Bright BRITE Science Results

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With BRITE-Constellation entering its fourth year of science operations, it is timely to look at the results obtained already. They form a rich map of contemporary precision physics of stars mostly more massive than the Sun. A structured summarizing outline is given.

1 Introduction: BRITEland

When BRITE-Constellation was conceived and built (Weiss et al., 2014), asteroseismology was at the top of the list of its science objectives. In the first ∼4 years of science operations, this obvious expectation was fully confirmed by the results obtained. In addition, a much clearer view has emerged of what other fields BRITE is making important contributions to: Binaries, circumstellar matter, exoplanets, magnetic fields, stellar rotation, mass loss, stellar winds, etc. all add extra dimensions. These dimensions do not define parallel worlds. Instead, where they intersect, ideas collide and become seeds of new studies. One of the foundations of the BRITE-Constellation concept has also been nicely confirmed: For bright stars, long, dense series of high-quality spectra either exist already or new ones can be obtained, and the same holds for wavelengths other than those covered by BRITE and/or other observing techniques.

The BRITE science homeland is best delineated in the Hertzsprung-Russell diagram and extends from Luminous Blue Variables at the hot and red supergiants at the cool luminous end, both with mostly slow variations, to δ Scuti, γ Dor, and rapidly oscillating Ap stars at the low-luminosity/rapid-variability end. For parallel observations in the blue and the red BRITE passbands, the B spectral class is the sweet spot because, around these temperatures, both passbands produce data with similar signal-to-noise ratio.

This overview is based on all publications available in the SAO/NASA Astrophysics Data System (Kurtz et al., 2000) at the time of the Third BRITE-Constellation Science Conference and on the presentations made at Special Session SS 17 of the 2017 European Week of Astronomy and Space Science[1]. Papers included in these proceedings of the Third BRITE-Constellation Science Conference are only very briefly mentioned and referenced as "BSC3". Papers that appeared in the proceedings of the Second BRITE-Constellation Science Conference (eds. K. Zwintz and E. Poretti), which took place in Innsbruck (Austria) in 2016, are here identified as "BSC2". Proceedings are not available from the first BRITE-Constellation Science Conference (2015 in Gdańsk Sobieszewo, Poland).

[1] http://space.asu. cas.cz/ ewass17-soc/Presentations/SS17.html; referred to below as "EWASS"

2 Stellar pulsations

2.1 Pulsating stars in binaries

Asteroseismology yields precise stellar masses and radii; however, without additional constraints, both mass and radius cannot be obtained. In the pre-Gaia era, stellar radii were notoriously imprecise. However, even Gaia cannot overcome the uncertainties resulting from interstellar extinction. Therefore, it is very important to study pulsating stars in binaries for which accurate radii and/or masses have been derived (radius determinations are typically technically easier). The price to be paid is that the assignment of pulsation frequencies to the members of a binary can be ambiguous.

One of the first BRITE-based publications (Pigulski et al., 2016) concerned β Cen which consists of two giants with fairly similar mass, both of which are probably hybrid SPB/β Cep stars. This pair has a visual companion. A total of eight probable g-mode and nine probable p-mode frequencies were identified. The orbital period is close to a year (357 d) so that it is difficult to cross-identify stars and frequencies.

It has been suggested (e.g., Waelkens & Rufener, 1983) that, in very close binaries, p-mode pulsations are not excited or are strongly damped. BRITE observations (Pigulski, EWASS) of the very close ($P_{orb} = 1.7$ d) 17+9 $M_\odot$ eclipsing binary δ Pic detected a frequency near 6.5 c/d with a semi-amplitude of 2.4 mmag, rendering the β Cep component the most distorted pulsating star known. Since pulsation amplitudes in some less-distorted stars are higher, an anti-correlation between distortion and p-mode amplitude is not excluded.

Pulsations can also be used to trace other effects exerted by a companion, for instance on the internal stellar structure. HD 201433 contains an SPB star in a close binary ($P_{orb} = 3.3$ d) with a distant ($P_{orb} = 154$ d) companion. From optical spectra, Kallinger et al. (2017) derive a surface rotation period near 5 d. In the BRITE photometry, they find an increase of the rotational splitting with frequency indicative of non-rigid rotation. The authors' modeling of the frequency spectrum suggests that the stellar core rotates with a period around 330 d, providing strong evidence of substantial tidal acceleration of the surface rotation.

2.2 Orbitally induced pulsations (heartbeats)

So-called heartbeat light curves (Fuller, 2017, and references therein) can occur during periastron passages in close eccentric binaries and are composed of tidally excited pulsations of one or both stars and of a complex single feature resulting from the distortion of the stars and their mutual irradiation around their closest approach. Resonances can arise from chance coincidences of orbital overtone frequencies with stellar eigenfrequencies or, in some cases, from the locking of tidal distortions to an eigenmode. The observable signature of the distortion+irradiation is very sensitive to the inclination angle which is uniquely encapsulated in the variability. As a result, the inclination angle can be modelled with an accuracy of a fraction of a degree, even in non-eclipsing systems and in the absence of interferometric data.

Although about 1/10 of all massive stars are magnetic (Wade et al., 2014), only a few binaries are known to include a high-mass magnetic star. In ϵ Lup, both stars of the inner 4.6-d pair are magnetic, with opposite polarities. Mass and radius determinations therefore provide a unique opportunity for comparison with model calculations. As shown by Wade et al. (EWASS), the nominal accuracy of 0.1 deg of heartbeat-driven inclination-angle measurements is required to permit meaningful conclusions - not a straightforward task, even for eclipsing binaries. One of the most massive binaries (about 23 + 19 $M_\odot$) with a diagnosed heartbeat is ι Ori; the BRITE observations were modeled by Pablo et al. (2017). Pigulski (BSC3) presented similar analyses of BRITE observations of the two systems τ Ori and τ Lib.

2.3 Isolated pulsating stars

Pulsating stars studied in isolation may well be members of binary or multiple systems. However, the presence of a companion does not enter into the analysis.

Classical δ Cephei stars are still the synonym of pulsating stars. BRITE has observed nine of them (Smolenski et al., BSC2, EWASS, and BSC3), which is nearly as many as contributed by all other space photometers together. However, δ Cepheids are not nearly as simple as elementary textbooks suggest. Most of them form well-defined sequences in Petersen diagrams (overtone to fundamental mode period ratio vs. period of fundamental mode), but only long sequences of consecutive pulsation cycles observed with space precision, as enabled by BRITE, reveal significant deviations from strictly repetitive light curves. These variations of the light-curve shapes may result from resonances with nonradial modes or contain stochastic elements. They do not require a recalibration of the cosmic yardstick, but δ Cephei stars may not be precision standard candles because their mean brightness cannot be derived with confidence from single-cycle observations.

α Cir is the brightest rapidly oscillating Ap star. The BRITE light curve exhibits the typical overall pattern of an oblique magnetic pulsator although the signature of the spot around the south pole was not unambiguously detected (Weiss et al., 2016). Also, the oscillatory phase shifts of the pulsation frequencies are in agreement with this model. For the periods as short as 5-10 min, these observations made good use of the temporal signal sampling delivered by BRITE-Constellation. Since this study reported one of the very first results obtained with BRITE, the good agreement with earlier space photometry from the star tracker of the WIRE satellite (Bruntt et al., 2009) provided an important initial quality assurance.

Another comprehensive comparison was performed by Handler et al. (2017) between BRITE space and multi-site ground-based photometry. The much cleaner BRITE window function enabled the resolution of various aliasing issues, and changes in both amplitude and frequency were also measured. In addition to nine p modes, there are seven g modes, six of which were discovered with BRITE. The authors attribute this latter achievement to superior noise characteristics of BRITE at frequencies around 0.5 c/d. The ability to study both p and g modes in such hybrid SPB/β Cep stars is of high importance for tests of pulsation models.

In fact, because opacity makes stars non-transparent, the ultimate goal of the study of pulsating stars is the comparison of frequencies found in observations and stellar models. On the other hand, opacity has the capacity of reducing detailed confrontations of data and models to very crude affairs. Such failed comparisons occur if models do not feature frequencies in the range where they are observed. While there may be many reasons for this, Daszyńska-Daszkiewicz et al. (BSC2, 2017, BSC3) argue that the proper reproduction of p modes and the at most marginal excitation of g modes in models for several hybrid SPB/β Cep stars suggests a problem with the opacities used. This work strongly underlines the importance of equipment such as BRITE that can study p modes and g modes simultaneously and with little bias.

The doubt raised by Daszyńska-Daszkiewicz et al. (2017) in the standard opacities finds support in the fact that their ad hoc modifications of OPLIB opacities at the same three temperatures produce a satisfactory agreement for five different stars. In the most critical temperature range around log T = 5.46, the contribution by nickel to the opacity is maximal. The ultimate photometric model discriminator would be the ratio of the bolometric flux perturbation to the radial displacement at the photospheric level. Unfortunately, the separation in wavelength between the blue and the red BRITE passband is not quite large enough to measure this ratio.

In BRITEland as defined in the Introduction, the instability region nearest the Sun is that of the g-mode γ Dor variables. It is also populated with the coolest δ Scu stars, which are p-mode pulsators. γ Dor stars are interesting because their pulsations are driven by periodic convective flux blocking. Frequencies near 1 c/d make them difficult targets for ground-based observations. The first studies with BRITE of a γ Dor star (Goessl et al., EWASS; Zwintz et al., 2017) found a decrease of the frequency spacing with frequency, i.e., an inward increase of the rotation frequency. Superimposed wiggles in the period-spacing pattern also suggest one or two zones with major chemical gradients and, therefore, are indicative of low mixing.

3 Magnetic fields, stellar winds, pulsationally driven mass loss, and convetive overshooting

With a fraction of about one tenth of all massive stars (Wade et al., 2014), magnetic stars form an important group of photometrically variable massive stars. The main timescale is rotation, which modulates the aspect of magnetospheres (where present), the geometry of wind flow lines, the amount of wind absorption, the appearance of star spots, etc. A BRITE example that is well illustrated in combination with optical and UV spectroscopy is the supergiant ζ Ori (Buysschaert et al., 2017). A general review of magnetic stars observed by BRITE is available from Shultz (BSC3). The largest ground-based observing campaign prompted by BRITE has been dedicated to spectropolarimetry of all 573 stars brighter than 4th magnitude in V (Neiner et al., BSC2). This campaign has led to the discovery of several dozen new magnetic stars.

Stellar winds block part of the stellar flux and re-radiate it to the photosphere, the temperature of which is thereby increased. If this so-called line blanketing is time dependent, it may be photometrically detectable. For instance, part of the rotational variability of magnetic stars should be due to variable line blanketing. Krtička & Feldmeier (EWASS) added the interesting idea that the high intrinsic instability of radiatively driven winds could lead to rapid stochastic flux variations. For their firm identification, one would ideally combine space photometry with high-definition spectroscopy of wind line profiles. It could be most intriguing to monitor simultaneously so-called Discrete Absorption Components (DACs) of wind lines. A BRITE-intensive review of photosphere-wind connections in luminous O-type stars was prepared by Ramiaramanantsoa et al. (BSC3).

Measuring the mass-loss rates due to stellar winds requires simultaneous knowledge of the velocity and the temperature/ionization profiles. An additional sanity check point is, therefore, very valuable. Such an opportunity arises in the case of colliding winds. Richardson et al. (2017) found that, in the O7.5+WC8 system γ^2 Vel, the BRITE light curve tracks the equivalent width of the C III 5696 wind line. Accordingly, there is little continuum variability, and the authors conclude that variations of both excess light and excess line emission are proportional to the inverse of the orbital separation of the two stars.

Be stars build self-ejected disks but are near-main-sequence stars and, therefore, do not possess strong photospheric radiative winds. The disk matter is probably elevated above the photosphere by the combination of rapid rotation (about 80% of the critical rate) and nonradial pulsation. The multi-mode character of the pulsation leads to mass-loss episodes which may be repetitive on a very wide range of timescales (Rivinius et al., BSC2; Baade et al., BSC2 and BSC3; Baade et al., 2016, 2017).

Even without seismology-enabling pulsations, photometry and spectroscopy can reveal important information about internal parameters. As Ratajczak et al. (BSC2, EWASS, BSC3) illustrate, the empirical mass-radius relation for massive eclipsing binaries can discriminate between evolutionary models with different values of the convective-overshoot parameter.

4 Accretion and debris disks

When stars evolving in a close binary system reach their Roche limit, matter begins to overflow to the companion where it collects in an accretion disk. One of the first variable stars discovered was β Lyrae which is a mass-exchanging binary undergoing eclipses with a period of nearly 13 d. For a long time, β Lyr seemed to contradict stellar evolution theory because the more massive component remained invisible in spectra. Eventually, it was realized that the current primary (and former secondary) is permanently occulted by a thick accretion disk. Rucinski et al. (BSC3) analyzed the very detailed light curve secured by BRITE. Using the same data with 10 secondary minima in 2016, Pavlovski et al. (EWASS) reconstructed edge-on images of the disk as seen at several orbital phases.

β Pic is one of the few pre-main-sequence stars within reach of BRITE. Among them, this star is currently unique in that it has (at least) one planet. The $\sim$20-year orbit of β Pic b is probably not eclipsing. On the other hand, it is seen at such a large angle that its Hill sphere may transit the central star. This opens up the exciting possibility that a circumplanetary ring or a moon may be discovered. By the time of BSC3, this had not yet happened (Zwintz et al.) but another time window exists after the return of β Pic from behind the Sun in 2017 November.

5 Conclusions

BRITE-Constellation is characterized by

- high cadence
- long monitoring intervals
- good stability and clean window function
- pipeline data processing
- a large and growing archive

Therefore, BRITE-Constellation is the space photometer of choice for stars brighter than 5.5 mag to study

- pulsations (rotational, chemical, and density profiles; opacities)
- surface structures (magnetic fields, starspots)
- mass loss (radiatively and/or pulsationally driven)
- circumstellar matter (accretion, decretion, and debris disks; ejecta)
- eclipses (stars, disks), transits (Hill spheres of exoplanets), and tidal effects (heartbeats).

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