On the non-variability of HR 7653 (15 Vul) based on BRITE data

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(Submitted on 16.05.2017. Accepted on 03.08.2017)

Abstract. We present space-based BRITE photometric observations of the metallic line (CP1) star HR 7653 (15 Vul). This chemically peculiar star of the upper main sequence was suspected to show variability due to rotation and a magnetic field. Such a variability is quite unusual among the, in general, non-magnetic CP1 stars. We investigated the astrophysical parameters of HR 7653 placing it close to the terminal age main sequence or even in the subgiant phase. The longest BRITE data set has a time base of 18.01 d from which we conclude that there are no coherent long-period variations (>1 d) visible above 2.1 mmag in the red and 6.6 mmag in the blue. Furthermore, we searched for δ Scuti type pulsations. On the basis of a discrete Fourier analysis method, we find no peaks in the Fourier spectra above 0.5 mmag and 8.6 mmag, for the red and blue filters, respectively.

Key words: stars: early-type – stars: fundamental parameters – techniques: photometric

Introduction

Chemically peculiar (CP) stars are upper main sequence objects (spectral types early B to early F) whose spectra are characterized by abnormally strong (or weak) absorption lines that indicate peculiar surface elemental abundances. CP stars constitute about 10% of upper main sequence stars and are commonly subdivided into four classes (Preston, 1974): metallic line (or Am) stars (CP1), magnetic Ap stars (CP2), HgMn stars (CP3), and He-weak stars (CP4).

Here we concentrate on the non-magnetic CP1 stars which were first described by Titus & Morgan (1940) using spectra of Hyades cluster members. They could be easily identified using classification resolution spectroscopy by their spectral types obtained from the calcium K line (k), hydrogen lines (h), and metallic lines (m). The classical CP1 stars are defined as Sp(k) < Sp(h) < Sp(m), where '<' denotes 'earlier than'. In general, CP1 stars are characterized by overabundances of metallic elements heavier than iron, whereas calcium, scandium, carbon, nitrogen and oxygen are solar or underabundant (Hui-Bon-Hoa, 2000).

Two different models based upon atomic diffusion were developed to explain the CP1 phenomenon. Watson (1971) proposed that the separation of chemical elements occurred just below the hydrogen convection zone where calcium has a small radiative acceleration. This implies that on the main sequence a very small mass fraction has anomalous abundances. In the second model, proposed by Richer et al. (2000), the separation occurs much deeper in the stellar interior. Therefore, on the main sequence, a much larger mass fraction has anomalous abundances. In general, a cut-off rotational velocity for such objects (∼90 km/s) is predicted Richer et al., 2000), above which meridional circulation leads to a mixing in the stellar atmosphere. As a result, the typical abundance pattern vanishes.

Generally, CP1 stars are not expected to show rotational light variability. Interestingly, Balona et al. (2015) using ultra-precise Kepler photometry, have found that most of the investigated CP1 stars exhibit light curves indicative of rotational modulation due to star spots. With an amplitude of up to 200 ppm, detection of such variability is reserved for high-precision (space) photometry.

Recently, Smalley et al. (2017) investigated the (δ Scuti type) pulsational behaviour of a large sample of A-type and CP1 stars with spectral types from LAMOST and light curves from WASP. They found evidence that the incidence of pulsations in CP1 stars decreases with increasing metallicity (degree of chemical peculiarity). They also presented evidence that suggests turbulent pressure to be the main driving mechanism in pulsating CP1 stars, rather than the κ-mechanism, which is expected to be suppressed by gravitational settling in these stars.

Here, we present the photometric data from the BRITE Constellation satellite mission for HR 7653 (15 Vul), a classical CP1 star which was suspected to show variability (Kuvshinov et al., 1976) due to rotation and a magnetic field.

First, we summarise our knowledge about HR 7653 and then we present a time-series analysis resulting in the non-variability of the star with very low upper limits.

The target HR 7653

HR 7653 (15 Vul, $V = 4.65\,\mathrm{mag}$) has been analysed both photometrically and spectroscopically, in the past. Çay et al. (2016) derived detailed atmospheric abundances and also summarized the previously-published astrophysical parameters. They found the following values: $T_\mathrm{eff} = 7825(100)\,\mathrm{K}$, $\log g = 3.45(10)\,\mathrm{cm\,s^{-1}}$, and $\upsilon \sin i = 9.2(5)\,\mathrm{km\,s^{-1}}$, respectively. Those values are based on spectrophotometry and Hγ profile fitting. However, the published values from the literature cover a wider range (Çay et al., 2016):

- T_eff: $7500 - 8040\,\mathrm{K}$
- $\log g$: $3.2 - 3.7\,\mathrm{cm\,s^{-1}}$
- $\upsilon \sin i$: $9.5 - 23\,\mathrm{km\,s^{-1}}$

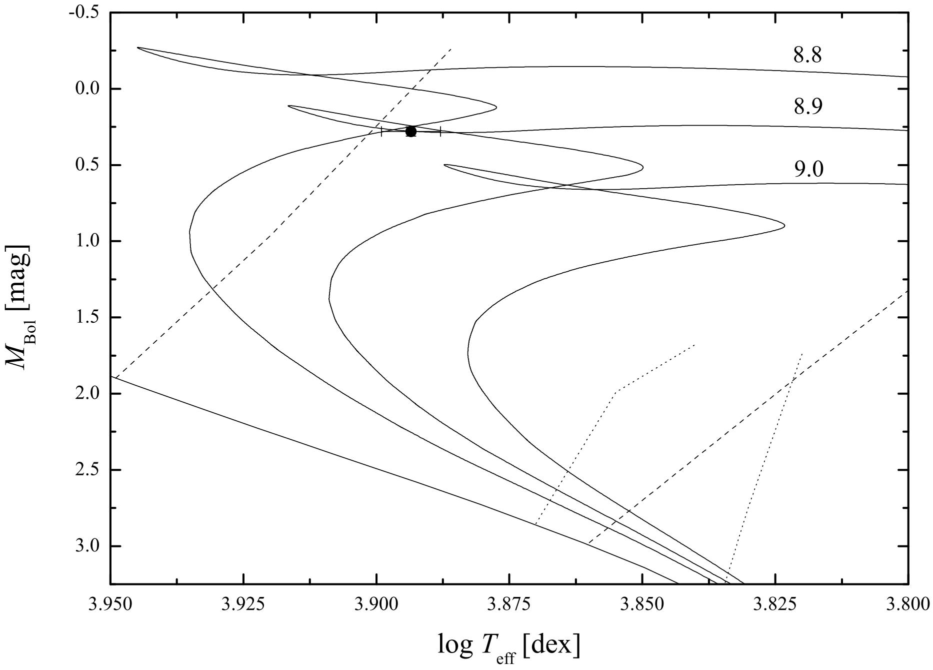

Fig. 1. The location of HR 7653 in the M_{Bol} versus $\log T_{\mathrm{eff}}$ diagram. The borders of the δ Scuti (dashed lines) and γ Doradus (dotted lines) instability strips are indicated, which were taken from Breger & Pamyatnykh (1998) and Dupret et al. (2004), respectively. The isochrones with corresponding masses indicated in solar units are from the PARSEC database (Bressan et al., 2012) for solar metallicity (Z = 0.019 dex).

First, we want to analyse the evolutionary status of HR 7653, i.e. locating it in the Hertzsprung-Russell diagram. The M_{Bol} value was directly calculated from the astrometric parallax (13.8(2) mas) of the Hipparcos mission (van Leeuwen, 2007) with the reddening ($A_{\mathrm{V}} = 0.08$ mag) deduced from Strömgren $uvby\beta$ photometry (Paunzen, 2015). No parallax in the Gaia DR1 is available. The bolometric correction was taken from Netopil et al. (2007). The errors of the bolometric magnitude and luminosity was directly deduced from the error of the parallax. Finally, we calculated $M_{\mathrm{Bol}} = 0.28(3)$ mag and $\log L/L_{\odot} = 1.79(1)$ (using $M_{\mathrm{Bol}}(\odot) = 4.75$ mag).

Figure 1 shows the location of HR 7653 in the M_{Bol} versus $\log T_{\mathrm{eff}}$ diagram. The borders of the δ Scuti (dashed lines) and γ Doradus (dotted lines) instability strips are indicated, which were taken from Breger & Pamyatnykh (1998) and Dupret et al. (2004), respectively. The isochrones are from the PARSEC database (Bressan et al., 2012) for solar metallicity (Z = 0.019 dex). It is seen that HR 7653 is within and close to the blue border of the δ Scuti instability strip and thus far away from the γ Doradus border. For the evolutionary status, two distinct scenarios are possible. As-

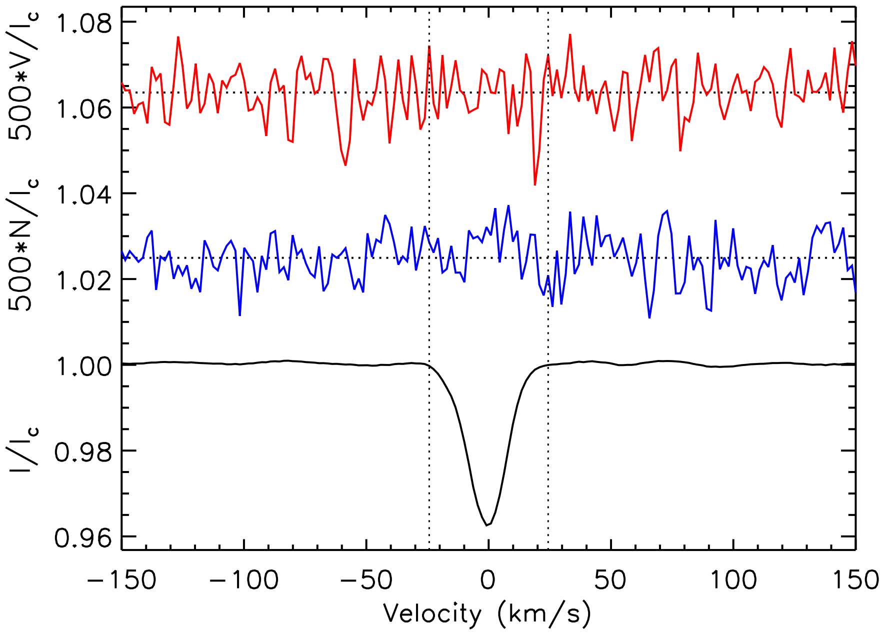

Fig. 2. Stokes V (top, red), diagnostic null (middle, blue), and Stokes I (bottom, black) LSD profiles calculated from the spectropolarimetric observation obtained with ESPaDOnS. No signal is apparent in either the Stokes V or diagnostic null profiles, which have been scaled by a factor of 500 for clarity. The vertical dotted lines correspond to the integration limits used to calculate the longitudinal field strength of 3.8(3.5) G.

suming $\log t/yr = 8.8$, the star is still on the main sequence whereas it is already in the subgiant phase for $\log t/yr = 8.9$. However, the $\log g$ values differ only marginally from 3.51 to 3.55 for these two scenarios which makes a discrimination impossible. But the independently derived $\log g$ range is perfectly in line with the value of 3.45(10) listed by Çay et al. (2016).

That HR 7653 is a classical CP1 star, is proven by the elemental abundances published by Çay et al. (2016) and others. The light elements C, N, O, and S are almost solar abundant whereas Mg, Ca, and Sc are underabundant and the rare earth elements are strongly overabundant (Talon et al., 2006).

Our knowledge about the possible binary nature of HR 7653 is manifold (e.g. Abt 1961). Rudd & Stickland (1977) analysed their own and archival radial velocities concluding that they failed to determine whether this system is a spectroscopic binary. At this point they suggested to adopt a constant radial velocity of $-26.4(4)\,\mathrm{km\,s^{-1}}$ which was later confirmed by Takeda (1984) and Çay et al. (2016). The multiplicity survey of A-type stars, sensitive to companions beyond 30 AU by De Rosa et al. (2014) gave a null result for HR 7653. They used a combination of adaptive optics imaging and a multi-epoch common proper motion search. Therefore, it seems that HR 7653 is one of the rare known single CP1 stars.

The detection of a magnetic field and an induced photometric variability with a period of 14 days was reported by Kuvshinov et al. (1976). They presented photoelectric Johnson UBV photometry showing a variability with amplitudes from about 0.03 to 0.05 mag. They presented 60 measurements of the longitudinal magnetic field strength resulting in a maximum of 720 Oe. However, Kuvshinov et al. (1976) also reported the detection of a magnetic field in HR 1389 (68 Tau) which has double the strength as that of HR 7653. Later on, Landstreet (1982) was not able to detect any significant magnetic field in HR 1389.

Bychkov et al. (2009), in their compilation of magnetic field measurements, reported a mean magnetic field for HD 189849 of $\langle B_e \rangle = 247.5(66.7)$ G. However, the diverse nature of the measurements included in their compendium (a blend of good and poor quality observations, obtained from both reliable and unreliable sources) sometimes leads to misleading results, particularly at low field strengths.

Sikora et al. (in preparation) obtained a single ESPaDOnS observation of HR 7653 in circular polarisation mode to help resolve this puzzle. The spectrum, analyzed using the state-of-the-art LSD procedure (Donati et al. 1997, Kochukhov et al. 2010) yielded no detection of circular polarization in the mean line, and a longitudinal magnetic field of 3.8(3.5) G. Moreover, the spectral lines show no evidence of distortion as might result from the presence of surface chemical abundance nonuniformities (Figure 2). These results are fully consistent with 15 Vul being a normal CP1 star, with no evidence of any measureable magnetic field.

The reported photometric variability was challenged by Garrido et al. (1980) on the basis of 46 nights within 81 days. They found no variability in the range from hours to days with an amplitude larger than 10 mmag.

BRITE photometric observations

The photometric observations were carried out with three BRITE – Constellation satellites: BRITE-Austria (hereafter BAb), BRITE-Toronto (BTr), and UniBRITE (UBr). Each satellite hosts an optical telescope of 3 cm aperture, feeding an uncooled CCD, and is equipped with a single filter. BAb has a blue filter (390 – 460 nm) whereas BTr and UBr have a red filter (550 – 700 nm). The orbital periods are close to 100 min, enabling continuous observations of the chosen target fields for up to 30 min per orbit.

HR 7653 was observed within the Field IDs[9] 10-Cyg-II-2015 (June 1st, 2015 to November 25th, 2015) and 17-CygLyr-I-2016 (April 4th, 2016 to October 3rd, 2016). In 2016 UBr observed continuously for 18.01 d and BTr for 12.44 d, while BAb observed for 29.51 d, but in four discontinuous blocks. In 2016 data were only obtained by BTr for 7.31 d.

The reductions of the photometric data of the BRITE satellites were carried out with a pipeline that takes into account bad pixels, columns affected by readout dark current, image motion, and PSF variations (Popowicz 2016; Popowicz et al., 2017). The photometry still needs to be decorrelated for several factors, for example temperature variations within the satellites and

[9] `http://brite.craq-astro.ca/doku.php?id=fields`

detectors during the orbit and on longer time scales, before a scientific analyses of the intrinsic stellar variability can be done. We applied the basic process of decorrelation as has been described in detail by Pigulski et al. (2016) and the *BRITE Photometry Cookbook*[10].

While correlations were no very strong in three of the datasets (BAb and UBr data from 10-Cyg-II-2015 and BTr data from 17-CygLyr-I-2016) the situation was different for the BTr data from 10-Cyg-II-2015. For these data multiple decorrelations with the x and y image centroid positions were performed to remove significant correlations. This resulted in a large drop of scatter of around 50% compared to the pipeline data. The results of these decorrelations are shown in Figure 3.

The light curves were examined in more detail using the PERIOD04 program (Lenz & Breger 2005). It employs a discrete Fourier transform allowing a least-squares fitting of multiple frequencies to data. Figure 4 shows the periodograms for the BRITE data. Other than some signal due to aliases of the satellites' orbital periods, there are no significant peaks above the median amplitude noise level.

To place upper limits on possible δ Scuti like variations, we used the median amplitude of the periodogram. We find the following noise levels in the Fourier spectra for the 10-Cyg-II-2015 datasets: BAb: 2.60 mmag; BTr: 0.15 mmag, UBr: 0.55 mmag and for 17-CygLyr-I-2016 BTr: 0.29 mmag. Setting the detection threshold as four times the noise level (Breger et al. 1993) gives upper limits to the variability as 0.60 mmag in the blue (10-Cyg-II-2015 BTr) and 10.4 mmag in the red (10-Cyg-II-2015 BAb). However, as neither of these periodograms have peaks that reach their detection thresholds, the upper limit on the variability can be given by the amplitude of their highest peaks, which are 0.5 mmag in the blue and 8.6 mmag in the red.

We were looking for variations on all accessible time scales. The longest data set observed by UBr has a time base of 18.01 d and that by BAb has a time base of 15.49 d. In these data sets no coherent long-period variations (>1 d) above 2.1 mmag and 6.6 mmag, in the red and blue filters, respectively. This is in agreement with the results by Garrido et al. (1980) and clearly contradict the findings by Kuvshinov et al. (1976).

Those are by far the most precise photometric measurements available for HR 7653.

Conclusions

Looking in the literature reveals several interesting and contradictory results for the chemically peculiar star HR 7653. The abundance pattern is typical for a classical non-magnetic CP1 (Am) star with a low rotational velocity. Although most of these objects are found in spectroscopic binary systems, HR 7653 seems to be a single star (Rudd & Stickland 1977). The presence of a magnetic field together with signs of rotational variability caused by surface spots was reported and then questioned. The search for variability was ambiguous and inconsistent.

[10] `http://brite.craq-astro.ca/lib/exe/fetch.php?media=bac-1.6.pdf`

With the help of a precise Hipparcos parallax and a published effective temperature value, we were able to estimate its age between 630 and 800 Myr using recent isochrones. The evolutionary status is between the end of the main sequence and the subgiant phase. HR 7653 is located within the classical δ Scuti instability strip close to the blue border. This makes a possible pulsation very interesting for stellar evolutionary models.

We presented the analysis of space-based two filter photometric data from the BRITE satellites. The data were observed during two runs separated by about five months. The high cadence and the quality of the observations make them perfectly suited to shed more light on the photometric behaviour of HR 7653 compared to previous ground-based observations.

On the basis of a discrete Fourier analysis method, we find no peaks in the Fourier spectra above 0.5 mmag and 8.6 mmag, for the red and blue filters, respectively. If δ Scuti type pulsation is present, the amplitude has to be lower than these values for the given filter. This is an important result for pulsational models of stars close to the terminal age main sequence or in their subgiant phase.

The longest data set observed by UBr has a time base of 18.01 d and that by BAb has a time base of 15.49 d. From these we conclude that there are no coherent long-period variations (>1 d) above 2.1 mmag in the red and 6.6 mmag in the blue. This would rule out variability caused by surface spots as a result of an organized stable magnetic field.

We conclude that HR 7653 is a non-magnetic and non-pulsating (down to 0.5 mmag) classical single CP1 star.

Acknowledgements

The paper is based on data collected by the BRITE Constellation satellite mission, designed, built, launched, operated and supported by the Austrian Research Promotion Agency (FFG), the University of Vienna, the Technical University of Graz, the Canadian Space Agency (CSA), the University of Toronto Institute for Aerospace Studies (UTIAS), the Foundation for Polish Science & Technology (FNiTP MNiSW), and National Science Centre (NCN). A. Pigulski acknowledges support from the Polish NCN grant no. 2016/21/B/ST9/01126. A. Popowicz acknowledges support from the Polish NCN grant no. 2016/21/D/ST9/00656. GAW acknowledges Discovery Grant support from the Natural Sciences and Engineering Research Council (NSERC) of Canada. WW was supported by the Austrian Space Agency (FFG).

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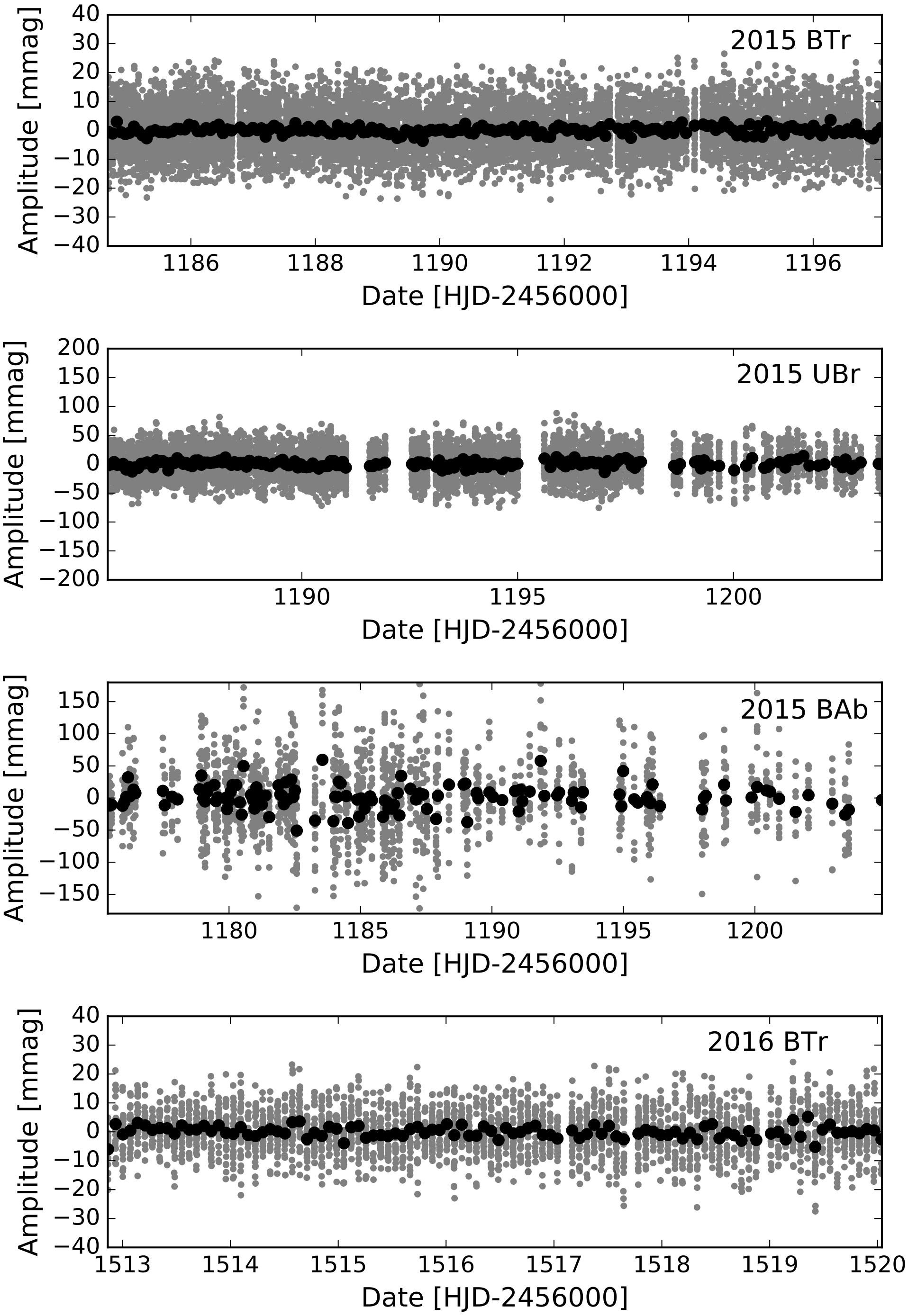

Fig. 3. BRITE photometry of 15 Vul after applying the decorrelations described in the text. The individual data points are shown as grey dots and the filled-circles indicate the per-orbit mean values.

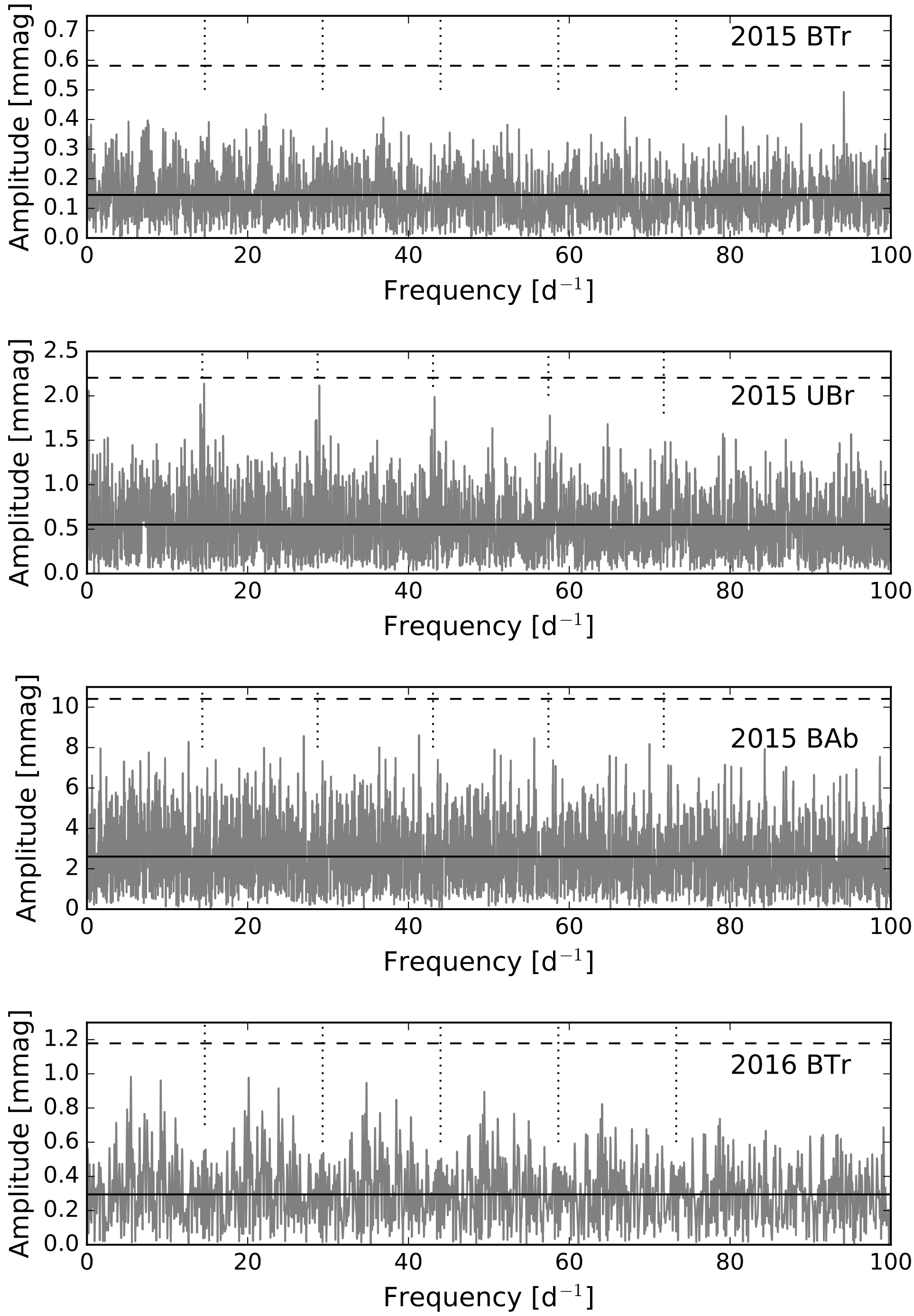

Fig. 4. Periodograms of BRITE data for 15 Vul. There is some signal due to aliases the satellites' orbital periods, as indicated by the vertical dotted lines. The median noise level is indicated by the horizontal line. There are no peaks higher than four times the noise level (horizontal dashed line).