The BRITE Nano-Satellite Constellation Mission

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Abstract

BRITE-Constellation, short for "BRIght Target Explorer - Constellation," is a group of six seven-kilogram nanosatellites from Austria, Poland and Canada carrying three-centimeter aperture optical telescopes. The purpose of the mission is to photometrically measure low-level oscillations and temperature variations in stars brighter than visual magnitude 4.0, with unprecedented precision and temporal coverage not achievable through terrestrial-based methods. These stars turn out, for the most part, to be among the most luminous – either massive stars during their whole lifetimes or medium-mass stars at the very end of their nuclear burning phases. Such stars dominate the ecology of the Universe and the current massive ones are believed to represent the lower mass-range of the first stars ever formed (although long gone from the local Universe). Astronomers are eager to measure the variable behavior of luminous stars in order to explore their inner workings in a unique way. BRITE-Constellation will investigate the role that stellar winds play in setting up future stellar life cycles, and will measure pulsations to probe the histories and ages of luminous stars through asteroseismology. Furthermore, as tests with engineering models have demonstrated, it will probably be possible to perform photometry with reduced accuracy of many more stars down to perhaps magnitude 7. The three-axis pointing performance (1 arcminute RMS stability) of each BRITE satellite is a significant advancement by the University of Toronto's Space Flight Laboratory over anything that has ever flown before on a nanosatellite, and is a critical element that enables this high precision photometry mission. The University of Vienna and FFG/ALR (Austria's space agency) are financing the development of two satellites and development is nearing completion while the Polish Academy of Sciences is preparing two additional satellites. The Canadian Space Agency is expected to fund soon two satellites in the Constellation. This paper will summarize the science objectives of the mission and describe the progress to date.

Introduction

Luminous stars dominate the ecology of the Universe. During their relatively brief lives, massive luminous stars gradually eject enriched gas into the interstellar medium, adding heavy elements critical to the formation of future stars, terrestrial planets and organics. In their spectacular deaths as supernova explosions, massive stars with initial mass above 8 solar masses violently inject even more crucial ingredients into the mix. The first generation of massive stars in the history of the Universe may have laid the imprint for all future stellar history. Yet, massive stars – rapidly spinning and with radiation fields whose pressure resists gravity itself – are arguably the least understood, despite being the brightest members of the familiar constellations of the night sky. Other less-massive stars, in the range ~1-8 solar masses, also contribute to the ecology of the Universe only at the end of their lives, when they brighten by factors of a thousand and shed off their outer tenuous layers. They are thus feeding the Interstellar

Medium with heavy elements, which play a crucial role in generating and evolving stars of the next generation.

A group of nanosatellites in space, called BRITE-Constellation (BRIght Target Explorer - Constellation), will capture the light shed by luminous stars and in turn shed light on their structures and histories, uncovering unique clues to the origins of our own Sun and Earth. The BRITE-Constellation will be a cost-effective fleet of six nanosatellites based on pioneering Canadian space technology, built in partnership with Austrian, Canadian and Polish space scientists. The BRITE nanosats will survey the sky, measuring the brightness and temperature variations of the brightest stars on timescales ranging from hours to months, and possibly even years. The photometric data of luminous stars will provide time series with unprecedented precision that cannot be obtained from the ground even with larger telescopes due to limitations imposed by the terrestrial atmosphere. Furthermore, high spectral and time resolution spectroscopy can be obtained for these bright stars even with moderately sized telescope which can be much easier accessed than large 8m-class telescopes. Such complimentary observations are imperative for a full exploitation of the scientific information carried by high precision photometry – and vice verse – by spectroscopy. BRITE-Constellation will investigate the role stellar winds play in setting up future stellar life cycles, and reveal pulsations that will allow astronomers to probe luminous star histories and ages through *asteroseismology*.

Each BRITE nanosat will carry a telescope (with no moving parts, hence only one bandpass filter per satellite) and detector with a large field of view (~25 degrees across) that can monitor multiple target stars, so that differential photometry can be obtained both in brightness and color with precision better than 0.1% for a single observation. The Constellation of six BRITE nanosats offers an order-of-magnitude improvement in science return over a single nanosat, since it allows the use of a different filter in each satellite and provides much better time and sky coverage.

The BRITE network will also collect this quality of data on a wide variety of other star types and phenomena. For example, the detection of exoplanetary transits around other stars will put our own planetary system in context, and the pulsations of red giants will test and refine models of the eventual fate of the Sun.

BRITE-Constellation will be the first network of satellites devoted to a fundamental problem in astrophysics, extending and supplementing the spectacular success of SFL with the Canadian MOST microsatellite into the domain of nanosats and providing on-orbit experience for future coordinated satellite networks. With its multi-color option and basically unlimited access to the entire sky, BRITE-Constellation occupies a research niche not accessible to the current much larger space photometric missions, namely CoRoT and Kepler. BRITE-Constellation will exploit and enhance recent Canadian advances in precise attitude control that have opened up for space science the domain of very low cost, miniature spacecraft, allowing a scientific return that otherwise would have had price tags 10 to 100 times higher. BRITE-Constellation will allow the Canadian space industry and scientific community to extend their leading positions in smallsat technologies and stellar astrophysics.

The BRITE-Constellation will consist of six virtually identical nanosatellites, each about seven kilograms in mass and 20x20x20cm in dimensions. Several key technologies for the BRITE satellites are available from the CanX-2 nanosatellite project (launched in early 2007) and the CanX-4/CanX-5 formation flying mission (launched in late 2008). BRITE has been designated CanX-3 by the UTIAS Space Flight Laboratory. This paper summarizes the main scientific objectives of BRITE and provides the current design status.

Science Objectives

The primary goal of BRITE-Constellation is to constrain the basic properties of intrinsically luminous stars – i.e. stars that most affect the ecology of the Universe – by measuring their oscillations on time scales less than an hour to months, based on multi-broadband, ultra-high precision, and continuous photometric time-series from space. The science objectives are:

- To understand luminous stars and the life-cycle of matter.
- To investigate the variability and structure of the most luminous stars in our Galaxy.

Life Cycle of Matter

The Big Bang led to a Universe in which matter existed in the form of hydrogen and helium, plus a smattering of lithium and beryllium. Heavier elements did not exist and hence no planets like Earth or life as we know it were possible. About 400 million years after the Big Bang, however, gravity had caused the densest regions of this primordial gas to collapse locally. The first stars had formed, and the life cycle of matter had started. In this cycle, driven by stars like a motor, matter is continuously transformed between hot plasma in stars and cool dust and gas in the Interstellar Medium (ISM). In each cycle, stellar nuclear processes transform hydrogen and helium into heavier elements (the latter being summarized as metals). Some of these are returned to the ISM, and thus the ISM is enriched. Understanding this life cycle of matter is thus crucial for understanding not only the evolution of stars, but also the evolution of the galaxies in which they live, and the formation of planets like Earth (see Figure 1).

For all stages of stellar evolution – condensation from the ISM, ignition of hydrogen, evolution to giants, and eventually ending their lives with either a whimper or a bang – there is a strict rule: massive stars are hotter, develop faster and die earlier. Despite their much lower mass, smaller stars survive well beyond the short lives of their massive brethren: they have less fuel but are so much less luminous that they last much longer. Indeed, there are still low mass (less than 1 solar mass) stars that were formed as part of the first or second stellar generation. They are nearly as old as our Universe and we can see the paucity of metals in the early Universe in their spectra.

Stars spend 80 to 90 percent of their lives in a stage called the Main Sequence (MS), where their source of power is the fusion of hydrogen into helium. For a star like the Sun, this phase lasts about 10 billion years, and, like the Sun, 95 percent of all stars born so far are still in this stage. On the other hand, stars with more than 8 solar masses live only less than 100 million years and, therefore, hundreds to thousands of generations of “heavyweights” have come and gone since the Big Bang. These massive stars have dominated the chemical evolution of our Universe.

Roughly 97 percent of single stars or stars in wide binaries that evolved off the MS within the ~14 billion years since the Big Bang became Asymptotic Giant Branch (AGB) stars (stars that first burn hydrogen then helium then have degenerate carbon and oxygen cores, then becoming large and luminous before finally contracting to the nuclearly inert White Dwarf stage). The nuclear reactions that occur in AGB stars are responsible for at least half of the carbon in the Universe, and for approximately 200 neutron-rich isotopes of elements like tin, cadmium, and lead. Observations show that AGB stars pulsate and lose matter in the form of powerful winds which carry out freshly made carbon and neutron-rich elements as well as dust grains that have formed in the star’s relatively cool outer atmosphere. By producing the dust grains that so efficiently cool molecular gas clouds (of which stars are born!), AGB stars pave the way for the formation of the next generation of stars and planets.

The most massive stars follow a different path from that of their smaller brethren. After a relatively brief MS phase, a single star that started out with 8 or more solar masses also forms a carbon-oxygen core. But this core is not degenerate, and hence can contract until another set of nuclear reactions kicks in, producing neon nuclei as well as more oxygen. The cycle of contracting, heating, and ignition continues until a core of iron-peak elements is formed, and no further energy generation by nuclear fusion processes is possible. As lighter elements progressively continue to burn in shells above it, the iron core grows in mass beyond 1.4 solar masses. At that point, it becomes unstable and collapses in only a fraction of a second. Almost all of the gravitational potential energy is released and the star's outer layers are expelled at high velocities – astronomers observe a Type II or, for the most massive stars, a Type Ib or Ic Supernova. This process returns to the ISM chemical elements produced in their interiors, as well as during the explosion.

Metals dominate the opacity of matter and hence govern a star's structure through their influence on the balance of collapse and nuclear energy production. Metals determine the onset of turbulent mixing and therefore the speed of stellar evolution. More generally, life on earth – and eventually beyond – would be impossible without metals, all generated in stellar processes and being part of the life cycle of matter.

Obviously, the importance of massive stars is significantly out of proportion to their scant number. But through their strong stellar winds and eventually explosion as a supernova, they provide most of the mechanical energy input into the ISM. They also generate most of the UV ionizing radiation in galaxies and power the far-IR luminosities through the heating of dust – besides being the primary sources of C, N, and O enrichment of the ISM. Massive stars contribute to the most energetic phenomenon yet found, emitting gamma-ray bursts as they collapse into black holes.

The evolution of massive stars is difficult to model, mostly because they lose significant mass in strong winds, which are driven by radiation pressure acting on spectral lines of highly ionized metals. A significant fraction of the mass of a very massive star is lost already during its core-hydrogen MS lifetime, followed by a very unstable post MS phase – we observe the remaining bare helium cores as so-called Wolf-Rayet stars. Again, the presence and amount of metals comes into play. In a similar vein, metals also influence the star-formation process and affect the distribution of initial masses, as well as the highest mass, with which stars are born.

But winds are not the only uncertainty in our understanding of massive stars: mixing and convection, and the effects of rotation and stellar magnetic fields, are other physical processes that we presently do not know how to treat properly, yet are certain to affect the behaviour and evolution of massive stars. As an integral part of testing and constraining the models, new observations are urgently required.

Figure 1: NGC 346, a stellar cluster with ongoing star formation (HST image).

Variability and Structure of Stars

Many stars vary in brightness, and these variations help us understand the stars, their evolution and their internal structure. A wide range of phenomena opens up between two extremes. Supernova explosions and gamma-ray bursts present one extreme, when a single star becomes as bright as 10^{12} stars in a whole giant galaxy and can be seen at cosmological distances. At the other extreme of stellar variability are seismic oscillations, usually simultaneously excited in many modes, at the level of a few parts per million.

Similar to oscillations in the Earth and the Sun, stellar oscillations permit one to determine structural parameters such as the density distribution, internal rotation, or presence of magnetic fields. Detecting and analysing such miniscule asteroseismic oscillations in solar-type stars was the primary goal in building the highly successful micro-satellite mission MOST, the first Canadian astronomy satellite and the first Canadian research satellite to be launched in over 30 years, which was followed in 2006 by CoRoT and in 2009 by Kepler. The analysis of these data not only sheds light on how the Sun evolves, but also helps in understanding the oldest solar-type (i.e. moderate and low mass) stars which survived from the earliest stages of the Universe.

The project proposed here, BRITE-Constellation, is a complementary satellite project, which targets the most luminous stars. As discussed above, those luminous stars that are also massive, live short lives, typically thousands of times shorter than solar-type stars, yet their evolution is crucial for the Universe as their successive generations produce heavy elements, the material of which we are made. The most massive stars are much rarer than less massive ones, but their high luminosity gives them, along with lower-mass stars in their final high-luminosity phase, a tremendous advantage: They can be seen from large distances. In fact, the apparently brightest stars in the sky as viewed from Earth are at the same time – in the majority of cases – the intrinsically brightest stars. Thus, their variability can be studied with very modest sized instruments, as long as such instruments can be made to work stably and consistently over long periods of time of the order of days, weeks or months.
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Primary Stellar Targets

Intrinsically luminous stars that are the best targets for BRITE-Constellation fall into two groups:

1. Hot luminous stars – these are **O and B stars**, which make up about half of the stars brighter than V = 4.0. A study of the variability in O and B stars has the potential to lead to the solution of two of the outstanding problems of stellar structure and evolution: the size of convective cores in massive stars and the influence of rotation.
2. Cool luminous stars – these are **Asymptotic Giant Branch (AGB) Stars**, **Red Giants and Red Supergiants** (see Figure 2). High precision, long-time monitoring of these stars will help to measure the typical time scales involved in surface fluctuations and thus to constrain internal convection models in AGB stars and red supergiants.

The BRITE-Constellation

BRITE-Constellation aims to be a modest sized instrument operating in low Earth orbit, above the effects of the atmosphere, capable of fulfilling the science objectives as are described above. It consists of six nanosatellites, each equipped with a small-lens telescope, able to observe the brightest stars in the sky to visual magnitude 4.0, over a field-of-view of 25 degrees, with a sampling time of at least once per satellite orbit (typically 100 minutes), and with a differential brightness measurement accurate to at least 0.1% per sampling time (all numbers are minimum requirements; according to tests with an engineering model the actual performance will be better). A cluster of six satellites is needed to improve the duty cycle and to obtain colour information. Currently, three satellites are planned with a blue filter, two with a red filter and one with a UV filter, although the final decision on the latter is still pending.

In the microspace philosophy, nanosatellites and microsatellites are built with the notion that reliability is related to complexity and that simple satellites are intrinsically more reliable and less expensive. In this philosophy, mechanisms are avoided wherever possible to reduce complexity and development cost. By following this approach while acknowledging the need for two different optical filters, the concept of

BRITE-Constellation was born. The idea is to have each satellite carry a fixed optical filter with combinations of identical satellites providing crucial increased observational coverage.

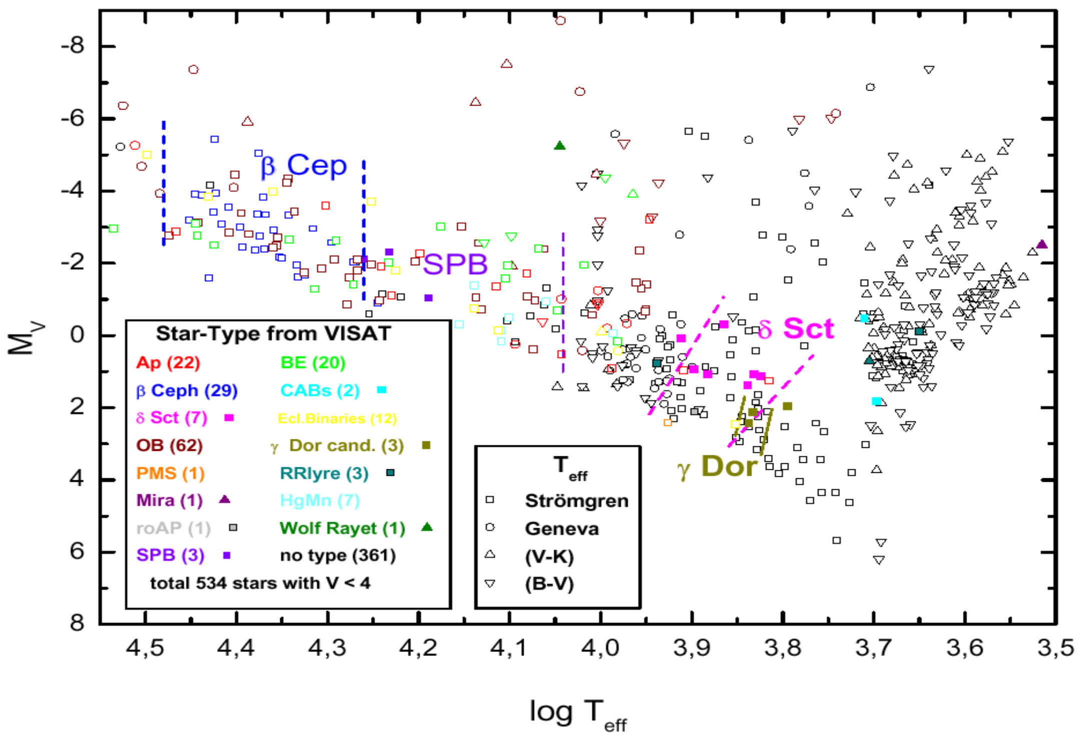

Figure 2: This is an H-R diagram of the ~600 stars brighter than V = 4 indicating also the diversity of some of the pulsating star types accessible to BRITE-Constellation. Temperatures have been estimated via various color systems, while M_V was derived from Hipparcos astrometric satellite parallaxes.

Colour Information

In the past, colour information in asteroseismology has proven to be very useful, if not crucial, not only for mode identification, but also to provide other physical information that is not contained in the one-filter oscillation frequencies themselves. Solar and solar-like asteroseismology is based on regular patterns seen in the oscillation frequencies of the asymptotic regime. So-called “avoided crossings” can destroy this regular pattern and render normal asteroseismology techniques useless, based on large and small differences and on echelle diagrams. Even moderate stellar rotation introduces asymmetries and coupling, which complicate even more any expected regular pattern. Indeed, most of our prime massive-star targets near the MS will have high rotation speeds. A method for mode identification is then required for such cases, in addition to most of the kappa-driven non-radially pulsating stars. Colour can provide mode identification through the linearization of the photometric variations of a non-radially pulsating star. The potential for mode identification with 2 or more colors is illustrated in (Fig. 3) for ß Cep type pulsators (J. Daszynska, priv. comm.). The ratio of pulsation amplitudes for different filters (U, B, and R in this case) is plotted in this figure depending on the phase shift of the same pulsation mode, but observed in the respective colour. Pulsation modes with increasing radial node numbers (n) are plotted with the same color.

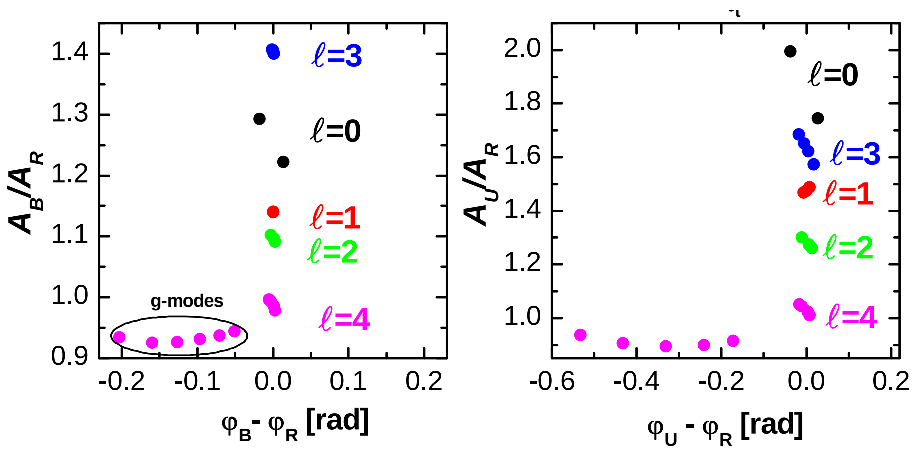

Figure 3: Diagnostic phase-amplitude ratio diagram for Beta Cephei pulsators.different mass, based on B, R and U filters.

Why is it important to identify observed frequencies with pulsation modes? Because each mode is described by a specific eigenfunction and different eigenfunctions are sensitive to different sections of the star. This property allows one to peel down a star like an onion and thus to determine its internal structure. Unfortunately, different modes may result in very similar frequencies and it is therefore important to attribute to each observed frequency the correct pulsation mode. Also, slight changes of stellar-model parameters like temperature, mass, luminosity or chemistry, result in frequency changes, so that one often cannot derive an unambiguous stellar model from observed frequencies, unless additional information is available for mode identification.

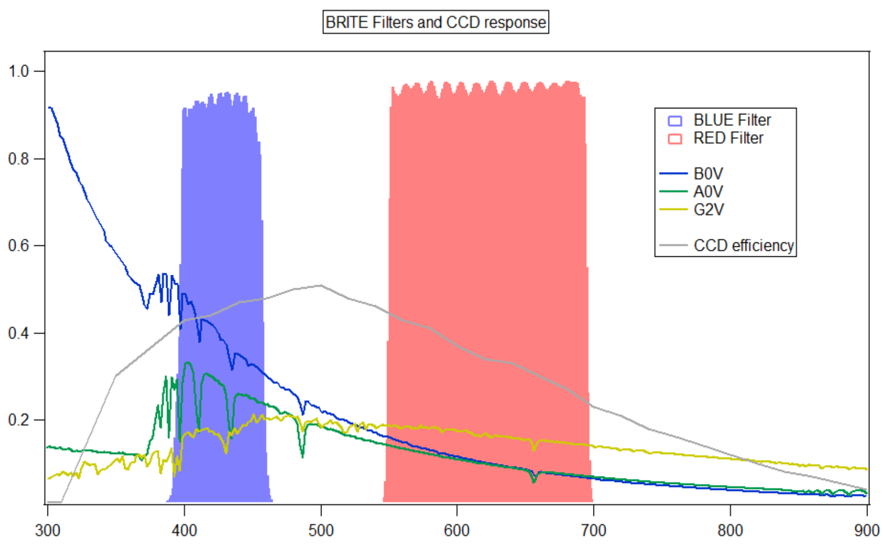

Fig. 4: Flux distribution for early B, A and G-type stars (very hot, hot, cool), sensitivity distribution for the chosen Kodak CCD, and filter transmission for the B and R instrument.

Practical considerations indicate that the best two-colour system would have the largest possible separation in optical wavelength with minimum overlap, hence the decision to have the B and R filter baseline (see Fig. 4). However, a UV filter, although more challenging, would provide an additional wavelength base and larger amplitudes for most variables. It would also be of great importance for removing current large inconsistencies (reaching 10 to 20%) in the constant-star, all-sky UV photometry; in effect, a BRITE-UV satellite could establish a very useful new reference UV-photometric system.

Duty Cycle

One element that contributes to the extraordinary success of MOST is the very clean Fourier spectral window of its observations. This results from the use of "continuous viewing zones" from a dawn-dusk sun-synchronous orbit that allows nearly uninterrupted observations of target stars for up to seven weeks. A high duty cycle of close to 95% is thus possible. The continuous viewing zones, however, do not cover the entire sky. As BRITE-Constellation will have to observe in essentially all directions of the sky where the brightest stars are found, it cannot use the same observing strategy as that for MOST. As a consequence, BRITE targets will be occulted by Earth during part of the satellite orbit and the duty cycle will consequently be significantly less than 100%. An obvious way out of this dilemma is to observe the same target with a different satellite (but same filter) in a slightly different orbit, while it is not observable from the other nanosatellite. Merging the data from two or three such BRITE satellites will improve significantly the spectral window. While the best situation is obviously achieved when the star can be observed continuously from several BRITE satellites in each filter, the situation of a duty cycle relatively close to 100% can be achieved with two BRITE satellites in properly chosen orbits. Figure 5 illustrates how an improved duty cycle will help in unambiguous frequency detection. One observation from the ground per night (asterisk) only reveals the variability of the star (purple dashed line). Many observations per night indicate the order of magnitude for the pulsation period, but due to observational errors (symbol size) the frequency solution would be ambiguous (e.g., blue & black dotted sinusoids). Only closing the gap between the two nightly blocks of data (increasing the duty cycle) allows one to indentify the nature of the target, in this example a multiperiodic variable star (red light curve).

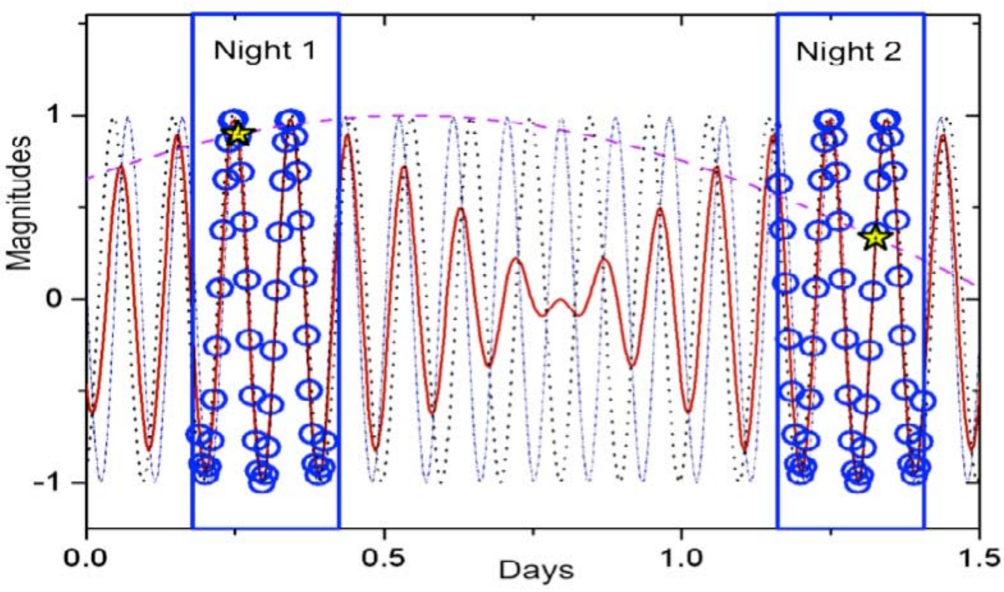

Figure 5: Possible "solutions" for a periodic variable depending on the duty cycle of the time series.

Target Selection

There are about 600 stars brighter than V = 4.0 in the sky and observable at the proposed precision level with BRITE Constellation. Considering the typical time scales for their variability ranging from a few hours to several days and aiming for a frequency resolution sufficient for asteroseismology, these stars need to be continuously observed for at least three months and at least at two different epochs. BRITE-Constellation expects to observe on average four stars simultaneously. Assuming a lifetime of three years for the mission, one would need about a dozen identical nanosatellites to perform all these observations. However, the scientific goal of BRITE-Constellation can be achieved with a well selected subsample of the stars that statistically covers the entire parameter space. Furthermore, BRITE-Constellation can concentrate on star-rich fields, such as that centred on Orion, with (a maximum of) 16 target stars brighter than V = 3.5.

Four-Satellite Constellation

Before the recent announcement that Poland will add two satellites to the BRITE constellation, most plans were based on an assumption of four satellites in two pairs. The operation of two pairs of nanosats would significantly improve the coverage of the parameter space (compared to only one BRITE), and in particular the statistical significance of the science conclusions to be drawn. The best configuration would be to have two launches, each with a pair of BRITE nanosats with each kind of filter, and each orbit pair separated in the sky as much as possible. This is the rationale behind the **BRITE-Constellation** of four individual satellites. The University of Vienna has already funded UTIAS/SFL to build one satellite, called UNIBRITE. The Technical University of Graz is also cooperating with UTIAS/SFL to produce a second, called BRITE-Austria. Each of these two BRITE satellites will have a different filter, along the lines noted above. The Canadian government will fund another pair of satellites. The addition of two satellites from Poland will result in a constellation of six. These additional satellites will serve to further improve the duty cycle of the observations and potentially add an ultra-violet capability to enhance the frequency detection.

BRITE-Constellation Bonus

BRITE-Constellation will fill an important and potentially very valuable void in astrophysical datasets. There have been numerous high-impact photometric surveys in recent decades (including microlensing surveys unsuitable for asteroseismology, gamma-ray burst optical transient surveys also unsuitable for asteroseismology, and single-star, high cadence observations subject to reduced precision, scintillation noise, and extinction-variation errors) but none have been able to observe and characterize the brightest stars. The overall scientific goals of the BRITE-Constellation mission are somewhat similar to those of MOST, CoRoT and Kepler, but emphasize a different niche of star variability research in three different ways:

1. The majority of the apparently brightest stars in the sky are also intrinsically bright (have high luminosities). High-luminosity stars are relatively large and of lower density and thus expected to show slower variations, which demands long and continuous data sets for detection. As these brightest targets are distributed all over the sky, full access to both hemispheres is required for BRITE-Constellation.

   MOST, having the ability to observe the same point of the sky for up to 7 weeks, is essentially a single-star instrument for bright stars ($V < 6$) and can be used for photometry of fainter ($6 < V < 13$) stars only within a field of 50 arc-min. While rapid, coherent variations of bright stars can be observed by MOST with a high precision reaching a few parts in a million, the slow variations will be more suited to observation by BRITE. Thus, the regimes of MOST and of BRITE-Constellation are complementary.

   The French-led space photometry mission CoRoT on the other hand allows one to stare at stars fainter than V=5.5 in a given target field of 1.3° x 1.3° for up to 150 days. However, the accessible sky is limited to two “CoRoT eyes” with a diameter of about 20° each, and which are close to the Galactic centre and anticentre, respectively.

   The NASA mission Kepler, for comparison, has a considerably larger field of view than CoRoT with more than 10° in diameter and which will be photometrically monitored for 3.5 years. But observations are restricted to a field in the constellation of Cygnus and to stars fainter than V=9.

2. While the above-mentioned photometric space missions MOST, CoRoT, and Kepler cannot provide any colour information on their target variability, BRITE-Constellation will consist of 6 nanosatellites with either a blue, red, and one of the satellites with a UV filter. Hence, two- (three-) color information will be available for each of the bright BRITE-Constellation target stars. This additional information (besides pulsation frequencies) is needed for a proper asteroseismic modelling of stars.
3. Experience with MOST, CoRoT, and Kepler has clearly indicated that for a full exploitation of the scientific content of space photometric data, high spectral resolution and signal-to-noise spectroscopy is also needed. The same experience tells us that such complementary spectroscopy becomes dramatically more difficult to achieve if the stars in question are faint. Kepler, for example, resorts to the 10m Keck telescope, and CoRoT has to rely on granting telescope time by ESO to get access to the 8m VLT's. Focussing on very bright stars, to the contrary, allows one to obtain the needed high quality data even with moderate-sized telescopes in the 3m class.

The BRITE Nanosatellite Design

Scientific Requirements

BRITE is a differential photometry mission: the field of view should contain at least two stars for simultaneous observations, to remove any correlated variations in the signal resulting from instrumental (e.g. slight detector gain variations due to thermal changes) and/or environmental (e.g. the rapidly varying Earth's magnetic field) influences on the photometric response of the detector. While a stable, calibrated instrument outside the Earth's atmosphere may be able to provide high quality photometry of single objects, such calibrations will be possible only after obtaining many differential observations of several stars. Thus, at least at the beginning, the mission will be limited in scope to regions where bright stars appear in groups. The massive, blue stars are exactly such: they tend to appear in groups in the wide band close to the Milky Way occupying about one third of the whole sky. In addition, with a sufficiently wide field of view, it will not be difficult to find regions of the sky with two or more stars brighter than V=3.5. (Figure 6). Table 1 summarizes the minimum mission requirements for BRITE-Constellation in the extremely conservative case of stars with a brightness of at least V=3.5.

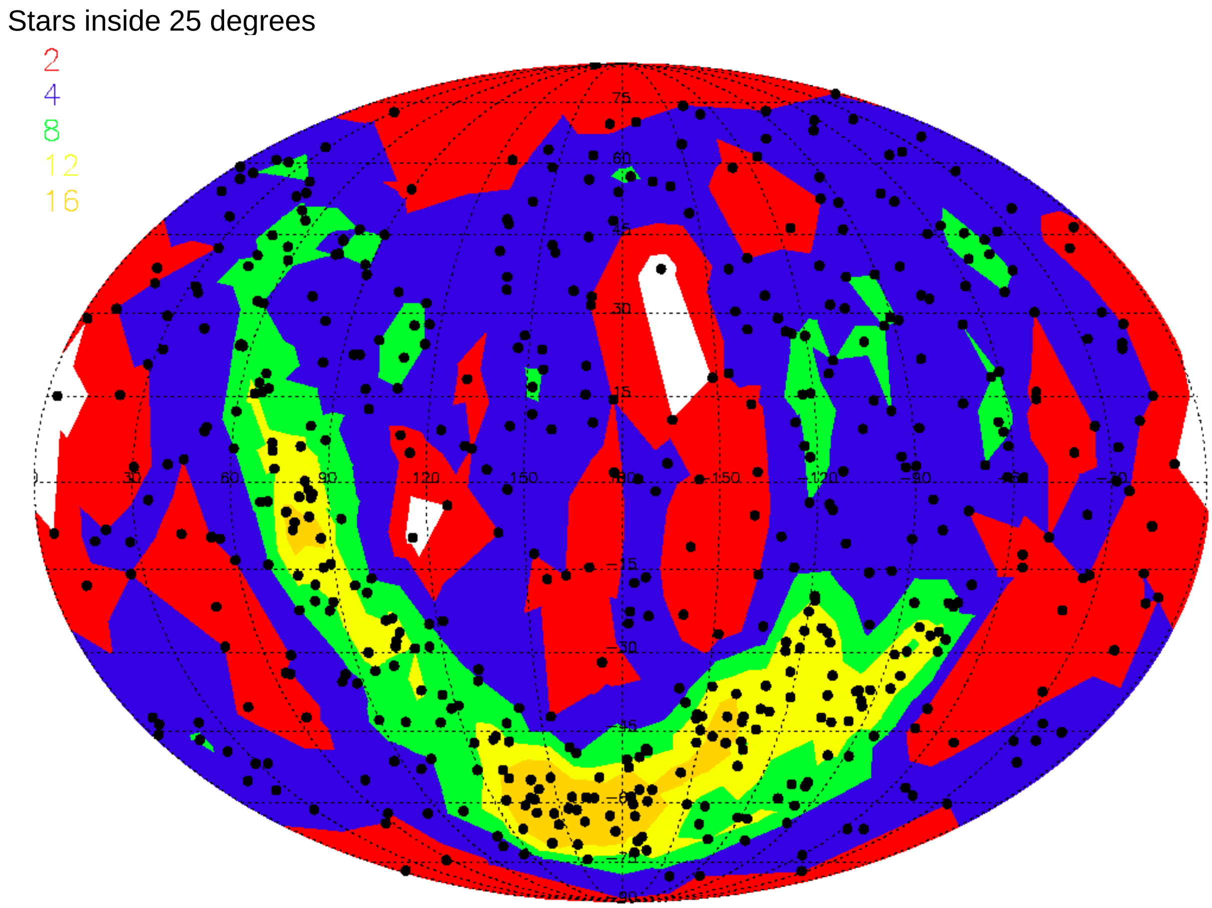

Figure 6: The number of stars to V=3.5 apparent magnitude in 25° diameter fields of view. The numbers in the upper left indicate the number of stars included in this field for a given pointing of BRITE by colour coding. Only for 3 stars will it not be possible to observe at least one other bright star at the same time. In the best case 15 more stars can be observed simultaneously.

Table 1: Minimum Scientific Requirements

Scientific requirement	Minimum requirements
Apparent V magnitude limit	+3.5
Positional constraints	None, all parts of the sky
Field of view	>25 degrees diameter
Differential photometry error per single observation	<0.1%
Error of amplitude spectrum for >month	$<2\times10^{-5}$ (or 20 ppm)
Cadence (repeat of the same field)	<100 minutes
Duration of the mission	> 2 years

CCD Detector

The science payload of the satellite will consist of a small lens-based camera and a two-dimensional array detector. The lens system (slightly different for the blue and red versions) has an aperture of 30mm and focal length of 70mm, so to acquire the 25 degree field, a full 35 mm format (36 × 24 mm) detector is used. Although CMOS detectors have low power consumption and simpler support electronics, we chose a Kodak CCD for its low dark current, relatively low readout noise and good quantum efficiency, using microlenses and an interline transfer readout system which overcomes the lack of a mechanical shutter.

The CCD is not cooled, but simulations indicate that the typical interior temperature in the detector region will be 10-20 C. There is a heater to stabilize the detector temperature, and several temperature sensors will monitor the temperature of the CCD and electronics. Extensive tests and calibrations have been and will continue to be made over a temperature range of -20 C to +60 C, at integration intervals up to 90 seconds. For most BRITE fields, exposure will generally be well under 10 seconds.

Table 2: Detector Characteristics

CCD Parameter	Value
Active rows, columns	4008 x 2672
Pixel size	9 µm x 9 µm
Peak quantum efficiency	50.00%
Saturation signal	40,000 – 60,000 electrons
Readout Noise (at 20 C)	15 electrons/pixel
Dark current hot pixels (20 C) 99 % of pixels	< 4 electrons/s
Dark current hot pixels (20 C) 99.5 % of pixels	< 21 electrons/s
Readout Frequency	10 MHz

Optical System

The satellite Attitude Control System is based on the UTIAS Space Flight Laboratory's high performance attitude control technology and is expected to provide RMS stability of one arcminute (or full-width half-maximum ~2.2 arcmin). The size of the satellite and low complexity of the mission suggest a lens system with a lens aperture of 2.5 – 3.5 cm. The optical properties, depending on pixel size, will not be difficult to meet for parameters as given in Table 3. The field of view (FOV) side dimensions are for the smaller dimension of the chip.

The BRITE science instrument consists of a moderate field-of-view lens 30mm in diameter and 70mm in focal length. While it is possible to use a commercial, off-the-shelf lens, there are numerous compelling reasons to design a custom optical system. The primary drivers are vignetting and stray light suppression. A double-Gauss lens system can be custom designed to eliminate vignetting. However, such a system would require a relatively large stray light baffle unsuitable for BRITE satellites.

Table 3: Optical System Properties

Parameter	Value
Pixel (microns)	8
F (mm)	70
Scale (″/pix)	23.6
FOV side (degrees)	25 (circ) x 19.8

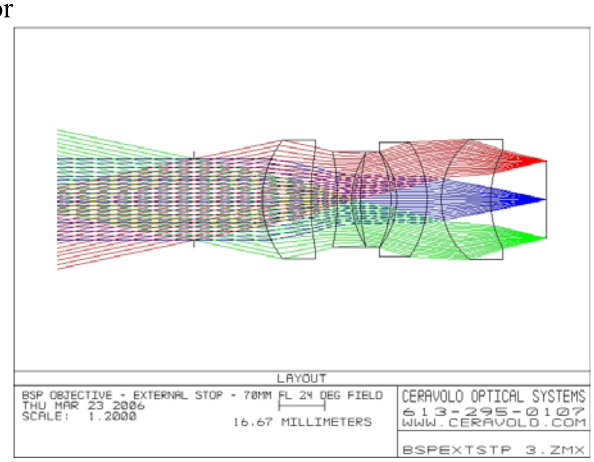

Figure 7: External Aperture Stop Configuration

Since the science instrument is not required to form sharp images, due to the unfilled pixels of the CCD detector combined with the wide field, there is some latitude to pursue non-conventional design approaches better suited to stray light suppression. The lens design has been generated that is suited to the physical limitations of the 20cm cube nanosatellite bus used for BRITE. It uses an external aperture stop configuration that allows for a very compact and effective baffle (Figure 7). The filter is located at the external pupil (stop), and the image is telecentric, which is well matched to the angular acceptance angles of the microlenses on the detector.

Table 4: BRITE Satellite Bus Specifications

Satellite Specification	***Value***
Volume	20×20×20cm
Mass	5.0kg
Attitude Determination	10 arcseconds
Attitude Control Accuracy	Better than 1.0°
Attitude Control Stability	1 arcminute RMS
Power	5.4W to 10W
Bus Voltage	4.0V (nominal)
Battery Capacity	5.3Ah
Data Downlink	Up to 256Kbps
Payload Data Storage	Up to 256MB

Because there are spikes in the point spread function which cause aliasing (undersampling) problems, the telescope is adjusted to be somewhat out of focus, and the pointing jitter of the spacecraft will contribute sufficient movement to smooth out the sum of many tens or hundreds of exposures made during a single orbit, sufficient to meet the requirement of 0.001 magnitude minimum accuracy per orbit.

Satellite Bus

Table 4 summarizes the top-level characteristics of the BRITE satellite bus. The BRITE bus is a 20cm cube. Each BRITE satellite has a nominal mass of 7kg. Figure 8 shows the dimensions of the satellite and indicates the launch rails, where the satellite interfaces with the UTIAS/SFL XPOD ejection system (Figure 9).

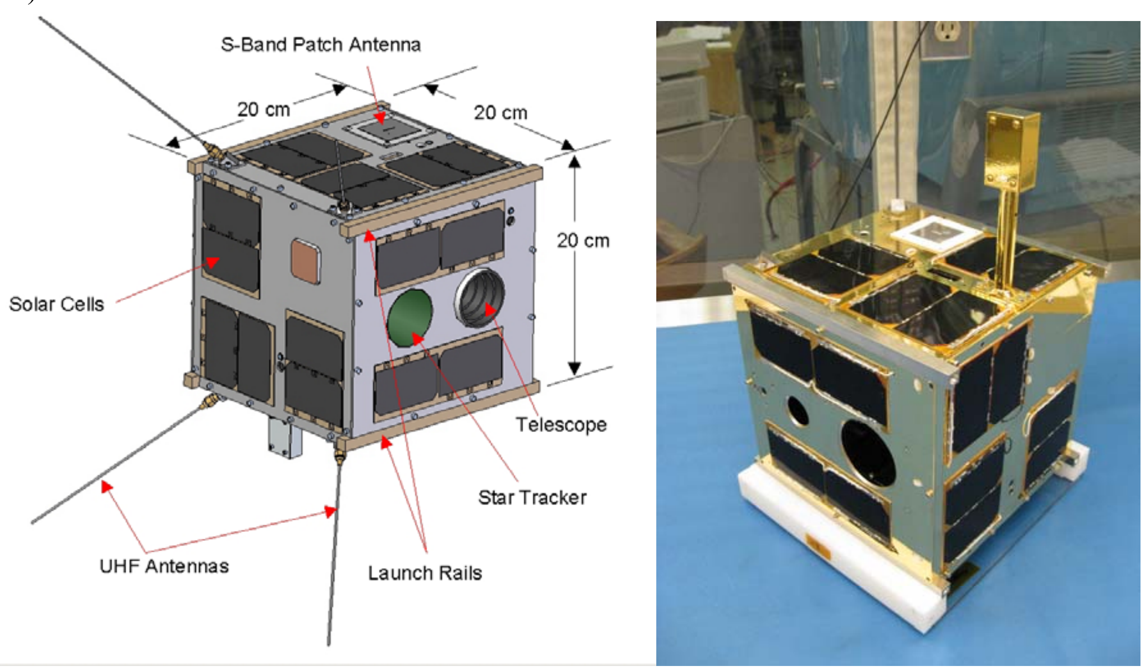

Figure 8: The BRITE Satellite Bus

Figure 9: XPOD Ejection System for BRITE Satellites.

Attitude Determination and Control

The BRITE satellite bus houses three orthogonal reaction wheels (developed by Sinclair Interplanetary in collaboration with UTIAS/SFL) and three orthogonal vacuum-core magnetorquer coils for three-axis attitude control and momentum dumping. Attitude determination is provided by a magnetometer and six SFL-developed sun sensor packages, each of which is equipped with coarse and fine sun-sensing elements. Figure 10 illustrates a number of these components. The bus will also carry a nanosatellite star tracker developed by Sinclair Interplanetary, Ryerson University, and UTIAS/SFL. This will enable attitude determination to within one arcminute, attitude control accuracy to better than a degree, and attitude precision to within one arcminute RMS.

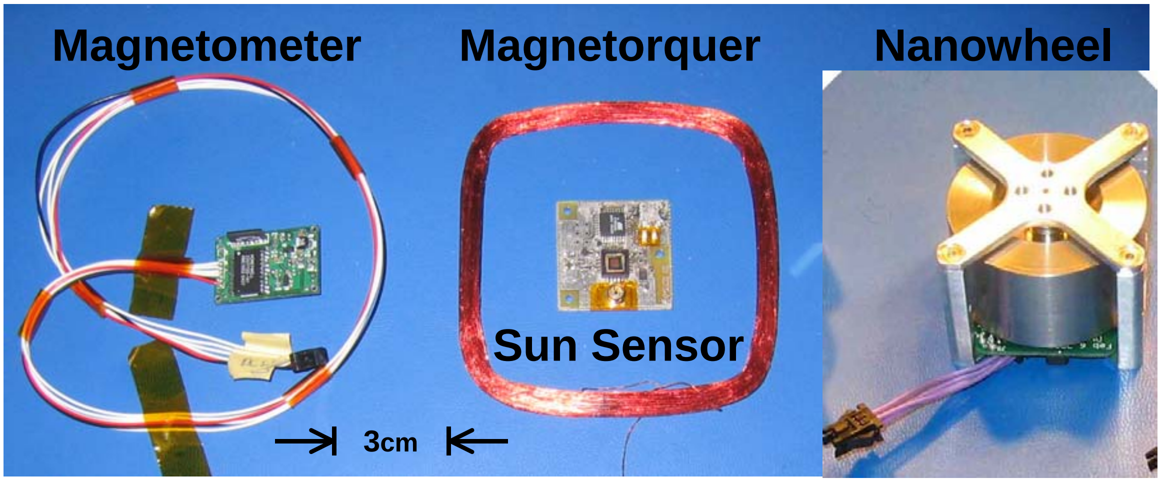

Figure 10: Attitude Control Hardware

Computers

The satellite contains a main on-board computer (OBC) and an attitude determination and control computer (Figure 11). These computers use an identical design, which is built around an ARM7 processor operating at approximately 40MHz. Each OBC contains 256KB of FLASH memory for code storage, 1MB of EDAC protected SRAM for storage of data and variables and 256MB of Flash for long-term storage of telemetry and payload data. The satellite also has a third "payload" OBC (of the same design as the main and ADCS OBCs) dedicated to operation of the telescope. Communication between the telescope and the payload OBC is asynchronous serial with a maximum data rate of 115.2kbps.

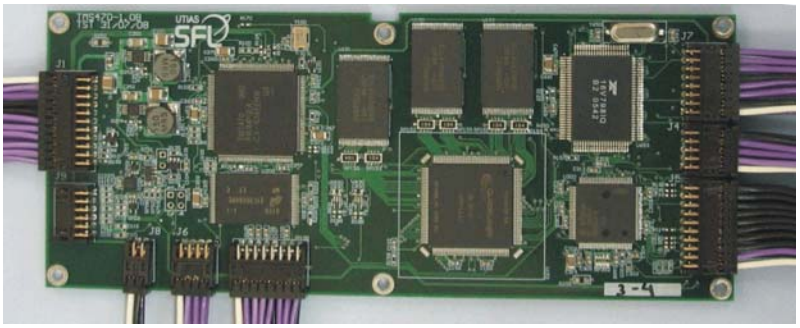

Figure 11: On-Board Computer

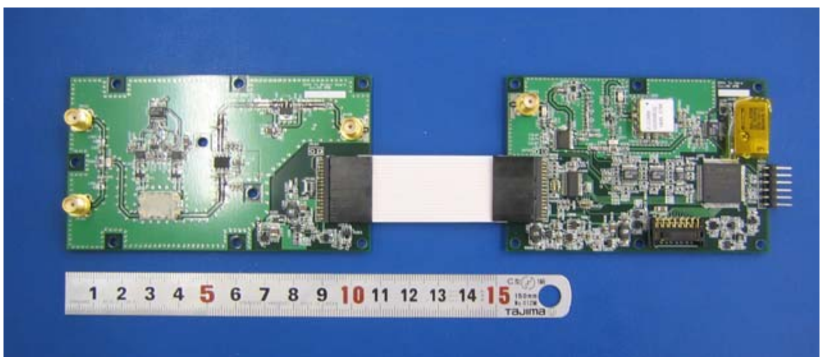

Figure 12: UHF Transceiver

Power

The power system uses direct energy transfer to distribute power generated by high-efficiency triple-junction solar cells to the satellite components. The bus voltage is unregulated and is nominally 4.0V. A 5.3Ah rechargeable lithium-ion battery provides power for use during eclipses and periods of peak power usage. In the nominal case, at least six cells can be placed on a face for a maximum instantaneous power generation of about 10W. The worst-case power generation (when in the sun) is approximately 5.4W.

Communications

The uplink is provided through a SFL-developed UHF receiver. An S-band transmitter (Figure 12), also developed at SFL provides the primary downlink and can work at data rates from 32Kbps to 256Kbps. Each radio system is housed in a separate enclosure to minimize noise and interference. The UHF transceiver communicates with the ground via a pre-deployed quad-canted monopole antenna array, which provides near omni-directional coverage. The S-band transmitter uses two 5.5×5.5cm SFL-developed patch antennas installed on opposite sides of the spacecraft. Combined, these patches provide near omni-directional coverage.

Thermal Control

Thermal control on the GNB is provided primarily through passive measures. Thermal coatings and tapes are used on the external spacecraft surfaces to keep the orbit average satellite temperature at approximately 10°C to 30°C. Thermal control of individual components is achieved using a variety of techniques including thermal isolation and heat sinking. An optional temperature-controlled battery heater can also be included if required.

Telescope and Baffle

The BRITE instrument is composed of three major sections: the electronics & detector enclosure, the optical cell, and the baffle (Figure 13). The CCD detector chosen for the BRITE-Constellation mission is a commercial unit by Kodak. The optics design facilitates the use of a short baffle and is illustrated in Figure .

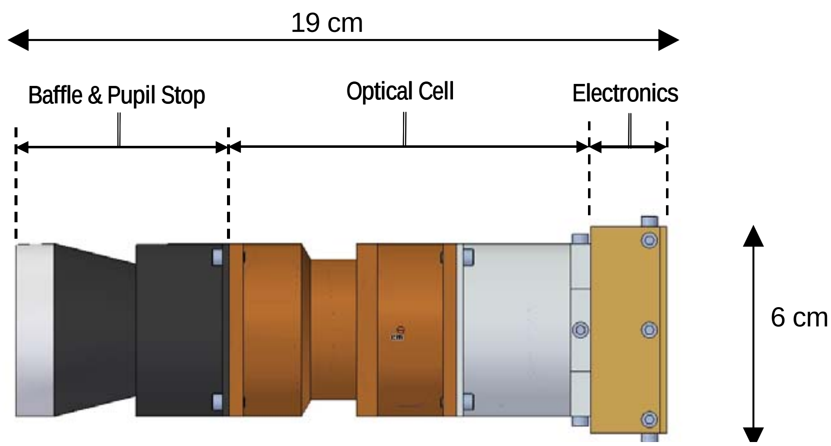

Figure 13: BRITE Telescope and Baffle

Conclusion

BRITE-Constellation will provide essential data that will help astronomers understand the most luminous stars in the Galaxy through asteroseismology. These stars govern the life cycle of matter and are key to comprehending the way in which the Universe has evolved. By using six, seven-kilogram satellites in low Earth orbit, BRITE-Constellation will provide photometric time-series to better than 0.1% precision per data point, far exceeding anything that has been accomplished to date using ground-based techniques. The BRITE-Constellation mission complements the MOST mission by viewing targets with oscillation periods up to months. Only a 30-mm aperture telescope is needed and the latest CCD detector technology can be used. To obtain colour information and improve duty cycle coverage, the satellites will operate in pairs, with each satellite having a fixed red, blue, or UV filter. The University of Vienna and FFG/ALR (Austrian space agency) have funded the construction of two satellites. The Polish Academy of Sciences has funding for two additional satellites. The Canadian Space Agency is expected to fund the remaining two satellites to complete the constellation of six.

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