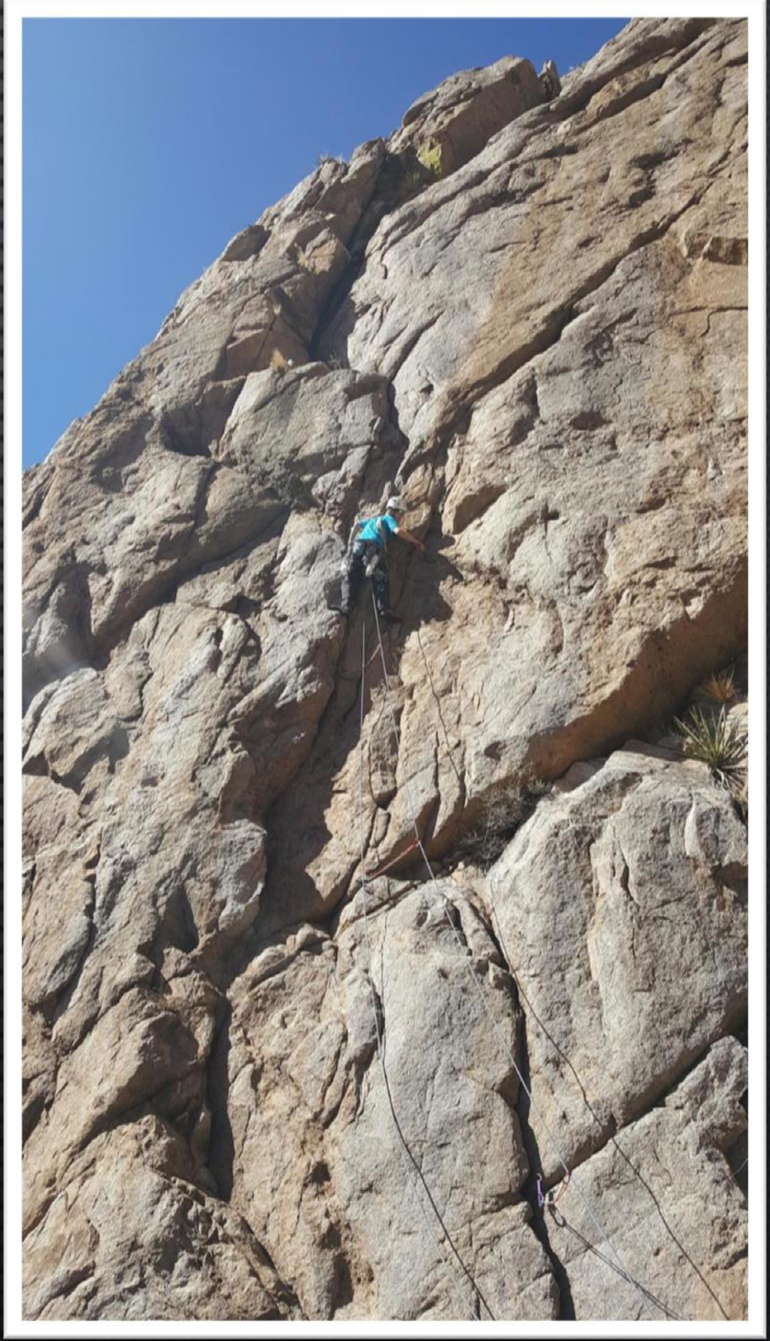
SPECTROSCOPY OF BE STARS: WHY IT'S FUN AND WORTH DOING

Drew Chojnowski, NMSU Astronomy

Sacramento Mountains Spectroscopy Workshop 2019

A Bit About Me

- B.S. in Physics & Astronomy from Texas Christian University (2011).
- 4th year graduate student at New Mexico State University (NMSU).
- PhD thesis title: **"The Circumstellar Disks and Binary Companions of Be Stars"** (defending this fall)
- Funded via position as "Plate design coordinator" for the Apache Point Observatory Galactic Evolution Experiment (APOGEE) from 2011-present.
- Mostly interested in massive things that make emission lines (Be/B[e]/RRM stars, AGN, exotic binaries).
- Also interested in magnetic stars OBA stars, with and without emission lines.
- Avid climber of the Organ Mountains.



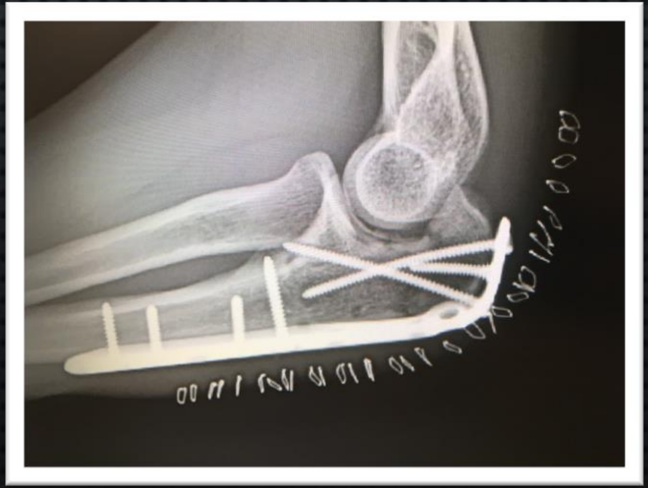
Rock Climbing is Dangerous???

- On January 14, 2019, I suffered from a bad lead climbing wall on the route "Black Streak" (5.10b) at La Cueva.
- Failed to clip the 4th bolt, fell about 20ft, and hit the ledge below before my belayer could catch me.
- Managed to walk out (slowly) and drive home.
- After a few hours, my girlfriend convinced me to go to the ER because my head was still bleeding.

FAIR WARNING: the next slide shows the damage


REI


R
SS



Credentials

Classical Be Stars | B[e] Stars | Magnetic A/B Stars

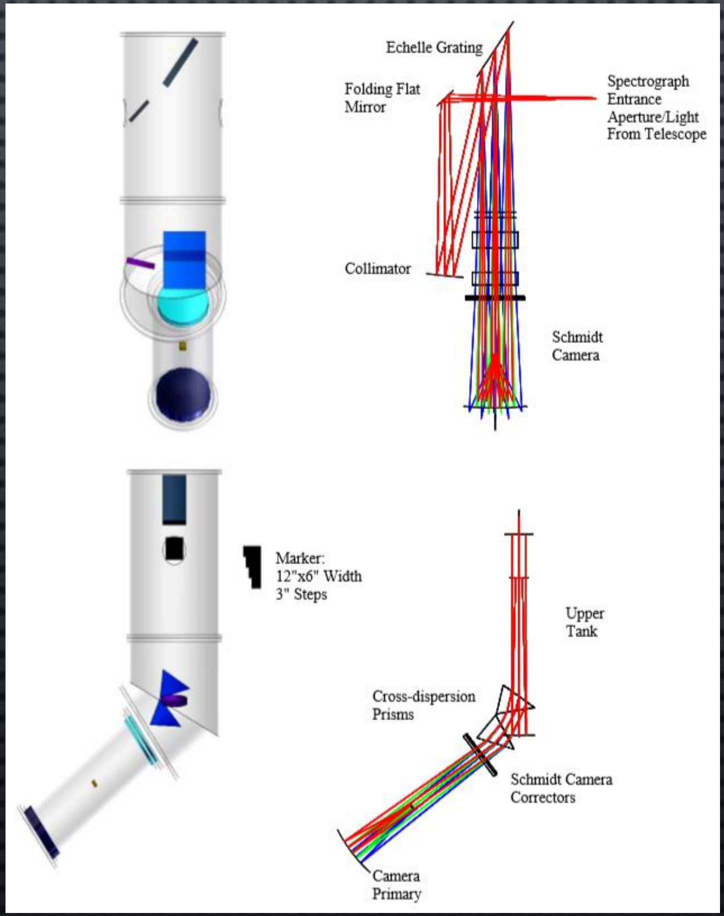
- Discovery of Two Rare Rigidly Rotating Magnetosphere Stars in the APOGEE Survey.
  - Eikenberry, Chojnowski et al. (04/2014, ApJ Letters)
- High-resolution H-band Spectroscopy of Be Stars with SDSS-IIIAPOGEE: I. Line Identifications and Line Profiles
  - Chojnowski et al. (01/2015, AJ)
- Characterizing the Rigidly Rotating Magnetosphere Stars HD 345439 and HD 23478
  - Wisniewski, Chojnowski et al. (10/2015, ApJ Letters)
- An Infrared Diffuse Circumstellar Band? The Unusual 1.5272 Micron DIB In the Red Square Nebula
  - Zasowski, Chojnowski et al. (10/2015, ApJ)
- High-resolution H-band Spectroscopy of Be Stars with SDSS-III/APOGEE. II. Line Profile and Radial Velocity Variability
  - Chojnowski et al. (04/2017, AJ)
- Outbursts and Disk Variability in Be Stars
  - Labadie-Bartz, Chojnowski et al. (02/2018, AJ)
- Toward Understanding the B[e] Phenomenon. VII. AS 386, a Single-lined Binary with a Candidate Black Hole Component
  - Miroshnichenko et al. (04/2018, ApJ)
- The Remarkable Be+sdOB Binary HD 55606. I. Orbital and Stellar Parameters
  - Chojnowski et al. (09/2018, ApJ)
- Discovery of Resolved Magnetically Split Lines in SDSS/APOGEE Spectra of 157 Ap/Bp Stars
  - Chojnowski et al. (02/2019, accepted to ApJ Letters)

Telescopes/Instruments I Use

Apache Point Observatory (APO)

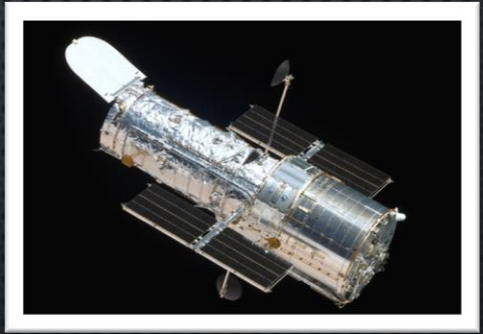
APO 3.5m telescope

ARCES (echelle) Spectrograph

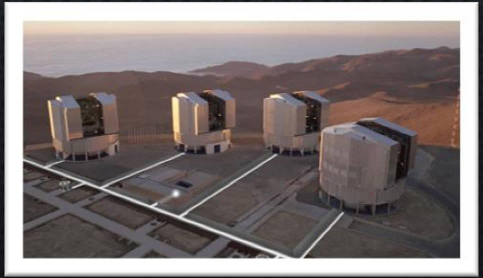


$R = \lambda/\Delta\lambda = 31{,}500$
3500 – 10200 Å

APOGEE Spectrograph



HST



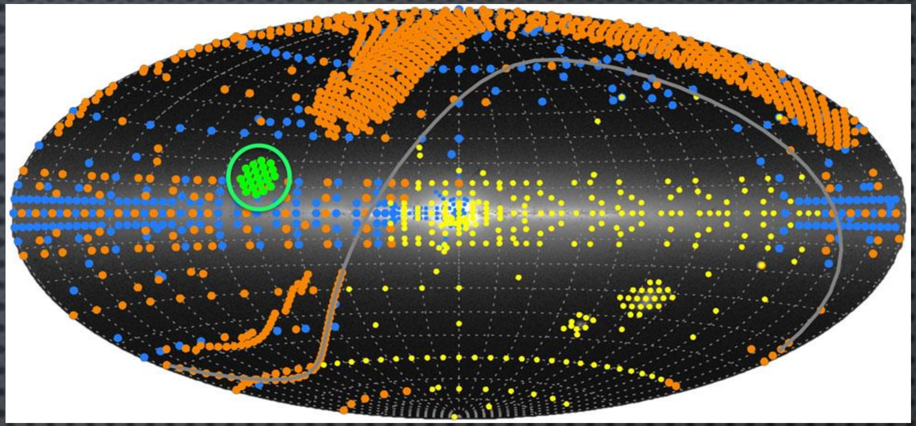
VLT

Sloan Digital Sky Survey (SDSS)

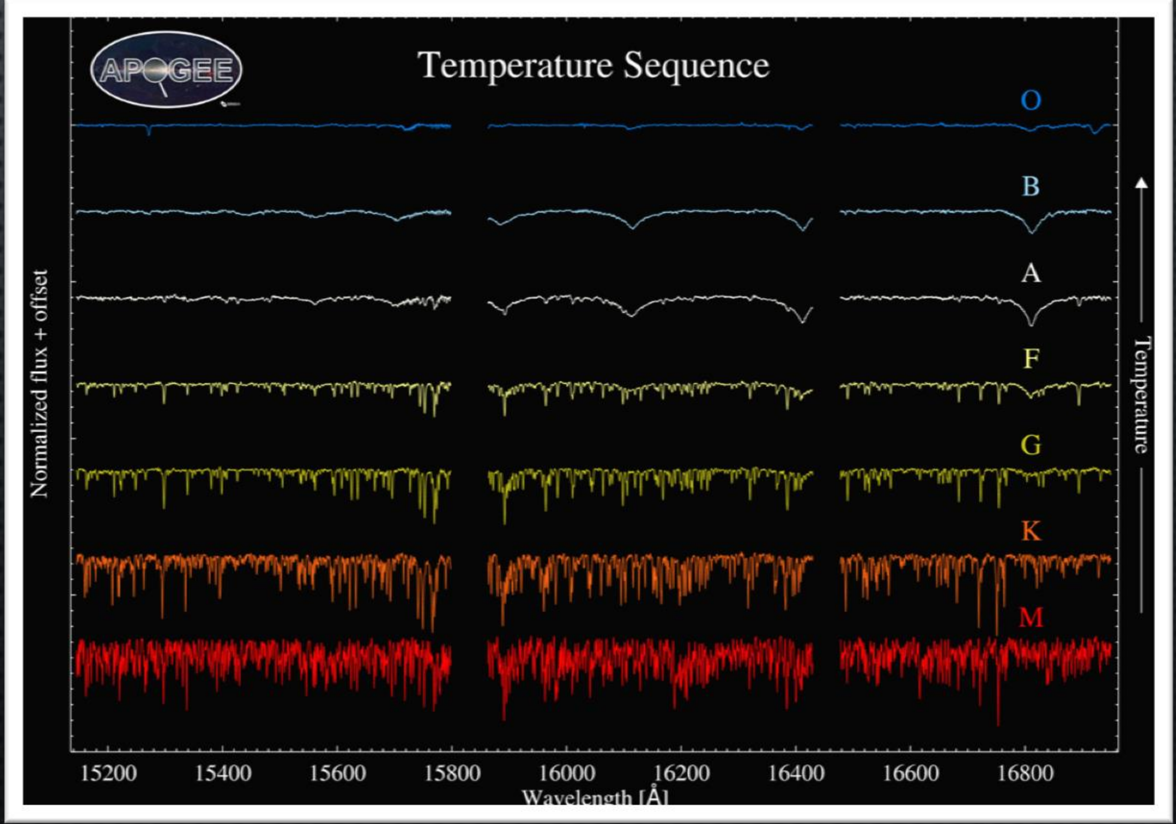
- Operating the Sloan 2.5m telescope at Apache Point Observatory (APO) since 2000, and on the Du Pont 2.5m telescope at Las Campanas Observatory (LCO) since 2017.
- Originally an extragalactic imaging/spectroscopy survey. The imager was retired in 2009.
- Now consists of 4 spectroscopic sub-surveys:
    - **eBOSS**: low-resolution fiber spectra of galaxies and quasars.
    - **MaNGA**: integral-field unit (IFU) spectroscopy of "nearby" galaxies.
    - **APOGEE2-North**: high-resolution, *H*-band spectroscopy of mostly Red Giant Branch (RGB) stars in the Milky Way.
    - **APOGEE2-South**: the same, but using a replica instrument installed on the Du Point 2.5m telescope at Las Campanas Observatory in Chile.

SDSS/APOGEE

- Operates in the near-infrared, specifically in the *H*-band (15145 – 16960 Å).
- Multi-fiber spectrographs that acquire 300 spectra of different stars simultaneously.
- My job involves using catalog photometry to preferentially select Red Giant targets.
- Holes are then drilled on aluminum plates at the positions of target coordinates I provide.
- Once delivered to the observatory, fiber optics are plugged into the holes in the plates.
- Finally, the plates+fibers are put into cartidges and loaded into the focal plane of the telescope.



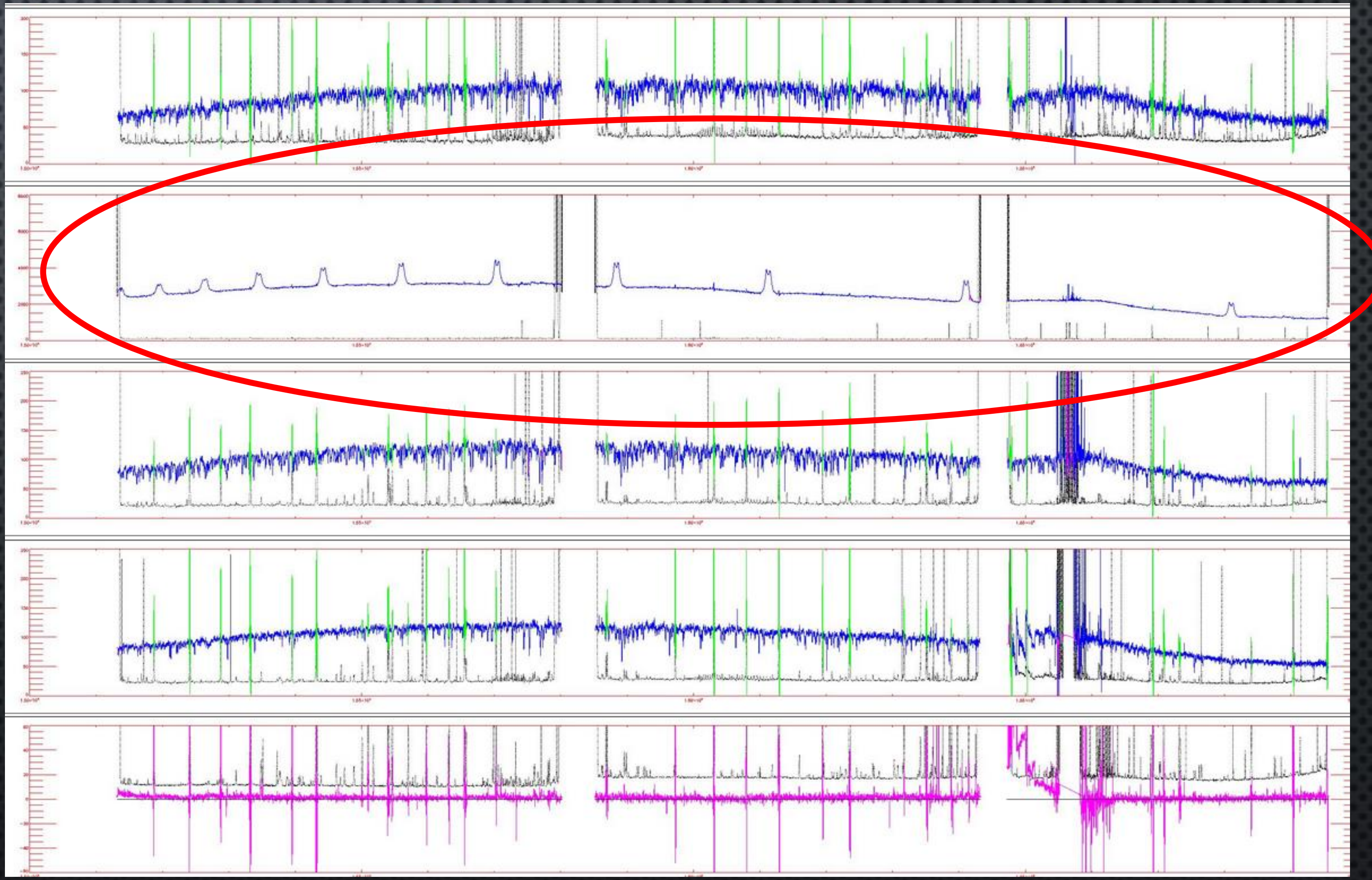
APOGEE field Plan (outdated)



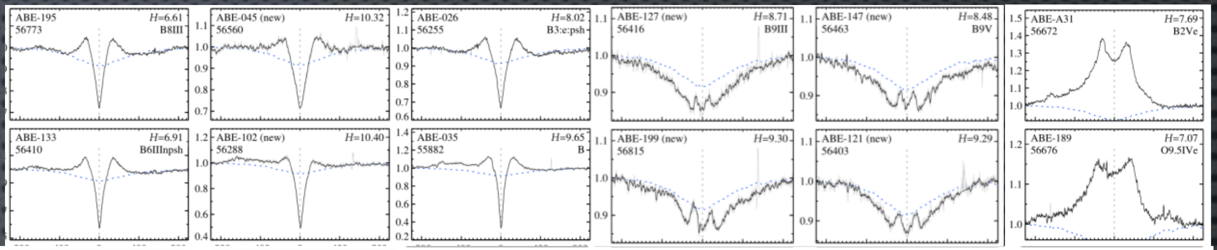
APOGEE spectral type montage

APOGEE Telluric Standard Stars

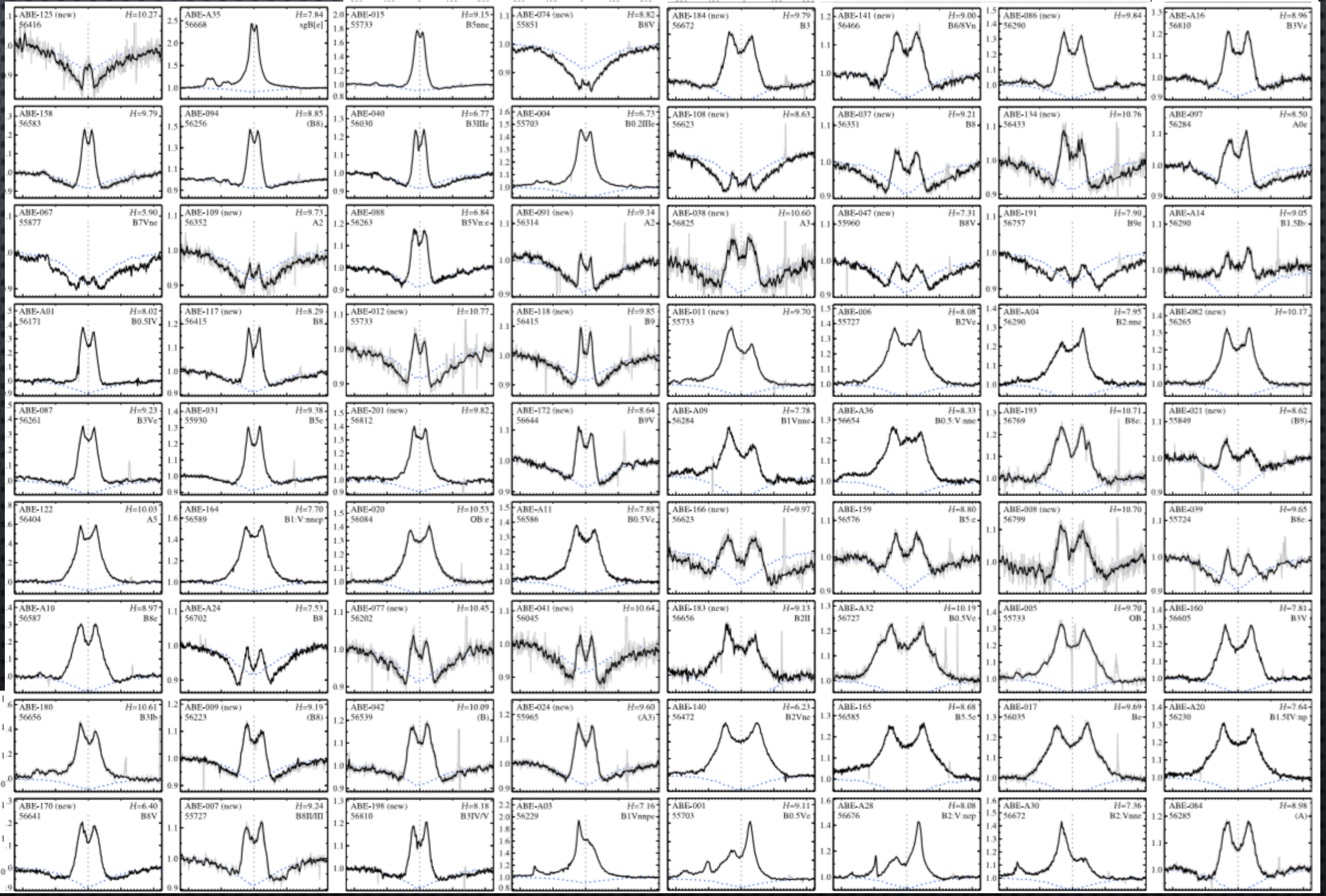
- Near-infrared (NIR) spectroscopy is challenging due to strong contributions from "airglow emission" and "telluric absorption".
- 250/300 APOGEE fibers are typically devoted to red giant stars.
- 35/300 APOGEE fibers are devoted to random sky positions in order to remove airglow emission lines.
- 15/300 APOGEE fibers are devoted to random blue stars (**telluric standard stars**) so that can telluric absorption can be corrected.
- Along with normal A/B type stars, things like Be stars and Ap/Bp stars make it into the telluric standard star sample.

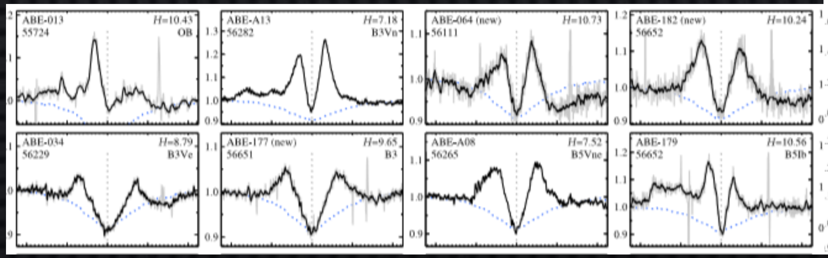


The APOGEE Be Star Catalog



- >600 Be stars observed
- >4000 individual spectra.
- ~13% increase in # of known Be stars (~300 new examples).
- ~33% increase in # of known RRM stars (2 new examples).
- ~14% increase in # of known Be+sdO binaries (1 new example)
- Numerous observations of extragalactic Be & B[e] stars.





A Spectrum is Worth a Thousand Images

HD 6226 (B3 IVe)

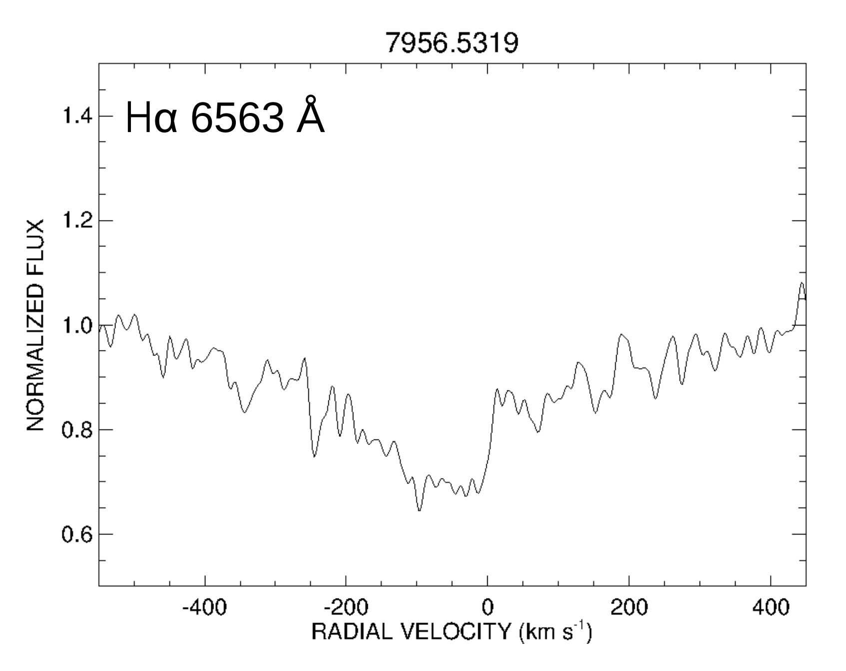
A classical Be star that can't decide if it wants to Be or not to Be. Dense spectroscopic coverage over past years has revealed numerous disk loss/creation events. The star is currently in a diskless state.

HD 55606 (B3 Vnnpe)

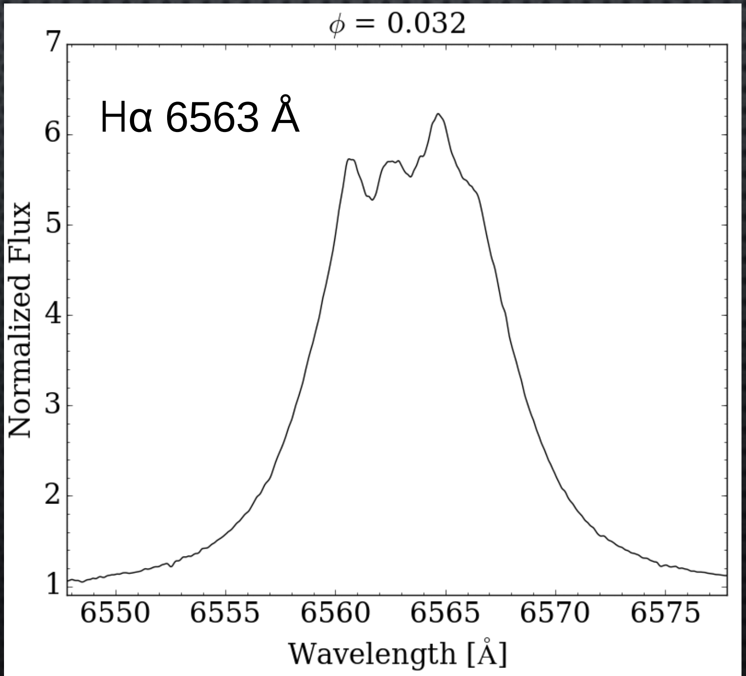
A classical Be star that stole the hydrogen envelope from it's binary companion, which is now about the size/mass of the Sun but 5-10 times hotter! (subdwarf O-type star)

HD 23478 (B3 IVpe)

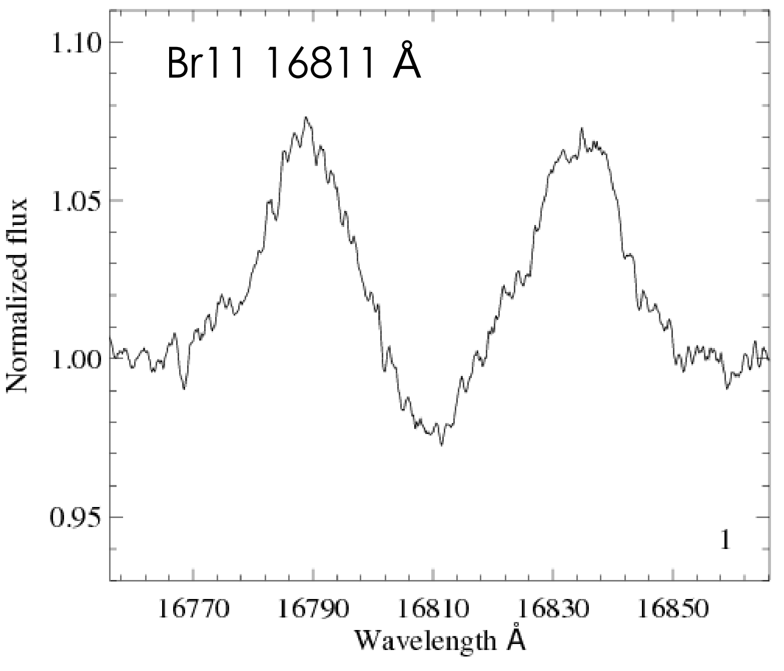
A highly magnetized Rigidly Rotating Magnetosphere (RRM) star. The emission forms in a disk or lobes of gas lost from the star in winds and subsequently trapped by the magnetic field.



Noel Richardson et al. (in prep)



Chojnowski et al. (2018)



Eikenberry et al. (2014)

Non-supergiant B-type Emission Line Stars

Classical Be

- Most common B-type emission star… >2000 known in the Milky Way Galaxy
- Keplerian disks made of gas ejected by the star
- Rotate near critical breakup limit
- Non-radial pulsators
- No dust & no forbidden emission lines
- No magnetic field

B[e]

- Very rare… <200 (?) known in the Galaxy
- [Forbidden] emission lines
- IR excess and presence of warm dust
- Central star difficult to diagnose
- Can be young pre-main-sequence or evolved supergiant.
- Most are unclassified…

RRM

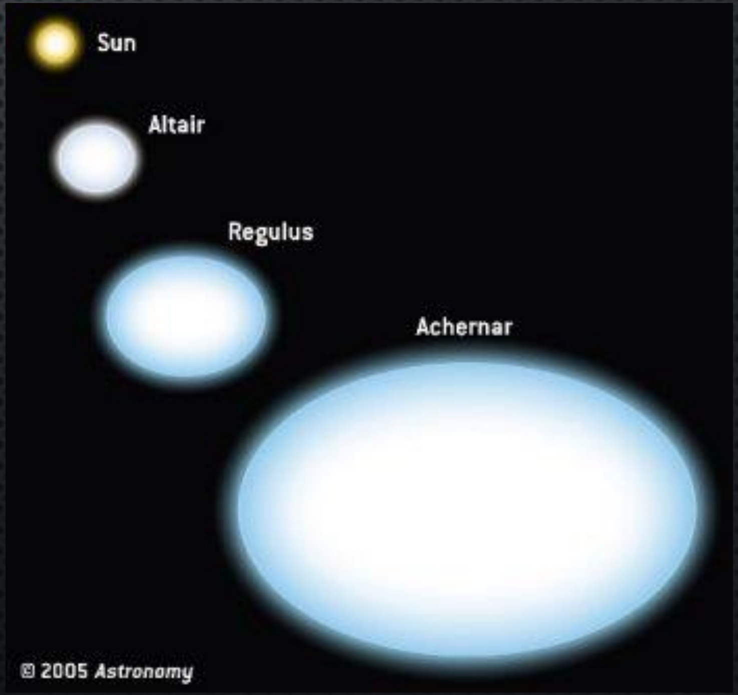
- Super rare… <20 (?) known in the Galaxy
- Strong magnetic field of unexplained origin
- Stellar wind trapped by magnetic field, forced to co-rotate with star… "Rigidly Rotating Magnetospheres"
- Leads to weak hydrogen emission with very wide double peak separation

As with all OB stars, Be stars are often/usually members of binary systems!!!

Classical Be Stars

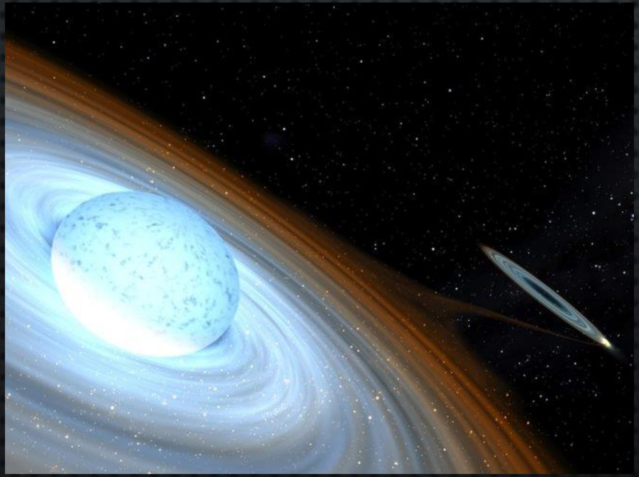
Be Stars: still enigmatic after 100+ years of research

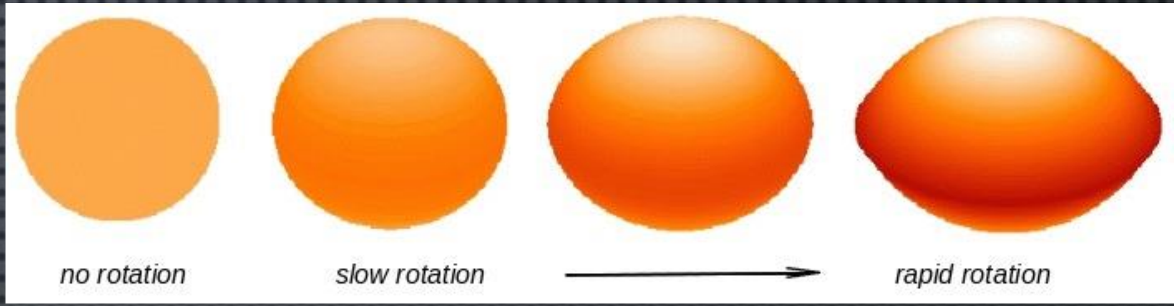
- Classical Be stars = rapidly-rotating, main-sequence to giant stars of B spectral type which have or once had emission in the Balmer series (namely, Hα).
- Emission lines are formed in “viscous decretion disks” made of gas ejected from the stellar surface.
- The most rapidly-rotating non-degenerate stars; close to but not quite critical rotation.
- They are non-radial pulsators… effects seen in photometry and spectroscopy.
- As with all OB stars, a very large fraction of Be stars are in binaries.
- Several thousand known in the Milky Way Galaxy (maybe 15-20% of B stars)
- They are variable over almost all time scales!!!
- The key mysteries:
  - How do they form their disks?
  - Why are they rotating so fast?

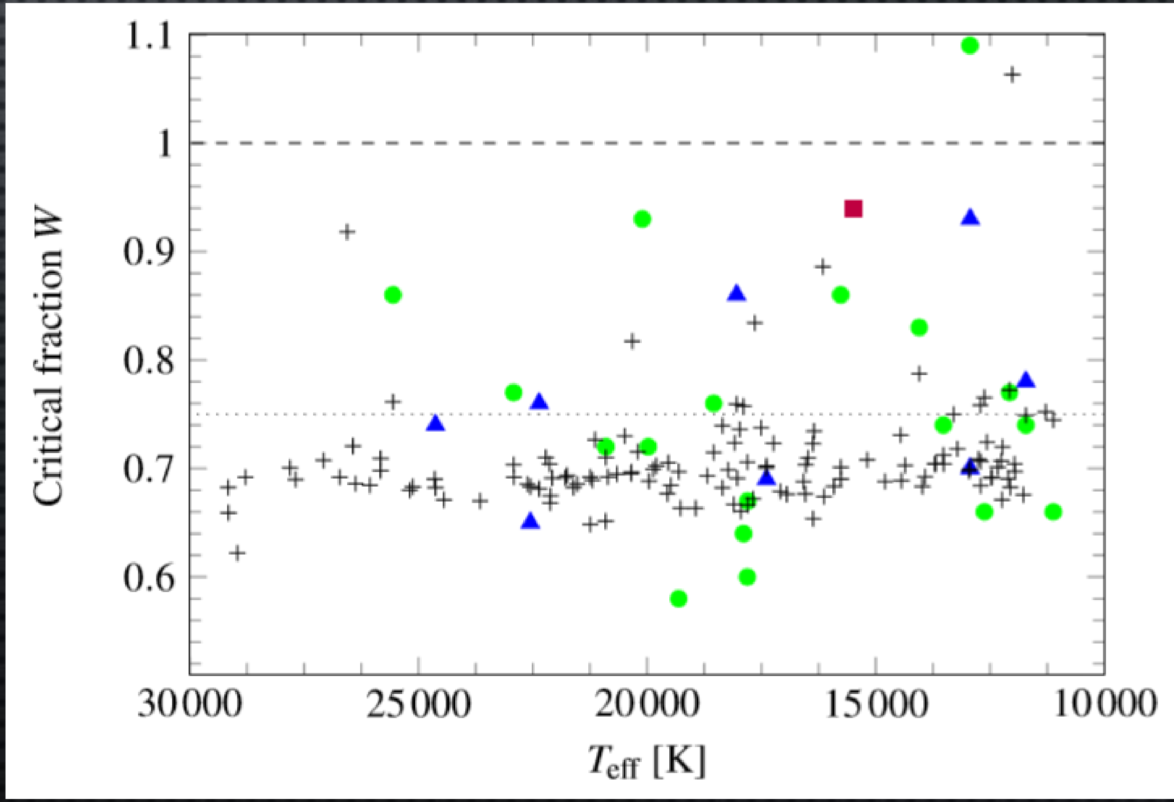


Not Quite Critical Rotation

- Observed rotational velocities of Be stars are too low to explain the ejection of surface gas.
- Perhaps stellar pulsation assists to help launch gas off the star, but this has never been proven.
- Variable rotational velocities?



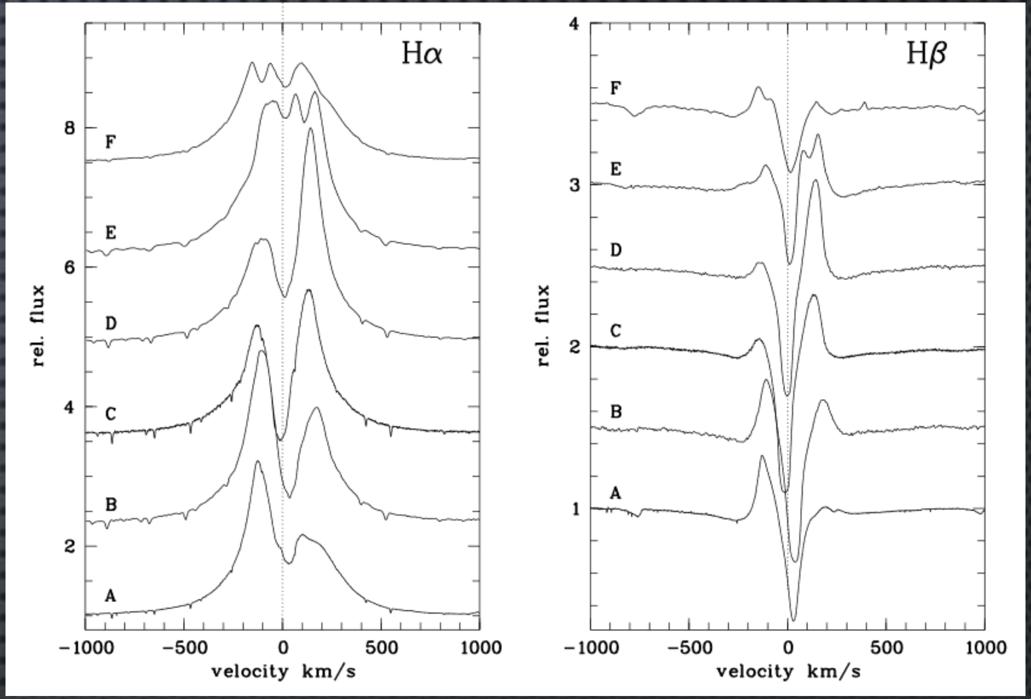




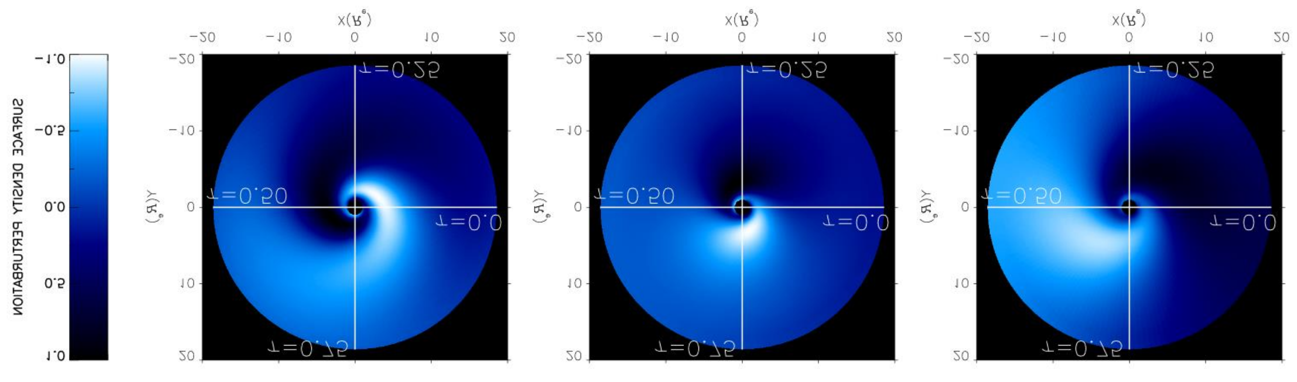
Rivinius+ 2013

V/R Variability

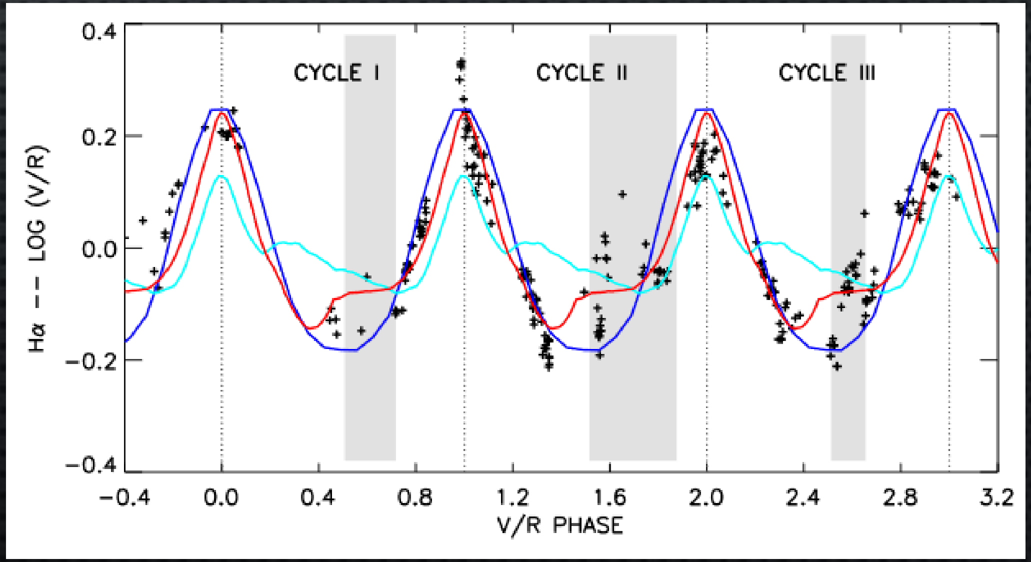
- The disks of some Be stars occasionally or cyclically undergo variations in relative heights of the V & R peaks.
- Caused by the slow precession of a one-spiral-armed density wave in the disk.
- Typical cycle lengths: a few to ~10 years.
- Fairly well modeled/reproduced by a global oscillation model (simulate a Keplerian rotating disk, and introduce various perturbations).



Stefl+ 2008

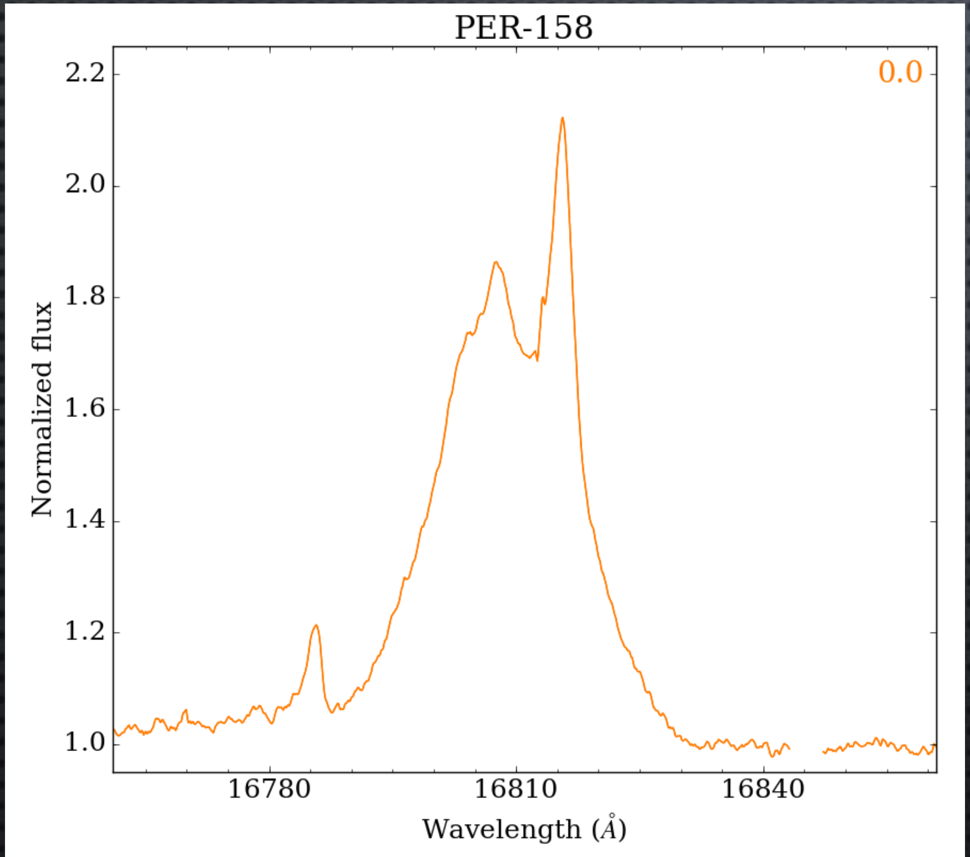


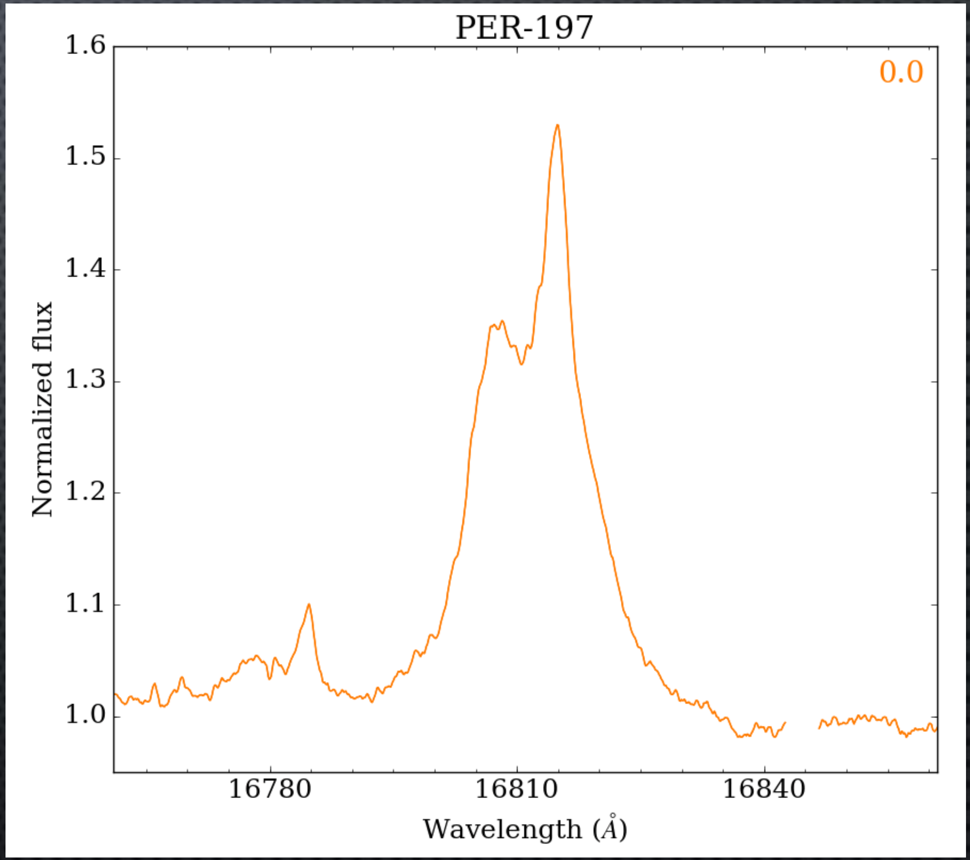
Escalono+ 2015



Escalono+ 2015

V/R Variability Examples

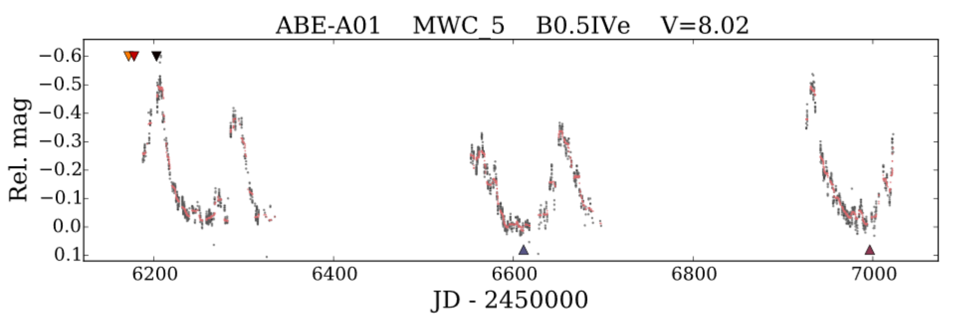


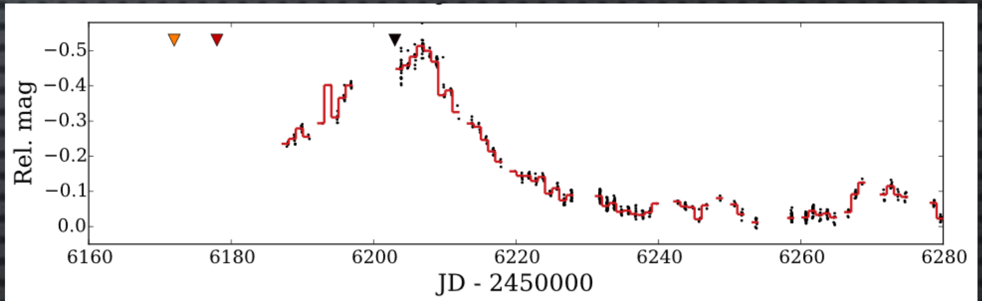


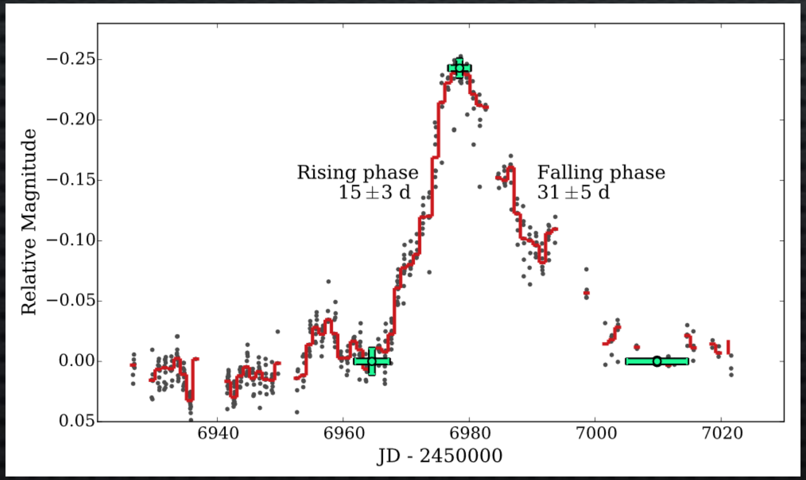
SDSS/APOGEE specra of Be stars from the Double Cluster (h & χ Persei)
The hydrogen Br11 line is shown (16811 Å)

Outbursts

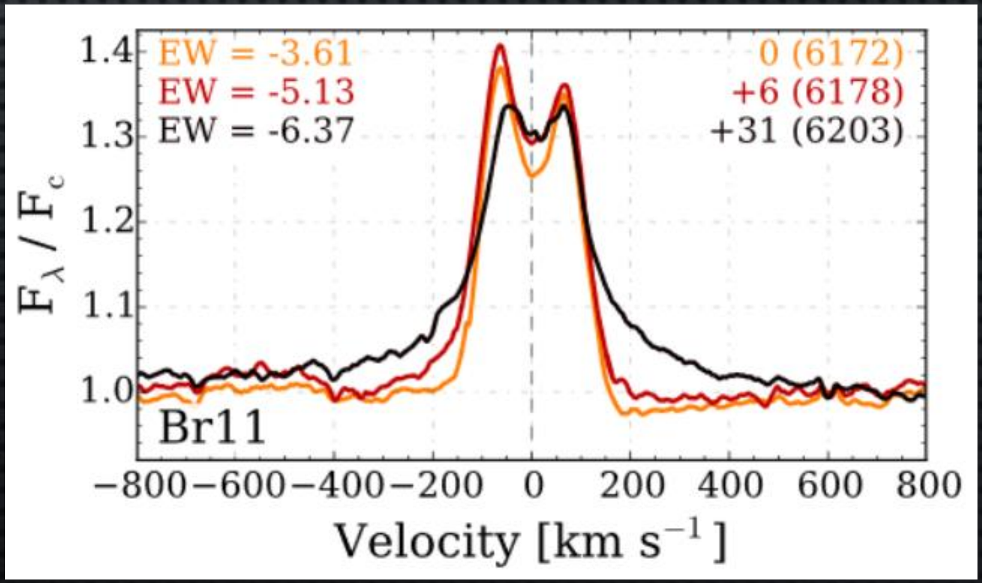
- Many Be stars undergo periodic "outbursts".
- The outbursts are presumably caused by the stars ejecting fresh material from their surfaces, thus fueling their disks.
- The brightness of the star suddenly increases or decreases (depending on inclination angle).
- Emission lines in the spectra change as well, often developing wide wings.



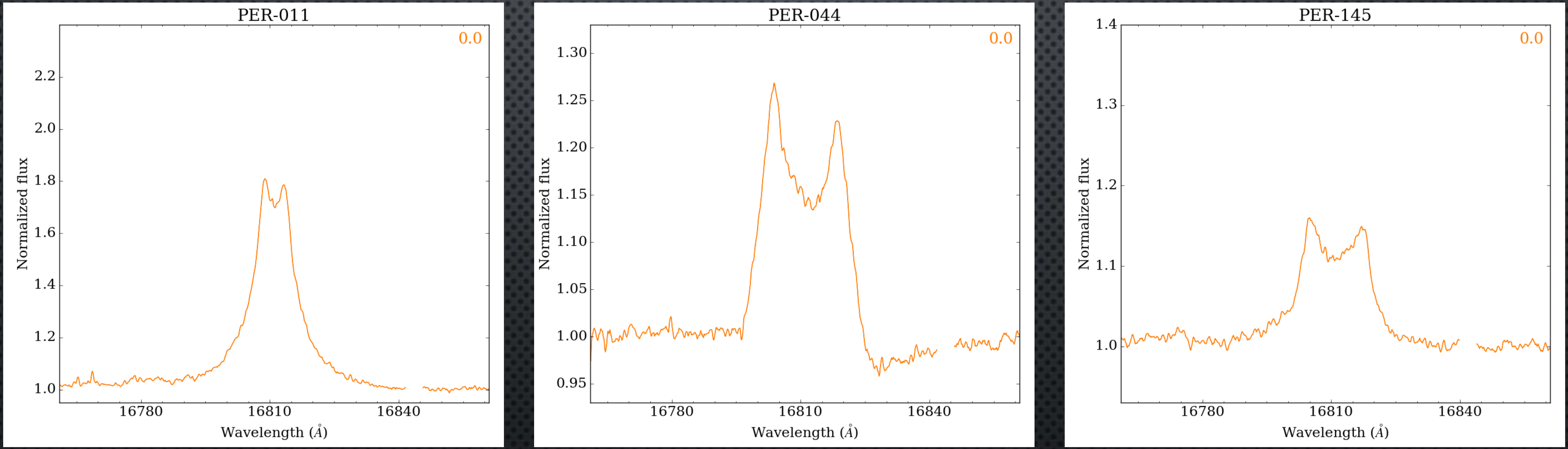




Labadie-Bartz et al. 2018



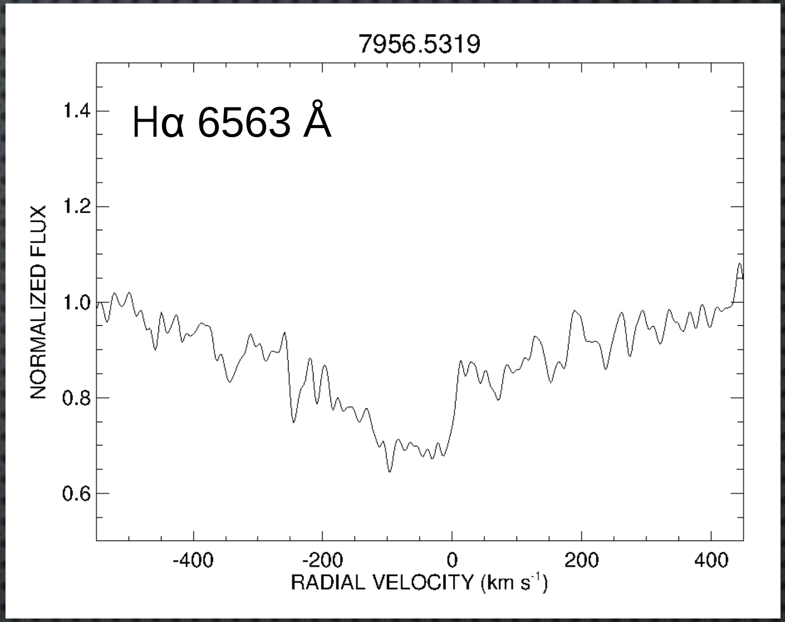
Outburst Examples



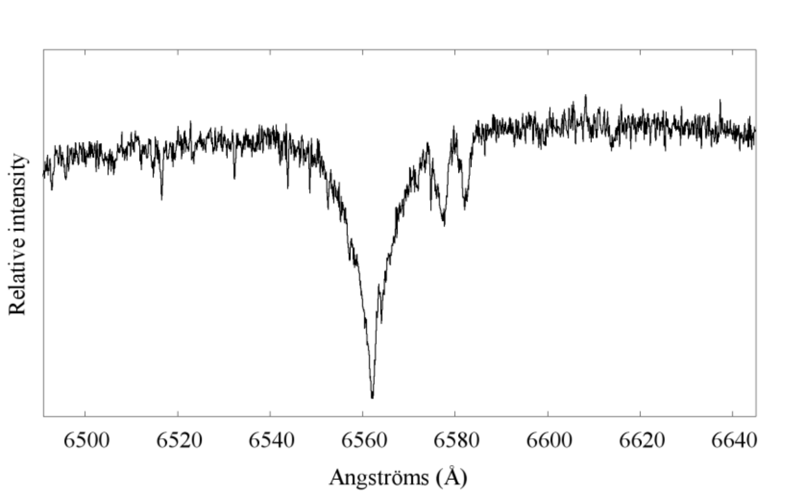
SDSS/APOGEE specra of Be stars from the Double Cluster (h & χ Persei)
The hydrogen Br11 line is shown (16811 Å)

To Be or not to Be: Transient Disks

- The Be phenomenon has an ON/OFF switch.
- **DISK LOSS:** Many Be stars periodically “lose” their disks, i.e. all observational evidence of the disk disappears.
  - Typically a slow process, taking place over month or several month timescales.
  - Where does the gas go? Evidence suggests it is lost to the interstellar medium.
- **DISK CREATION/RENEWAL:** In other cases, what was previously thought to be a normal B-type star may develop an emission spectrum.
  - Can happen quite suddenly, with emission starting to show up over day or week timescales.
  - Now the star is forever considered a Be star.

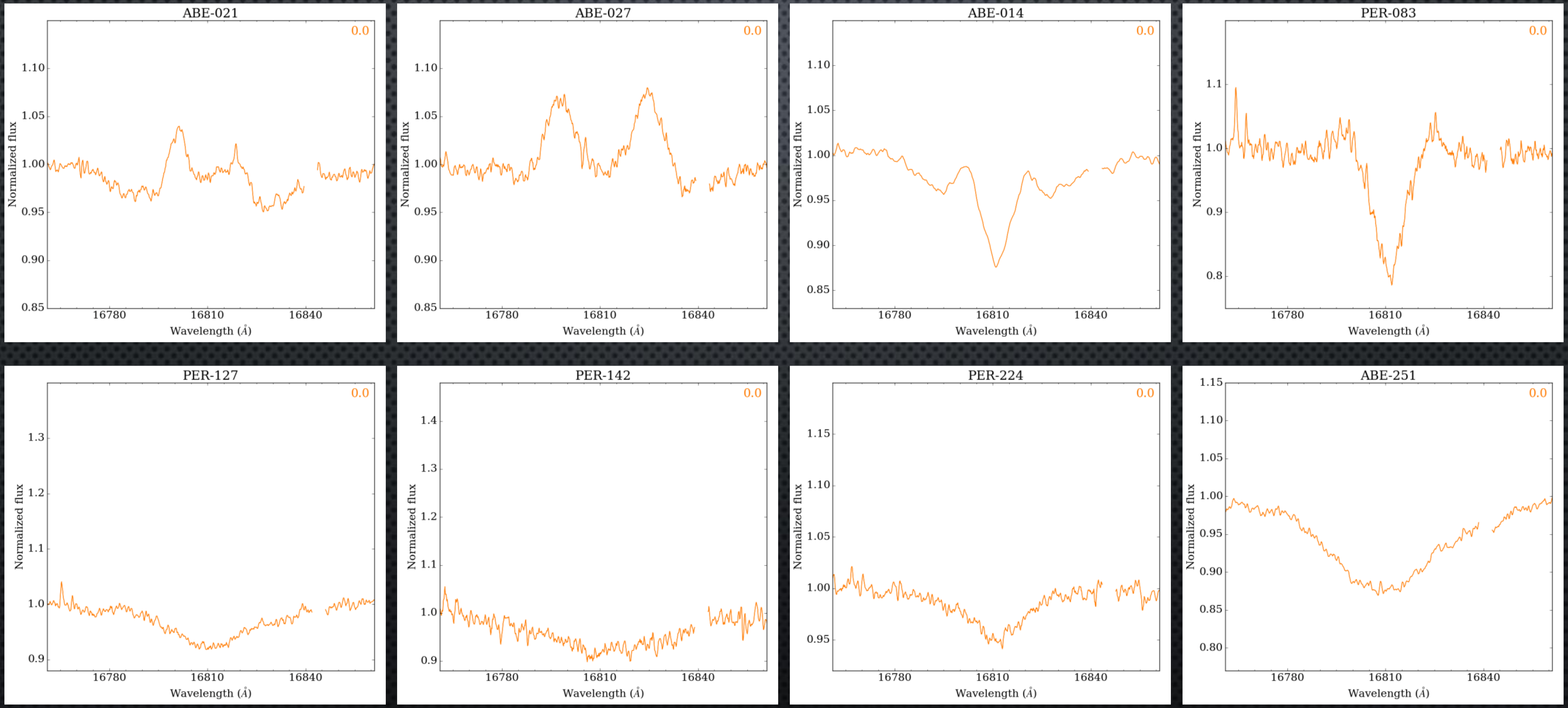


Noel Richardson et al. (in prep)

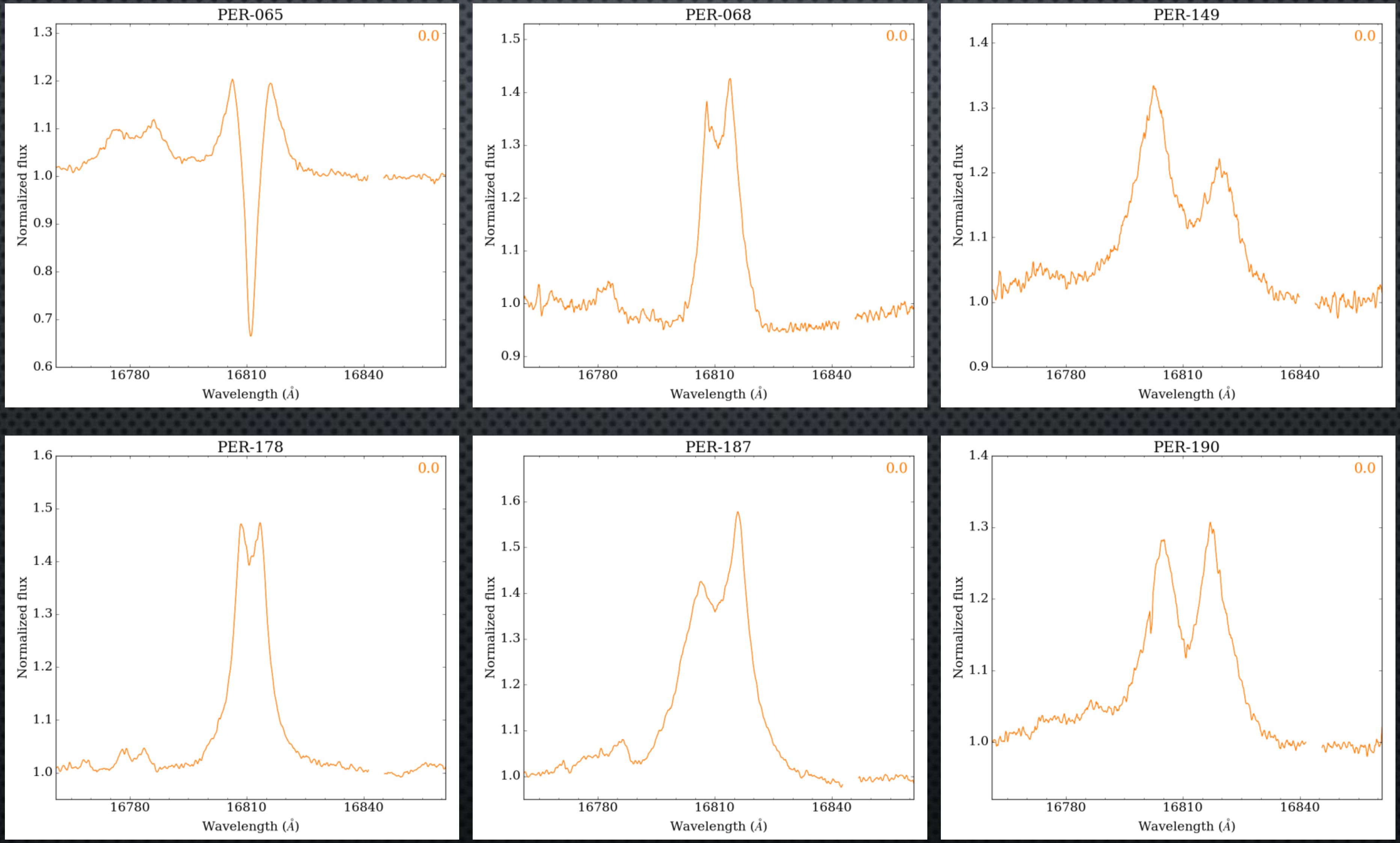


Recent spectrum from Joe Daglen

To Be or not to Be: Transient Disks

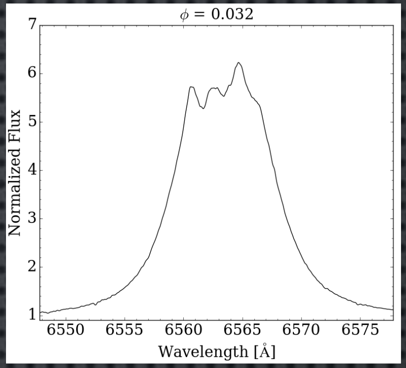


That said, some Be disks are quite stable…

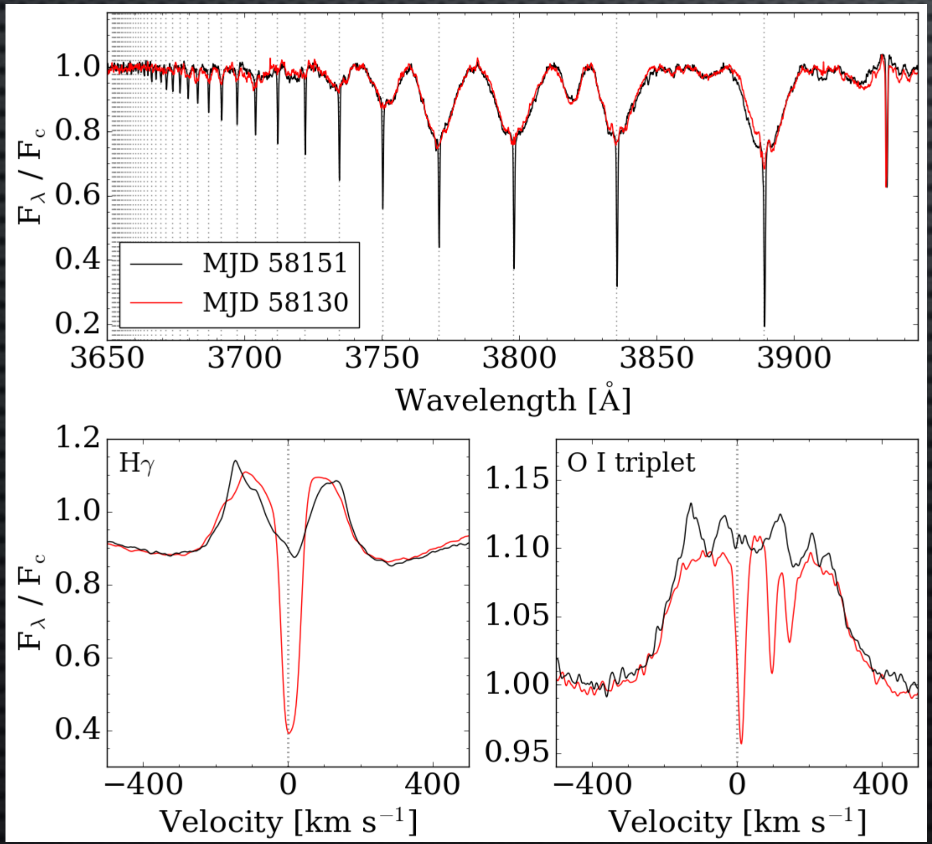


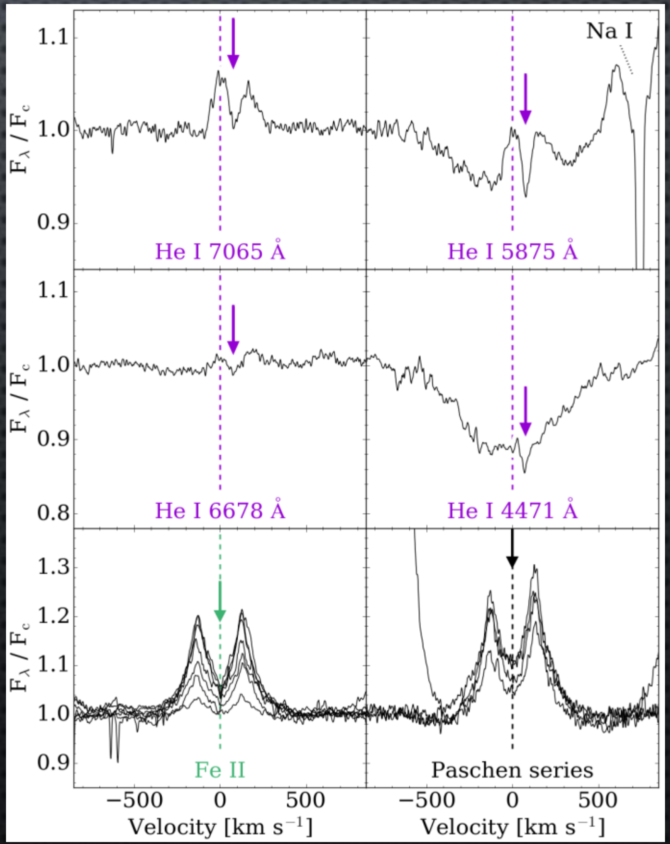
HD 55606: My Favorite Be Star

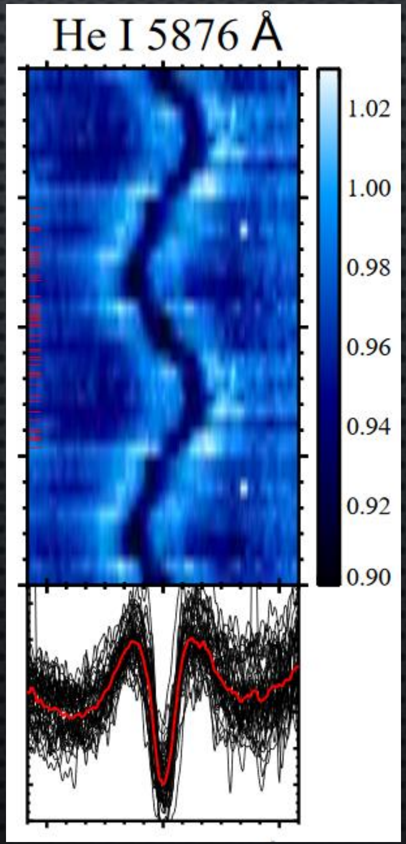
Hα



- Identified as unusual based on abnormally strong metallic emission lines in APOGEE spectra.
- Subsequently obtained about 50 spectra from APO 3.5m/ARCES.



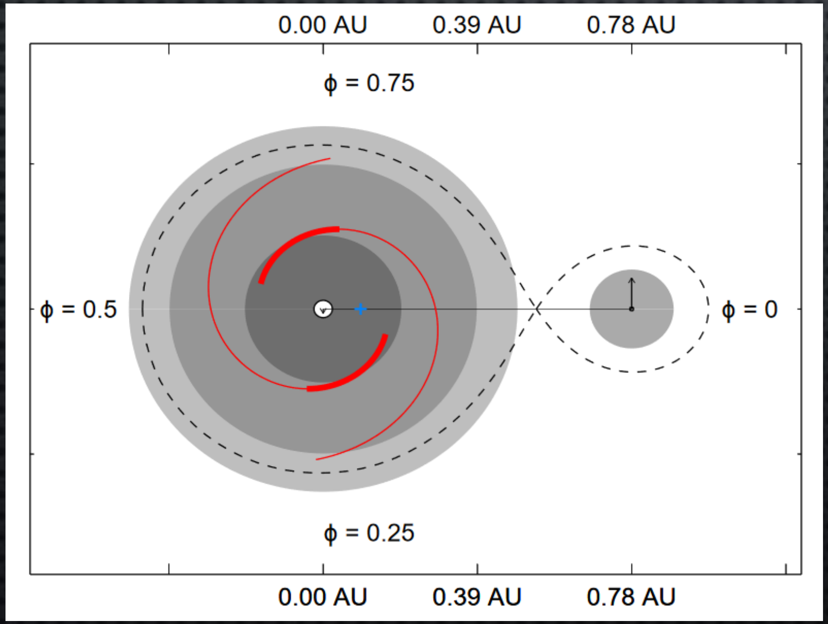


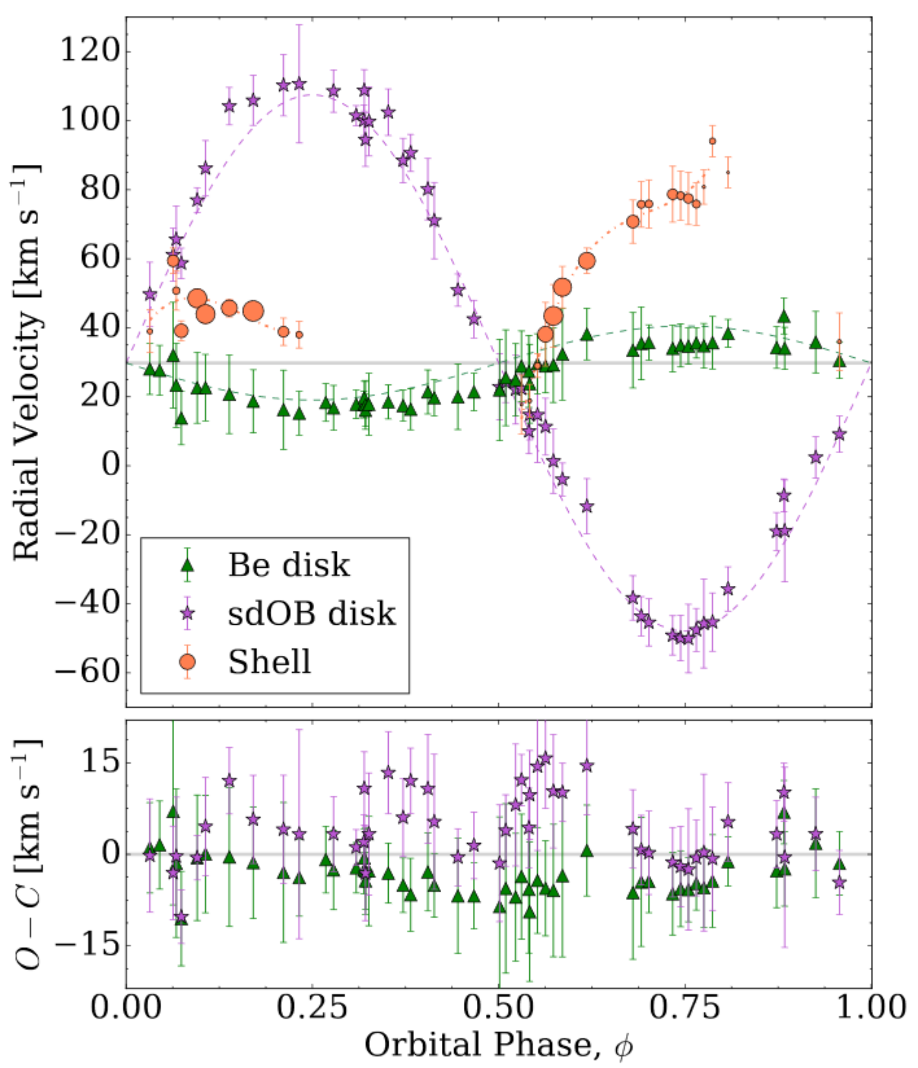


Chojnowski et al. 2018

HD 55606: A Be+sdO Binary

- It turns out HD 55606 is one of just a few known examples of a Be star in a binary with a subdwarf O-type (sdO) star.
- The outer layers of the sdO star were previously stripped by the Be star.
- There is ongoing mass transfer, possibly in the form of the sdO star accreting Be disk.





Chojnowski et al. 2018

The Other Known Be+sdO Binaries (Northern Sky)

Orbital Parameters Known (observe for fun)

- Phi Per (HD 10516), V = 4.1
- 59 Cyg (HD 200120), V = 4.5
- 60 Cyg (HD 200310), V = 6.0
- HR 2142 (HD 41335), V = 5.0
- FY CMa (HD 58978), V = 5.4
- o Pup (HD 63462), V = 4.5

Orbital Parameters Unknown (observe for science)

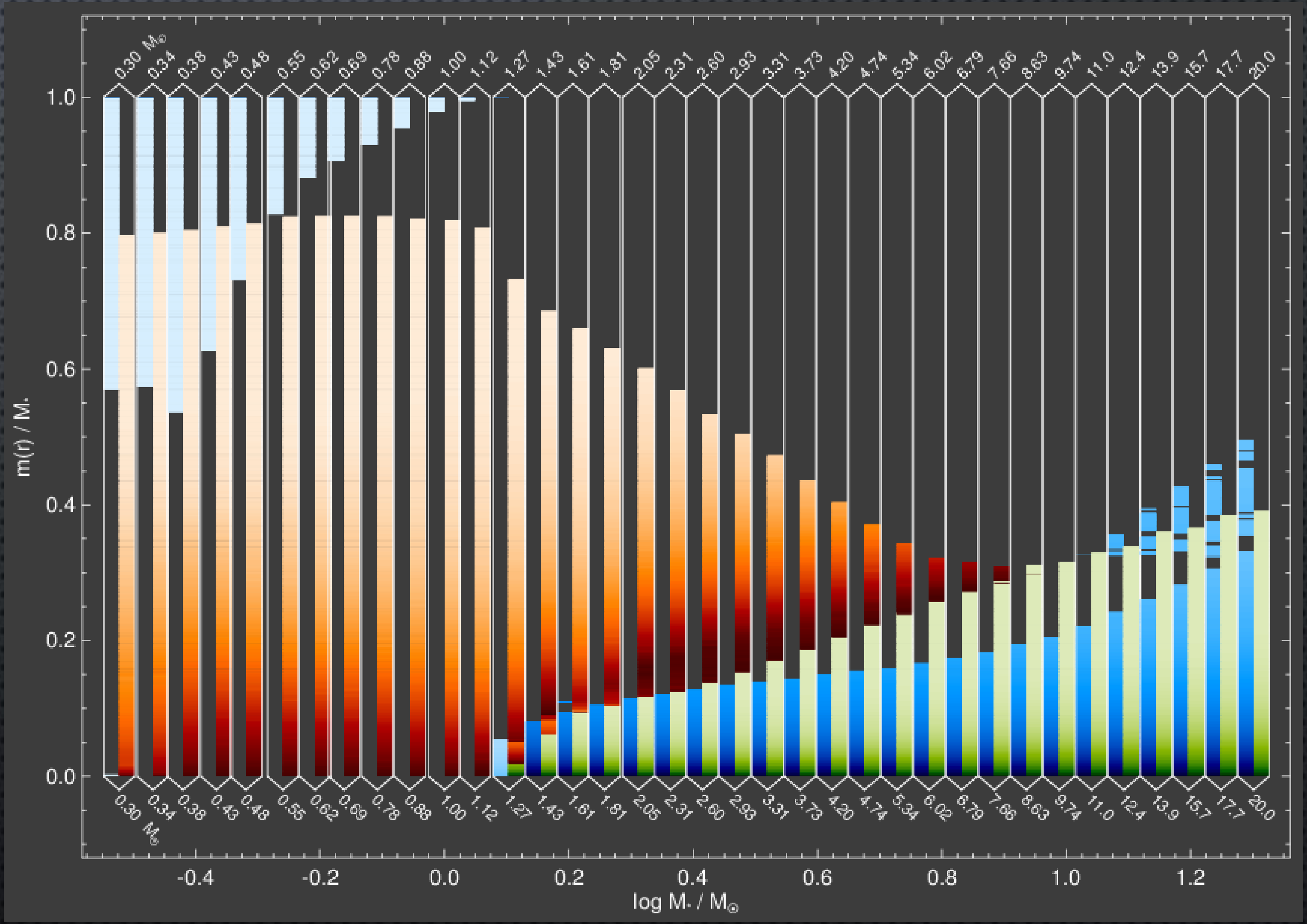
- HD 161306, V = 8.3
- HD 29441, V = 7.6
- HD 43544, V = 6.4
- HD 60855, V = 5.5
- HD 51354, V = 7.2
- HD 214168, V = 6.9
- HD 194335, V = 5.9
- HD 191610, V = 5.2

Up now!

RRM stars

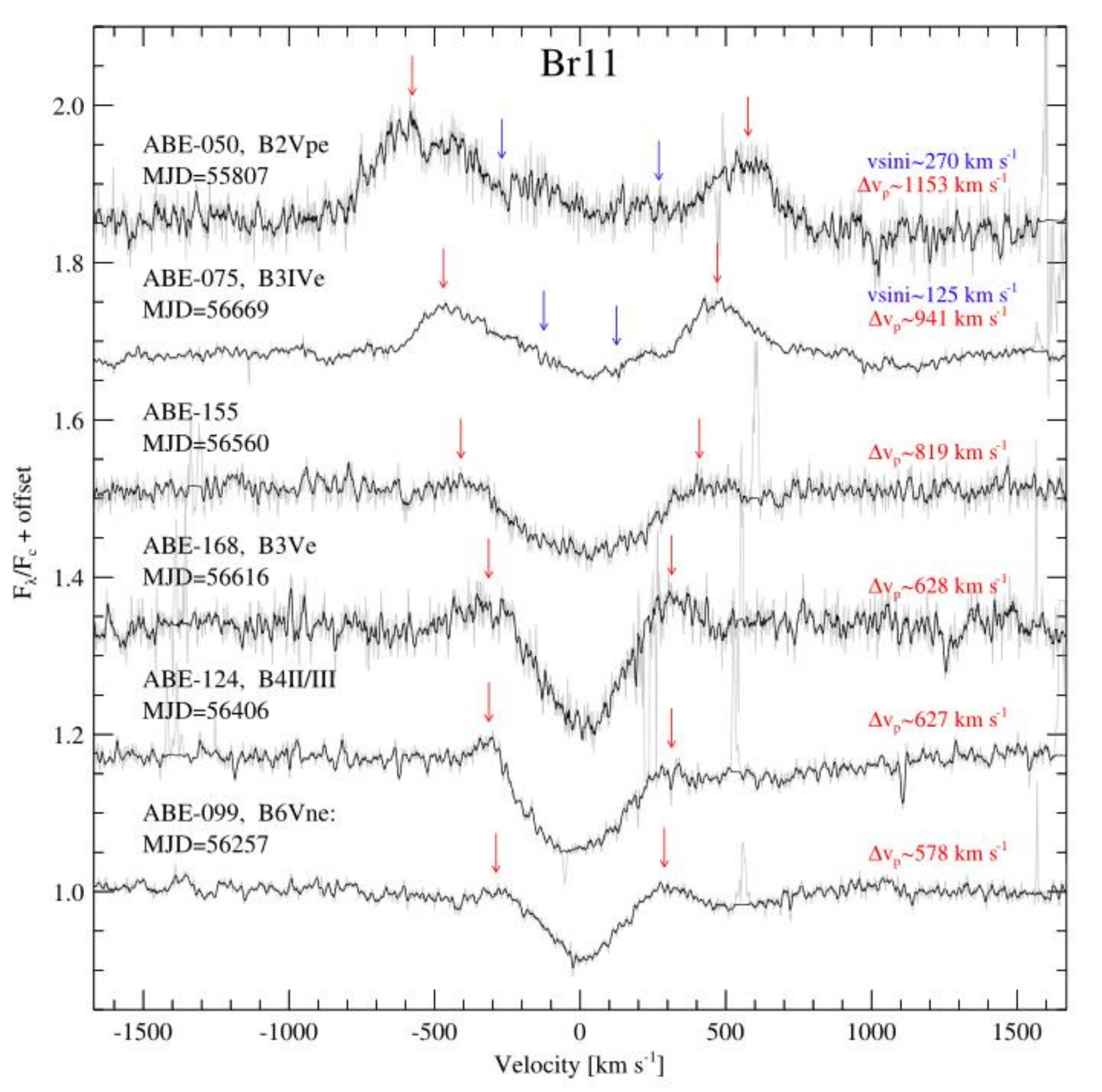
RRM Stars: Rare & Unexpected

- Massive/hot stars should not have significant surface convection zones, so they don't get their B fields the same way the Sun does.
- The origin of strong B fields in some OB stars is unknown…. Fossil fields? Stellar mergers?
- Highly rare – very few examples known with circumstellar emission.



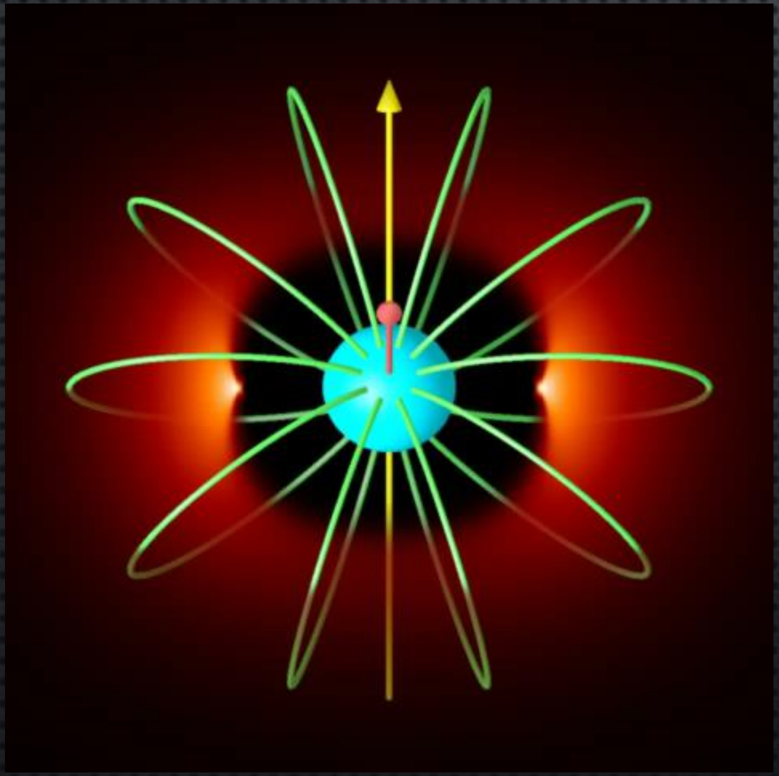
Rigidly Rotating Magnetospheres

- The weak hydrogen emission observed in RRM stars is caused by strong stellar wind being trapped by the magnetic field and hence exposed to the hot star.
- The gas is forced to rotate at the same speed as the surface of the star.
- Therefore, the variability of Hα emission repeats every time the star rotates… typically a day or less.
- **Very wide emission peaks is a dead giveaway.**
- Often "chemically peculiar" spectra (He-strong).
- Magnetic braking.

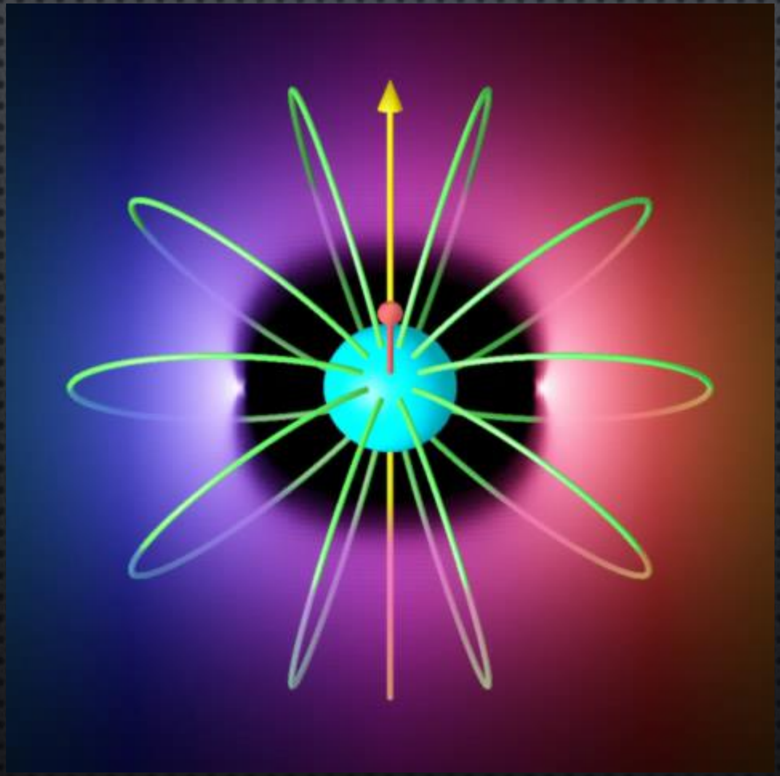


The Prototypical RRM Star: σ Ori E (HD 37479)

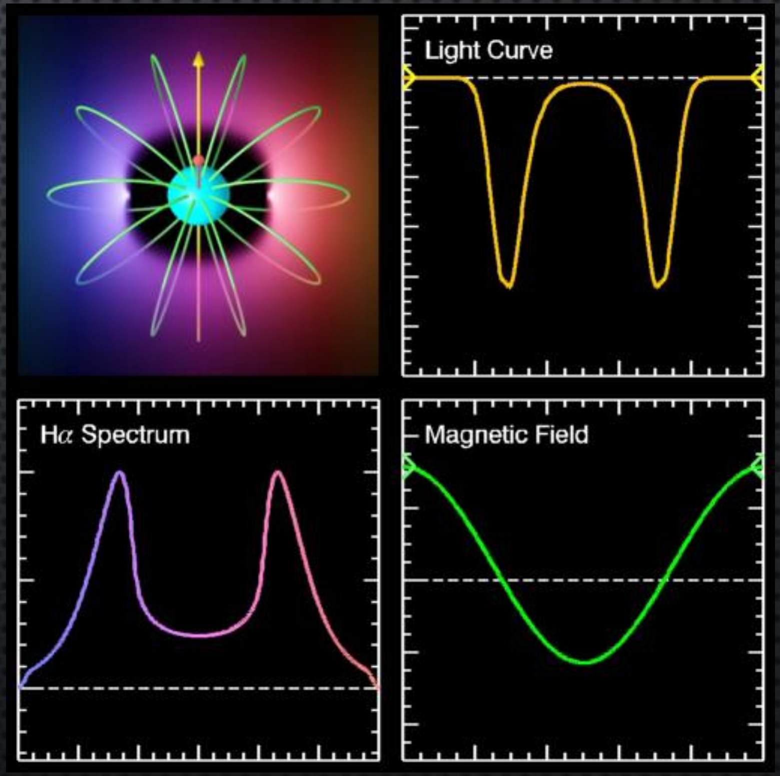
Magnetospheric matter distribution, with brightness coding for relative optical depth



Color indicates the line-of-sight velocity of the material (blue indicating motion towards the observer, and red motion away)



Light curve, Ha emission and mean longitudinal field strength.

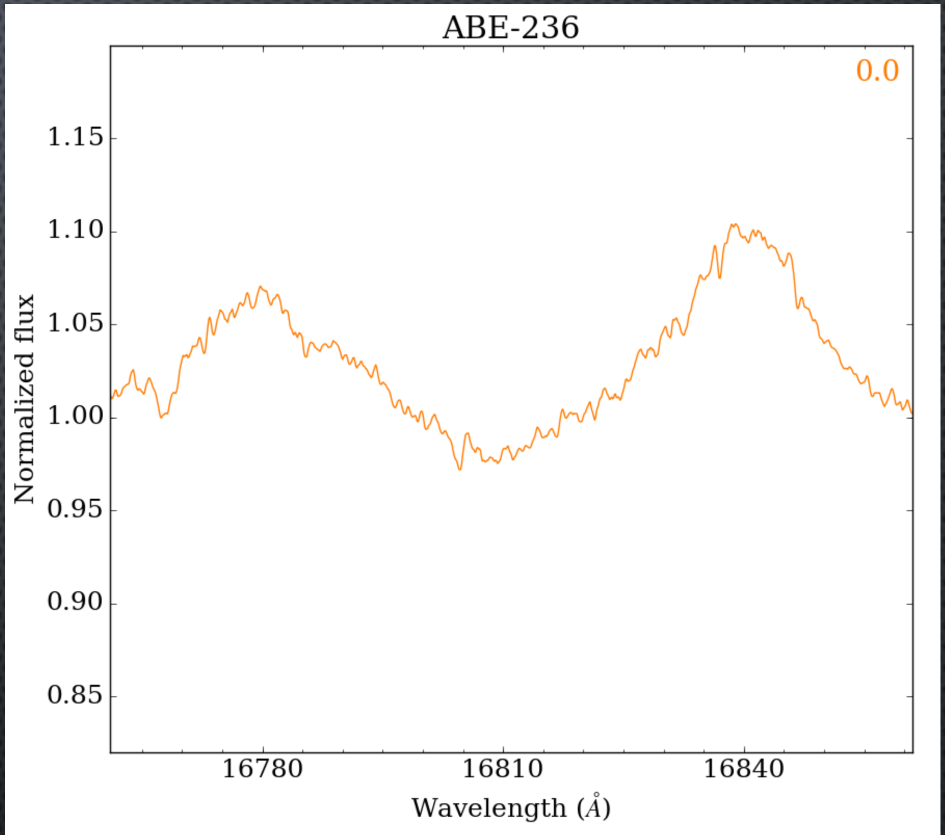


Movies from Richard Townsend's website

The Known RRM Stars

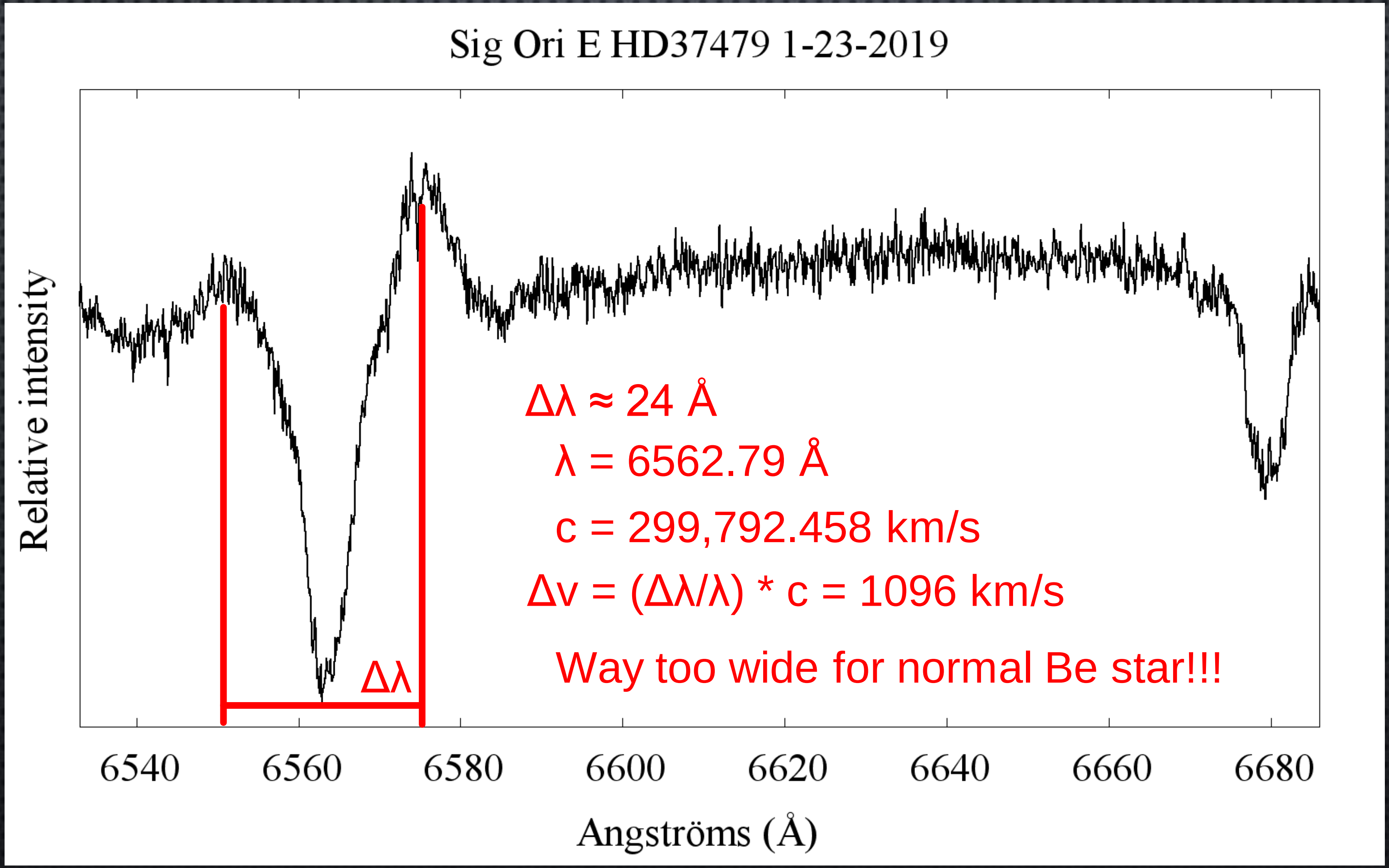
- To the best of my knowledge, there are still only 8 known examples of B stars with emission line RRM.
- It's a very hot topic lately…
- Spectroscopic survey of B stars should find more.

  - σ Ori E, V = 6.46, B2IV-Vp
  - HR 7355, V = 6.01, B2Vnn
  - HR 7185, V = 6.40, B5IV
  - HR 5907, V = 5.40, B2V
  - HD 23478, V = 6.67, B3IV
  - HD 345439, V = 11.11, B1-2V
  - HD 164492C, V = 6.80, B1V
  - CPD-62 2124, V = 10.99, B0



SDSS/APOGEE spectra of σ Ori E
The hydrogen Br11 line is shown (16811 Å)

How To Discover RRM Stars

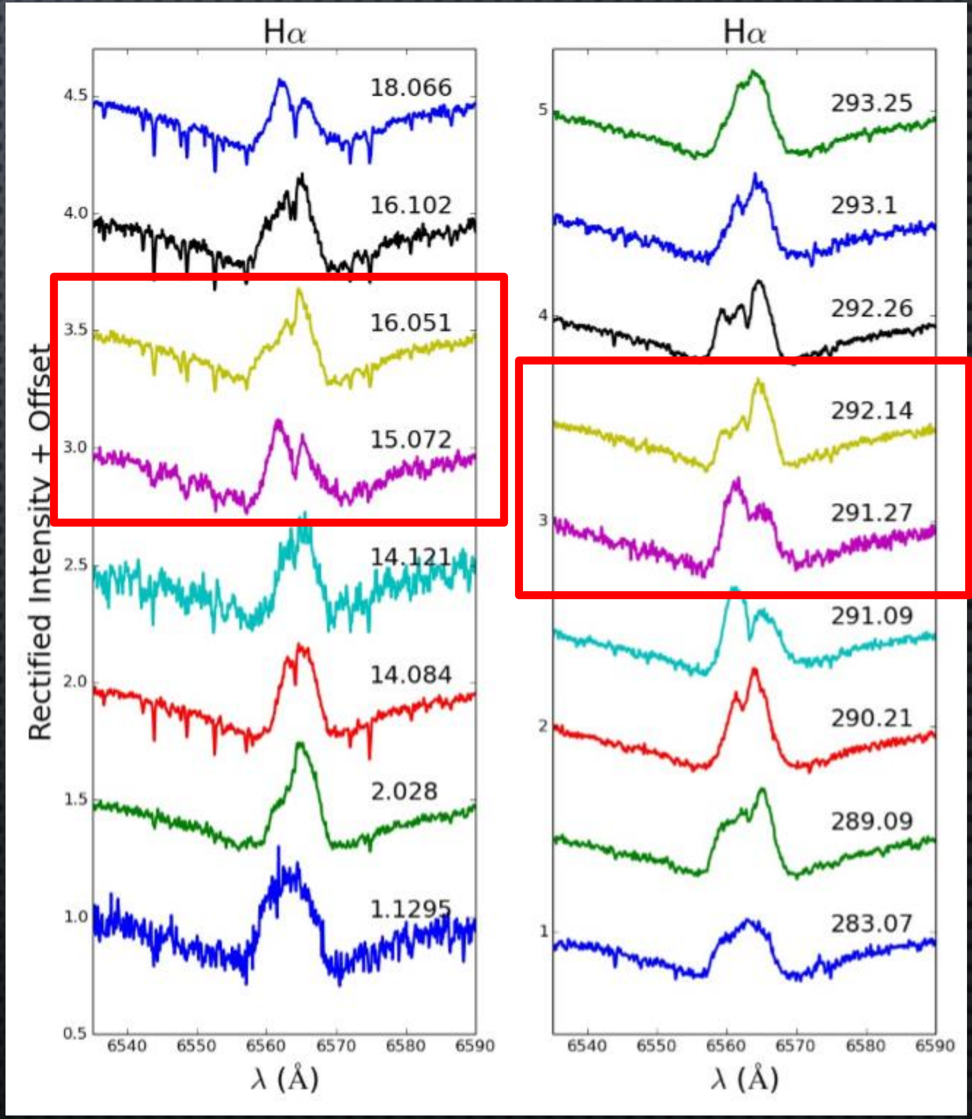


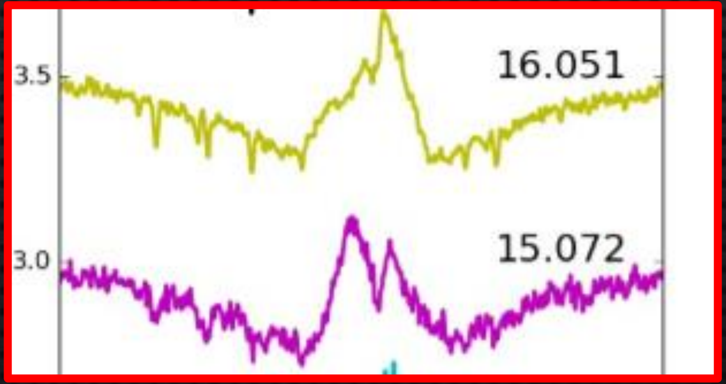
If you observe Hα peak separations wider than 12 Å, contact me.

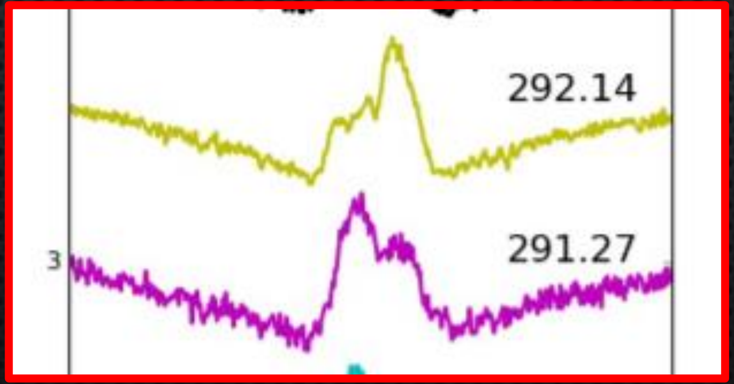
Recent spectrum from Joe Daglen

HD 63021: Why We Need Help

- The variability appears to be periodic, i.e. the same general pattern repeats.
- The period seems to be less than day! Very fast!
- Nightly operating budget of APO observatory: $10,000
- Repeated observations of HD 63021 on a nightly basis may help us determine the nature of the object(s).







Recap of Things You can Observe/Discover

- V/R variability
  - Normal timescales: years to decade
  - Abnormal timescales/time to contact an astronomer: less than a month
- Outbursts
  - Can occur quickly over hour timescales
- Disk Loss/Creation
  - Disk loss proceeds slowly, usually over months.
  - Disk creation can immediately, from one night to the next.
- Binary star periods
  - In the case of Be+sdO binaries, periods are between 1-4 months.
  - Variability pattern should repeat over orbital period
- New RRM stars
  - Observe "normal" B/Be stars. As many as you Can.
  - Look for very wide emission peak separation
  - Variability of the emission should repeat over the rotational period of the star… usually less than 1.5 days.
- HD 63021
  - Is probably an exotic binary.
  - Period of a day or less.
  - Dense spectroscopic observations needed to measure period & search for evidence of a second star

End of slideshow