The B[e] Star CI Cam in the Optical Range

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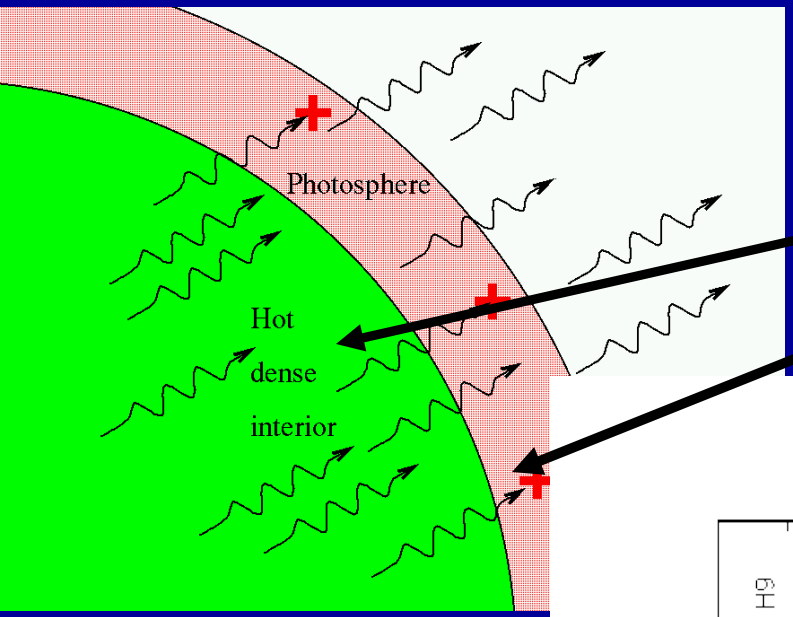
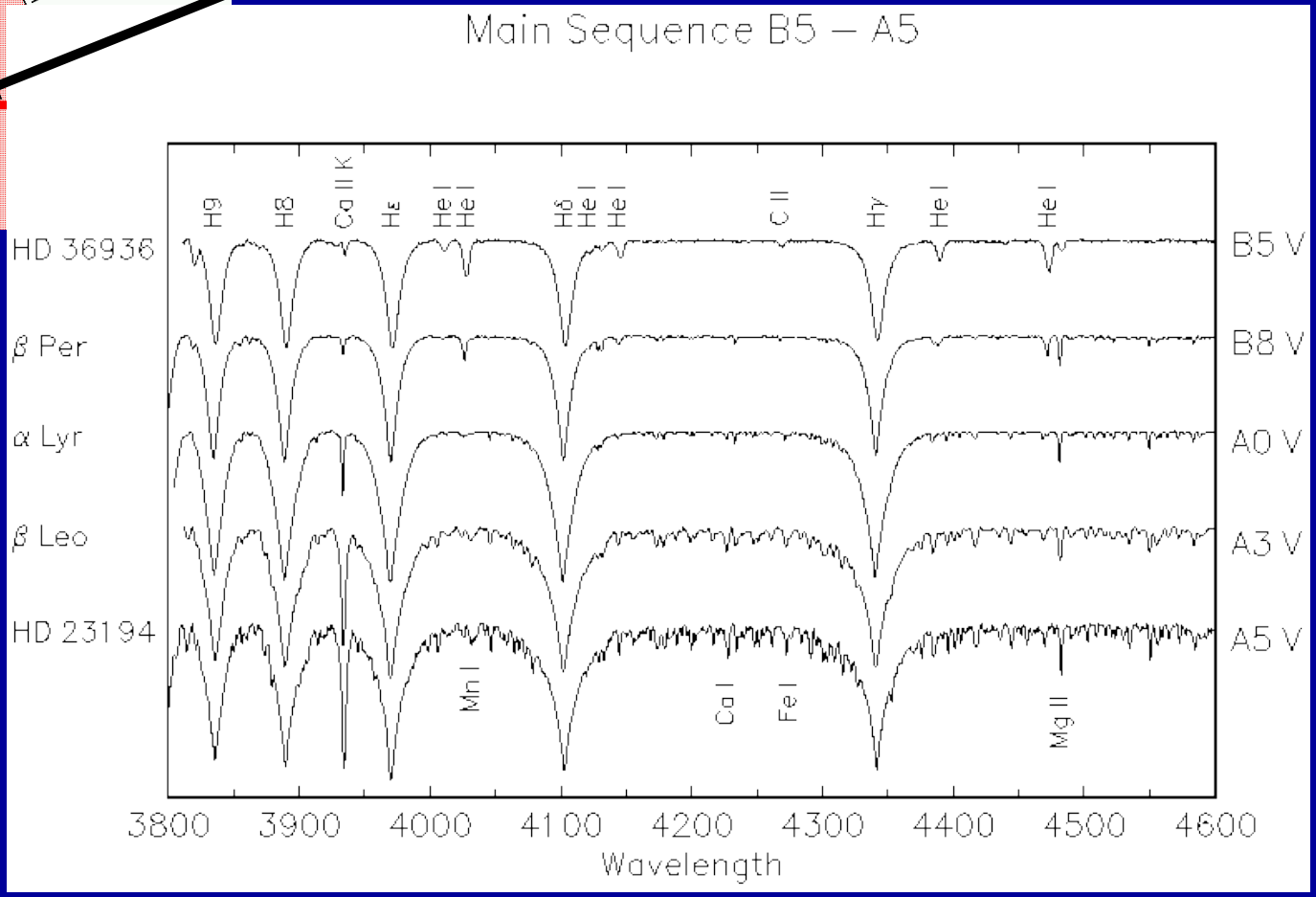
Normal Stars



Photosphere – continuum

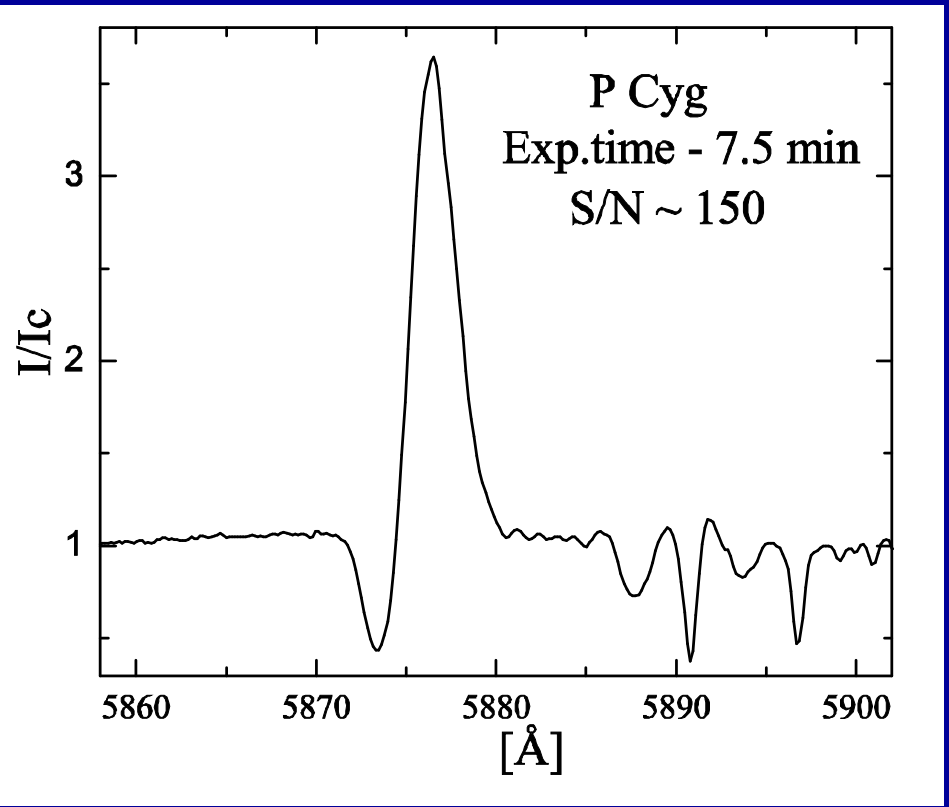
Atmosphere – absorption lines



Emission Lines/Circumstellar Material

Stellar Winds/Spherical

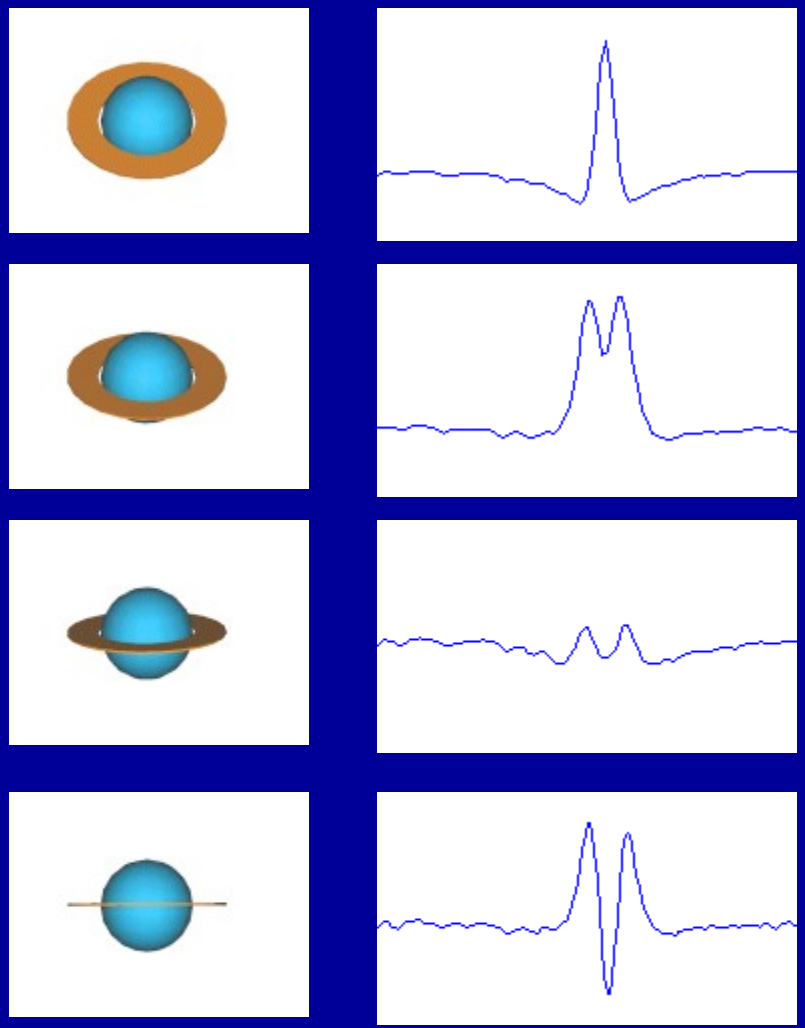
Supergiants/Slow Rotation



Spectrum from the Three College Observatory, 0.81-m telescope, R ~12,000

Be Phenomenon/Disks

Near MS/Fast Rotation



Groups of Emission-Line Stars

Be stars - phenomenon/evolutionary stage – 1866

T Tau stars – pre-main-sequence low-mass stars – 1945

Herbig Ae/Be – pre-main-sequence intermediate-mass – 1960

Luminous Blue Variables – evolutionary stage of very massive stars – 1970's

Vega-type – main-sequence stars with debris protostellar envelopes – 1984

Proto-Planetary Nebulae – transition objects/late evolutionary stage of low-mass stars – 1988

B[e] stars – phenomenon in a wide variety of objects – 1976

The B[e] Phenomenon

Discovery – Allen & Swings(1976, A&A, 47, 293)

- 65 B-type stars (out of 700) with forbidden line emission ([Fe II], [O I], [O III]) and IR excess at λ=2 μm

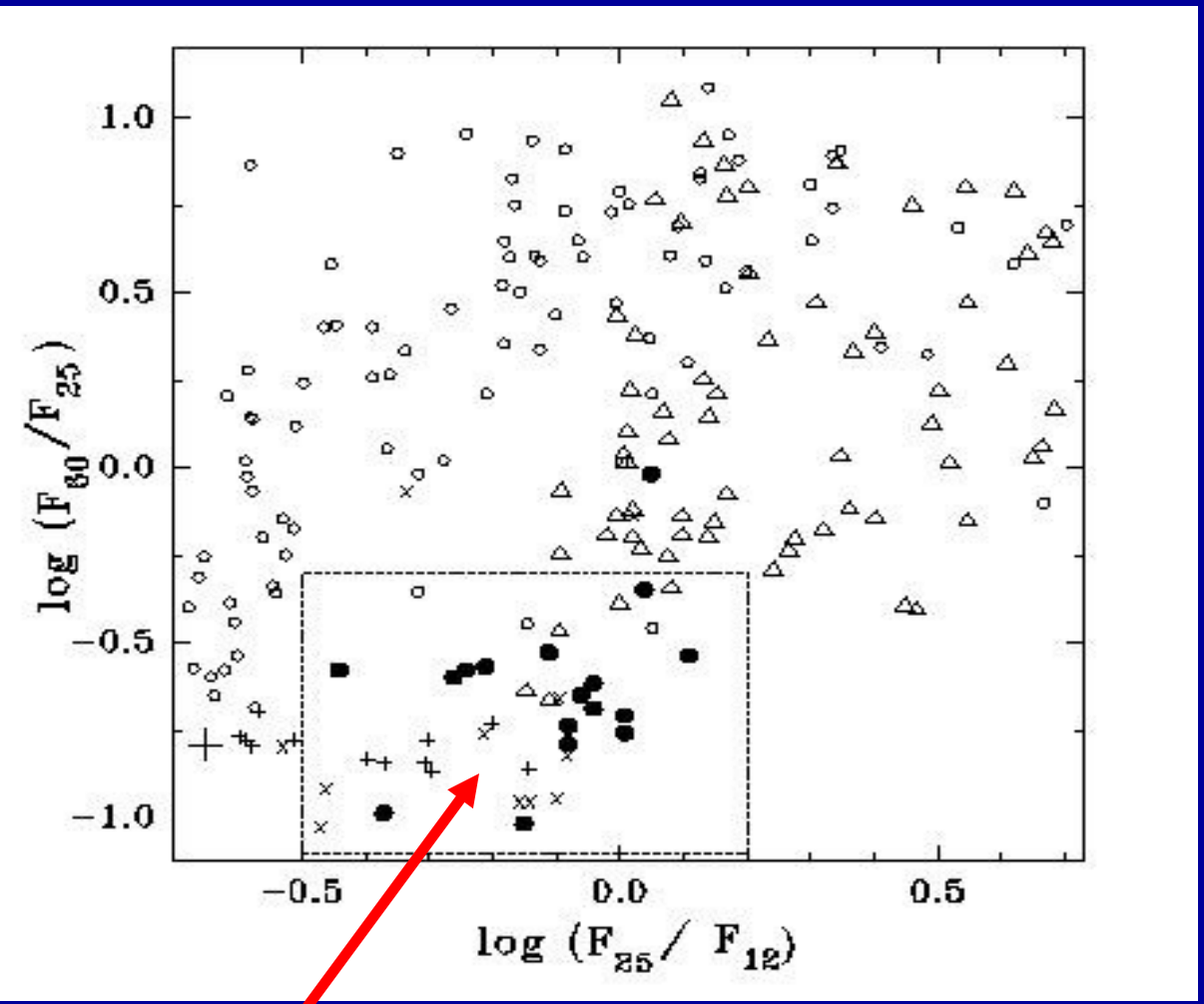
- Five groups of B[e] stars: **supergiant B[e], pre-main-sequence B[e], compact Planetary Nebulae B[e], symbiotic B[e], and unclassified B[e]**

- Key features: large envelopes/disks + circumstellar dust

- 32 unclassified B[e] – no absorption lines detected → no distance OR mixture of features from different groups

Most of these became FS CMa objects (Miroshnichenko 2007) + ~50 newly found (Miroshnichenko et al. 2011, Kuratova et al. 2017)

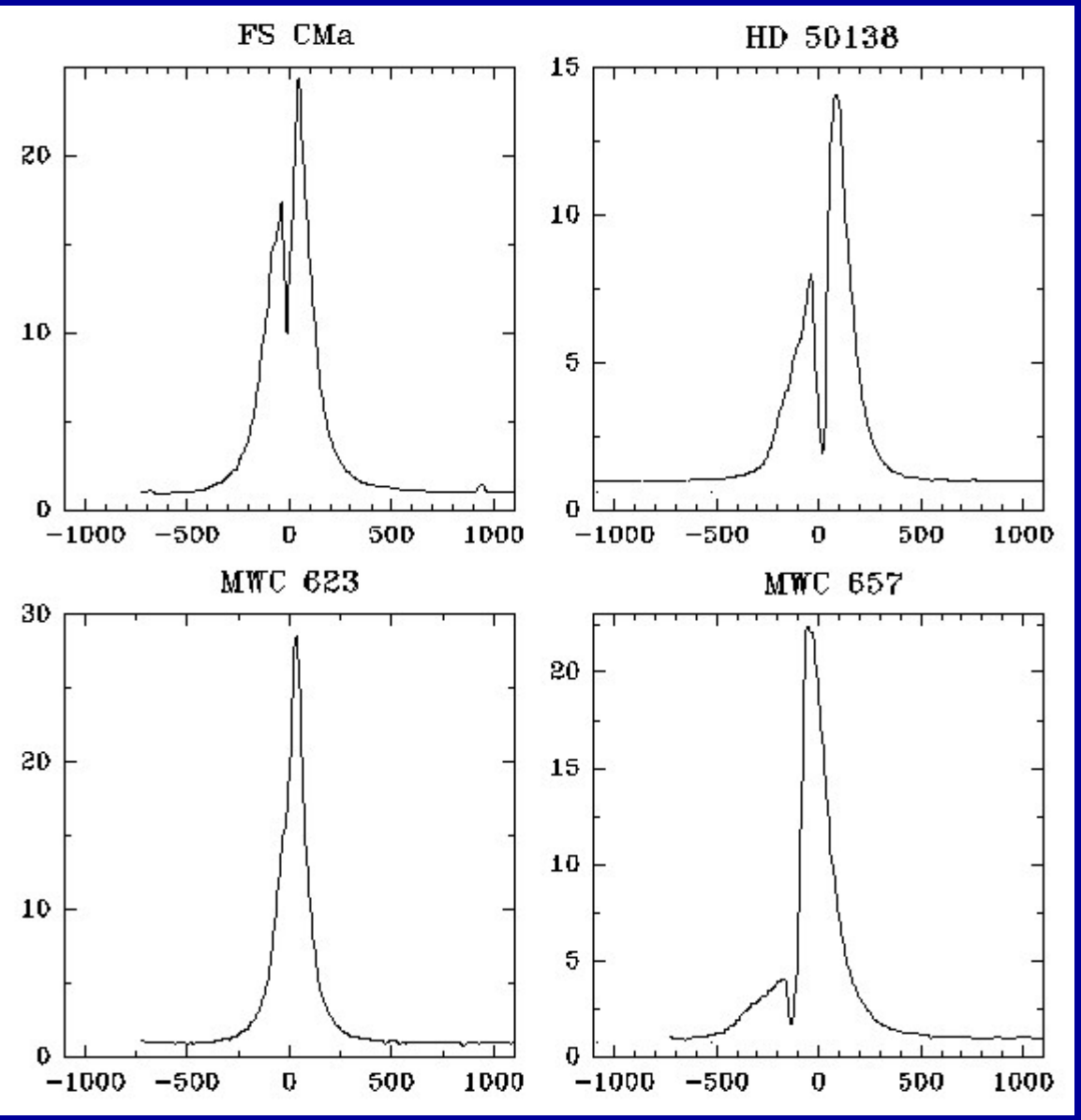
IRAS color-color diagram



- • - FS CMa stars
- Δ - Herbig Ae/Be
- o - Vega-type
- × - symbiotic stars
- \+ - VV Cep binaries

Dusty envelopes of FS CMa stars are compact

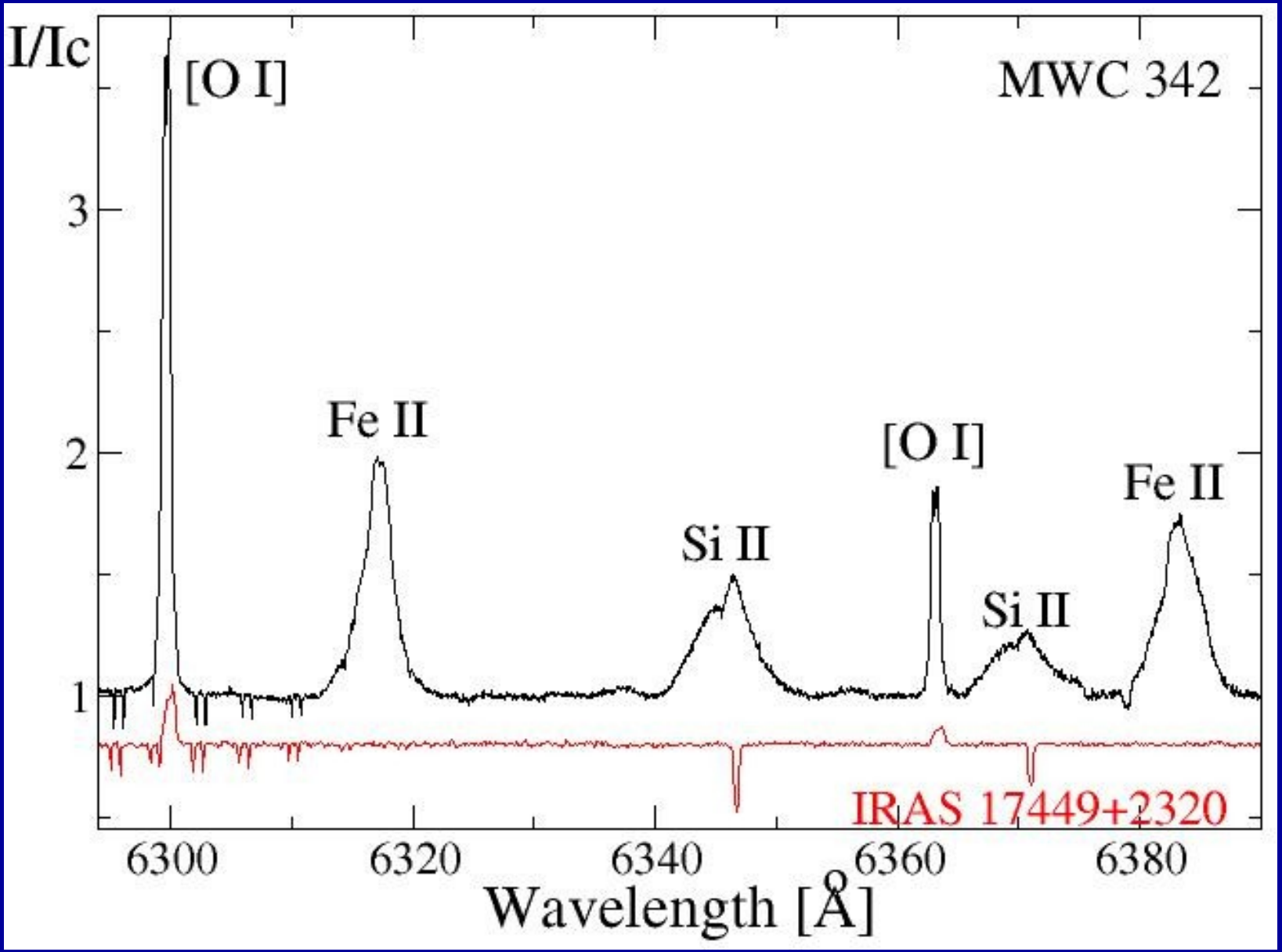
Strong Line Emission



Average Hα EW is an order of magnitude stronger than in Be stars

~100 times higher mass loss rates than typical for dwarf B and Be stars are required to explain these emission-line strenghts

Typical Spectra of unclB[e] Objects

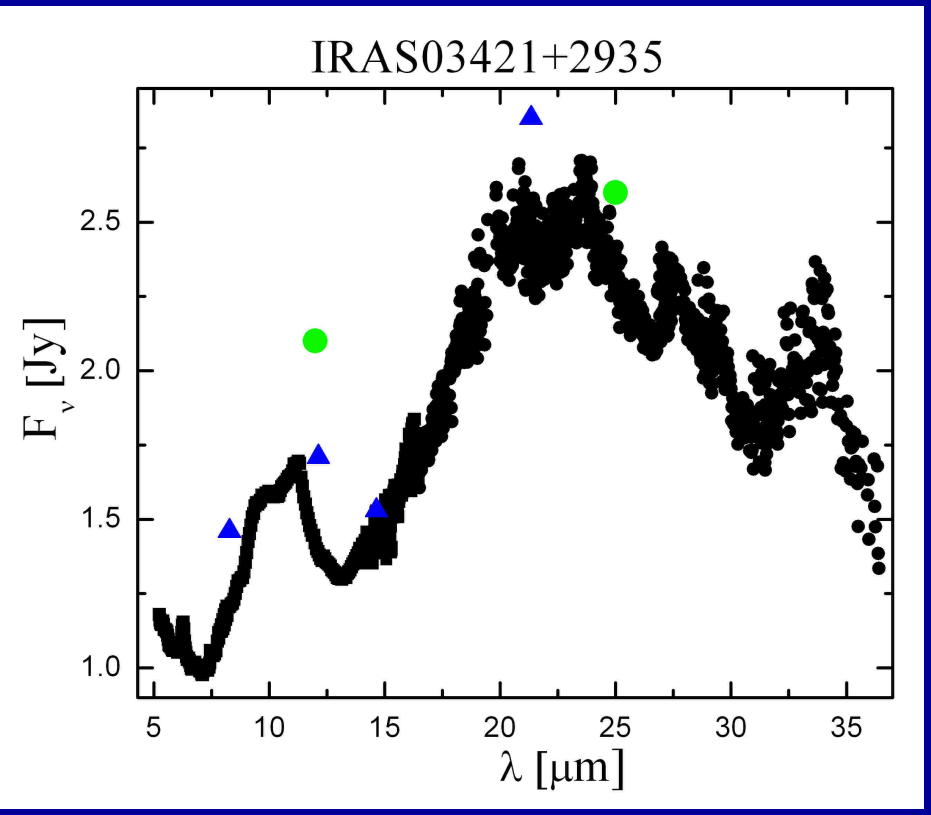


B1[e]

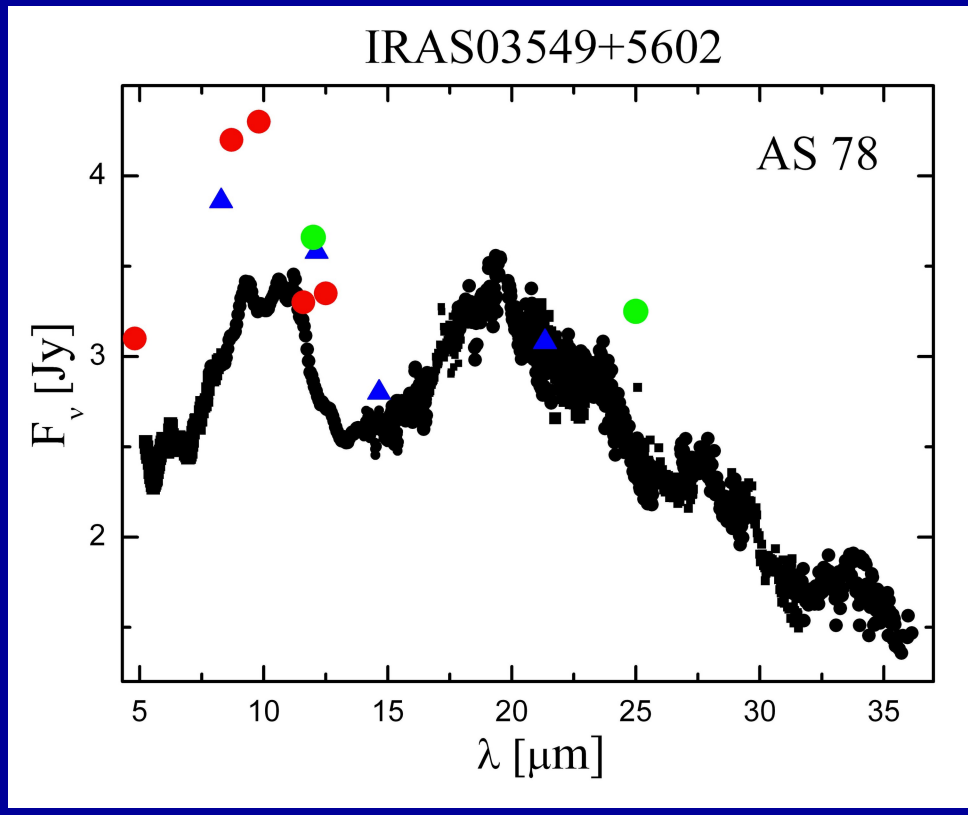
A0[e]

Dust Properties: Spitzer Data

Miroshnichenko et al. (2011, IAU Symposium 272, p.412)



MWC 728 – B6 Ve + G8 III binary system



AS 78 – B[e] object with P Cyg type line profiles

CI Cam – Brief History of Studies

1933 – discovery as an emission-line star in the Mount Wilson spectroscopic survey (MWC 84, Merrill & Burwell)

1971 – discovery of a strong IR excess (Allen, Swings)

1976 – selection to the first list of peculiar Be or B[e] stars by Allen & Swings

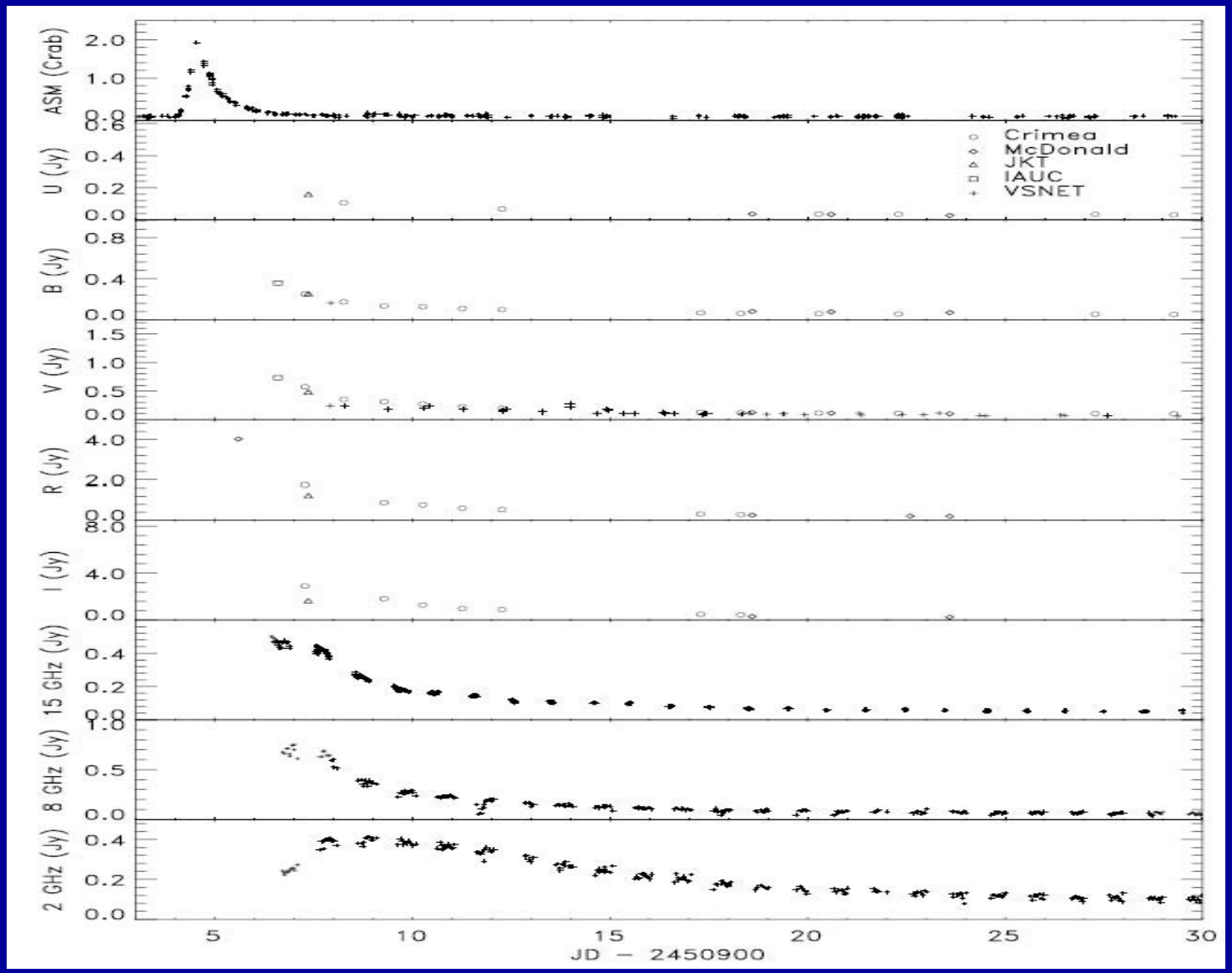
1995 – erroneous identification of absorption lines of a cool companion (Miroshnichenko)

1998 – multiwavelength outburst on March 31/April 1

2002 – discovery of the 19.41-day period in photometric and spectroscopic data (Goranskij, Barsukova, et al.)

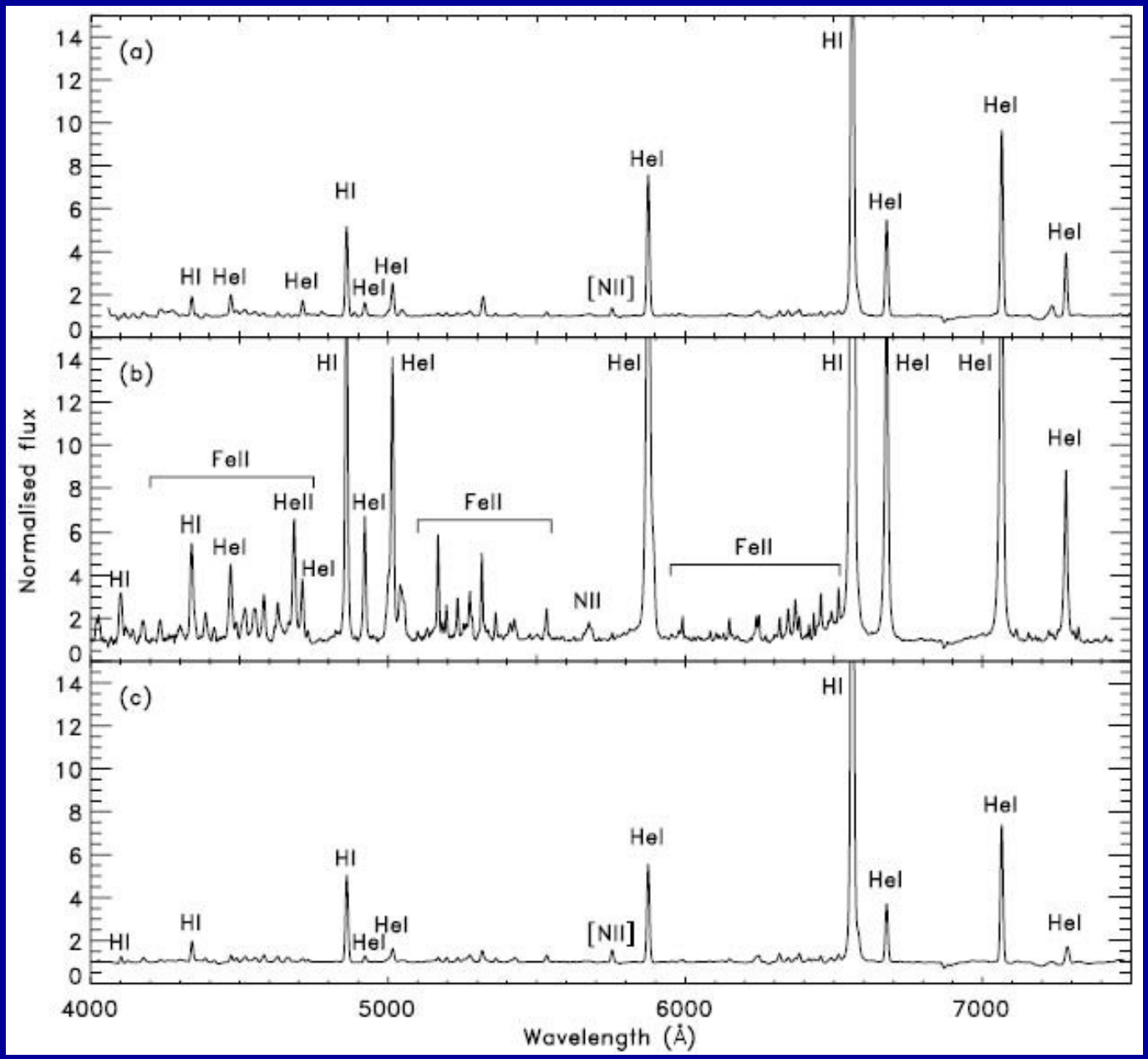
2008 – discovery of pulsations (Barsukova, Goranskij, ATel#1381)

CI Cam = MWC 84



Lx ~ 10^{33} erg/s – quiescence, ~10^{37} erg/s - outburst

CI Cam = MWC 84



01/27/1998

04/04/1998

3 days after the outburst

02/06/2000

from Hynes et al. (2002)

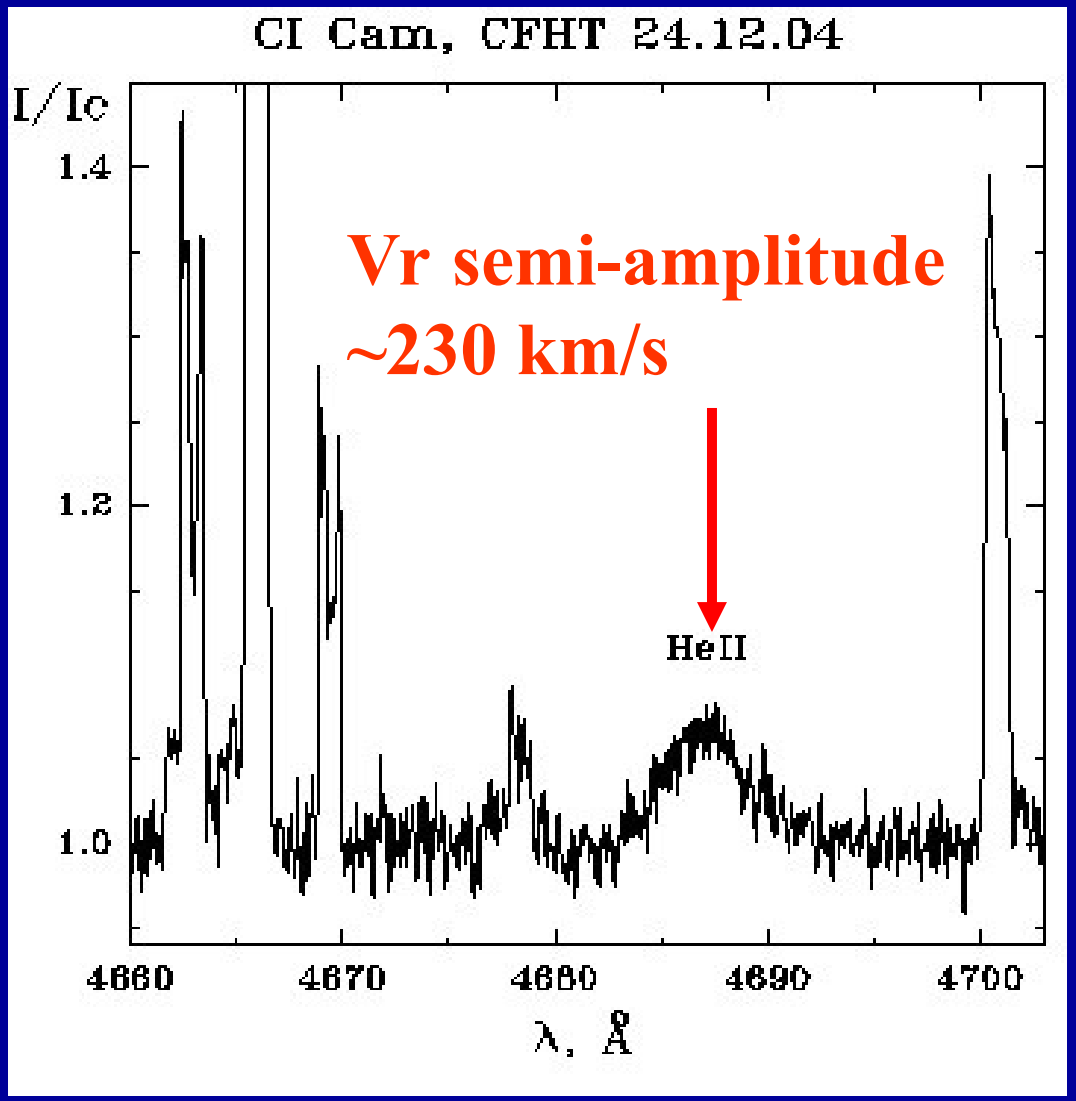
CI Cam – Outburst Interpretation

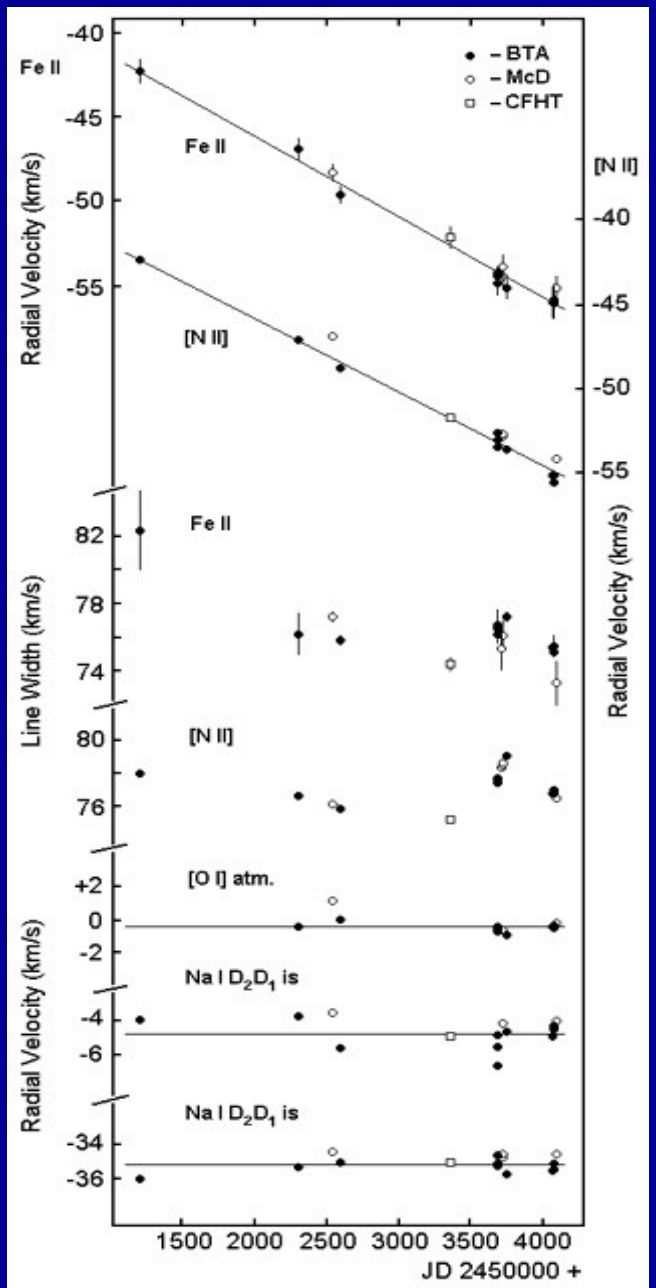
Thermonuclear runaway on a white dwarf surface – Orlandini et al. (2000, A&A, 356, 163)

Brief burst of supercritical accretion onto a neutron star or a black hole – Hynes et al. (2002, A&A, 392, 991)

Passage of a black hole through a dense disk of the B[e] supergiant causing an instability in a compact disk of a black hole – Robinson et al. (2002, ApJ, 565, 1169)

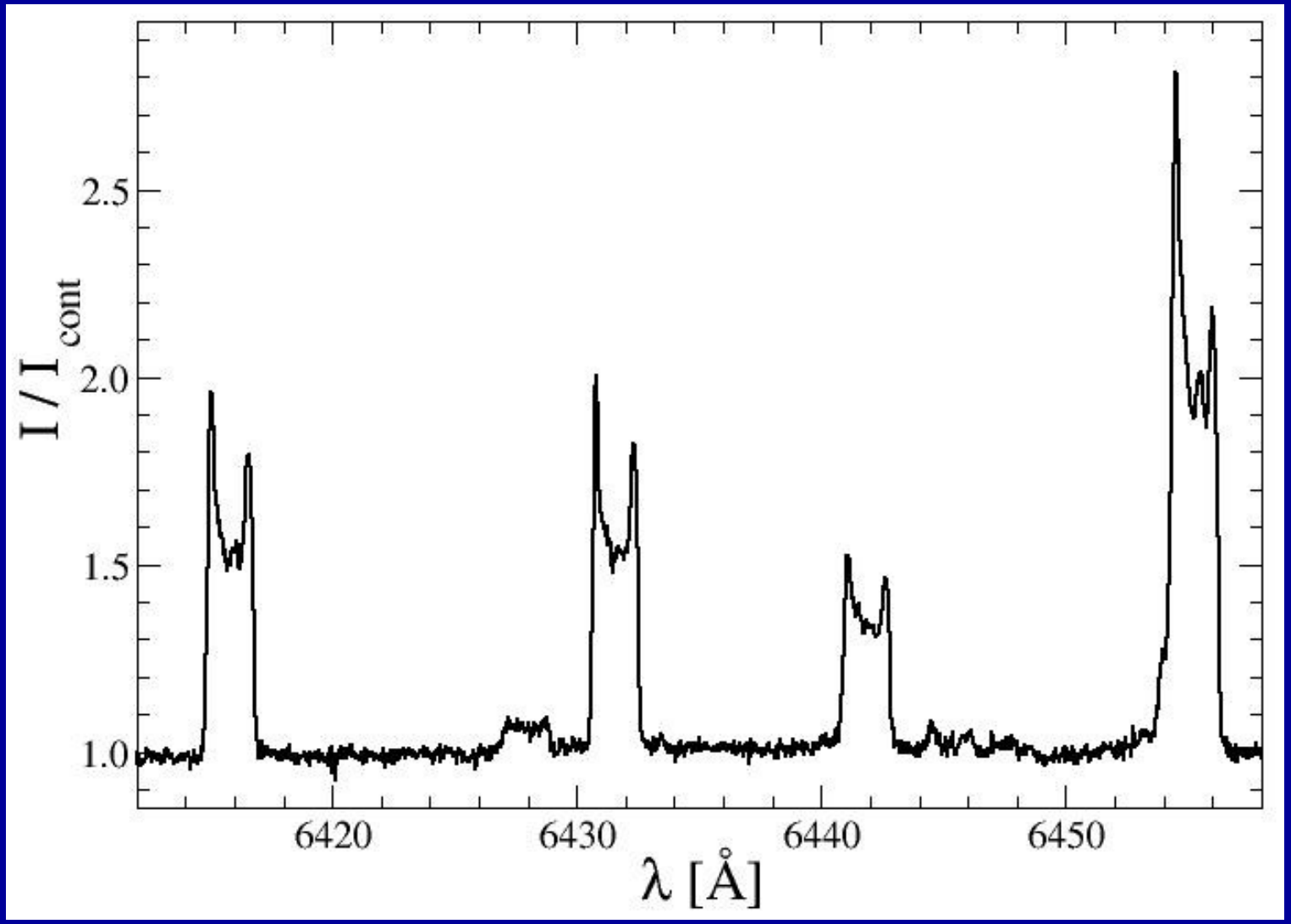
Binarity Signatures: Variable Lines





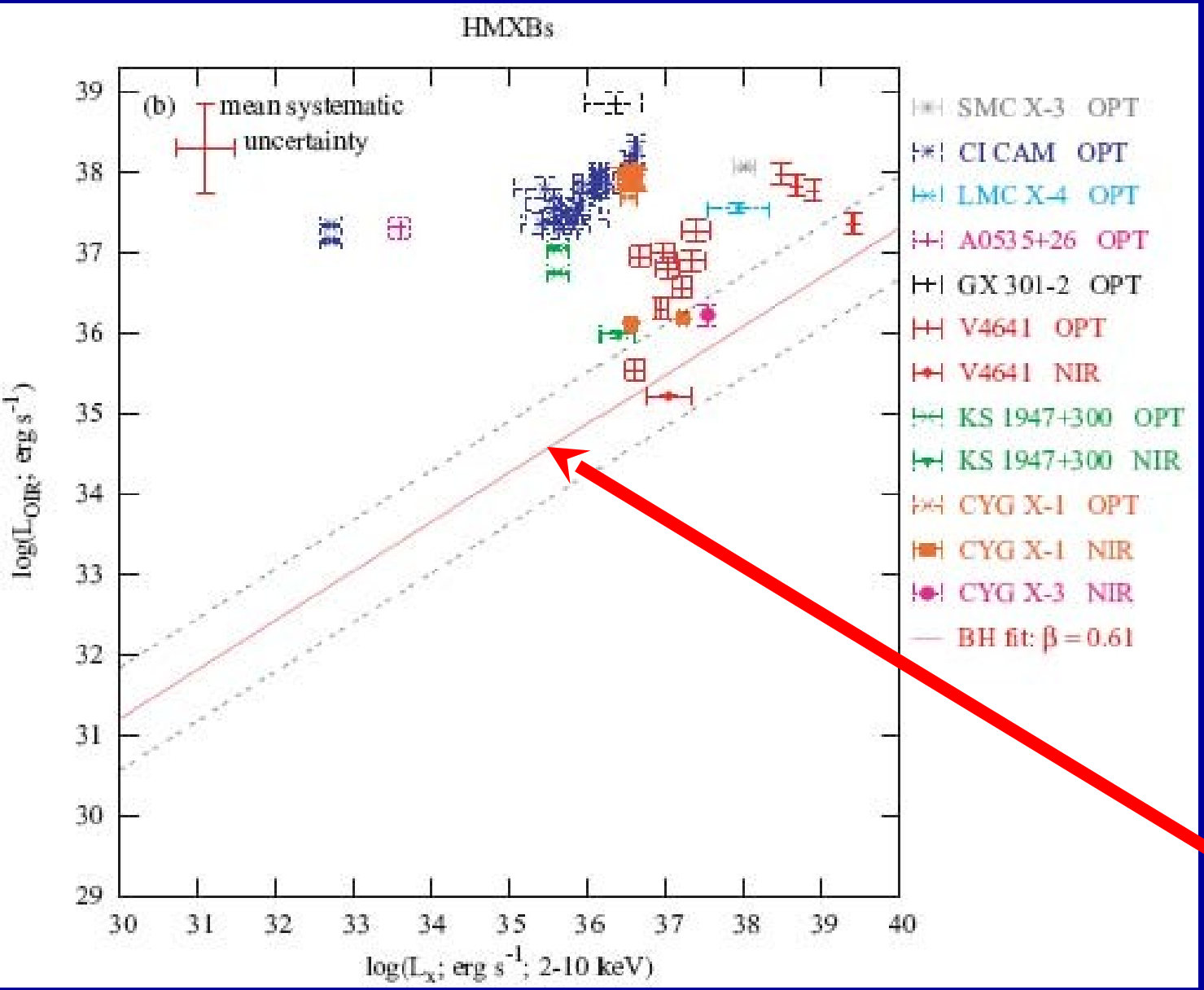
From Barsukova et al. (2007), Astronomer's Telegram, No. 1036

CI Cam – Fe II Emission Lines



CFHT spectrum (R ~ 65,000) taken on 2018/11/20

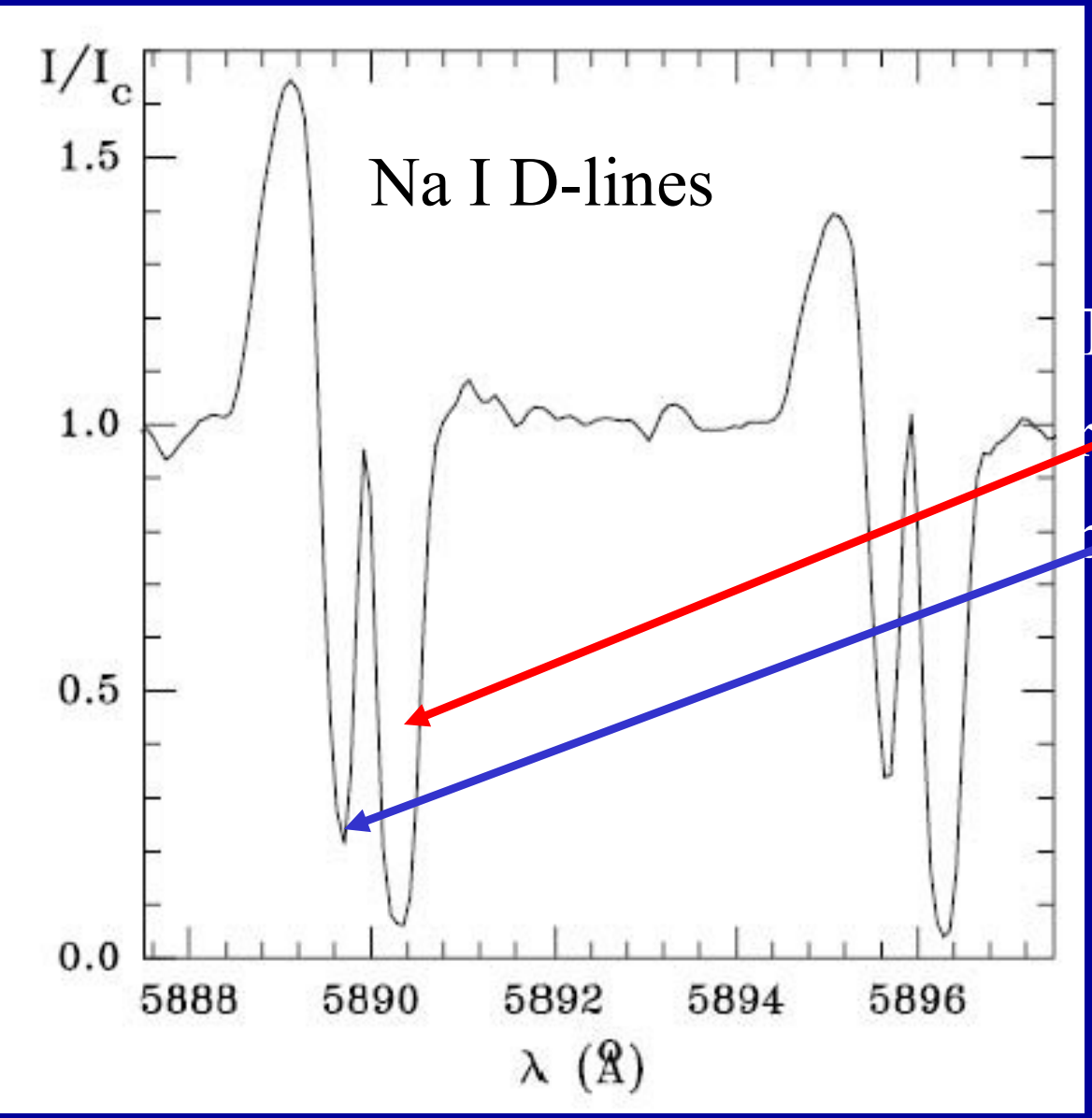
CI Cam – X-ray



From Russell et al. (2006) MNRAS, 371, 1334

Fit obtained for low-mass black hole X-ray binaries

CI Cam – Distance Problem



Published distance range: 1−17 kpc

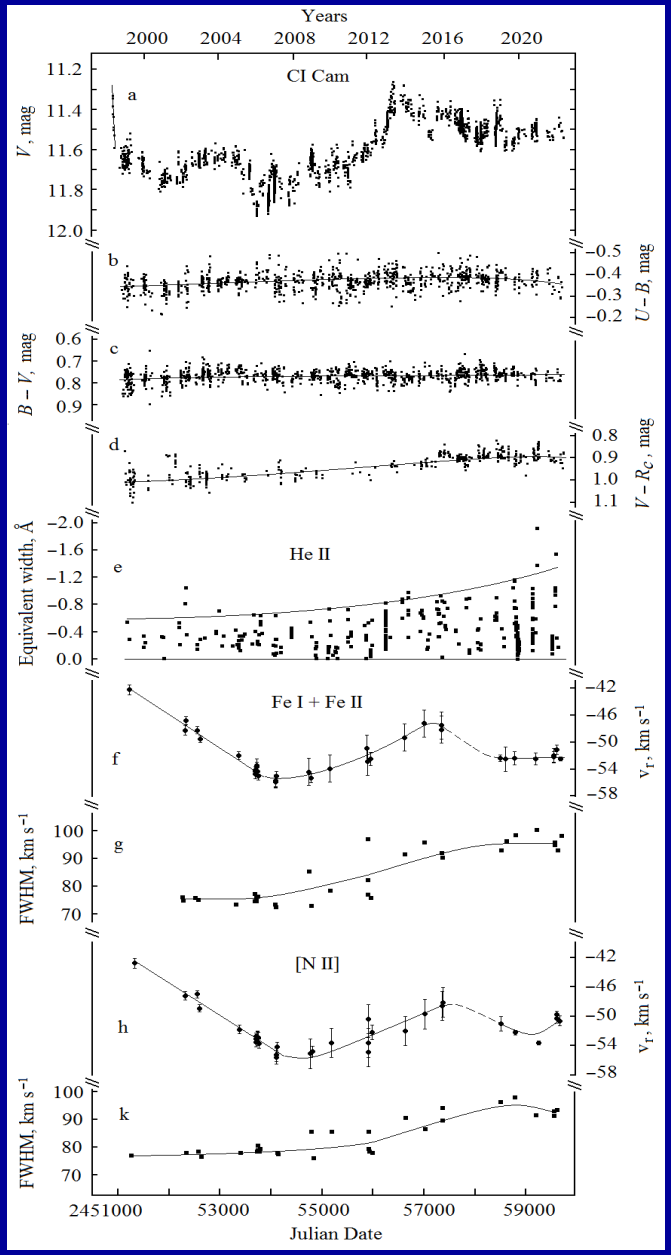
Two components:

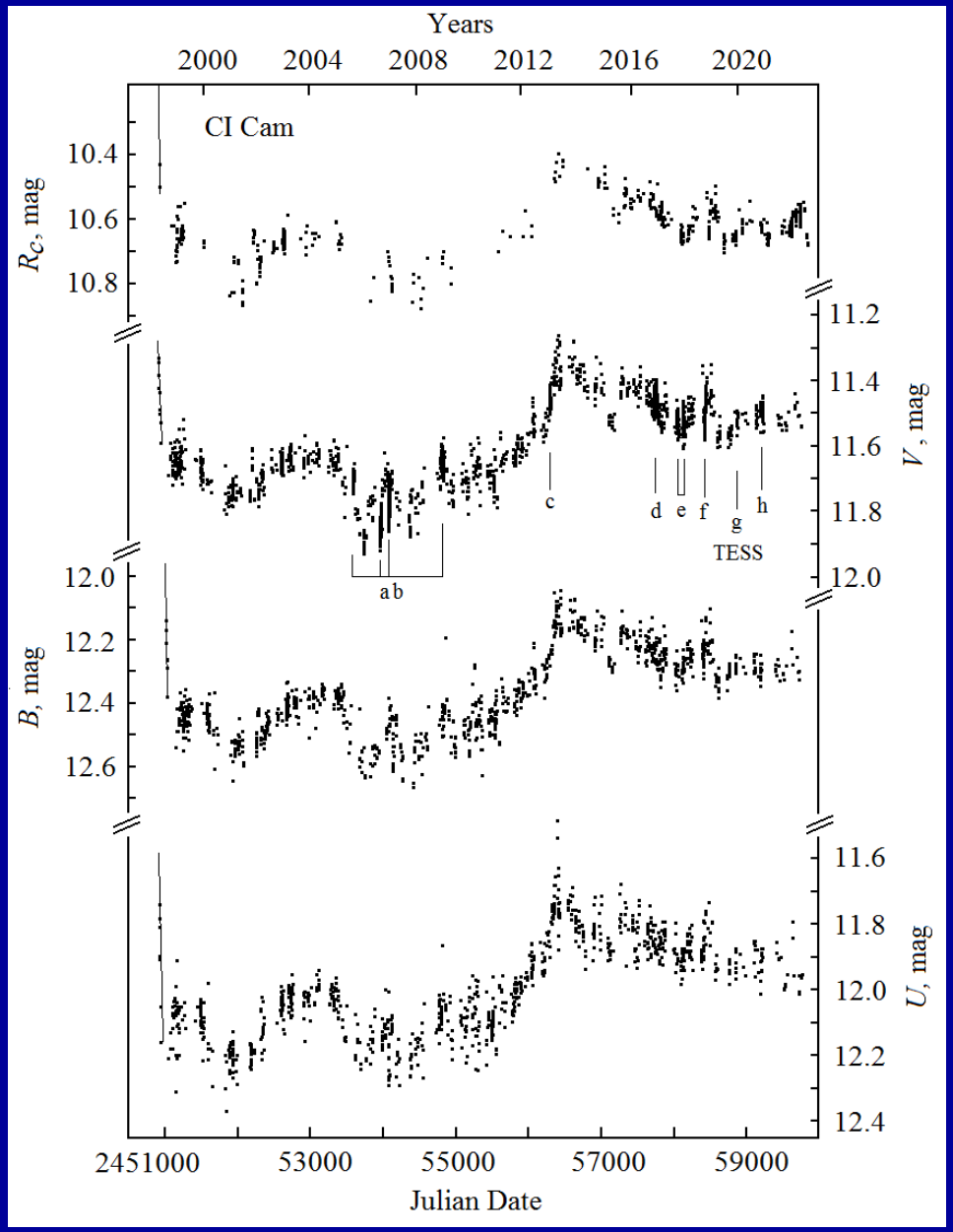
red – local arm

blue – Perseus arm

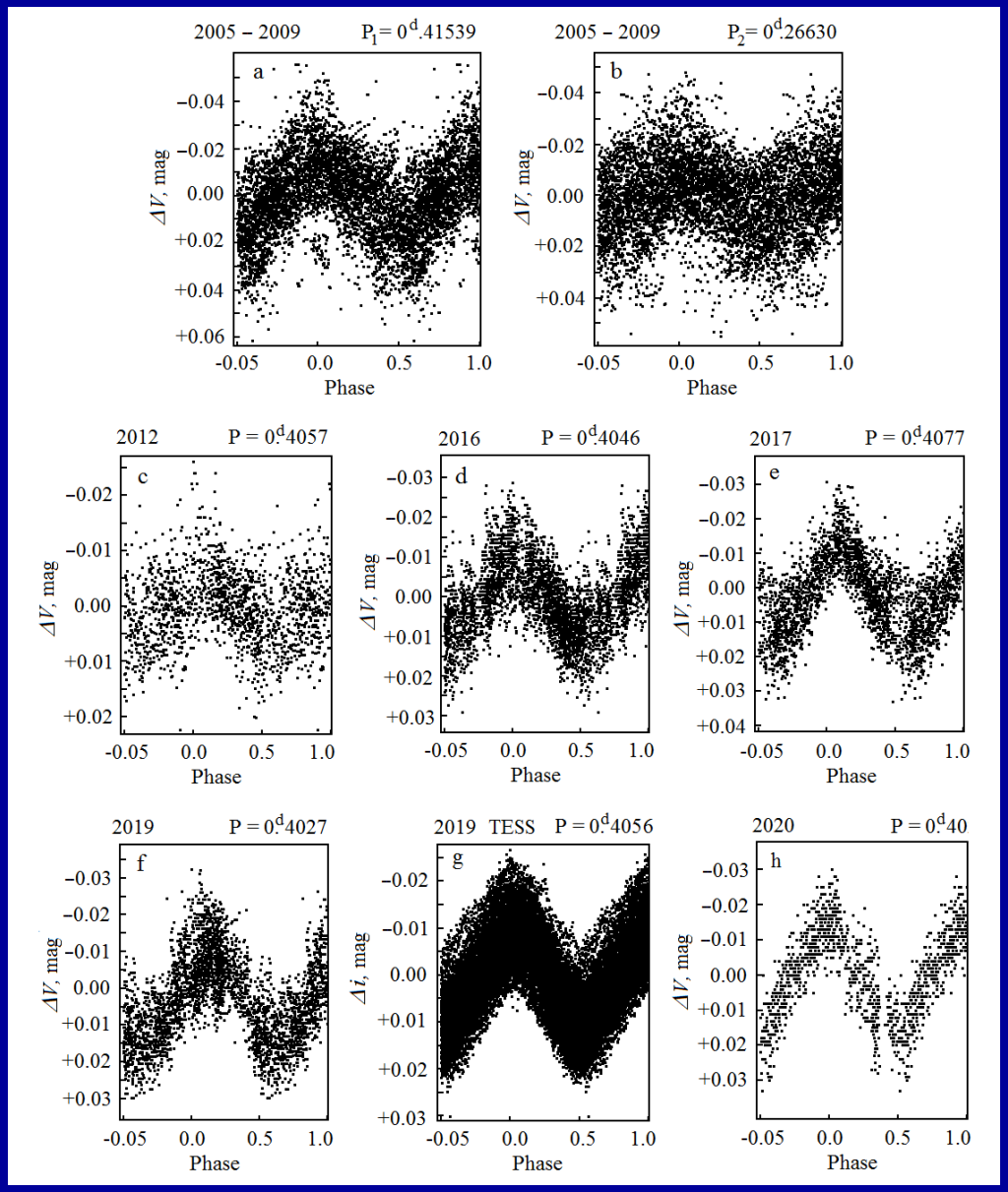
Interstellar NaI D-line profiles suggest a distance of 2−3 kpc (Miroshnichenko et al. (2002)

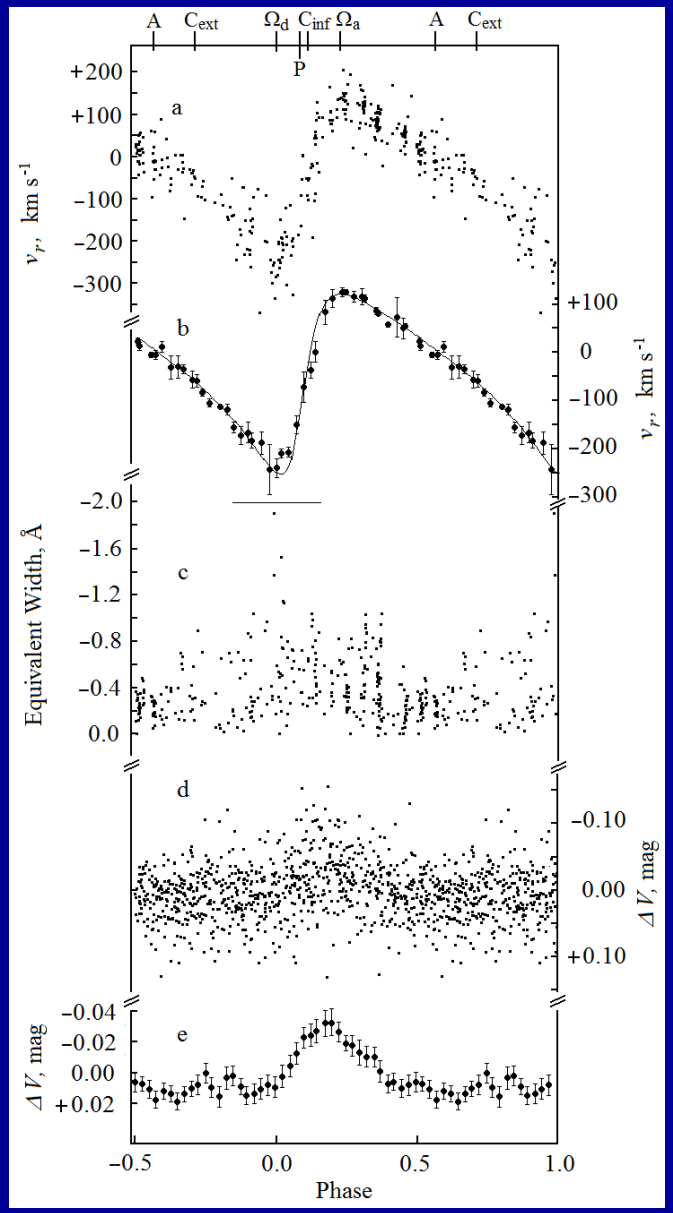
CI Cam: Photometric Variations





CI Cam: Pulsations and Orbit





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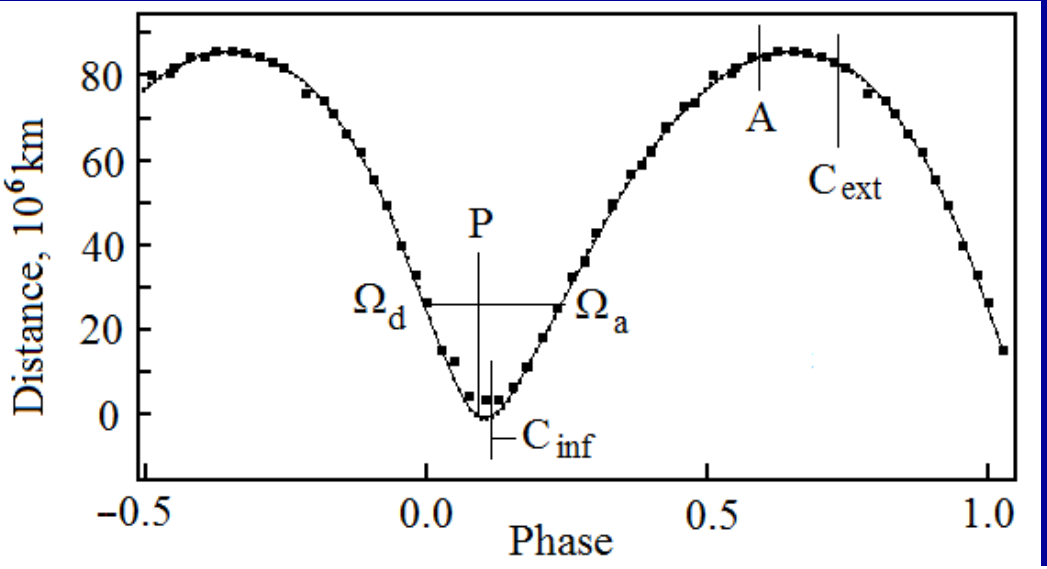
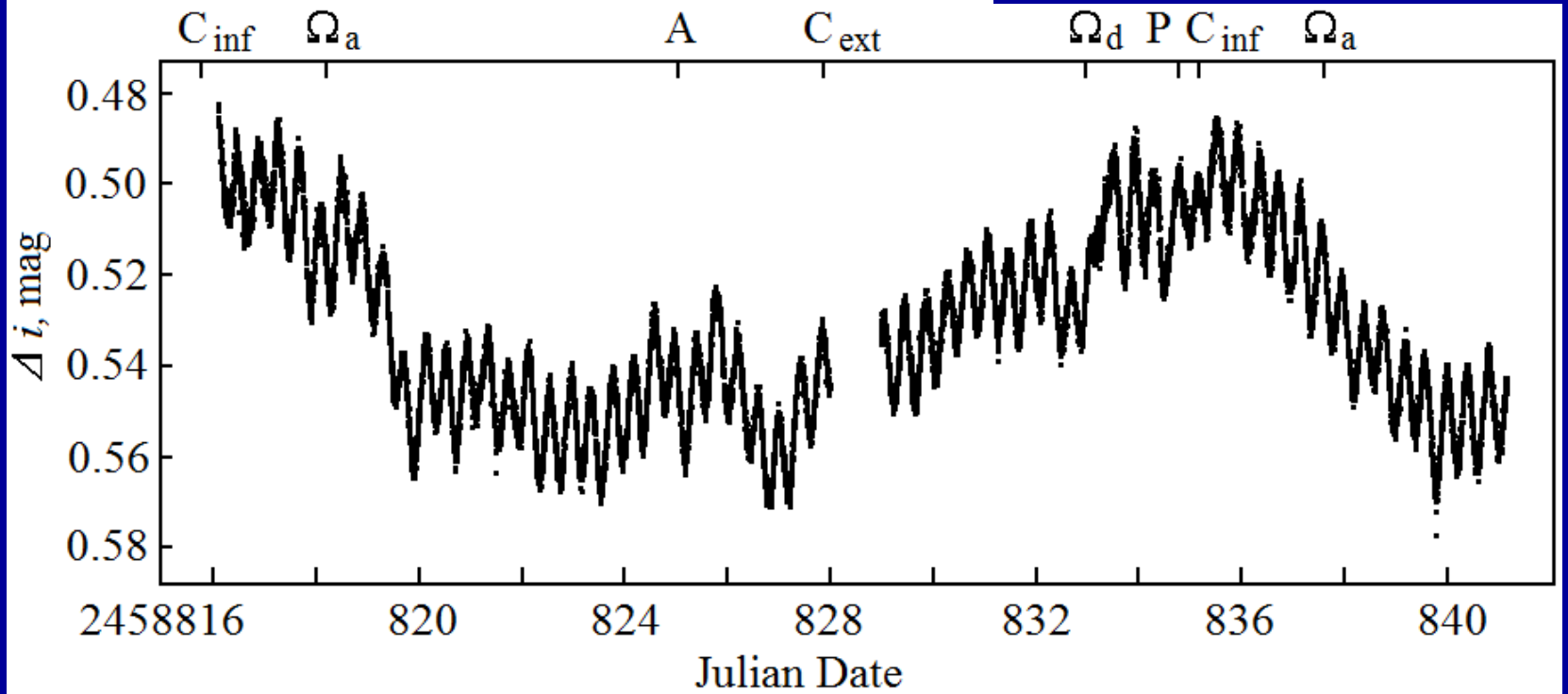


A – apastron

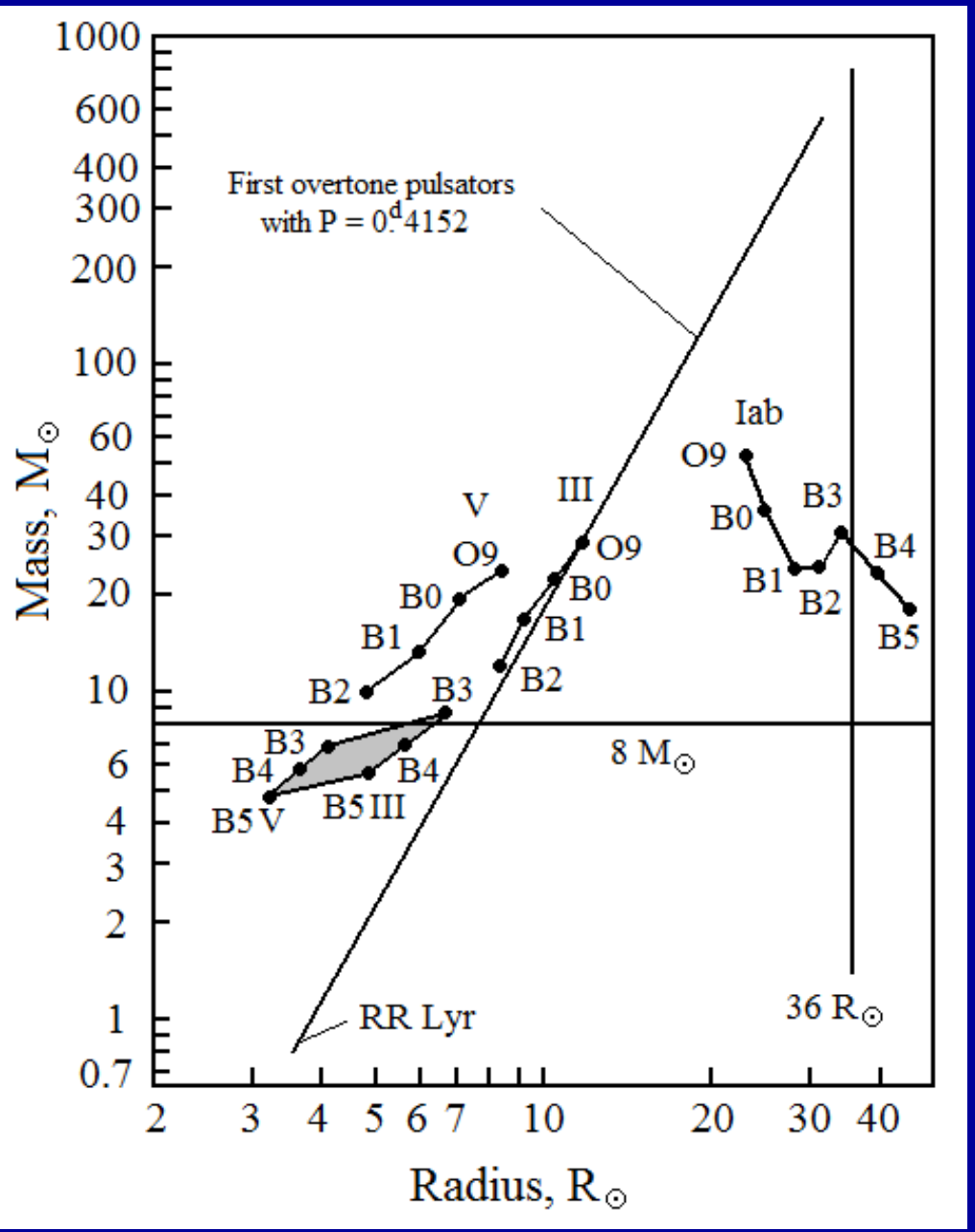
P – periastron

Q – nodes

C - conjunctions



Pulsations and Physical Parameters



$$Q = P \sqrt{\rho}$$

Q – pulsation constant

P – pulsation period

ρ – average density

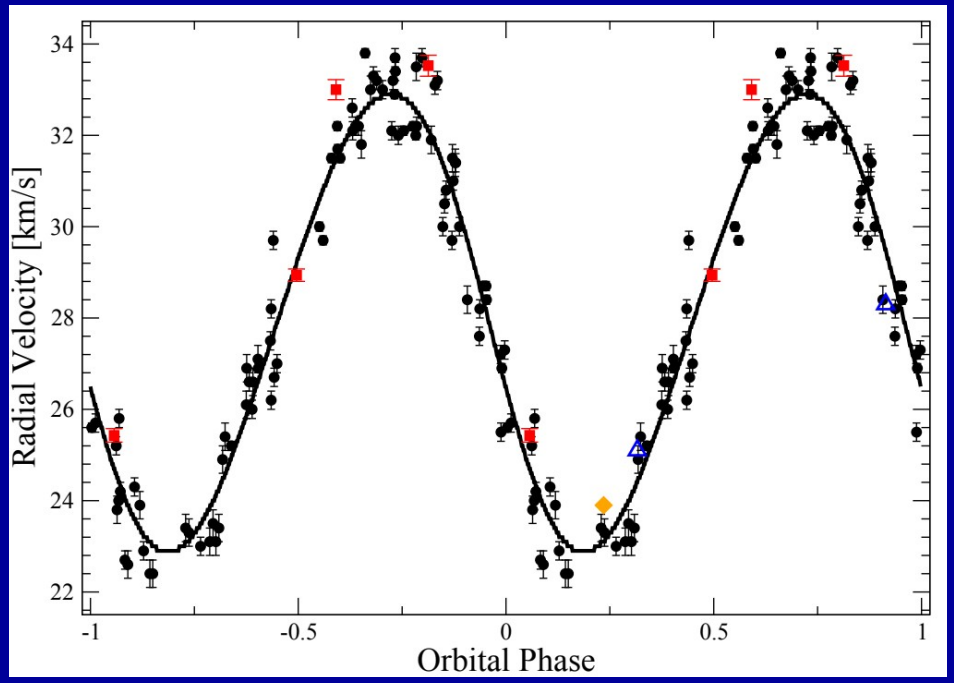
$$\rho = M/(4/3\pi R^3)$$

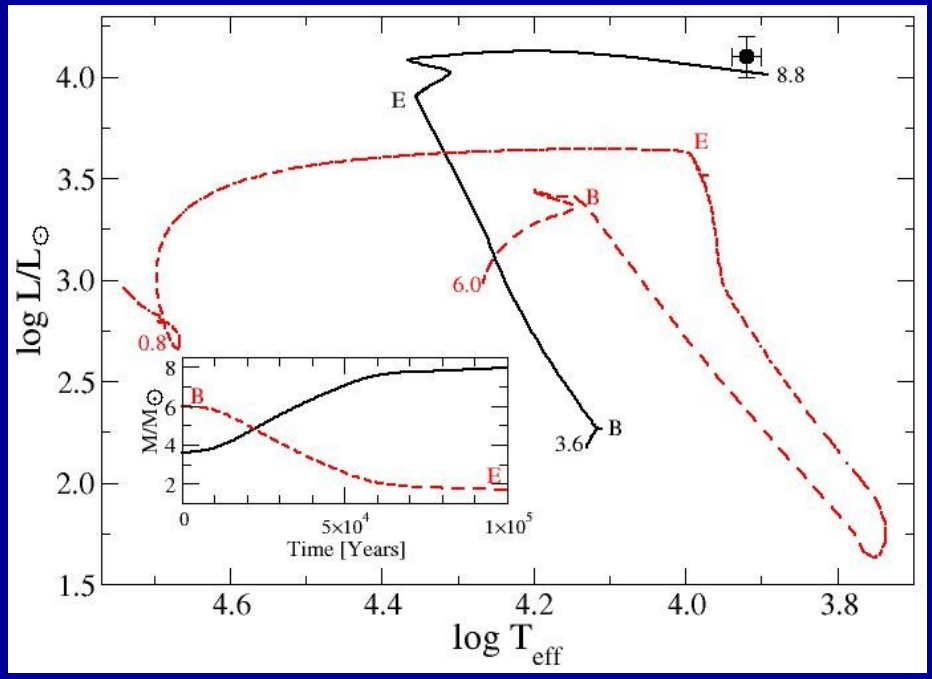
$$M = (4/3\pi R^3)\,(Q/P)^2$$

$Q_{1H} = 0.0272$

(for the first overtone)

3 Pup: Single–Line Binary





Orbital period: 137.3±0.1 days, K_1 = 5.0±0.8 km/s,

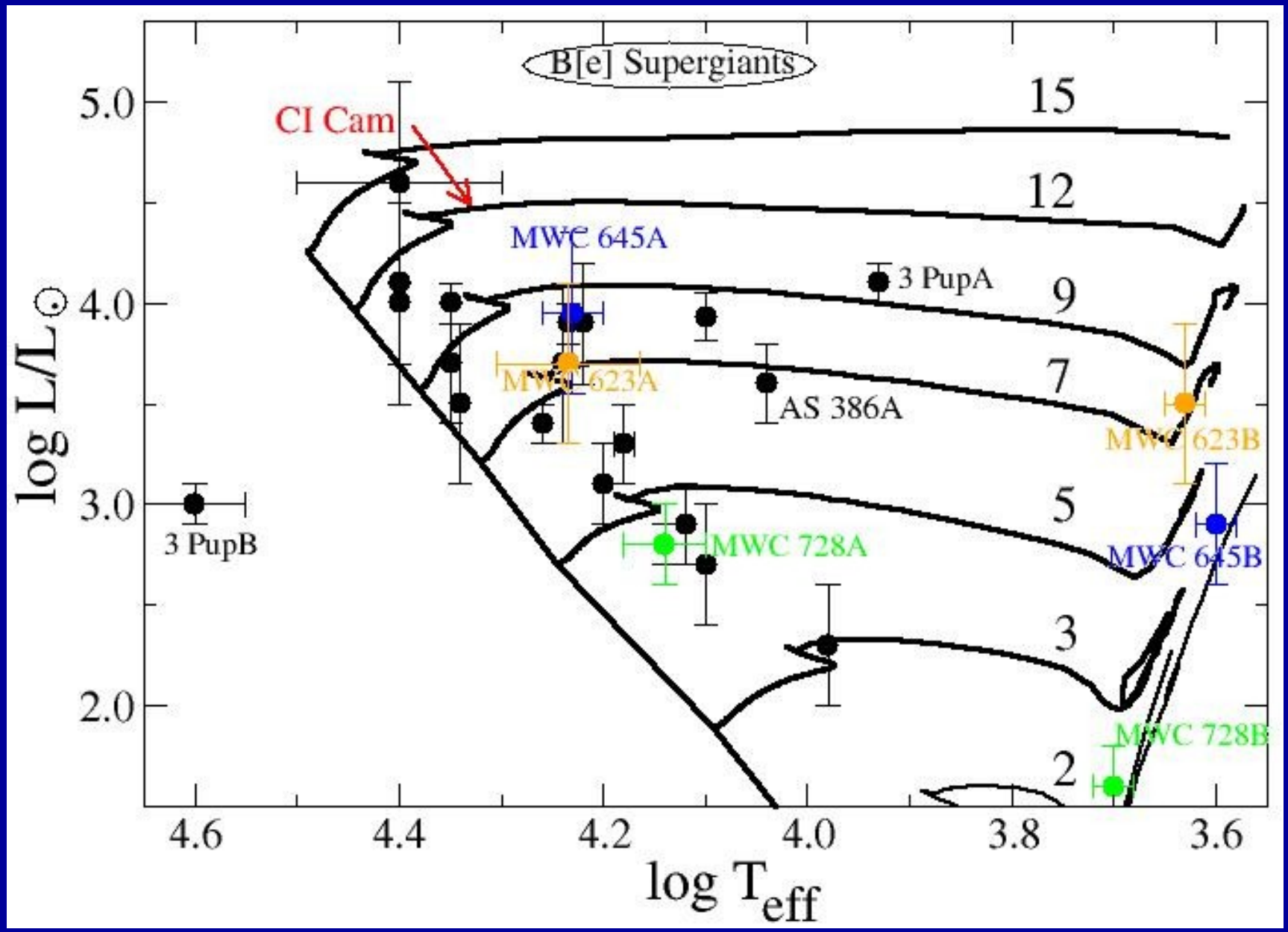
e = 0.05±0.05, $f(M_2) = 1.8\ 10^{-3}\ M_\odot$

Initial masses: $M_1 = 3.6\ M_\odot$ $M_2 = 6.0\ M_\odot$

Current masses: $M_1 = 8.8\ M_\odot$ $M_2 = 0.8\ M_\odot$

Miroshnichenko et al. (2020, ApJ, 897, id. 48)

FS CMa objects on HR diagram



FS CMa Type Binary Model

Nature of FS CMa Stars

Single stars?

Too high mass loss rates for objects with nearly MS luminosity ($>10^{-7}$ $M_\odot$ yr^{-1} for $3 - 10$ $M_\odot$)

Results of a merger? No obvious events in ~100 years.

Interacting (post mass transfer) binaries?

Can explain the presence of abundant circumstellar matter! (e.g., models by Wellstein, Langer, & Braun 2001; van Rensbergen 2006, 2008, 2011; Deschamps et al. 2015): the gainer cannot take the entire mass, transferred from the donor.

Conclusions on CI Cam

- Optical brightness measured since the outburst in 1998 and slowly increases with time.
- Rapid variability of the He II 4686 Å line was detected.
- The line forms in the material located around a faint secondary on an elliptical orbit with an eccentricity of 0.43 – 0.49.
- Radial pulsations of the primary companion in the first overtone are detected and allowed to constrain the spectral type at B0 – B2 III and mass at 12-22 $M_{\odot}$.
- If the secondary is a white/helium dwarf with a mass < 1 $M_{\odot}$, then the mass function limits the primary to M <12 $M_{\odot}$ and R<8.3 $R_{\odot}$.
- Overall our results are consistent with a conclusion that CI Cam can be a member of the FS CMa objects group.
- Tertiary component has been suspected in the system.