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# HD 213258: A new rapidly oscillating, super slowly rotating, strongly magnetic Ap star in a spectroscopic binary

G. Mathys[1], V. Khalack[2], O. Kobzar[2], F. LeBlanc[2], and P. L. North[3]

[1] European Southern Observatory, Alonso de Cordova 3107, Vitacura, Santiago, Chile
e-mail: gmathys@eso.org
[2] Département de Physique et d'Astronomie, Université de Moncton, Moncton E1A 3E9, NB, Canada
[3] Institut de Physique, Laboratoire d'Astrophysique, Ecole Polytechnique Fédérale de Lausanne (EPFL), Observatoire de Sauverny, 1290 Versoix, Switzerland

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**ABSTRACT**

We report on HD 213258, an Ap star that we recently identified as presenting a unique combination of rare, remarkable properties. Our study of this star is based on ESPaDOnS Stokes *I* and *V* data obtained at seven epochs spanning a time interval slightly shorter than 2 yr, on TESS data, and on radial velocity measurements from the CORAVEL data base. We confirm that HD 213258, which was originally suspected to be an F str $\lambda$ 4077 star, is definitely an Ap star. We found that, in its spectrum, the Fe II $\lambda$ 6149.2 Å line is resolved into its two magnetically split components. The mean magnetic field modulus of HD 213258, $\langle B \rangle \sim 3.8$ kG, which we determined from this splitting, does not show significant variations over ~2 yr. Comparing our mean longitudinal field determinations with a couple of measurements from the literature, we show that the stellar rotation period is likely of the order of 50 yr, with a reversal of the field polarity. Moreover, HD 213258 is a rapidly oscillating Ap (roAp) star, in which high overtone pulsations with a period of 7.58 min are detected. Finally, we confirm that HD 213258 has a mean radial velocity exceeding (in absolute value) that of at least 99% of Ap stars. The radial velocity shows low amplitude variations, which suggests that the star is a single-line spectroscopic binary. It is also a known astrometric binary. While its orbital elements remain to be determined, its orbital period is likely one of the shortest known for a binary roAp star. Its secondary is close to the borderline between stellar and substellar objects. There is a significant probability that it is a brown dwarf. The pair represents a combination that has never been observed before. Most of the above-mentioned properties taken in isolation are only observed in a small fraction of the whole population of Ap stars. Thus, the probability that a single star possesses all of them is extremely low. This makes HD 213258 an exceptionally interesting object that deserves to be studied in detail in the future.

**Key words.** stars: individual: HD 213258 – stars: chemically peculiar – stars: magnetic field – stars: rotation – stars: oscillations

## 1. Introduction

The peculiarity of HD 213258 (also known as BD+35 4815) was first reported by Bidelman (1985). He assigned it to a new group of upper main-sequence chemically peculiar (CP) stars that he had recently identified (Bidelman 1981): the F str $\lambda$ 4077 stars. Originally, this classification referred to stars whose spectra resemble those of Am stars but show an abnormally strong Sr II $\lambda$ 4077 Å line. However, as noted by North (1987), a specific definition of the criteria that allow one to distinguish F str $\lambda$ 4077 stars from Am, Ap Sr, or $\lambda$ Boo stars was missing at the time[1]. This left some ambiguity in the classification. As a matter of fact, in their Table 3, North & Duquennoy (1991) flagged HD 213258 as a possible Ap star. Nevertheless, it was not included in the Catalogue of Ap, HgMn, and Am stars (Renson & Manfroid 2009).

In this short note, we report that HD 213258 has a quasi-unique combination of rare, remarkable properties with respect to its magnetic field (Sect. 2), its rotation (Sect. 3), its space velocity and its binarity (Sect. 4), and its pulsation (Sect. 5). As a conclusion, in Sect. 6 we show why this combination of properties makes HD 213258 an object of exceptional interest that deserves to be studied in detail in the future.

## 2. Magnetic field

The ESPaDOnS (Echelle SpectroPolarimetric Device for the Observation of Stars) spectrograph at the Canada-France-Hawaii Telescope (CFHT) was used to record Stokes *I* and *V* spectra of HD 213258 at seven epochs between November 2020 and October 2022. They cover the spectral range 3700–10 000 Å, at a resolving power $R \sim 65\,000$. They were reduced by the CFHT team using the dedicated software package Libre-ESPrIT (Donati et al. 1997). The resulting S/N in Stokes *I* reaches its maximum of about 400 or more in echelle order #32 (7080 Å). A portion of one of these spectra is shown for illustration in Fig. 1. The sharpness of the spectral lines is striking. One can see that the Fe II $\lambda$ 6149.2 Å line is resolved into its magnetically split components. This is indicative of a very low projected equatorial velocity $v \sin i$ and of the presence of a strong magnetic field. The quantitative determination of the latter is discussed below.

One can also note in the spectrum the presence of strong lines that are characteristic of typical Ap stars, such as Nd III $\lambda$ 6145.1 Å, Cr II $\lambda$ 6147.1 Å, Pr III $\lambda$ 6160.2 Å, and Pr III $\lambda$ 6161.2 Å. The presence of these lines resolves the

[1] Later, North & Duquennoy (1991) found that at least half of F str $\lambda$ 4077 stars are main-sequence Ba stars, which owe their chemical peculiarity to binary evolution.

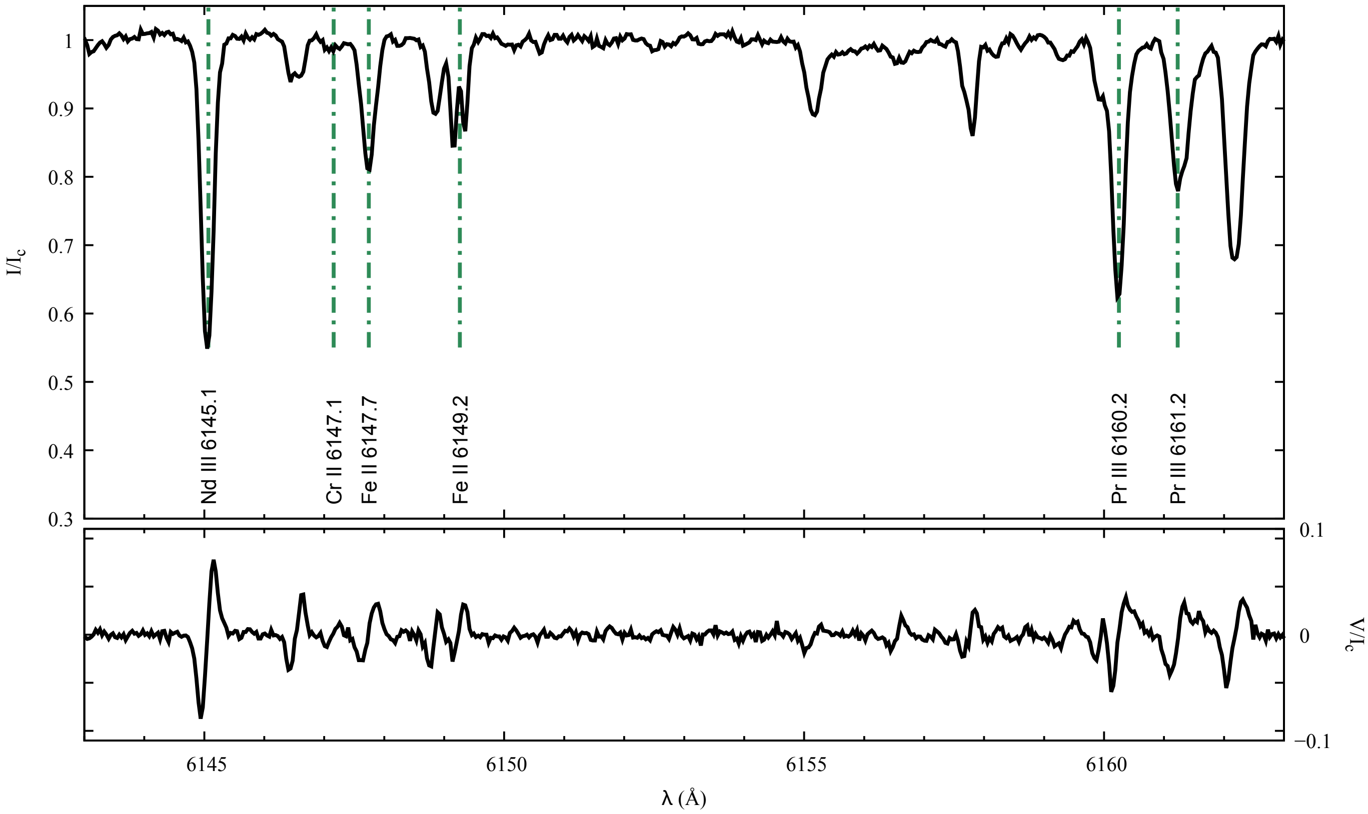


**Fig. 1.** Portion of the spectrum of HD 213258 recorded on HJD 2,459,180.728 in Stokes $I$ (*top*) and $V$ (*bottom*), showing the resolved magnetically split line Fe II $\lambda$ 6149.2 Å. A few other lines that are typical of Ap stars are identified. The spectrum has been normalised to the continuum ($I_c$), and the wavelength scale has been converted to the laboratory reference frame.

ambiguity that affected the original classification of HD 213258 and indicates that it is definitely an Ap star.

On the other hand, all the lines present in the observed spectrum show clear Stokes $V$ signatures. They reveal the presence of a sizeable component of the magnetic field along the line of sight, which does not average out over the stellar hemisphere that was visible at the epoch of the observation.

The mean magnetic field modulus, $\langle B \rangle$, defined as the line-intensity-weighted average over the visible stellar hemisphere of the modulus of the magnetic vector, was determined from the wavelength separation of the resolved components of the Fe II $\lambda$ 6149.2 Å line. The magnetic splitting pattern of this line is a doublet. The value of $\langle B \rangle$ is derived via application of the following formula:

$$\lambda_r - \lambda_b = g\,\Delta\lambda_Z\,\langle B \rangle. \quad (1)$$

In this equation, $\lambda_r$ and $\lambda_b$ are, respectively, the wavelengths of the red and blue split line components; $g$ is the Landé factor of the split level of the transition ($g = 2.70$; Sugar & Corliss 1985); $\Delta\lambda_Z = k\,\lambda_0^2$, with $k = 4.67 \times 10^{-13}$ Å$^{-1}$ G$^{-1}$; $\lambda_0 = 6149.258$ Å is the nominal wavelength of the considered transition.

The procedure used to measure the wavelengths $\lambda_b$ and $\lambda_r$ of the Fe II $\lambda$ 6149.2 Å split line components has been described in detail by Mathys & Lanz (1992) and by Mathys et al. (1997). As in many other Ap stars, the Fe II $\lambda$ 6149.2 Å line in HD 213258 is blended on the blue side with an unidentified rare-earth line. We disentangled its contribution from that of the two Fe II $\lambda$ 6149.2 Å line components by fitting three Gaussians to them. As shown by Mathys et al. (1997), this represents a very effective way to achieve consistent determinations of the wavelengths $\lambda_b$ and $\lambda_r$, and hence of the value of $\langle B \rangle$.

The difficulty in estimating the uncertainty affecting the derived values of the mean magnetic field modulus was discussed in detail by Mathys et al. (1997). In the present case, since the measurements obtained thus far have only sampled a fraction of the stellar rotation cycle (see Sect. 3), we followed the prescription of these authors and estimated the uncertainty of the $\langle B \rangle$ determinations in HD 213258 to be of the order of 40 G from a comparison of the profile of the Fe II $\lambda$ 6149.2 Å line in HD 213258 with its profile in other stars for which this uncertainty is better constrained.

The mean longitudinal magnetic field, $\langle B_z \rangle$, is the line-intensity-weighted average over the visible stellar hemisphere of the component of the magnetic vector along the line of sight. It is determined from the wavelength shift of the spectral lines between the two circular polarisations via application of the following formula:

$$\lambda_R - \lambda_L = 2\,\bar{g}\,\Delta\lambda_Z\,\langle B_z \rangle, \quad (2)$$

where $\lambda_R$ (respectively $\lambda_L$) is the wavelength of the centre of gravity of the line in right (respectively left) circular polarisation and $\bar{g}$ is the effective Landé factor of the transition. The value of $\langle B_z \rangle$ is determined through a least-squares fit of the measured values of $\lambda_R - \lambda_L$ by a function of the form given above. The standard error, $\sigma_z$, that was derived from that least-squares analysis was used as an estimate of the uncertainty of the obtained value of $\langle B_z \rangle$.

The results of the magnetic measurements of HD 213258 are presented in Table 1. Column 1 gives the heliocentric Julian

**Table 1.** Mean magnetic field modulus, mean longitudinal magnetic field, and heliocentric radial velocity measurements.

| HJD | $\langle B\rangle$ (G) | $\langle B_z\rangle$ (G) | $\sigma_z$ (G) | $N$ | $v_r$ (km s$^{-1}$) | $\sigma_r$ (km s$^{-1}$) |
|---|---|---|---|---|---|---|
| 2459180.728 | 3815 | −992 | 33 | 50 | −87.64 | 0.15 |
| 2459181.714 | 3755 | −1000 | 33 | 50 | −87.76 | 0.15 |
| 2459361.124 | 3905 | −963 | 31 | 50 | −88.97 | 0.15 |
| 2459832.014 | 3827 | −891 | 29 | 50 | −87.91 | 0.13 |
| 2459835.847 | 3916 | −896 | 26 | 50 | −87.95 | 0.14 |
| 2459836.993 | 3877 | −920 | 28 | 49 | −87.55 | 0.11 |
| 2459868.858 | 3774 | −885 | 26 | 50 | −87.85 | 0.13 |

date of mid-exposure for each of the analysed spectra. The mean magnetic field modulus values are listed in Col. 2. Columns 3–5 present the results of the determination of the mean longitudinal magnetic field: its value, $\langle B_z\rangle$, its uncertainty, $\sigma_z$, and the number, $N$, of diagnostic lines that were measured. They are lines of Fe I, which span the wavelength range 4175−6180 Å. The same lines were also used to derive the radial velocity of HD 213358, from a least-squares fit of the wavelength shifts of the centres of gravity of the Stokes $I$ line profiles with respect to their laboratory values against these laboratory values, using the same diagnostic lines as for the $\langle B_z\rangle$ determinations. The derived values of the heliocentric radial velocity, $v_r$, and their uncertainties, $\sigma_v$ (that is, the standard error of the least-squares analysis), are given in Cols. 6 and 7 of Table 1.

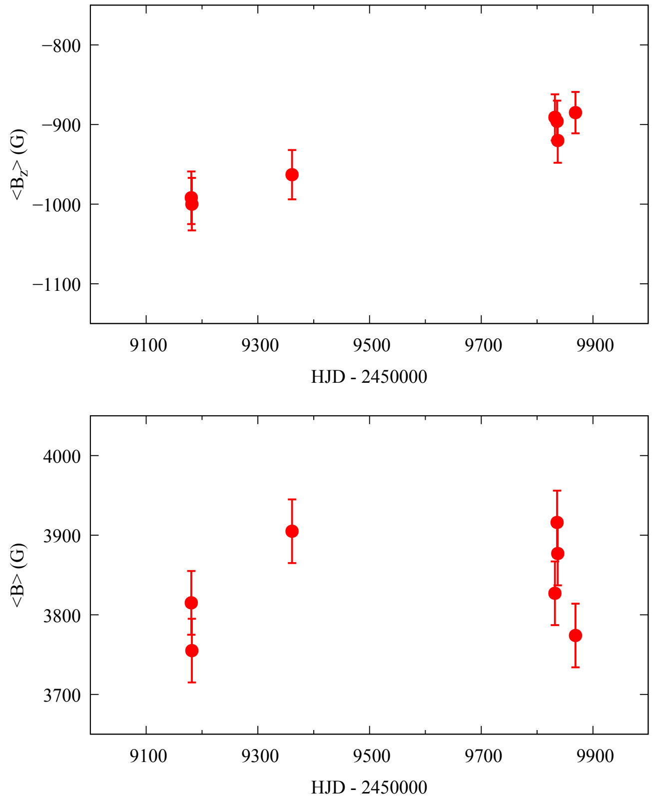


**Fig. 2.** Mean longitudinal magnetic field (*top*) and mean magnetic field modulus (*bottom*) of HD 213258 against time.

## 3. Rotation

The magnetic measurements of Sect. 2 are plotted against time in Fig. 2. In the upper panel, the mean longitudinal magnetic field shows an apparently linear trend from the first epoch of observation to the most recent one, from more negative to less negative values. All $\langle B_z\rangle$ values are comprised in a narrow range, between −1000 G and −885 G. However, two earlier mean longitudinal magnetic field determinations from the literature, performed by North et al. (1992) using spectra recorded with the Zeeman analyser of the Main Stellar Spectrograph of the 6 m BTA telescope at the Special Astrophysical Observatory (Panchuk et al. 2014) on August 12 and 13, 1989, respectively yielded $\langle B_z\rangle = -198 \pm 133$ G and $\langle B_z\rangle = 210 \pm 108$ G. Given the uncertainties affecting them, these measurements do not significantly differ from each other, nor from zero. They represent a strong indication that the overall amplitude of variation in $\langle B_z\rangle$ in HD 213258 is considerably greater than that observed over ~2 yr with ESPaDOnS, and hence that the stellar rotation period must vastly exceed two years. Thus, HD 213258 is a newly identified member of the group of super slowly rotating Ap (ssrAp) stars (Mathys 2020).

The magnetic measurements obtained so far have sampled the rotation cycle too sparsely to constrain the shapes of the variation curves of either $\langle B\rangle$ or $\langle B_z\rangle$. Even trying to characterise these shapes under the frequently made assumption of a magnetic field structure that is to first order dipolar would represent an over-interpretation of the available data. Therefore, the discussion below is based on a linear approximation, which is sufficient for setting meaningful constraints on the lower limit of the rotation period. Indeed, from one extremum to the next, and away from both extrema, a straight line does not drastically depart from the actual sinusoidal shape of the $\langle B_z\rangle$ variation curve that corresponds to a dipole.

Extrapolating the linear trend of variation in the mean longitudinal magnetic field observed over the past two years (690 days), it would take HD 213258 of the order of 5060 days from the most recent ESPaDOnS observation to get back to a value of $\langle B_z\rangle \sim 0$ G, which is close to the value derived in 1989. This suggests a minimum value of ~5750 days for half the rotation period. The full rotation period should be at least twice as long, that is, have a minimum value of about 11 500 days, or 31.5 yr. However, the time elapsed between the observations of North et al. (1992) and the first of the present ESPaDOnS observations is 11 432 days. These observations were definitely obtained at very different rotation phases, so they are inconsistent with values of the rotation period close to 11 500 days. The actual period must be much longer. Accordingly, the $\langle B_z\rangle$ values from 1989 and 2020 cannot both be close to the extrema of the mean longitudinal magnetic field. Either the negative $\langle B_z\rangle$ extremum must have an absolute value greater than 1 kG, or $\langle B_z\rangle$ must become positive over part of the rotation cycle and reach a positive extremum, or both extrema must be outside the range of $\langle B_z\rangle$ values that have been observed so far. For instance, if $\langle B_z\rangle$ was close to its negative extremum in 2020, and if its variation curve is approximately symmetric about this extremum, the mean longitudinal magnetic field could plausibly have been positive between ~1989 and ~2002, and it could have gone through its positive extremum around 1995 or 1996. This suggests that the minimum value of the rotation period should be at least of the order of 50 yr. The period might even be a few years longer if over part of it $\langle B_z\rangle$ reached values more negative than −1.0 kG. While consideration of the mean magnetic field modulus sets an upper limit to the maximum absolute value of the mean

**Table 2.** Heliocentric radial velocity measurements obtained with CORAVEL.

| HJD | $v_r$ (km s$^{-1}$) | $\sigma_r$ (km s$^{-1}$) |
|---|---|---|
| 2447006.619 | −87.15 | 0.41 |
| 2447007.598 | −87.52 | 0.56 |
| 2447401.503 | −86.01 | 0.43 |
| 2447762.523 | −88.78 | 0.56 |
| 2447801.446 | −88.57 | 0.60 |
| 2447856.353 | −88.65 | 0.58 |
| 2448223.251 | −88.58 | 0.49 |
| 2448510.469 | −87.41 | 0.60 |
| 2448585.308 | −86.50 | 0.55 |
| 2448917.417 | −87.38 | 0.63 |

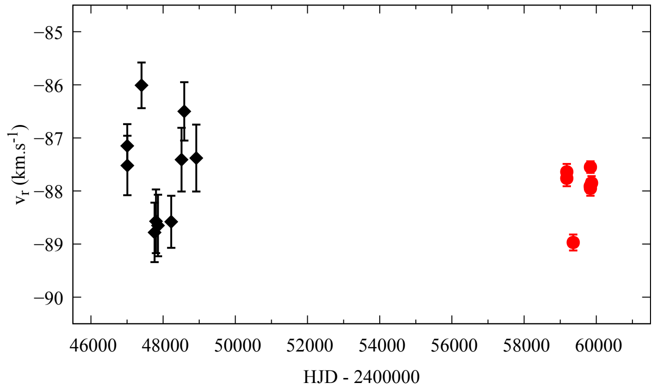


**Fig. 3.** Heliocentric radial velocity of HD 213258 against time. Black diamonds identify the measurements based on CORAVEL observations and red dots those based on ESPaDOnS spectra.

longitudinal field, comparison with other stars, such as HD 93507 (Mathys 2017), shows that values as negative as $\langle B_z \rangle = -1.25$ kG could be reached by HD 213258.

The lower panel of Fig. 2 shows the measurements of the mean magnetic field modulus of HD 213258. This field moment does not show any significant variation over the 2-yr time interval spanned by the ESPaDOnS spectra. This is not unexpected, as 2 yr probably represents less than 0.04 rotation periods. The relative amplitude of the variations in $\langle B \rangle$ does not exceed 30% in most Ap stars (Mathys 2017), so such variations may not be detectable over too small a fraction of a rotation cycle.

## 4. Radial velocity and binarity

The spectral line measurements carried out to determine the mean longitudinal magnetic field were used to derive the heliocentric radial velocity of HD 213258 at the seven epochs of observation with ESPaDOnS. The average of the seven individual values, −87.95 km s$^{-1}$, is consistent with the average radial velocity computed by North & Duquennoy (1991) from six CORAVEL (CORrelation-RAdial-VELocities) measurements, −86.8 km s$^{-1}$. These six CORAVEL values, together with four later ones, are listed in Table 2. All the radial velocity values of Tables 1 and 2 are also plotted in Fig. 3. The CORAVEL and ESPaDOnS datasets appear mutually consistent, in line with the conclusion reached by Mathys (2017) for other stars observed with these two instruments. We also confirm the claim by North & Duquennoy (1991) that the radial velocity of HD 213258 is definitely variable. In particular, the difference between the measurement obtained on JD 2459361 and the six other contemporaneous radial velocity determinations, although small (of the order of 1 km s$^{-1}$), is highly significant. North & Duquennoy (1991) contemplated the possibility that the radial velocity variations that they detected reflect the changing aspect of the visible hemisphere of a spotted star over its rotation period. This interpretation can be ruled out given the above-mentioned strong evidence that the rotation period of the star is of the order of decades. Thus, HD 213258 must almost certainly be part of a single-lined spectroscopic binary system. Indeed, no obvious evidence of a secondary was found in the spectra.

There are too few radial velocity measurements and the epochs of CORAVEL and ESPaDOnS observations are too far apart from each other to allow the orbital elements to be determined. Consideration of Fig. 3 suggests that the orbital period may be of the order of weeks, or possibly longer. Indeed, radial velocity values determined from observations obtained on two to three consecutive or nearly consecutive nights do not show any significant variations, but variations occur between such groups of observations spaced from each other by a few weeks. In any case, the orbital period of HD 213258 must be much shorter than its rotational period. This occurs frequently for ssrAp stars in binaries (Mathys 2017). More observations are needed to characterise the system better.

Furthermore, from analysis of the proper motion anomaly between the HIPPARCOS catalogue and the Early Third Data Release of the *Gaia* catalogue, Brandt (2021) and Kervella et al. (2022) also show that HD 213258 is an astrometric binary. Assuming a circular orbit observed face-on and using the mass estimate $m_1 = 1.70\,M_\odot$ for the Ap primary, Kervella et al. (2022) derived estimates of the mass, $m_2$, of the secondary: $m_2 = 129.33\,M_J$ for an orbital radius $r = 3$ au (corresponding to an orbital period $P_{orb} \sim 4.0$ yr), $m_2 = 69.56\,M_J$ for $r = 5$ au ($P_{orb} \sim 11.2$ yr), and $m_2 = 87.97\,M_J$ for $r = 10$ au ($P_{orb} \sim 31.6$ yr). This puts the secondary of HD 213258 close to the borderline between stellar and substellar objects. There is a significant probability that it is a brown dwarf.

The average value of the heliocentric radial velocity of HD 213258, of the order of −88 km s$^{-1}$, is exceptionally large (in absolute value) for an Ap star. For instance, in the systematic study of a sample of 186 Ap stars by Levato et al. (1996), the values of the heliocentric radial velocity range from −40 to 42 km s$^{-1}$. However, as noted by North & Duquennoy (1991), the space velocity of HD 213258 is essentially radial, so while large, it is not extreme. We are not aware of any modern study of the space velocity distribution of Ap stars, so we cannot at present put the high radial velocity of HD 213258 in perspective, nor understand its implications (if any) for the other stellar properties.

## 5. Pulsation

The star HD 213258 was observed twice, in Sectors 16 and 56, by the space telescope TESS (Transiting Exoplanet Survey Satellite) during the first 4 yr of its operation. Employing the utilities of the Lightkurve Python package designed for analysis of *Kepler* and TESS data (Lightkurve Collaboration 2018) and a Python code developed by Jonathan Labadie-Bartz (priv. comm.), the TESS images of this target observed in Sector 56 with a cadence of 158 s were downloaded from the Mikulski

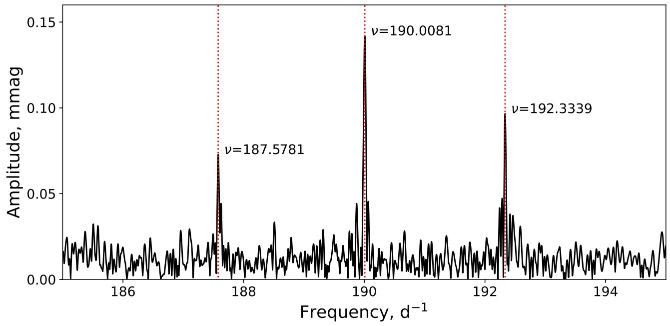


**Fig. 4.** High-overtone pulsations of HD 213258 detected during the analysis of photometric data in Sector 56 provided by TESS. Vertical dotted red lines specify the position of three significant signals in the Lomb-Scargle periodogram.

Archive for Space Telescopes (MAST)[2]. The light curve was extracted from the TESS full frame images in a manner similar to in Labadie-Bartz et al. (2022). The cut-out images with a size of 24 × 24 pixels were used to infer the raw light curve of HD 213258 and to remove the sky background using the principal component analysis detrending method. The derived flux was transformed to stellar magnitudes and analysed for periodic variability using a Lomb-Scargle periodogram (VanderPlas 2018).

The Lomb-Scargle periodogram clearly shows a distinguishable triplet at frequencies around 190 $d^{-1}$ (see Fig. 4). The central mode has the highest amplitude and corresponds to the period $P = 7.579(2)$ min. There are three frequencies with significant amplitudes that are split with an average frequency separation of $\delta\nu = 2.38(5)\, d^{-1}$. This kind of high-overtone pulsation is typically observed in rapidly oscillating Ap (roAp) stars (Kurtz 1982). The detection of roAp-type pulsations and a significant magnetic field in HD 213258 (see Fig. 2) are strong pieces of evidence that it is a CP roAp star with extremely slow rotation (see Sect. 3).

## 6. Conclusion

The Ap star HD 213258 presents a quasi-unique combination of remarkable properties, each of which is observed in isolation in only a small fraction of the entire population of Ap stars. A few percent of these stars have rotation periods longer than 1 yr (Mathys 2017; Shultz et al. 2018). The longest period that has been accurately determined for an Ap star is that of HD 50169, which is 29 yr (Mathys et al. 2019). The only Ap star for which a lower limit of the period value greater than 50 yr has been set is $\gamma$ Equ (Bychkov et al. 2016). If HD 213258 has a rotation period of the order of 50 yr, as we contend, it is one of the most promising candidates for detailed study of extremely slow rotation in Ap stars.

The lack of rotational broadening of the spectral lines of the ssrAp stars lends itself well to the resolution of magnetically split lines. But the number of stars that show such resolution remains small, of the order of a few percent of all Ap stars (Mathys 2017), as the threshold of detection of magnetically resolved lines in the visible is of the order of 2 kG and magnetic fields of several kilogauss are rare. Thus, the fact that the Fe II $\lambda$ 6149.2 Å line is resolved into its magnetic components in HD 213258 is a distinctive trait.

While the rate of occurrence of roAp stars among ssrAp stars, which may reach ~20%, is considerably higher than the fraction of roAp stars among all Ap stars (Mathys et al. 2022), roAp stars seldom belong to binary systems (Hubrig et al. 2000; Schöller et al. 2012; Hey et al. 2019). Such binary systems are wide: the shortest orbital period that has been accurately determined for a pair containing an roAp star, HD 42659, is $93\overset{d}{.}2$ (Hartmann & Hatzes 2015). The radial velocity measurements obtained thus far for the roAp star HD 213258 (see Tables 1 and 2) do not rule out the possibility of a shorter period: it will be very valuable to determine $v_r$ at additional epochs to constrain its orbital elements. Even more remarkably, there is a significant probability that the secondary of the pair is substellar. If confirmed, this would make HD 213258 the first roAp star known to have a brown dwarf companion. In any event, it is certainly the roAp star with the least massive companion known to date.

Furthermore, it is rather uncommon for roAp stars to have very strong magnetic fields. For instance, of the 44 roAp stars for which an averaged value of the magnetic field is given in Table 1 of Smalley et al. (2015), only 8 (18%) have field values greater than 3.5 kG. Admittedly, this statistic is very approximative since it is based on inhomogeneous literature sources and magnetic field measurements of differing completeness and quality. But this does not detract from the fact that, with $\langle B \rangle \sim 3.8$ kG, HD 213258 ranks among the most strongly magnetic roAp stars.

Finally, as illustrated in Sect. 4, the mean radial velocity of HD 213258 appears greater than that of more than 99% of Ap stars.

In summary, each of the above-mentioned properties of HD 213258 taken in isolation puts it in a minority group of Ap stars that may represent between ~20% and less than 1% of the whole population of Ap stars. What makes HD 213258 especially remarkable is that it presents a combination of all these rare properties. Such a combination must have a very low probability of occurring, and to the best of our knowledge, HD 213258 is as of now the only known Ap star possessing it. For instance, $\gamma$ Equ is an roAp star that has a magnetic field of the same order of magnitude as that of HD 213258 and a rotation period that is probably longer than that of HD 213258. But while the importance of the much higher space velocity of HD 213258 is unclear, the fact that its companion is much closer than that of $\gamma$ Equ and that it has a very low mass and may plausibly be a brown dwarf marks HD 213258 as truly unique. The purpose of this note is to call the attention of the stellar astrophysics community to this star so that it receives the attention it deserves. For instance, this star is an excellent workbench for studying the effects of a strong magnetic field and of a companion on the atmospheric and pulsation properties of Ap stars. We are currently working to determine its fundamental parameters, the chemical abundances in its atmosphere, and their vertical stratification. The results of this detailed analysis will be the subject of a future paper.

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