Chemically Peculiar Stars

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About myself

- 2003: PhD from Uppsala university
- 2004-2005: Postdoc positions in Vienna university and NORDITA
- 2006: Back in Uppsala as a research assistant and then lecturer
- 2017: Professor in astronomy

- Scientific interests and expertise https://www.astro.uu.se/~oleg/
  - High-resolution spectroscopy and spectropolarimetry
  - Stellar spectra and atmospheres
  - Chemically peculiar stars
  - Magnetic fields in stars (main sequence stars from early-B to late M)

Outline

- Definition and classification of CP stars
- Physical mechanism responsible for the CP-star phenomenon
- Rotation and binarity of CP stars
- Incidence of CP stars
- Rotational and pulsational variability of CP stars
- Quantitative spectroscopic analysis
  - Parameter determination and model atmospheres
  - Chemical abundance patterns
  - Non-uniform abundance distributions

Definition and classification

- Upper main sequence stars with non-solar surface chemical composition; chemically peculiar (CP) stars
  - Spectral classification from different sources (e.g. Skiff 2014)
  - Renson et al. (2009) catalogue
  - Catalogues incomplete for $V > 10$

"Magnetic"= strong (~kG) global field

"Non-magnetic"= no or weak ($\lesssim$10 G) field

	T_{eff} (K)	Magnetic stars	Non-magnetic stars	
CP2	7 000–10 000	Ap SrCrEu A3–F0	Am, λ Boo A0–F0	CP1
CP2	10 000–14 000	Ap Si B8–A2	HgMn B6–B9	CP3
CP4	13 000–18 000	He-weak Si, SrTi B3–B7	He-weak PGa B4–B5	CP3
CP4	18 000–22 000	He-strong B1–B2		

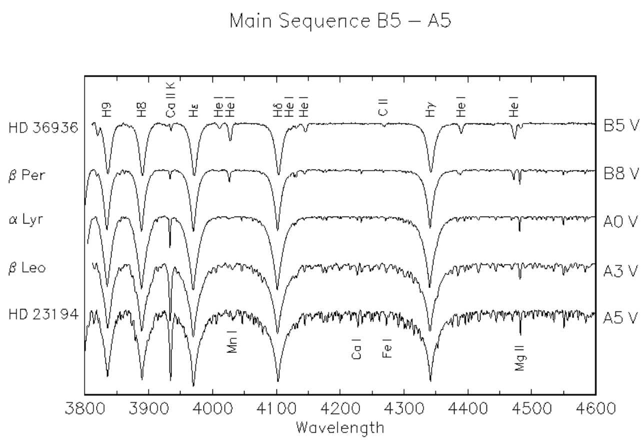
ApBp=mCP

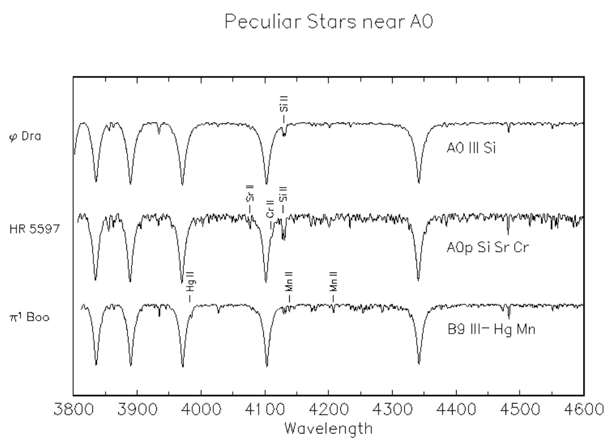
Kurtz & Martinez (2000) Preston (1974)

Spectral classification

- Objects deviating from standard spectral type progression
- Abnormal strength of lines visible in low-resolution spectra
- Currently lack of consistent approach to classification (e.g. Ap SrCrEu=A2 SiEu)

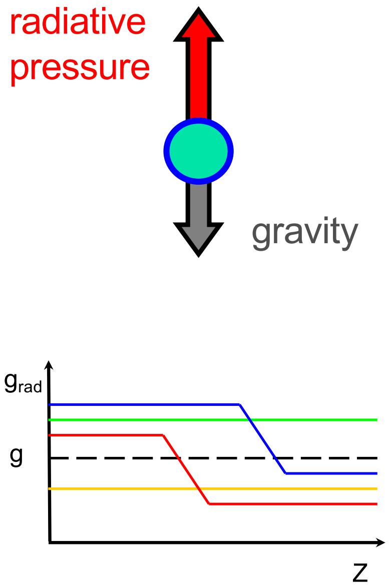
Harvard spectral classification work ~1890

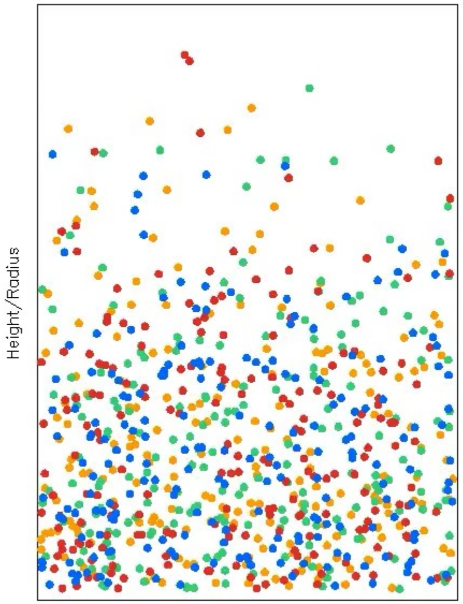




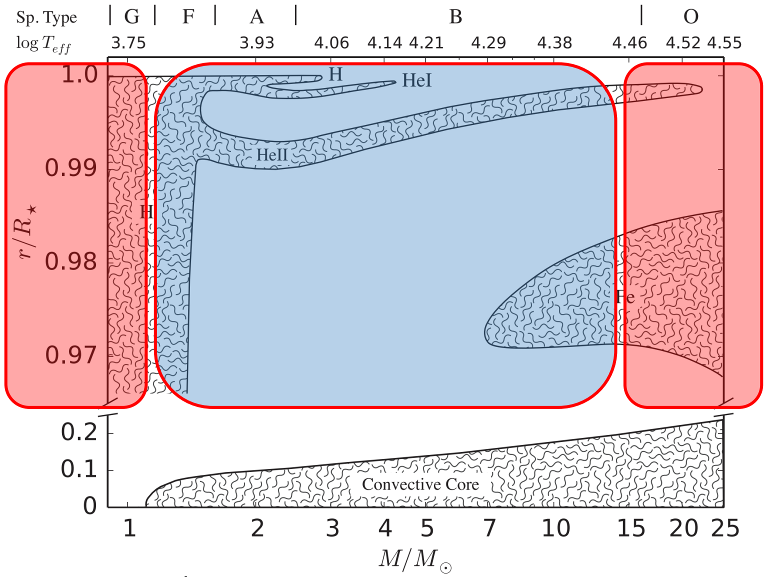
Why do CP stars exist?

- Radiative diffusion operating in hydrodynamically stable stellar surface layers
- Such stability is found in slowly rotating intermediate-mass stars





Cantiello & Braithwaite (2009)

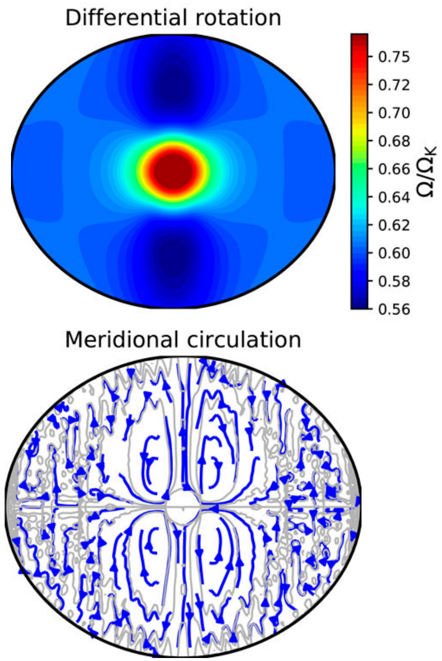


Unstable / mixed (convection, mass loss, fast rotation)

Stable (weak convection, no mass loss, slow rotation)

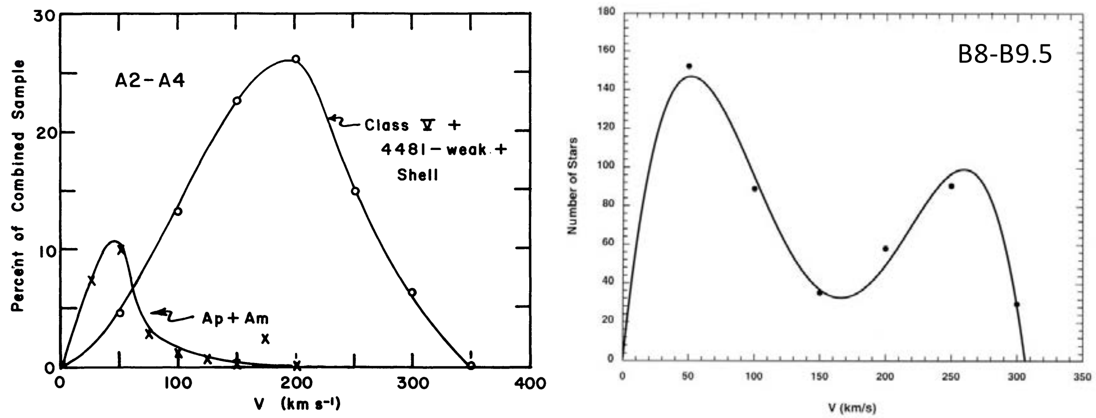
Rotation of CP stars

- Stars do no rotate as solid bodies. Rapid rotation leads to internal flows (e.g. meridional circulation), mixes envelope layers, counteracts radiative diffusion



2D model of fast-rotating 2 $M_\odot$ star (Reese 2022)

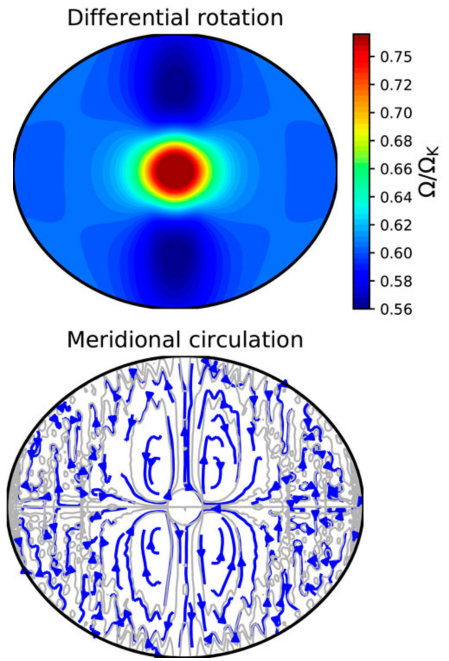
- Slow rotation ($V_{eq}\lesssim$120 km/s) is a prerequisite for CP-star phenomenon (except λ Boo stars)



Abt et al. (1995, 2002)

Rotation of CP stars

- Stars do no rotate as solid bodies. Rapid rotation leads to internal flows (e.g. meridional circulation), mixes envelope layers, counteracts radiative diffusion

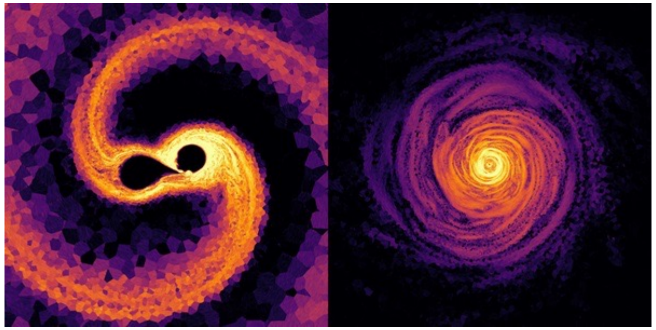


2D model of fast-rotating 2 $M_{\odot}$ star (Reese 2022)

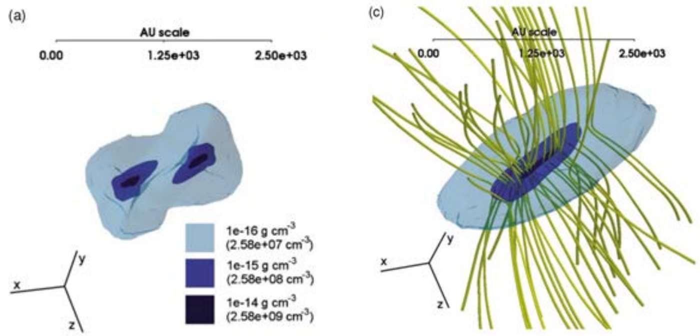
- Slow rotation ($V_{eq} \lesssim 120$ km/s) is a prerequisite for CP-star phenomenon (except λ Boo stars)
  - Am and HgMn stars: loss of angular momentum due to orbital synchronization in close binaries
  - ApBp stars: loss of angular momentum due to star-disk-wind magnetic interaction

Binarity of CP stars

- Different observed binary incidence for magnetic and non-magnetic CP stars
  - Low incidence of close (P_{orb}<10 d) binaries among ApBp stars; SB2 and EB systems are rare; normal incidence of wide binaries
    - Magnetic field is generated in binary mergers
    - Protostellar cloud fragmentation is impeded by primordial field
  - High incidence of close binaries among Am and HgMn stars; SB2 and EB systems are common; normal incidence of wide binaries
    - Stellar rotation is slowed down due to binary interaction



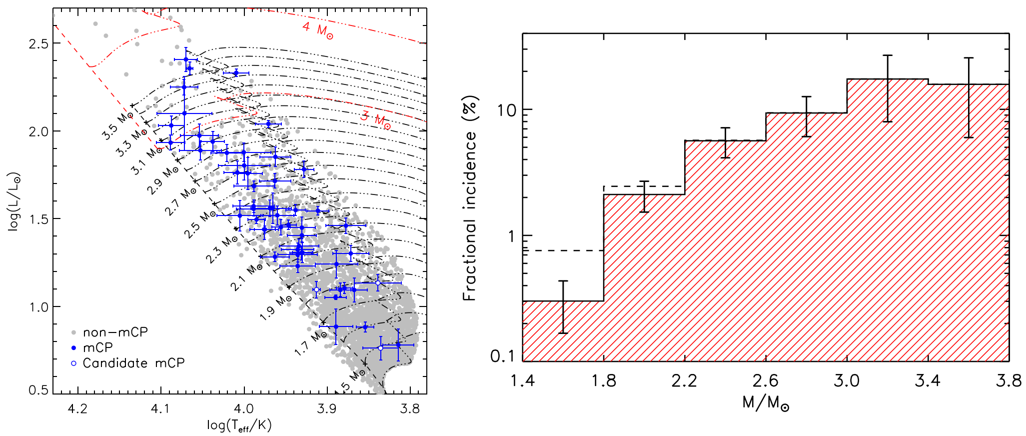
Schneider et al. (2019)



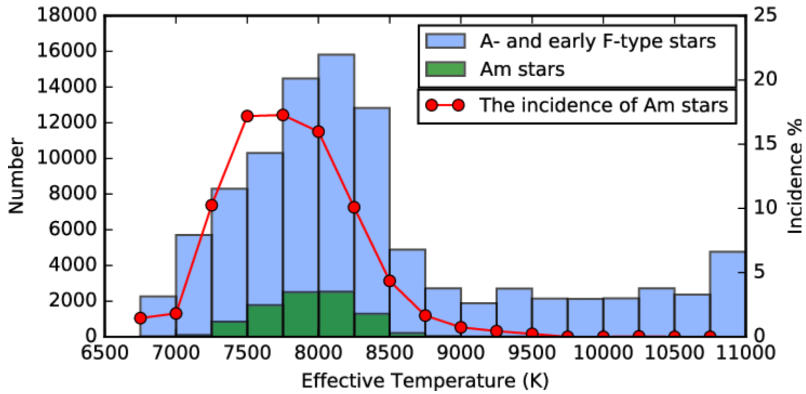
Duffin et al. (2009)

Incidence of CP stars

- Depends on spectral type. Up to 20-25% for all CP classes combined
- ≤10% for magnetic CP (ApBp) stars
- All slowly rotating A and B stars are chemically peculiar



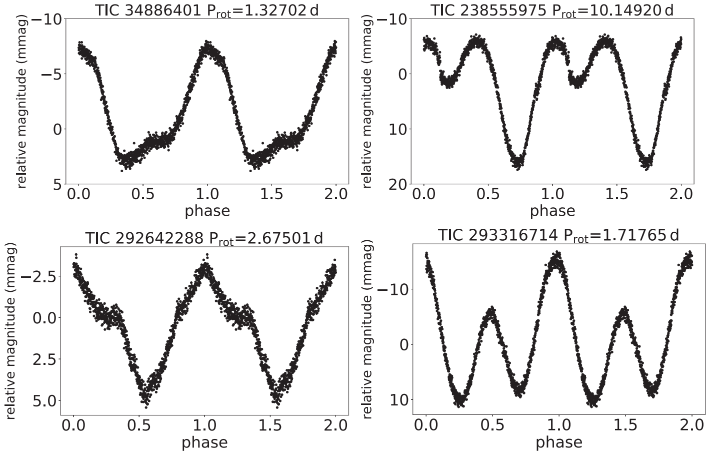
Magnetic CP stars within 100 pc (Sikora et al. 2019)



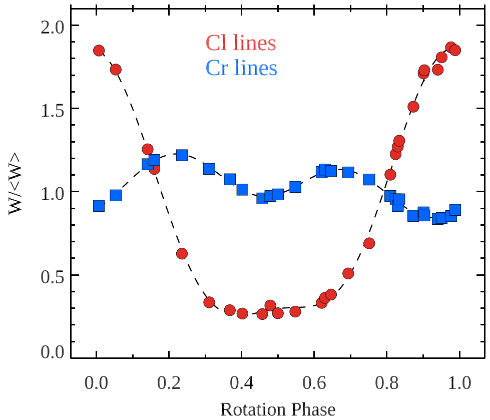
Am stars in LAMOST DR5 (Qin et al. 2019)

Rotational variability

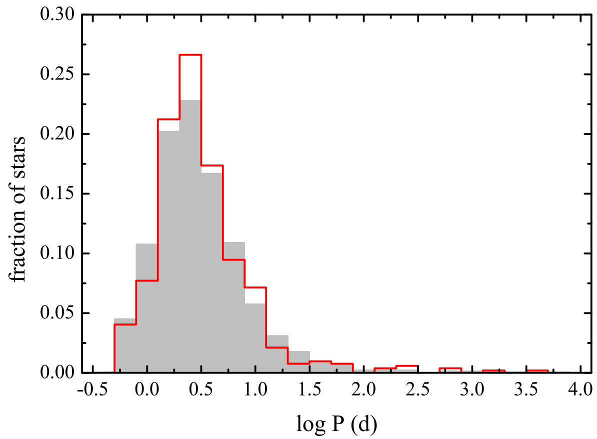
- Surface spots of chemical elements => rotational modulation of photometry, flux distributions, line intensities and profiles
  - Magnetic CP stars (α^2 CVn variables): high-amplitude variability due to stable spots; P_{rot} is typically a few days but can be up to ~100 years



TESS photometry of mCP stars from LAMOST DR9 catalogue (Shi et al. 2023)



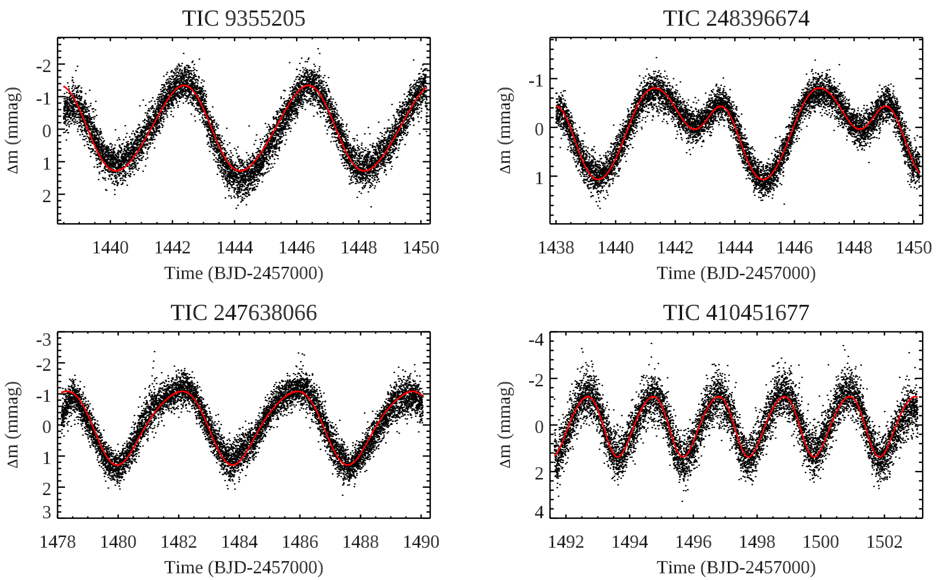
Relative EW variation of Cl and Cr lines in α^2 CVn (Kochukhov & Ryabchikova 2018)



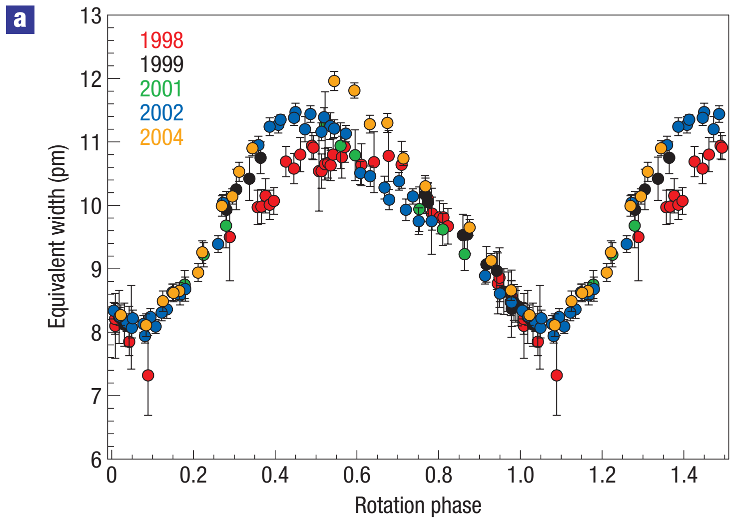
Netopil et al. (2017)

Rotational variability

- Surface spots of chemical elements => rotational modulation of photometry, flux distributions, line intensities and profiles
  - HgMn, PGA stars: low-amplitude variability due to evolving spots
  - Am, λ Boo stars: no systematic evidence of rotational variability



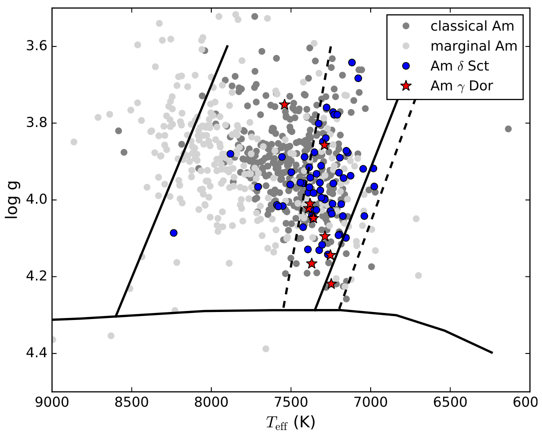
TESS photometry of HgMn stars (Kochukhov et al. 2021)



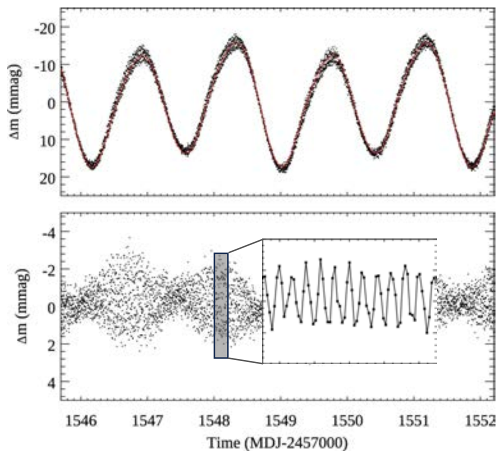
Hg II EW variation in α And (Kochukhov et al. 2007)

Pulsational variability and asteroseismology

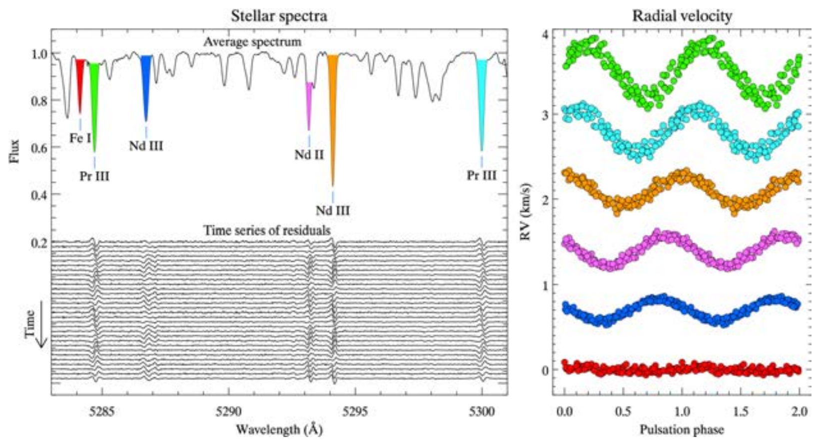
- HgMn and hot mCP stars: occasionally pulsate in g-modes (SPB); interior abundances and magnetic field from magneto-asteroseismology
- Am stars: p-mode δ Scuti and g-mode γ Dor pulsations; predicted not to pulsate
- Cool mCP stars: global p-mode pulsations shaped by magnetic field (rapidly oscillating Ap stars); solar-like asteroseismic analysis, atmospheric tomography



Pulsating and constant Am stars (Smalley et al. 2017)



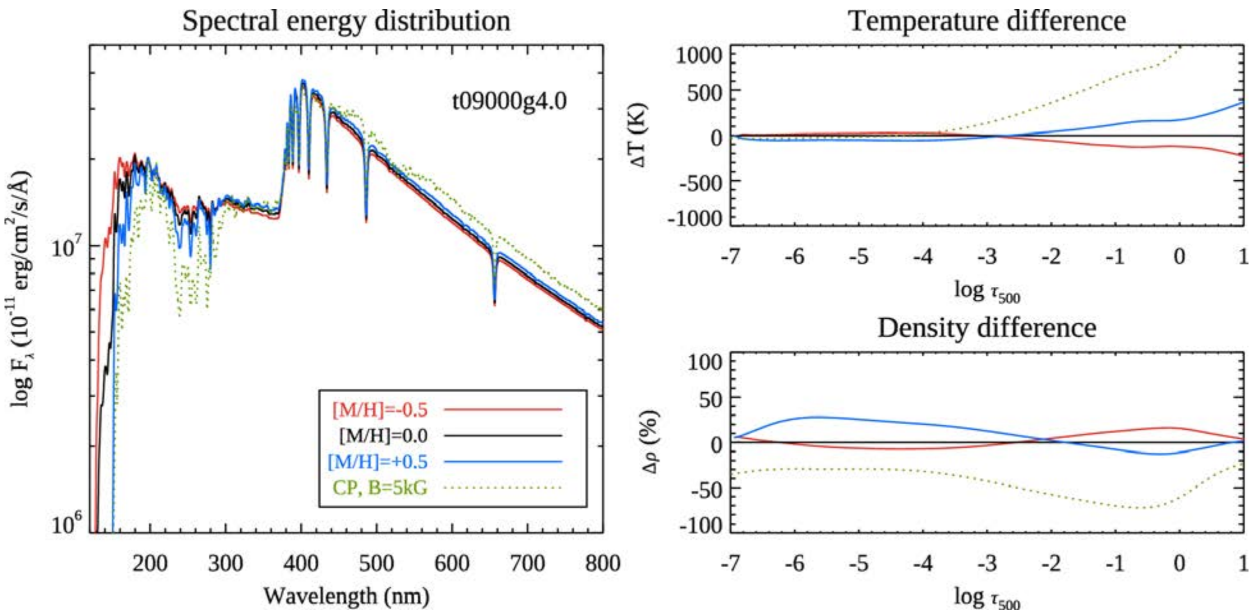
Typical light curve of a roAp star



Spectroscopic pulsational variability of a roAp star (Kochukhov et al. 2007)

Atmospheric parameters and structure

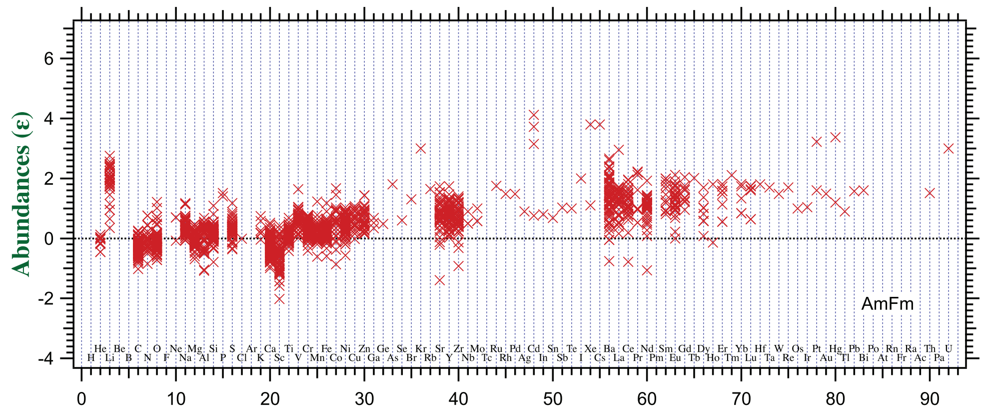
- SED and atmospheric structure are modified by the flux redistribution from UV to optical and NIR
- Am and HgMn stars: small effect; normal methods and calibrations are applicable
- mCP stars: large effect; individual abundances are required for model-based stellar parameter determination; CP-star specific empirical calibrations for T_{eff}, log g, …



mCP star toolbox:
Theoretical: LLmodels code (Shulyak et al. 2004, Khan & Shulyak 2006)
Empirical: T_{eff} calibrations (Landstreet et al. 2007, Netopil et al. 2008)

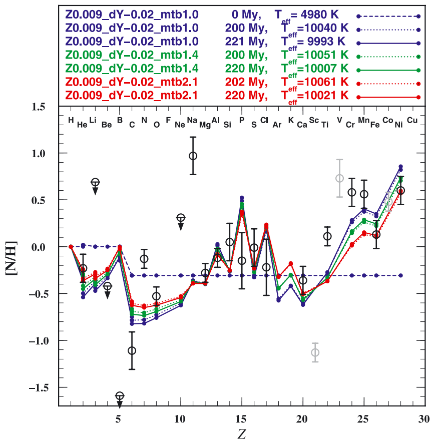
Abundance analyses of Am stars

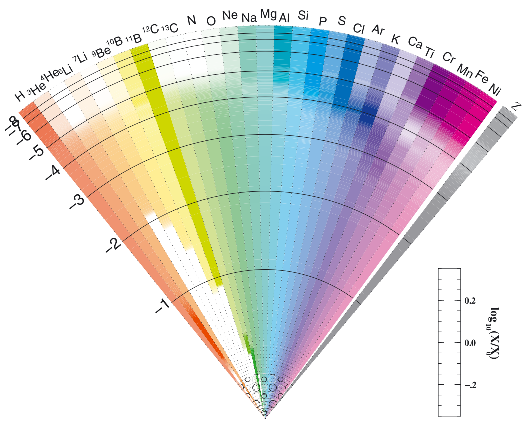
- Am stars: +0.5:+1.0 dex for Fe-peak, Sr-Zr, REEs, -0.5:-1.0 dex for CNO, Ca, Sc
  - Detailed diffusion theory predictions
  - Mild version of Am peculiarity: marginal Am (Am:), superficially normal

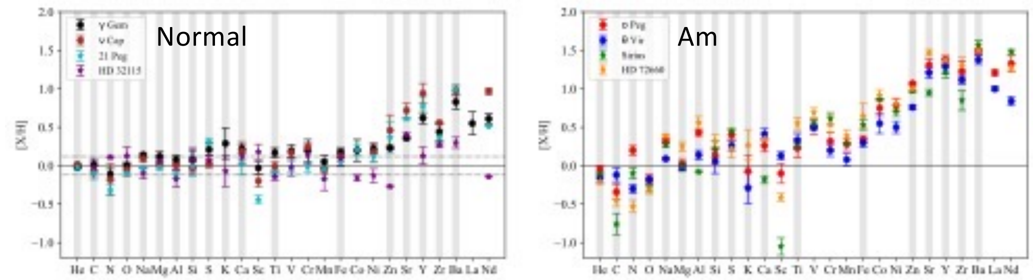


Ghazaryan et al. (2018)

Michaud et al. (2011)



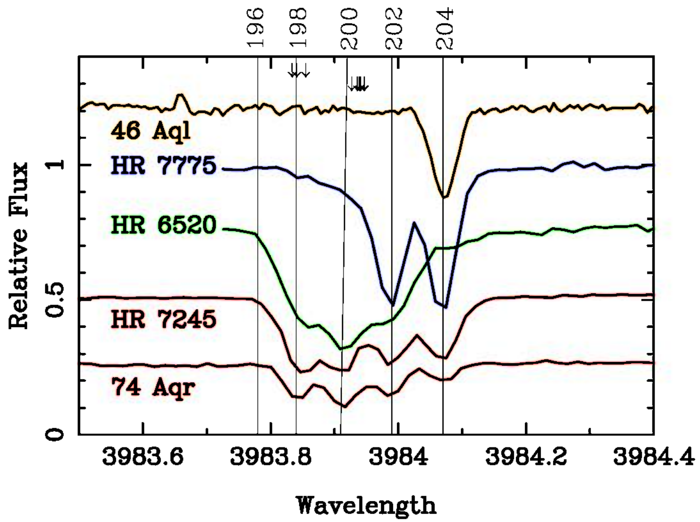




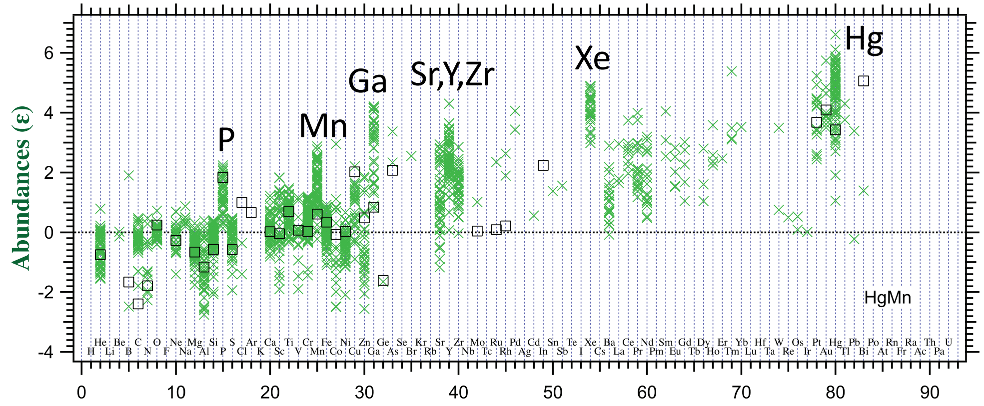
Romanovskaya et al. (2023)

Abundance analyses of HgMn stars

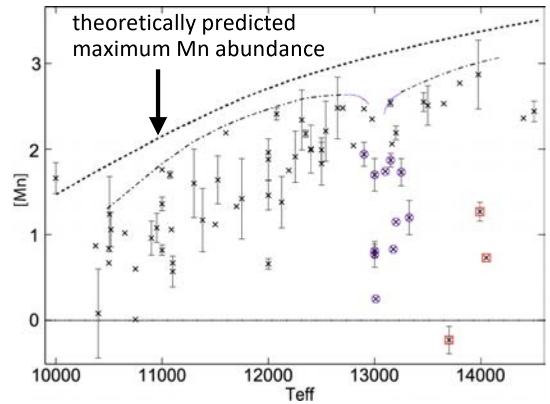
- HgMn stars: +2:+6 dex for P, Mn, Ga, Sr-Zr, Xe, Hg, -1 dex for He
  - T_{eff} abundance trends
  - Isotopic anomalies for He, Ga, Hg, Pt



Hg II line in the spectra of HgMn stars
(Cowley et al. 2008)

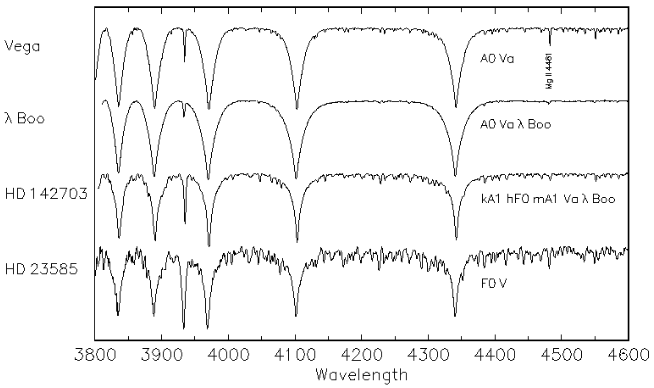


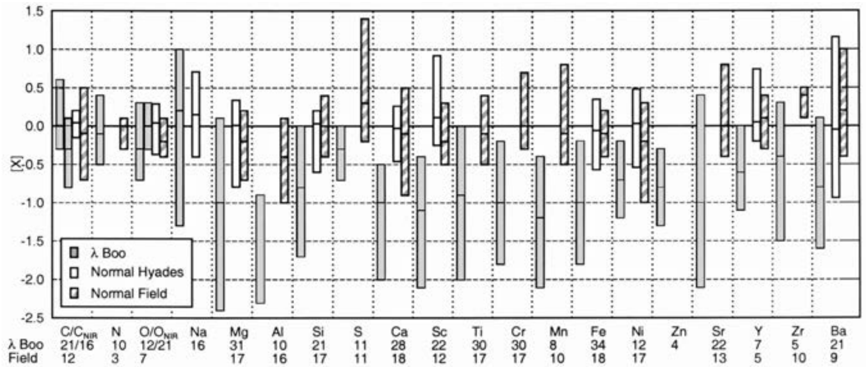
Ghazaryan et al. (2018)



Abundance analyses of λ Boo stars

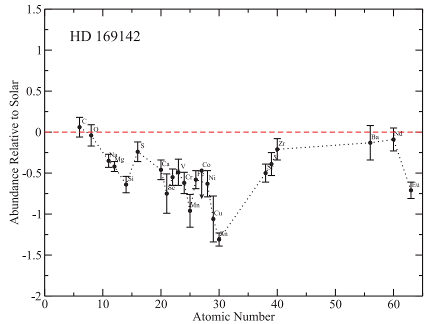
- Normal A stars which have accreted metal-depleted gas. Normal rotation rates. Normal CNO, underabundant heavy elements

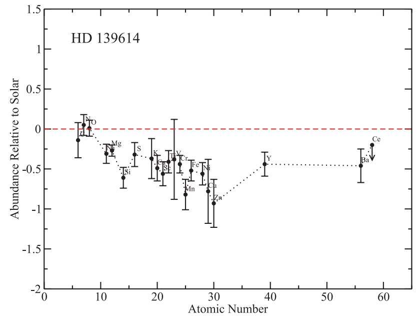




Heiter (2002)

- ~50% of Herbig AeBe stars exhibit λ Boo abundance patterns

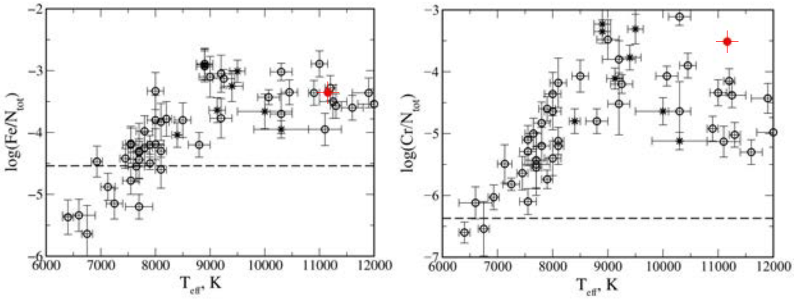




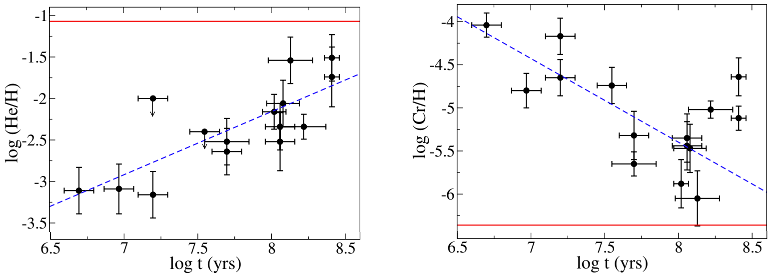
Folsom et al. (2012)

Abundance analyses of magnetic CP stars

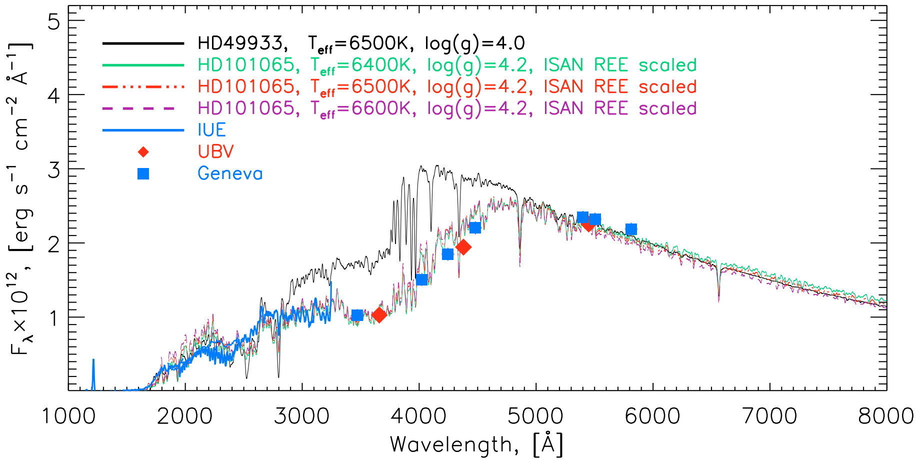
- mCP stars: largest chemical anomalies
  - Abundance trends with T_{eff} and age
  - Incomplete line lists, magnetic field, non-uniform chemistry, …



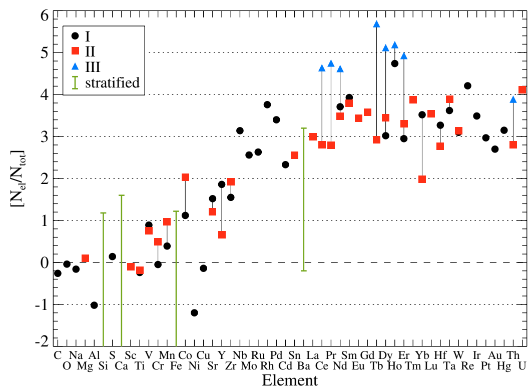
Potravnov et al. (2023)



Bailey et al. (2014)

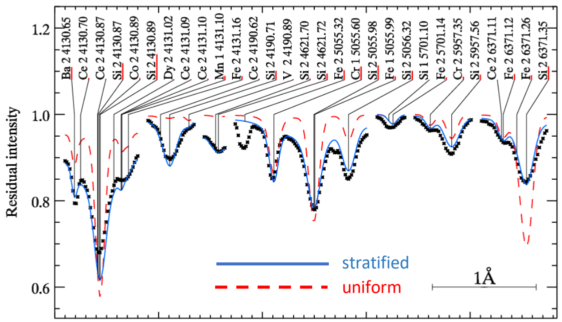


HD 101065= Przybylski's star (Shulyak et al. 2010)

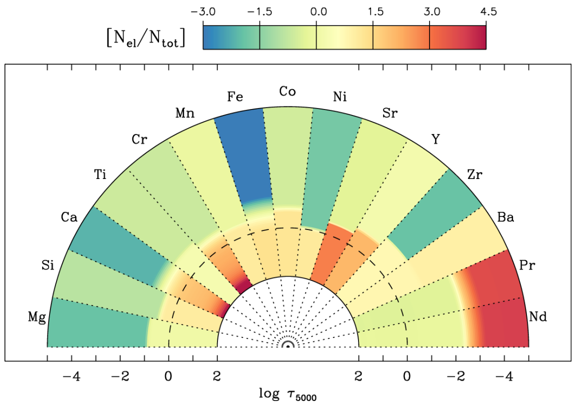


Non-uniform chemical distributions

- Anomalous shapes and intensities of spectral lines => vertical composition gradients in line-forming regions

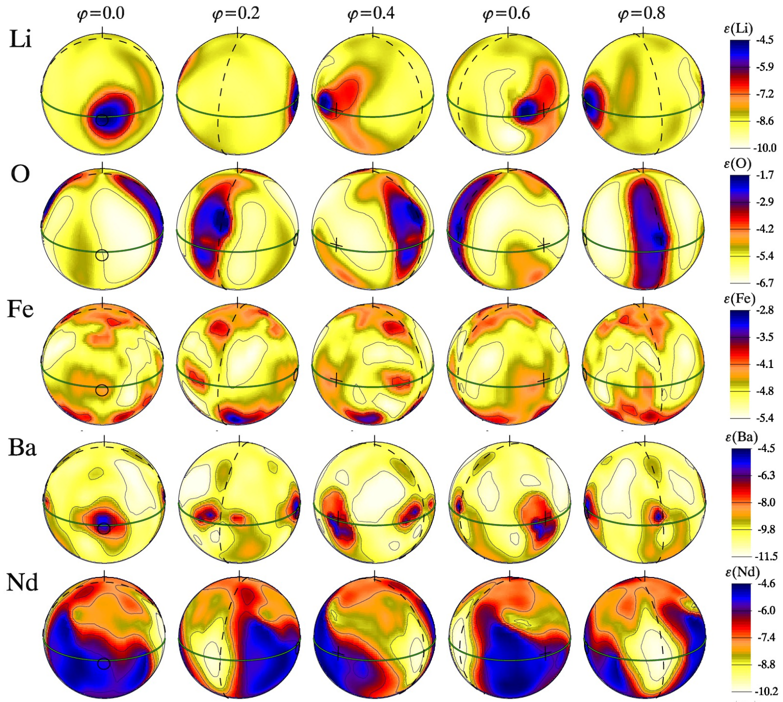


Kochukhov et al. (2006)



Shulyak et al. (2009)

- Rotationally modulated line profiles => horizontal distibution of chemical spots



Kochukhov et al. (2004)

Wider relevance for astrophysics

- CP stars as unique astrophysical laboratories. Studying a range of processes that are universally important but have more subtle manifestation in other stars
- Magnetohydrodynamics
  - Stability and evolution of fossil magnetic fields
  - Interplay between the field and mixing, pulsations, convection, rotation,…
- Testbeds for laboratory astrophysics
  - Often the only available hot narrow line stars
  - Line lists of heavy elements; kilonova proxies
- Stellar evolution
  - Role of magnetic fields
  - Precursors of magnetic WDs, magnetars