"BRITE": THE BRIGHT TARGET EXPLORER

An unsolicited proposal submitted to the Science Branch of the Canadian Space Agency

June 1, 2004

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Summary

Massive, luminous stars dominate the ecology of the Universe. Above 8 solar masses, their remnant cores implode into a neutron star or black hole, leading to high-speed ejection of remaining outer layers rich in nuclear-processed matter. Above about 20 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, because of their rapid rotation and strong radiation pressure, which often nearly overcome the gravity that keeps these stars together. Partly because of this, massive stars tend to be unstable.

We intend to build a nano-satellite, BRITE (BRIght Target Explorer), and use it (i) to examine – with unprecedented precision and time-coverage – the instability properties of a broad cross-section of massive stars; and (ii) to take advantage of the instabilities to find periodic variations, 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 among the brightest stars in the sky, concentrated mostly in the Milky Way band and down to magnitude +3.5, on time scales ranging from hours to months. We will use a large field of view (minimum 15 degrees) containing multiple stars, so that we can obtain differential photometry with precision better than 0.1% per 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 to the detection and study of g-mode oscillations in solar type stars, to detection of planetary transits in stars more massive than the Sun.

BRITE will 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, low-cost spacecraft. A successful mission will allow Canadian industry to expand its dominant expertise in this area. Of particular importance are the very low cost and the scientific value of the mission, which otherwise may have been a technology demonstration satellite. Because it will study the brightest visible stars in the sky, BRITE will also have a special appeal to the public, including young people.

1. Introduction

Practically all stars vary in brightness. Thanks to these light variations, we can say quite much about the stars, their evolution and internal structure. A wide range of phenomena open up between the extremes: Supernova explosions, the extreme in stellar variability, are the largest known releases of energy from single stellar objects when a single star becomes as bright as 10^{12} stars in the whole galaxy and for several weeks can be seen from cosmological distances. The other extreme in the variation range are 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 or presence of magnetic fields. 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 was built specifically 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 Galaxy's life.

Here we propose a complementary satellite project which will study the most massive stars. These stars live short, 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 of. They also send out into space hard UV photons of extreme importance for the interstellar matter and for the organic matter forming on interstellar grains. The most luminous stars are very rare in space, but their high luminosity gives them a tremendous advantage over intrinsically faint objects: They can be seen from large distances. In fact, the apparently brightest stars on our sky are – in their majority – the intrinsically brightest stars. Thus, when the temporal variation is concerned, they 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 of the order of days, weeks or months.

We propose a nanosatellite BRITE equipped with a small-lens telescope, able to observe the brightest stars in the sky to +3.5 magnitude (with possible extension by one magnitude), over a field-of-view larger than 15 degrees, with a sampling time of every satellite orbit (typically 100 minutes), or more often, the effective exposure time utilization (duty cycle) >15% and with the differential photometry precision for a single observation better than 0.1%. The primary mission will concentrate on precise photometry of massive, luminous stars to study brightness variability over times scales from hours to several months.

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

The hot, OB stars are the most frequent sub-sample among massive luminous stars and they are the prime focus of this proposal. Massive, OB 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 OB stars evolve very rapidly, they process gas quickly. They return a substantial fraction of their original mass to the interstellar medium through their winds and in 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 basically only hydrogen and helium, were massive stars that quickly enriched the Universe in heavier elements and drastically changed the fate of the next stellar generations by modifying the opacity of the matter.

In spite of their rarity, the OB stars make up more than half of the stars brighter than V = +3.5 because their high luminosities permit us to see all of the stars within a very large volume of space. This is both a blessing and a curse: a blessing because there are many very bright stars, so it is possible to observe them with very high signal to noise; 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.

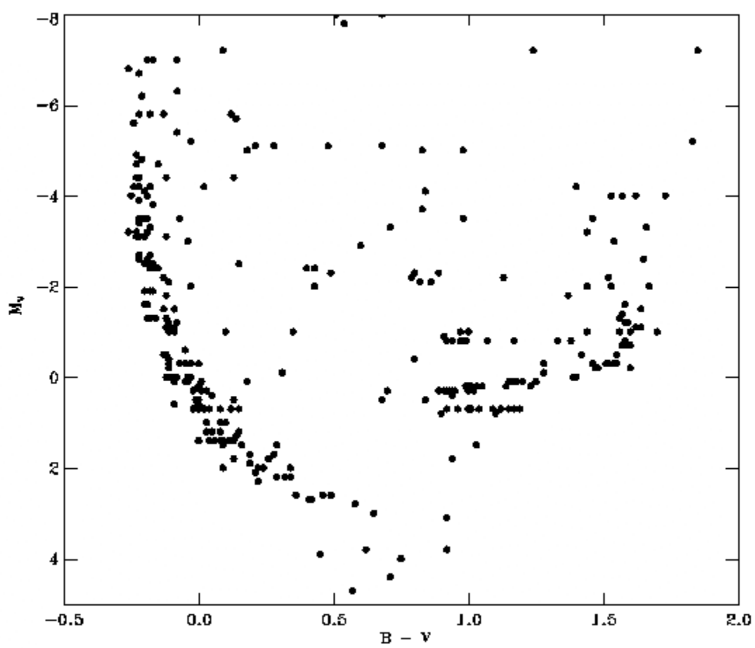


Fig.1. The colour-magnitude diagram for the brightest stars in the sky +3.5 apparent magnitude. Note the large number of blue, massive stars, mostly belonging to the well defined Main Sequence in the left part of the diagram, but also the K-type giant branch and absence of Sun analogues among the brightest stars in the sky (the Sun would be located at M_V=+4.7, close to the lowest point defined by Alpha Cen A).

The best solution to these problems is to launch a wide-field imaging telescope into space. This removes the problem of determining extinction and allows us to obtain much more accurate photometry. Moreover, there are many regions near the Gould Belt (close to the Milky Way) where such an instrument will find many targets within the same field. This alleviates the problems caused by the atmosphere and 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 period 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 OB stars and other interesting targets of opportunity.

A study of variability in OB 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:

- The sizes of the convective cores determine the amount of fuel available, thus the lifetime of the star as well as, e.g., the amount of heavy elements it will return to the interstellar medium. It is difficult to predict the size of a convective core because of our poor understanding of convection and semi-convection. This leads to large uncertainties in the stellar life cycle.
- Massive stars rotate rapidly. This is important because it drives currents that can mix gas that has been processed by thermonuclear reactions with unprocessed gas. The redistribution of angular momentum during evolution is of interest from several points of view. Neither white dwarfs nor neutron stars are extremely rapid rotators. This requires that the cores shed their angular momentum. This can be done most easily through their stellar winds if they are coupled to the stars by magnetic fields, but this raises the question of how the angular momentum is redistributed in the star as the surface rotation is slowed by the magnetic wind.

The properties of stellar cores and stellar rotation profiles can, in principle, be determined by asteroseismology. In practice, there are difficulties. Pressure (sound) waves, usually called p-waves or p-modes, do not penetrate the core unless they have very low radial order. On the other hand, pulsation modes restored by buoyancy, called gravity or g-waves, have good sensitivity to the core's properties. These are commonly found in massive stars. However, there are two problems with using g-waves for asteroseismology:

- First, if many g-modes are excited, the rotational splitting of the modes will cause interference among adjacent, or even distant, modes in rapidly rotating stars that will make it very difficult to identify which modes are present. Fortunately the available data suggests that only a few modes are excited in each star. This is, in itself, a puzzle that needs to be addressed.
- Second, pulsation theory can only deal with rotation using perturbations. This is fine as long as the pulsation periods are longer than the rotation period, but this is rarely the case in OB stars. This is a significant problem, but argues for the importance of an observational attack on the problem.

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.

Spectroscopic studies have produced more definitive results for a few stars. Fullerton, Gies and Bolton (1991) found radial pulsations in the O7I(f) star HD34656, which lies on the blue extension of the Beta Cephei instability strip. They found indications of nonradial pulsation in most of 30 O stars they surveyed (Fullerton, Gies and Bolton 1996), but were unable to determine the properties of the pulsation in individual stars. They found that main sequence stars earlier than O7 did not show line profile variations (lpv). Among the remaining stars in their sample, the amplitude of the line profile variations increased with increasing luminosity. De Jong et al. (1999) discovered nonradial pulsation in two O supergiants, Xi Persei and Lambda Cephei. Reid and Howarth (1996) found nonradial pulsations in the O4I(n)f star Zeta Puppis, one of the most luminous stars in the galaxy. They also found dynamical variations in the wind from this star that are correlated with the velocity field in the photosphere. Several other studies of optical and UV have obtained similar results (e.g., Kaper et al. 1996, de Jong et al. 2001). In every case, they have found that the variability had a time-scale consistent with the expected rotation period of the star, but the variations were not phase coherent for longer than a few weeks.

Our knowledge of the pulsation properties in the spectral type range O9.7-B9 is much more complete because there have been numerous photometric and spectroscopic surveys of these stars. There are at least four types of variables in this region of the H-R diagram: the Beta Cephei stars, the slowly pulsating B stars, the Lambda Eridani stars, and the Alpha Cygni stars. The most complete, distance limited survey (Waelkens et al. 1998) suggests that radial and nonradial pulsation is more the rule than the exception in this region. It is possible that a survey with sufficient sensitivity would show that all stars in this region of the H-R diagram are pulsationally unstable.

The Beta Cephei instability strip starts as a narrow region at spectral type B4IV and then extends blueward while with the luminosity gradually increasing. Near B0, the instability strip starts to widen until it takes in nearly all of the O stars. Some stars in this region pulsate radially. They may also have nonradial pulsations, while others are nonradial pulsators only. Several groups have done asteroseismological studies of Beta Cephei stars (e.g. Balona et al.1997, Aerts et al. 2004). There are a dozen of these stars within the minimum magnitude proposed for BRITE that span a range of projected rotational velocities (Vsini). Many of them have only limited ground-based photometry. If they are multiperiodic, they provide an excellent opportunity to test the effects of rotation on hot star models.

The slowly pulsating B (SPB) stars are found in a one magnitude wide instability strip that extends from B3 to B9. They are stars that are pulsating in multiple g-modes with periods of the order of one to a few days. Most are slow rotators with Vsin i < 90 km s^{-1}, but there are also a few rapid rotators (Aerts et al. 1999). Because they are pulsating in many modes with periods over a day, several years of observations are required to separate the modes. Thus it is unlikely that the BRITE mission can make a significant contribution to the study of these stars. However, it would be useful to observe a couple to determine if there are lower amplitude modes present than can be detected with ground-based photometry.

There has been some controversy about the cause of the variability of the Lambda Eridani variables. Most astronomers believe that they are nonradially pulsating Be stars, but there are a few that believe that at least some vary because of rotational effects due to structures in the photospheres or disks of these stars (cf. Baade and Balona 1994 for a discussion of these issues). Most of the disagreement probably arises because the short campaigns on these stars produce errors in the periods that do not allow a clear distinction between commensurable (i.e. rotational) and non-commensurable (i.e. pulsational) periods. One of the important tasks for the BRITE mission is to obtain data strings that are sufficiently long to determine whether the variability in these stars is due to rotation or pulsation.

The Lambda Eridani variables are found between O9.7 and B6 in the H-R diagram in regions that overlap the Beta Cephei and SPB star instability strip. A survey by Rivinius, Baade and Stefl (2003) determined that nearly all are pulsating in the l=|m|=2 mode, and whenever a Lambda Eridani variable has been studied in detail, additional modes have been detected. It is not clear what causes the ejection of the emission disk around Be stars. Rapid rotation was considered the most likely mechanism for many years. Bolton (1982) suggested that positive interference between multiple nonradial g-modes might account for the ejection and variability of the emission disk around Lambda Eridani. However, subsequent work did not support his suggestion (Bolton and Stefl 1990). In a recent review, Porter and Rivinius (2003) conclude that nonradial pulsation may not be as important as previously thought, but it may be relevant in certain cases. They note that there are indications that magnetic fields may also be important. They conclude that Lambda Eridani variables are in a "unique position to contribute to knowledge of asymmetric mass loss processes, stellar angular momentum distribution evolution, asteroseismology, and magnetic field evolution". Thus they are prime targets to meet the goals of the BRITE mission.

According to pulsation theory, there are no pulsating stars near the main sequence between spectral type B9 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 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.

The Alpha Cygni Variables are nonradially pulsating bright giant and supergiant B and A type stars. Lucy (1976) identified sixteen periods between 100.8 and 6.9 days in the prototype, Alpha Cygni (A2Iae). He suggested that the pulsational instability may extend down to periods "at which the atmospheric oscillations become progressive, possibly giving rise to the observed mass loss." BRITE is extremely well suited to look for these shorter periods and to study multimode nonradial pulsations in earlier type Alpha Cygni variables, where the periods will be shorter.

3. The ancillary science and the extended BRITE

In the minimum mission, BRITE will observe bright, luminous stars which are concentrated along the Milky Way. BRITE fields of 15x15 degrees will contain typically 2 to 6 such stars permitting precise differential photometry of uncorrelated stellar variations (see Sections 5 & 6). 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 achieved either by (1) an increase of the field of view or (2) by setting the limiting magnitude one magnitude deeper, at +4.5 mag. An increase of the FOV to 30x30 degrees will give on the average 6.2 stars to +3.5 mag, while an increase in depth to +4.5 mag. will give about 4 times more objects per each 15x15 degree field. These extensions of the BRITE scope, or some compromise between them, should be considered during the design stage. It is possible that BRITE will provide high quality single-object photometry, without referencing to other stars, but this will be established only after an extensive differential photometry period.

Similarly to what is currently being experienced 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, ending "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 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 >hours. The newly identified class of Gamma Dor variables which probably oscillate in g-modes must be better studied and defined;
- Discovery of Delta Scuti variables among insufficiently studied bright stars: The recent discovery of Altair's variability (Buzasi et al. 2004) illustrates how satellite-based observations (the WIRE star tracker in this case) can: (i) confront structure/pulsation models; (ii) estimate stellar parameters, and (iii) start to test the effects of rotation on pulsation;
- 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.
- 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?
- Finding bright stars which are <u>not variable</u> and which can be used as high quality photometric standards;
- Close binaries among the brightest stars: Of the 60 or more stars brighter than 4th magnitude and listed in the General Catalog 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, which will be simultaneously observed spectroscopically from the ground.

4. The bright star variability survey context

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. 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 it to be observed at peak brightness!

Microlensing surveys – the most successful of these have been the MACHO Project, OGLE I, II, and currently III, and EROS. In every 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 and full well capacity of the CCD detectors. Typically, 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, this data has 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 are 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 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 dwarfs, targets 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, there are no suitable facilities 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. The background

The present proposal is a logical development on the space research in astronomy utilizing small satellites which was started with the highly successful satellite MOST. This pioneering micro-satellite, was the first to demonstrate that a micro-satellite bus can be stabilised to levels required for astronomy research. The current performance level of the stabilisation system of 3 arc-seconds 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 scientifically profitable mission. The 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; they prepared in April 2004 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 (from now on called the "Dynacon Study") felt that it would benefit from setting particular specifications of that; as the result, the 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. As an explanation (see more in Sec.82.), 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 nanosatellites 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.

The name of the BRITE satellite project, as described in the Dynacon study was 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.

The overall scientific goals of the BRITE mission are somewhat similar to those of MOST, but relate to a different niche of the 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 apparently brightest stars in the sky are intrinsically bright (have high luminosities), (3) The high luminosity stars are expected to show slow variations.

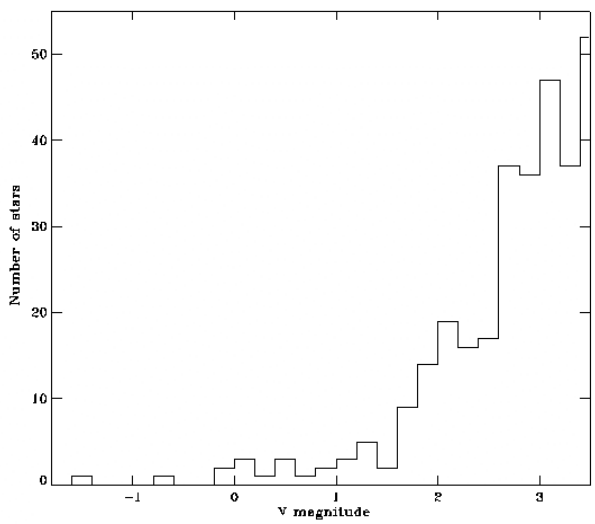


Fig.2. The histogram showing the numbers of the apparently brightest stars in the sky to +3.5 stellar magnitude. There are 91 stars brighter than +2.5 magnitude and 286 stars brighter than +3.5 magnitude; the increase is at an approximate rate of 4x per one magnitude interval. The brightest star, Sirius, is at –1.6 magnitude. The whole brightness range for the difference of 5 magnitudes corresponds to the ratio of 100 times.

1) The small size of the optical instrument results in a limitation to the apparently brightest stars in the sky. These brightest objects are exactly those whose variability in 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 the atmospheric extinction corrections which may introduce errors reaching 1%; 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 reaching a few parts in a million, the 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 to months.

2) A large fraction of 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 that the spatial geometric dilution ($1/r^2$) effects in the observed light intensity. When looking at 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 magnitude –1.5].

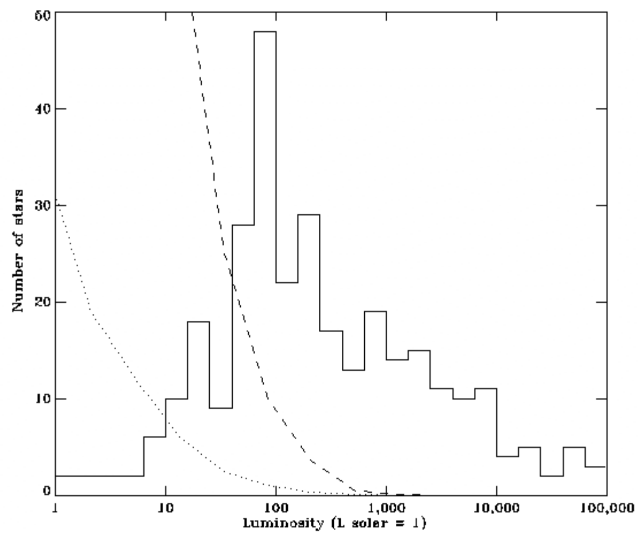


Fig.3. Intrinsic luminosities of the apparently brightest stars to +3.5 magnitude. The apparent magnitudes have been converted to luminosities using the known distances of the stars. Note that the x-axis has the logarithmic scaling and that the luminosity is expressed in solar units; a star like the 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 arbitrary vertical scaling) is very different, with the important luminous stars being in fact very rare.

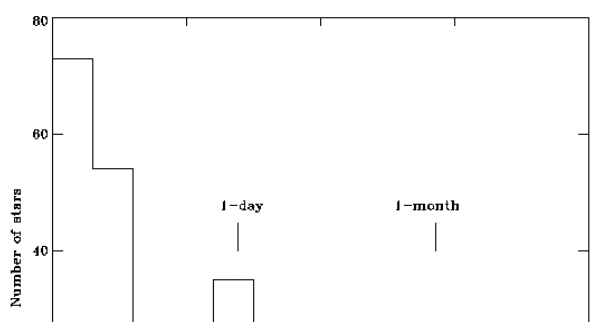


Fig.4. The histogram of the predicted approximate dynamical time scales for stars brighter than +3.5 apparent magnitude, plotted using the logarithmic units of the dynamical time scale in the x-axis. The bins have width of 0.3 in the logarithm (factor of 2 in time) and the dynamical time scales are expressed 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 $t_{dyn} \sim 1/\mathrm{sqrt}(G*\mathrm{rho})$, where rho~$M/R^3$ was scaled relative to the solar values, with M estimated from the luminosities L.

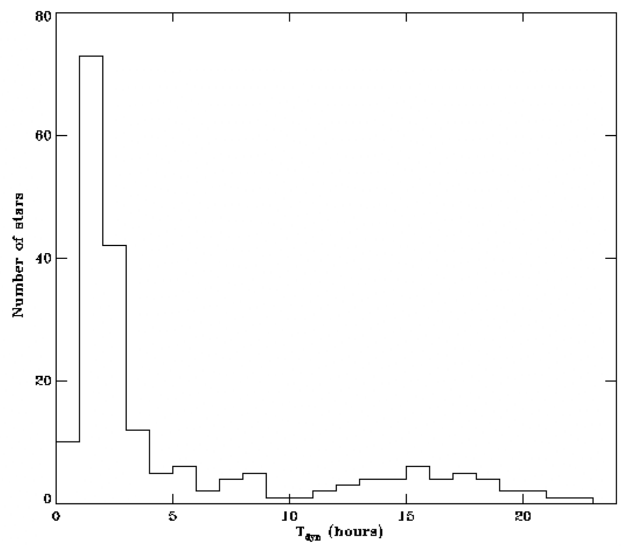


Fig.5. The same data as in the previous figure, but plotted in linear units and only for the short period domain of time scales shorter than one day. Note that the peak at the left are the solar-type stars which are being studied by MOST. This shows the complementary character of both missions with BRITE 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 modes (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 the frequency space and their mutual relations in frequencies and intensities are a mine of information about the 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 may have to be limited to stellar fields of 15x15 degrees; this sets a limit on the sky coverage with to slightly over 1/3 of the whole sky where most bright stars are concentrated. There are 286 stars brighter than +3.5 magnitude in the sky. The minimum mission should last minimum 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; the extension of the duration of the mission will be the simplest low cost addition to the value of the mission.

Property	Minimum requirements
Apparent magnitude limit	+3.5
Positional constraints	None, all parts of the sky
Field of view	>15x15 degrees
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

Number of stars per 15x15 deg field	Percentage of the sky
>2	37.5
>3	20.4
>4	12.7
>5	6.5

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 magnetic field) influences on the photometric response of the detector. While a stable, calibrated instrument outside the Earth 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 the percentage amount of the sky accessible to multi-star differential photometry.

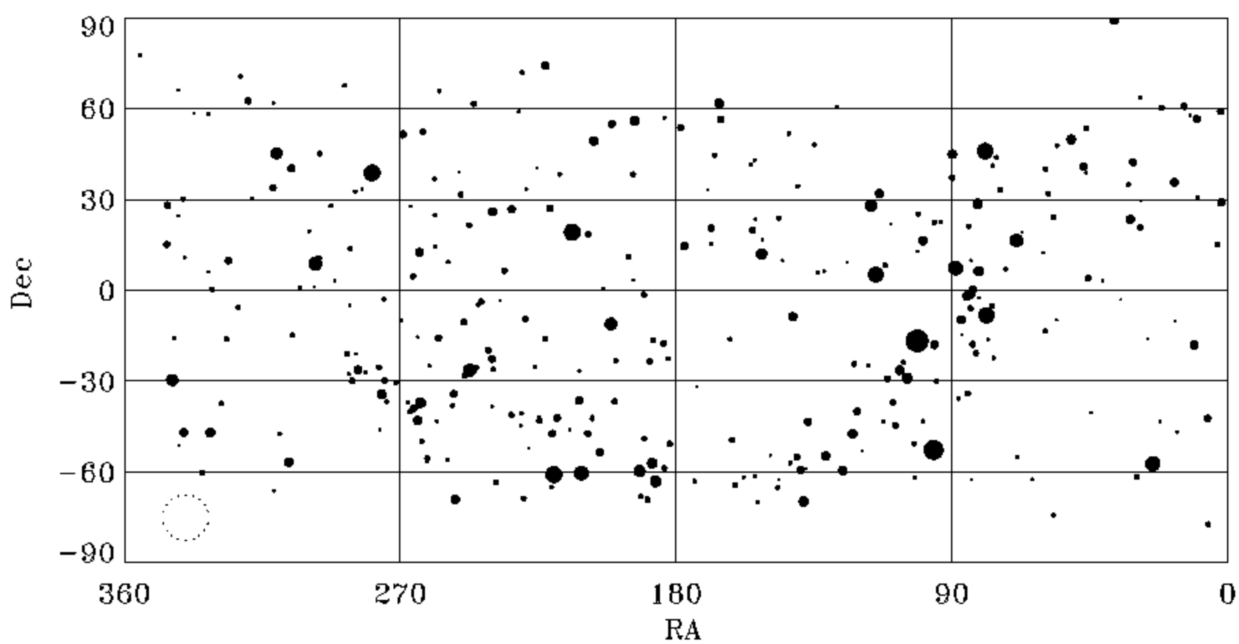


Fig.6. Map of the sky with stars to +3.5 apparent magnitude. The circle in the lower left corner represents the field of view of 15 degrees in diameter. Note the density enhancement along the Milky Way.

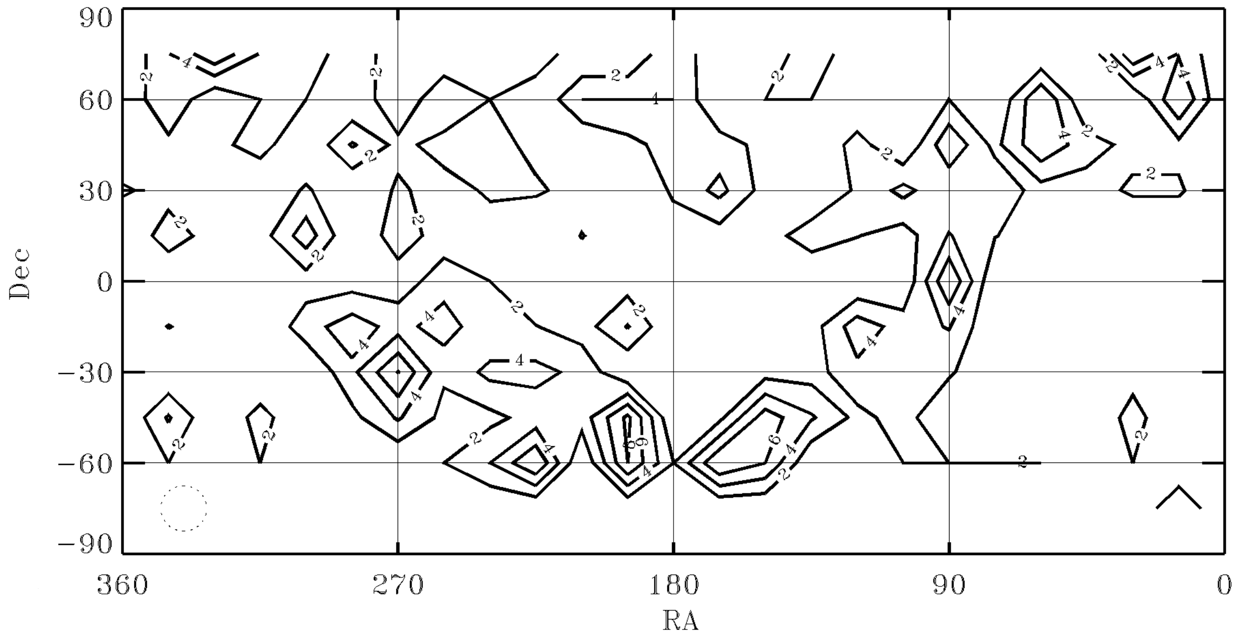


Fig.7. The sky density of stars to +3.5 apparent magnitude calculated for 15x15 degree fields. The contours are at intervals of 2, 4, 6, and 8 stars per field. The goals of the minimum mission can be accomplished in areas with star densities >2 per field. An extension in depth by one magnitude will increase stellar densities per 15x15 degree field by approximately 4 times; the same gain can be achieved by increasing the field size to 30x30 degrees.

7. Technical specifications of the optical instrument payload

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 with prices at the level >US$130. Their essential properties are summarized in the table below.

When compared with the CCD detectors, properties of CMOS detectors are generally poorer and less convenient for scientific applications (Janesick 2002), although manufacturers improve their products and thinned, back-illuminated CMOS devices are now being considered (same ref.). Compared with the CCD's, they have much 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 for 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	0.13 – 0.53 W
Number of pixels	1024x1024 to 1280x1024
Pixel size	6 – 25 micron
Effective QE	20 – 30%

Janesick 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 what and how to observe a particular section of the light sensitive area.

The rapid build-up of the dark signal charge will require the BRITE camera to operate with short exposure times, of the order of <5 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 the accuracy of 0.001 mag. or better per one 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, band-pass 89 nm) is $f_0=9.1\times10^5$ photons/sec/cm^2. The photon flux f_m scales with the magnitude m as $f_m = f_0 \times 10^{-0.4m}$, so for m=+3.5 it will be ~36,000 photons/s. This number will hold, when translated to the electron charge, assuming a lens of the diameter of 5 cm^2 area and an overall QE of 20%. The charge can be increased to ~70,000 el/s using a space-qualified MOST filter which admits about 2x more light than the V-filter. For an area of 20x20 pixels, assuming a dark current of 500 el/s/pix, the total dark signal charge will be ~20,000 el /s. The resulting signal-to-noise ratio of S/N ~3000 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 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=+4.9, which appears to be a realistic limit for a mission utilizing the CMOS with a lens system of dimensions as small as planned here.

The estimate above is admittedly very simplified because noise properties of CMOS detectors are currently poorly documented so that laboratory tests will be needed. 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 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 of calibrating the relative pixel sensitivities using the "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 the cosmic ray bombardment..

While our current understanding unambiguously points at a CMOS detector, use of a CCD detector should be considered early in the design stage for the following reasons: The CCD detectors are 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: Instead many, short, averaged integrations necessary for CMOS, the data taking would be through single, long, CCD integrations.

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). Assuming a scale of 0.9arcmin per pixel, the field of view (FOV) of the optical system will be 15x15 degrees for a detector of 1kx1k pixels. The size of the satellite and low complexity of the mission suggest a lens system. For a system with the aperture of 2.5 cm (the central stop, the front lens may be bigger), depending on the pixel size, the optical properties will not be difficult to meet:

pixel (microns)	linear FOV side (mm)	F mm	f/ for D=25mm
15	15.3	58	f/2.3
25	25.6	97	f/3.9

Very preliminary discussions with Mr. Peter Ceravolo of Ceravolo Optical Systems (www.ceravolo.com; he participated in the design and construction of the MOST optics) indicated that there should be absolutely no difficulty with manufacturing a lens system with the properties as above for very moderate costs of $2k-3k (as per information regarding fabrication from BMV Optical in Ottawa). By making a system rather than using an off the shelf unit, the issues of vignetting as well as of 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, changes of filters are 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 the band-pass about two times wider than the V-filter may be good choice.

The optical system must take into account the sources of scattered light from the Sun, Moon and bright Earth by provision of a baffling system. This can be achieved by having the optical instrument “buried” inside the satellite by 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 & the optical system be tested on stars from ground before integration with the satellite bus. Such tests would not be difficult to make yet could easily detect problems with stray light, optical tightness of the instrument, etc.

8. Technical specifications of the satellite

8.1. Main science requirements

Size and mass	The size and mass of the satellite must be sufficient to house a small lens telescope (aperture of about 2.5 cm) with a panoramic detector (CMOS or CCD), computer(s) and mass memory to store data of up to 2 days of observations, all the telemetry and radio link sub-systems and the thermal and solar-power management systems.
ACS: Pointing, object acquisition	Better than half degree in any part of the sky away from the Sun, the bright Earth and the Moon.
ACS: Field re-acquisition	Acquisition after each passage of the satellite on the other side of the Earth. If possible, utilizing low inertia of the satellite and the implied agility in pointing, >2 fields will be observed during each orbit, where each field is re-acquired when the Earth occults the previous one.
ACS: Error during pointed observations (1-sigma)	Smaller than one arc minute (1/60 degree) over duration of an observation of up to 15 minutes.
ACS: Flat field images	A provision to obtain untracked 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 more than 2 fields are observed per each 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 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 data rate)	Two full 1kx1k images per day at 2Byte/pixel for acquisition and flat-field monitoring. Maximum telemetry load: 2MB/day.
Orbit	No stringent limitations. It should permit at least one observation of at least 15 minute duration per each satellite orbit (typically 100 minutes).

8.2. The CanX program at UTIAS

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). 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 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, Inc. 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 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.

BRITE will draw upon CanX-2 component and system design heritage to provide a schedule advantage and risk mitigation (CanX-2 is expected to launch before BRITE in 2005). In addition, the Dynacon/UTIAS-SFL team has already prepared a system requirements report for CSA in relation to a nanosatellite high-performance attitude control (NanoHPAC) system within the context of the bright star photometry mission embodied by BRITE. BRITE may utilize a 10x10x30 cm Triple-Cubesat form factor (consistent with a P-POD launch tube) or a 15x15x15cm form factor based on an enhanced UofTokyo-ISSL nanosatellite separation system design (a larger 15x15x20cm form factor is also possible).

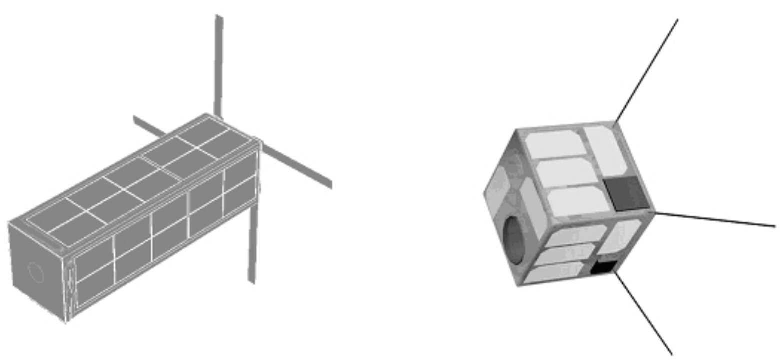


Fig.8. The Triple Cubesat 30x10x10cm and the 15 cm Cube

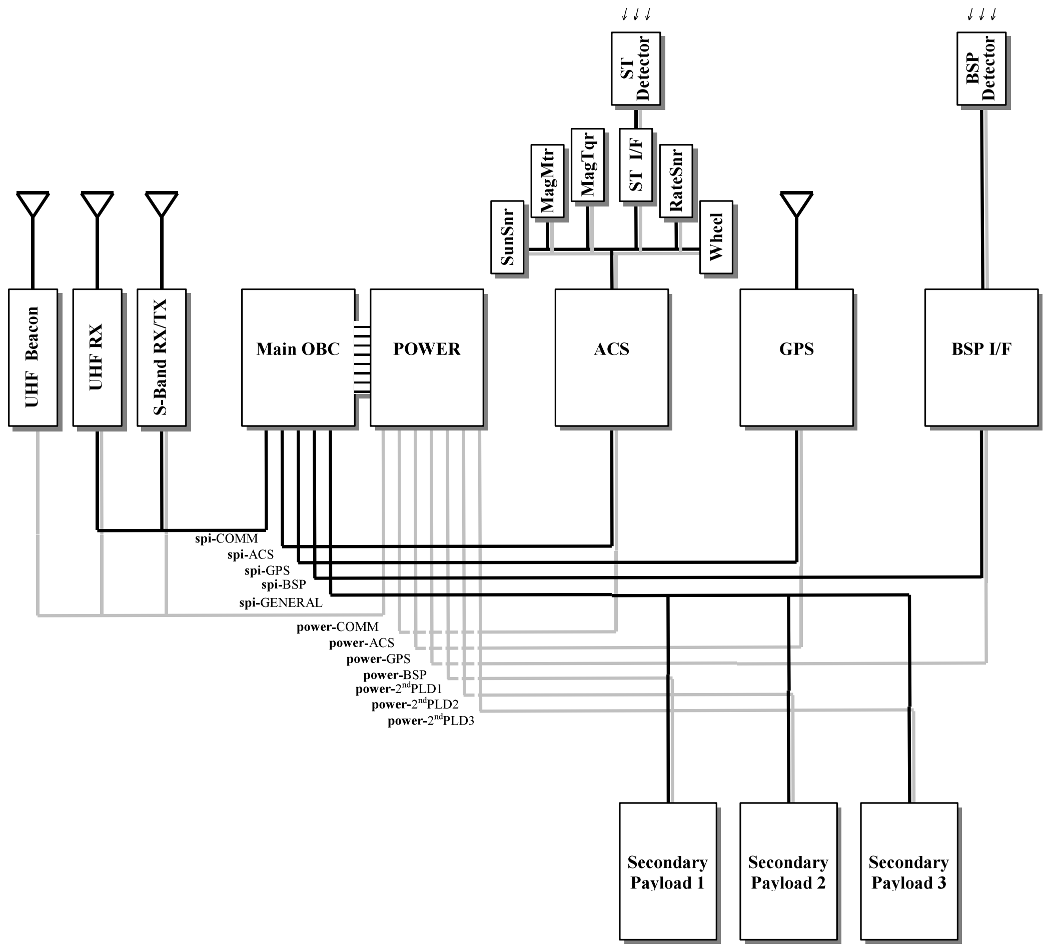
8.3. The technical description of the CanX nanosatellites

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 the figure.

Parameter	BRITE	CanX-2
Form-factor	10x10x30cm Triple-Cubesat, 15x15x15cm Cube, or 15x15x20 cm Block	10x10x20 Double-Cubesat
Primary Payload	2.5 cm aperture, 15° FOV telescope for Bright-Star Photometry	Dual-band GPS receiver for Atmospheric Occultation Experiment
Secondary Payload	To be determined, probably not enough power for a secondary payload	Atmospheric Spectrometer, Nano-calorimeter, Surface Material Experiment, Communication Protocol Software
Attitude Control	Three-axis stabilized augmented with Star-Tracker and Reaction wheels, 1 arc-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. The satellite architecture and the power constraints

The satellite does not present any technological difficulties given the very highly developed design and current realisation of the CanX-2 mission. The main design constraint for the current mission is the low power supplied by the solar panels. The total solar power per 10x10cm is 13.6W. Taking into account the foreshortening effects and solar panel efficiency, the need for surface-mounted communication antennas, as well the fact that small solar panels are not produced in convenient sizes (to utilize side walls of 10x10cm or 15x15cm), the expected total power supply will be limited to ~4-6W. A careful analysis in the Dynacon Report of the power requirements shows that the Attitude Control System will need between 1W (in safehold 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 system as they typically consume >5W; however, a CMOS Active-Array detector system may need only 0.25-0.5W. Of the other satellite systems, the transmitter is expected to require the largest amount of power (3W when operating, but only 0.3W orbital average); the thermal control, OBC, receiver and the beacon are expected to require <0.25W each. The power restrictions may be alleviated by permanent (non-articulated) extensions which are allowed in the Cube and Block form-factors.



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

8.5. The launch vehicle and orbit

In order to reduce the launch costs, the spacecraft will seek to utilize excess capacity of an existing launch. As such, the spacecraft will not be able to ask for a specific launch vehicle nor orbit. Therefore to increase the chance for securing such low-cost launch, the spacecraft design shall be compatible with the launch environments of the following launch vehicles:

- Rockot
- Dniepr
- Proton
- Delta-II

Likewise, the spacecraft shall 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 worst case communication link analysis and thermal analysis. Most sun-synchronous satellites are launched into the 10:30am pass orbits for least amount of clouds in the Earth (nadir) direction.
- Orbit 2: 500 km, 40-deg (Low Earth orbit). This orbit shall be considered for the worst case power generation because of long, half-orbit sun occultations.
- Orbit 3: Non-circular orbits, TBD apogee and perigee. This orbit shall be considered as the worst-case data-throughput.

Since the satellite telemetry will be very similar to that of MOST, the satellite up- and down-links can be done utilizing the existing MOST ground stations at UTIAS, possibly UBC and Vienna, Austria. These stations are not used for most of the time and become active only during the MOST overhead passages in the evenings. Most likely, BRITE will not have an dusk-dawn Sun-synchronous orbit, so chances of conflict in the ground station use 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 funds building a nanosatellite like BRITE 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,
- 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 involved and interested parties is tentatively scheduled by the Austrian side for October 2004. Beside the Canadian and Austrian participants, representatives of other institutes who have already experience with nanosatellites, like Norway, may take part. Joining and aligning of efforts will certainly be very highly profitable for science and well as technology aspects of the missions. Besides, having the unique expertise with the small-payload 3-axis stabilization, Canada may play a leading role in a small, highly specialized consortium. One of the possibilities to be discussed would be an active participation of foreign MSc graduate students in the UTIAS micro- and nanosatellite programs.

10. Teaching and outreach

Students at UTIAS/SFL and the University of Toronto Department of Astronomy will have the opportunity to participate in related projects, much in the same way as students participated in the MOST program. The BRITE creates a unique opportunity for inter-disciplinary research. Having the imaging capability and being simpler and easier to comprehend than MOST, the mission has a capability to generate even stronger public interest than this highly successful research satellite.

Improving science literacy and numeracy, and increasing the number of students who are interested in, and qualified for careers in science, technology, engineering, and mathematics (STEM), are high priorities for Canada. NSERC has recently initiated a new program – CRYSTAL: Centres for Research in Youth, Science Teaching and Learning – to address these issues. Astronomy and space have the capacity to attract young people to careers in STEM. 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.

The BRITE satellite will have special connections with students at all levels, and with amateur astronomers and the public, particularly to student societies such as Astronomy and Space Exploration Society (http://asx.sa.utoronto.ca). Canadians take pride in their country's achievements. Images from the BRITE satellite will make its accomplishments real. The satellite studies stars which all can see, and “the stars belong to everyone”. Graduate students in science and engineering (and possibly math and statistics) will be involved in the development of the satellite, and the analysis of the data. Data from the satellite can be used by undergraduate and 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 teams, 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). Large numbers of amateur astronomers, some of whom have professional-quality equipment, can 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 the BRITE satellite 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.

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