"BRITE", The BRIght Target Explorer: an Unbiased, Systematic Study of Stellar Variability among the Most Massive Stars

A proposal submitted to the Science Branch of the Canadian Space Agency

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Summary

Massive, luminous stars dominate the ecology of the Universe. Above about 8 solar masses, their remnant cores implode into a neutron star (black hole for > ~25 M(Sun)), leading to high-speed ejection of remaining outer layers rich in nuclear-processed matter. Above about 15 solar masses, massive stars produce strong winds essentially all their lives (unlike lower mass stars), more gradually but equally significantly enriching the interstellar medium with heavy nuclei. From a cosmological point of view, the contribution of massive stars was especially important early on: all first-generation stars are believed to have been very massive. Yet, massive stars are among the least understood stars because of their rapid rotation and strong radiation pressure, which often nearly overcome the gravity that keeps them together. Consequently, massive stars tend to be highly unstable and thus variable.

We intend to build a nano-satellite, BRITE (BRIght Target Explorer), and use it (i) to examine – with unprecedented precision and time-coverage – the instabilities of a broad cross-section of massive stars; and (ii) to take advantage of the instabilities to find periodic components, and to use these to verify and test our understanding of the structure of massive stars, including the poorly-understood processes of rotation and convection. We will do this by measuring variability of the intrinsically luminous stars, which dominate the brightest stars in the sky, concentrated mostly in the Milky Way band and down to visual magnitude +3.5, on timescales ranging from hours to months, possibly even longer. We will use a large field of view (~25 degrees across) containing multiple stars, so that we can obtain differential photometry with precision better than 0.1% for a single observation. The list of ancillary science projects, for objects simultaneously accessible in the same field of view, is extensive, ranging from the characterization of red-giant variability, the detection and study of *g*-mode oscillations in solar type stars, to the detection of planetary transits in stars more massive than the Sun.

BRITE will considerably extend and supplement the spectacularly successful Canadian microsatellite MOST into the domain of nanosatellites. It will utilize the recent improvements in nano-satellite 3-axis stability control to the level of 1 arc-minute, opening up for astronomy a new domain of miniature, very low-cost spacecraft. A successful mission will allow Canadian industry to expand its already dominant expertise in this area. Of particular importance are the very low cost and the high scientific value of the mission, which otherwise may have merely been a technology demonstration satellite. Because it will study the brightest visible stars in the sky, BRITE will also provide a special appeal to the public, including young people.

1. Introduction

Practically all stars vary in brightness at some level. Thanks to these light variations, we can extract a considerable amount of physical information about internal stellar structure and evolution. A wide range of variability phenomena emerges between two extremes: Supernova explosions, the ultimate in stellar variability, are the largest known releases of energy from a single stellar object, which can become as bright as 10^{11} stars in a whole galaxy and for several weeks can be seen from cosmological distances. In 0.1% of these cases, we witness from some random position in the whole visible Universe the accompanying phenomenon of Gamma-ray Bursters, as relativistic jets associated with the type Ib,c supernova implosion/explosion are directed towards Earth. The other extreme in the variation range consists of "seismic" oscillations, usually simultaneously excited in many modes, at the level of a few parts per million; these permit in-depth studies of stellar structure and evolution of stars for structural parameters such as the density distribution, internal rotation and/or presence of magnetic fields. The highly successful micro-satellite mission MOST, the first Canadian astronomy satellite and the first entirely Canadian research satellite to be launched in over 30 years, was built primarily to detect and analyze miniscule asteroseismic oscillations of solar-type stars. Analysis of such stars can shed light on how the Sun evolves, but also can help in understanding the oldest, solar-type (i.e., moderate and low mass) stars which survived from the earliest stages of the Galaxy's life.

Here we propose a complementary satellite project which will study large numbers of massive stars. These stars live short lives, typically hundreds to thousands of times shorter than solar-type stars, yet their evolution is crucial for the properties of the Universe. Successive generations of massive stars produced and ejected copious quantities of heavy elements, the material of which we are made. The majority of massive stars are also extremely hot and luminous; they therefore emit huge numbers of hard UV photons that are of extreme importance for heating the interstellar matter and promote the formation of organic matter on interstellar grains. The more luminous (hence massive) a star is, the rarer it is, according to the so-called Initial Mass Function (IMF), an apparently universal, power-law relation that gives the relative numbers of stars of different mass at the time of their birth from a natal interstellar cloud. The IMF goes like $N(M)\, dM \sim M^{-2}\, dM$, except possibly for very low mass stars, where it flattens out and turns over. The Main-Sequence (MS) stellar luminosity goes as $L \sim M^{+4}$ (from 15-20 solar masses down to the point where stars become fully convective at about 0.4 solar masses where it changes into $L{\sim}M^{+2.5}$) so that luminous stars more than make up for their relatively low numbers, as far as radiative output is concerned. Wind output is even more impressive along the (upper) MS, $dM/dt \sim L^{1.6} \sim M^{5}$! For example, a MS star of ~20 times the mass of the Sun will inject high-speed atomic nuclei and electrons into the ISM, at a rate that is $\sim 10^{6}$ times greater than that of the Sun. The high luminosity of massive stars gives them a tremendous advantage over intrinsically faint objects: They can be seen from large distances to trace matter within our own Galaxy and far beyond. In fact, the **apparently** brightest stars in the sky are – in the majority – also the **intrinsically** brightest stars (see below)! Thus, as far as temporal variations are concerned, these stars can be studied with very moderate-size instruments, as long as such instruments can be made to work stably and consistently over long periods of time, ranging from days and weeks to months.

We propose to build and launch a nanosatellite, BRITE, equipped with a small telescope, able to simultaneously image all the brightest stars in the sky down to +3.5 visual magnitude (with possible extension by one magnitude), over a field-of-view of 25 degrees per exposure. With a minimum sampling time of each satellite orbit (typically 100 minutes), the effective exposure time utilization (duty cycle) will be >15% for a given star (this number can be improved for an agile stabilisation and slewing system). The primary mission will concentrate on precision photometry at the 0.1% level or better of massive, luminous stars to study brightness variability over times scales from hours to several months, possibly even years.

This proposal includes results of the BRITE Concept Study which addressed angular and thermal noise properties of CMOS detectors as well as a preliminary design of the optical system[1]. The Study was conducted by a team from the University of Toronto, UTIAS and Dynacon and was led by the PI of this proposal. It is submitted to the CSA simultaneously with this proposal.

2. The main science: Variability of luminous, massive stars

The hot, massive, luminous O and B stars, along with their descendants: supergiants of all types and Wolf-Rayet stars, are the prime focus of this proposal. Massive, B and especially O stars have a very low space density, but they play an important role in the chemical evolution of the galaxy and the dynamics of the interstellar medium. Their high ultraviolet fluxes strongly influence the ionization of the interstellar gas and the evolution of dust. Since O and B stars evolve very rapidly, they process gas quickly. Those above 15 M(Sun), B0 on the MS, return a substantial fraction of their original mass back to the interstellar medium through their winds and those above 8 M(Sun), B2 on the MS, through the supernovae explosions at the ends of their lives. This material is substantially enriched in heavy elements, especially the r-process elements heavier than iron. The first generation of stars formed in the Universe, when it contained essentially only 76% hydrogen and 24% helium and no heavier elements, were likely very massive stars (~100 to 1000 M(Sun); thus, in a sense, today's upper mass limit was yesterday's lower limit!) that quickly re-ionized the Universe and enriched it in heaviest elements, drastically changing forever the fate of the next stellar generations which modified the opacity of the matter by subsequent buildup of C, N, O, Mg, Si, Fe of which we and the Earth are made.

In spite of their rarity, the O and B stars make up a significant fraction of the stars brighter than +3.5 apparent magnitude (see Figure 1) because their high intrinsic luminosities permit us to see all of these stars within a larger (still relatively local, i.e. where interstellar extinction is relatively low) volume of space than is the case for intrinsically fainter stars. This is both a blessing – because there are many very bright stars, so it is possible to observe them with very high signal to noise; and a curse – because the usual ground-based methods of spectroscopy and photometry require large amounts of time to study a single object, and suitable comparison stars for precise differential photometry are almost always too far away on the sky to allow accurate measurement of the atmospheric extinction.

The best solution to these problems is to launch a wide-field imaging telescope into space. This removes the problem of determining and eliminating the variable effects of the Earth's atmospheric extinction and allows us to obtain far more accurate photometry. Moreover, there are many regions (e.g. near the Gould Belt, close to the Milky Way plane) where such an instrument will find many targets within the same field. This alleviates the problems caused by a shortage of suitable comparison stars for such bright stars. It also gives us a big multiplex advantage over ground-based observations, because the large field we are proposing will allow us to observe many more stars in a given time interval than is possible from the ground. Thus we propose to build and launch a wide-field photometric telescope to study the time variability of the O and B stars and their descendants, as well as other interesting targets of opportunity that come along for the ride.

[1] Canadian Space Agency, Contract number 9F007-046080/001/ST, CSA Technical Authority: Alain Ouellet

Among the unsolved problems in stellar structure and evolution of the upper H-R diagram, two stand out: the size of convective cores in hot stars and the influence of rotation (possibly coupled with the presence of magnetic fields). In hot stars, the cores are convective, because the energy generation rate is highly centrally concentrated (due to the extreme temperature sensitivity of the CNO cycle). The size of the convective core determines how much fuel is available, and thus the lifetime of the star, as well as, e.g., the amount of heavy elements it will return to the interstellar medium. The size of this core mixing region is very difficult to predict, for two reasons. First, convective bubbles may overshoot into the surrounding stable, radiative region; this enlarges the effective amount of available fuel. Second, as the star evolves, the convective core shrinks; the regions just outside, with a molecular weight gradient, are unstable to semi-convection, which can mix material on a slower timescale. The properties of convective overshoot and semi-convection are still very poorly understood, leading to large uncertainties in the stellar life cycle.

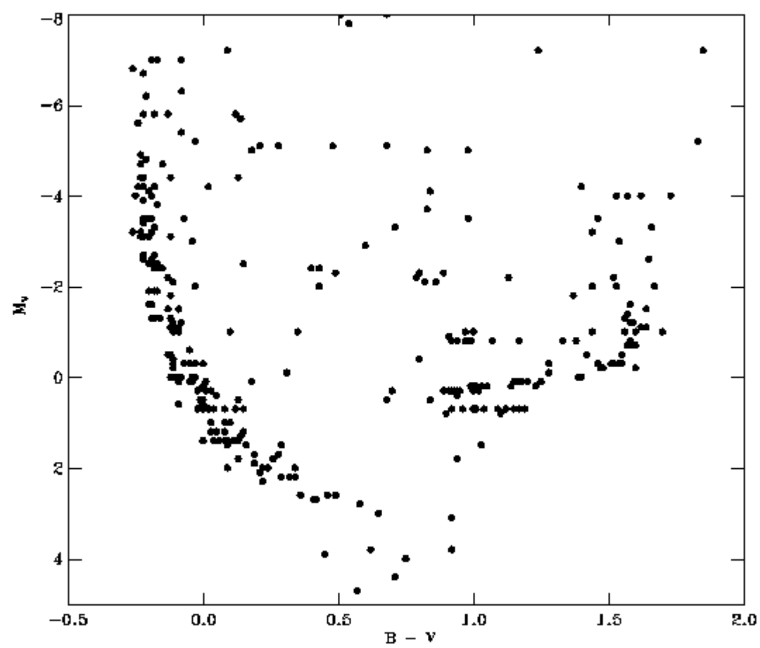

Fig.1: The colour – absolute magnitude diagram for the 286 brightest stars in the sky down to +3.5 visual apparent magnitude. Note the large number of blue, massive stars, mostly belonging to the well-defined Main Sequence in the left part of the diagram (i.e., the positions of O and B stars, with $M_v < 0$), but also the K-type giant branch and absence of Sun analogues among these brightest stars in the sky (the Sun would be located at M_V=+4.7, close to the lowest point in this plot, defined by Alpha Cen A). This diagram shows the observed (apparent) data without any reddening corrections.

The second outstanding problem in stellar evolution is the influence of rotation. The most massive stars rotate rapidly. This is of interest both as it leads to another source of mixing of material, and from a more general point of view of the evolution of angular momentum. For instance, neither white dwarfs nor neutron stars are born rotating extremely rapidly, which means the progenitor stars have to shed their angular momentum. This will happen most easily through mass loss, i.e. by stellar winds. In order for the core to slow down, however, the angular momentum in the star needs to be redistributed. This is only partly understood, as the role of magnetic fields is unclear. Observationally, we know it happens fairly effectively in the low-mass Sun, where helioseismology has shown that the core is in rough co-rotation with the envelope.

The properties of the stellar cores as well as the stellar rotation profiles can, in principle, be determined through asteroseismology. In practice, there are difficulties. First, pulsation modes for which the restoring force is pressure (i.e., sound waves, called pressure or simply *p*-modes) do not penetrate the core very well, unless they have very low radial order. These modes are sensed in helioseismology, and this is the reason that the core of the Sun is still relatively poorly constrained by helioseismological models. On the other hand, pulsation modes restored by buoyancy (called gravity or *g*-modes) do have good sensitivity to the core's properties. These have yet to be discovered in the Sun or in sun-like stars, but, as will become clear below, they are found in many massive stars.

For massive stars, however, there is another problem: As yet, pulsation theory can deal with rotation only perturbatively. Effectively, this means that there is no known way to deal with pulsation modes whose periods are comparable to, or shorter than, the rotation period. This is the situation that faces us for nearly all massive stars, so we have a significant problem in interpreting their pulsations. This is as another reason to explore the question observationally!

The primary goal of BRITE is to explore the brightest stars, many of which are main sequence stars much more massive and luminous than the Sun. For some of these stars, variability has already been found. Progress in understanding the variability, however, has been slow. Partly, this is because of the theoretical problems alluded to above, but to a large extent it is also because of the difficulty of observing often weak pulsation modes with periods of the order of a day. Below, we briefly describe the different types of variables known (for more information, see, e.g., the review by Gautschy & Saio 1996), and discuss the tremendous advantage that BRITE would have in this area. Although they are less luminous than our prime targets, the O and B stars, we start with F-type stars, which can be seen as a transition from solar type to massive stars, and thereafter work our way up to higher masses. It will become clear that the known variables are well represented among the brightest stars. It is a given that many unknown variables are waiting to be discovered or properly quantified at the high photometric precision and appropriate time coverage sought for in this project. In the discussion below, we illustrate variability at various levels in the H-R diagram, without attempting to be complete.

Among the F-type stars, an interesting group of variables has recently been identified (Kaye et al. 1999), called Gamma Doradus variables (the prototype, Gamma Dor, has V=4.2, hence a bit below the initial threshold for BRITE). They have spectral types ranging from F7 to A5, and show brightness and line-profile variations with multiple periods in the range 0.3-3 days, and with amplitudes of a few 0.1 to 10% in brightness and 1 to 4 km/s in radial velocity. Given their periods, the pulsations must be high order gravity modes, but it is not yet understood what mechanism drives the pulsations. For the amplitudes, the lower ends of the quoted ranges are likely set by sensitivity, not by a physical mechanism. Thus, we do not yet know whether sufficient numbers of modes can be identified for a meaningful asteroseismological analysis. BRITE will be very useful here as numerous bright Gamma Dor stars are expected to remain to be identified among low-amplitude pulsators. Interestingly, a range in rotation period is observed, giving the possibility of calibrating theories for rotational effects on the pulsations.

Going towards earlier types, we next encounter the Delta Scuti variables (prototype Delta Scuti has V=4.7). These have shorter-period (down to 0.02 day), *p*-mode pulsations, and hence are better suited for MOST (and indeed are among MOST's targets). If a star was in the FOV of BRITE, one could look for variations with longer periods associated with *g*-modes, although this would be hampered by the short-period variability. A more secure contribution would be to look for low-level variation in stars that are in the Delta Scuti instability strip, but appear to be stable in ground-based observations. This might uncover low-amplitude Delta Scutis, or, more interestingly, new types of variables, confirming perhaps the possible new class of low-amplitude, long-period (about 1 day) A-star pulsators reported in Hipparcos photometry by Koen (2001).

According to pulsation theory, there are no pulsating stars near the main sequence between spectral type B7 and the blue edge of the Delta Scuti instability strip. On the other hand, we know of no large scale photometric or spectroscopic surveys that prove that such an "oasis" really exists. It is very important to carry out a survey of stars in this region to establish their constancy to the greatest precision possible. In addition, it is very important to determine whether or not there are any stable stars among the earlier stars because any such stars will be a challenge to pulsation theory. Moreover, it is important to identify stable stars to the highest possible precision because they will be excellent candidates for absolute flux calibration standards. A new calibration is needed to replace the one based on Vega, both because Vega is a low-amplitude variable star and a more accurate calibration is needed to fully exploit improvements in the distances and angular sizes of stars obtained by Hipparcos and optical interferometers.

Going up further in mass to the B-type stars, one encounters another recently identified group of pulsators, the Slowly Pulsating B stars (SPB). These are multi-periodic, low-amplitude variables of spectral type B3 to B8, with periods between about 1 and 3 days (prototype 53 Per; V=4.8; brighter examples include: Omicron Vel, Zeta Cas, Gamma Mus, Iota Her, Tau Her, all V~3.7). Goals here would be to identify the complete set of pulsation periods, and also to infer rotation rates. Some of the rotation periods are relatively long, such as the 5.4 day rotation period of Zeta Cas, implying that pulsational models may still be relatively reliable.

Among the earlier B-type stars are found the Beta Cepheid variables (prototype Beta Cep, V=3.2; other bright examples: Delta Cet, V=4.0; Alpha Lup, V=2.3). The observed pulsations in these stars are predominantly radial pressure modes, with periods of less than about 7 hours. With BRITE, it would be possible to find weaker, longer period, non-radial modes, and attempt full asteroseismological analysis. Weaker modes may be expected. For instance, Spica (Alpha Vir, V=1.0) used to be a Beta Cep variable, but the amplitude became undetectable in the 1970's. A reverse change, from undetectable to large amplitude, was seen in 27 CMa (V=4.6). Currently, Spica still shows spectral line variability suggestive of non-radial oscillations. Could these be present in active Beta Cepheid variables too?

Many SPB and Beta Cep pulsators remain to be found among bright stars. With amplitudes small amplitudes (currently 0.01 to 0.1 mag., but can be smaller), they require systematic surveys. For example, the Hipparcos mission identified about 200 new SPB's among 267 new variable B stars (Waelkens et al., 1998, A&A 330, 215). The SPB's are particularly interesting, since they pulsate in *g*-modes, which probe the core much better than *p*-modes.

Among the earlier B-type stars, as well as among the late-type O stars, are the OBe stars, early-type stars with not only normal, fast stellar winds, but also strong, slow, equatorial outflows (which lead to emission lines denoted by the "e" in the spectral type). These stars rotate very rapidly, likely at close to break-up rates. This probably causes the equatorial outflows, but it is not clear how. Most, if not all, Be stars show photometric and spectroscopic variability (examples are Zeta Oph, V=2.6; Gamma Cas, V=2.4; Zeta Tau, V=3.0). Typical periods are 0.5 to 2 days, with amplitudes of only 0.5 to 3% in brightness, but up to a few 10 km/s in velocity (as inferred from line profile variations). Most variations are thought to be due to non-radial, *g*-mode pulsations. Recent extensive spectroscopic monitoring campaigns, in particular that based on some 3000 spectra by Rivinius et al.(2002), found striking similarities in the line profiles, suggesting that the main periods are due to l=2, m=2 non-radial g-modes.

Photometry has shown that many Be stars have multiple modes. The nature of the driving mechanism is unclear. Empirically, the presence of pulsations seems to be correlated with the presence of the equatorial outflows. Goals for BRITE would be to get full sets of periods, down to good limits, and check B stars without emission lines for the presence of low-level pulsations. It may also be possible to identify rotation periods, as has been done for some non-Be stars with peculiar abundances and relatively strong magnetic fields (which showed relatively large rotational modulation). Furthermore, for the Be stars with later spectral types, for which photometric periods but no line-profile variations were found, BRITE could verify whether there is just one photometric period (in which case it likely is the rotation rate), or whether the variability is multiperiodic.

Towards even more massive stars, the situation becomes confused. In spite of considerable effort over the last twenty years, we know relatively little about the variability of O stars and B supergiants. The most extensive photometric studies have been carried out by van Genderen and collaborators (cf. van Genderen 1991 and references therein). His data are adequate to determine periods greater than one day, but his data strings are either too short or too aliased to find shorter periods. He has found some very luminous stars that appear to pulsate radially with periods up to a few weeks. No clear pattern is present in the properties of stars that vary and those that don't. Furthermore his light curves nearly always have large scatter about the periodic variation. It is impossible to tell whether this is due to stochastic variability, due to variations in the wind density or chaotic variations in the brightness of the stars he observed, unresolved short-period variability, or problems with the period determination due to the shortcomings of his data.

As for the most massive stars of all, one can ask the question: Is there a real cut-off at the highest luminosities or is the observed empirical Humphreys-Davidson (H-D; 1994) limit simply a result of a statistical petering out of the upper IMF? One needs to look at the theory behind this limit, too: When H-burning is exhausted in the cores of massive stars before He-burning sets in, shell H-burning forces the envelope to expand rapidly, making the star cross the upper H-R diagram on a relatively short (Kelvin-Helmholtz) time scale (i.e., in the H-R gap). But when the envelope reaches its Eddington limit (observationally the H-D limit) somewhere on the way for massive stars, where the opacity-driven radiation pressure exceeds gravity, the star becomes highly unstable and begins to oscillate and lose mass episodically at very high rates in what is called a Luminous Blue Variable a la Eta Carinae (although not all of them are blue; some occur towards the yellow and even red stage of luminous hypergiants). This effect can set in even earlier or at lower luminosities for rapidly rotating stars. So the question arises: Do instabilities increase systematically as one approaches the H-D limit, aided by rotation? BRITE will help answer this fundamental question, because it will allow us to probe a relatively large volume of massive (hence intrinsically luminous) stars. Among the modes of instability are NRP and radial pulsations, but also so-called "strange-mode" pulsations (Glatzel 1994), that until now have only been predicted and never detected before in stars. The most massive, densest stars are expected to reveal this mode of pulsation, with very short periods, of order 10 – 30 minutes. With BRITE, pulsations of all kinds will be sought clear across the upper H-R diagram, where stars are linked by horizontal evolution, unlike the lower H-R diagram, where post-MS evolution is largely vertical. Furthermore, blind surveys such as BRITE are bound to provide the best unbiased answers to the basic question of instabilities of massive stars, which are, in many ways, the dominant motors of the ecology of the Universe.

3. Ancillary science

In the minimum mission, BRITE will observe all bright, luminous stars which are concentrated along the Milky Way. BRITE fields of 25 degrees in diameter, in 61% of cases will contain typically 3 such stars, permitting precise differential photometry of uncorrelated stellar variations (see Sections 5 & 6 for the statistics of bright star fields). While the selected fields may also contain other, different targets, the full access for precise differential photometry of all bright stars in sparsely populated fields will be considerably enhanced by extending the limiting magnitude one magnitude deeper, to +4.5 mag, if feasible, thus giving about 4 times more objects per field. It is possible that BRITE will provide high-quality single-object photometry, without referring to other stars, but this will be established only after an extensive differential photometry period. In any case, BRITE will be able to look at **all bright stars** down to a given magnitude level, without any other bias. (We note that there is at least one bright star in each BRITE field, see the table in Sec.6). Such blind surveys are being preferred more and more in modern astronomy, to reveal true properties of samples without pre-selection.

Like with MOST, we anticipate many entirely unpredictable and serendipitous discoveries. However, some areas of ancillary science can be broadly delineated:

- K-giants: According to Henry et al. (2000), there is a transition in cool-giant variability between G8III and K2III; it appears that the amplitudes are low in this range, but at least 20 per cent of the stars are variable. WIRE star-tracker photometry of Alpha UMa inspired some interesting theoretical discussion (Dziembowski et al. 2001) about the nature and excitation of the modes, concluding that "regardless of what the excitation mechanism is, the data on normal-mode frequencies will be very useful as a constraint on stellar parameters and models". We note that MOST discovered during the commissioning period an unexpected 5.8 day periodicity in Aldebaran, the bright K5III star. The implications of the known, wide range of metallicities in K-type giants for their variations properties should be observationally explored.
- Characterization of large-scale surface structures on cool-star surfaces: Many bright stars require long term photometric monitoring. Currently, discoveries of spots on bright stars are biased toward stars with the largest spots. Variations of stars with small spots, such as the Sun, are not detectable using ground observations because of their low precision.
- Discovery and characterisation of *g*-mode oscillations in solar-type stars: These modes may be detectable and studied by MOST, but with difficulty as they are expected to have periods of several hours.
- Discovery of planetary transits in bright stars: Currently, the radial velocity studies are biased towards low-mass stars as these produce larger reflect motions than massive stars. Detection of transits may be the only technique for planet detection in massive stars, but the amplitude of such transits in the case of massive stars is too small to be readily observed from the Earth's surface.
- Serendipitous or unexpected events such as very bright Gamma Ray Bursts (so far never observed, but possible) or bright comets.
- Interesting individual stars: Is Alpha Per really constant, even though it is in the Cepheid instability strip? Is the light curve of Polaris mono-periodic? Has Spica really stopped pulsating at a milli-magnitude level?
- Close binaries among the brightest stars: Of the 60 or more stars brighter than 4th magnitude and listed in the General Catalogue of Variable Stars, fully a third are eclipsing, ellipsoidal or spectroscopic binaries. BRITE will provide light curves of unprecedented precision and continuity for these stars, some of which will be simultaneously observed spectroscopically from the ground.

4. The BRITE survey in context with others

The BRITE satellite will fill an important and potentially very valuable void in astrophysical datasets. There have been numerous high-impact photometric surveys in recent decades but none have been able to observe and characterise the brightest stars. In a sense, the brightest stars in the sky are “too obvious”, but in reality also difficult to observe well photometrically. Indeed, when extremely rare bright objects such as SN 1987A appeared, very few of the most capable instruments could be modified in a way which would allow them to be observed at peak brightness! Below are several recent key photometric surveys.

Microlensing surveys – the most successful of these have been the MACHO Project, OGLE I, II, and currently III, and EROS. In each case, the signal-to-noise requirement has been (at most) 100:1 per observation. Indeed, 30:1 (and lower) is and was acceptable for this purpose. The bright limit for all of these projects was set by the combination of the exposure time to reach sufficiently faint and thus large numbers of stars, and full well capacity of the CCD detectors. Typically, with the telescopes used, stars must be fainter than R=11.0 mag. to ensure that all photometry is unsaturated. The cadence of observations was typically once-per-night with (very rare) repeat observations at intervals as short as 5 minutes. None of the data from these surveys are suitable for asteroseismology purposes.

Gamma-ray burst optical transient surveys – The two all-sky surveys which have acquired significant data are ROTSE (LANL) and Super-LOTIS (LLNL). The design requirements here were for wide-field (17 degrees), and rapid response. When bursts were not in progress (essentially all of the time!) these systems would survey the available sky. The cadence of observations per field was (at most) twice per night and the bright limit for useable photometry was approximately R=8.0 mag. Due to crowding and sky background, these data have a peak signal-to-noise of about 50:1 and in many cases (such as in the Milky Way) much lower. The data from both ROTSE and Super-LOTIS is completely unsuitable for asteroseismology purposes.

Single-star, high-cadence photometry – There is a significant number of studies of individual high-interest stars. The Whole Earth Telescope (WET) is an endeavour of observatories organized across widely-distributed longitudes on Earth to allow near-continuous observations of stars. This network does not run continuously and has concentrated on individual objects like pulsating white dwarfs and Delta Scuti pulsators in the past. A total of twenty WET campaigns have been reported in the literature to date. The most impressive example of the power of WET campaigns for faint, rapidly varying stars is found in Winget (1991). (Note: There are no bright white dwarf targets appropriate for BRITE; indeed WET has now run out of new white dwarf targets because of their dependence on small observatories.)

Unlike microlensing and gamma-ray burst surveys, WET runs do strive for high signal-to-noise. Same-telescope, point-to-point precision depends on the brightness of the target, but can be as high as 500:1. Unfortunately, systematics across telescopes and observing conditions reduce the accuracy to about 100:1. The use of smaller, ground-based telescopes leads to the inevitable introduction of scintillation noise and extinction-variation induced errors. Indeed, the researchers in WET report that they have great difficulty working on bright stars because of the different mechanical (i.e., CCD shutter) and electrical (i.e., photomultiplier dead time) limitations of each facility's photometer.

In short, no suitable facilities exist anywhere for high-precision, long time-baseline observations of the brightest stars. BRITE will fill an important observational niche. By operating above the atmosphere with a small aperture, it simultaneously eliminates problems associated with saturation, scintillation noise, and atmospheric extinction variations. The stars for which we have the greatest actual ability to pin down astrophysical characteristics (such as metallicity, surface gravity, effective temperature, etc) to high precision are the brightest stars. Asteroseismology is a window into the interior of such stars and BRITE will provide us with key information on the structure of these stars.

5. The case for a nanosatellite mission

5.1. Background

The present proposal is a logical development in astronomical space research by utilizing small satellites, which was started with the highly successful MOST satellite. This pioneering micro-satellite was the first to demonstrate that a micro-satellite bus can be stabilised to the high levels required in forefront astronomical research. The current performance level of the stabilisation system of ~one arc-second is much better than when MOST was proposed as the first Canadian micro-satellite in 1997; at that time, performance at 15 – 25 arc-seconds was considered technologically challenging for micro-satellites, but sufficient for a scientifically profitable mission. The Attitude Control System (ACS) was developed by Dynacon Inc., the primary industrial contractor for MOST. This company is now developing a new ACS system for still smaller spacecraft in the nanosatellite range of 1 – 10 kg; in April 2004 they prepared a report for the Technology Branch of CSA in which a complete NanoHPAC, High Performance Attitude Control for a technology demonstration nanosatellite was described (CSA contract deliverable 9F028-034300/004/MTB). The authors of the study (hereafter called the "Dynacon Study") felt that it would benefit from targeting particular specifications; as a result, a study was done in close collaboration with the Space Flight Laboratory of the University of Toronto Institute for Aerospace Studies (SFL-UTIAS) and with the PI of this proposal. To be more explicit (see Sec.8.2.), the SFL-UTIAS conducts the Canadian Advanced Nanospace eXperiment (CanX) program to provide cost-effective access to space for the research and development community at home and abroad through the use of nano-satellites and pico-satellites. These miniature spacecraft employ state-of-the-art technologies and subsystems, including high-performance computers, miniaturized attitude control sensors and actuators, and high-speed communication devices; the CanX spacecraft are designed and built by Masters students at the University of Toronto, under the close supervision of professional staff.

As described in the Dynacon study, the BRITE satellite project was originally referred to as the "NanoHPAC Flight Demonstration Satellite" or the "Bright Star Photometry (BSP)" mission. It is described as CanX-3 in the SFL-UTIAS documents.

5.2. The general concept

The term "minimum mission" will be used in the description of BRITE. Thus, many specific definitions, such as the faintest objects to be observed, the required numbers of observations per unit of time, etc., should be read as the minimum requirements for a scientifically useful satellite mission. It is very likely that the final design will be able to improve on many of these specifications.

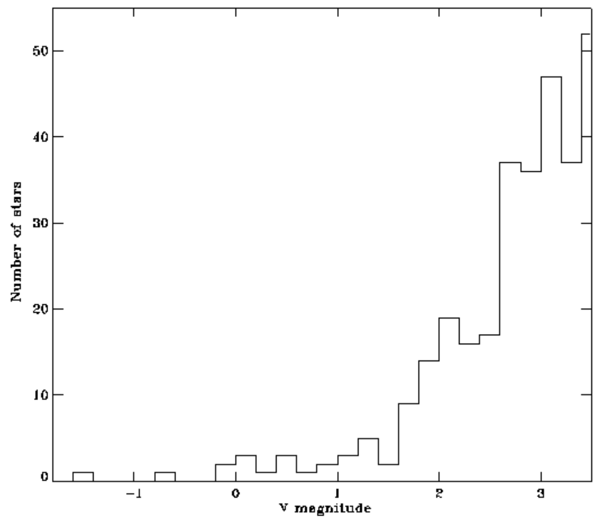

Fig.2: Histogram showing numbers of the apparently brightest stars in the sky to +3.5 stellar magnitude. There are 91 stars brighter than +2.5 magnitude and 286 stars brighter than +3.5 magnitude; the increase is at an approximate rate of 4x per one magnitude interval. The brightest star, Sirius, is at –1.6 magnitude. The whole brightness range for a difference of 5 magnitudes corresponds to the ratio of 100. Note that the "Observer's Handbook of the Royal Astronomical Society of Canada" lists actually 313 stars to about +3.5 magnitude, but a strict limit set at this brightness level leaves 286 stars.

The overall scientific goals of the BRITE mission are somewhat similar to those of MOST, but relate to a different niche of star-variability research with three important points: (1) There exists a need for precise analysis of apparently bright stars in the variability regime of variations slower than observable with MOST (>hours), (2) The majority of the apparently brightest stars in the sky are also intrinsically bright (have high luminosities), (3) The high luminosity stars are expected to show slower variations. In more detail:

1) The small size of the optical instrument results in a limitation to the apparently brightest stars that are accessible in the sky. These brightest objects are exactly those whose variability on time scales longer than hours is the most difficult to study from the ground. This is because the standard technique of precise photometric referencing of stars to their neighbours encounters difficulties with terrestrial atmospheric extinction corrections, which may introduce errors reaching 1% or more; paradoxically, fainter stars referenced to each other over arc-minute fields can routinely provide photometry accurate to 0.1% or better. MOST, which can observe the same point of the sky for up to 7 weeks, is essentially a single-star instrument for bright stars and can be used for differential photometry of fainter ($6<V<13$) stars only within a field of 50 arc-min. While rapid variations of the bright stars can be observed by MOST with a high precision in the Fourier domain, reaching an unprecedented level of a few parts in a million, slow variations cannot be observed that precisely and may contain systematic effects which are hard to quantify. Thus, the regimes of MOST and of BRITE are complementary, with BRITE specifically addressing slow variations taking place in hours to weeks and months.

2) A large fraction of the apparently brightest stars in the sky are also intrinsically luminous stars (Figures 2 & 3). This is because the actual range of stellar luminosities is much larger than the spatial geometric dilution ($1/r^2$) effects in the observed light intensity. When looking at the brightest stars in the sky, we see preferentially the most luminous and distant stars. The apparently bright, nearby stars – like the

prime MOST target Procyon – are an exception rather than a rule. [Note: The stellar magnitude range of –1.5 to +3.5 corresponds to the brightness ratio of 100 times; Sirius, the brightest star has apparent magnitude –1.5].

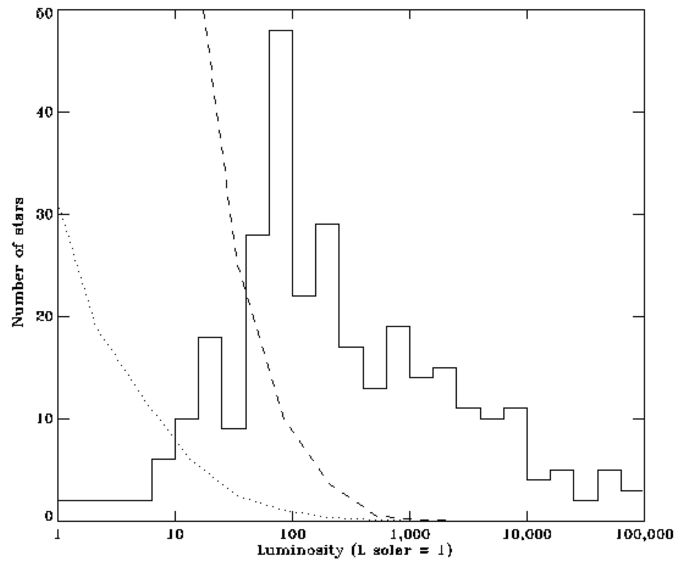

Fig.3:Intrinsic luminosities of the apparently brightest stars to +3.5 visual magnitude. The apparent magnitudes have been converted to luminosities using the known distances and bolometric corrections of the stars. Note that the x-axis has logarithmic scaling and that the luminosity is expressed in solar units; a star like the Sun would be at the left edge of the figure while brighter Procyon is at 7.2 solar luminosities. Most apparently bright stars are also intrinsically very luminous. The true spatial frequency in the Galaxy (broken lines with two arbitrary vertical scaling factors) is very different, with the most luminous stars being in fact very rare. Note that the peak coincides with MS stars of the late B spectral type, with early B at about 1000 solar luminosities and mid O further to the right. Later spectral types can be found blended in with these here, for giants and supergiants.

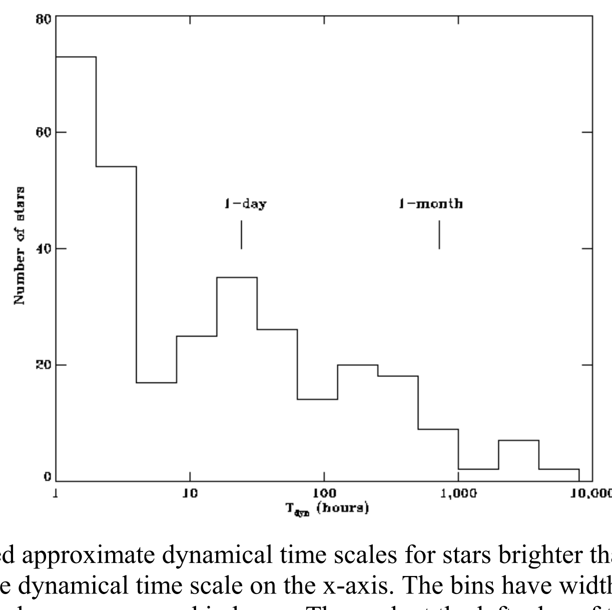

Fig.4: The histogram of the predicted approximate dynamical time scales for stars brighter than +3.5 apparent visual magnitude, plotted using logarithmic units of the dynamical time scale on the x-axis. The bins have width of 0.3 in the logarithm (factor of 2 in time) and the dynamical time scales are expressed in hours. The peak at the left edge of the short time scales is resolved into finer, linear units in the next figure. The dynamical time scales were calculated using the familiar free-fall formula $t_{dyn} \sim 1/\mathrm{sqrt}(G*rho)$, where mean density $rho \sim M/R^3$ was scaled relative to the solar value, with M estimated from the luminosities L.

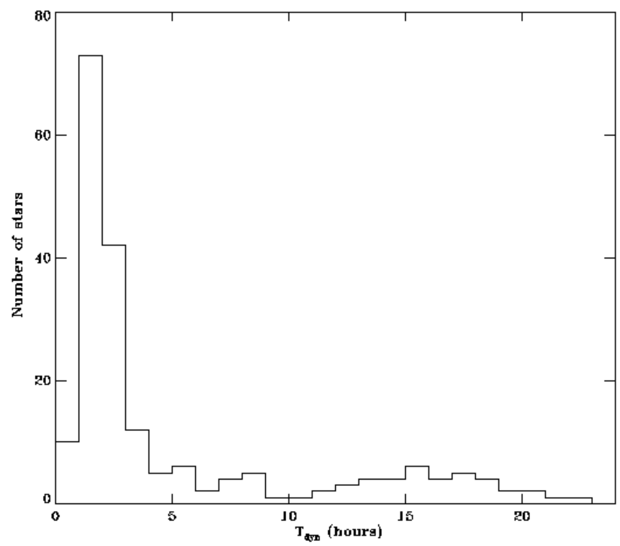

Fig.5: The same data as in the previous figure, but plotted in linear units and only for the short period domain of time scales shorter than one day. Note that the peak at the left refers to the solar-type stars which are being studied by MOST. This shows the complementary character of both missions, with BRITE covering all time scales longer than about 3-5 hours.

3) The characteristic frequency of asteroseismic oscillations, and in fact of most dynamic phenomena in stars, is known to be similar to, or at least of the order of, the "dynamical time scale", t_{dyn}. Such a time scale can be estimated from the known parameters of stars and can serve as a very approximate prediction of the actual oscillation periods (Figures 4 & 5). The *p*-modes (pressure modes), targeted in solar stars by MOST, and the elusive *g*-modes (gravity modes) are or the order of t_{dyn}, with the former appearing at higher frequencies and with the latter expected at substantially lower frequencies (*g*-modes in most evolved stars are expected to be very slow, e.g. for an A0Ia star may have periods of up to 100 days) .The presence of various oscillation modes, their exact location in frequency space and their mutual relations in frequency and intensity, would provide a gold-mine of information on stellar structure.

6. Scientific requirements

The requirements discussed below are for the "minimum mission" of BRITE and may be improved at the design stage. Because of the instrumental limitations (a lens system coupled with a CMOS detector requiring only a moderately fast f/ratio), the minimum mission will have to be limited to stellar fields of 25 degrees in diameter. This impacts the number of stars which can be simultaneously observed by BRITE. There are 286 stars brighter than +3.5 visual magnitude in the whole sky; if at least 2 stars were to be observed per field, 78% of the sky would be accessible for high quality photometry (see the table below). The minimum mission should last for a minimum of two years with very low operating costs (thanks to utilisation of the MOST ground segment). Extensions of the mission should be – at the design stage – in the choice of (1) the field of view and the resulting the sky coverage and of (2) the magnitude limit. An extension of the duration of the mission will be the simplest low cost addition to the value of the mission.

Number of stars per 25 deg diameter circular field	**Percentage of the sky**
≥1	100
≥2	78
≥3	61
≥4	43
≥5	29
≥6	20

We propose 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 appear in the wide band close to the Milky Way occupying about 1/3 of the whole sky. The table above illustrates in percentage the amount of the sky accessible to multi-star differential photometry.

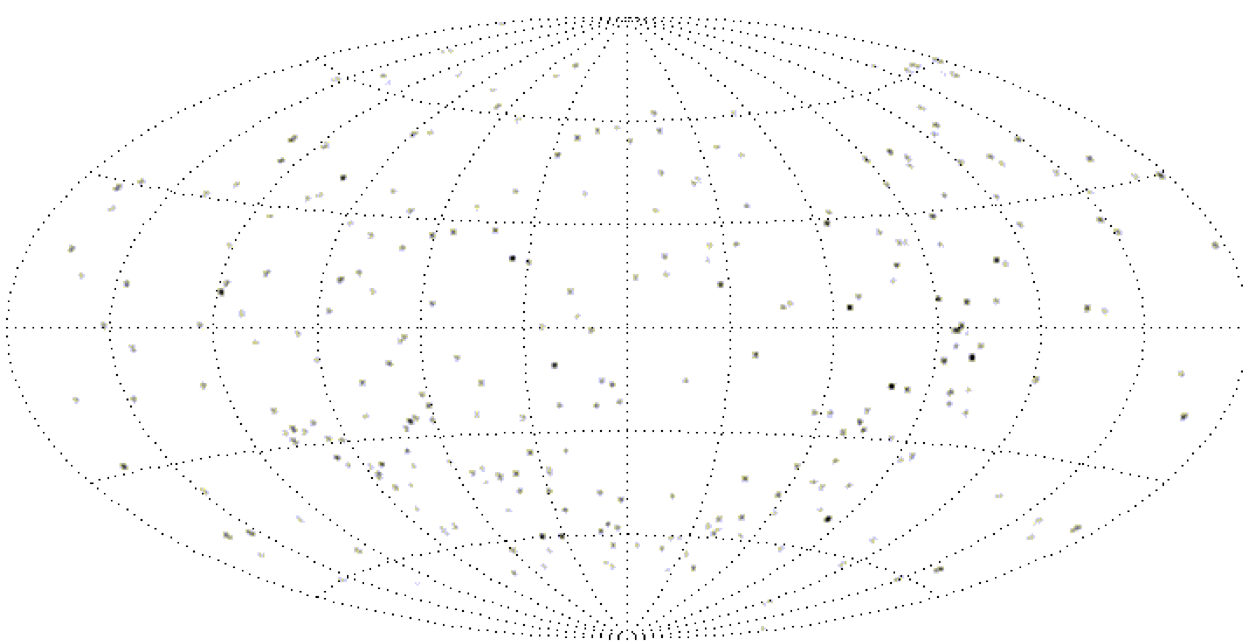

Fig.6: Map of the sky with stars to +3.5 apparent visual magnitude in the Aitoff equal area projection. Note the density enhancement along the Milky Way (it is actually better visible in the next figure.

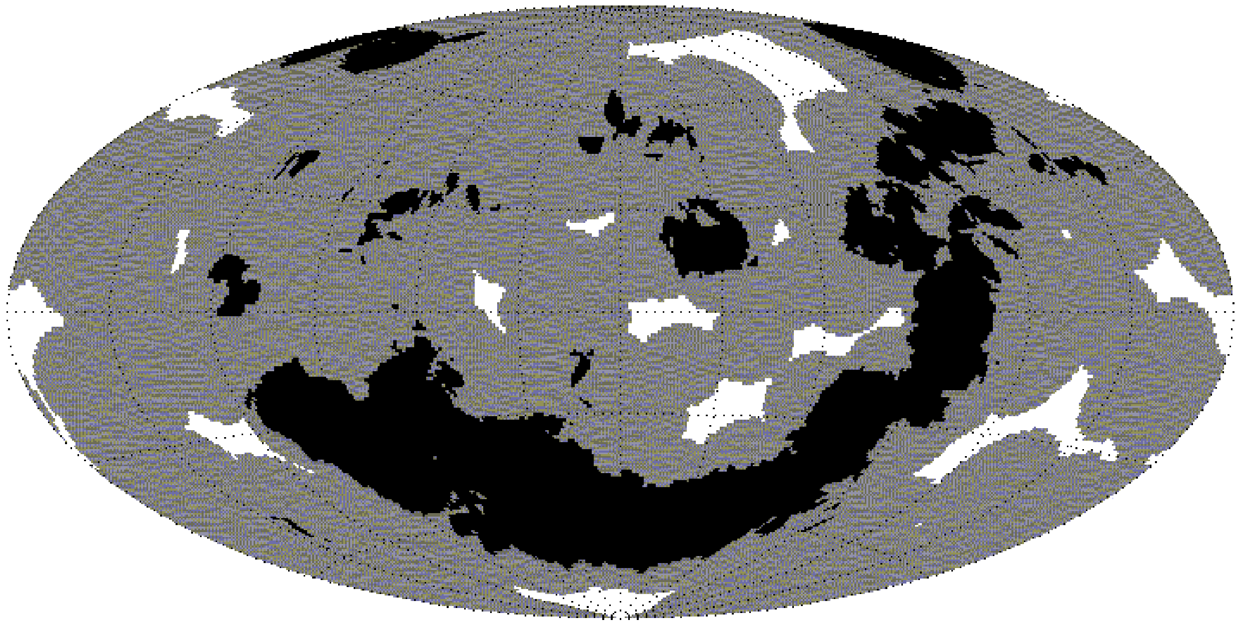

Fig.7: The density of stars to +3.5 apparent magnitude calculated for 25 degree diameter fields. The black areas mark fields where at least 6 stars per field will be observable while the grey areas mark fields with at least 2 stars per field. At least one star is present in every point of the sky so that an extension of the mission, after the internal stability of the instrument is verified, will be able to study all bright stars in the sky.

Scientific requirement	Minimum requirements
Apparent 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

7. Technical specifications of the optical instrument payload

This section contains information and results obtained during a Concept Study conducted in January – April 2005 by a small team led by the PI of this proposal, see the footnote in page 4.

7.1. The CMOS detector

The science payload of the satellite will consist of a small lens-based camera and a two-dimensional array detector. The power limitations suggest a low-power CMOS detector. Many low-power devices utilizing CMOS technology are currently available for the photo camera market, and recently they have become quite large, up to the full 35mm format (36 × 24mm). Current properties of relevant example devices are summarized in the table below. The prices of such devices are very modest compared with CCD detectors of comparable size.

When compared with CCD detectors, properties of CMOS detectors are slightly poorer and less convenient for scientific applications (Janesick 2002), although manufacturers are rapidly improving their products with thinned, back-illuminated CMOS devices are now being considered (Janesick and Putnam 2003). Compared with CCD's, they have larger dark current signal, poorer effective quantum efficiency (QE; here meant as a product of the QE per pixel times the geometric factor related to utilization of the front side of the detector) and their performance is especially poor in fast (low f/ratio) optical systems due to difficulties of oblique-angle photon penetration. Thus, they have not found yet many scientific applications, although some first attempts must be noted (Bonanno et al. 2003; and
http://www.fillfactory.com/htm/technology/pdf/pw00limits.pdf
http://www.fillfactory.com/htm/technology/pdf/iris_cets.pdf
http://www.fillfactory.com/htm/technology/pdf/space97.pdf)

Property	**Typical parameters**
Power Consumption	0.08 – 0.5 W
Number of pixels	1280 x 1024 to 4556 x 3044
Pixel size	5 – 8 micron
Effective QE	10 – 50%
Full well capacity	20,000 – 60,000 el
Dark current (at 25 C)	1.0 – 220 el/sec
Readout noise	3 – 35 el
ADU resolution	10 – 12 bit/ADU
Sensitivity non-uniformity	0.4 – 1.0%
Radiation hardening	Yes, for some models
Manufacturers	Fill Factory (now Cypress) Canon (in DSLR camera) Micron (formerly Photobit)
Typical cost (US$)	250 – 1,000

Janesick (2002) estimates that the overall reduction in the effective S/N, for large-pixel (i.e., deeper charge wall, >15 micron) CMOS detectors, when expressed relative to CCD's, is at the level of 2 – 5 times. However, their use with computers is much simplified, as they can be directly addressed without any need for complex and power-hungry clocking circuits, which are essential in CCD's. Thus, these systems are sometimes called Active Pixel Sensors (APS) to indicate that they can be easily re-configured in terms of active windows, even to the extent that logical circuits can decide how to observe a particular section of the light sensitive area. In recent months, FillFactory, Micron and Canon have produced chips or whole cameras which have quite decent performance compared with CCDs, and which would perform more than adequately in BRITE. Our Concept Study confirmed, for example, that a CMOS detector manufactured by Canon, even at room temperature shows the dark current as low (<1 el/sec/pixel) as typically observed in thermo-electrically cooled CCD detectors.

The build-up of charges at typically low number (12 bit or 4096) levels to reach the A/D circuitry saturation will require the BRITE camera to operate with short exposure times, of the order of <30 seconds. An observation will be an average of many such short exposures, which – in turn – sets demands on the on-board computer of the satellite, but may help in eliminating cosmic ray events. The goal will be to achieve an accuracy of 0.001 mag. or better per 15-minute observation.

One can estimate the magnitude limit for a target accuracy better than 0.001 mag. using the following reasoning: The photon flux from a 0-magnitude star (like Vega) in the visual V-band (wavelength 550 nm, in a conservatively assumed band-pass of 89 nm) is $f_0=1.0\times10^4$ photons/nm/sec/cm^2. The photon flux f_m scales with the magnitude, m, as $f_m = f_0\times10^{-0.4m}$, so for m=+3.5 it will be ~400 photons/nm/s/cm^2. This number will hold, when translated to electron charge, assuming a lens of diameter of 5 cm^2 area and an overall QE of 20%. The charge is ~120,000 el/s/cm^2 using a space-qualified MOST filter with a bandwidth 300nm centered on 550nm, which admits about 3× more light than the V-filter. For an area of 50 pixels, assuming a dark current of 220 el/s/pix for the sensor we currently most favour for its pixel size and dimensions (IBIS4-14000), the total dark signal charge will be ~11,000 el /s. The resulting signal-to-noise ratio of S/N ~ 1000 in 10 seconds will be further increased by averaging many exposures; thus an achievable signal-to-noise ratio for a +3.5 mag star should be S/N ~ 10^4 for an accumulated observation of 15 minutes. The ADC unit should be able to handle the 12 bit conversion. It should be noted that with the numbers as above, the stellar and dark current signals will be comparable for V = +8.5, which appears to be a realistic limit for a mission utilizing CMOS with a lens system of dimensions as small as planned here.

The above estimate is a pessimistic one since we now know that the dark current much below the assumed value. In our Concept Study, we have carried out thermal noise and angular sensitivity tests on two CMOS detectors, Canon and Micron, used in the Electrim camera[2]. We found that the Canon camera CMOS has an exceptionally low dark current of <1 e-/sec/pixel, but the detector shows angular sensitivity variations which are most probably due to the Bayer-matrix and IR filters and/or to micro-lenses above the active surface. The variations are at a level of about 15% – 20% within the 25 degree diameter field with even larger effects when a commercial lens is used (without a provision for perpendicular incidence of light). The Electrim camera showed very small sensitivity variations of <3% across the field, but this camera has a large dark current and a limitation due to its 8-bit on its A/D converter.

[2] The third CMOS detector, IBIS4-14000, which is our preferred sensor, has been ordered by Dynacon for internal tests in the future.

Currently, the CMOS technology changes at almost a monthly rate so we cannot suggest a particular model for BRITE. Because of the low cost of the CMOS detectors, it is proposed that several units be acquired and tested before the final selection.

Probably the most difficult aspect to quantify at this stage is the contribution of the detector photometric non-uniformity to the total error budget. While the manufacturer specifications give numbers similar to those for CCD's (typically 0.4% – 1.0%), the selected detector will have to be fully characterized before launch. Also, the satellite design must include a provision for calibrating the relative pixel sensitivities using "flat-field" exposures of the bright cloudy Earth. This need will be of great importance as the flat-field images will permit determination of the combined effects of the vignetting of the optical system, of the non-perpendicular (limited f/ratio) illumination effects for the CMOS detector as well as pixel sensitivity losses due to the aging of the detector under cosmic ray bombardment. Further sensitivity calibration will be obtained from stellar measurements, using the experience gained with large terrestrial CCD mosaic cameras in major observatories, all of which suffer from serious scattered light problems.

While our current understanding unambiguously points to a CMOS detector, use of a CCD detector should be considered early in the design stage for the following reasons: CCD detectors are still better than CMOS detectors for scientific use, but require power in excess of typically 5W; BRITE may have only about 1W for the detector operations. However, the high power requirements in CCD's occur only during the readout stage while – for long exposures – the power consumption is minimal. It should be explored if a rechargeable battery could be used between readouts. The mode of operation for a CCD-based system would be different: While many short, averaged integrations would be necessary with CMOS, a few long integrations can be made with a CCD.

7.2. The optical system

The satellite Attitude Control System based on the nanoHPAC design is expected to provide 1-sigma stability of 1-arcmin (or FWHM~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 central stop, the front lens may be bigger). As demonstrated in the BRITE Concept Study, the optical properties, depending on the pixel size, will not be difficult to meet for parameters as in the table below. The field of view (FOV) side dimensions are for the smaller dimension of the chip, assuming a detector of 4560 × 3048 pixels, such as IBIS4-14000; a beam of f/2 has been assumed.

pixel (microns)	**F mm**	**Scale ″/pix**	**FOV side in degrees**
6	50	24	20
8	70	23	19
8	50	32	27

The Concept Study presents a possible optical lens design which insures perpendicular illumination of the detector over the whole field of view of 25 degrees in diameter (Figure 8).

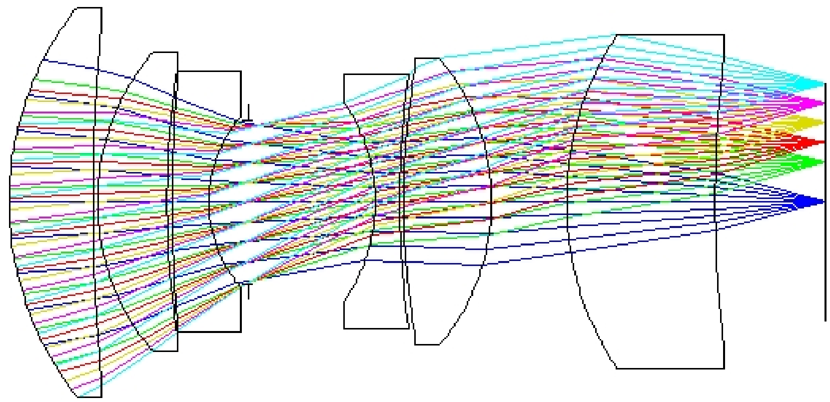

Figure 8: A lens system presented in the BRITE Concept Study.

Preliminary discussions with Mr. Peter Ceravolo of Ceravolo Optical Systems (www.ceravolo.com; he participated in the design and construction of the MOST optics and in the BRITE Concept Study) indicated that there should be absolutely no difficulty with manufacturing a lens system with the properties as above for very moderate costs of about $3,000 (as per information regarding fabrication from BMV Optical in Ottawa). By custom-making such a system rather than using an off-the-shelf unit, the issues of vignetting as well as the best Point Spread Function for the large camera pixels could be fully addressed. Also, some types of glass and of optical cements used in commercial multi-lens systems may be sensitive to the UV and CR environment. There exists also an issue of the lens system stability and resistance to vibrations during the launch so that a special high quality mount will have to be used.

The satellite shall have no moving parts. Thus, changing filters is excluded, while requirements on the photometric quality of the mission demand utilization of an optical filter. The selection of the filter should be done at the design stage. The space-qualified filter of MOST, with a band-pass about two times wider than the standard V-filter, may be a good choice.

The optical system must eliminate sources of scattered light from the Sun, Moon and bright Earth by providing a baffle system. This can be achieved by having the optical instrument "buried" inside the satellite at some depth. With the overall dimensions of the camera of 7cm to 12cm, this should be achievable with at least one satellite dimension larger than 10cm.

It is proposed that the detector & optical system be tested on stars from the ground before integration with the satellite bus. Such tests would not be difficult to make, yet could easily reveal any problems, should they arise, with stray light, optical tightness of the instrument, etc.

8. Technical specifications of the satellite

8.1. Main Science-Derived Requirements

Size and mass	The satellite must house a small telescope (aperture of 25 or 35 mm) with a panoramic detector (CMOS or CCD), computer(s) and mass memory to store up to 2 days worth of observations, communications hardware (including radios and telemetry electronics), attitude control components, thermal control components, and power system hardware (including battery and power distribution unit)
ACS: Pointing, object acquisition	Better than half degree in any part of the sky away from the Sun, the bright Earth and Moon.
ACS: Field re-acquisition	Acquisition after each eclipse by Earth. If possible, the low inertia of the satellite and the agility of the ACS will be exploited to observe 2 or more fields each orbit. This will require multiple target field acquisitions.
ACS: Error during pointed observations (1-sigma)	Smaller than one arc minute (1/60 degree) over the duration of an observation of up to 15 minutes.
ACS: Flat field images	A provision to obtain images of fields without stars, in particular, of the bright cloud-covered Earth.
Duty cycle (exposure time/total time)	>15%; this figure-of-merit will improve if 2 or more fields are observed per orbit.
Data processing	Averaging/medianing of individual short exposures of windowed images for improvement of S/N and for cosmic ray removal. Compacting of data for efficient telemetry assuming 2 contacts per day of 15 minutes
Data storage & telemetry (minimum data rate)	Up to 15 stars observed, each in a 20x20 pixel window at 2Bytes/pixel resulting in 12kB per observation. Combined 15-minutes observations (consisting of many short exposures) can be co-added on board. With one target field per orbit and up to 15 orbits per day, the minimum telemetry load: 180 kB/day. The minimum data storage for up to 2 days: 360kB.
Data storage & telemetry (maximum acquisition data rate)	Two 1K × 1K sub-fields per day at 2Byte/pixel for initial acquisition and flat-field monitoring. Maximum telemetry load: 2MB/day (assuming at least 50% compression of data). [Consider full 3.6K × 3.6K images at lower rates].
Orbit	No stringent limitations. It should permit at least one observation of at least 15 minute duration per satellite orbit (typically 100 minutes).

8.2. The CanX Program at UTIAS/SFL

The proposed mission draws upon the knowledge and lessons learned from the Canadian Advanced Nanospace experiment (CanX) program established at the University of Toronto Institute for Aerospace Studies (UTIAS) Space Flight Laboratory (SFL). The primary objective of the CanX program is to train students at the graduate level. Students form a tightly integrated satellite design team whose objective is to design, develop and launch a complete satellite mission within the time it takes to complete a Masters degree. Another objective of the CanX program is aggressive experimentation in space within the context of a short (typically two-year) schedule and tight budget resulting in moderately higher risks. BRITE (also known at UTIAS/SFL as "CanX-3") will benefit from several critical components that are currently under development by UTIAS/SFL staff for the CanX-2 project. These include high-performance computers, miniaturized attitude control sensors and actuators, high-efficiency power systems, and high-speed communication devices. BRITE will also benefit from the lessons learned arising from the CanX-1 project and substantially from more staff involvement than was possible for CanX-1. As a result, the BRITE student team will work closely with UTIAS/SFL and Dynacon staff. Staff will provide project management, supervision and mentoring in addition to the provision of critical satellite hardware to ensure that a minimum level of reliability is provided for the satellite, as can be reasonably expected from the proposed budget.

There are a number of approaches for launching a nanosatellite. The BRITE team may choose to adopt the Stanford/CalPoly "CubeSat" standard, making the satellite compatible with the CalPoly "P-POD" launch tube – a separation system that is pre-integrated with its satellite(s) prior to launch site delivery. This was the approach used to launch CanX-1 and two Danish satellites in June 2003. Another approach, one that is being adopted for CanX-2 and future CanX satellites, is to utilize an enhanced nanosatellite separation system from the University of Tokyo – the so-called "T-POD" (see Figure 9) – that will allow launch co-sharing, but will ensure independent and gentle satellite separation. BRITE will use the latter approach. Significant advances are currently being made by UTIAS/SFL working in collaboration with Japanese nanosatellite developers to ensure that this separation system is ready and space qualified by 2005 (as part of the European SSETI Express mission).

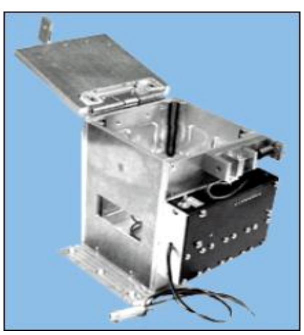

Figure 9: T-POD Ejection

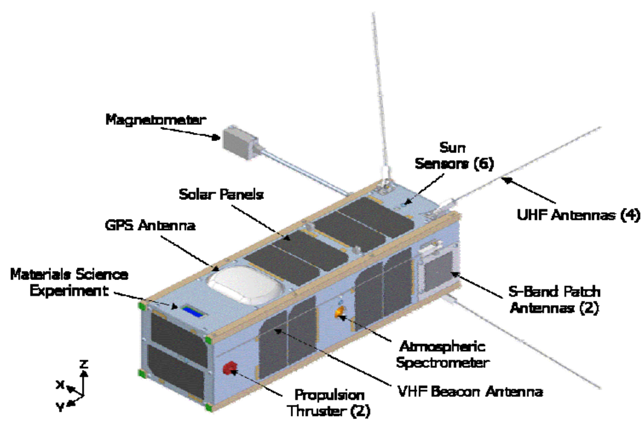

Figure 10: CanX-2 Solid Model

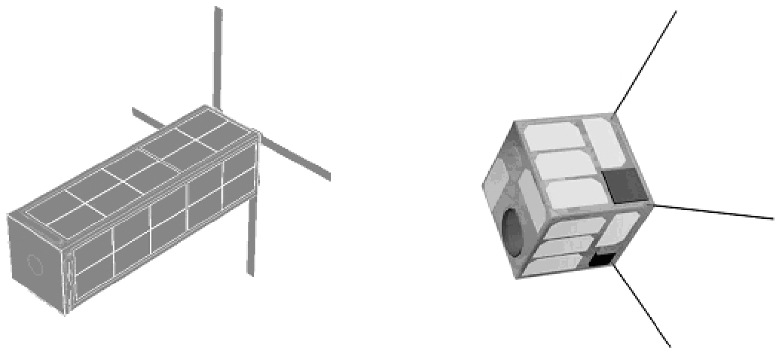

Figure 11. Possible form factors for BRITE – Triple Cubesat 30x10x10cm and 15-cm Cube

8.3. BRITE and CanX-2

The major differences between CanX-2 and BRITE are the enhanced attitude control system and the science instrument. Both of these will require substantial power to operate, and mass and surface openings for optics. The differences in the driving requirements for the current mission are summarized in the table, with pictures of the Triple-Cubesat and of the 15cm Cube shown in Figure 11. An exploded view of BRITE is shown in Figure 12.

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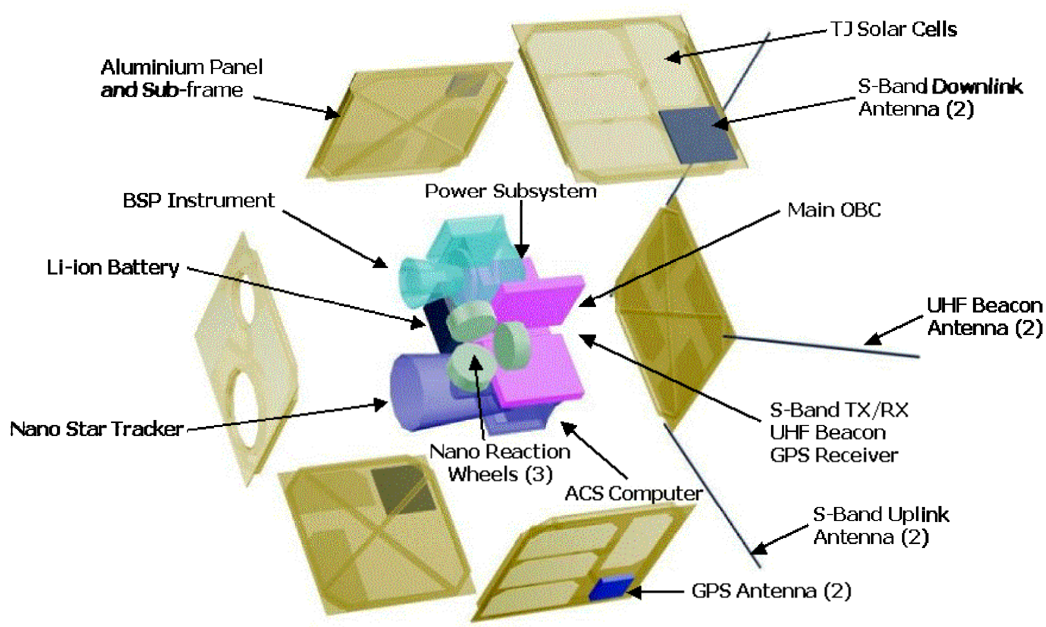

Figure 12: Exploded View of BRITE

Parameter	BRITE	CanX-2
Form-factor	10×10×30cm Triple-Cubesat, 15×15×15cm Cube, or 15×15×20 cm Block	10×10×30 Triple-Cubesat
Primary Payload	25 or 35 mm aperture, 25° FOV telescope for Bright-Star Photometry	Science: Dual-band GPS receiver for Atmospheric Occultation Experiment Engineering: Experimental cold gas propulsion system, S-band transmitter, Nanosatellite reaction wheel.
Secondary Payload	To be determined, probably not enough power for a secondary payload	Science: Atmospheric Spectrometer, Surface Material Experiment, Communication Protocol Software
Attitude Control	Three-axis stabilized augmented with Star-Tracker and three reaction wheels, 1arc-min capable	Three-axis stabilized, magnetic controlled with single-axis momentum-biased
Power Use, W	7.1 W max instantaneous	5.8 W max instantaneous
Orbit-Averaged Energy Balance, Wh	4.6 Wh nominal generated 3.5 Wh nominal consumed	3.2 Wh nominal generated 1.7 Wh nominal consumed
Data rate, kbps	32kbps	2.4kbps 32 kbps experimental
Data throughput, MB	1MB/day typical 6MB+/day possible	1MB/day (2.4kbps)
Frequency	S-Band, 2.29 GHz	UHF, 430MHz

8.4. Satellite Architecture and Power Constraints

The satellite does not present any technological difficulties given the mature design and development stage of the CanX-2 (see Figure 13 for a block diagram of the BRITE satellite architecture). The main design constraint for BRITE is the limited power supplied by the solar panels. The total solar power per 10×10cm is 13.6W. After taking into account solar panel efficiency, the effects of temperature and incidence angle, the surface area needed for communication antennas, in addition to the inability to ensure 100% coverage (packing density) of solar cells on the remaining surface (i.e., it is not possible to fully utilize all available area due to the finite shape and size of the solar cells), the expected total power supply will be limited to approximately 4 – 6W. A thorough analysis of power requirements shows that the Attitude Control System will need between 1W (in safe-hold mode) to 2.75 – 3W (in fine pointing, with all subsystems running, including the reaction wheels, magnetometers, magneto-torquers, rate sensors, star tracker). This means that the science instrument cannot utilize a CCD detector since the typical power consumption for these devices is more than 5 W. However, a CMOS detector typically needs only 0.25 – 0.5 W. Of the other satellite systems, the transmitter is expected to require the largest amount of power (3 W when operating, but only 0.3 W orbital average). The thermal control system, OBC, receiver and beacon are expected to require less than 0.25 W each. Power generation may be improved by using satellite form factors with increased surface area.

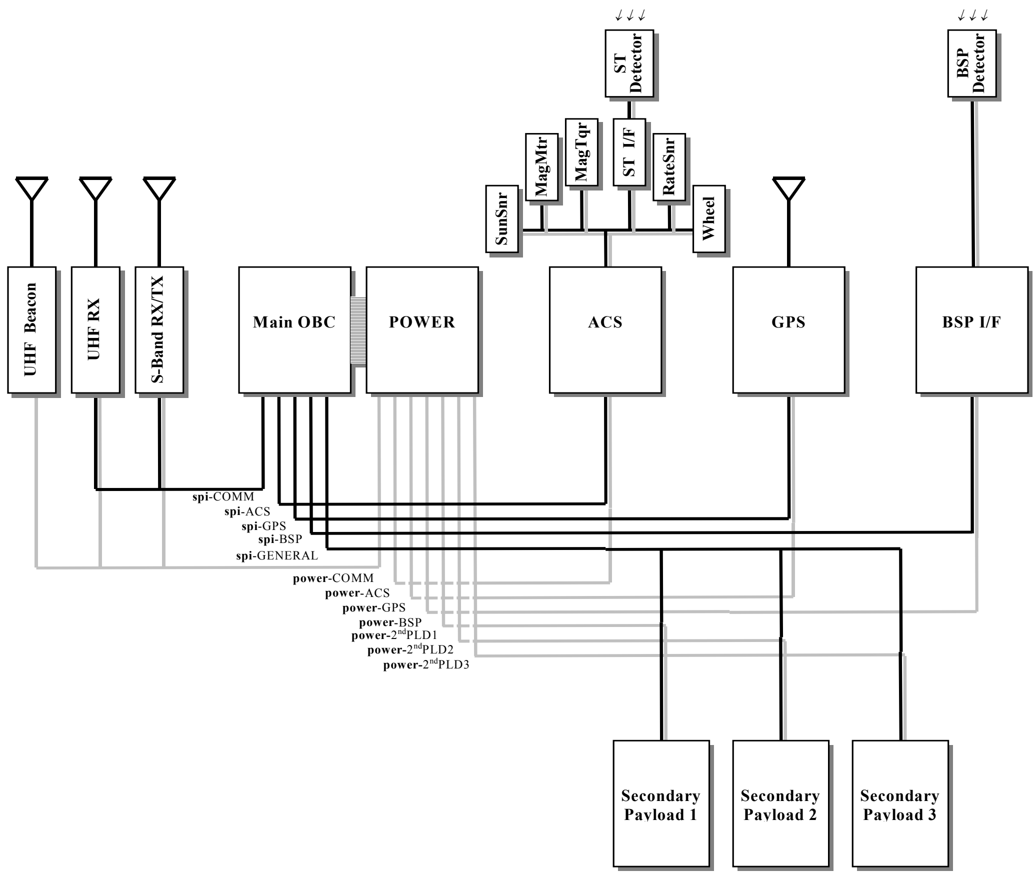

Figure 13: Possible BRITE satellite architecture (the drawing assumes existence of secondary payloads, the need of which is to be determined).

8.5. Launch Vehicle and Orbit

In order to minimize launch costs, a nanosatellite will utilize the excess capacity of another party's launch. As a consequence, the nanosatellite developers are typically not able to choose their launch vehicle and orbit, and these quantities remain unknown well into the satellite development program. To increase the number of launch opportunities, therefore, BRITE shall be compatible with the launch environments of the following launch vehicles:

- Rockot
- Dnepr
- Proton
- Delta-II

BRITE shall also be operable in various orbits. The following orbits shall be used for the mission design:

- **Orbit 1:** 900 km, dawn-dusk sun-synchronous, similar to MOST's. This orbit shall be considered for the worstcase communication link analysis and thermal analysis. Most sun-synchronous

satellites are launched into 10:30am ascending node orbits for minimum cloud cover in support of Earth observation missions.
- **Orbit 2:** 500 km, 40-degree inclination. This orbit shall be considered for worst-case power generation because of long, half-orbit eclipses.
- **Orbit 3:** Non-circular orbit, TBD apogee and perigee. This orbit shall be considered for worst-case data throughput.

Since BRITE telemetry will be very similar to that of MOST, the satellite up- and down-links can be supported by using the existing MOST ground stations at UTIAS/SFL, and possibly those at UBC and the University of Vienna. These stations are inactive for extended periods each day and come alive only during MOST passes in the morning and late afternoon. It is likely that BRITE will not have a dawn-dusk line of nodes, so the chances of conflict with MOST are minimal.

9. Cooperation with Austria

Professor Werner Weiss, one of the members of the MOST Science Team and facilitator of the use of the Vienna ground station for MOST telemetry download contacts, proposed that the Austrian Space Agency fund building a nanosatellite like BRITE (most likely just a copy of it) in Austria. This is a very attractive proposition which can considerably enhance the scientific returns of BRITE by division of targets or of photometric band-passes for simultaneous observations.

Currently, discussions within the Austrian community, with ASA and with the BRITE team concern the following subjects:
- Extent of scientific/technical cooperation with Canada, in particular with reference to a planned MOU between the Canadian and Austrian space agencies,
- Scientific case for a second BRITE mission,
- Scientific task distribution between the two planned nanosatellites,
- Technical similarities and differences (such as different filter band-passes, a complementary orbit to increase the time coverage, etc.);
- Institute and laboratories in Austria which potentially can contribute to second nanosatellite project;
- Launch issues;
- Budget and time table for the second nanosatellite.

A meeting of all Austrian parties interested in CUBESATs took place on Sept. 29, 2004, where BRITE was one of considered options. In a meeting on April 13, 2005, the BRITE concept was presented at the Technical University of Graz to the potential partners and to the representatives of the Austrian Forschungsfoerderungsgesellschaft (FFG), Department of Space and Aeronautics (former ASA), and was very well received. Prof. Weiss will reply with a proposal for a nanosatellite like BRITE to a call for the 3rd Austrian Space Programme, to be issued in May, with a deadline of July 5th, 2005. Having an unique expertise with the small-payload 3-axis stabilization, Canada may play a leading role in a small, highly specialized consortium dedicated to this nanosatellite. One of the possibilities to be discussed would be an active participation of Austrian MSc graduate students in the UTIAS micro- and nanosatellite programs. Dr. Robert Zee from UTIAS was invited in April 2005 to Vienna for a discussion of technical and administrative issues relevant for the planned cooperation and with the goal to build a nanosatellite like BRITE under the Austrian auspices.

10. Teaching and outreach

Improving science literacy and numeracy, increasing the number of students who are interested in, and qualified for careers in science, technology, engineering, and mathematics (STEM), and training these highly-qualified STEM personnel, are three high priorities for Canada. NSERC, for instance, has recently demonstrated its interest and concern by initiating two education programs: PromoScience, to support STEM promotion and outreach, and CRYSTAL, to promote effective STEM teaching and learning. It also puts increasing weight, in judging Discovery Grant applications, on the applicant's ability and willingness to engage in training, education, and outreach beyond the graduate and post-doc levels.

Graduate and undergraduate students at both UTIAS/SFL and the University of Toronto Department of Astronomy and Astrophysics (DAA) will have the opportunity to participate in BRITE-related projects, in the same way as students participated in the MOST program. BRITE can provide highly-motivating projects for students at a variety of levels, and in a variety of disciplines. In particular, undergraduate research is highly valued at the University of Toronto, and elsewhere in North America, and the BRITE science team have extensive experience in this area. BRITE provides unique opportunities for inter-disciplinary research, including the engineering-astronomy interface in mission development, and the astronomy-physics-statistics interface in data analysis and interpretation. Data from the satellite can even be used by senior high school students to develop and integrate their science, math, and computing skills; they will be motivated by doing real science, with real data. The infrastructure for doing this has been developed by a member of the science team, through an undergraduate research website at the University of Toronto (http://www.astro.utoronto.ca/~percy/index.html), and through the NSF-funded ($300K) project "Hands-On Astrophysics" (http://hoa.aavso.org). Undergraduate students can also promote, and participate in BRITE through student societies such as the University of Toronto Astronomy and Space Exploration Society (http://asx.sa.utoronto.ca) which attracts audiences of over 1000 to some of its public events.

Astronomy and space have the capacity to attract young people to careers in STEM. BRITE, having the imaging capability, and being simpler to comprehend than MOST, will have special connections with students at the school level (astronomy is now a compulsory topic in elementary and secondary school in Ontario and most other provinces in Canada), and with amateur astronomers and the public. Canadians take pride in their country's achievements. Images from BRITE will make its accomplishments real. The satellite studies stars which all can see, and "the stars belong to everyone".

Amateur (volunteer) astronomers, along with professional astronomers and students, have an important role in bringing astronomy to schoolchildren, teachers, and to the public. In particular, the Royal Astronomical Society of Canada (RASC), with 5000 mostly-amateur members in 27 Centres across the country, was the 2003 winner of NSERC's Michael Smith Award, for outstanding contributions to science outreach. Amateur astronomers, some of whom have professional-quality equipment, can also provide ground-based support observations for the project. Several Canadian amateurs have been nationally or internationally recognized for work of this kind.

The education and outreach program for BRITE can be delivered by the Canadian Astronomical Society's Canadian astronomy education website (http://www.cascaeducation.ca), which was supported by NSERC's PromoScience program, and Ontario's Youth Science and Technology Awareness Program, and which is maintained by CASCA's education coordinator.

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2004 May 30

To whom it may concern:

This is to certify my agreement to be an active participant in the scientific team for the BRITE satellite. I have done, or will do, the following:

1) I have been an active participant in developing and writing the primary scientific proposal in this submission, and I have made some suggestions for ancillary science that are also included in the proposal.

2) During the pre-launch phase of the BRITE project I will devote up to 20 percent of my research time to:
   a) Work with the design team to insure that the design of the scientific payload and spacecraft will be capable of achieving our minimum scienctific goals;
   b) Work with the Science Team to devise tests and calibrations to be done on the scientific payload to ensure that it meets the specifications required to achieve our minimum scientific goals;
   c) Assist the entire team in carrying out and interpreting these tests, as required;
   d) Work with the science team to select target fields and order them in priority to maximize the scientific return from the BRITE mission;
   e) Look for possible collaborations with amateur and professional photometrists and professional spectroscopists to extend and augment our data on the more interesting targets.

3) During the post-launch phase I will devote up to 40% of my research time to:
   a) Collaborate with the scientific team in analyzing, interpreting, and publishing the data obtained by BRITE;
   b) Work actively to promote collaborative programs with ground-based amateur and professional observers;
   c) Take an active part in public outreach activities related to the BRITE mission.

Yours truly,

C. T. Bolton, Ph.D., FRSC
Professor of Astronomy and Astrophysics

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Marten H. van Kerkwijk
Professor of Astronomy

May 25, 2004

Prof. Slavek Rucinski
Department of Astronomy & Astrophysics
60 Saint George Street
Toronto, ON M5S 3H8

Dear Slavek,

this is to confirm that I am happy to participate in the nano-satellite mission aimed at obtaining accurate lightcurves of bright stars. I hope to contribute in many aspects, but probably can do most on the following topics: (i) target selection among main-sequence stars; (ii) helping make optimal observing plans; (iii) developing read-out and on-board analysis techniques with which to get accurate photometry of as many stars as possible to the ground; and (iv) analysis and write-up of results, again especially for main-sequence stars.

All best regards,

Marten van Kerkwijk

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Stefan W. Mochnacki
Associate Professor

May 28, 2004

Dr. S. M. Rucinski,
Associate Director,
David Dunlap Observatory,
Box 360,
Richmond Hill, ON L4C 4Y6

Dear Slavek

I wish to acknowledge and accept your invitation for me to join the Science Team for the BRITE nanosat project. I very much look forward to participating in this project as a member of the Science Team. I see my functions as the following:

- To provide guidance and analyses regarding the choice and application of the imaging sensor.
- To assist in formulating the data reduction pipeline and associated algorithms, collaborating in the development of software where necessary.
- To analyse observations of close binary stars.
- To participate in formulating the observing programme to ensure that enough close binary stars are adequately observed during the mission to meet my science goals.

I intend to make this an important part of my NSERC grant application later this year.

Yours Sincerely,

S. W. Mochnacki

Stefan Mochnacki

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DÉPARTEMENT de physique

May 25, 2004

Dr. Slavek Rucinski
Associate Director & Professor
David Dunlap Observatory
University of Toronto
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Dear Slavek,

This is to confirm my enthused participation as Science Team Member for the project that you are leading of a Canadian micro-satellite to carry out extensive high-precision photometry from space of the brightest stars in the sky. I will participate in all stages, including establishing the design parameters, establishing the science goals and analysis/publication of the results. Mostly some of the latter will involve students.

Sincerely,

Tony Moffat

Tony Moffat
Professor

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25 May 2004

Professor Slavek Rucinski
Department of Astronomy and Astrophysics
University of Toronto

Dear Slavek,

I look forward to participating actively in the science team for the *Bright Star Photometry* satellite. I can offer expertise in three areas:

Research: My primary area of research is variable stars and stellar evolution. I have a special interest in bright variable stars, and have studied a substantial fraction of the stars in the *Bright Star Catalogue* over the course of my career. My research has been supported consistently by NSERC (and previously NRC) and I have published about 200 refereed and other papers on this topic. I have a special interest in the types of variable stars which will be represented in the BSP sample: Be stars, β Cephei stars, B-type supergiant variables, δ Scuti stars, pulsating red giants, as well as several individual variable stars such as Polaris. I am excited by the number of scientific problems which could be addressed by the BSP mission. I am also aware (based on past history) that the BSP mission will probably reveal new problems, as it opens up the "ultra-high precision window".

Education: I am known both locally and internationally for facilitating research by undergraduate students, and outstanding senior high school students through the University of Toronto Mentorship Program, and I recently received the university's Northrop Frye Award for such work. I also co-directed (with the late Dr. Janet Mattei) the *Hands-On Astrophysics* project, with $300,000 of NSF funding. This is an activity-based project which uses the observation and analysis of variable stars to develop and integrate high school students' skills in science, math, and computing. In all of this work, I use variable star data, such as that which will come from the BSP mission, to enable students to learn science and math by doing real science with real data. Once data from the BSP mission is available, I am willing to help to set up an infrastructure to make it available to students for study and analysis.

Outreach: I am active in several outreach organizations, both national and international, and I chair the Education and Outreach Committee of the Canadian Astronomical Society (CASCA). Under my direction, CASCA recently developed the *Canadian astronomy education website*, which could be used to deliver the education and outreach component of the

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BSP mission. I work closely with the Royal Astronomical Society of Canada (2003 winner of NSERC's Michael Smith Award for excellence in science outreach); the RASC can also help to deliver this program. I have close connections with the school system (I am cross-appointed to the Faculty of Education at the University of Toronto); space and astronomy are now compulsory parts of the elementary and secondary school science curriculum in Ontario and other provinces. The BSP mission can help to demonstrate to schoolchildren how Canadian innovation in space technology can advance our understanding of the universe.

Yours sincerely,

John R. Percy
Professor of Astronomy & Astrophysics
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May 29, 2004

Dr. Slavek Rucinski
Bright Star Photometry Mission PI
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Dear Dr. Rucinski,

This is a letter confirming my intended participation in the bright star photometry nanosat mission currently called "BRITE" being submitted for consideration to the Canadian Space Agency.

My particular research interests in this mission involve the pulsation modes of F- and G-type supergiants. In particular, high-precision photometry of Polaris, an unusual Cepheid variable, may provide significant new information regarding the behaviour of stars near the boundaries of the classical Cepheid Instability Strip. Furthermore, apparently stable supergiants such as alpha Per have revealed themselves to be very low amplitude pulsators from precision radial velocity programs. Since these objects are only discovered accidentally when used as standard stars for such programs, this mission will provide a true census of modal behaviour for similar supergiants.

I will be providing the database design and interfaces for all photometry and relevant mission science information for the use of collaborators and all other researchers. Since I currrently maintain three large photometry databases associated with my work (MACHO, SuperMACHO, and a copy of the NSVS), I believe that I am the most appropriate Co-I for this work.

Please feel free to contact me if you have any additional issues and/or concerns.

Yours truly,

D. L. Welch

Douglas L. Welch
Professor