# BRITE-Constellation: astrophysics with nano-satellites

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The BRITE nano-satellite mission is the first space mission which uses nano-satellites for photometry of stars. The mission comprises of a constellation of six satellites. Each of the three contributing countries, Austria, Canada, and Poland, buildt two satellites. For Austria and Poland these were the first national scientific satellites. By now, BRITE satellites gathered data for about 500 bright stars during 25 campaigns in the selected stellar fields. For most of the observed stars, BRITE photometry is the best photometry ever made. We show that the photometry allows to detect periodic signals with amplitudes as small as 0.1 – 0.2 mmag. This opens an unprecedented opportunity to study a low-level variability in very bright stars. Combined with other data, like spectroscopy or polarimetry, the BRITE data may allow for a comprehensive analysis of many astrophysical phenomena, especially in massive luminous stars, the primary targets of the BRITE mission. Some highlights of the science made using BRITE data are presented.

## 1 Introduction

The BRITE-Constellation (Weiss et al., 2014; Pablo et al., 2016) is the on-going space mission comprised of a constellation of five nano-satellites carrying out two-band photometry in wide fields. The idea of using so small satellites (BRITE satellites are cubes with a side of 20 cm) for photometry dates back to late 1990s[1], when Prof. S. Ruciński and his colleagues from the University of Toronto, Canada, discussed the possibilities of observing bright stars from space. The main technical problem discussed in the context of using nano-satellites in space was how to stabilize in three dimensions a spacecraft having a very small mass. The idea resulted in launching in 2003 the first Canadian space telescope MOST (Microvariability and Oscillations of STars, Rucinski et al., 2003; Walker et al., 2003), a micro-satellite of the size of $60\,\mathrm{cm} \times 60\,\mathrm{cm} \times 24\,\mathrm{cm}$.

The success of the MOST project, also in stabilizing a low-mass satellite, resulted in the development of the BRIght Target Explorer (BRITE) mission, which consists of six nano-satellites, launched in 2013 – 2014, now known as BRITE-Constellation. Five of the six launched BRITE nano-satellites (hereafter BRITEs) are working[2]. BRITEs were the first nano-satellites aimed at doing space photometry in the visual domain. Presently, we witness an enormous increase of the number of launched nano-satellites, used for many purposes, including science (see, for example, Koudelka

[1]For the early history of the BRITE mission see the article by Slavek Rucinski, http://www.astro.utoronto.ca/~rucinski/BRITE/Early_history_of_BRITE.pdf

[2]One of the Canadian BRITEs, BRITE-Montréal (BMb), did not detach from the launching rocket for unknown reasons and has been lost.

et al., 2017). The BRITE satellites host wide-field ($20° \times 24°$ field of view) 3-cm refracting telescopes, which feed uncooled CCD detectors. The stellar images are intentionally defocused to spread stellar profiles over larger area. The angular resolution in BRITE images is of the order of a few arc minutes.

The idea of using nano-satellites for scientific space missions has many advantages, of which a relatively low cost is of the primary importance. Such a satellite can be afforded even by a single university, like in the case of UniBRITE (UBr), funded by University of Vienna, Austria. This is also a good starting point for countries, which begin to develop their own space industry. The BRITEs are good examples, because they are the first Austrian and Polish scientific satellites. Building nano-satellites allows to achieve know-how required to successfully design much more advanced space projects in the future.

## 2 The BRITE sky

Originally, it was expected that BRITEs would provide data only for stars brighter than fourth magnitude in $V$ band (e.g., Weiss et al., 2008) with a possibility of somewhat less precise photometry for fainter stars achieved by means of the on-board stacking. Such a limiting magnitude would mean that the sample of the possible targets would consist of only about 500 brightest stars in the sky. While on-board stacking has been abandoned after several trials,[3] the reality showed that good-quality photometry can be obtained for targets as faint as 6th magnitude, especially when observing with red-filter BRITEs with longer-than-average exposure times. This increased the number of potential BRITE targets several times. The median $V$ magnitude of 452 stars observed by BRITEs by now amounts to 4.23 mag, ranging between −0.7 (Canopus) and 7.7 (WR 40) mag.

The BRITE targets are observed in campaigns, which typically last 5 − 6 months, during which a series of images for 10 − 40 pre-selected bright targets in the observed field (named after covered constellation(s)) is acquired by two or three BRITEs[4]. The photometry is reduced by means of the photometric pipelines described by Popowicz et al. (2017). Fig. 1 shows the location of BRITE fields observed so far in the sky. With one exception, they are located close to the Galactic plane, predominantly in the southern hemisphere along the Gould Belt.

Having a small telescope in space, the observing possibility is naturally limited to the brightest stars. There is, however, an important scientific motivation behind observing the brightest stars. The bright sky is dominated by intrinsically luminous stars, which are very important in the context of stellar and galaxy evolution. Most of these stars are massive enough to end their stellar lives as the core-collapse supernovae. Therefore, recognizing details of their internal structure may have a major impact on many branches of astrophysics. There are also many other assets of studying bright stars. They usually have a long record of archival observations, especially spectroscopic. Even if not, the new spectroscopy can be easily achieved

[3]The main reason for suspending stacking observations was the imperfect stability of satellites in the presence of a large number of hot pixels.

[4]This observing strategy is aimed at obtaining two-band photometry. However, there are exceptions. If a field is not rich in very bright stars, only a single red-filter satellite makes observations with longer-than-typical exposures, optimized for fainter stars. An exception is also the Crux/Carina I field, in which all five BRITEs made observations.

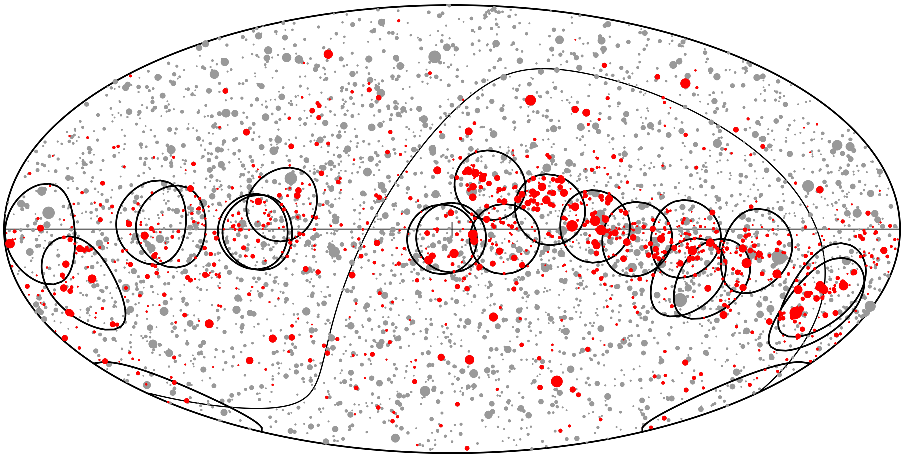

Fig. 1: Stars brighter than $V = 6$ mag in Galactic coordinates shown in the Aitoff projection. The horizontal line marks the Galactic plane; the curved one, the celestial equator. The BRITE fields observed by now are encircled. Stars of spectral types O and B are shown with red colour, the remaining stars are plotted with grey dots.

with a small (that is, no-time-allocation-committee) telescope[5]. Bright stars happen to be relatively close, which means that some of them may have interferometric orbits. This allows to derive stellar masses for non-eclipsing systems; a good example is $\beta$ Cen (Pigulski et al., 2016). BRITE mission is also accompanied by the spectropolarimetric survey of bright stars (Neiner et al., 2017), extremely useful for the studies of magnetic stars.

The field selection in BRITE project is aimed at maximizing the scientific output, but has also technical limitations (e.g., relatively large number of bright stars is needed for efficient tracking). Fortunately, the near-Galactic plane fields comply with this requirement: they contain large number of bright targets proposed for scientific studies. The bright star sample within the reach of BRITEs is dominated by the hot massive objects. Nearly 60% of all stars observed by BRITE, are stars of spectral types O and B at the main-sequence and early post-main sequence stages of evolution (Fig. 1). This fact defines the possible science that can be made with the BRITE sample; some examples are given in the next section.

Finally, BRITEs can be used for observing targets of opportunity. An example of this kind of observation was the 2016 − 2017 campaign in the Vela/Pictor II field, in which one of the primary targets was $\beta$ Pic. The campaign lasted much longer than a typical 140 − 180 days and was extended to 229 days. All this in the hope that the predicted eclipse by the Hill's sphere of $\beta$ Pic b planet (Wang et al., 2016; Stuik et al., 2017) would be detected.

[5]The ground-based support to BRITE is organized within the Ground-Based Observing Team (GBOT), http://www.univie.ac.at/brite-constellation/gbot/gbot-facilities/.

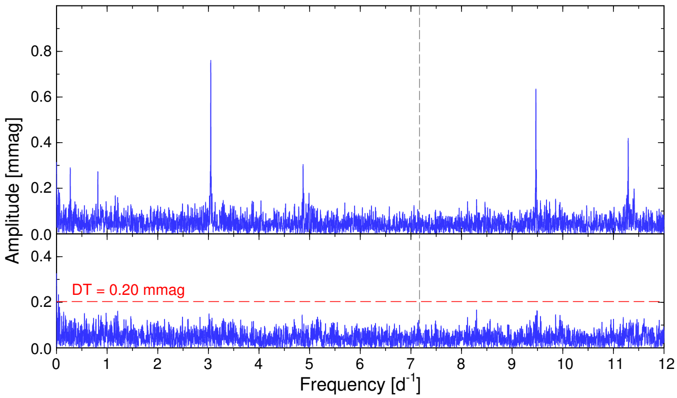


Fig. 2: Top panel: Fourier frequency spectrum of the combined blue- and red-filter data of the new $\beta$ Cep/SPB hybrid star $\alpha$ Cru. Botom panel: Frequency spectrum of the residuals after subtracting the detected four terms. The dashed horizontal line corresponds to the detection threshold, DT, of four times the average noise. Nyquist frequency related to the orbital sampling is shown as a vertical dashed line.

## 3 Several science highlights

The BRITE mission is aimed at obtaining precise two-band photometry, subsequently used to characterize stellar variability. Most of the targets observed by BRITEs show variability on the time scale of hours and days. The variability is due to pulsations, rotation, binarity and other phenomena. Therefore, the optimal length of the BRITE campaign was chosen to be several months, limited also by the constraints dictated by the low-Earth orbits. The precision of the photometry achieved with the BRITE data depends on magnitude, but a general conclusion is that for stars brighter than fourth magnitude the precision (per orbit) is better than 1 mmag (Popowicz et al., 2017). During several months of observation, 1000 – 1500 orbits were covered. These numbers translate into the detection threshold of the order of 0.1 – 0.2 mmag in the best cases, which is the amplitude limit for detecting periodic signals in the BRITE data. This means that for virtually all observed objects BRITEs provide the best photometry ever made. Fig. 2 shows an example of a variable star discovered with BRITE photometry. In this case, the detection threshold of about 0.2 mmag was achieved. This allowed to find four pulsation modes, all with amplitudes below 1 mmag.

The limited space of this article allows to present only a few scientific results of the mission. The subjectively chosen examples of the BRITE science are the following.

- *O-type stars.* The intrinsic variability of O-type stars is complicated and its true nature is far from being understood. One of the most important problems is the location of the source of variability (surface, stellar wind) and its origin (pulsation, rotation, magnetic field, density clumps in the wind). With BRITE data, the number of O-type stars observed from space was nearly doubled. The most massive (and the brightest in the sky) O-type star observed by BRITEs is the O4 I(n)fp star $\zeta$ Pup. BRITE photometry allowed Ramiaramanantsoa et al. (2018) characterize its variability as a superposition of the rotation-induced periodic variability and a stochastic component. By combining photometric data with spectroscopy, these authors showed for the first time that the two Corotating Interaction Regions (CIRs) are driven by bright photospheric spots, which also cause periodic photometric variability. They also showed that the spectroscopic evidence of wind clumps correlates with the amplitude of stochastic variability, which means that wind clumps have likely photospheric origin.

- *Be stars.* One of the problems related to Be stars, the non-supergiant fast-rotating B-type stars showing emission in H$\alpha$, is the explanation how stellar matter is transferred from star into the circumstellar decretion disk in the situation when rotation is sub-critical. The solution, based on the interaction of closely-spaced $g$ modes, has been proposed in the past on the grounds of spectroscopy (Rivinius et al., 1998), but this scenario got a strong support using BRITE data. Baade et al. (2016, 2017, 2018) showed that at least in some stars, the 'outbursts' during which the matter is transferred into the disk occur due to the interaction of two closely-spaced (and observed in photometry) $g$ modes.

- *Main-sequence pulsating stars.* An in-depth seismic modelling of $\beta$ Cep stars, $p$-mode massive main-sequence pulsators, was possible by now only for a handful of stars showing a dozen or so pulsation modes. With BRITE data, this number was expected to be significantly increased, and this is indeed the case. BRITE data reveal the presence of a large number of low-amplitude modes in many stars, enabling to make a progress in their seismic modelling, the more that many stellar parameters, like masses, can be precisely derived for some of them. A good example is the mentioned $\beta$ Cen (Pigulski et al., 2016), for which BRITE data allowed to find 17 pulsation modes, of which only two were known earlier. Even for $\nu$ Eri, a target of several extensive ground-based observing campaigns, six new $g$ modes were found in BRITE photometry (Handler et al., 2017). In general, BRITE data allowed to reveal $g$ modes in many known $\beta$ Cep-type stars. This shows that hybridity is a very common phenomenon among early B-type stars. Some interesting results were also obtained for less massive main-sequence pulsators. Kallinger et al. (2017) found that the internal rotation of the SPB-type star V389 Cyg is slow, but the outer layers rotate two orders of magnitude faster due to tidal spinning up by the companion. Zwintz et al. (2017) identified period-spacing pattern in the frequency spectrum of the $\gamma$ Dor star 43 Cyg, which allowed them to constrain the internal rotation rate in this star.

- *Binaries.* About a half of a sample of BRITE targets are binaries, including many close ones. Pablo et al. (2017) discovered the first massive (total mass of about $36\,\mathrm{M}_\odot$) heartbeat star with tidally excited oscillations (TEOs). This is $\iota$ Ori, in which at least five TEOs were found in BRITE photometry. Several other massive heartbeat stars were already identified in the BRITE data. BRITE photometry allowed also to discover $p$-mode pulsations in several very close binaries, some of which are eclipsing (Pigulski et al., 2017). In this way, the damping effect of a distortion of a companion on $p$-mode pulsations can be studied observationally.

BRITE observations satisfy and sometimes even exceed the expectations. The first published science as well as the preliminary analysis of the data we work on, already allows to announce the success of the mission. Nevertheless, the mission is ongoing and all five satellites are still gathering data. This makes the perspectives of doing science with BRITE data promising, especially for objects, for which the study of variability on a time scale longer than a single BRITE campaign is crucial.

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