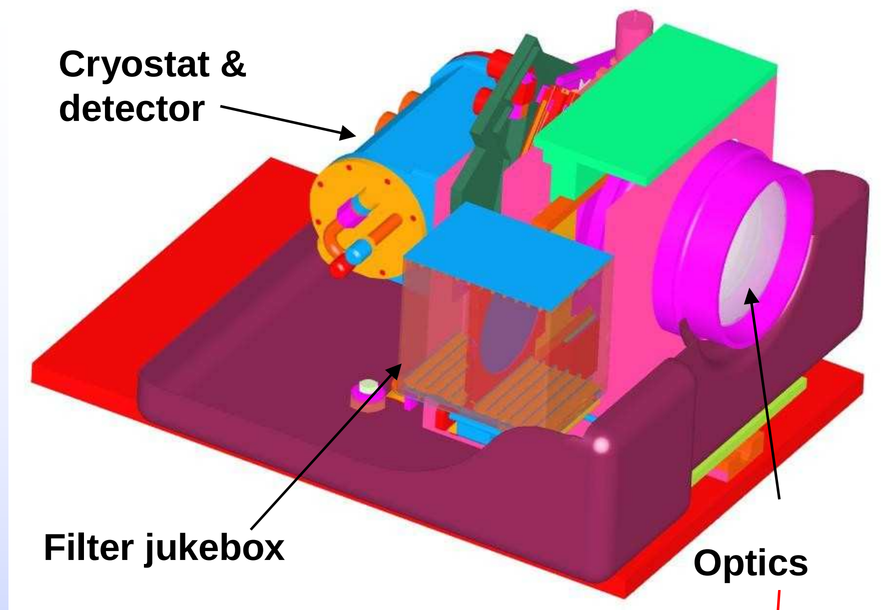
SALTICAM: UV-Vis High-Speed CCD Camera

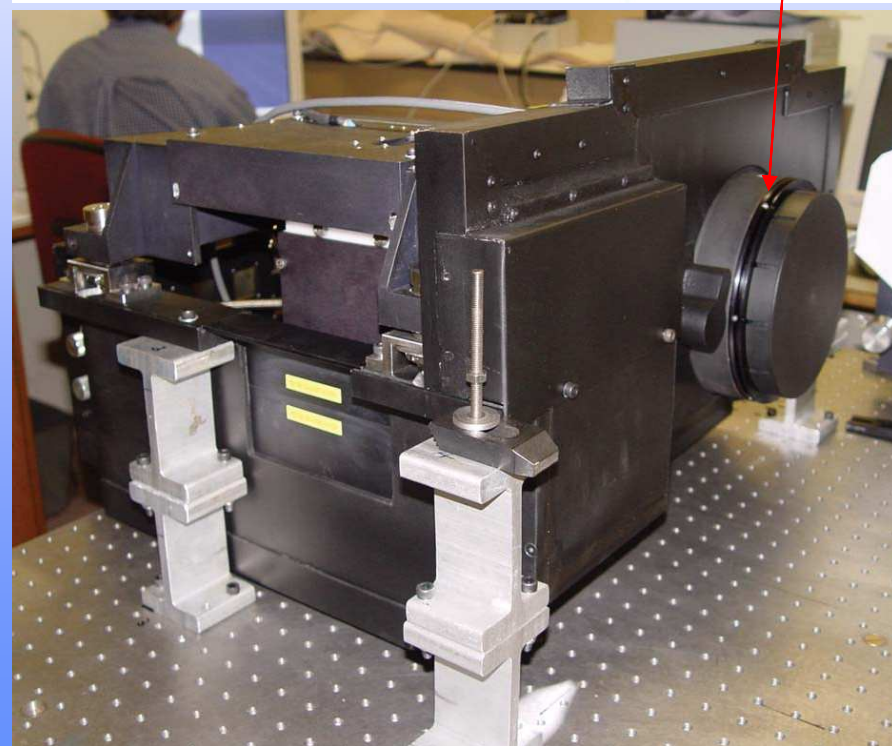
An efficient "video" (~15 Hz) camera over entire science FoV (8 arcmin), using FT E2V 44-82 CCDs (2k x 4k).

Efficient in the UV/blue (capable down to atmospheric cutoff at 320nm)

Capable of broad to narrow band imaging (Johnson-Cousins; SLOAN & Strömgren filters, narrow band & Hα) high time-resolution (to ~70 ms) photometry (with slot mask).

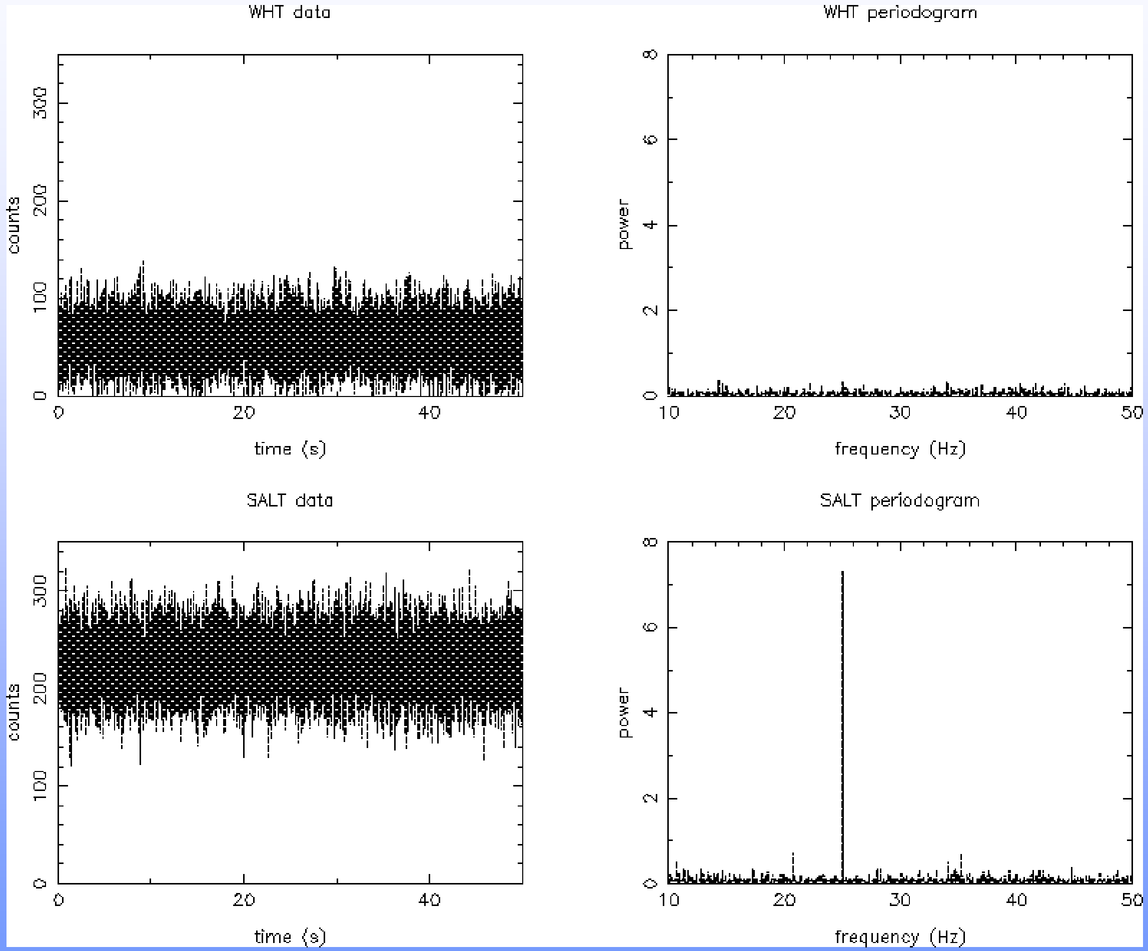






SALTICAM in the lab

Aperture advantage: searching for weak periodicities

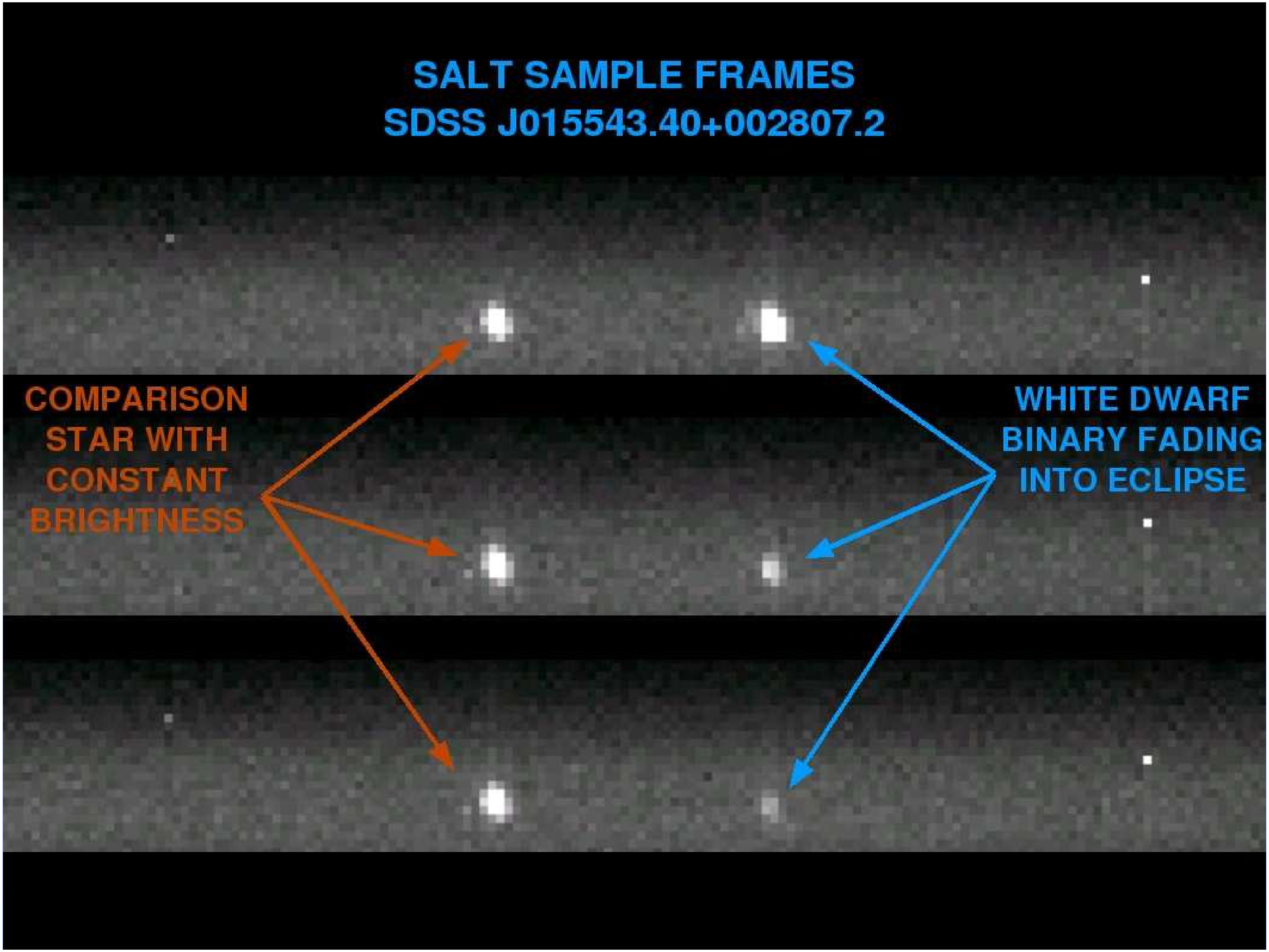


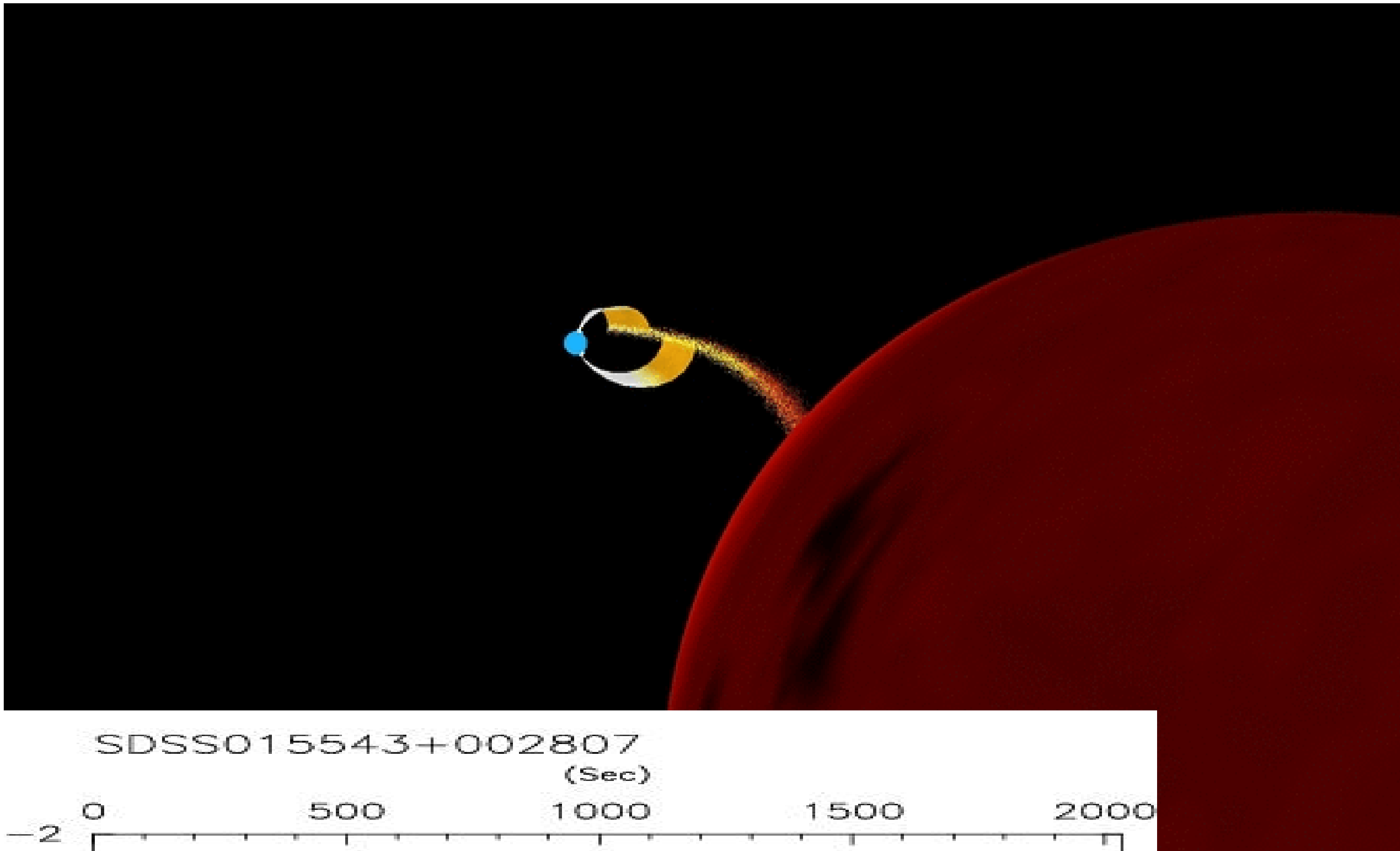
This shows simulated light-curves and periodograms obtained with ULTRACAM on the WHT and SALT. The source is an *R* =16 variable star observed during bright time in 1 arcsecond seeing using 5 millisecond exposures. The source is varying with an amplitude of 2.5% and a period of 40 milliseconds.

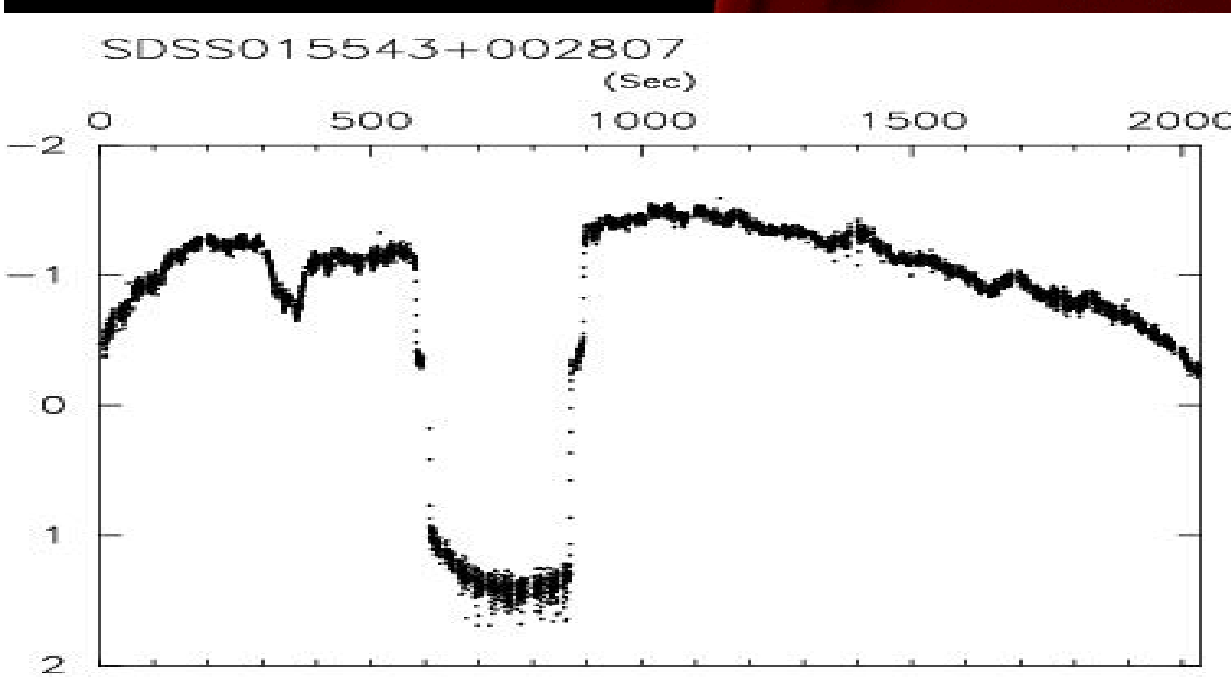
(courtesy of Vik Dhillon)

Detection of *periodic signals* greatly benefits from increased aperture

- ***power ∝ aperture^4***


SALT SAMPLE FRAMES
SDSS J015543.40+002807.2
COMPARISON STAR WITH CONSTANT BRIGHTNESS
WHITE DWARF BINARY FADING INTO ECLIPSE




SDSS015543+002807
(Sec)
0
500
1000
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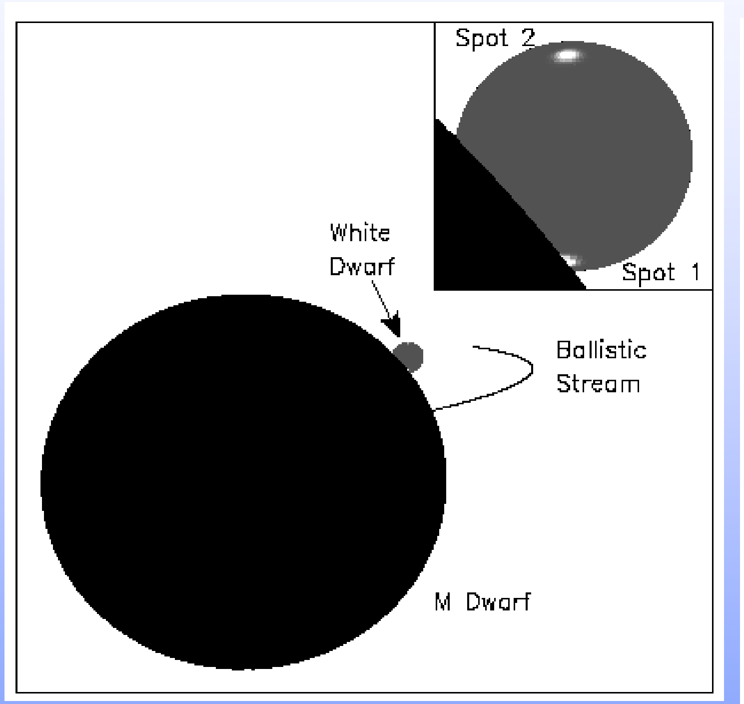
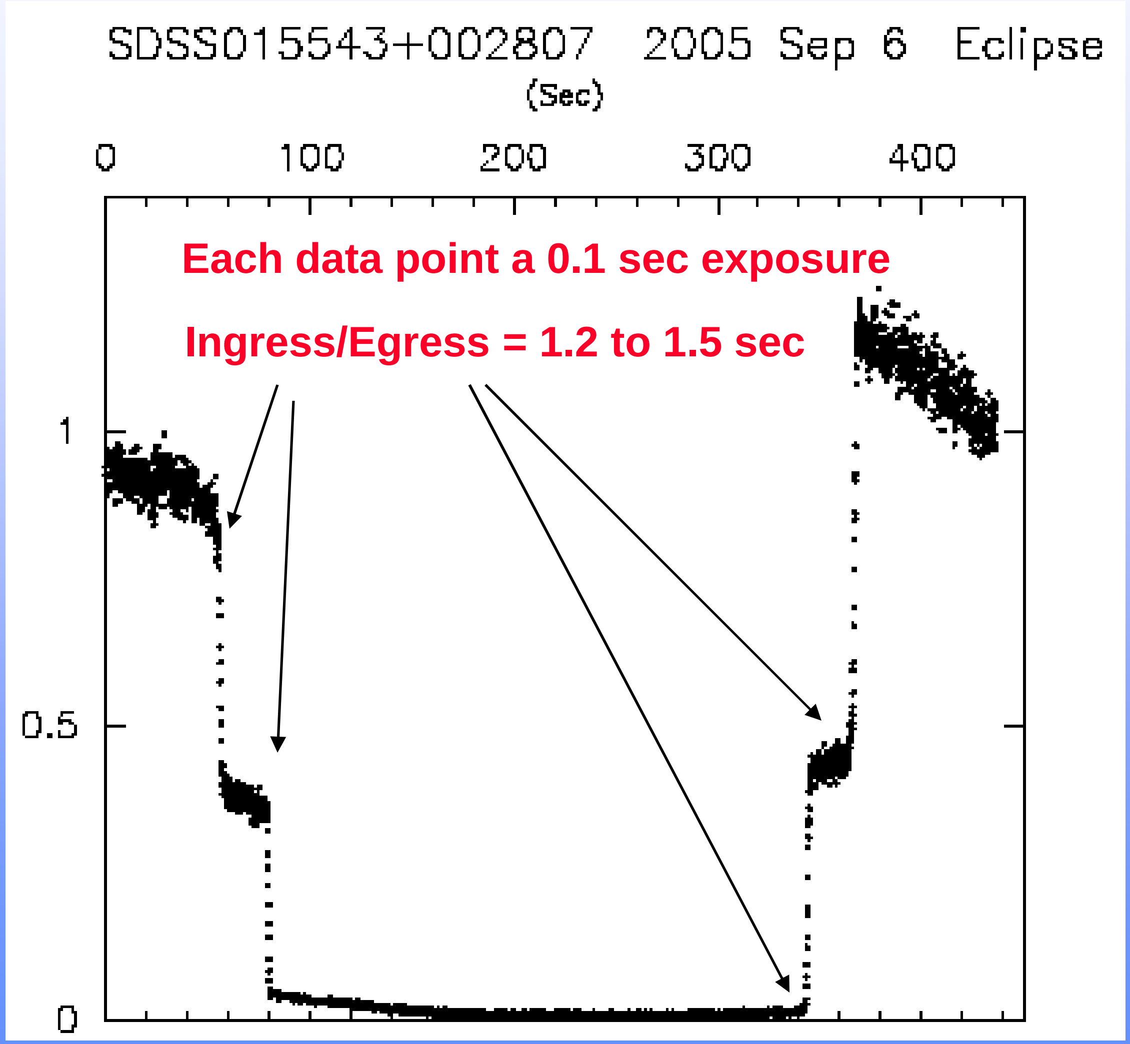
2

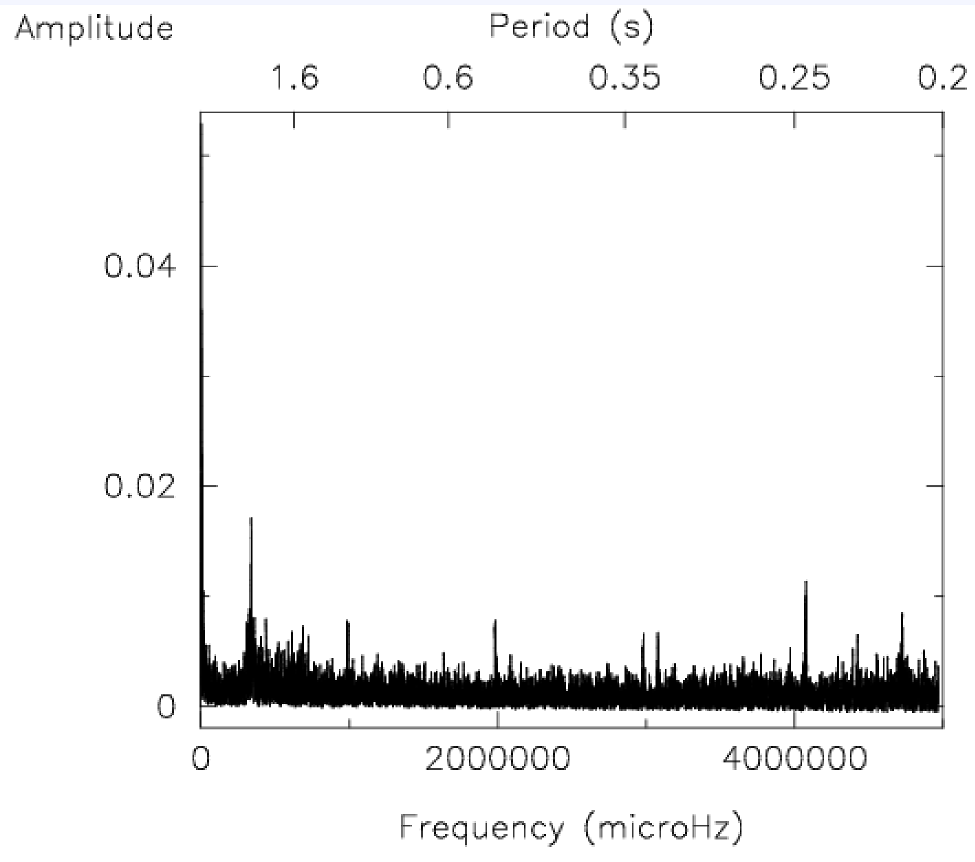
SALT First- Science: HTRA

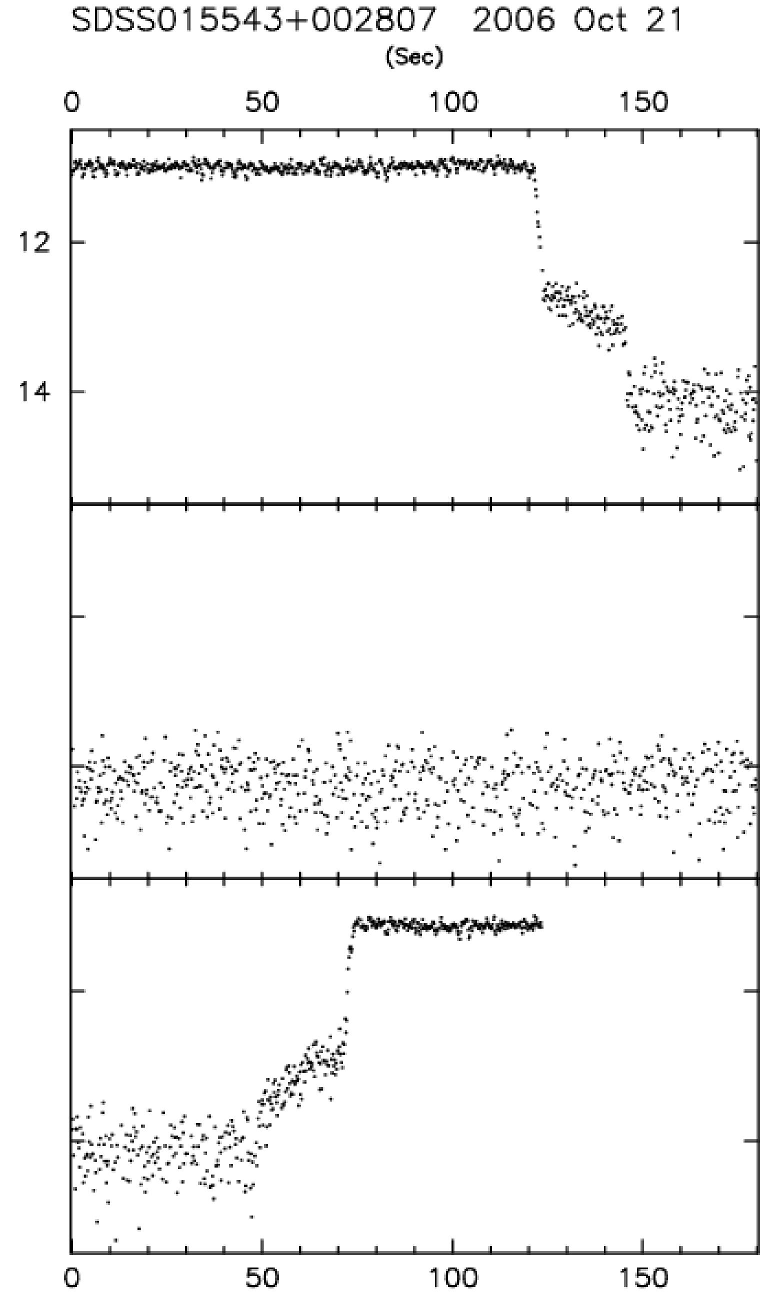
An example: a light curve of an eclipsing magnetic CV (Polar) taken with SALTICAM





More recent observations were taken in a low accretion state

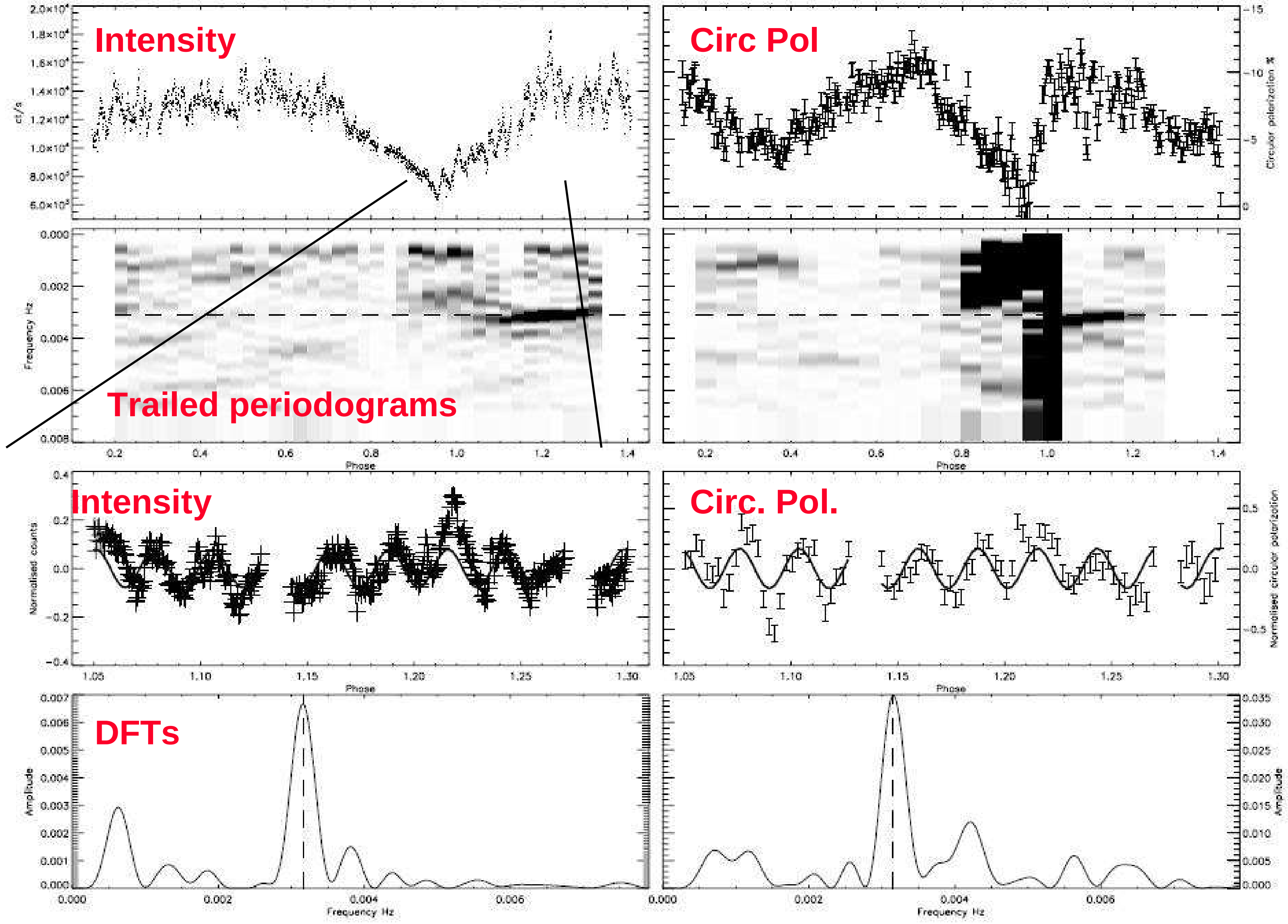




- **QPOs at ~2.5 sec detected**
- **Oscillations in flux tubes in a magnetically confined accretion column**

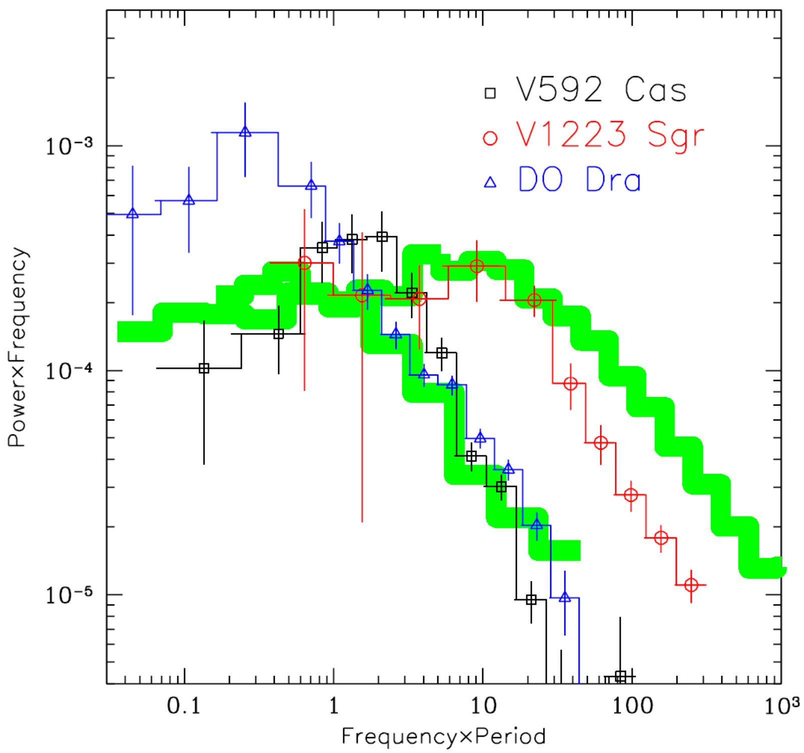
New INTEGRAL/SWIFT source 1GRJ 14536-5522

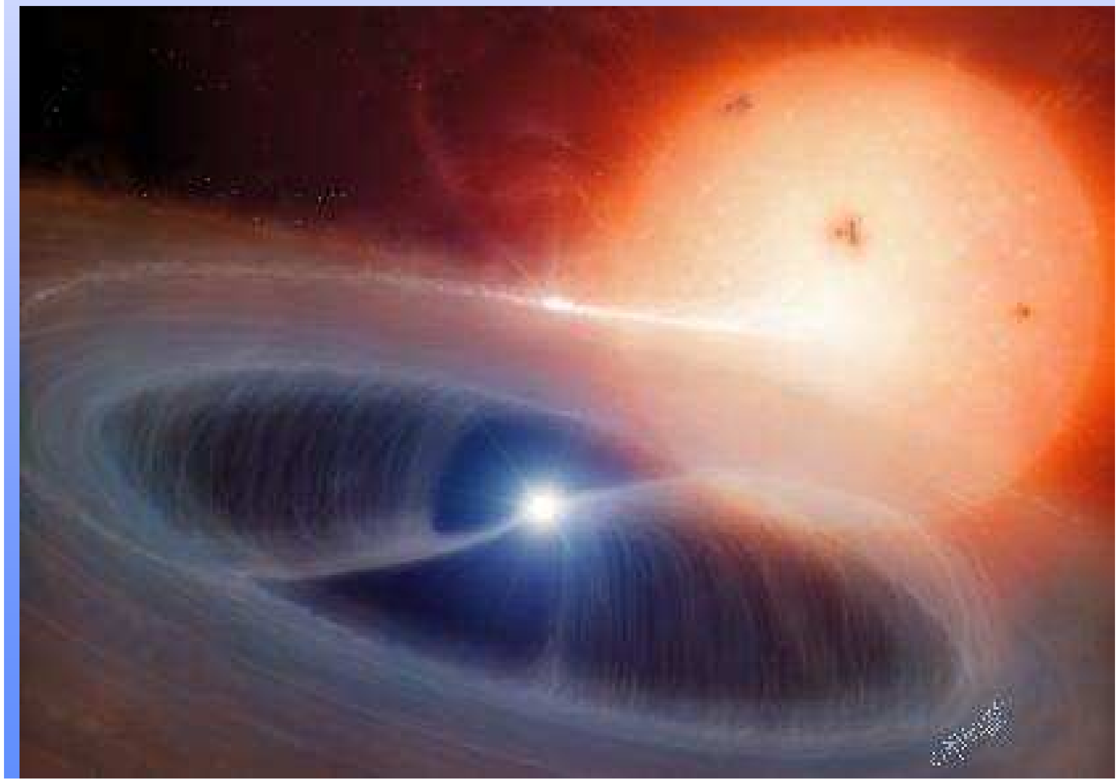
- **SAAO 1.9-m HIPPO All-Stokes photopolarimetry**
- **SALTICAM fast photometry**



SALT Observations of Intermediate Polars

- **IPs are mCVs systems, usually with truncated accretion disks**
- **Program primarily aimed to look for wavelength dependencies in the spin and beat modulations of IPs**
- **Also looking at the flickering & aperiodic behaviour of IPs (with Alexei Kniazev & Mikhail Revnivtsev)**
  - **Power density spectra evidence of missing inner disk?**
  - **Disrupted power law**





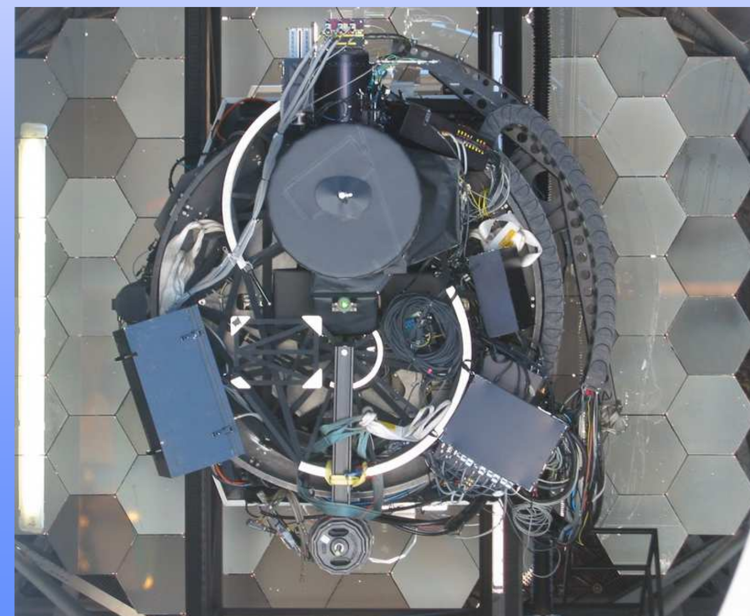
Polarimetric Observations of Magnetic CVs using The Robert Stobie Spectrograph (RSS)
(built at U. Wisconsin, Rutgers & SAAO)

An efficient and versatile Imaging Spectrograph

- **capable of UV spectroscopy**
- **high time resolution ablility (~10 Hz)**
- **polarimetry capability: imaging & spectropolarimetry, incl. All-Stokes (*Q,U,V,I*)**
- **Fabry Perot imaging (many narrow filters)**
- **multiple object spectroscopy**
  ~100 objects at once

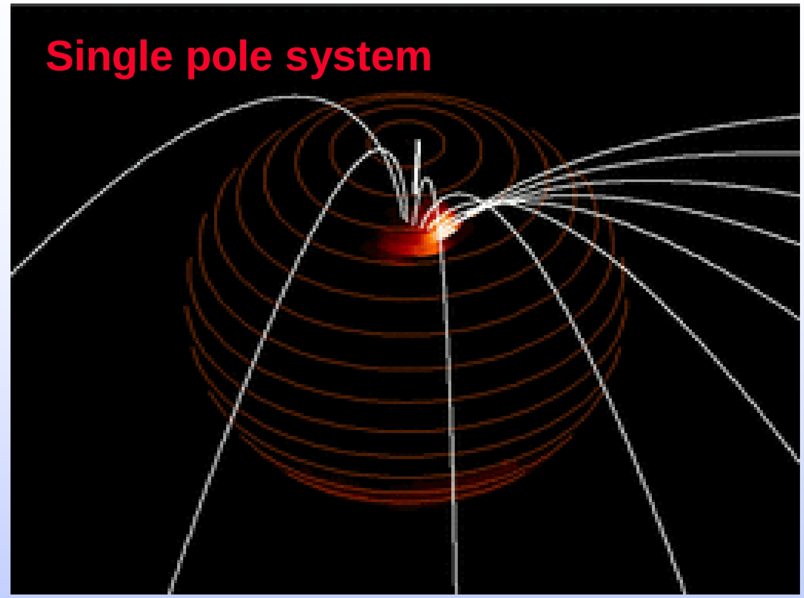
Named in memory of Bob Stobie, previous SAAO Director & 'father' of SALT.

RSS in lab at Wisconsin (Feb 2005)



RSS installed on SALT (Oct 2005)

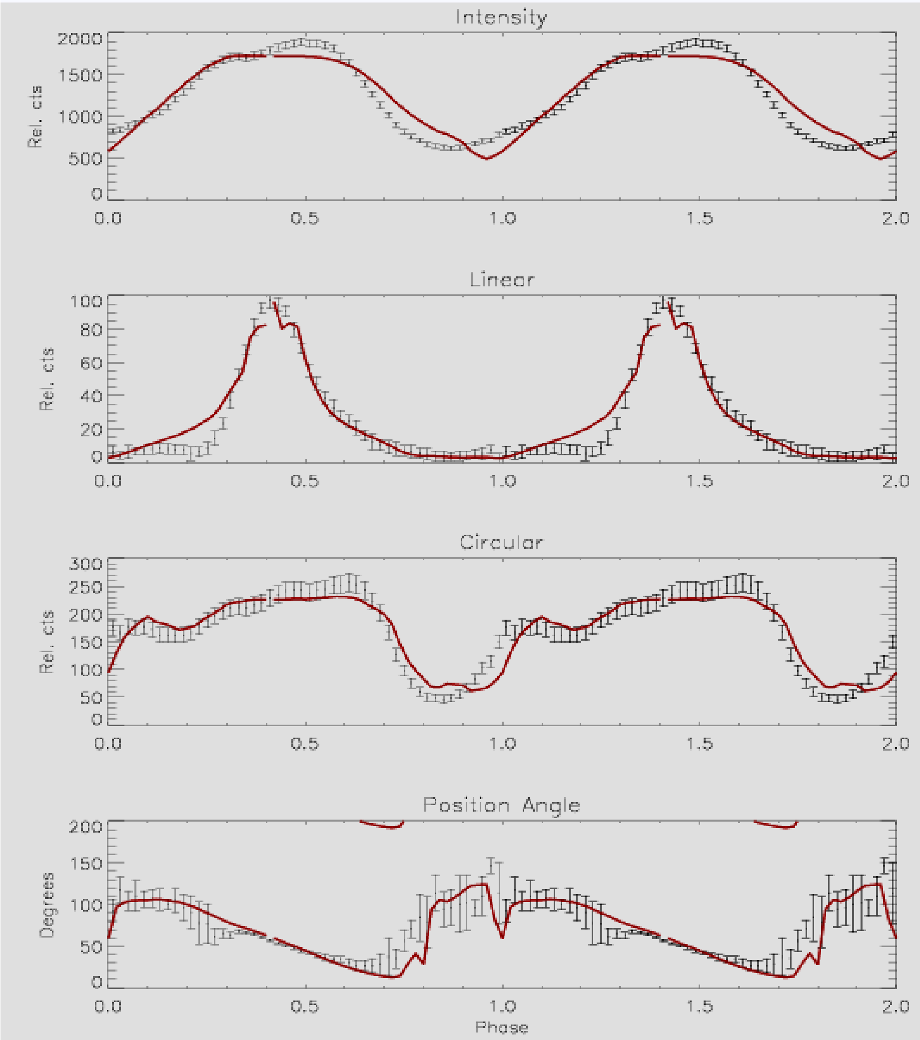
Future Program: Determining Magnetic Field Strength & Geometry in Polars



Fit cyclotron models (plasma temp & density, cyclotron opacity, B & θ) to all-Stokes polarimetry

- using Potter's "Stokes imaging" technique

- fits model to data using a genetic Algorithm



Example: V834 Cen, P_{orb}= 101 min
SAAO 1.9-m photopolarimetry

Extend to spectropolarimetry

Example: QS Tel phase resolved spectra

Average spectra and models centred on three different orbital phases.

Poor fits by single temp Models.

Different shock models are used to fit different phases.

- **not simple**

- **Stokes imaging needs to be extended to *spectropolarimetric* observations *– from SALT***

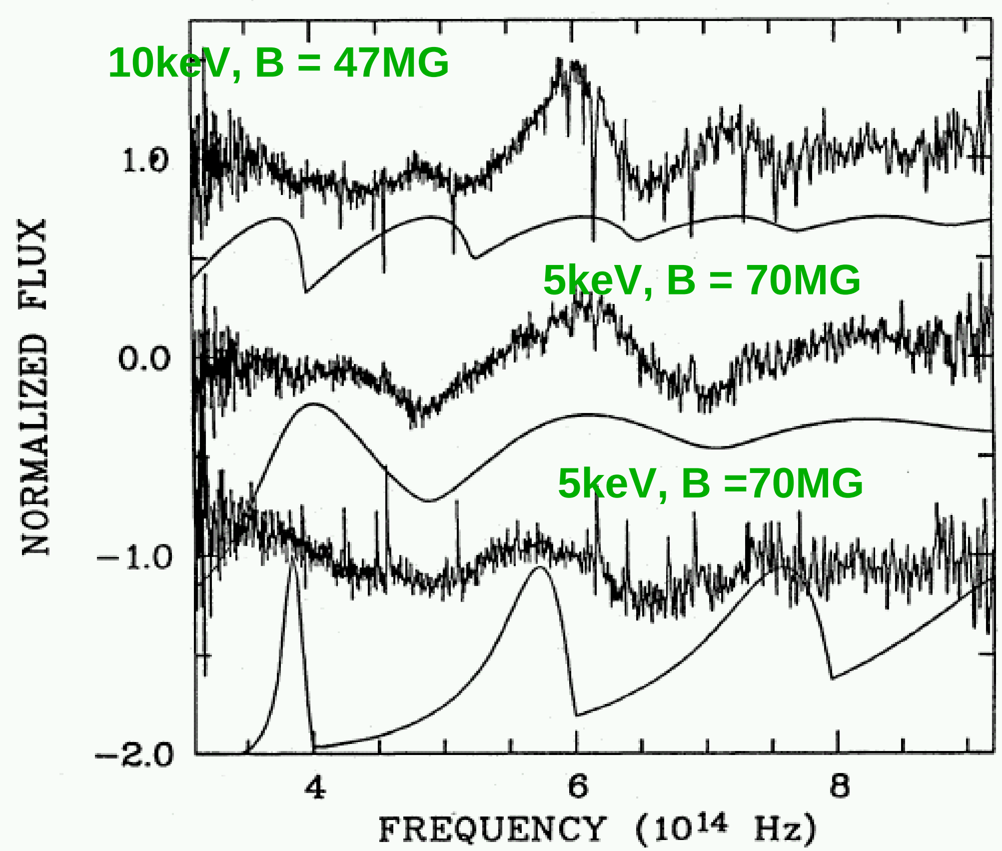


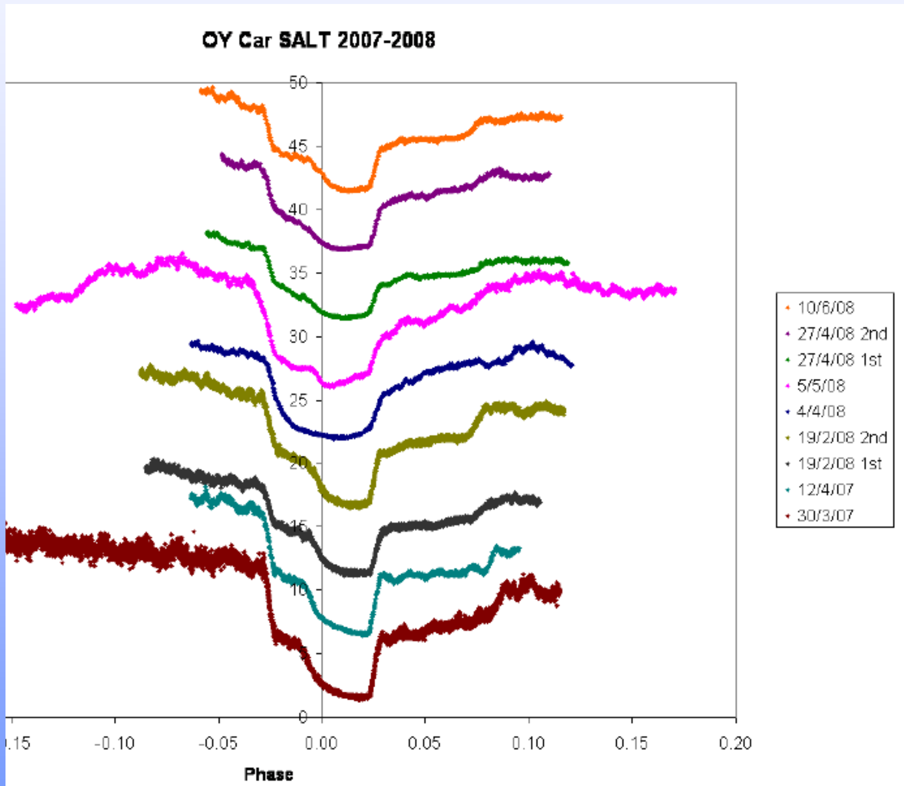
Fig. 11. Normalized cyclotron spectra of RXJ 1938 for three selected phases, $\phi_{\rm NEL} = 0.06, 0.19$, and 0.73, respectively, from top to bottom. The smooth curves below the observed spectra are normalized and suitably scaled cyclotron absorption coefficients using using parameters (from top to bottom) $kT = 10, 5, 5$ keV , $B = 47, 70, 70$ MG and $\chi = 80°, 40°, 80°$

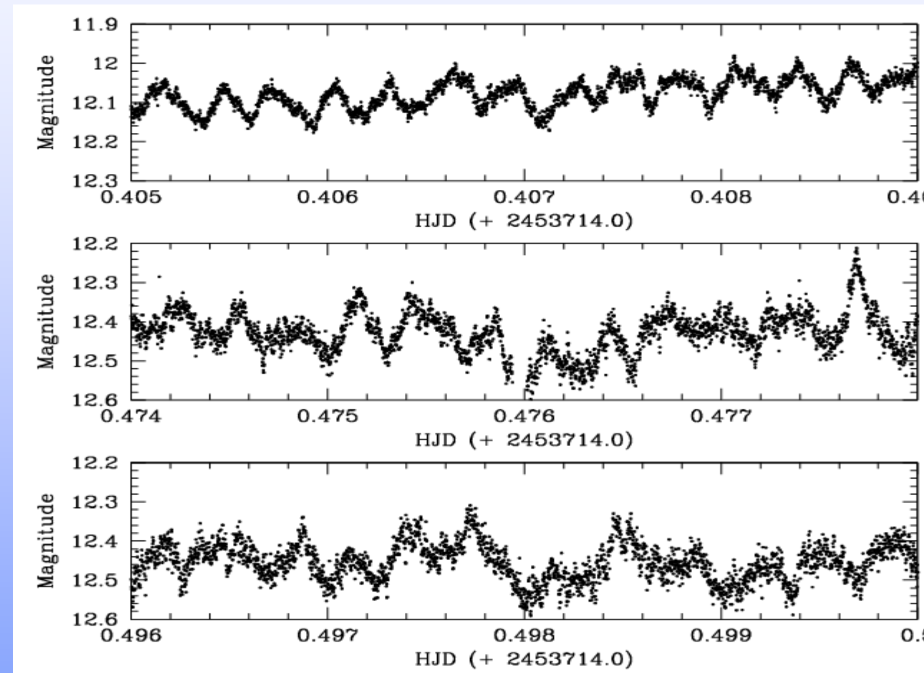
Schwope et al. 1995 293, 764

Other SALTICAM examples:

1. Eclipse curve changes during DN outbursts & super-outbursts
2. Observing DNOs & QPOs through outbursts

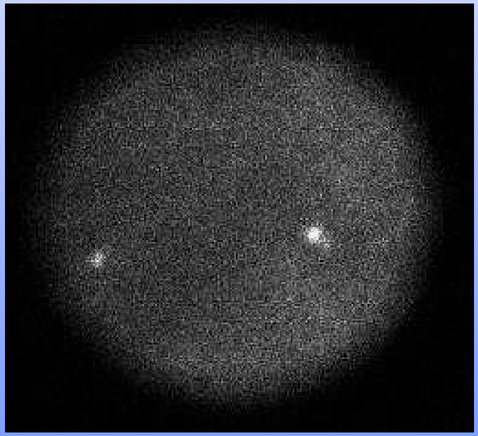
All benefit from HTRA and ToO capabilities of SALT

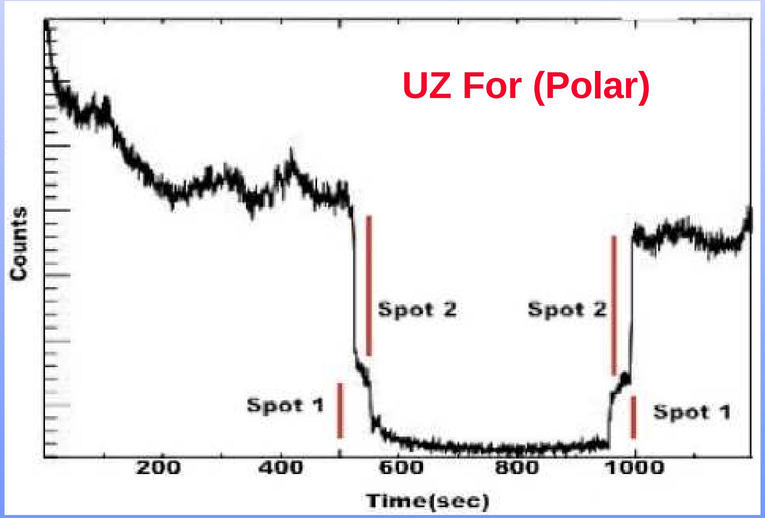




Recent SALT experiments with a photon counting camera

- The *Berkeley Visible Image Tube (BVIT)* installed at SALT Auxiliary Focus
- A very high time resolution imaging photometer.
  - Enables a new time domain for astronomical observations with full imaging capability
    - » Time resolution (time stamping for each photon) to ~microsecond
    - » BVIT is a simple instrument with minimal observational setup requirements and a high degree of post acquisition data flexibility.
- Based on Microchannel Plate & strip anode detector





- Prototype built with low QE S20 photocathode (peak of ~10% QE peaking at ~400nm)
- Now upgraded to Super GenII, with ~20x improvement in count rate

Future Multi-λ Observing Plans:
utilizing Southern African radio, optical and γ-ray facilities, potentially combined with other facilities (e.g. ASTROSAT)

HESS, SALT and MeerKAT

FINAL REMARKS

- **CVs of all flavours are complex multi-emission source systems which vary on all timescales**
- **Understanding them requires a multi-wavelength approach, often greatly benefiting from simultaneous or contemporaneous observations**
- **High time resolution observations are probing new areas**
- **Although SALT is unconventional in design – with a limited observing window – it is nonetheless well suited for multi-λ supporting observations:**
    - **Queue scheduling & ToO ability**
    - **Large aperture**
    - **High time resolution capabilities**
    - **Polarimetric capabilities**
- **SALT is well poised to exploit the possibilities of multi-wavelength observations with other facilities, regional (MeerKAT, HESS) and global (e.g. ASTROSAT).**
- **With IUCAA a member of the SALT consortium, many in this audience should consider the future possibilities!**

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