

Review of Observational and Theoretical Studies of roAp Stars: Postprint

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Abstract

roAp stars (rapidly oscillating A-type chemically peculiar stars) are a class of pulsating variable stars in the main-sequence stage that exhibit non-radial high-order p-mode pulsations. With the increasing detection capabilities of optical telescopes, especially space-based optical telescopes, more and more roAp stars and their various pulsation modes have been observed, leading to rapid development in the observational and theoretical studies of roAp stars. This paper reviews the chemical abundance peculiarities of roAp stars, pulsation excitation theory, and the current status of observational research, summarizes the observational characteristics of roAp stars and the progress in asteroseismology, and discusses unresolved issues such as the pulsation excitation mechanism.

Full Text

Preamble

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A Review of Observational and Theoretical Studies of roAp Stars

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Abstract

Rapidly oscillating Ap (roAp) stars are a class of pulsating variable stars on the main sequence that exhibit non-radial, high-order p-mode oscillations. With the increasing detection capabilities of optical telescopes, particularly space-based missions, an ever-growing number of roAp stars and their diverse pulsation modes have been discovered, leading to rapid advances in both observational and theoretical research. This review summarizes the chemical abundance peculiarities, pulsation excitation theories, and current observational status of roAp stars. We compile the observed characteristics of roAp stars and progress in their asteroseismology, and discuss unresolved issues such as pulsation excitation mechanisms.

Keywords: roAp stars; stellar pulsation; asteroseismology

1 Introduction

Stellar elemental abundances are generally thought to be determined primarily by the chemical composition of their birth molecular clouds, evolving throughout stellar evolution. During star formation and evolution, the abundances of various elements maintain roughly solar proportions relative to corresponding solar abundances. However, in certain stars, physical processes enhance or deplete specific elements, creating chemical abundance anomalies. Among early B to early F-type stars, approximately 10% are slow rotators in which some elements (primarily rare earth elements) are transported to the stellar surface by strong radiative pressure in their convection zones, resulting in enhanced abundances of these elements. These stars are known as chemically peculiar (CP) stars.

CP stars consist of four main subgroups: (1) Am stars, which show deficiencies in Ca and Sc but enhancements in Fe-group and heavy elements; (2) Ap stars, characterized by enhanced Si, Cr, Sr, Eu, or rare earth elements, also known as magnetic Ap stars due to their ubiquitous strong magnetic fields; (3) HgMn stars, with high abundances of Hg, Mn, and other heavy metals; and (4) He-weak stars with weak He lines. Am and Ap stars share similar spectral features, with the primary distinction being the presence of strong magnetic fields in Ap stars. However, at low spectral resolution, magnetic effects cannot be observed spectroscopically, making this difference difficult to identify and potentially introducing errors in statistical studies.

Strong magnetic fields represent the most important property of Ap stars and are nearly universal. Typical effective magnetic field strengths range from $(1-2) \times 10^{-4}$ T, with maximum values reaching 2×10^{-3} T. Compared to other CP stars lacking magnetic signatures, Ap stars experience magnetic braking that slows their rotation, with some Ap stars having rotation periods lasting several centuries. Strong magnetic fields can also suppress convection, providing a stable environment for many ions with absorption features. In this environment, radiative pressure can cause ions to rise against gravity to the sur-

face, while other elements, particularly He, sink to deeper layers. Consequently, element stratification under magnetic influence leads to non-uniform surface distributions of chemical elements such as La, Pr, Si, Cr, Sr, Eu, and Nd, with abundances up to one million times solar in some cases.

Element stratification is most pronounced near the magnetic poles, where enhanced elements form spots in the stellar atmosphere. These spots cause differential absorption and re-radiation at varying wavelengths and flux levels, creating brightness differences relative to surrounding regions. As the star rotates, brightness varies periodically. This variation is stable and can be explained by the oblique rotator model: the star possesses a dipolar magnetic field whose axis is inclined to the rotation axis. As the star rotates, these spots periodically produce spectroscopic and photometric variations (see Figure 1 [Figure 1: see original paper]). Photometric variations can also reveal information about surface “spots.” For example, the light curve of TYC 2488-1241-1 shows a single sinusoidal-like function, suggesting possibly only one “spot,” while KIC 10685175 exhibits multiple sinusoidal components, indicating multiple surface “spots.”

Observations of Ap stars overlapping with the classical pulsation instability strip on the Hertzsprung-Russell (HR) diagram revealed that some Ap stars show pulsations, designated as rapidly oscillating Ap (roAp) stars. Although designated “A,” roAp stars actually span spectral types from late B to early F ($15,000 \text{ K} > T_{\text{eff}} > 7,500 \text{ K}$), with masses around $2 M_{\odot}$, surface magnetic fields of several hundred to several thousand Gauss, rotation periods ranging from days to decades, and short pulsation periods of approximately 4-15 minutes in non-radial, high-order p-modes. They occupy the overlapping region between the lower part of the classical pulsation instability strip and the area just above the main sequence. In this region, two other classes of multi-mode pulsators are found: γ Dor variables pulsating in g-modes with periods of about 0.25-3 days, and δ Scuti variables pulsating in p-modes with periods of several hours. Compared to δ Scuti stars, which also exhibit p-mode pulsations, roAp stars have much shorter periods (4-15 minutes) and very low amplitudes ($\Delta B < 0.034 \text{ mag}$). Combined with the oblique rotator model, this framework successfully explains the observed rotational splitting of pulsation frequencies and the modulation of pulsation amplitudes and phases caused by rotation. Some roAp stars exhibit more than one pulsation mode, and some even show simultaneous δ Scuti and γ Dor pulsations. More detailed observational properties will be presented in Section 4.

Studying these pulsations through asteroseismology can reveal properties such as rotational inclination, magnetic obliquity, magnetic field strength, radius, mass, and age, enabling more precise determination of stellar ages and evolutionary stages. By combining effective temperature, luminosity, and metallicity information to construct asteroseismic models and calculate intrinsic pulsation modes, comparison with observed multi-mode pulsation data yields information about internal structure and evolution, helping us understand the physical processes within stars and the mechanisms generating pulsations.

This paper is organized as follows: Sections 2 and 3 describe observational techniques and properties of roAp stars; Section 4 discusses pulsation excitation theories; Section 5 addresses current research problems; and finally, we present a summary and outlook.

2 Observational Techniques for roAp Stars

Since Kurtz discovered the first roAp star, a total of 77 roAp stars have been discovered through ground-based and space observations as of December 2020 (see Table 2). The combination of rapid pulsations and small amplitudes makes roAp stars challenging to observe. For a long time, time-series photometry from ground-based telescopes has been used to study roAp star pulsations, geometric structures, and asteroseismology. For example, during the early phase, Kurtz and colleagues discovered most roAp stars through this approach. With the advent of space telescopes like Kepler and TESS, pulsations with amplitudes far below ground-based detection limits can now be detected.

The Kepler telescope operated in two modes: long-cadence (LC) with 29.43-minute integration times, and short-cadence (SC) with 58.85-second integration times. During its four-year primary mission, Kepler observed most stars in LC mode, with relatively few targets in SC mode. Using Kepler SC data, five roAp stars have been discovered. Murphy et al. noted that although LC mode suffers from super-Nyquist frequency issues, heliocentric timing corrections can resolve this problem. Hey et al. used this method to identify six roAp candidates. However, Shi et al., studying the roAp star KIC 10685175 observed by both Kepler LC and TESS, found that while Hey et al. had confirmed it as a roAp star using Kepler LC data, they did not identify the true pulsation frequency, instead mistaking the beat frequency between the pulsation and Nyquist frequency for the actual pulsation frequency, demonstrating that super-Nyquist issues persist in LC mode.

TESS' s observational strategy divides each celestial hemisphere into 13 sectors, observing each for 27 days. In addition to 30-minute integration mode, 20,000 stars per sector are observed in 2-minute mode. Although reduced integration time decreases signal-to-noise ratio compared to Kepler LC mode, it is clearly more suitable for studying roAp pulsations with periods of several minutes. TESS has opened a new window for roAp star discovery, having already found many multi-mode roAp stars. By re-observing most known roAp stars, TESS will also reveal additional pulsation modes. Similarly, the multiple rotational splittings discovered in known or newly found roAp stars will provide further constraints on rotational inclinations and magnetic obliquities.

The main differences between ground-based and space photometric observations of roAp stars are: (1) Detectable pulsation amplitudes from the ground typically range from 5×10^{-4} mag to 10×10^{-3} mag, whereas Kepler can detect variations of a few micro-magnitudes. (2) Since pulsation amplitudes are largest in the B band for roAp stars, ground observations are usually conducted in B

band, while Kepler and TESS observe in much broader bands (Kepler: ~400-900 nm; TESS: ~600-1,100 nm), where pulsation amplitudes may be [22] times smaller than in B band.

In addition to time-series photometry, roAp stars can also be studied through time-series spectroscopy. In fact, spectroscopy is more sensitive than photometry for detecting roAp pulsations, as radial velocity amplitudes of certain spectral lines (mostly from rare earth elements) can reach several km/s. However, spectroscopic observations struggle to simultaneously maintain high temporal resolution, high signal-to-noise ratio, and efficiency. Therefore, time-series photometric observations remain necessary and effective alongside spectroscopy.

3 Observational Characteristics of roAp Stars

Studies of roAp star observational characteristics reveal that most share common properties, though individual stars exhibit special behaviors. Summarizing these common properties helps us understand how roAp stars differ from other variables, while differences among roAp stars provide opportunities to investigate special physical processes.

3.1 General Observational Properties

In the frequency spectra of most roAp stars (e.g., KIC 10685175, see Figure 2 [Figure 2: see original paper]), multiple pulsation frequencies appear rather than a single one. These frequencies are equally spaced within measurement uncertainties, with spacing equal to the rotation frequency. Depending on the pulsation mode, frequencies may split into triplets, quintuplets, or higher-order multiplets. Figure 2 shows an example of pulsation frequencies split into a quintuplet by the rotation frequency.

Kurtz proposed the oblique pulsator model based on the oblique rotator model: in this framework, the magnetic axis has an inclination relative to the rotation axis, while the pulsation axis is nearly coincident with the magnetic axis (the angle can be neglected). The model incorporates both magnetic field and rotation effects, assuming magnetic effects on frequency splitting dominate over rotational effects. This model also explains why the amplitudes of left and right split frequencies are unequal, providing a relationship between amplitude ratio A and magnetic obliquity β and inclination i :

$$\frac{A_{+1}^{(1)} + A_{-1}^{(1)}}{A_0^{(1)}} = \tan i \tan \beta \quad (\text{triplet})$$

$$\frac{A_{+2}^{(2)} + A_{-2}^{(2)}}{A_0^{(2)}} = \tan i \tan \beta \quad (\text{quintuplet})$$

where superscripts and subscripts represent the spherical harmonic degree ℓ and azimuthal order m in asteroseismology, as illustrated in the frequency spectrum example in Figure 2.

The oblique rotator model also enables measurement of internal magnetic fields. For the simplest case of a dipolar magnetic field ($\ell = 1$), under perturbation approximation, the magnetically perturbed pulsation frequency is:

$$\omega = \omega^{(0)} + \omega_{\text{mag}}^{(1)}$$

where $\omega^{(0)}$ is the unperturbed frequency, and $\omega_{\text{mag}}^{(1)}$ relates to corresponding amplitudes A as:

$$\frac{\omega_{\text{mag},+1}^{(1)} - \omega_{\text{mag},-1}^{(1)}}{A_{+1}^{(1)} - A_{-1}^{(1)}} = \frac{\omega_{\text{mag},0}^{(1)}}{A_0^{(1)}} = \Omega$$

where $|m|$ represents the perturbation of pulsation frequencies for $\ell = 1$, and Ω is the rotation frequency. For a dipolar magnetic field, the frequency perturbation $\omega_{\text{mag}}^{(1)}$ is:

$$\omega_{\text{mag},|m|}^{(1)} = \frac{3m^2}{4\ell(\ell+1)} K_{\text{mag}}$$

where the ratio of coefficient K_{mag} to $\omega^{(0)}$ equals the ratio of magnetic pressure P_{mag} to gas pressure P_{gas} :

$$\frac{K_{\text{mag}}}{\omega^{(0)}} = \frac{P_{\text{mag}}}{P_{\text{gas}}}$$

If more than one frequency set is observed in a roAp star, asteroseismic analysis can identify pulsation modes and determine stellar parameters. For example, rotation splitting frequency spacing can estimate rotation velocity, relative amplitude variations of rotation-split modes can estimate rotational inclination, and large frequency separation (frequency differences between modes with same ℓ , adjacent radial order n , and $m = 0$) can determine mean stellar density.

Taking HR 3831 as an example, dividing observational data into segments of 50 pulsation cycles and calculating amplitude and phase for each segment reveals temporal variations in pulsation amplitude and phase. When these variations are folded with rotational phase, the pattern becomes more regular with a period exactly equal to the rotation period. This phenomenon, called rotational modulation of pulsation (see Figure 3 [Figure 3: see original paper]), was first discovered by Kurtz et al. It can also be explained by the oblique rotator model. Figure 4 [Figure 4: see original paper] illustrates pulsations at different rotational phases. At phase 0, the magnetic north pole lies along the line of sight.

Since the pulsation axis nearly coincides with the magnetic axis and pulsation amplitude is largest near the pulsation poles, the observed amplitude is maximum. At phase 0.25, the magnetic axis flips, the pulsation reverses phase, amplitude becomes symmetric about the equator, resulting in zero amplitude and a π phase jump. At phase 0.5, although the magnetic south pole faces the observer, the large angle to the line of sight means observed pulsations mainly come from the equatorial region, producing a secondary amplitude maximum smaller than at phase 0.

3.2 roAp Stars with Special Characteristics

Some roAp stars deviate significantly from average values in parameters such as effective temperature, rotation period, and pulsation period. Since these parameters relate to physical properties, they warrant detailed investigation. The distribution of roAp stars across the classical pulsation instability strip draws attention to their effective temperatures. The hottest known roAp star is HD 43226 with $T_{\text{eff}} = 8,293$ K, located between the red and blue edges of the classical instability strip. The coolest is HD 258048 at 6,600 K, beyond the red edge, similar to HD 216641 (6,640 K) and HD 154708 (6,800 K). Rotation period correlates with magnetic field strength; roAp stars with rotation periods exceeding 1,000 days include HD 166473 (10.5 years) and HD 201601 (4,190 days, >11 years). Pulsation period relates to evolutionary stage; the longest periods belong to HD 116114 (21 minutes) and HD 177765 (23.6 minutes). The largest pulsation amplitude is found in 2MASS J19400781-4420093 (0.034 mag).

HD 42659 is the only known roAp star in a binary system, requiring further study of how binarity affects pulsation, evolution, and magnetic fields. KIC 8677585 is the only variable star exhibiting simultaneous δ Scuti, γ Dor, and roAp pulsations (see Figure 5 [Figure 5: see original paper]). The mechanism capable of exciting two different pulsation types and whether such stars are common deserve exploration. KIC 10195926 is an evolved roAp star beyond the main sequence, whereas most roAp stars are main-sequence objects. Long-term observations of HR 3831 have also revealed short-lived pulsation modes; HD 12932 shows similar mode variability, with previously observed frequencies disappearing and new modes appearing in later observations. However, these remain isolated cases preventing more systematic investigation.

Some roAp stars exhibit only a single pulsation frequency, such as HD 161459 and HD 196470, while others show multiple modes. HD 63087 (see Figure 6 [Figure 6: see original paper]) displays six modes including three single frequencies, two triplets, and one quintuplet. Some suggest that apparently single-mode roAp stars may harbor undetected pulsation modes. With improved detection capabilities, more multi-mode roAp stars will be discovered. For example, HD 134214 [Figure 134214: see original paper] showed only one pulsation frequency in analyses by Kreidl & Kurtz and Kurtz et al., but Gruberbauer et al. found at least two modes with different m -values. In the HR diagram region where Ap stars overlap the classical instability strip, some Ap stars show no detected pulsa-

tions. Similarly, some low-amplitude pulsations may remain undetected due to observational limitations. Time-series spectroscopy can detect roAp stars with even lower pulsation amplitudes, having discovered 16 roAp stars not found photometrically, including HD 115226 and HD 116114.

Magnetic fields in some roAp stars distort pulsation modes. Normally, pulsation amplitude distribution across the stellar surface is symmetric about the equatorial axis, but magnetic effects create deviations. This produces special observational signatures, such as non-zero pulsation amplitude near rotational phase 0.25 and phase jumps different from π . Many roAp stars show such distortion, including KIC 10685175 (see Figure 7 [Figure 7: see original paper]) and HD 99563. Saio incorporated magnetic field effects into theoretical models to fit optimal rotational inclinations and magnetic obliquities. Assuming a roAp star is unaffected by magnetic distortion, rotational inclination and magnetic obliquity can also be calculated from amplitude ratios of rotationally split modes. Large discrepancies between these two methods indicate genuine magnetic influence on pulsation modes. For KIC 10685175 (see Figure 8 [Figure 8: see original paper]), the calculated inclinations and obliquities differ between magnetic and non-magnetic cases, with the non-magnetic model providing poorer fits to observations.

4 Pulsation Excitation Mechanisms in roAp Stars

The pulsation excitation mechanism in roAp stars remains a subject of intense debate and an unresolved problem. Since roAp stars overlap with δ Scuti stars on the HR diagram, the δ -mechanism operating in the He II ionization zone was initially considered. However, because most He in roAp stars lacks sufficient radiative support and sinks deeper under gravity, whether the residual He II zone can excite the δ -mechanism is questionable. Cox et al. verified that metallic peculiarity and pulsation can coexist in linear radial pulsation models of δ Scuti stars with low He abundance and no convection. This can occur within 200-500 K of the red edge of the classical instability strip, with the range depending on He abundance. Dolez et al. incorporated stellar wind effects into their models. Dolez & Gough calculated that element stratification is most pronounced near magnetic poles, where He should be depleted first, yet observations show maximum pulsation amplitudes near magnetic poles. Therefore, Dolez et al. added wind effects to atomic diffusion models, allowing He to accumulate near magnetic poles and excite pulsations. Besides the He II zone, Matthews suggested that the Si IV ionization zone could excite the δ -mechanism where Si abundance is sufficient at the poles, proposing that Si abundance might distinguish roAp stars from non-pulsating Ap stars.

The more widely accepted model involves pulsation excitation in the H I zone, as it better fits observed high-order modes. Gautschy et al. proposed that roAp stars may have chromospheres with a peculiar temperature-optical depth relationship causing temperature increases at low optical depths near the surface, allowing stable high-order p-modes. Balmforth et al. suggested that strong

magnetic fields suppress convection only in polar regions while it persists near the equator, establishing a “spot” model retaining convection only in magnetic equatorial regions. Results show that the α -mechanism can be excited in the H I zone at the poles, while convection and turbulence prevent excitation near the equator—similar to solar oscillations. In Saio’s non-adiabatic pulsation model, convection in the envelope is completely suppressed, with direct magnetic effects on oscillations considered. He found that all high-order modes distorted by magnetic fields can be stabilized, making distorted dipole and quadrupole modes more easily excited in roAp stars. Theado et al. considered models with and without envelope convection suppression, along with different metallicities and abundance profiles. Different models yield similar theoretical red and blue edges of the pulsation instability strip, but these are hotter than those from standard models, actually failing to match current observations.

Besides the α -mechanism, alternative explanations exist. In 1983, Shibahashi proposed magnetic overstability convection, where overstability is caused by restoring forces of magnetic field lines (frozen into plasma like rubber bands) that inhibit convective motions in superadiabatic atmospheric regions. Heat exchange between mass elements and their surroundings causes oscillations to grow. These oscillations have much shorter periods than radial fundamental modes and are very high overtones symmetric about the magnetic axis.

Testing and constraining theoretical models requires discovering more roAp stars to accurately delineate their distribution and boundaries on the HR diagram, enabling more comprehensive understanding of roAp star pulsation properties.

5 Unresolved Problems

Many questions about roAp stars remain unanswered. Cunha et al. calculated an upper limit for roAp star pulsation frequencies—the cutoff frequency—above which seismic waves would penetrate the stellar surface and dissipate, preventing stable existence (see Figure 9 [Figure 9: see original paper]). However, some roAp stars exhibit pulsation modes above this cutoff frequency, such as HD 24355 and HD 42659, whose frequencies far exceed the theoretical limit. The conditions allowing stable pulsations above cutoff frequency thus remain an open question.

Additionally, the location of roAp stars on the HR diagram appears shifted toward the red edge of the theoretical instability strip calculated by Cunha, with no roAp stars at the blue edge and some beyond the theoretical strip (see Figure 10 [Figure 10: see original paper]). This suggests that in regions outside the red edge, certain pulsation modes may be excited under specific physical conditions.

Questions also arise regarding pulsation mode selection in roAp stars. The distribution of radial order n is broad, ranging from 15 to 75. A single excitation mechanism would struggle to produce such a wide range of radial orders. Previously, magnetic fields were thought to suppress low-order modes, but low-order

pulsations have been increasingly detected. Murphy et al.'s theoretical models suggest low-order modes can be excited under He-depleted conditions depending on magnetic field strength. When polar magnetic field B_p exceeds 0.15 T, any mode can be excited; when $B_p > 0.4$ T, no modes are excited; and when B_p is between 0.15–0.4 T, only radial and low-order g-modes can be excited. Cunha et al., using models with convection suppressed only at the poles, proposed two excitation mechanisms: low-order modes excited by the α -mechanism and high-order modes excited by convection. Theoretical instability strips are calculated assuming complete convection suppression by magnetic fields. Introducing turbulent pressure excitation mechanisms would also expand the instability strip.

Solving these problems requires expanding the roAp star sample through unbiased surveys of Ap stars. However, current ground-based discoveries are limited to cool Ap stars. Future work should focus on searching for roAp stars among hot Ap stars. Accurate stellar parameters—radius, effective temperature, luminosity—are essential for precise HR diagram positions. TESS, as an ongoing space mission, provides data quantity and quality well-suited for roAp star discovery and asteroseismic studies.

6 Summary and Outlook

roAp stars are pulsating variables on the main sequence with spectral types from late B to early F, exhibiting rapid 4–15 minute pulsations, strong magnetic fields, and enhanced abundances of certain metals. Since their rotation and magnetic axes are generally non-aligned, brightness variations occur when the magnetic axis forms an angle with the line of sight. These variations originate from element-enhanced spots near magnetic poles and are stable enough to accurately determine rotation periods. Rotation also affects pulsations through frequency splitting and amplitude/phase modulation.

Both time-series photometry and spectroscopy are used to study roAp pulsations. Spectroscopy can detect weaker pulsations, but photometry provides more asteroseismic information. For a long time, roAp photometry was limited to ground-based observations. The launches of Kepler and TESS have significantly advanced roAp star detection, greatly expanding the sample. As of December 2020, 77 roAp stars have been discovered, with TESS expected to find more.

The pulsation excitation mechanism is widely believed to be the α -mechanism in the H I ionization zone. However, special characteristics of some roAp stars prompt further theoretical consideration: Why are roAp stars concentrated at the red edge of the instability strip? Why do some lie beyond the theoretical red edge? Why do some roAp stars have multiple frequencies while others have only one? How can some roAp stars support pulsations above the cut-off frequency? How are low-order modes and δ Scuti-type pulsations excited in individual roAp stars? These questions motivate deeper investigation into

excitation mechanisms, suggesting two possible mechanisms: low-order modes excited by the α -mechanism and high-order modes excited by convection.

Further research requires more unbiased samples with accurate stellar parameters. As detection precision improves, more roAp stars will be discovered to accurately determine their distribution on the HR diagram, and known roAp stars can be re-observed and studied in greater depth. Detecting more pulsation modes will enable asteroseismic studies, providing richer information for theoretical investigations.

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