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Pulsation of chemically peculiar stars

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Abstract. This paper reviews our current knowledge about pulsating chemically peculiar (CP) stars. CP stars are slowly rotating upper main-sequence objects, efficiently employing diffusion in their atmospheres. They can be divided into magnetic and non-magnetic objects. Magnetic activity significantly influence their pulsational characteristics. Only a handful of magnetic, classical pulsating objects are now known. The only exceptions are about 70 rapidly oscillating Ap stars, which seem to be located within a very tight astrophysical parameter space. Still, many observational and theoretical efforts are needed to understand all important physical aspects and their interrelationships. The most important steps to reach these goals are reviewed.

Keywords. chemically peculiar stars, pulsating stars, rotation, magnetic field

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1. Introduction

The chemically peculiar (CP) stars of the upper main sequence (MS) have been targets of astrophysical studies since their discovery by the American astronomer Antonia Maury (1897). Most of the early research was devoted to detecting peculiar features in their spectra and characterizing their photometric behaviour. The main characteristics of classical CP stars are peculiar and often variable line strengths, the quadrature of line variability with radial velocity changes, photometric variability of the same periodicity and coincidence of extrema. Slow rotation was inferred from the sharpness of the spectral lines. Overabundances of several orders of magnitude compared to the Sun were derived for silicon, chromium, strontium, europium, and other heavy elements (Ghazaryan et al. 2018).

CP stars cover the spectral range from early B- to early F-type, i.e., stars whose stellar atmospheres are not affected by significant convection or mass loss. This led to the theory that diffusion, combined with slow rotation, is accountable for the elemental peculiarities found on their stellar surfaces (Alecian 2023). This implies that CP stars are actually Population I objects characterized by an overall solar abundance (reflecting a similar spread as in the solar neighbourhood). The incidence of CP stars among all MS objects of the same spectral types can reach up to 15%.

Babcock (1947) discovered a global dipolar magnetic field in the star 78 Virginis, which was followed by a catalogue of similar stars in which the variability of the field strength in many CP stars—including even a reversal of magnetic polarity—was found. Stibbs (1950) introduced the ‘oblique rotator’ concept of slowly rotating stars with non-coincidence of the magnetic and rotational axes. This model reproduces the variability and reversals of the magnetic field strength. Due to the chemical abundance concentrations at the magnetic poles, spectral and related photometric variabilities and radial velocity variations of the appearing and receding patches on the stellar surface are easily understood.

Table 1. Main characteristics of the six commonly used CP subgroups, including their designation according to Preston (1974).

Classical name	**Prestonsâ€™s group**	**Discovery criteria**	**Spectral types**	**Temperature domain**	**Magnetic**
λ Bootis		weak Mg II and weak metals	A0-â€“F0	7500–9000	N
Amâ€“-Fm	CP1	weak Ca II and/or Sc II; enhanced metals	A0-â€“F4	7000–10,000	N
Bpâ€“-Ap	CP2	enhanced Sr, Cr, Eu, and/or Si	B6-â€“F4	7000–16,000	Y
HgMn	CP3	enhanced Hg II and/or Mn II	A0–B6	10,500–16,000	N
Heâ€“weak	CP4	weak He I compared with colours	B2-â€“B8	14,000–20,000	Y
Heâ€“strong		enhanced He I compared with colours	B0-â€“B2	20,000–27,000	Y

Preston (1974) was the first to divide CP stars into four subclasses (CP1 to CP4). Later, these subclasses were extended by inclusion of He-strong (Pedersen & Thomsen 1977) and λ Bootis (Paunzen et al. 2002b) stars.

There are many different types of pulsating stars in the region of the Hertzsprung–Russell diagram (HRD) where CP objects are also located. This allows testing and improving of pulsational models by considering diffusion processes in a stellar magnetic field's presence or absence. Furthermore, we also have a precise knowledge of the rotational properties of CP stars, which helps to calibrate frequency splitting patterns, for example. Finally, the differences in astrophysical parameters of 'normal' and CP stars will help to understand the excitation mechanism and possible deviations of frequencies and amplitudes.

This article reviews our current knowledge of pulsating CP stars.

2. Theories explaining the CP phenomenon

Theories explaining the abundance patterns are manifold. Here, we will give a brief overview.

The observed abundance pattern of CP1 stars is defined by the diffusion of elements and the disappearance of the outer convection zone associated with helium ionization because of the gravitational settling of Helium (Théado et al. 2005). These authors predict a cut-off rotational velocity for such objects (about 100 km s^{-1}), above which meridional circulation leads to a mixing in the stellar atmosphere.

In CP2 and CP4 stars, due to additional magnetic diffusion the chemical abundance concentrations at the magnetic poles, as well as the spectral and related photometric variabilities, are also easily understood, as are radial velocity variations of the appearing and receding patches on the stellar surface (Alecian 2015).

CP3 stars are characterized by strong lines of ionized Hg and/or Mn with overabundances by up to six orders of magnitude relative to their solar abundances (Paunzen et al. 2021). Several mechanisms play significant roles in understanding these extreme peculiarities: radiatively driven diffusion, mass loss, mixing, light-induced drift, and possibly weak magnetic fields. However, there is as yet no satisfactory model to explain the abundance pattern (Adelman et al. 2003).

The λ Bootis stars are heavily depleted in refractory (iron-peak) elements, by up to 2 dex, but they exhibit solar abundances of the volatile elements C, N, O, and S (Murphy et al. 2020). To explain the peculiar chemical abundances of these stars, it has been suggested that they may originate from selective accretion of circumstellar material. One of the principal features of that hypothesis is that the observed abundance anomalies are restricted to the stellar surface (Alacoria et al. 2022).

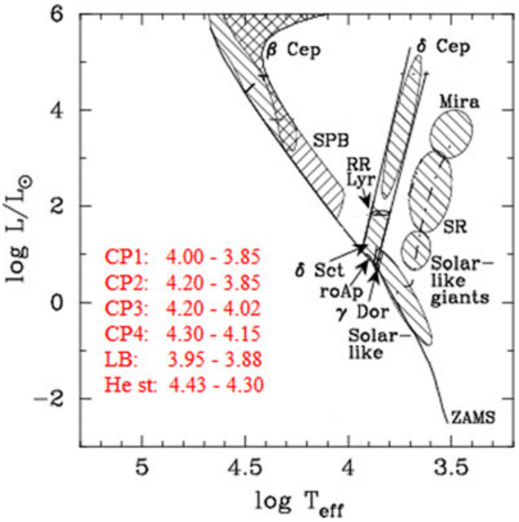

Figure 1. HRD showing the different types of pulsating variables and the temperature range where CP stars are found. CP stars populate the entire region from the zero-age main sequence to the terminal-age main sequence (luminosity classes V and IV). The $\log T_{\rm eff}$ values for the different subgroups (according to Table 1) are listed at bottom left.

Generally, CP1 and λ Bootis stars are not expected to show rotational light variability. As regards CP3 stars, Kochukhov et al. (2021) found rotational variability with amplitudes of 0.1–3 mmag in 84% of 64 objects. Using ultra-precise *Kepler* photometry, Balona et al. (2015) found that most of the Am stars they investigated show light curves indicative of rotational modulation due to star spots. With an amplitude of up to 200 ppm, observing this variability is reserved for high-precision (space) photometry. However, the interpretation of the corresponding light curves as a manifestation of surface spots is still debatable (Henriksen et al. 2023).

3. Classical pulsating variables in the CP star domain

Pulsating stars allow one to probe stellar interiors, which are not accessible to direct observations. A star's physical conditions and processes can only be observed through their influence on the pulsation periods and amplitudes. Pulsation characteristics allow one to derive basic stellar fundamental properties, such as mass, radius, and distance (Gilliland et al. 2010).

There are many different types of pulsating stars in the region of the HRD found where the CP objects are also located. Here is a summary of the subclasses.

- δ Scuti stars are multiperiodic pulsating variables located in the lower section of the Cepheid instability strip. They have periods generally between 0.02 and 0.25 days. They pulsate in low-order p modes (Breger et al. 2009).
- γ Doradus stars are pulsating intermediate-mass, late-A/early-F stars located at the cool border of the classical δ Scuti instability strip. They pulsate in high-order g modes (Guzik et al. 2000).
- hybrid δ Scuti/γ Doradus stars exhibit pulsational characteristics of both groups (Keen et al. 2015).
- β Cephei stars are short-period main-sequence variables with periods between 3 and 8 hours of spectral type O9 to B3. They pulsate in low-order p or g modes (Neilson & Ignace 2015).

- Slowly Pulsating B-type (SPB) stars are main-sequence B-type stars which exhibit multi-periodic, high-order, and low-degree g modes with periods of about one day (**?**)

Figure 1 shows the HRD with the different pulsating variables and the temperature range where the CP stars are found.

4. Pulsating CP stars

Analysing magnetic and non-magnetic pulsating stars helps to answer the following questions.

- Why do only a few magnetic CP stars pulsate?
- What are the main atmospheric differences between pulsating and non-pulsating CP and 'normal' stars?
- Do CP stars pulsate with the same modes, frequencies, and amplitudes as their 'normal' pulsating counterparts?
- Is it possible to select pulsating CP stars based on spectroscopic data?
- Is it possible to define an instability strip for pulsating CP stars? If so, what determines the borders?
- How does the magnetic field influence pulsational characteristics?
- Are the current pulsational models able to explain the observed frequencies and amplitudes?
- Is there a coupling between rotation and pulsation?

In the following, we will describe our current knowledge in more detail.

4.1. *CP1 stars*

Smalley et al. (2011) found about 200 CP1 stars showing low-amplitude γ Doradus and δ Scuti-type pulsations. This was very surprising because, in the narrow region of the HRD where γ Doradus stars are found, the convective zones associated with partial He and H ionization begin to merge and form a single convective envelope. The exact extension of the convective envelope is uncertain and depends on the treatment of convection (Dupret et al. 2004). The evolution of the convective core depends on the mass of the star.

The convective core grows for lower masses, leaving a discontinuity in the chemical composition. In the two cases of a shrinking and growing convective core, the determination of its exact extension is subject to significant uncertainties. Herein lies the promising diagnostic capability of gravity modes. They penetrate deep inside the star and carry information about the physical conditions close to the convective core. These waves are also sensitive to chemical gradients, influencing their periods (Dupret et al. 2007). Possible g modes in solar-type stars have their amplitudes damped by the thick envelope convection zone, and pure g modes are not predicted to be pulsationally unstable in δ Scuti stars, so this deep insight is not possible for such stars. Thus, γ Doradus stars represent a unique test bench for stellar evolution, pulsation, and convection theories.

From a large sample of 'normal' A-type and CP1 stars observed based on ground-based photometry, Smalley et al. (2017) found that δ Scuti pulsations in CP1 stars are mostly confined to a region close to the red edge of the corresponding instability strip, at temperatures cooler than 7600 K. No correlation between amplitude and metallicity was found. For unknown reasons, the incidence of pulsations in CP1 stars decreases noticeably in more peculiar objects. The amplitudes are lower than those of 'normal' A-type pulsators. These authors speculate that CP1 stars have, on average, higher radial order modes excited due to the turbulent pressure being more efficient as the depleted He is offset by an increased hydrogen number density.

4.2. CP2 stars

Classical CP2 and CP4 stars possess strong, large-scale organized magnetic fields of up to several kG. The observed field is always higher than a lower limit of 100 G for the longitudinal field, corresponding to a polar field of about 300 G. Sub-Gauss fields have been detected convincingly in the bright A-type star Vega and a few other A-type stars (Petit et al. 2010).

Therefore, we have to distinguish between magnetic 'normal' pulsating A- and B-type stars and classical CP2 and CP4 stars. To date, five of such magnetic pulsating δ Scuti stars have been reported: HD 432, HD 21190, HD 41641, HD 67523, and HD 188774 (Thomson-Paressant & Neiner 2021). Magnetic field detection is not always unambiguous and is still controversial for some of these objects. None of these stars show any signs of the abundance pattern typical of CP stars. However, they are essential objects to test pulsational models in the presence of an ultra-weak magnetic field.

Cunha et al. (2019) presented an analysis of photometric light curves of the Transiting Exoplanet Survey Satellite (TESS) mission, searching for pulsation characteristics among 83 CP2 stars. They found five suspected δ Scuti/γ Doradus variables, but could not confirm their true nature. Furthermore, Skarka et al. (2019) presented a pulsating CP component in an eclipsing binary system for which a detailed analysis is still pending.

In summary, these cases show how rare the combination of a stable magnetic field and stellar pulsation is.

4.3. CP3 stars

It is commonly accepted that many CP3 stars (up to 90%) are members of binary systems (Paunzen et al. 2021). Consequently, the tidal interaction induced by the presence of a companion star is thought to significantly impact the observed chemical peculiarities.

In general, CP3 stars fall into the region of β Cephei p-mode pulsators and the SPB g-mode variables. There are also some hybrid plusators known which are poorly understood. Kochukhov et al. (2021) investigated 64 CP3 stars using 2 minute-cadence light curves of the TESS mission. They found seven objects showing multiperidodic behaviour in the frequency domain expected for pulsation. However, the frequencies are incompatible with standard pulsational models for the corresponding astrophysical parameters. One explanation would be to take into account the possible variability of the secondary component.

The CP3 star HD 29589 was analysed by Niemczura et al. (2022), who found 20 high-order g modes and regular period spacing, which they interpreted as being due to the presence of consecutive prograde dipole modes.

Therefore, CP3 stars are excellent tracers to test the pulsational theories of β Cephei pulsators and SPB objects in the light of the CP phenomenon.

4.4. CP4 and He-strong stars

This subgroup mainly covers the β Cephei instability region in the HRD. What was stated for the CP2 stars is also true here. One has distinguish between magnetic 'normal' pulsators and classical CP stars.

HD 886 (γ Peg) is a β Cephei pulsator with a magnetic field of 10 G which varies with the primary pulsation frequency (Butkovskaya & Plachinda 2007). Owing to the magnetic field being frozen in the plasma, the initial hypothesis is that radial pulsations of the star result in the homothetic variation of the magnetic dipole.

The very slowly rotating (period longer than 30 years) and radially pulsating β Cephei-type star HD 46328 (ξ^1 CMa) exhibits a magnetic field of about 200 G (Erba et al. 2021).

It shows emission in Hα, which is modulated by the pulsation frequency. Together with significant variability in UV flux, this could lead to a more detailed explanation of the excitation mechanism for this stellar variability group.

No other similar pulsators have been detected to date.

4.5. λ *Bootis stars*

Paunzen et al. (2002a) found that at least 70% of all λ Bootis-type stars inside the classical instability strip pulsate, and they do so with high overtone modes (Q values smaller than 0.020 d). Only a few stars, if any, pulsate in the fundamental mode. Compared to δ Scuti stars, the cool and hot borders of the instability strip of the λ Bootis stars are shifted to the blue. Paunzen et al. (2002a) found that the period–luminosity–colour relation is, within the errors, identical to that of normal δ Scuti stars. No clear evidence for a statistically significant metallicity term was detected.

More recently, Murphy et al. (2020) analysed TESS light curves of 70 southern λ Bootis stars. They confirmed the results of Paunzen et al. (2002a) and concluded that these objects are only superficially metal-weak.

4.6. *Rapidly oscillating Ap (roAp) stars*

About 70 magnetic CP stars exhibit photometric variability in the period range from 5 to 25 minutes (high-overtone, low-degree, and non-radial pulsation modes). These stars are known as rapidly oscillating Ap (roAp) stars (Holdsworth et al. 2021). Several ground-based surveys were dedicated to searching for these objects (Paunzen et al. 2015; Joshi et al. 2016).

Observations imply a relationship exists between the excitation mechanism of pulsations in roAp stars and their heavy element distribution. Several opacity bumps are predicted to occur in the stellar atmosphere, which drive the pulsation (Théado et al. 2009). However, this cannot reproduce observations of the highest frequency modes in some stars. In these cases, Cunha et al. (2013) proposed that a mechanism linked to turbulent pressure may play a role in the excitation of these highest-frequency modes.

Murphy et al. (2020) presented a δ Scuti/roAp hybrid pulsator (KIC 11296437) with a mean magnetic field modulus of 2.8 kG. This could be a key object for understanding the different excitation modes in such stars.

Only a stringent astrophysical parameter and atmosphere regime seems to excite pulsation, which explains the rarity of these stars.

5. Conclusions and outlook

Pulsating variables which also show chemical peculiarities (mainly caused by diffusion processes), can help to understand the various driving mechanisms. Our current knowledge reveals that we know only a handful of pulsating magnetic CP stars. This suggests that a stable magnetic field prevents the excitation of pulsations. Nevertheless, modern, accurate space-based, long-term ground-based photometric data must be thoroughly analysed to find more such objects.

The situation as regards non-magnetic pulsating CP stars is much more promising. A significant number of CP1, CP3, and λ Bootis stars are known to be δ Scuti and γ Doradus pulsators. To date, no clear correlations between the degree of peculiarity and the pulsation characteristics have been found.

Still, several issues are urgently needed to study these phenomena in more detail.

- A systematic search for magnetic fields in pulsating variables;
- A more precise determination of the astrophysical parameters;

- A study of upper limits of amplitudes of non-variable CP stars;
- A study of star cluster members; and
- A study of non-variable stars.

Such comprehensive studies would help to shed more light on this very important research topic.

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