1 Introduction to BLAST

The "Balloon-borne Large-Aperture Sub-millimeter Telescope" (BLAST) incorporates a 2.0 m mirror with plans to increase to a 2.5 m mirror. The telescope will operate on a Long Duration Balloon (LDB) platform with large format bolometer arrays at 250, 350 and 500 µm. BLAST will address some of the most important Galactic and cosmological questions regarding the formation and evolution of stars, galaxies and clusters. It will conduct large-area sensitive Galactic and extragalactic surveys which will: (i) identify large numbers of distant high-redshift galaxies; (ii) measure cold pre-stellar sources associated with the earliest stages of star and planet formation; (iii) make high-resolution maps of diffuse Galactic emission from low to high Galactic latitudes.

The primary advantage of BLAST over existing and planned bolometer arrays such as SCUBA on the JCMT, SHARC on the CSO (including their respective upgrades) and HAWC on SOFIA is the dramatically increased atmospheric transmission at balloon altitudes which results in greatly enhanced sensitivity at wavelengths ≤ 500 µm. BLAST complements FIRST satellite by overlapping the FIRST frequency coverage and will have the ability to test new technologies for future space-based missions. BLAST is the only instrument with sufficient field of view, sensitivity, and integration time to conduct follow-up surveys of SIRTF/MIPS at 200-400 µm.

2 Science Goals of BLAST

BLAST will be the first balloon-borne telescope to take advantage of the bolometric focal plane arrays being developed for FIRST. It will be capable of probing the sub-mm with high spatial resolution and sensitivity providing the opportunity to conduct unique Galactic and extragalactic surveys. Compared to the pioneering flights of PRONAOS, BLAST will have an advantage of > 100 times the mapping speed. The scientific motivations for BLAST are similar to those of FIRST and are achievable within 3–5 years with a series of LDB flights.

We expect BLAST to achieve the following science goals:

- Conduct large-area extragalactic 200–500 µm surveys and detect ~ 150 and ~ 1500 high-z galaxies in the test flight and long-duration flights respectively.

- Measure the confusion noise at 200–500 µm thereby laying the foundation for future BLAST and FIRST survey strategies. It will also allow a study of the clustering of dust-emitting galaxies over an important range of angular scales.

- Combine the BLAST 200–500 µm spectral energy distributions (SEDs) and source counts with those of SCUBA at 850 µm. This will determine the redshifts, rest-frame luminosities, star formation rates (SFRs), and evolutionary history of starburst galaxies in the high-z universe. It will also identify the galaxy populations responsible for producing the far-IR background.

- Conduct Galactic surveys of molecular clouds and identify dense, cold pre-stellar (Class-0) cores associated with the earliest stages of star formation. Combining the 200-500 µm BLAST data with...
SCUBA data at 850 µm will determine their density and temperature structures which are sensitive to the details of the clouds collapse.

- Survey the diffuse Galactic emission and make detailed comparisons with surveys at longer and shorter wavelengths (CGPS, SCUBA, MSX).
- Observe objects within our solar system including the planets and large asteroids.

3 Extragalactic Surveys

The first extragalactic sub-mm (850 micron) surveys have already been completed by SCUBA covering areas of 0.002–0.12 deg² with respective 3σ depths in the range 1.5 < $S(\text{mJy})$ < 8. Observations of starburst galaxies in the high-z universe at sub-mm wavelengths have a particular advantage compared to the optical and FIR due to the strong negative k-correction which enhances the observed sub-mm fluxes by factors of 3–10 at $z > 1$ (Figure 1). The combination of SCUBA surveys with the necessary shorter wavelength sub-mm data from experiments like BLAST (and later from FIRST) will provide powerful constraints on our understanding of the models and processes by which galaxies and clusters form and subsequently evolve. The following preliminary results from SCUBA surveys (see other contributions to this Proceedings) alone have already made a significant impact on several cosmological questions and have demonstrated the importance of further shorter wavelength sub-mm cosmological studies:

- Approximately 30–50% of the FIR–sub-mm background detected by COBE has been resolved into individual galaxies at flux densities $S_{850\mu m} > 2$ mJy. Existing surveys, which are confusion-limited at about this flux level, are within a factor of only a few in sensitivity of resolving the entire sub-mm/FIR background.
- Sub-mm sources generally appear to be associated with $z > 1$ optical and weak radio galaxies, although there is still much debate about the fraction of sources at $z \geq 2$.
- The faint sub-mm source-counts at 850 µm are reasonably well determined between 1–8 mJy and significantly exceed a no-evolution model, requiring roughly $(1 + z)^3$ evolution out to $z \sim 1$, but with little constraint at higher redshifts.
- At high-redshift ($2 < z < 4$) the sub-mm surveys appear to find $\sim 5$ times the star formation rate observed in the optical surveys, although the effects of dust obscuration and incompleteness in the optical are still debated.

3.1 Why an LDB experiment at 200–500 µm?

Detailed interpretation of the sub-mm sources is severely hindered by uncertainties in their redshift distributions and luminosities. These uncertainties result directly from the sub-mm positional errors of $\sim 3''$ that are typical for even the highest S/N sub-mm detections, and from the lack of sub-mm data measuring the redshifted FIR spectral peak at 200–450 µm.

![Figure 1: Flux density vs. redshift for luminous ($L_{\text{FIR}}/L_{\odot} \sim 10^{12}$) starburst galaxies.](image)

This ambiguity in the redshift of individual sub-mm sources will be resolved with the BLAST surveys. The complementary depths of the BLAST 200-500 µm and SCUBA 850 µm surveys provide a measure of the 200/850 µm flux ratio, which is an extremely powerful and independent diagnostic of the redshift (Figure 2). For example if there are 5σ SCUBA sources ($S_{850\mu m} > 13$ mJy) with no BLAST 5σ counterparts at 300 µm, i.e. $S_{300\mu m} < 50$ mJy, then the 300/850 µm flux ratio must be $\leq 4$. This implies that the sub-mm source must be a galaxy at $z \geq 3$ for all typical starburst SEDs.

3.2 Predicted Source-counts and Extragalactic Confusion

The BLAST surveys will measure the surface-density of the brighter sources (20–1000 mJy) at 200 – 500 µm, extending the flux range of the sub-mm source-counts from $\sim 15$ to $\sim 1000$. This will allow an accurate determination of the model that describes the evolution of high-z...
Figure 2: 300/850 µm flux ratio vs. redshift for Arp220, Mrk231 and M82. The shaded area shows the redshift range consistent with SCUBA sources > 13 mJy with no BLAST 5σ counterparts at 300 µm.

starburst galaxies. A prediction of the 200–500 µm source-counts can be derived from preliminary evolutionary models that fit the observed counts at FIR and sub-mm-wavelengths (Figure 3).

Due to extragalactic sources, SCUBA 850 µm surveys with 15″ resolution are confused at a depth of 3σ < 2 mJy which corresponds to a source density ~ 4000 ± 1500 deg⁻². Extrapolation to shorter wavelengths implies that confusion at 300 µm will begin to become significant at 3σ ~ 25–35 mJy. Representative estimates of the extragalactic 3σ confusion noise at 300–500 µm are 30 mJy for a primary mirror diameter of 2.0 m (appropriate for the test-flight) and 25 mJy for a 2.5 m primary (planned for the LDB flight). The initial BLAST surveys will measure the true confusion level and hence will influence the strategies for both future BLAST and FIRST surveys at 200–500 µm. A statistical P(D) analysis and correlation analysis of the noise in our surveys will yield information on the source counts well below the conventional confusion limit.

During the first 6 hour test flight BLAST may conduct a 0.55 deg² extragalactic survey of the Lockman Hole and ISO ELAIS regions at 300–750 µm with a 1σ sensitivity of ~ 10 mJy. The alternative surveys outlined in table 3.1 will detect similar numbers of galaxies at the different flux levels, and therefore we can choose to match the BLAST surveys to the coverage of the existing and future 850 µm SCUBA and 1100 µm BOLOCAM/CSO surveys in addition to the future high-resolution deep AXAF and XMM surveys of these regions (Figure 3). The X-ray follow-up data are crucial for determining the fraction of AGN in such samples.

By combining these data with mid-IR observations from SIRTF we can accurately measure the spectral energy distributions across the rest-frame FIR peak, constrain the redshifts, bolometric luminosities, SFRs and evolutionary history of high-z starburst galaxies. Together with a deep 20 cm VLA survey, deep near-IR and optical imaging, we will determine the nature of the population of high-z galaxies that contribute the dominant fraction of the extragalactic FIR-mm background.

4 Galactic Plane Surveys

Over the last decade, sub-mm astronomy has revealed a class of heavily embedded, pre-stellar cores that are “invisible” or faint at FIR wavelengths, and yet are relatively strong sub-mm sources. These low-mass Class 0 and Class I sources are beginning their main accretion phase prior to collapse, and hence represent the earliest and most exciting stages of star-formation. The mechanism by which these young, accreting protostars form and evolve is still poorly understood. BLAST will carry out a significant unbiased census of star-forming cores in a large number of molecular clouds as part of a sensitive large-area Galactic plane survey.

By conducting the BLAST survey in fields previously observed by IRAS and ISO, and in the future with SIRTF and SOFIA, we can determine the relative fraction of
6 hour 300 µm test-flight survey strategies: D=2.0 m, θ = 41″

| survey area (sq. degrees) | 1σ depth (mJy) | no. of pixels | no. of detected galaxies > 5σ | no. of > 10σ galaxies | z > 1 | z > 3 |
|---------------------------|---------------|---------------|-------------------------------|-----------------------|-------|-------|
| 0.24                      | 7             | 2352          | 120                           | 34                    | 110   | 18    |
| 0.55                      | 10            | 4800          | 150                           | 40                    | 135   | 20    |
| 1.1                       | 15            | 10800         | 135                           | 30                    | 125   | 16    |
| 4.4                       | 30            | 43200         | 120                           | 30                    | 110   | 13    |

50 hour 300 µm LDB survey strategies: D=2.5 m, θ = 32″

| survey area (sq. degrees) | 1σ depth (mJy) | no. of pixels | no. of detected galaxies > 5σ | no. of > 10σ galaxies | z > 1 | z > 3 |
|---------------------------|---------------|---------------|-------------------------------|-----------------------|-------|-------|
| 1.7                       | 5             | 16777         | 1420                          | 450                   | 1300  | 250   |
| 3.3                       | 7             | 32884         | 1670                          | 480                   | 1530  | 250   |
| 6.8                       | 10            | 67111         | 1870                          | 500                   | 1680  | 250   |
| 15.4                      | 15            | 151000        | 1890                          | 420                   | 1740  | 220   |
| 61.6                      | 30            | 604000        | 1680                          | 420                   | 1530  | 180   |

Table 1: Estimated number of galaxies detected in test flight and LDB surveys. Illustrative redshift distributions for galaxies detected with a S/N > 5 are included. The entire LDB flight will be 250 hours allowing for several such surveys. These calculations use very conservative estimates of the NEFDs.

Class0 and Class I sources. This fraction will indicate the dynamical timescale for accretion and subsequent collapse. We can also trace how this fraction changes with the level of overall star formation in different molecular cloud complexes, since the environment of the parent cloud (ionization field, shocks, turbulent fragmentation) is expected to effect the early evolution of the condensing cores.

Figure 4 illustrates that BLAST will have sufficient sensitivity at 300-450 µm to detect the pre-stellar and protostellar clumps within individual molecular clouds and to measure the radial density profiles in the extended envelopes of the protostars. These will discriminate between thermally-supported or magnetically-supported cores. Molecular lines provide powerful signatures of infall and the BLAST LDB surveys will provide a dramatic increase in the statistical samples of pre-stellar cores for spectroscopic follow-up at mm-wavelengths.

These data will measure the variations in column densities and sub-mm spectral indices which reflect variations in the temperatures (10–30 K) and/or dust emissivity (β = 0 – 2) within the star forming envelopes. The combination of longer wavelength surveys (e.g. SCUBA/JCMT at 850 µm and BOLOCAM/CSO at 1100 µm), and short sub-mm wavelength data (BLAST at 350, 250 µm) can resolve this ambiguity since BLAST...
will be more sensitive to temperature variations of the cold dust ($T < 20$ K). Having determined the dust temperature we can then estimate the mass and luminosity distribution of the pre-stellar clumps.

Although the origin of the stellar initial mass function is not well understood, it is probably determined at the earliest stage of pre-stellar collapse, so it is important to have a large, complete sample of Class 0 cores. In $< 6$ hours BLAST will conduct a $\sim 50$ deg$^2$ 300 $\mu$m survey of molecular clouds, including Orion, Taurus and Ophiuchus, with a 3$\sigma$ sensitivity of 300 mJy. This is equivalent to a mass sensitivity $\sim 0.05$ $M_\odot$.

5 LDB Surveys

The 250 hour LDB flights will concentrate on larger and deeper surveys of Galactic and extragalactic target regions. The increased observation time and the planned addition of a larger primary will increase sensitivities and resolution while lowering confusion limits, thereby improving the statistics of the sub-mm source-counts. In particular, increased counts at faint flux levels will provide the best discrimination between the possible evolutionary models and will follow up on the more extensive SCUBA, SIRTF, AXAF and XMM surveys. As Table 3 indicates, the improved instrument will detect thousands of high-$z$ galaxies during one of several 50 hour surveys in a single LDB flight. Possible LDB extragalactic survey targets include: (i) for Northern hemisphere flights, the Lockman Hole, and ELAIS N2, ELAIS N1, the HDF-North and flanking fields and future LMT 1100 $\mu$m surveys; (ii) for Southern hemisphere flights, the MARANO field and the HDF-South.

We will also survey a large ($> 25\%$) fraction of the Galactic plane concentrating on regions undergoing high and low-mass star formation.

6 Instrument

The design and specifications of BLAST are driven by science goals, availability of existing instrumentation and the practical limitations of ballooning. The following sections describe the instrumental requirements needed to meet the science goals.

The decision to use an LDB platform for this experiment takes into consideration a combination of sensitivity, cost, and time-scale. When comparing this experiment to ground-based or airborne observations, the clear advantage is greater atmospheric transmission (Figure 6) at balloon altitudes (35-40 km). The high atmospheric emission at lower altitudes (SOFIA and SCUBA) limits the instrument sensitivity and, in some of the higher frequency bands, makes the measurement virtually impossible without the use sub-orbital and orbital platforms.

Figure 6: Atmospheric transmission at balloon and SOFIA altitudes.

6.1 Optical Design:

The BLAST gondola is designed to hold a mirror up to 2.5 m in diameter. The test flight will use a 2.0 m spherical mirror currently being fabricated as part of the FIRST development. A schematic of the gondola and telescope is shown in Figure 7. The secondary mirror will be designed to give diffraction limited performance over a $10' \times 10'$ FOV at the Cassegrain focus at $\lambda = 300$ $\mu$m. The estimated antenna efficiency is $\geq 80\%$ and is determined by a combination of the 10 $\mu$m rms surface roughness of the primary and the quality of the re-imaging optics.

Figure 7: The BLAST telescope.

Radiation from the telescope will enter the cryostat through a 5–6 cm diameter vacuum window near the Cassegrain focus. We will use a telescope focal ratio of
Table 2: Telescope and Receiver Parameters

| Parameter                        | Value                                |
|----------------------------------|--------------------------------------|
| Telescope:                       |                                      |
| Temperature                      | 300K (230K for North American Flight) |
| Used diameter                    | 1.9 m (secondary mirror is pupil stop) |
| Emissivity                       | 0.04                                 |
| Detectors:                       |                                      |
| Bolometer optical NEP            | $3.0 \times 10^{-19}$ W/√Hz            |
| Bolometer quantum efficiency     | 0.8                                  |
| Bolometer feed-horn efficiency   | 0.7                                  |
| Throughput for each pixel        | $A\Omega = \lambda^2 (2f_{\lambda}$ feed-horns) |
| Bolometers:                      |                                      |
| Central wavelengths              | 250 350 500 µm                        |
| Number of pixels                 | 149 88 43                             |
| Beam FWHM                        | 30 41 59 arcseconds                   |
| Field of view for each array     | 6.5 x 13 arcminutes                   |
| Overall instrument transmission  | 30%                                  |
| Filter widths ($\lambda/\Delta\lambda$) | 3                                    |
| Observing efficiency             | 90%                                  |

Table 3: BLAST loading, BLIP noise, and Sensitivities

| Band (µm) | 250 | 350 | 500 |
|-----------|-----|-----|-----|
| Backgrnd. power (pW) | 25.6 | 18.3 | 13.5 |
| Backgrnd.-lim. NEP $\sqrt{\text{Hz}} (10^{-17})$ | 20 | 14 | 10 |
| NEFD mJy-√s | 236 | 241 | 239 |
| $\Delta S(1\sigma,1\text{hr})$ (1 deg²) mJy | 38 | 36 | 36 |
| $\Delta S(1\sigma,6\text{hr})$ (1 deg²) mJy | 15.5 | 14.7 | 14.6 |

6.2 Detectors.

The BLAST focal plane will consist of arrays of 149, 88 and 43 detectors at 250, 350, and 500 µm respectively. The detectors will be silicon nitride micromesh (“spider-web”) bolometric detectors coupled with $2f_{\lambda}$ feedhorn arrays. The detector and feedhorn technology is well established and has been tested using the BOLOCAM instrument in late 1999. The sensitivity of the detectors is limited by photon shot noise from the telescope and atmospheric emission. Table 2 gives the telescope and detector parameters. We estimate a total emissivity for the warm optics of ≃ 5% dominated by blockage from the secondary mirror and supports. We estimate the optical efficiency of the cold filters and optics to be $\epsilon_{\text{opt}} \geq 0.2$ based on measurements with similar bolometers coupled to horn arrays at millimeter wavelengths in the BOLOCAM test dewar. The estimated detector NEFD’s assuming a 10% bandwidth are given in Table 3.

7 Conclusion

BLAST will be the first balloon-borne instrument to take advantage of a new generation of bolometric instrument on FIRST.
integral step in our understanding of this field in the pre-
FIRST era. After an initial test flight in 2002, the instru-
ment will have its first Long Duration Balloon flight from
Antarctica in 2003.

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