Paolo de Bernardis and Andrew Lange †

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Andrew Lange was the Marvin L. Goldberger Professor of Physics at the California Institute of Technology

2006 Balzan Prize for Observational Astronomy and Astrophysics
For their contributions to cosmology, in particular the BOOMERanG Antarctic balloon experiment.

Institutions Administering Research Funds:
- Università di Roma "La Sapienza"
- California Institute of Technology (Caltech)

Adviser for the Balzan General Prize Committee: Per Olof Lindblad

Observation of the Cosmic Microwave Background (CMB)

Observations of the finest details of the Cosmic Microwave Background (CMB) have the potential to explain some of the unresolved problems of modern cosmology, such as the existence of an inflation process in the very early Universe, the existence and the nature of dark matter and dark energy, and the formation of structures in the Universe. Paolo de Bernardis and Andrew Lange have used the second half of their Balzan Prize to finance two experimental investigations: one on CMB polarization and the other on the formation of cosmic structures. Tragically, Andrew Lange died on 22nd January 2010. His colleagues Tom Soifer and James Bock, at the California Institute of Technology are now managing his Balzan research project.

An Experimental Investigation of the First Stages of the Formation of Cosmic Structures
This project has been carried out under the responsibility of Professor Paolo de Bernardis. It is aimed at measuring the effect of the first structures on the background CMB light: in fact phenomena like the Sunyaev Zeldovich Effect (SZE) in the first

clusters of Galaxies and resonant emission/absorption lines in the first structures leave an imprint in the CMB, which can be used to trace them.

This project uses and original approach, performing *spectroscopic* measurements of CMB anisotropy. After the photometric measurements of CMB anisotropy and polarization, these spectroscopic measurements promise to open a new dimension in CMB research. The advantage of this approach, in particular for the measurements of the SZE, has been analyzed thoroughly in publication [1]. The possibility to study the nature of dark matter using SZE measurements in clusters of galaxies in strong dynamical interaction has been analyzed in paper [2].

From the experimental point of view, this strategy requires building a *differential spectrometer*, matched to a large aperture telescope to achieve the necessary angular resolution. The system must be flown on a stratospheric balloon to cover the high-frequency side of the CMB spectrum, not accessible from the ground due to fluctuating atmospheric emission and absorption. This poses formidable experimental challenges, requiring cryogenic imaging detectors, cryogenic imaging spectrometers, a large telescope and a space mission.

A long preparation work is needed to qualify the method. Examples of technical publication analyzing possible systematic effects related to these measurements can be found in papers [3] and [4]; several more are in preparation. The first opportunity to test experimentally this idea will be with the forthcoming flight of the OLIMPO balloon-borne telescope (described in papers [5] and [6]). This has been recently upgraded with an ambient-temperature differential spectrometer, which can be inserted as a plug-in in the optical path between the telescope and the multi-band photometer, transforming the 4-bands photometer in a low-resolution spectrometer. It performance and scientific potential has been analyzed in paper [1].

We have completed a full phase-A study of an innovative satellite mission, called SAGACE, carried out by the “La Sapienza” group in the framework of the second project above. For a short description see [7]; the scientific potential of this configuration is also studied in paper [1]. The full study has been described in a long document (ref. KISAG- RP-010), which has been submitted to the Italian Space Agency for evaluation and possible implementation as a national small mission. We are also developing a differential spectrometer of this kind for the space mission Millimetron, a space-borne sub-millimeter telescope, 10 m in diameter and cooled below 10K. The ground-breaking scientific potential of a differential spectrometer on this mission is described in paper [1].

Balzan funds were used to acquire hardware to design and complete the instruments, to support the dedicated work of postdocs already trained on the BOOMERanG project, to support the collaboration with the Cardiff (Ade, Mauskopf) and Pasadena (Lange) groups for the development of subsystems, and the diffusion of cosmology results through the preparation of a book on observational cosmology [8]. In particular:

- Three post-doc fellowships at “La Sapienza”, focusing on the data analysis of the BOOMERanG and Planck experiments (M. Veneziani, P. de Bernardis, *et al*. [9]) and on the SAGACE study [7], have been assigned. One fellowship has been assigned to Dr. Gianluca Polenta. He is now a scientist at the Agenzia Spaziale Italiana Data Center (ASDC). A second fellowship has been assigned to Dr. Luca Lamagna, who is now a Researcher (TD) with Professor de Bernardis’ group in “La Sapienza”. The third fellowship has been assigned to Dr. Alessandro Schillaci, and he is currently a post-doc in Professor de Bernardis’ group.

- Support for the hardware of the large throughput Martin-Puplett interferometer built in our group. This instrument is a prototype for the missions described above. This has been the subject of the Ph.D. thesis of Dr. Alessandro Schillaci “*Millimetric spectropolarimetry of cosmological signals”* discussed in Dec. 2009 at “La Sapienza”.

- Support the development of a new kind of mm-wave detectors, the microwave kinetic inductance detectors [10].

- Cooperation with the Caltech group on CMB polarization measurements has also been supported, with the development of a parallel study carried out in Europe for a space mission devoted to CMB polarization. Two proposals have been submitted to ESA with Paolo de Bernardis serving as the PI and the collaboration of the US teams in addition to the European ones. The first one was for a low angular resolution polarimeter, called B-Pol [11]. The second one, called COrE, was for a much more ambitious system, a Planck-like multiband telescope, with a large cryogenic rotating HWP used as the first optical component to modulate the polarized signal [12]. We are also actively studying the impact of systematic effects on the scientific exploitation of these measurements (see e.g. [13]).

Researchers:
Martino Calvo
Luca Lamagna
Silvia Masi
Gianluca Polenta
Alessandro Schillaci

Publications:

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[6] L. Conversi, *et al., Extracting cosmological signals from foregrounds in deep mm maps of the sky*, "Astronomy & Astrophysics", 524, A7 (2010).

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An Experimental Investigation of CMB Polarization

Funding for Professor Andrew Lange's investigation was used to support an ambitious program of new ground-based and balloon-borne CMB experiments, and an emerging generation of young experimental cosmologists. The BOOMERanG CMB experiment, the basis of the 2006 Balzan Prize, demonstrated that the geometry of the universe was flat to high experimental accuracy, a measurement based on the apparent angular size of the first acoustic peak in the CMB temperature spatial power spectrum. This observation of a flat universe required a missing form of matter-energy density, obtained in the form a 'dark-energy' needed to explain the accelerating expansion of the universe from concurrent supernovae measurements. A flat universe is also consistent with the predictions of inflation, an exponential sub-luminal expansion in the early universe. While observations of the CMB are well-explained by inflation, the physics of inflation, which are thought to occur at high energy scales and possibly associated with grand unification, remain a deep mystery.

Funds from the Balzan Prize were thus applied to build upon the results of BOOMERanG, to probe the physical process of inflation via CMB polarization measurements. Depending on the physical process, inflation may produce a cosmological background of gravitational waves, detectable by a subtle signature in CMB polarization. Because gravitational waves possess a handedness, they can impart a handed 'B-mode' polarization pattern. Two experiments were initiated to search for this polarization pattern using new technology millimeter-wave focal plane detector arrays. The BICEP2 (Background Imaging of Cosmic Extragalactic Polarization) experiment is a degree-scale polarimeter currently carrying out science observations from the South Pole [1,2]. The receiver is in many ways similar to its predecessor experiment BICEP [3], which currently has the best upper limits on the inflationary polarization signal [4], and excellent control of systematic errors [5]. BICEP2 differs in that the focal plane has been greatly enhanced, going from individual detectors, similar to those used in the *Planck* satellite, to entirely microfabricated arrays with superconducting sensors and readouts [6,7]. BICEP2 was fielded at the South Pole in 2009, and has demonstrated 10 times faster observing speed compared with BICEP. The team has two seasons of high-quality CMB polarization data in hand, with excellent calibration measurements [8], and are working on new science publications in the coming year. Balzan funds enabled them to initiate BICEP2, and a more powerful successor experiment named the Keck Polarimeter Array, with support from the National Science Foundation and the W.M. Keck Foundation.

In parallel, the research group has been developing a powerful balloon experiment named SPIDER [9] that uses 6 new-technology focal plane arrays [10]. These arrays are similar to the focal plane developed for BICEP2, except with even higher sensitivity due to the lower atmospheric emission available on a high-altitude balloon. SPIDER will observe CMB polarization in multiple frequency bands, a key to discriminating cosmological polarization from polarized Galactic emission [11, 12]. The development of SPIDER is now reaching a critical stage. All major components of the experiment including the liquid helium cryostat [13] and experiment gondola are now in place. The first 150 GHz and 90 GHz receivers have been tested. This year the experiment will be integrated. The research group are working with the US balloon program to support an Antarctic long-duration balloon flight in early 2013. Major funding for SPIDER has been provided by the National Aeronautics and Space Administration.

Balzan funds have fostered a new generation of experimental scientists. Dr. John Kovac was supported while at Caltech, where he played a leadership role in the BICEP and BICEP2 program. He accepted a faculty position at Harvard University in 2009 and continues his close collaboration on these projects. Randol Aikin is a graduate student on BICEP2, who has seen the experiment from its inception. Mr. Aikin helped develop the focal planes, tested and calibrated the receiver, and is now leading the science data analysis. He plans to graduate from Caltech in 2013 to what will surely be a promising scientific career. Dr. Roger O'Brient is expert at developing the radio-frequency designs used in the new focal plane arrays, and has been instrumental in developing new detector concepts expanding on this promising and flexible technology to new scientific applications.

The research group was shocked and saddened by Professor Andrew Lange's tragic death in 2010, and greatly moved by the outpouring of sympathy and support from the worldwide scientific community in the months following. Professor Lange's thoughtful acceptance speech from the Balzan Prize ceremony was the centerpiece of a video tribute to his scientific career shown at his Caltech memorial. They feel a deep personal commitment to carry forward his legacy, a combination of passionate curiosity about the universe and its origins, experimental inventiveness, selfless teamwork, and his tremendous enthusiasm for scientific exploration. The experiments that Professor Lange began have been largely realized, and are now poised to return initial scientific results in the coming years thanks to the support of the Balzan Foundation.

Researchers:
Randol Aikin
James Bock
John Kovac
Roger O'Brient
Tom Soifer

Publications:

[1] R. W. Ogburn *et al.*, 2010, "The BICEP2 CMB Polarization Experiment", SPIE 7741, 40O.
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