The importance of the IR SPECTRAL DATA to study Be STARS

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POEMS

Physics of Extreme Massive Stars

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Schreiben des Herrn Prof. *Secchi*, Dir. der Sternwarte des Collegio Romano, an den Herausgeber.

Dans ma dernière je vous annonçais la grande facilité d'observer les spectres stellaires avec la nouvelle construction de spectroscope que j'ai réussi à combiner. Bientôt j'espère de pouvoir vous envoyer une liste des objets examinés, mais pour le moment je ne pourrais différer davantage à vous signaler une particularité curieuse de l'étoile γ Cassiopée, unique jusqu'à présent. Celle-ci est que pendant que la grande majorité des étoiles blanches montre la raie *f* très-nette et large, et comme α Lyre, Sirius etc., γ Cassiopée a à sa place une ligne lumineuse très-belle et bien plus brillante que tout le reste du spectre. La place de cette raie est, autant que j'en ai pu prendre des mesures, exactement coïncidente avec celle de *f*, et on peut très-bien en faire la comparaison avec l'étoile voisine β Cassiopée. La mesure je l'ai prise en plaçant une pointe de repère dans le chercheur et couvrant la raie dans la grande lunette avec la pointe micrométrique du spectroscope: si les deux lunettes sont portées de l'étoile γ à l'étoile β et placées de la même manière sur l'une et sur l'autre on trouve que la position de la raie luisante de la première cor-

…e. J'espère pouvoir
…manière plus exacte encore. En com-
…gase on trouve que la *f* tombe sur
…ette étoile présente. Du
… γ Cassiopée, n'est pas
…ais assez plus petites,
…toile présente donc un
…inaire des étoiles blanches.
…atique de l'effet de cette
…gne brille sur le reste du
…m brille sur le fond
…métal.
… les détails des autres étoiles. —
… résultats et a même vu avec sa
…sieurs beaux spectres avec
l'usage de ma combinaison.

Rome, 1866 Août 23. *A. Secchi.*

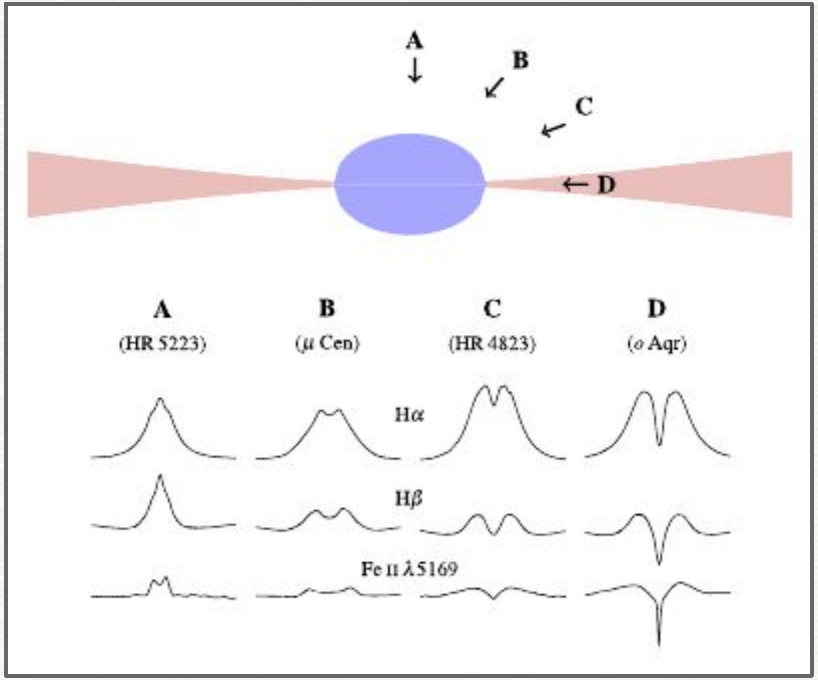
> “ […] I could not delay any longer in informing you of a curious particularity of the star γ Cass, unique until now. […] has in its place a very beautiful luminous line […] ”

"A non-supergiant B-type star whose spectrum has, or had at some time, one or more Balmer lines in emission."

Collins, 1987

On the origin of bright lines in spectra of stars of class B

(Otto Struve; 1931, Astrophysical Journal)



(Rivinius et al. 2013)

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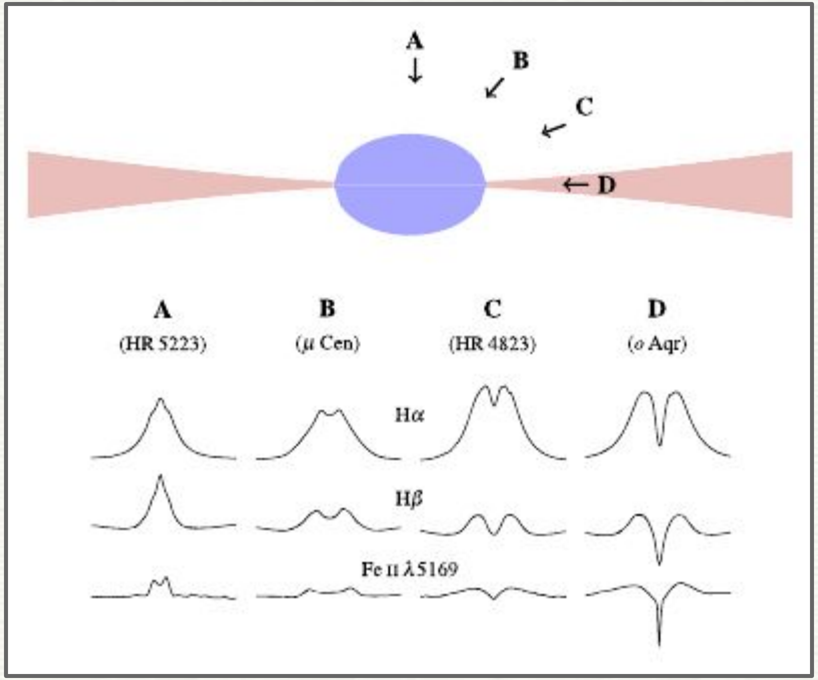

(Rivinius et al. 2013)

- Decretion disc
- Keplerian rotation
- Fed by mass ejected from the central star
- Governed by viscosity

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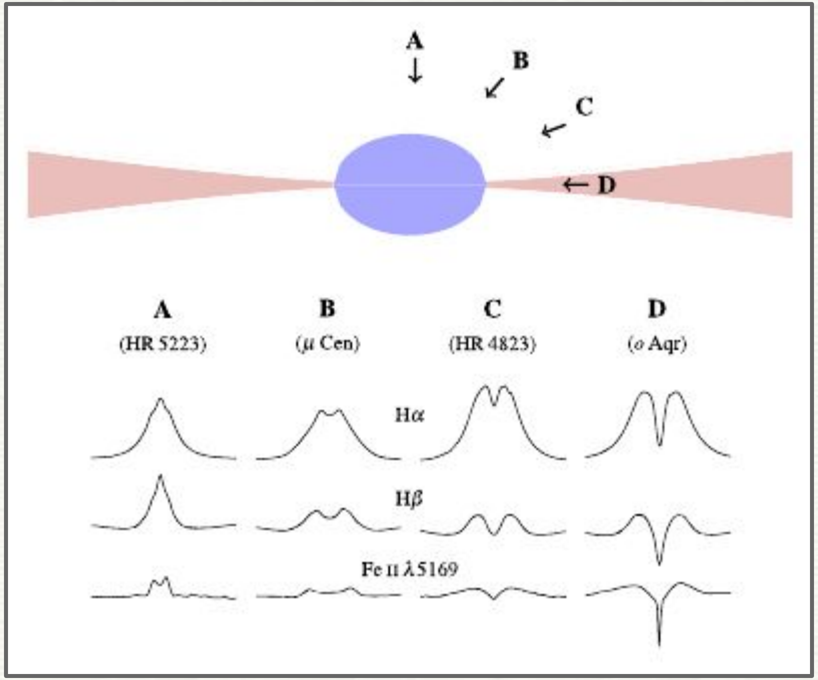

- Decretion disc
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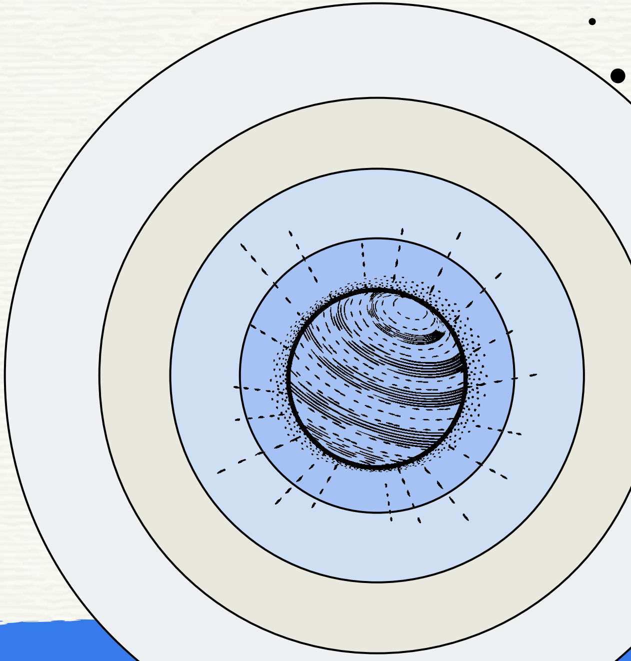
VISCOUS DECRETION DISK
(Lee et al. 1991).

(Rivinius et al. 2013)

Why we started to observe Be stars in the infrared spectral range?



Spectrophotometry of compact embedded infrared sources in the 0.6-1.0 micron wavelength region

(McGregor, Persson, Cohen; 1984, Astrophysical Journal)

Sources embedded in molecular clouds had been studied previously at infrared wavelength, where the effects of dust emission are less severe than in the optical spectral range.

The **0.6-1.0 μm spectra** of certain high-mass YSOs **shared many similarities with** those obtained from **Be stars**.

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The embedded objects possess circumstellar envelopes that have **similar physical conditions** to those in Be stars

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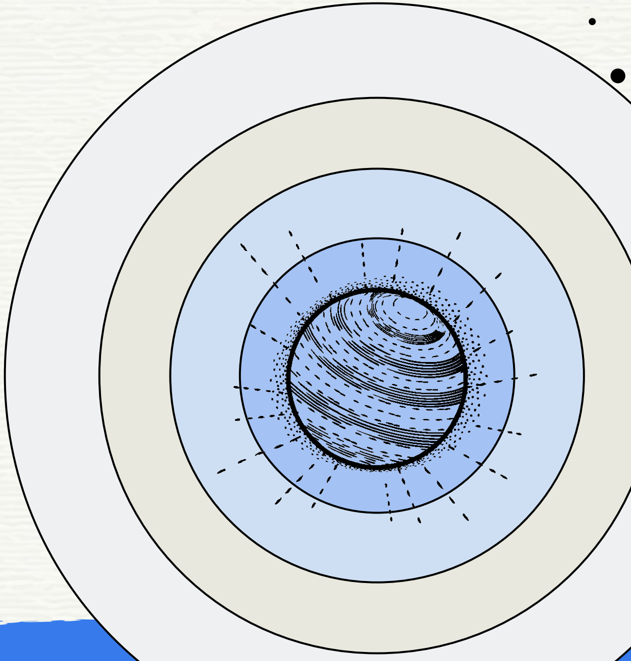
The **0.6-1.0 μm spectra** of certain high-mass YSOs **shared many similarities with** those obtained from **Be stars**.

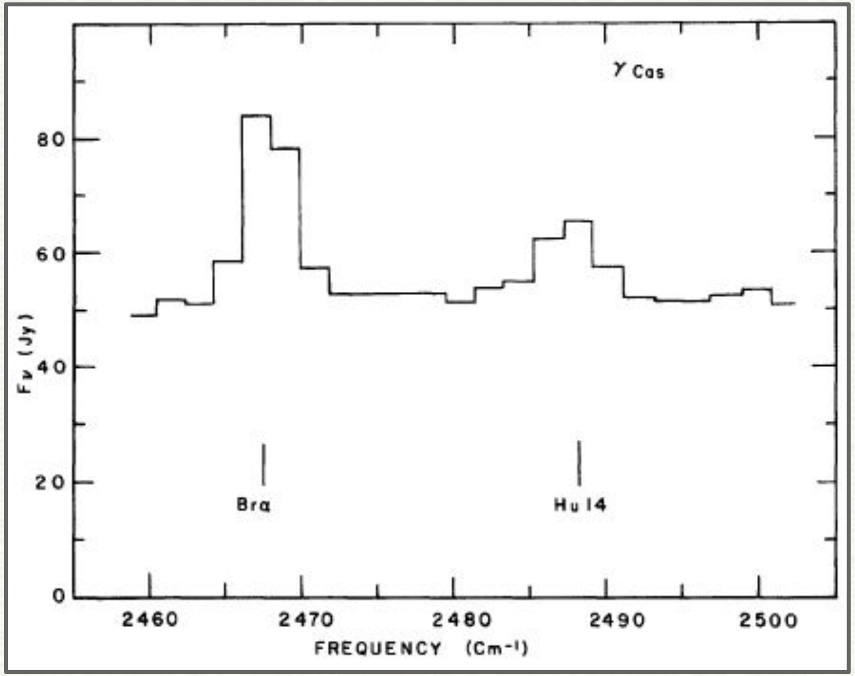
Let's observe Be stars in the IR spectral range!

What can we obtain from the IR spectra of Be stars? What are the advantages of observing in this spectral range?



Emission-line spectra of circumstellar envelopes: infrared hydrogen line fluxes from Be stars
(Persson, McGregor; 1985, Astronomical Journal)

13 Be stars observed:
7 with fluxes for eight emission lines in the range 1.28 - 4.67 μm
+
6 with only Brγ fluxes



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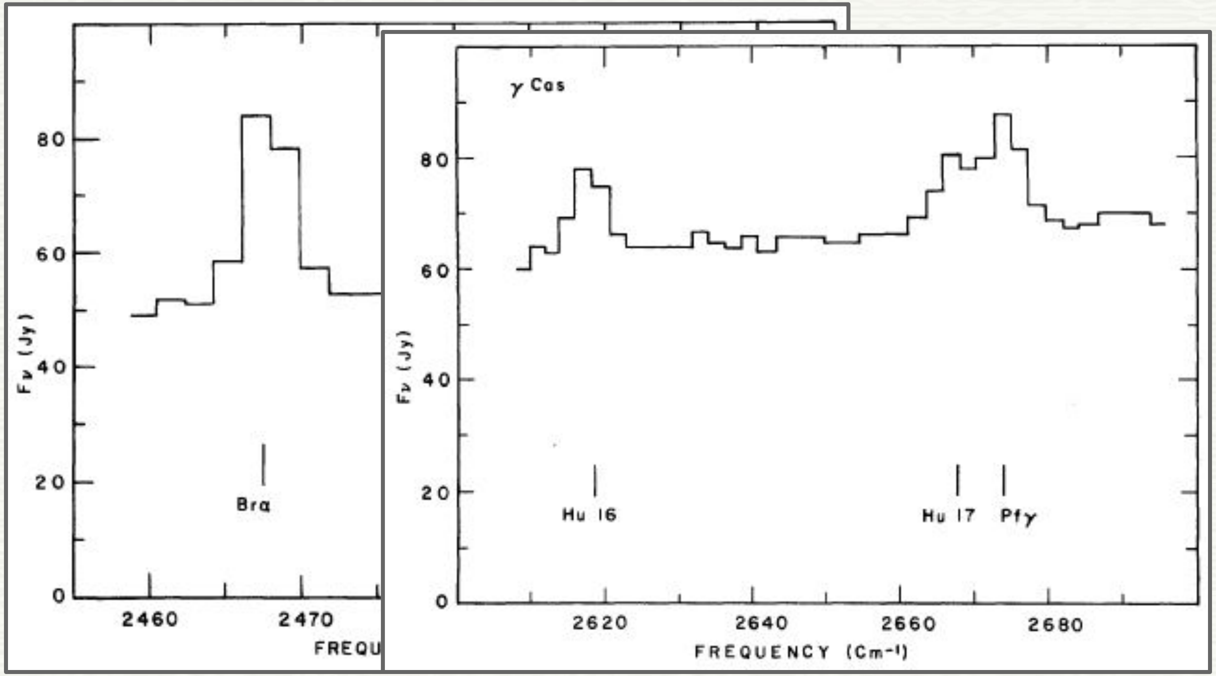
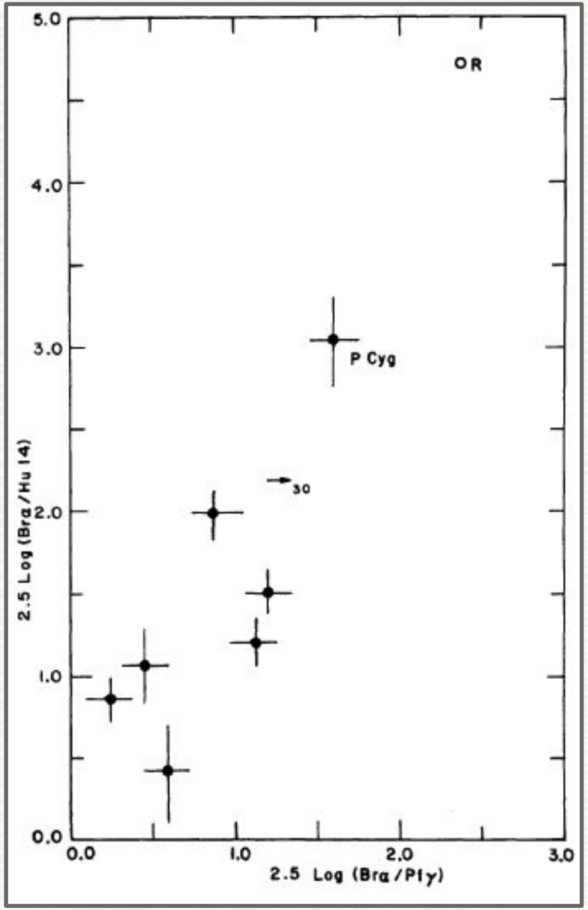




Brα/Pfγ vs Brα/Hu14 line-flux diagram

The points are distributed between the origin (equality of the lines) and the Case B recombination values

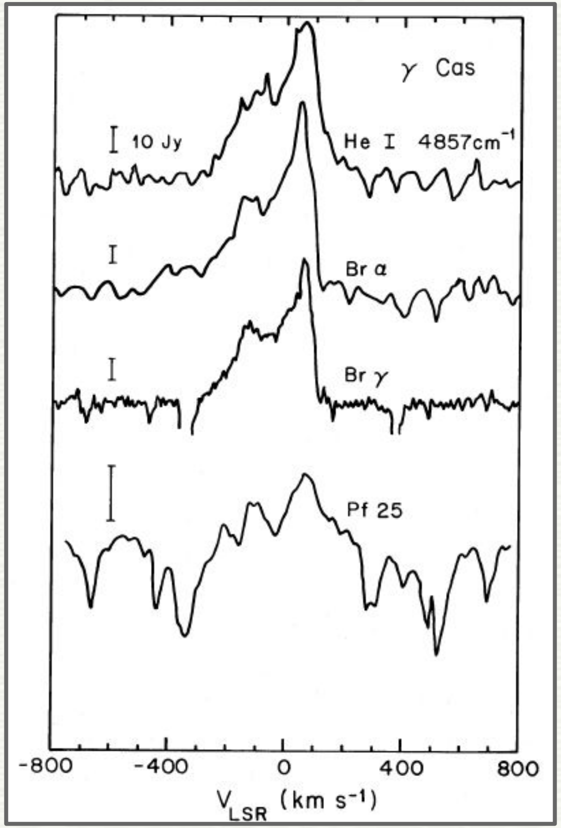
(Baker & Menzel 1938; Storey & Hummer 1995)

Can be understood qualitatively in terms of the line optical depths

Pfγ and Hu14: line strength smaller than Brα

(Persson, McGregor; 1985)

The infrared emission-line spectrum of γ Cassiopeiae
(Hamann, Simon; 1987, The Astrophysical Journal)



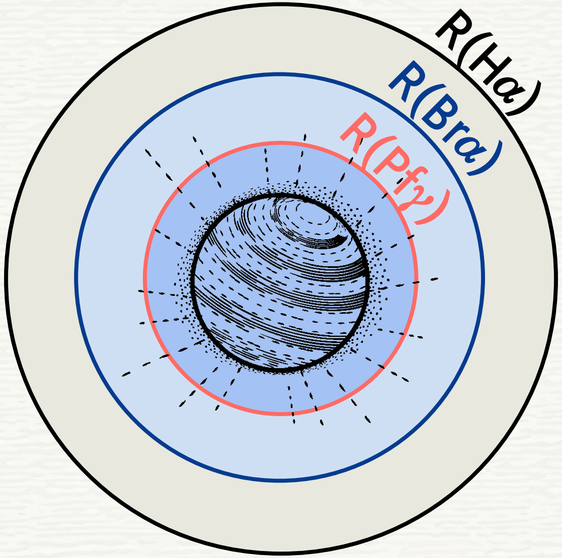
IR hydrogen lines:

- fluxes indicate that these lines are formed in a **small, dense, optically thick region** where the density declines sharply with distance from the star
- profiles and fluxes consistent with a **rotating circumstellar disc**, rather than a wind scenario

A study of the infrared spectrum of ψ Persei
I. A parameter study of the disc model

(Marlborough, Zijlstra, Waters; 1997, Astronomy & Astrophysics)

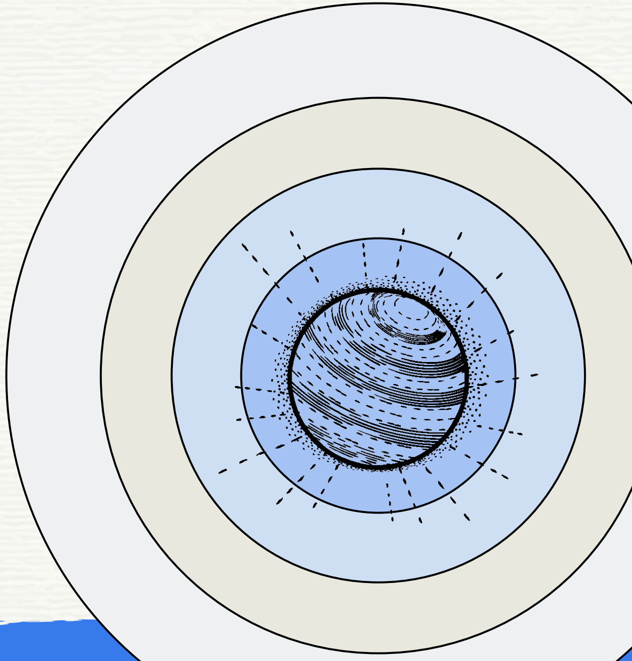
Hα and some IR lines (Brα, Brγ, Pfγ, Hu17)



Line behaviour depends on the following effects:

- the atomic parameters of the particular line,
- the temperature dependence of the recombination coefficient, and of the line source function,
- the size of the region in which a given line forms,
- the temperature gradient on the envelope,
- the velocity of their regions of formation (Waters & Marlborough, 1992)

IR recombination lines allows us to get information about the physical parameters of the circumstellar material!



A Spectral Atlas of Hot, Luminous Stars at 2 Microns

(Hanson, Conti, Rieke; 1996, Astrophysical Journal Supplement)

180 well-studied, optically visible, luminous stars **with or without emission**

➡ **Spectral classification system for the K band to be used to estimate effective temperatures of O and early-B stars**

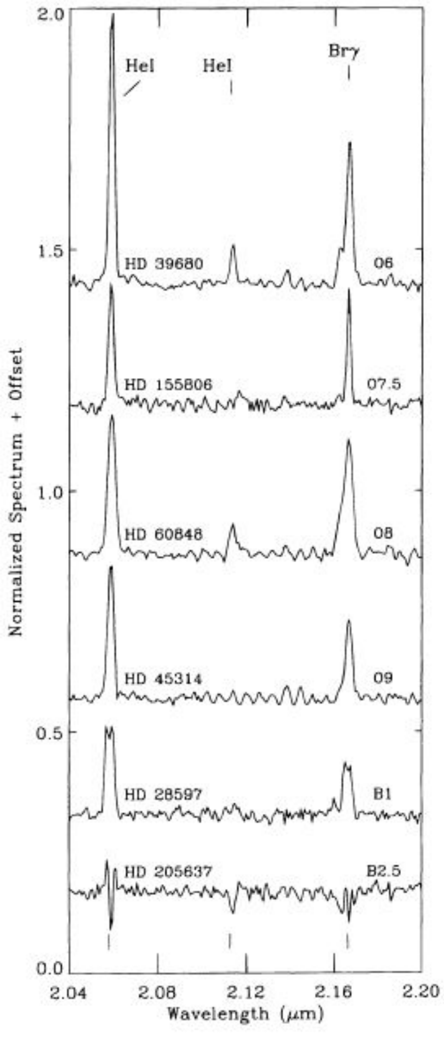


FIG. 28.—Spectra of Oe and Be stars

A representative sample of Be stars

I. **Sample selection, spectral classification and rotational velocities**
(Steele, Negueruela, Clark; 1999, Astronomy and Astrophysics Supplement)

II. **K band spectroscopy**
(Clark, Steele; 2000, Astronomy and Astrophysics Supplement)

III. **H band spectroscopy**
(Steele, Clark; 2001, Astronomy and Astrophysics)

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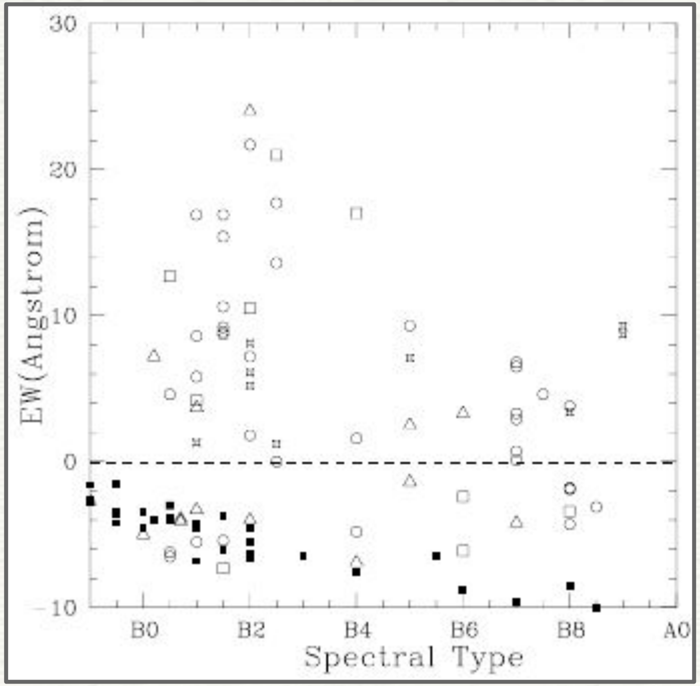
III. **H band spectroscopy**
(Steele, Clark; 2001, Astronomy and Astrophysics)

A representative sample of Be stars

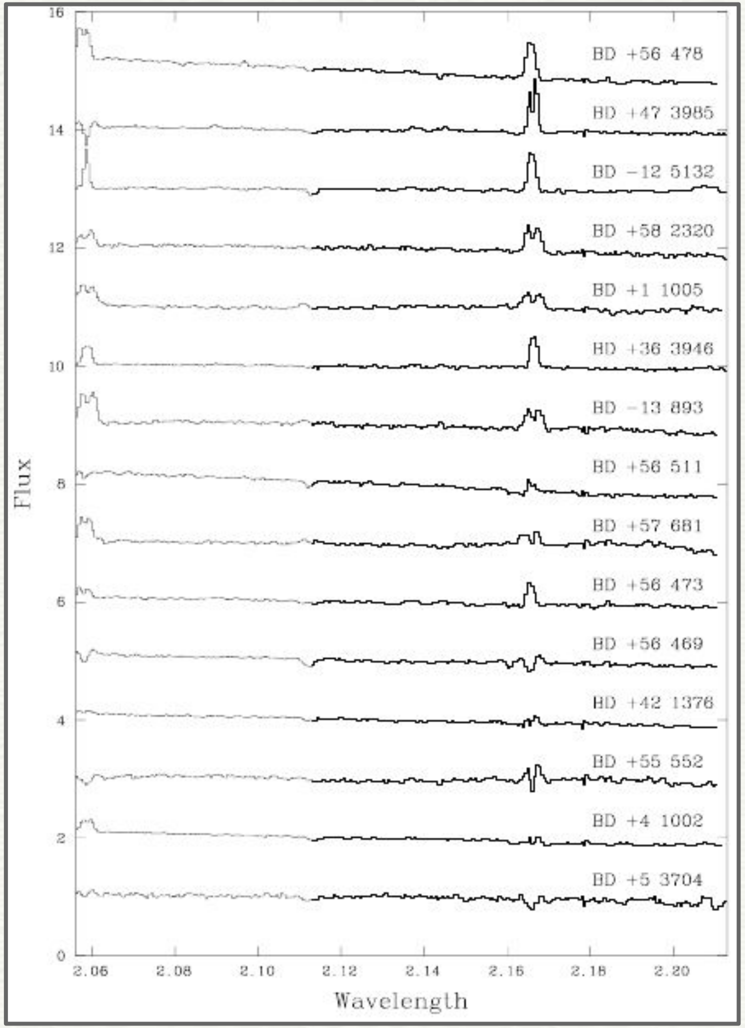
II. K band spectroscopy

2.05 - 2.22 μm spectra
66 isolated Be stars

General trend:
stronger Brα emission - early ST
No correlation with LC.

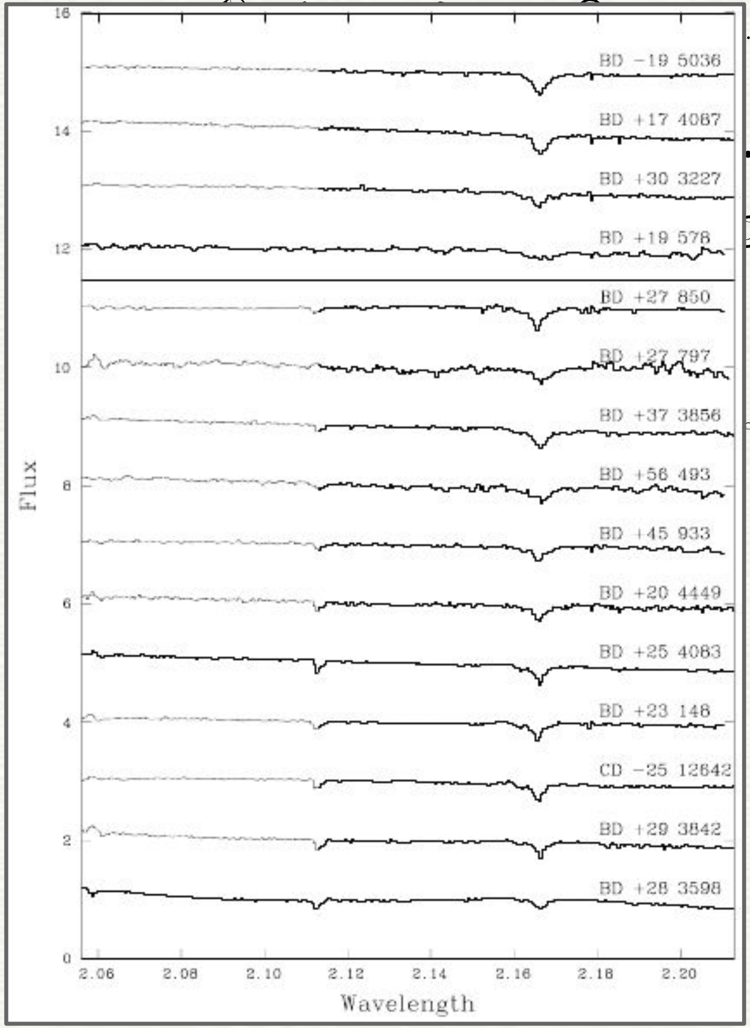


	Brγ	He I	Mg II	ST
Group 1	Emission	✔	✖	O9e - B3e
Group 2	Absorption	✔	✖	O9 - B3
Group 3	Emission	✖	Emission	B2e - B4e
Group 4	Absorption	✖	✖	B4 - B9
Group 5	Emission	✖	✖	B4e - B9e



Group 1

Groups 2 and 4



A representative sample of Be stars

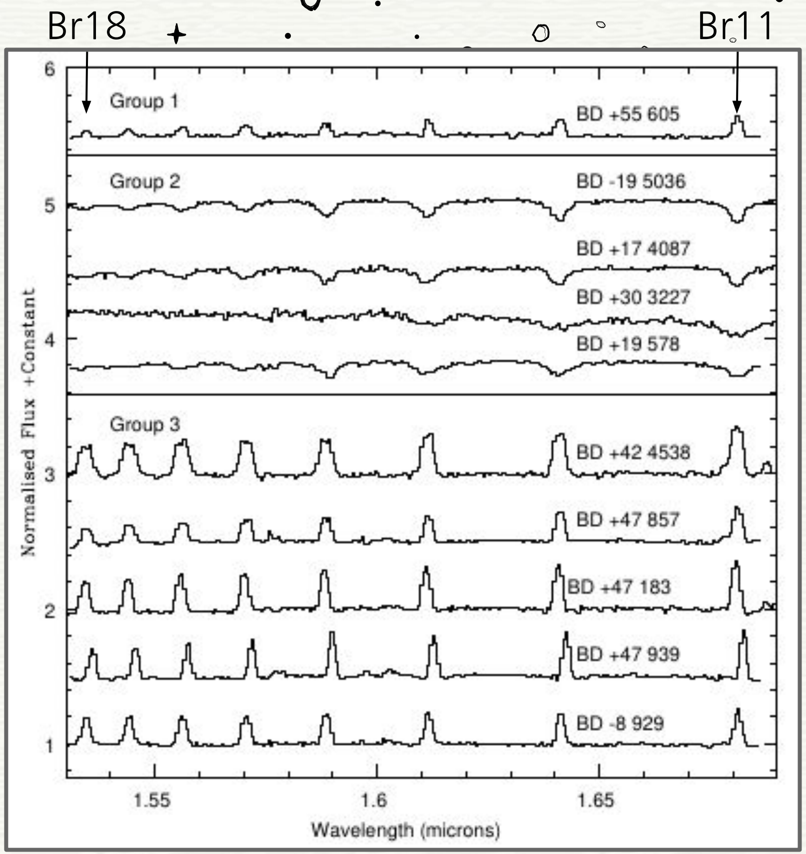
III. H band spectroscopy

57 isolated Be stars

Brγ in emission

↓

Br11 to Br18 in emission



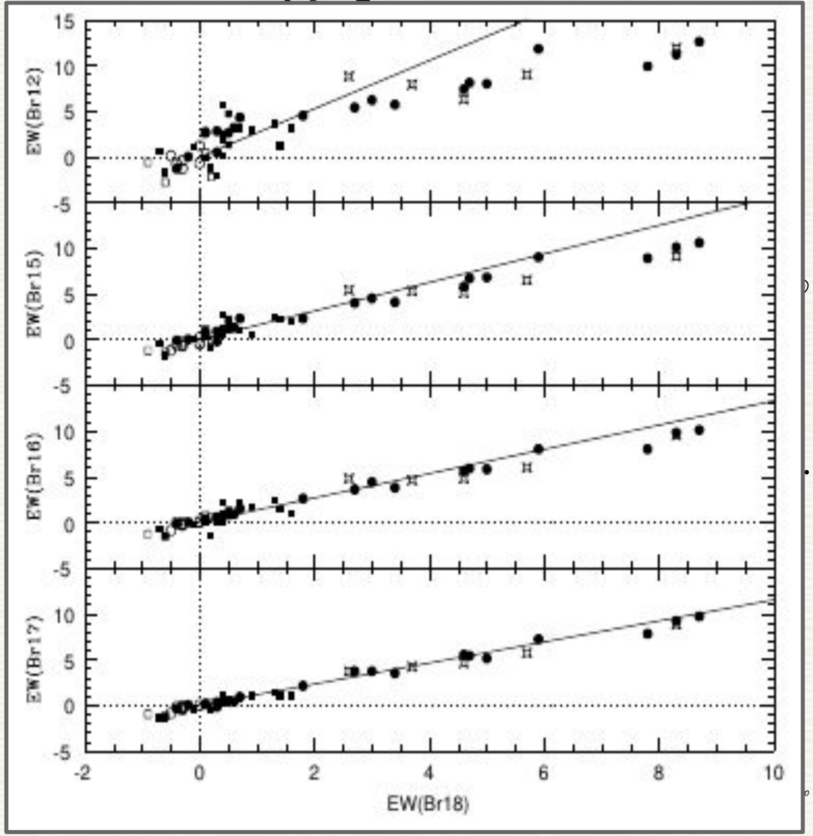
For comparison of Brackett line strengths between objects of different spectral type it is **necessary to remove the effect of the underlying photospheric absorption lines from the spectra!**

→ EW for normal B stars from previous works
(small contribution)

−

Agreement with case B

+



An atlas of 2.4 to 4.1 μm ISO/SWS spectra of early-type stars

(Lenorzer et al.; 2002, Astronomy and Astrophysics)

75 spectra of early type stars: O, B, Be, LBV

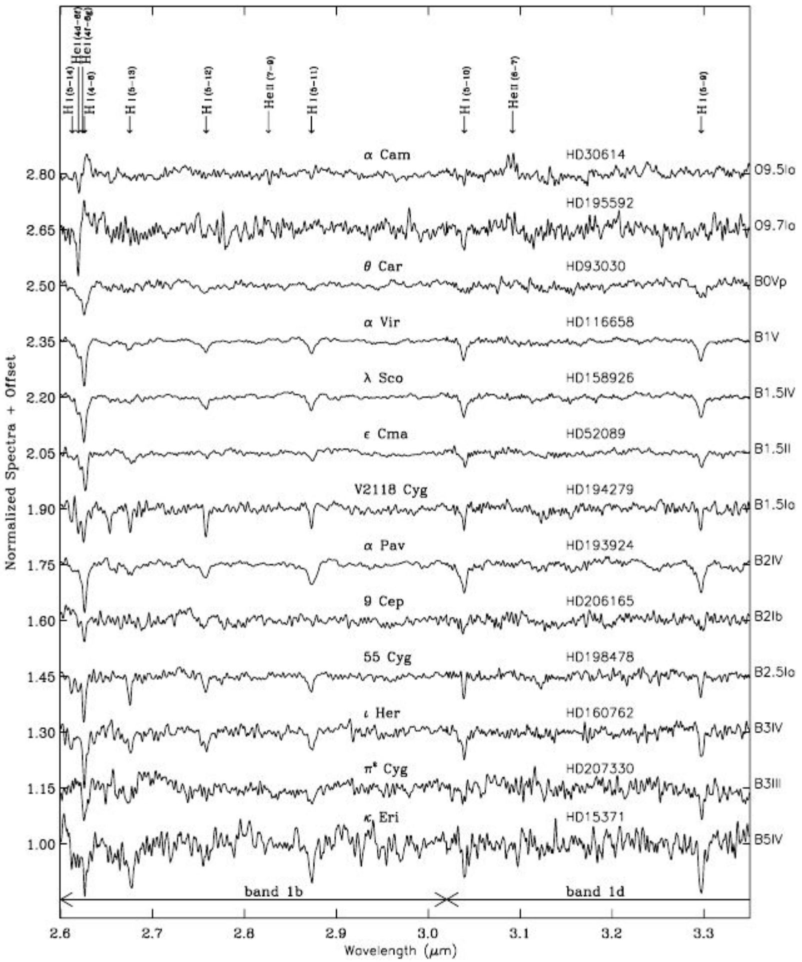


Fig. 2. The 2.6 to 3.35 μm region of the spectra of O9- to B5-type stars contains the Brβ line at λ 2.6259 μm and some of the Pfund series lines. A few helium lines are detected in the hottest stars and are identified with arrows in the top of the figure. The O supergiants show Brβ emission.

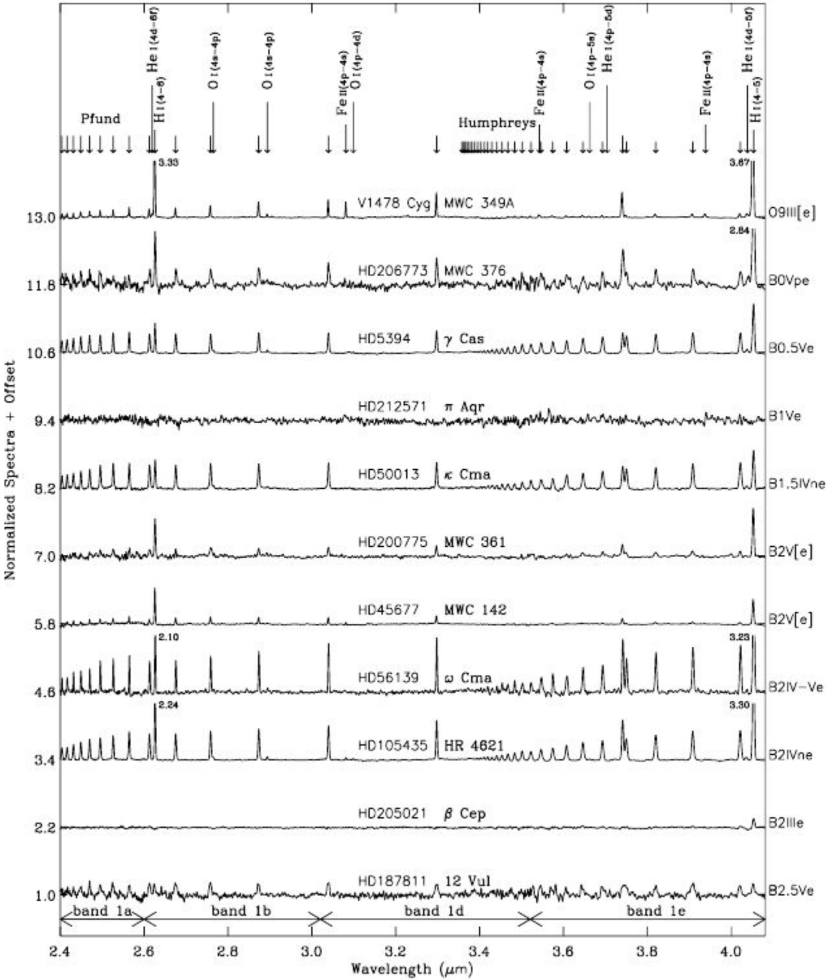


Fig. 5. The full band 1 spectra from 2.40 to 4.08 μm of B0e to B2.5e stars contain hydrogen lines of the Brackett, Pfund and Humphreys series. In most of the spectra, the only He I line present is at λ4.0377. A few stars also show some O I lines.

An atlas of 2.4 to 4.1 μm ISO/SWS spectra of early-type stars

(Lenorzer et al.; 2002, Astronomy and Astrophysics)

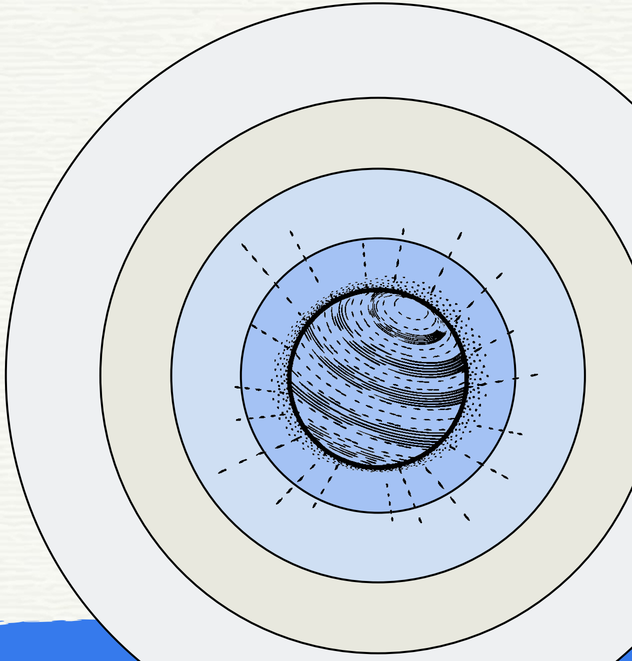
75 spectra of early type stars: O, B, Be, LBV

- **Formula** Pf and Br lines ⟶ **spectral type** for normal B-type dwarf to giant
- No dependence EW-ST for supergiants
- Brα sensitive indicator of the **mass loss**
- **No correlation** between intensity of emission lines with spectral type
- L-band contains three different hydrogen series lines (including Brα)

⟶ **the best band to derive physical properties**

IR recombination lines allows us to get information about the physical parameters of the circumstellar material!

- EW to correct from photospheric absorption (almost negligible for some lines)
- Numerous H lines!



Hydrogen infrared recombination lines as a diagnostic tool for the geometry of the circumstellar material of hot stars

(Lenorzer, de Koter, Waters; 2002, Astronomy and Astrophysics)

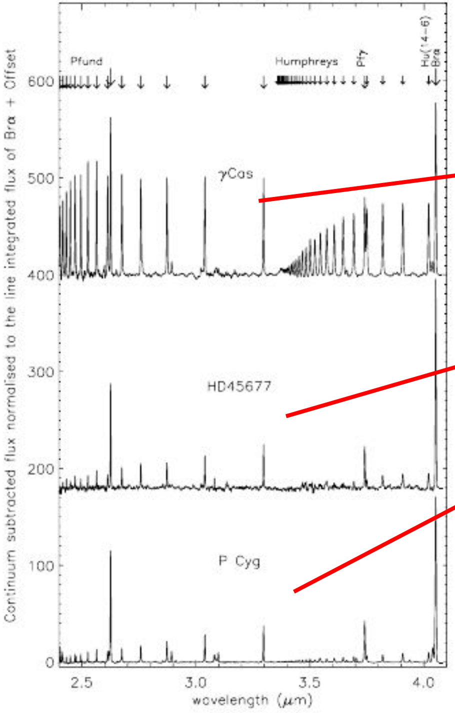


Fig. 1. Typical examples of the three classes of hot star IR spectra considered. Top spectrum: the Be star γ Cas; middle spectrum: the B[e] star HD 45677; lower spectrum: the LBV P Cygni (see text for discussion).

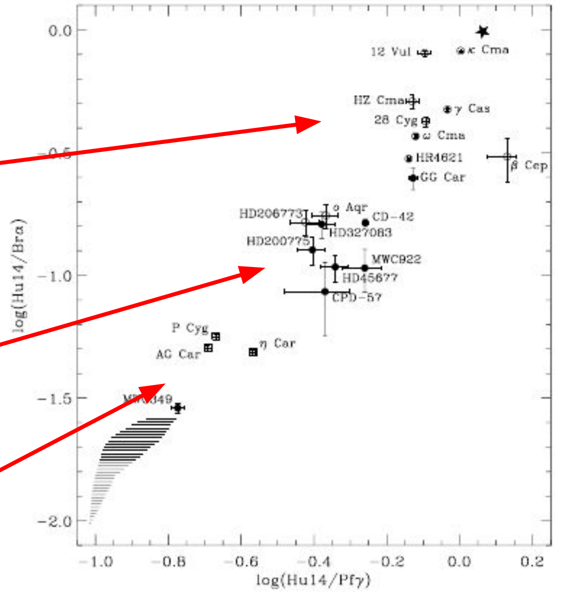


Fig. 2. Hu(14–6)/Brα versus Hu(14–6)/Pfγ line ratio diagram for the hot stars observed with ISO (Lenorzer et al. 2002). The different classes of objects, LBVs (squares), B[e] stars (filled circles) and Be stars (open circles), are well separated. The thick asterisks indicates the position of optically thick black body emission; the striped region shows the range of ratios for Menzel case B recombination, including collisional de-excitation, for temperatures higher than 10^4 K.

The line strengths are sensitive to the density of the emitting gas

Be-stars position is expected to vary along the diagonal

L-Band spectra of 13 Outbursting Be Stars

(Mennickent, Sabogal, Granada, Cidale; 2009, Publications of the Astronomical Society of the Pacific)

Be stars classified in three groups:

I. **Brα and Pfγ emissions as intense as Humphreys lines**

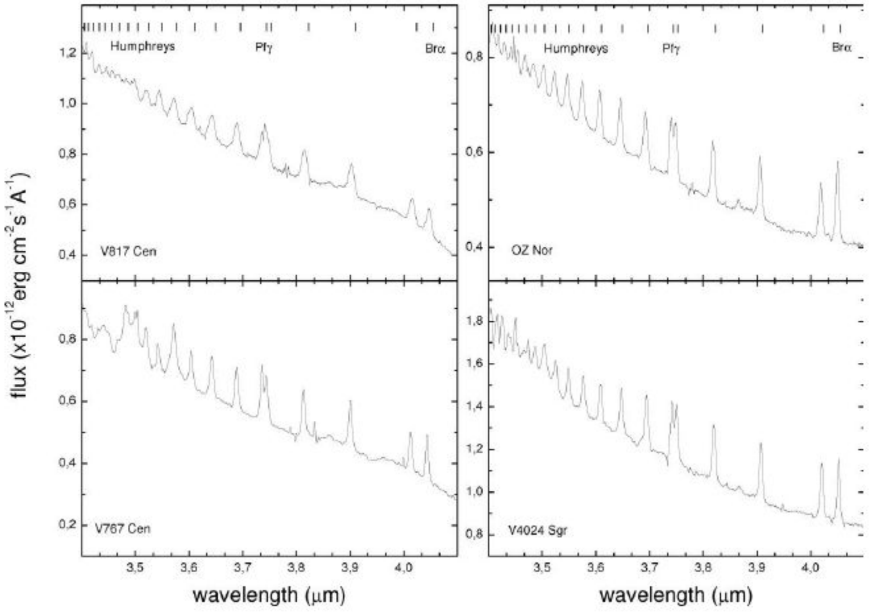


FIG. 1.—IR wide-slit spectra of stars of Group I.

L-Band spectra of 13 Outbursting Be Stars

(Mennickent, Sabogal, Granada, Cidale; 2009,
Publications of the Astronomical Society of the Pacific)

Be stars classified in three groups:

I. Brα and Pfγ emissions as intense as Humphreys lines
II. Brα and Pfγ emissions more intense than Humphreys lines

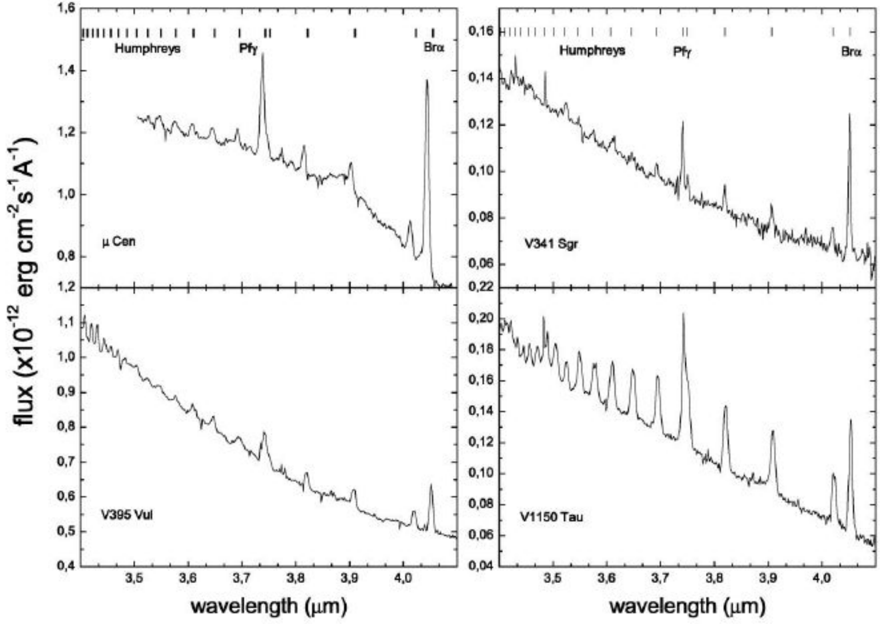


FIG. 2.—IR wide-slit spectra of stars of Group II and V 1150 Tau.

L-Band spectra of 13 Outbursting Be Stars

(Mennickent, Sabogal, Granada, Cidale; 2009,
Publications of the Astronomical Society of the Pacific)

Be stars classified in three groups:

I. Brα and Pfγ emissions as intense as Humphreys lines
II. Brα and Pfγ emissions more intense than Humphreys lines
III. **No line emission detected**

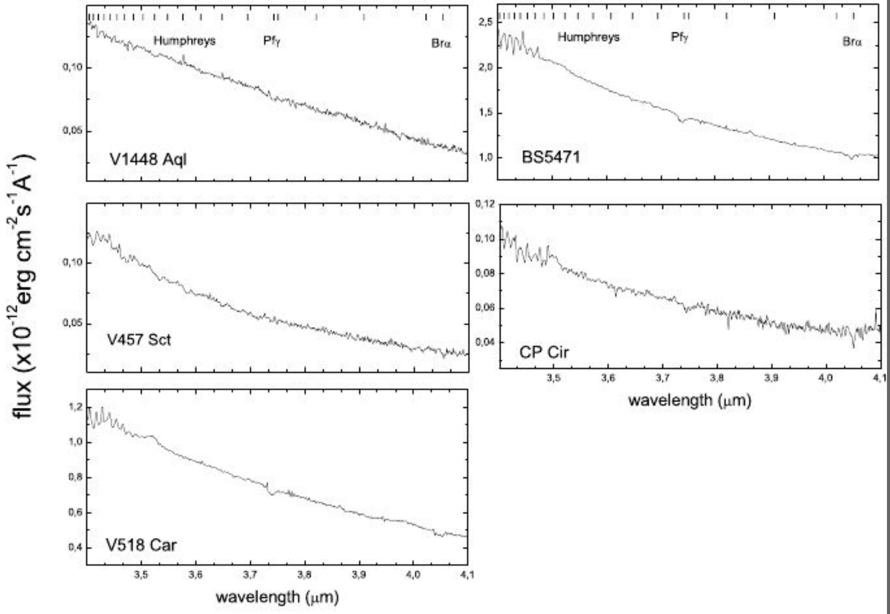


FIG. 3.—IR wide-slit spectra of stars of Group III and the B3V star BS 5471.

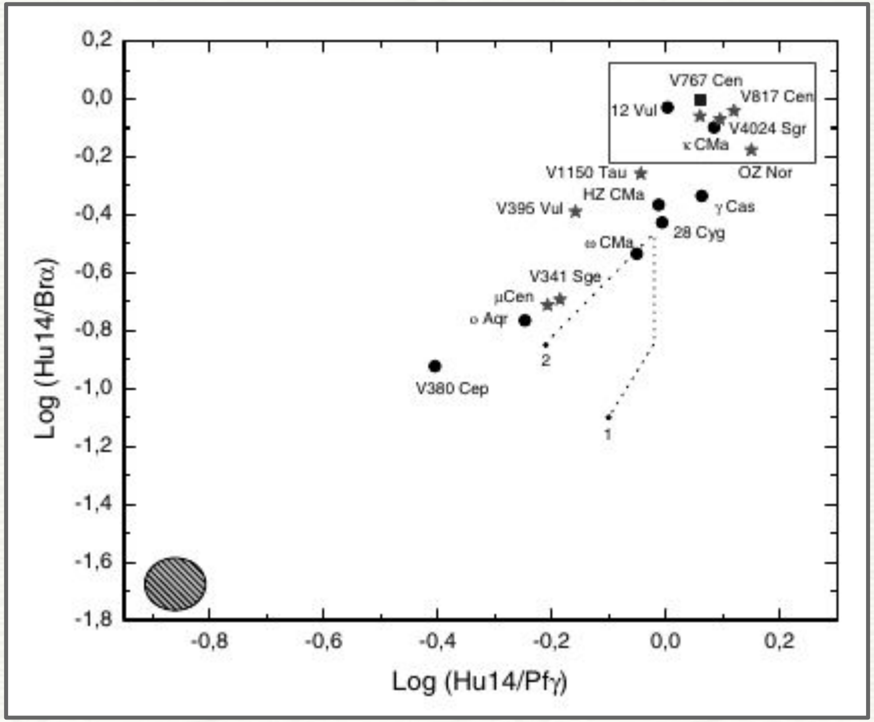
L-Band spectra of 13 Outbursting Be Stars

(Mennickent, Sabogal, Granada, Cidale; 2009,
Publications of the Astronomical Society of the Pacific)

Be stars classified in three groups:

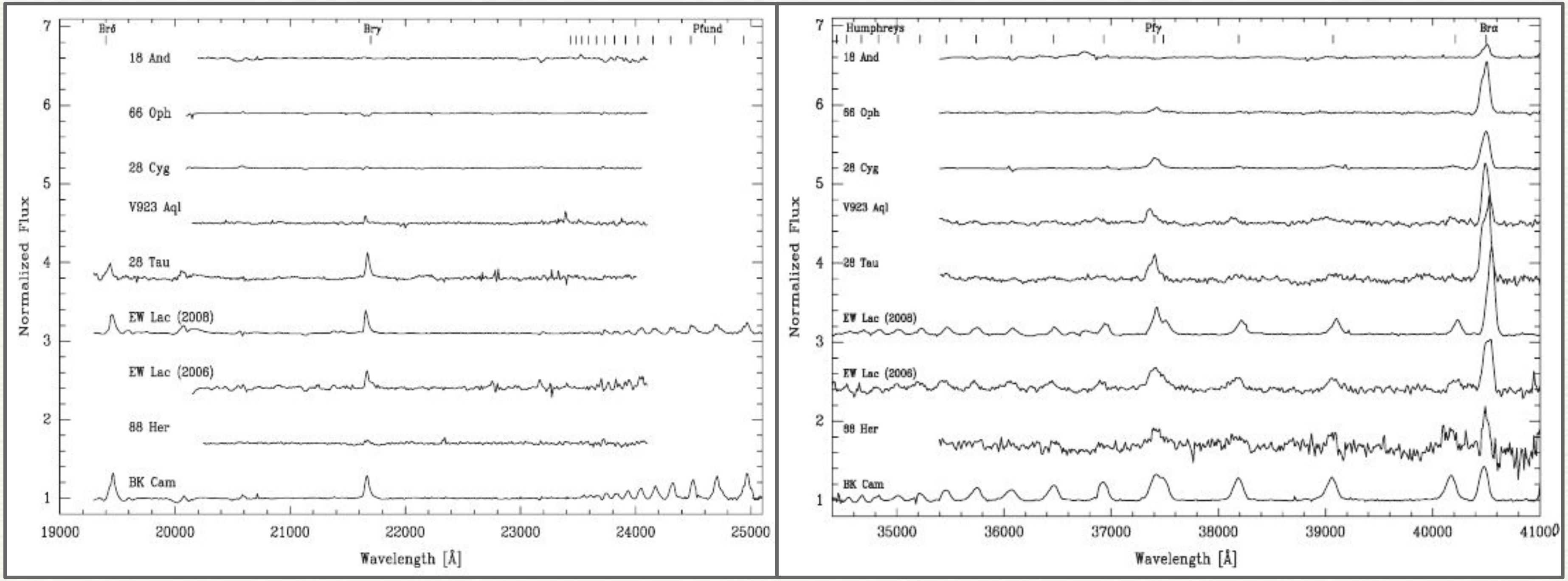
I. Brα and Pfγ emissions as intense as Humphreys lines
II. Brα and Pfγ emissions more intense than Humphreys lines
III. No line emission detected

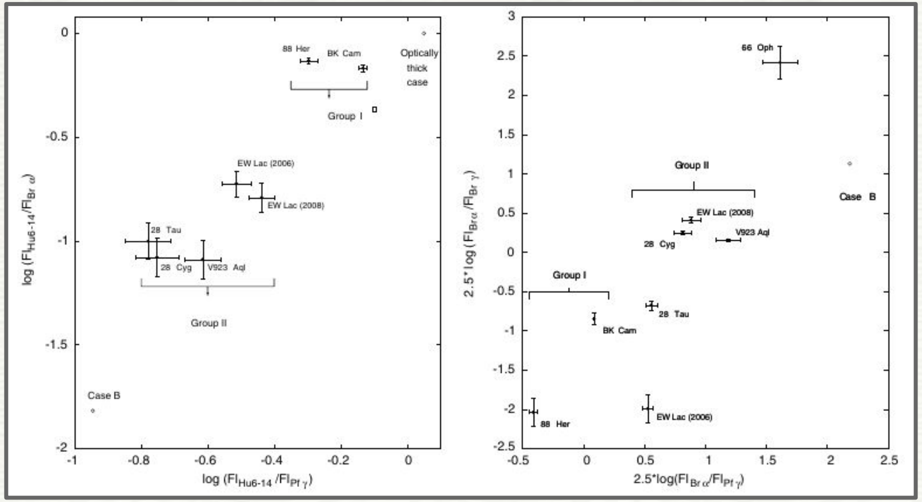
The empirical groups trace the optical depth of the circumstellar envelope

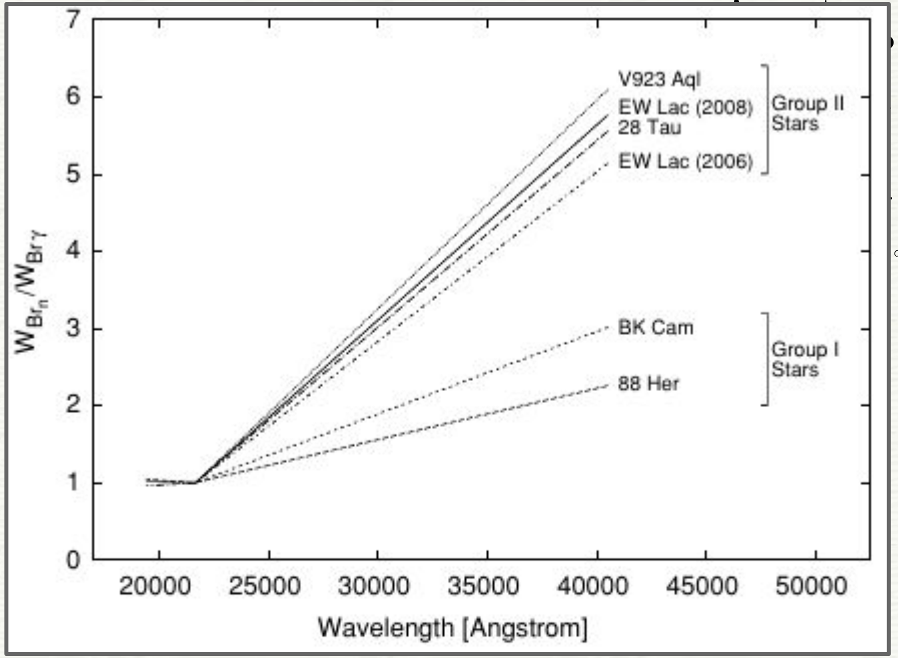


Simultaneous K- and L-band Spectroscopy of Be Stars: Circumstellar Envelope Properties from Hydrogen Emission Lines

(Granada, Arias, Cidale; 2010, The Astronomical Journal)







There exists a **clear difference in the slope** of the Brackett series for group I and group II stars.

(Granada et al.; 2010)

Simultaneous J-, H-, K- and L-band spectroscopic observations of galactic Be stars

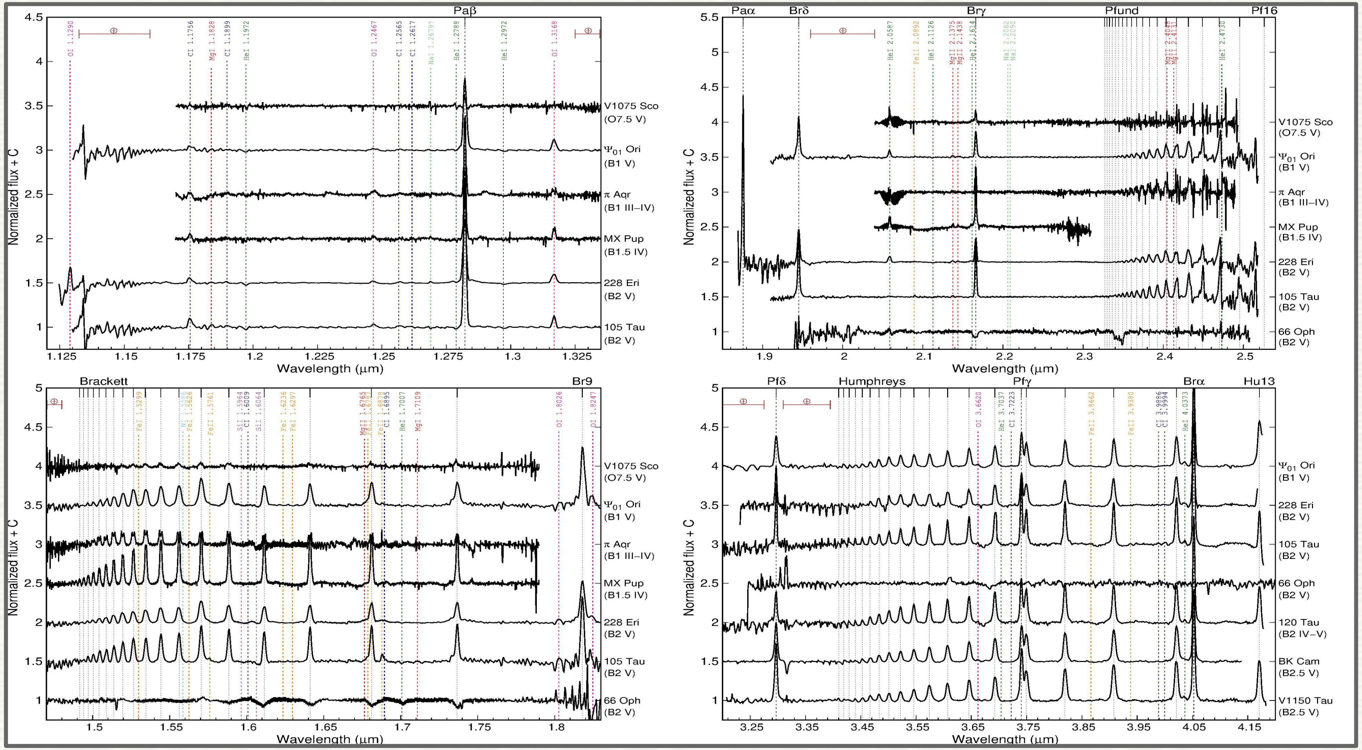
(Cochetti, Arias, Cidale, Granada, Torres; 2022, Astronomy & Astrophysics)

J

K

H

L



Mennickent's group classification

+

Granada's EW ratios

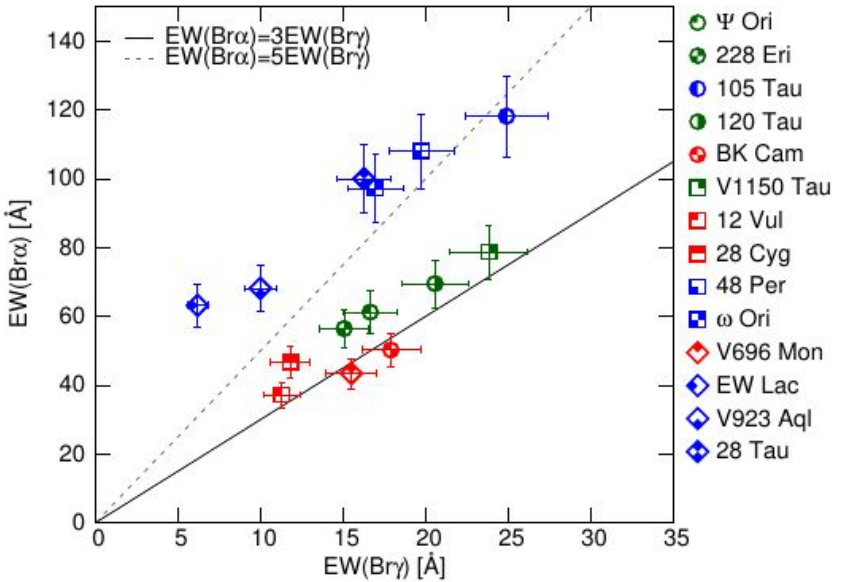
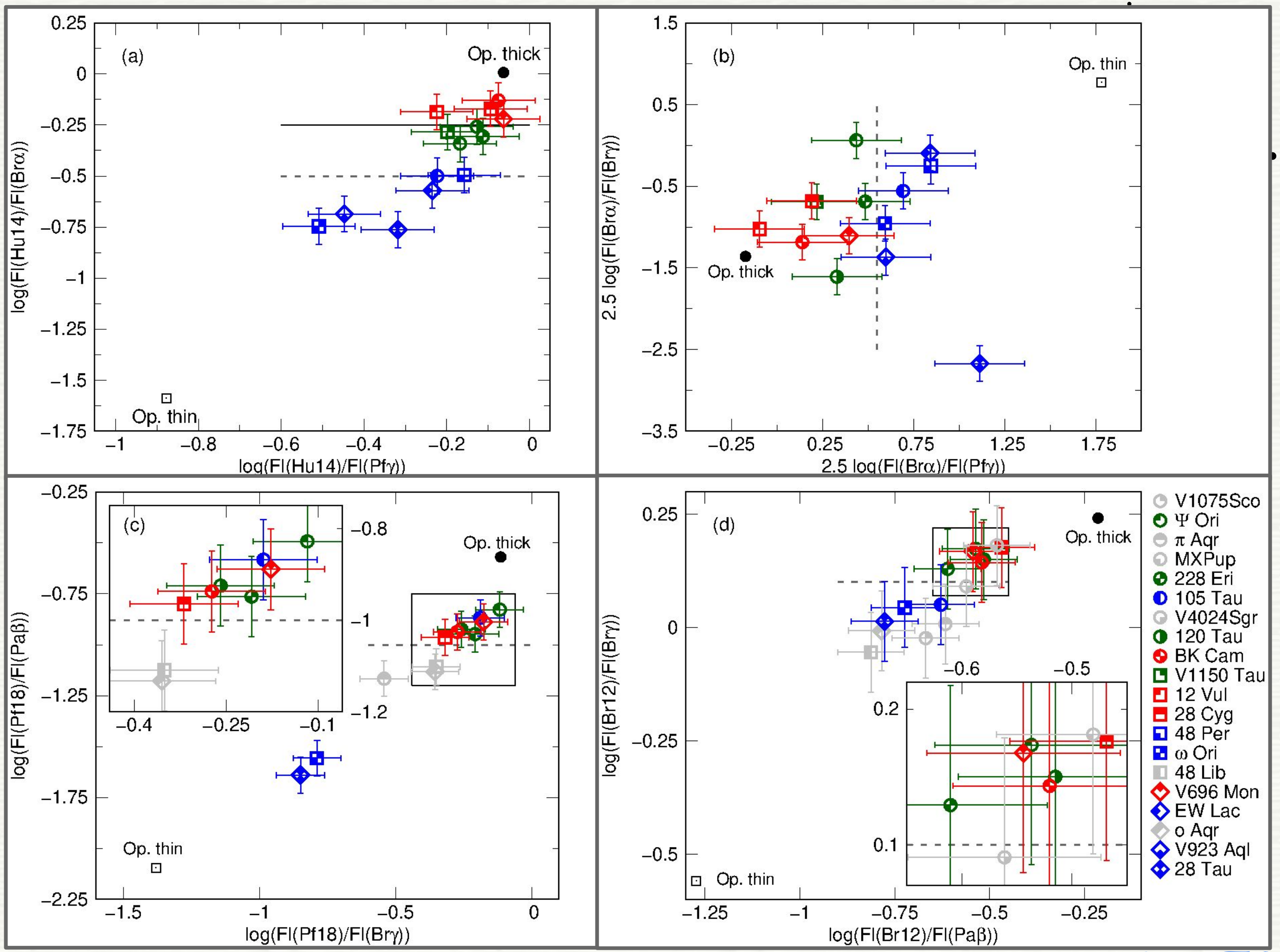


Fig. 4. EW(Brα) versus EW(Brγ). Red symbols are for group I stars, group II stars are plotted in blue, and green symbols are for the intermediate group I-II. The relations EW(Brα) = 3 EW(Brγ) and EW(Brα) = 5 EW(Brγ) are plotted in continuous and dashed lines, respectively.

(Cochetti et al.; 2022)

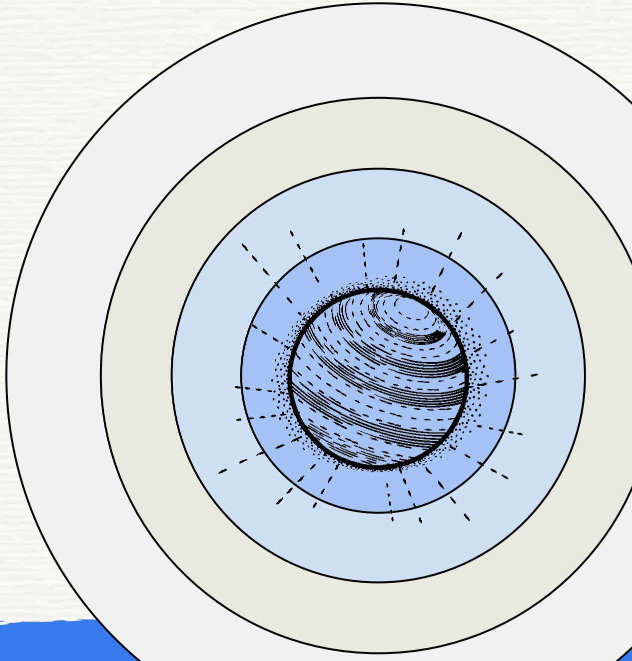


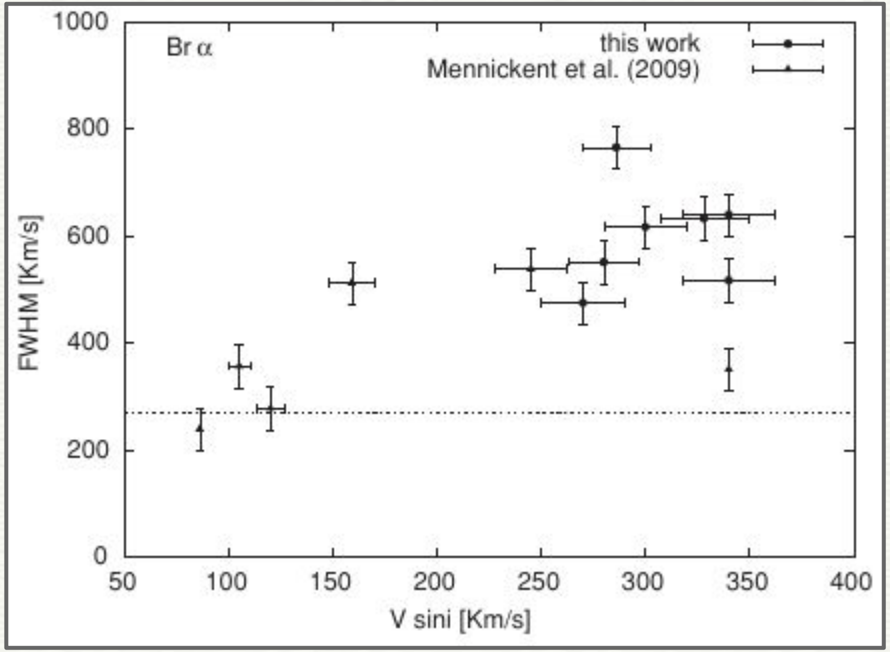
We define **new complementary criteria** to Mennickent's **classification** of Be stars according to their **disc opacity**.

(Cochetti et al.; 2022)

IR recombination lines allows us to get information about the physical parameters of the circumstellar material!

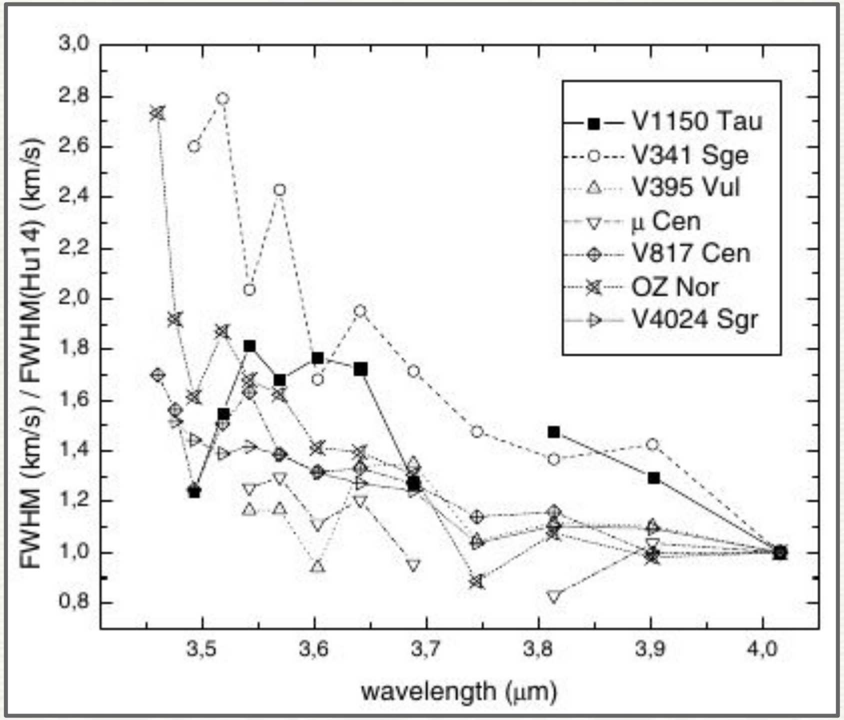
- EW to correct from photospheric absorption (almost negligible for some lines)
- Numerous H lines!
- Line strength depends on the optical depth of the envelopes

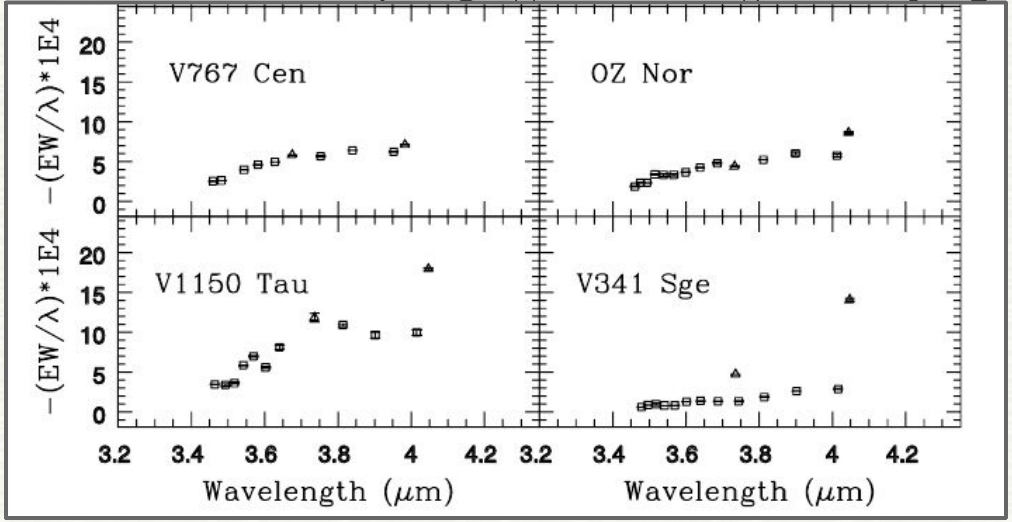




The strong correlation of IR lines FWHM with V sin i indicates that the origin of emission-line broadening is mainly rotational

(Granada et al.; 2010)

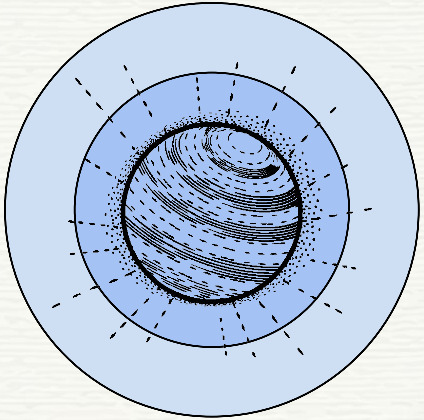


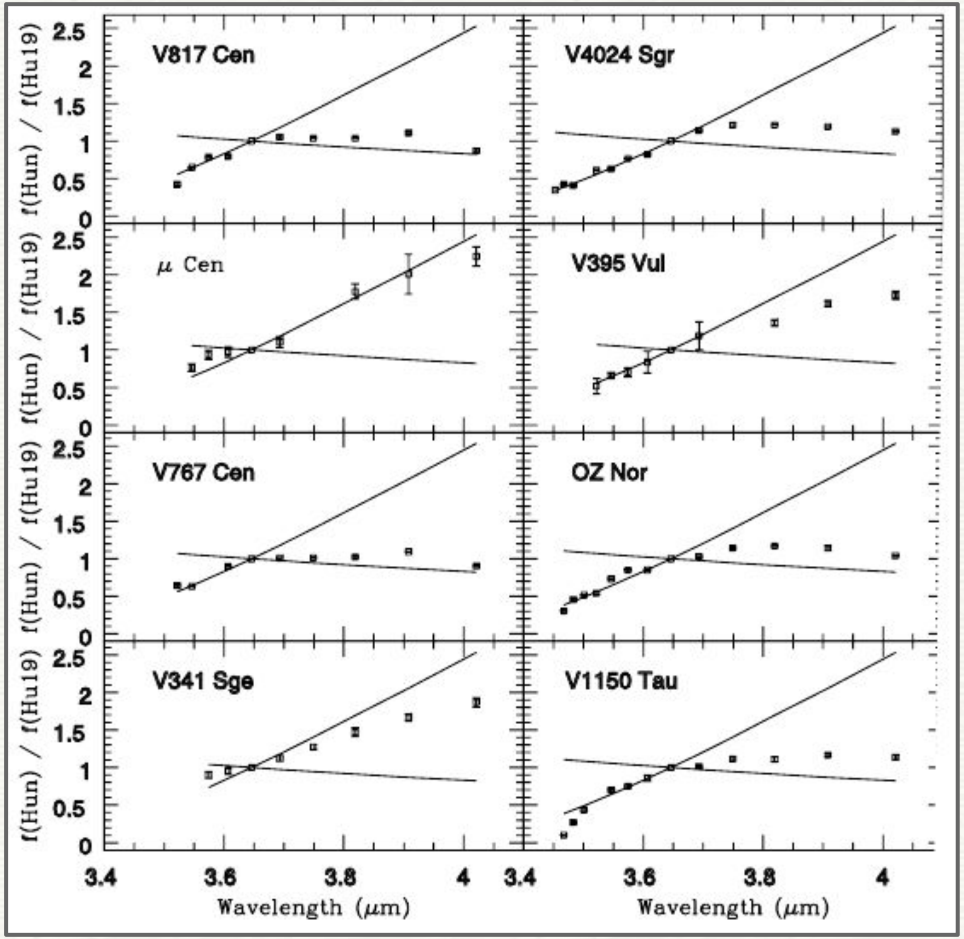


(Mennickent et al.; 2009)

Low-order
Humphreys lines

Higher-order
Humphreys lines





Even for Be stars with optically thick envelopes, high-order Humphreys lines probe optically thin inner regions

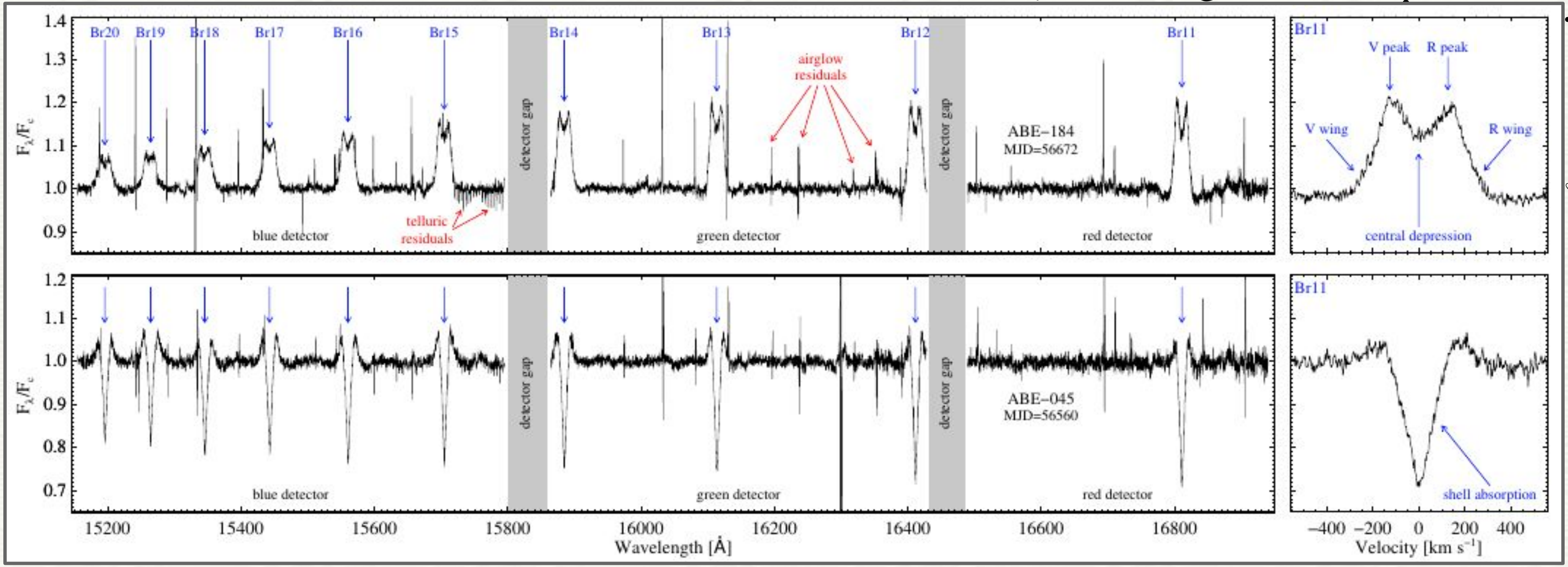
(Mennickent et al.; 2009)

High-Resolution H-Band Spectroscopy of Be Stars With SDSS-III/Apogee:
I. New Be Stars, Line Identifications, and Line Profiles
II. Line Profile and Radial Velocity Variability

(Chojnowski et al.; 2015 and 2017, The Astronomical Journal)

“[...] targeted by APOGEE as telluric standard stars and subsequently identified via visual inspection as Be stars based on HI Brackett series emission or shell absorption [...]”

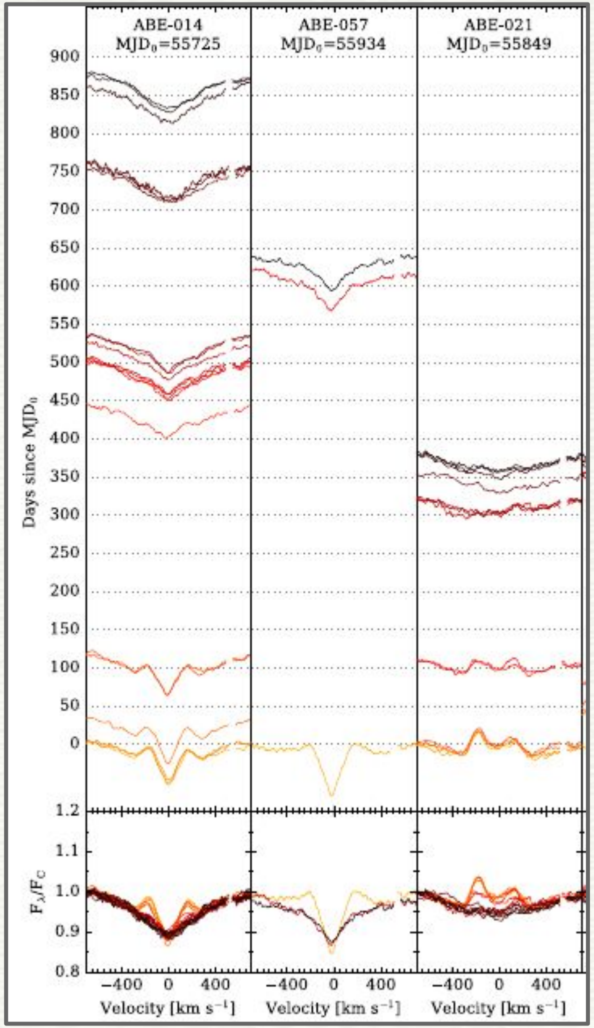
Discovery of new Be stars!
(and also emission lines that have been identified for the first time)

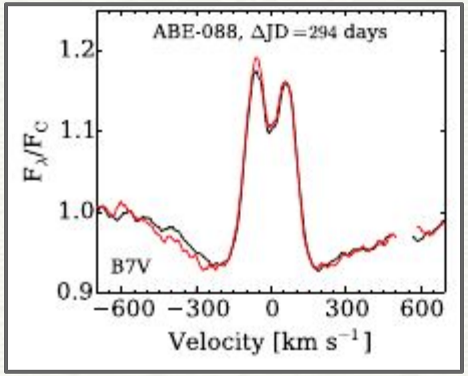


Average Br11 formation outer radius ~2.2 R★, and Br12-Br20 formation outer radii are interior to that of Br11

Brackett lines minimally affected by underlying photospheric absorption!

(Chojnowski et al.; 2015)

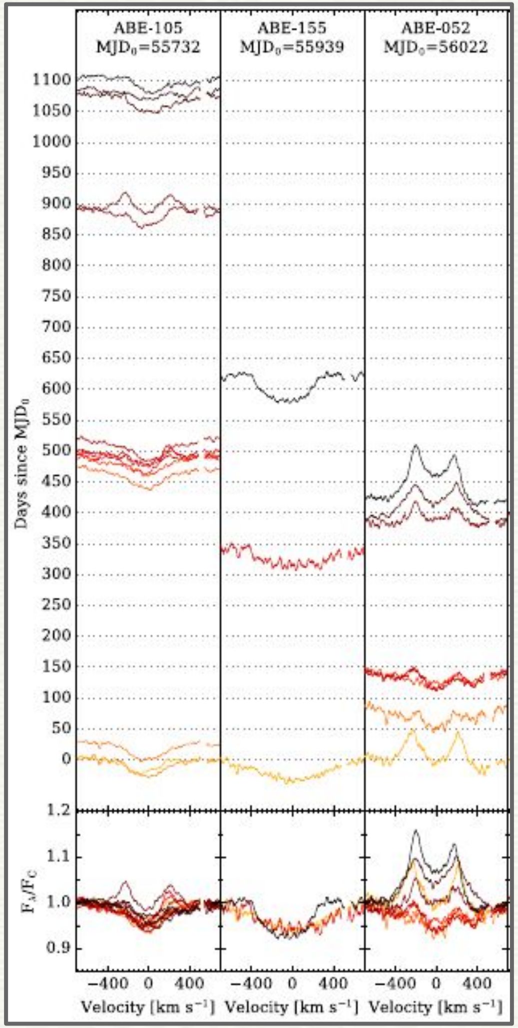




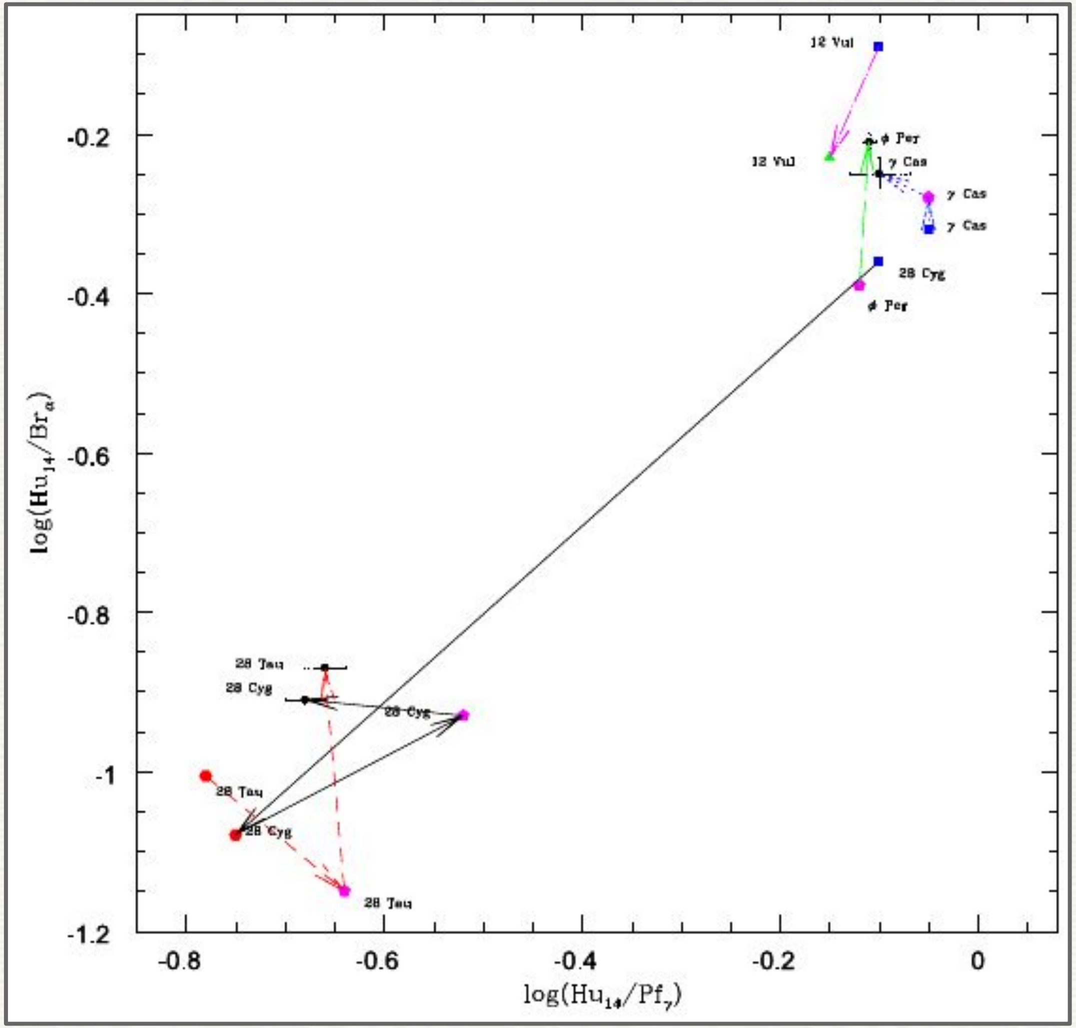
Stable discs

Decaying discs

Building-up discs



(Chojnowski et al.; 2017)

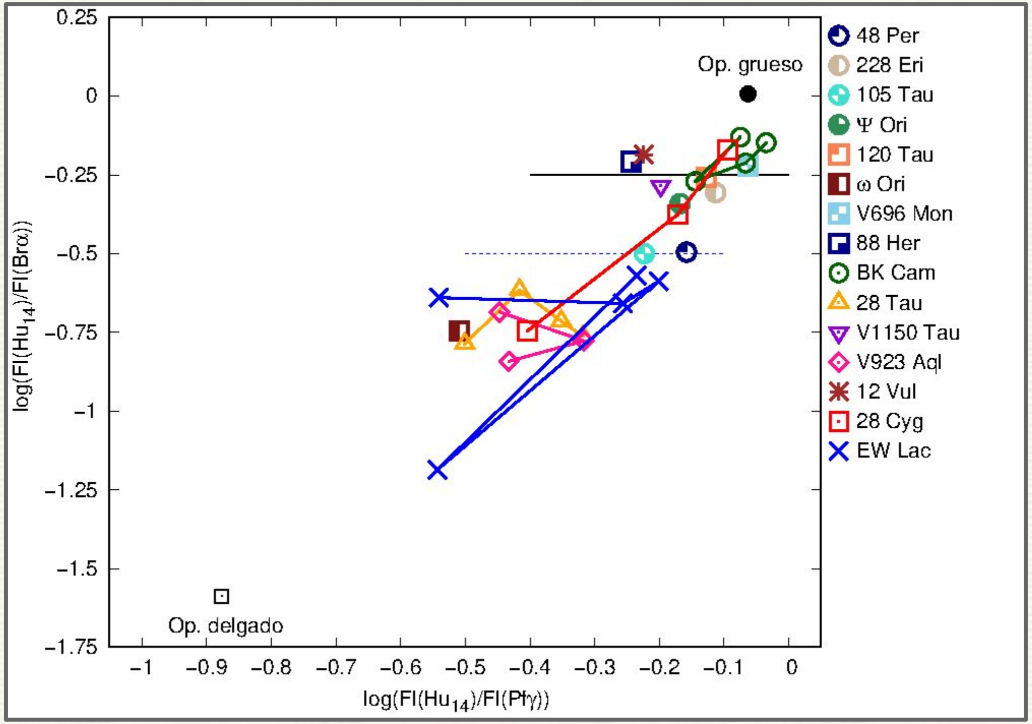


Evidence of Dissipation of Circumstellar Disks from L-band Spectra of Bright Galactic Be Stars
(Sabogal et al.; 2017, Publications of the Astronomical Society of the Pacific)

- Stable
- Decaying
- Building-up

Early-type Be stars can develop **optically thick** discs.

Late-type Be stars tends to have **optically thin** discs.



(Cochetti PhD Thesis; 2019)

- Stable
- Decaying
- Building-up

Multi-epoch L-band Spectroscopy of the Be Star μ Centauri Prior to Outburst

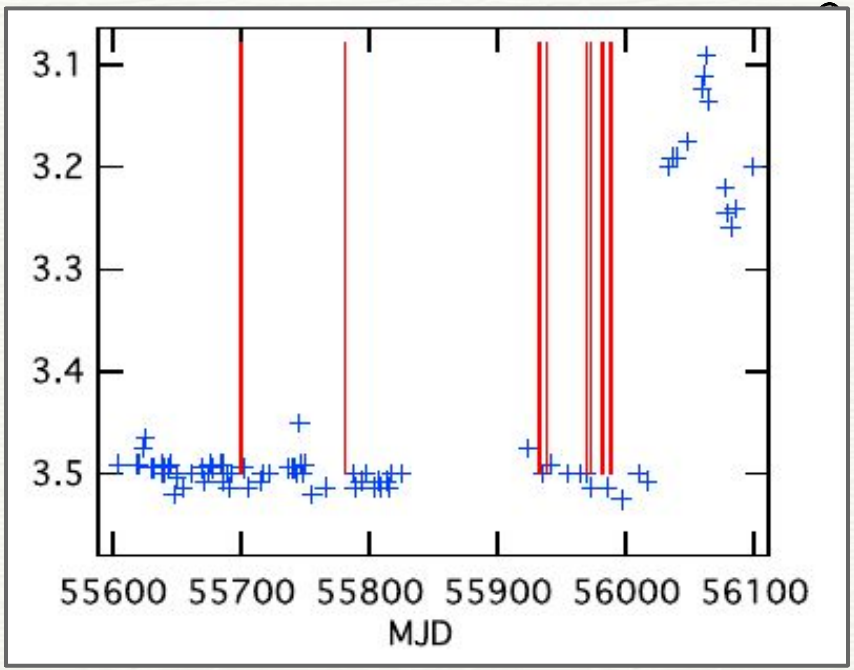
(Aguayo, Mennickent , Granada, and Otero; 2018, The Astronomical Journal)

μ Centauri

9 L-band spectra
(18-May-2011 to
1-March-2012)

➕

906 visual photometry
(1998 to 2014)



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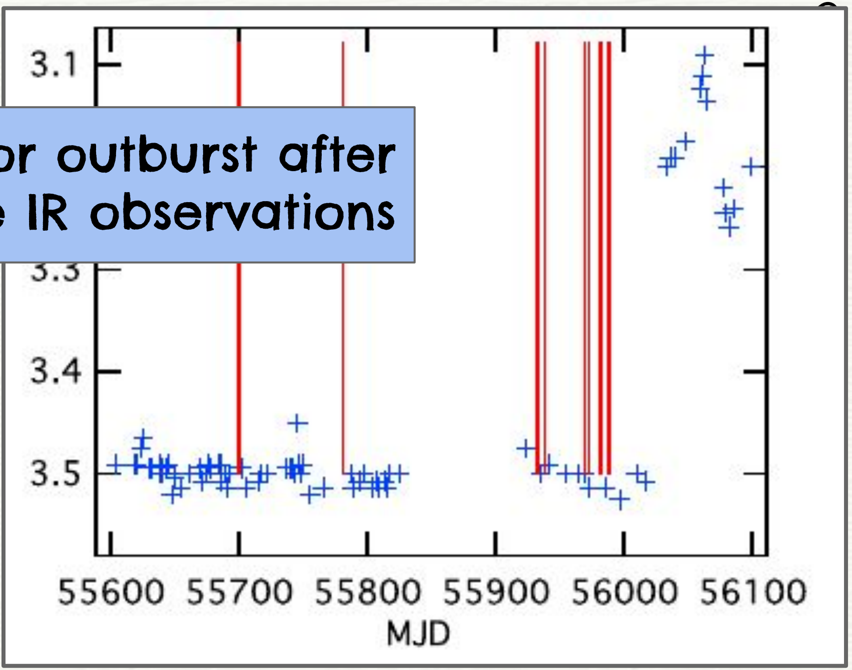
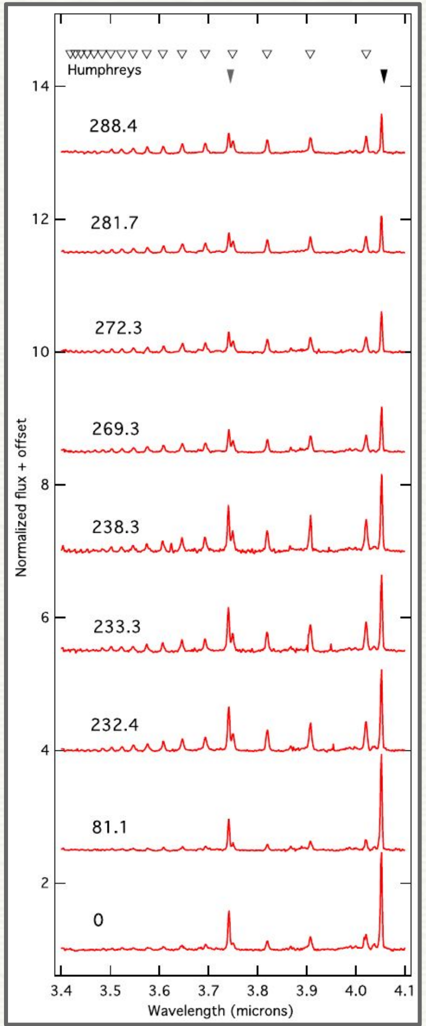
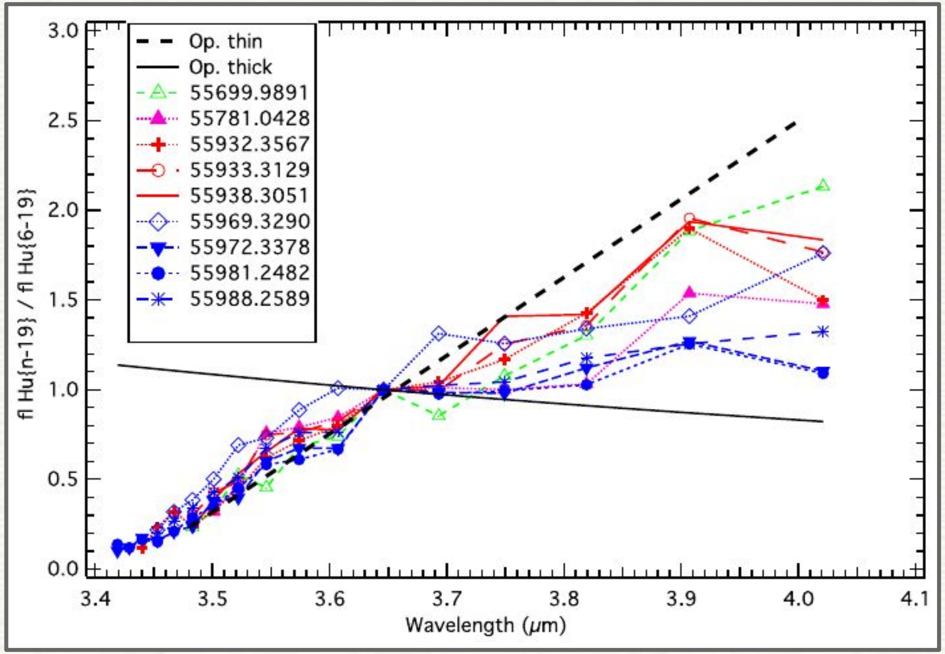


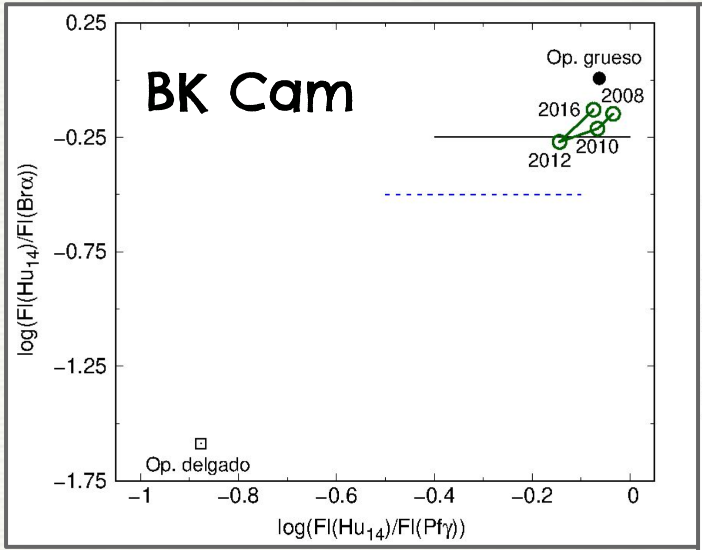
➡ Major outburst after the IR observations

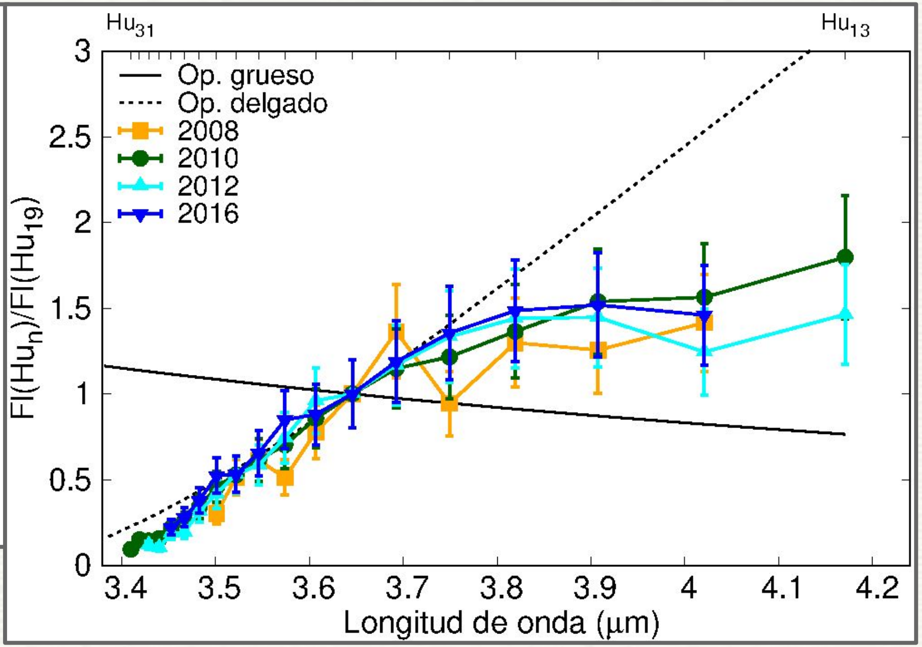




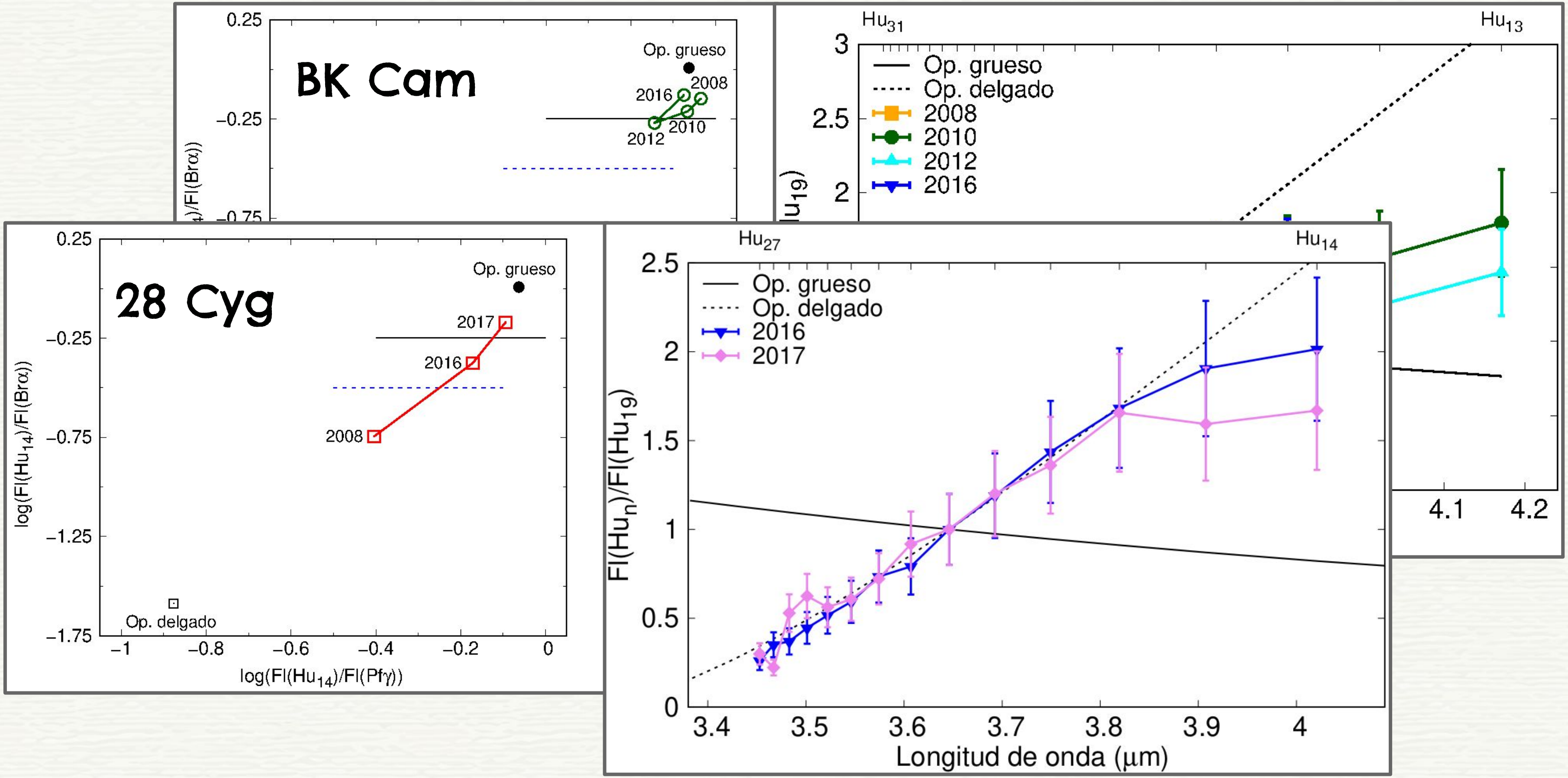
→ Estimation of the atomic column densities. The atomic column densities increased in a factor of 2.

The mass in the inner regions of the disc multiplied by a factor of 2





(Cochetti PhD Thesis; 2019)

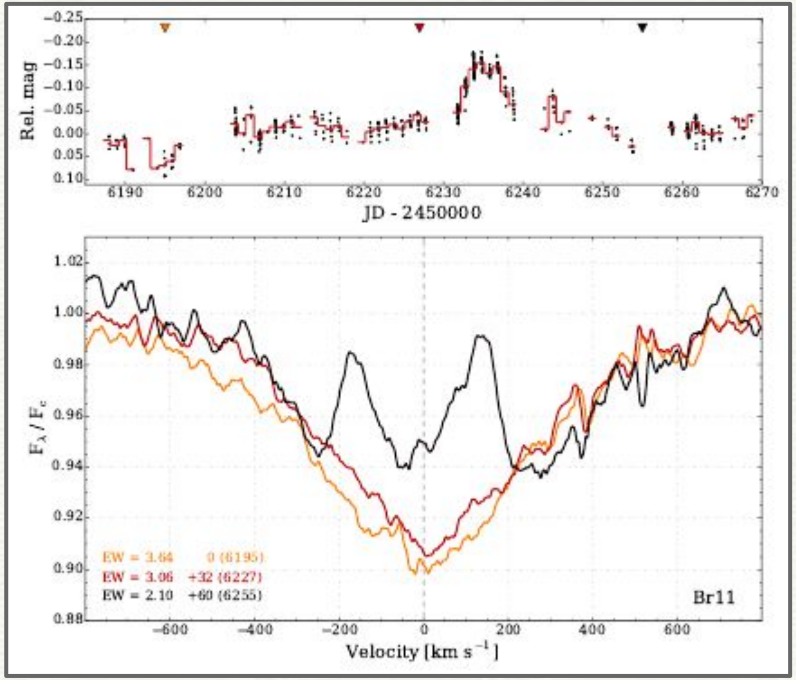


(Cochetti PhD Thesis; 2019)

Outbursts and disk variability in Be stars

(Labadie-Bartz et al.; 2018, The Astronomical Journal)

160 Galactic Be stars: R-band filter, Hα, Br11

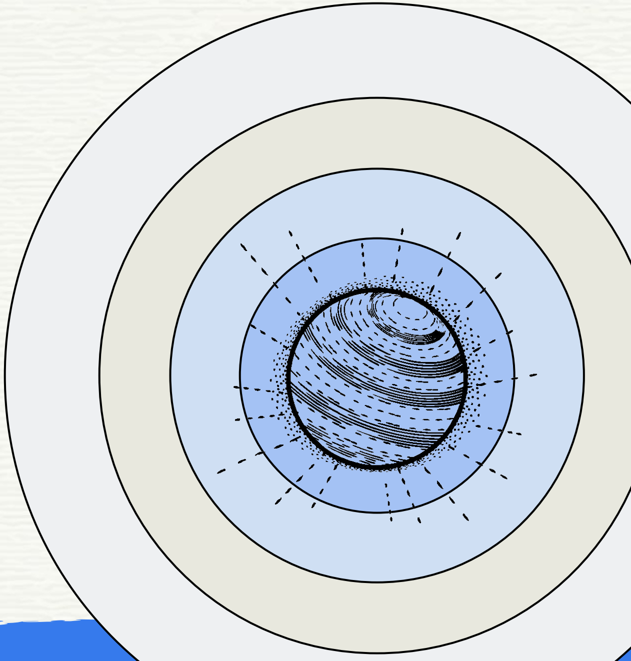


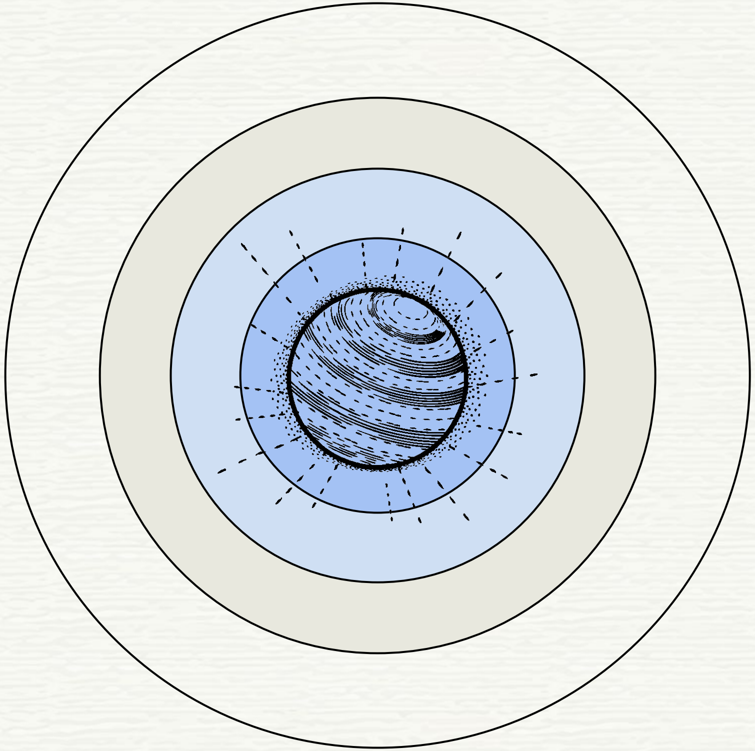
Photometric outbursts → injection of stellar material into the circumstellar environment

- Inner disc dissipates quickly for hotter stars (relative to the rising time)
- Pre-existing disc → falling phase will proceed more slowly

IR recombination lines allows us to get information about the physical parameters of the circumstellar material!

- EW to correct from photospheric absorption (almost negligible for some lines)
- Numerous H lines!
- Line strength depends on the optical depth of the envelopes
- Lines are formed closer to the star than those observed in the optical spectral range
- Higher-order lines maps regions with different optical depths
- Follow up changes in the disc!





The study of the IR emission lines is a great tool to obtain information about the physical structure and dynamics within the innermost part of the disc!

THANKS!

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POEMS

Physics of Extreme Massive Stars

Marie-Curie-RISE project funded by the European Union

The importance of the IR SPECTRAL DATA to study Be STARS

Why we started to observe Be stars in the infrared spectral range?
What can we obtain from the IR spectra of Be stars?
What are the advantages of observing in this spectral range?

Yanina Cochetti
IALP - FCAG
UNLP - CONICET

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