BLAST: Study of the Earliest Stages of Galactic Star Formation

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1 Introduction

Star formation is one of the most important areas of study in modern astrophysics. Over the past two decades, a reasonably robust evolutionary sequence has been established and widely accepted for the formation and evolution of low- and intermediate-mass stars ($M \leq 8 M_\odot$) within molecular clouds [e.g. 2; 3; 13; 16, and references therein]. However, several fundamental questions related to the earliest stages of star formation remain unanswered. The formation of high-mass stars is even more complicated due to their strong interaction with the environment, their intrinsically shorter evolutionary timescales and larger characteristic distances [e.g. 17].

In the current accepted scenario of low-mass star formation, the collapse of cold, dense cores/condensations in the parent cloud leads to the formation of gravitationally-bound pre-stellar cores, observable at submillimeter wavelengths, but opaque in the near-IR (NIR) and mid-IR (MIR) bands [e.g. 1]. Subsequently, pre-stellar cores evolve toward the formation of a central accreting protostar and disk, embedded within an infalling envelope of dust and gas. Proto-stellar objects are classified into different evolutionary phases (Class 0 to Class III, from less to more evolved stages) according to the relative mass distribution among the envelope, the circumstellar disk, and the central compact object. Observationally, this classification is also related to the shape of the spectral energy distribution (SED) [see, e.g. 9; 2]. Previous IR studies using IRAS, MSX, and ISO satellites in addition to ground-based NIR surveys have provided a complete census of Class I–III sources [e.g. 5]. However, only a few bona-fide Class 0 protostars are known to date. Observations at longer wavelengths are essential to detect and characterize even earlier evolutionary stages. In particular, surveys near the peak of the SED of these cold objects are fundamental to constrain their physical parameters.

Pre- and proto-stellar cores have been observed using several molecular tracers and have been surveyed even more efficiently in the submillimeter dust continuum where most of their radiation is emitted [see 13, for a review]. Surveys conducted by submillimeter bolometer arrays, such as MAMBO, SCUBA, and SIMBA represent the only way of deriving statistically-significant samples of pre-stellar objects. Nevertheless, such instruments sample the Rayleigh-Jeans tail of the SED and thus their sensitivity and/or spatial coverage is partially limited. In addition, high absorption in the atmosphere makes submillimeter observations very difficult from ground-based telescopes.

The Balloon-borne Large Aperture Submillimeter Telescope (BLAST) is the closest precursor of the SPIRE instrument on the Herschel satellite and has obtained the first submillimeter surveys which sample the peak of the SED of the coldest starless cores at the onset of gravitational collapse. Therefore, BLAST represents a significant observational advance in the field and will contribute significantly to answer some of the fundamental questions regarding the earliest stages of star formation.

In this contribution we present a general description of the telescope and summarize the observations performed during the 2005 and 2006 Long Duration Balloon (LDB) flights. In addition, we describe the Vela Molecular Ridge, a region extensively observed by BLAST, and discuss some of our preliminary results.

2 Balloon-borne Large Aperture Submillimeter Telescope

BLAST [15] is a 2-meter telescope designed to perform three-band photometry at 250, 350, and 500 µm, using the same bolometer arrays as the SPIRE instrument on Herschel. BLAST is operated during LDB flights above most of the atmosphere (at an altitude of about 40 km), and is characterized by the highest sensitivity in these wavebands obtained to date. This allows a mapping speed approximately an order-of-magnitude faster than any other existing submillimeter facility in terms of detecting compact cores and even a greater improvement in terms of measuring diffuse structures in the interstellar medium. Until Herschel is launched, BLAST is unique in its ability to derive large statistical samples of pre- and proto-stellar cores, providing the critical spectral coverage needed to constrain column densities, masses, luminosities and temperatures. In addition, BLAST large-scale surveys enable the study of the environmental effects on the early evolution of star formation, from the scale of a giant molecular cloud (GMC) to individual cold cores.

BLAST surveyed a total of ~ 20 deg^2 of the Galactic plane visible from the northern hemisphere during its 2005 flight, including extensive maps toward Vulpecula, Cygnus, Aquila, and Sagitta, well-known sites of high-mass star formation. A detailed analysis of the 4 deg^2 Vulpecula map has been published recently. In this region 60 compact submillimeter cores were detected simultaneously in the three wavebands and their temperature, mass, and luminosity were estimated [6]. Results and maps are publicly available and may be accessed from the BLAST web page[1]. The other regions will be the subject of subsequent papers.

During the 2006 LDB flight, BLAST surveyed ~ 200 deg^2 of the southern Galactic plane at nearly diffraction-limited resolution ($36''$, $42''$, and $60''$ in the three bands respectively). The surveyed area includes a ~ 50 deg^2 deep map of the Vela Molecular Ridge nested inside a shallower ~ 145 deg^2 area, ~ 3 deg^2 in Eta Carina, ~ 1 deg^2 map of the Gum nebula, and a ~ 3 deg^2 map towards the supernova remnant Pup A. In addition, during this flight BLAST conducted unprecedented extragalactic surveys towards the GOODS South field and the South Ecliptic Pole. Both Galactic and extragalactic data are being analyzed and will be published soon. The Galactic and extragalactic maps obtained by BLAST and the techniques used for map reconstruction and analysis will serve as a legacy to be followed by Herschel.

[1] http://blastexperiment.info/results.shtml

3 Vela Molecular Ridge

The Vela Molecular Ridge (VMR) is a complex of four GMCs (named, A, B, C, and D by Murphy & May [14]) firstly observed by May et al. [11] in the ^{12}CO(1–0) transition. It is located in the galactic plane ($b = \pm 3°$) and extends over 17° in longitude ($l \sim 257°$–$274°$) having a total mass $\geq 5 \times 10^5 M_\odot$ [14]. Clouds A, C, and D are at a distance of 700 ± 200 pc while Cloud B is ~ 2 kpc away [10].

The VMR is an actively low- and intermediate-mass star forming region. It has been searched for young stellar objects (YSO) by different authors, usually through the IRAS and/or MSX Point Source Catalogues (PSC). NIR observations of selected IRAS sources performed by Liseau et al. [10] produced the first catalogue of Class I objects in the VMR. Later observations discovered ~ 30 protostar candidates in Vela C [4] and a young population of Class I–III objects in Vela D [7]. Although Spitzer-MIPS, in addition to ground-based NIR observations, has identified a significant number of Class I–III protostars in Vela D, only a few Class 0 objects have been proposed to date [8]. Furthermore, an area of ~ 1 deg^2 within Vela D has been mapped in the 1.2 mm dust continuum providing a sample of ~ 30 dense cores [12]. However, this survey is not sensitive enough to obtain a complete census of pre- and proto-stellar cores in the region.

Recently, BLAST has characterized the cold dust emission in the VMR, resolving GMCs into different structures such as clumps, filaments and individual dense cores. We have identified and measured the flux densities of more than 1000 cores simultaneously in the three bands, having typical sizes of ~ 0.15 pc (Netterfield et al., in preparation). The SEDs of the coldest objects (starless and pre-stellar cores with $T \leq 20$ K) peak in the range ~ 100–$300\,\mu$m and are therefore well constrain by BLAST data alone. Assuming optically-thin emission from an isothermal modified blackbody we can fit the core SEDs and estimate their temperature, luminosity and mass. In the case of warmer sources the peak of the SED is shifted to shorter wavelengths and additional MIR data are needed to constrain the physical parameters. Proto-stellar cores basically consist of a central IR source embedded within a cooler envelope and thus cannot be described with a single-temperature model. In such cases, fitting the submillimeter/far-infrared (FIR) part of the SED with a single-temperature model (and leaving MIR data as upper limits) one can estimate the envelope properties.

Through the BLAST data alone, we have found that the temperatures of most of the cores are in the range 10–35 K. Assuming a distance of 700 pc for Clouds C, and D [10], we have estimated the core mass and luminosity distributions in these clouds. We find that the majority of the cores have masses and luminosities in the 1–30 $M_\odot$ and 1–10 $L_\odot$ ranges, respectively.

We are currently analyzing the data available at other wavelengths, looking for MIR counterparts in order to better constrain the physical parameters. A first analysis has revealed that ~ 200 BLAST cores may be associated with MIR sources from the IRAS and MSX PSCs. The correct identification of counterparts at shorter wavelengths is made difficult by crowding, by the low-angular resolution of the IRAS maps and also by the low-sensitivity of the MSX bands. The visual inspection of the same field at different wavelengths, in addition to appropriate cross-correlation among catalogues, is often necessary to determine the correct MIR counterpart to a given BLAST source, thus ensuring the correct source SED, from submm to MIR wavelengths. Using the SEDs and the identification of MIR counterparts one can form a census of cores covering all evolutionary phases. From a complete census of the cores one can then attempt to determine the lifetime of each evolutionary phase, which may help to distinguish among different star formation models.

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References

1. J.F. Alves, C.J. Lada, E.A. Lada, Nature **409**
2. P. André, D. Ward-Thompson, M. Barsony, ApJ **406**
3. P. André, D. Ward-Thompson, M. Barsony, *Protostars & Planets IV*. (AWB, 2000), pp. 59-+
4. D. Baba, S. Sato, C. Nagashima, et al., Astron. J. **132**
5. S. Bontemps, P. André, A.A. Kaas, et al., A&A **372**
6. E.L. Chapin, P.A.R. Ade, J.J. Bock, et al., ApJ **681**
7. M. De Luca, T. Giannini, D. Lorenzetti, et al., A&A **474**
8. T. Giannini, D. Lorenzetti, M. De Luca, et al., ApJ **671**
9. C.J. Lada & B.A. Wilking, ApJ **287**
10. R. Liseau, D. Lorenzetti, B. Nisini, et al., A&A **265**
11. J. May, D.C. Murphy, P. Thaddeus, A&AS **73**
12. F. Massi, M. De Luca, D. Elia, et al., A&A **466**
13. C.F. McKee & E.C. Ostriker, ARA&A **45**
14. D.C. Murphy & J. May, A&A **247**
15. E. Pascale, P.A.R. Ade, J.J. Bock, et al., ApJ **681**
16. F.H. Shu, Z.-Y. Li, A. Allen, ApJ **601**
17. H. Zinnecker & H. W. Yorke, ARA&A **45**