Brazilian Journal of Physics
ISSN: 0103-9733
luizno.bjp@gmail.com
Sociedade Brasileira de Física
Brasil

Vernon Jones, William
Highlights of the NASA Particle Astrophysics Program
Brazilian Journal of Physics, vol. 44, núm. 5, 2014, pp. 534-539
Sociedade Brasileira de Física
Sâo Paulo, Brasil

Braz J Phys (2014) 44:534–539
DOI 10.1007/s13538-014-0247-1

PARTICLES AND FIELDS

Highlights of the NASA Particle Astrophysics Program

William Vernon Jones

Received: 28 April 2014 / Published online: 15 August 2014

Abstract The NASA Particle Astrophysics Program covers Origin of the Elements, Nearest Sources of Cosmic Rays, How Cosmic Particle Accelerators Work, The Nature of Dark Matter, and Neutrino Astrophysics. Progress in each of these topics has come from sophisticated instrumentation flown on long duration balloon (LDB) flights around Antarctica over the past two decades. New opportunities including Super Pressure Balloons (SPB) and International Space Station (ISS) platforms are emerging for the next major step. Stable altitudes and long durations enabled by SPB flights ensure ultra-long duration balloon (ULDB) missions that can open doors to new science opportunities. The Alpha Magnetic Spectrometer (AMS) has been operating on the ISS since May 2011. The CALorimetric Electron Telescope (CALET) and Cosmic Ray Energetics And Mass (CREAM) experiments are being developed for launch to the Japanese Experiment Module Exposed Facility (JEM-EF) in 2015. And, the Extreme Universe Space Observatory (EUSO) is planned for launch to the ISS JEM-EF after 2017. Collectively, these four complementary ISS missions covering a large portion of the cosmic ray energy spectrum serve as a cosmic ray observatory.

Keywords Cosmic rays · Particle astrophysics · Balloons · LDB · ULDB · ISS observatory

W. V. Jones (✉)
Astrophysics Division DH000, Science Mission Directorate, NASA Headquarters, Washington DC 20546, USA
e-mail: w.vernon.jones@nasa.gov

1 Introduction

Cosmic-ray/particle astrophysics investigations are solicited as a program element in the Astronomy and Physics Research and Analysis (APRA) program of the NASA annual Research Opportunity in Space and Earth Science (ROSES) solicitation. This program element supports investigations related to understanding the origin, acceleration, and transport of galactic cosmic rays. Fundamental measurements include cosmic-ray elemental abundances, isotopic composition, and energy spectra, as well as searches for neutrinos, antimatter, exotic particles, and dark matter candidates. This program element has traditionally supported science investigations and/or technology development utilizing payloads flown on large stratospheric balloons that carry instruments above 99.5 % of Earth's atmosphere, or similar-class payloads flown as flights of opportunity on space missions. In recent years, it has also supported suborbital class investigations that utilize the ISS.

Amendment No. 11 to 2010 ROSES specifically solicited ISS investigations in competition with traditional suborbital investigations. This ISS opportunity is especially attractive for investigations that study the low fluxes of high-energy cosmic rays. Indeed, the very successful CREAM investigation proposed at the first opportunity to reconfigure its proven balloon payload for exposure on the ISS, including rephasing its existing balloon project budget to support the new project, dubbed ISS-CREAM. The AMS investigators had emphasized this advantage long before the 2010 ROSES amendment. A US science team was selected in response to a 2009 proposal to participate in CALET, and a different US science team was selected in 2012 to participate in JEM-EUSO.

2 NASA Long Duration Balloon Flights

2.1 Antarctic Ballooning

The vented zero-pressure (in equilibrium with the atmosphere) balloons used today have changed only incrementally from those introduced in the 1950s [1]. Since that time, large polyethylene balloons have been employed for a variety of scientific and technological pursuits. They offer a unique capability for frequent access to near-space for science and technology instruments ranging in mass from a few kilograms to more than 1,000 kg. They traditionally carried payloads for 1–2 days, but in the early 1990s, NASA extended balloon flight durations to 10–20 days by conducting launches in the constant sunlight during Antarctic summers. These so-called long duration balloon (LDB) flights employ zero-pressure polyethylene balloons identical to those utilized for conventional flights that are severely limited in duration by gas loss during day-night transitions.

The inauguration of LDB flights around Antarctica provided a sea change in scientific ballooning. These circumpolar flights have been spectacularly successful, with many investigations utilizing multiple flights of payloads that are recovered, refurbished, and reused to minimize life-cycle costs [2]. The attainment of 25–32 and 35–55-day flights, respectively, in two and three circumnavigations of Antarctica has greatly increased the expectations of scientific users. Requests for participation in the Antarctic LDB program, a NASA partnership with the US National Science Foundation Office of Polar Programs (NSF/OPP), exceed the current capacity of two or three flights per annual campaign.

2.2 Record Breaking 2012/2013 Austral Season

The 2012/2013 austral summer enabled an exceptional Antarctic campaign, with three large payloads flying for a total of 96 days. Their circumpolar trajectories are shown in Fig. 1. The Super-Trans-Iron Galactic Element Recorder (Super-TIGER) flew for a record 55 days collecting data on the origin of cosmic rays [3]. It was launched December 8, 2012 and terminated February 1, 2013, due to concerns about increasing instability in the jet stream over Antarctica. It set two duration records in nearly three circumnavigations of Antarctica: longest flight for a heavy scientific payload and longest flight of a heavy-lift balloon. The balloon-borne large-aperture submillimeter telescope (BLAST-Pol) mapped polarized dust emissions along the galactic plane during its 16-day mission [4], and the E and B experiment (EBEX) spent 25 days probing cosmic inflation and gravitational lensing [5].

The constant sunlight during local summer in the Polar Regions allows zero-pressure balloons to maintain their float altitudes for long periods of time. However, mid-latitude flights using zero-pressure balloons are limited to only a few days because ballast must be dropped at each day-night transition to maintain float altitude. The volumes of zero-pressure balloons used for conventional and polar LDB flights change as the ambient atmospheric pressure changes, causing a very large altitude droop at night. By contrast, a super-pressure balloon maintains nearly constant volume, thereby enabling LDB flights in non-polar latitudes. Super-pressure balloons capable of carrying heavy payloads to sufficiently high altitudes will undoubtedly bring another sea change in scientific ballooning by enabling LDB missions at mid-latitudes.

2.3 Ultra Long Duration Balloon Missions

Long-duration flights, and ultra long-duration flights when they become routine, offer a cost-effective way of carrying heavy payloads to the edge of space. More flights of longer duration are needed to fulfill the science goals of particle astrophysics. The 7 million cubic feet (MCF) super-pressure balloon (SPB) test flight launched in December 2008 and terminated in February 2009 after 54 days aloft during its third circumnavigation of Antarctica shows the promise of this entirely new launch vehicle. See Figs. 2 and 3. It achieved a new flight duration record, and its performance (altitude and differential pressure) remained steady with no gas loss. It was terminated only because its flight path was tending to go off the continent; otherwise, it could have flown considerably longer. This new capability will enable cost-effective observations in a variety of astrophysics and other disciplines.

The frequent access to space provided by smaller space missions (e.g., Small Explorers—SMEX) accelerated scientific and technical innovation in the space sciences. Balloon-borne payloads provide similar benefits at still lower cost, and a new generation of ULDB missions with 100 days or more of observing time near the top of the atmosphere is imminent.

3 Balloon-Borne Research Results From Antarctica

Antarctic LDB flights averaging about 17 days have supported various disciplines over the past two decades with important results. For example, Boomerang's detailed map of cosmic microwave background (CMB) temperature fluctuations showed the Euclidian geometry of the universe that led to the 2006 Balzan Prize for Astronomy and Physics [6]. More recent results include the unexpected surplus of high-energy cosmic ray electrons reported by the advanced thin ionization calorimeter (ATIC), likely from a previously unidentified and relatively nearby cosmic object within about 1 kpc of the Sun [7]. The balloon

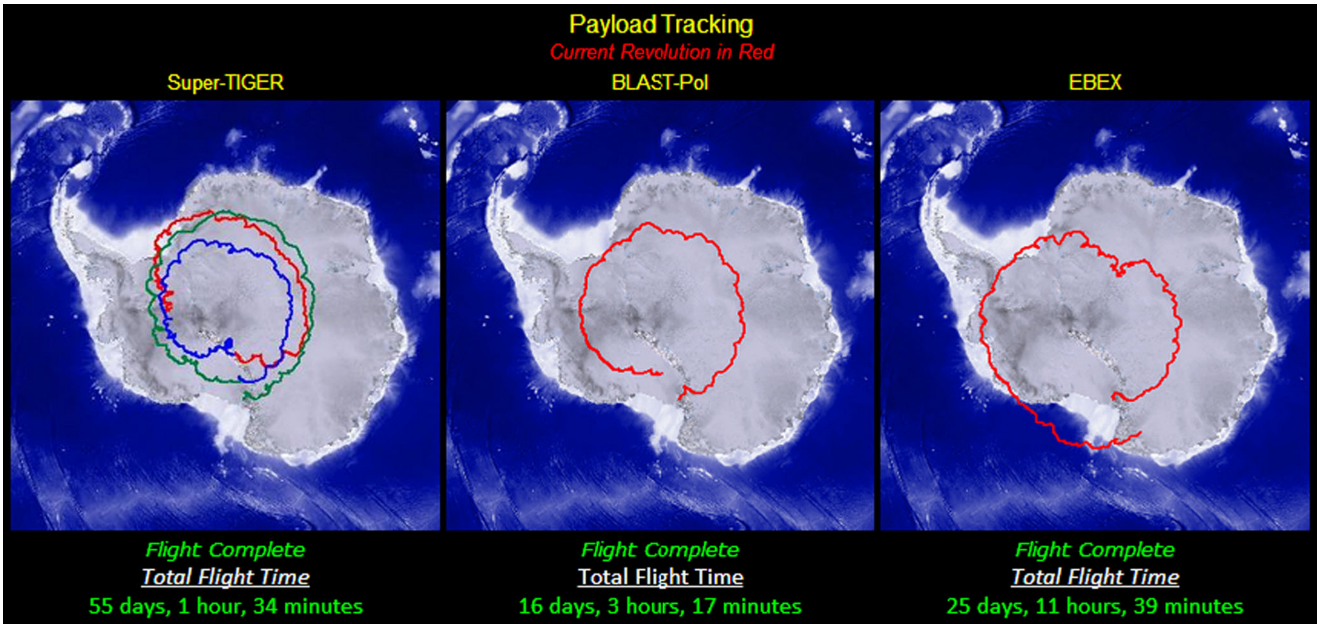

Fig. 1 Circumpolar trajectories around Antarctica for the three LDB balloon payloads (Super-TIGER, BLAST, and EBEX flown during the 2012–2013 austral season (http://www.csbf.nasa.gov/))

experiment with a superconducting spectrometer (BESS) has conducted a negative search for annihilation signatures of dark matter in the antiproton channel [8]. The electron excess in ATIC and lack of excess antiprotons in BESS provide interesting constraints on dark matter models. Traditional propagation models are constrained by the hardening of cosmic ray energy spectra below the "knee" reported by the CREAM experiment [9]. In six flights around Antarctica, the latter accumulated 161 days of exposure, believed to be a record for a balloon-borne investigation. The unique balloon-borne Antarctic Impulsive Transient Antenna (ANITA) designed to detect radio signals from the so-called Greisen-Zatsepin-Kuzmin (GZK) neutrinos has turned out to be sensitive also to the highest energy air showers around the GZK cutoff [10].

4 ISS Utilization to Support Particle Astrophysics

A large fraction of the objectives in the list of Greatest Unanswered Questions of Physics [11] can be answered

Fig. 2 A photograph of the 7 MCF super pressure balloon at float

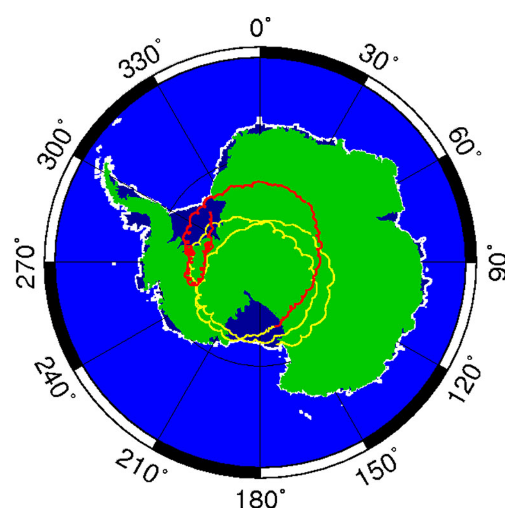

Fig. 3 The balloon's 54-day flight trajectory in Antarctica showing the turnaround of the polar vortex

by particle astrophysics research. Many of them are identified in NASA's Strategic Goals [12] and Science Plan [13] developed from decadal surveys with community input. Each of the investigations, AMS [14], CALET [15], CREAM [9], and JEM-EUSO [16], addresses one or more of these unanswered questions, and all four are well suited for the ISS. See Fig. 4. Their collective science objectives include: measuring the electron spectra with reliable statistics and high resolution to search for signatures of dark matter annihilation and to set limits on the mass of these particles; searching for evidence of a powerful nearby (<1 kpc) particle accelerator by detecting distinct features in high-energy spectra and possibly anisotropy in the arrival directions; measuring hydrogen to iron elemental spectra to understand their origin and source processes; determining the effects of particle propagation in the ISM via measurements of primary and secondary particles; extending direct particle measurements to beyond 10^{15} eV to study the nature of the "knee" in the all-particle spectrum; surveying the ultra high energy ($> 10^{19}$ eV) particle sky to discover their nature and measure their arrival directions to locate sources that are within 50 Mpc to test our understanding of fundamental physics in the universe far beyond Large Hadron Collider (LHC) energies, and to search for ultra high energy neutrinos [10]. The science objectives of these missions validate the importance of the ISS for enabling a wide range of investigations crucial for understanding our universe and its fundamental nature.

4.1 Alpha Magnetic Spectrometer

The AMS instrument was launched by Space Shuttle Endeavor and installed on the ISS in May 2011 to conduct a multimessenger search for dark matter in cosmic rays [14]. It will measure multiple annihilation mode decay products: positrons, antiprotons, anti-deuterons, and gamma rays: early results are featured at this conference. The precise AMS measurements utilizing technology developed in particle physics and modified for space application will provide the means to confirm or refute much of the existing data from balloon investigations. Matter is distinguished from antimatter by observing the oppositely curved tracks of particles with positive and negative charges traversing the strong magnetic field. In addition to measuring GeV cosmic-ray fluxes over most of the Earth's surface for the first time, the 1998 test flight showed the need to upgrade the instrument for the ISS mission. The upgrades included a stronger superconducting magnet, as well as additions of a Ring Imaging Cherenkov (RICH) detector, an Electromagnetic Calorimeter (ECAL), and a Transition Radiation Detector (TRD). These subsystems greatly extend the energy reach and mass resolution of the mission.

4.2 Calorimetric Electron Telescope

The CALET mission was conceived as a high-energy astrophysics observatory to extend the observations of Fermi and

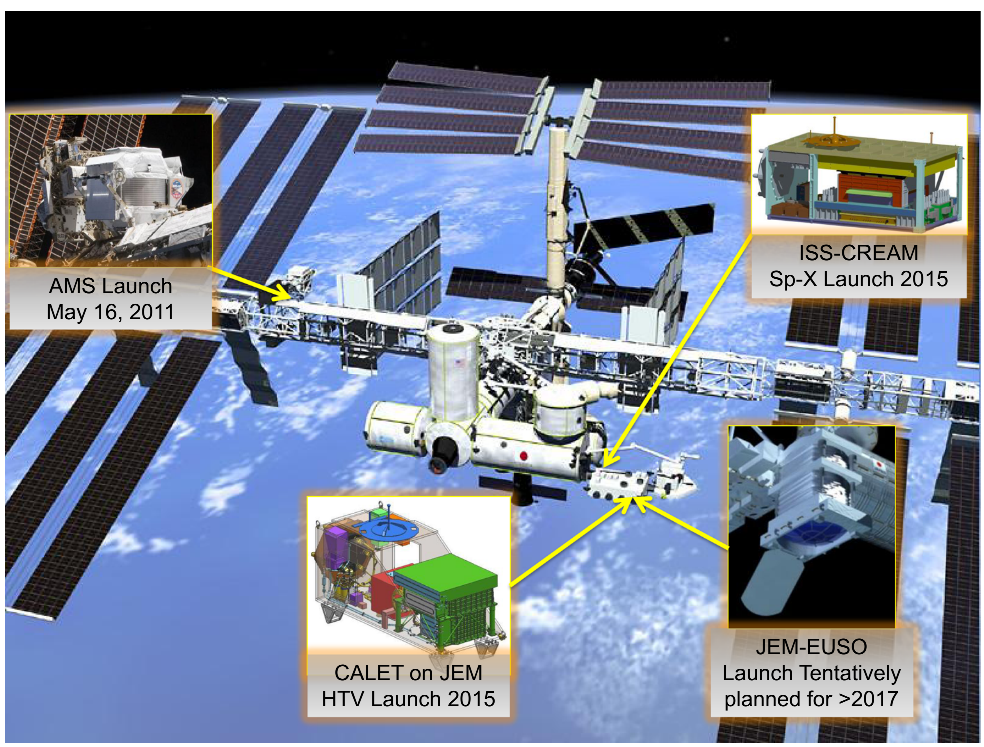

Fig. 4 Illustration of four cosmic ray/particle astrophysics instruments (AMS, CALET, CREAM, and JEM-EUSO) on the International Space Station that comprise a virtual Cosmic Ray Observatory in space

other experiments to high energies beyond those achievable from current or planned missions. Central to the design was a deep calorimeter (~30 radiation lengths) providing excellent energy resolution and high background rejection, enabling CALET to study high-energy electrons and high-energy gamma rays beyond the 300 GeV maximum energy of Fermi. The Japanese led CALET was proposed as an international project for ISS utilization. It will be launched on the JAXA HTV and placed on the Kibo Exposed Facility for its mission lifetime [15]. Japan invited teams from the US (CALET-US) and Italy (CALET-IT) to join the international program. JAXA requested the CALET team to study a reduced size ~500 kg instrument that could be approved for launch on the HTV within the up-mass budget available to Japan. The smaller configuration maintains the high quality of individual measurements, but with an integrated exposure reduced by a factor of ~3 compared to the original instrument. This limits the number of gamma ray sources that CALET will investigate at high energy, but it maintains the important objectives for high-energy electrons and nuclei. JAXA asked a scientific peer review panel to assess the viability of the reduced size. It found that CALET (small) remains an exciting scientific mission and recommended that it proceed with a 5-year lifetime. The final hurdle for the reduced size CALET was passed when the US and other international partners agreed to extend the lifetime of the ISS to 2020, thereby enabling a 5-year mission.

4.3 Cosmic Ray Energetics and Mass for the ISS

The CREAM investigation was conceived as a balloon-borne project to search for features in cosmic-ray elemental spectra and/or abundance changes related to the "knee" around 3×10^{15} eV in the all-particle spectrum [9]. The instrument was a quarter-scale version of the Advanced Cosmic-ray Composition Experiment for Space Station (ACCESS) prioritized in the 2001 decadal study report "Astronomy and Astrophysics in the New Millennium." The CREAM goal was to determine through a series of balloon flights whether and how the spectral "knee" is related to cosmic ray origin, acceleration, and propagation. CREAM accumulated ~161 days of exposure, more than any other balloon-borne instrument in six successful Antarctica LDB flights. Multiple charge measurements using timing, pixilated Si, and Cherenkov detectors, in addition to redundant, cross-calibrated energy measurements using a transition radiation detector and an ionization calorimeter, ensure precise measurements of individual elemental spectra from protons to Fe nuclei. The ongoing analysis indicates that higher statistics are critical for interpretation of the spectral hardening of individual elements observed in the data. The CREAM team has demonstrated that annual Antarctic flights are practical with two payloads that can be flown in alternate years. The data from each flight reduce the statistical uncertainties and extend the measurement reach to energies higher than previously possible. Ultimately, the data will provide substantial overlap and, thereby, calibration for ground-based indirect measurements at much higher energies.

4.4 Extreme Universe Space Observatory on the Japanese Experiment Module Exposed Facility

The JEM-EUSO mission would attach the EUSO instrument to the ISS JEM-EF [16]. It is being developed by a 13-country international collaboration led by JAXA and RIKEN (Institute of Physical and Chemical Research of Japan). It is planned for launch on the Japanese H2 Transfer Vehicle (HTV) not earlier than 2017. It would be the first spaced-based observatory using the Earth's atmosphere as a gigantic detector to observe a large number of extreme energy, >60 EeV, cosmic rays produced by the most powerful accelerators in the universe. Its goal is to open a new field of astronomy through the charged particle channel and, thereby, enlarge the energy reach of fundamental physics probes. The US would provide the key Global Light System (GLS), a ground-based worldwide network of remotely operated light sources (lasers and Xe flashers) for JEM-EUSO calibration and monitoring. The GLS will be located at 12 sites around the world, supplemented with an aircraft system. The calibrated UV lasers and Xenon flash lamps will generate calibrated optical signatures in the atmosphere within the field of view of JEM-EUSO with characteristics similar to the optical signals of cosmic-ray extensive air showers. Throughout its pioneering mission, JEM-EUSO will reconstruct the pointing directions and energy of the lasers and flash lamps to monitor the detector's triggers, and accuracy of energy and direction reconstruction. These are critical parameters for identifying the sources of the highest energy cosmic rays, and for evaluating the instrument performance. Starting in 2014, a prototype of the JEM-EUSO instrument will be flown on a balloon to test its design. The proposers will build prototypes of the GLS and use them to test and calibrate the balloon-borne prototype, dubbed EUSO-Balloon, during its flights. These contributions allow the US team to participate in all aspects of JEM-EUSO science, and the NASA ISS Program to contribute attachment point resources and upmass needed for the JEM-EUSO launch.

References

1. W. V. Jones, et al., Proc. 29th Int. Cosmic Ray Conf. Pune. **10**, 173–184 (2005)

2. E. S. Seo. Astropart. Phys. **39**(40), 76–87 (2012)
3. Binns, et al., The SuperTIGER Experiment, Abstract ID 0645 (This Conference)
4. M. J. Devlin, et al. Nature. **458**, 737–739 (2009)
5. S. Hanany. IEEE Trans. Appl. Supercond., vol. 13, p. 2128, arXiv:0304312 [abstract] (2003)
6. http://www.balzan.org/news-en/2006-balzan-prizewinners-september-2006_3495.html
7. J. J. Chang, et al. Nature. **456**, 362–365 (2008)
8. K. Abe, et al. Phys. Rev. Lett. **108**(5), 051102 (2012)
9. H. S. Ahn, et al. Astrophys. J. Lett. **714**, L89–L92 (2010)
10. P. W. Gorham, et al. Phys. Rev. D. **82**, 022004 (2010)
11. "A 21st Century Frontier of Discovery: The Physics of the Universe", A Report of the Interagency Working Group on the Physics of the Universe, National Science and Technology Council, Committee on Science. (2004)
12. "2006 NASA Strategic Plan". NP-2006-02-423-HQ. http://www.nasa.gov/about/budget/index.html
13. "Science Plan for NASA's Science Mission Directorate 2007-2016,". http://science.hq.nasa.gov/strategy/Science_Plan_07.pdf
14. M. Aguilar, et al. Phys. Rev. Lett. **110**, 141102 (2013)
15. S. Torii, et al. Proc. 29th Int. Cosmic Ray Conf. **6**, 344 (2011)
16. Y. Takahashi, et al. New J. Phys. **11**, 065009 (2009)