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Aspirations and Outlook for NASA Cosmic Ray Research on Balloons and in Space

W. Vernon Jones*

National Aeronautics and Space Administration, Science Mission Directorate, Astrophysics Division, DH000, Washington, DC 20546, USA

The cosmic-ray community has produced a steady stream of science results with both space-based and balloon-borne experiments. Low-energy cosmic rays have been studied with satellites since the dawn of the space age, but stratospheric balloons have provided all of the direct high-energy data. Results extending beyond 10^{14} eV from balloon flights in Antarctica now overlap indirect ground based observations in the energy range below the knee ($\sim 3 \times 10^{15}$ eV). Ultra long-duration balloon flights with super-pressure balloons might allow direct observations to reach 10^{15} eV within the next decade, but larger aperture space missions with longer exposures may be needed to connect cosmic ray composition to supernovae. Space instruments looking down on the Earth's atmosphere, creating a detector as wide as the Earth, could provide information about astrophysical accelerators involving the intense gravity around black holes, neutron stars, and the largest electromagnetic fields known.

KEYWORDS: High-energy cosmic rays, Antarctic balloon payloads, Super-pressure Balloons, Decadal Study, Electrons, Ultra heavy nuclei, Extreme energy cosmic rays

1. Introduction

The Astrophysics Division in the Science Mission Directorate of the U.S. National Aeronautics and Space Administration (NASA) supports basic research covering cosmic rays, along with the entire electromagnetic spectrum from radio to gamma rays. The Astronomy and Astrophysics Research and Analysis (APRA) program element in the annual Research Opportunities in Space and Earth Science (ROSES) solicitation seeks proposals for research activities that address: (i) state-of-the-art detector technology development for instruments that may become candidate experiments for future space flight opportunities; (ii) science and/or technology investigations that can be carried out with instruments flown on suborbital sounding rockets, stratospheric balloons, or other platforms; and (iii) supporting technology, laboratory research, and (with restrictions) ground-based observations that are directly applicable to space astrophysics investigations.

The Cosmic Ray Astrophysics portfolio in APRA 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. The current research program is dominated by experimental investigations utilizing large stratospheric balloons to carry instruments above about 99.5% of the Earth's atmosphere. Related research and technology activities, including studies of new instrument concepts that hold promise for cosmic ray science goals are also supported.

The term *balloon mission* would be appropriate for most of the cosmic ray investigations that have been supported within APRA, because they are similar in many respects to university-scale space flight missions. Most investigations are carried out by Principal Investigators (PI) that lead collaborations of 2 - 7 institutions, which separately submit Co-Investigator proposals for funding their tasks. Projects are typically reviewed every three years, although the average lifetime for an individual balloon mission is approximately 6 - 11 years. This is long compared to the annual review cycle, so a large fraction of the proposals are for continuation and/or modification of ongoing projects. The essentially level budget for this portfolio requires that old projects be phased out to start new investigations, which are selectable after competing favorably for funds freed up by completed projects. Budgets do not allow all worthy projects to be funded.

There is currently a dearth of cosmic ray space missions! This is in contrast to the near-dominance of cosmic ray instruments on early space missions, including the Pioneers, Voyagers, and Ulysses. The last *cosmic ray mission* selected and developed by NASA was the Advanced Composition Explorer (ACE) launched to the L1 LaGrangian point in 1997. Its prime objective was to determine and compare the elemental and isotopic composition of several distinct samples of matter including the solar corona, the interplanetary medium, the local interstellar medium, and galactic material. Note that only the latter addresses topics in the purview of the cosmic ray portfolio in NASA's Astrophysics Division. However, the community has benefited from NASA mission studies and selections by other countries and other agencies in the U.S., and the value of cosmic ray science is recognized. The second-highest *Prioritized Space-Based Small Initiative recommended in the most recent Decadal Study Astronomy and Astrophysics in the New Millennium* was the Advanced Cosmic-ray Composition Experiment for the Space Station (ACCESS).[1)] Hopefully, cosmic rays will also be prominently mentioned in the upcoming Decadal Study for 2010 2020.

*E-mail: w.vernon.jones@nasa.gov

2. Antarctic Balloon Missions

The cosmic ray community has been a major benefactor of the annual scientific balloon campaigns conducted by NASA and the U.S. National Science Foundation (NSF) in Antarctica. The unique atmospheric circulation around the South Pole during the austral summer allows balloon launches from a site near McMurdo Station, the U.S. logistics hub in Antarctica, with payload recovery from nearly the same spot weeks later. The constant daylight means no day- night temperature fluctuations, so the balloon stays at a nearly constant altitude throughout the flight. Each balloon circles the continent from one to three times between launch and recovery. After the flights are completed, the payloads are retrieved, brought back to McMurdo, and returned to their home institutions, where they can be refurbished and flown again. NASA and the NSF have achieved a new milestone in conducting scientific observations from balloons by launching three payloads within a single Antarctic summer in two consecutive seasons.

2.1 Flights during the 2006-2007 season

The Balloon-borne Large-Aperture Sub-millimeter Telescope (BLAST), the Solar Bolometric Imager (SBI), and the Antarctica Impulsive Transient Antenna (ANITA) were launched during the 2006-2007 season. With a 2-m primary mirror and large-format bolometer arrays operating at 250, 350 and 500 μm, BLAST conducted a sensitive, large-area (>>10 deg^2) sub-mm survey during an 11-day flight to address galactic and cosmological questions regarding the formation and evolution of stars, galaxies and clusters. Due to malfunction of the payload-parachute separation mechanism, the payload was badly damaged while being dragged along the ice by the parachute following a safe landing. SBI was planned to study irradiance variations at the upcoming sunspot minimum, when the local fields would be at their weakest, but it experienced an operational problem with the flight computer on ascent.

The ANITA payload was successfully flown for ~35 days. This investigation offers a unique capability, not achievable with either ground-based instruments or instruments on spacecraft, of monitoring neutrinos at extreme energies above $\sim 10^{18}$ eV. It places an antenna array at the virtual focus of a neutrino ice telescope having an area of a million square kilometers on board a balloon flying at ~40 km over the Antarctic continent.[2,3) The radio clarity of Antarctic ice, combined with the so-called Askaryan effect, enables a telescope with the dimensions needed to study cosmogenic neutrinos in an energy regime where they directly probe the nature of the highest energy particles in the universe. ANITA's quad-ridged horn antenna array was successfully employed throughout its flight, but the balloon trajectory was not typical of prior missions. (See Fig. 1.) The balloon headed South rather than West after launch, and the instrument nearly passed over the South Pole on its first revolution. This resulted in substantial anthropomorphic radio background from the South Pole station for a significant portion of the flight time. The on-board computer also experienced frequent crashes during the latter part of the flight. All together, about 15 days of data essentially free of anthropomorphic noise were collected. In parallel with the data analysis, the payload has been refurbished and upgraded to improve the overall detection efficiency for its second flight during the upcoming 2008-2009 season.

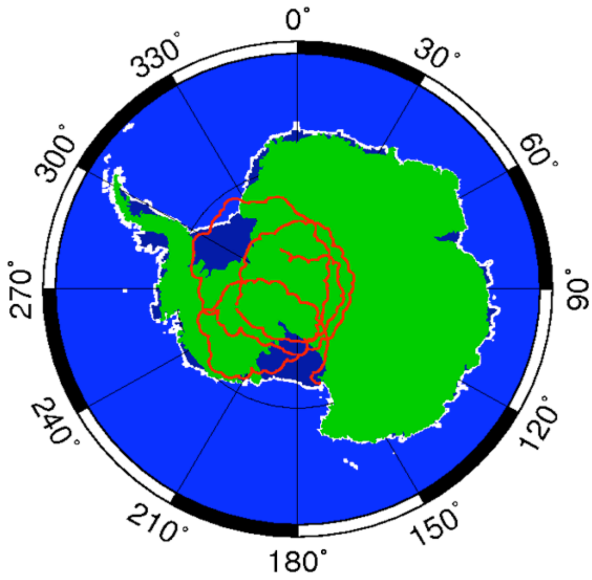

Fig. 1. Trajectory of ANITA payload flown ~35 days around the South Pole.

2.2 Flights during the 2007-2008 season

The 2007-2008 season was NASA's most successful ballooning campaign by far. Three science payloads were flown successfully, and together they were flown for about 79 days at altitudes averaging about 128,000 feet (~38 km). These missions are discussed in detail by the investigators in other presentations at this conference, so they are mentioned only very briefly here. They included the Cosmic Ray Energetics And Mass (CREAM) experiment led by the University of Maryland,[4,5] the Balloon-borne Experiment with a Superconducting Spectrometer (BESS) led jointly by the High Energy Accelerator Research Organization, Tsukuba, Japan and the NASA Goddard Space Flight Center,[6,7] and the Advanced Thin Ionization Calorimeter (ATIC) experiment led by Louisiana State University.[8,9]

The CREAM experiment measures elemental composition and energy spectra of very high-energy energy ($\sim 10^{10}$ to $> 5 \times 10^{14}$ eV) cosmic rays with better precision and higher statistics than any previous experiment. It is searching for characteristic changes associated with a limit to particle acceleration in supernovae, a goal that requires a series of long duration flights. Its third flight was launched December 19, 2007, and flew for 29 days. Combined with two previous flights of 42 days and 28 days, respectively, about 100 days of exposure have already been accumulated. Analysis of the collected data is underway, and the payload has been integrated for its fourth flight during the 2008-2009 season.

The BESS investigation performed precise measurements of cosmic-ray antiprotons with nine conventional balloon flights over a large fraction of a solar cycle before converting the instrument for long-duration Antarctic flights, starting in 2004. The most recent flight was during solar minimum conditions at the lowest possible geomagnetic cutoff, which provided the maximum measurement sensitivity to the possible presence of an exotic source. This second Antarctic flight was launched December 23, 2007, and it flew for ∼30 days. Its precise data will constrain models for dark matter, primordial black holes, and cosmological antimatter. The onboard data were recovered, but full payload recovery was deferred because of the difficult terrain where it landed.

The ATIC investigation is focusing on cosmic-ray electrons, the only component for which there is direct evidence of acceleration in supernova remnants. Electrons are of particular interest because they are subject to synchrotron energy losses that limit the distance they can travel through space. ATIC also measures high-energy ($< 5 \times 10^{10}$ to $\sim 10^{14}$ eV) cosmic-ray nuclei spectra. The third and last flight of ATIC was launched December 26, 2007, and recovered near the South Pole after a 19-day flight. The data accumulated from three flights of the instrument are being analyzed.

3. Super-Pressure Balloon Development

Over the past decade, NASA has been developing a super-pressure balloon (a.k.a. ultra long duration balloon - ULDB) capable of sustaining stable altitudes in non-Polar Regions. Zero-pressure balloons capable of carrying large payloads can maintain their float altitude for extended durations in Polar Regions, but for only a few days at mid-latitudes. The NASA super-pressure balloon concept has a lobed structural design, with a pumpkin-like shape, which should maintain high-altitude, long duration flights at any latitude with loads comparable to current zero-pressure balloons.[10)] The film provides the gas barrier and transfers local pressure loads to the tendons, which provide the global pressure-containing strength. These essentially constant volume systems require the balloon skin (gas bag) to be strong enough to withstand pressurization caused by solar radiation heating of the gas during the day, and still remain pressurized at night after the gas has cooled. No ballast is required to maintain altitude as long as the balloon remains pressurized. This is in contrast to the need to drop ballast equivalent to ∼7% of the suspended load at each day-night transition for a zero-pressure balloon.

A successful test flight of a 2 million cubic foot (MCF), about 0.06 million cubic meter, super-pressure balloon was launched from Fort Sumner, New Mexico, in June 2008. This 200-gore balloon was designed with an equator lobe angle of ∼55° using co-extruded film identical to that used for previous super-pressure balloons. Its design was based on information gathered from ∼4 m, ∼8.5 m, and ∼27 m diameter model balloon tests to understand a deployment issue encountered in prior pumpkin balloon flights. This test balloon fully deployed when it reached between 50 and 60 Pa differential pressure at its float altitude, which was the primary goal of this flight.

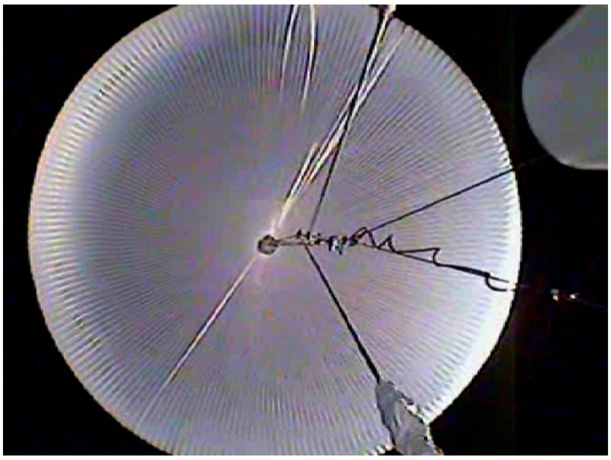

Fig. 2. Super-pressure pumpkin balloon deployed at float altitude.

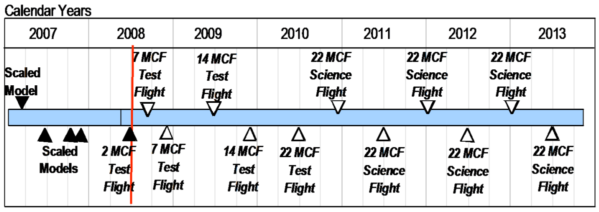

Fig. 3. Super-pressure balloon development schedule.

(See Fig. 2.) The balloon was subsequently pressurized, as planned, to ∼200 Pa, where it was held for some time. The ballast was then incrementally dropped to pressurize the balloon to the maximum extent possible. With all of the ballast expended, the maximum differential pressure in the balloon was ∼360 Pa. At that point the flight was terminated, and the balloon and payload were subsequently recovered. Figure 3 shows the tentative schedule for tests of increasingly larger balloons of essentially the same design.

4. Operating and launch-ready space missions

Data extending beyond 10^{14} eV from Antarctic balloon flights now overlap indirect ground based observations extending to the highest energies beyond 5×10^{19} eV. And, ULDB flights with super-pressure balloons might allow direct observations in the spectral "knee" region during the coming decade(s). But, development of larger aperture space missions with longer exposures is critical for major advances in this field, both from the standpoint of new data to address long-standing questions and from the perspective of priority within the space agency.

4.1 Operating space based instruments

The Advanced Composition Explorer (ACE) was the last of the *big* Explorers. It was selected before the program established the Mid- and Small-size Explorer categories known as MIDEX and SMEX missions. The suite of ACE instruments includes the Cosmic Ray Isotope Spectrometer (CRIS), which has measured cosmic rays for over a decade covering the charge range $3 \leq Z \leq 34$

and energy range ∼50 ≤ E ≤ 600 (MeV/nuc). It is comprised of four stacks of silicon wafers to make multiple dE/dx and E_{tot} measurements and a scintillating fiber hodoscope to measure trajectories. Its relatively large collecting power and excellent charge and mass resolution have set a new standard for elemental and isotopic abundances. Its isotopic abundance observations suggest that cosmic-ray sources are located in OB associations, where many young massive stars are producing core-collapse supernovae.[11)] The source material is estimated to be a mixture of ∼20% outflow of massive stars, including their Wolf-Rayet phase, and ∼80% normal, solar-system-like composition.

The Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) was launched in June 2006 on the zenith mounting of a Russian Resurs-DK1 Earth-observing satellite. This Italian-led instrument evolved from the Wizard collaboration with New Mexico State University (NMSU). Prototypes of the detectors were tested on NMSU balloon flights supported by NASA, which is currently funding some of the data analysis. The goal of PAMELA is precise measurements of cosmic antiparticles, electrons, and light nuclei in the energy range 10^2 - 10^6 MeV, with an enhanced upper energy limit for electrons.[12,13)] The ∼20.5 cm^2 sr instrument is based on a permanent Nd-Fe-B magnet spectrometer with a silicon tracking system to measure an incident particle's rigidity (momentum per unit charge).

4.2 Major mission nearly ready for launch

The Alpha Magnetic Spectrometer (AMS) sponsored by the U.S. Department of Energy (DOE) for installation on the International Space Station (ISS) has goals similar to PAMELA, but it is a more capable instrument with a much larger collection factor.[14–16)] At the inception of AMS, NASA agreed to support a test flight on the Space Shuttle followed by subsequent launch to the ISS for three years of operation. The test flight using a permanent magnet was successfully conducted as part of the June 2 - 12, 1998, STS-91 mission of Space Shuttle Discovery. In addition to measuring GeV cosmic-ray fluxes over most of the Earth's surface, that flight showed the need to upgrade the instrument with a superconducting magnet for the ISS mission. The upgraded instrument, which has been developed by a large international collaboration, is currently in its final phase of integration and poised to capitalize on the unique capabilities of the ISS. The science objectives include searches for antimatter and annihilation products of dark matter candidates, while simultaneously studying other fundamental physics problems that can be addressed with precise, high-statistics measurements of galactic cosmic rays.

The launch date of AMS has been uncertain since the 2003 Space Shuttle Columbia accident. At the time of this writing, it appears that AMS may be the only major physics observatory on the ISS U.S. National Laboratory. See Fig. 4 for an artist's concept of AMS on the ISS Truss. Plans are underway to establish a Physics Center at the University of Maryland to coordinate and lead its data analysis. The Maryland center would receive and store data as one of three AMS Regional Data Centers:

Fig. 4. Artist concept of AMS on the ISS Truss.

the other two are located in Italy and China. Like the other centers, it would provide access to data for visualization, detector verification studies, and data processing. In addition, it would have the unique and critical role as backup to the primary Payload Operations Control Center (POCC) at CERN. As the secondary POCC, it would provide commanding, storage and analysis of housekeeping data, as well as partial science data analysis for rapid quality control and feedback. Access to the database would be available to all members of the collaboration via a World Wide Web interface.

5. Concepts for New Space Missions

A series of decadal surveys has driven U.S. Astronomy and Astrophysics investigations over the past 50 years. NASA develops strategies for implementing the decadal study priorities in cooperation with other federal agencies and international partners. The ACCESS mission to measure cosmic ray composition from protons through iron at energies approaching the spectral knee was second-highest among the Prioritized Space-Based Small Initiatives recommended in the most recent Decadal Study.[1)] NASA attempted to implement this mission as a mid-size Explorer (MIDEX) mission. Two ACCESS proposals were submitted in response to the MIDEX solicitation, one on the ISS as described in the Decadal Study and one as a free flying satellite. Neither proposal was selected, and less than a year later the Space Shuttle Columbia accident effectively doomed the Space Shuttle as the long-term ISS servicing vehicle. The conventional wisdom is that ACCESS is unlikely to be flown on the ISS, in view of NASA's decision to terminate the Space Shuttle, in order to implement the U.S. Space Policy, a.k.a. the Vision for Space Exploration.

Recognizing the impact of not having a high-energy cosmic ray mission and concerned that the ISS may not be viable over the long term, a cosmic ray community workshop was organized in November 2007. This workshop was intended to focus the community's aspirations on common goals that could lead to a road map for its research. The prime objective was to identify realizable goals for cosmic rays that would be important in

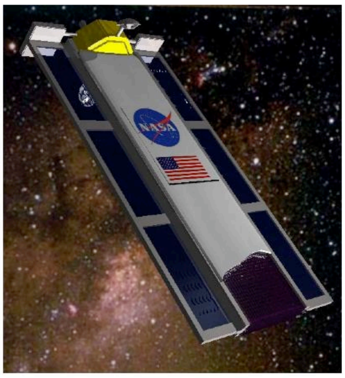

Fig. 5. Artist concept of OASIS: area dominated by ENTICE; weight dominated by twin HEPCaT modules.

the broader astrophysics context. This community activity is being carried out essentially in parallel with updates to the Scientific Ballooning Planning Team report[17] and concept studies for strategic missions solicited by NASA's Astrophysics Division. All three activities are intended to inform the Astronomy and Astrophysics Decadal Study for 2010-2020.

5.1 Medium-size strategic mission concept study

The Orbiting Astrophysical Spectrometer in Space (OASIS) concept to explore the origins of cosmic rays was among 19 Astrophysics Division forward planning studies competitively selected in early 2008.[18] This study will determine the feasibility and cost of a medium-size mission to identify local acceleration sites of galactic cosmic rays. This goal unifies the two instruments comprising OASIS: the Energetic Trans-Iron Composition Experiment (ENTICE) and the High Energy Particle Calorimeter Telescope (HEPCaT). See an artist concept in Fig. 5. With two large instruments optimized to focus on ultra heavy nuclei and electrons, OASIS is complementary to ACCESS, which was optimized to focus on cosmic-ray composition of all elements from protons to iron at energies approaching the spectral "knee".

The ENTICE instrument is based on experience from ACE/CRIS and the Trans Iron Galactic Element Recorder, the first balloon payload to make two circumnavigations of Antarctica. It would measure the relative abundance of each element above the iron peak, including the actinide elements, with high statistics. Measurement of elemental composition in the actinide group would set the timescale for nucleosynthesis and enable the most sensitive search to date for long-lived super-heavy elements expected to lie in the island of stability near element 110. The HEPCaT instrument draws heavily on the ACCESS calorimeter design and the ATIC balloon payload. It would search for a signature of nearby cosmic ray accelerators in the high-energy electron spectrum and measure secondary to primary element ratios (e.g. B/C). Both measurements would providing information on cosmic ray propagation.

5.2 Concepts to study extreme energy cosmic rays

Ground based measurements of the cosmic-ray all-particle spectrum extend above 10^{20} eV, where possible violations of the Greisen-Zatsepin-Kuzman (GZK) cutoff around 5×10^{19} eV have been reported: the preponderance of data confirms the cutoff. Interactions between such extreme energy cosmic rays and photons of the cosmic microwave background radiation limit the distance of their source to be less than about 100 Mpc. This opens up the exciting possibility of ultrahigh energy particle astronomy, since cosmic rays at such energies would experience minimal deflection by interstellar magnetic fields. The Auger collaboration has indicated a connection of its data with active galactic nuclei (AGN),[19] but a variety of astronomical sources have also been suggested. Other postulated sources include decay products of cosmological relics, a.k.a. topological defects, at a 10^{25} eV Grand Unification scale or super-heavy weakly interacting particles. Another class of sources would require new physics beyond Einstein, such as violation of Lorentz invariance, extra dimensions in the Universe, or quantum gravity effects. Ultrahigh energy cosmic rays offer a test of a wide class of theories. Their observation above the GZK cutoff could provide the first direct experimental measurements of the early universe around the era of Grand Unification.

Space-based experiments with 10 - 100 times larger apertures than ground-based observations would provide the sensitivity needed to bring the field of charged-particle astronomy into reality, including observations of both the Northern and Southern hemispheres. The Extreme Universe Space Observatory (EUSO) led by the European Space Agency (ESA) successfully completed a Phase A study in 2004.[20] When the phase B study was postponed, the Japanese and U.S. participants re-defined a single downward-looking air fluorescence detector attached to the Japanese Experiment Module/Exposure Facility on the ISS as JEM-EUSO. The free-flying Super-EUSO spacecraft proposed to the ESA Cosmic Visions program in 2007, with the promise of improved performance, was encouraged to pursue technology development. A collaboration led by the NASA Goddard Space Flight Center proposed launching a pair of satellites called the Orbiting Wide-angle Light-collectors (OWL) satellites into low Earth orbit.[21] Dual free-flying telescopes would offer the advantages of stereoscopic viewing for improved reconstruction and reduced systematic atmospheric effects, which would be particularly important for a space-based mission viewing a constantly changing atmospheric volume.

The JEM-EUSO concept would initially deploy in a nadir-viewing mode for about 3 years to achieve the lowest energy threshold possible. The capability for subsequent tilted-mode viewing for up to a decade would increase the aperture by a factor of 3 - 5, thereby collecting far more data at a higher threshold to explore the trans-GZK part of the spectrum. The OWL concept also proposed a variable aperture by orbiting initially at 1000 km altitude to achieve its largest aperture for $> 10^{20}$ eV showers. The orbit would subsequently be reduced to 500 km to lower the energy threshold to a few $\times 10^{19}$

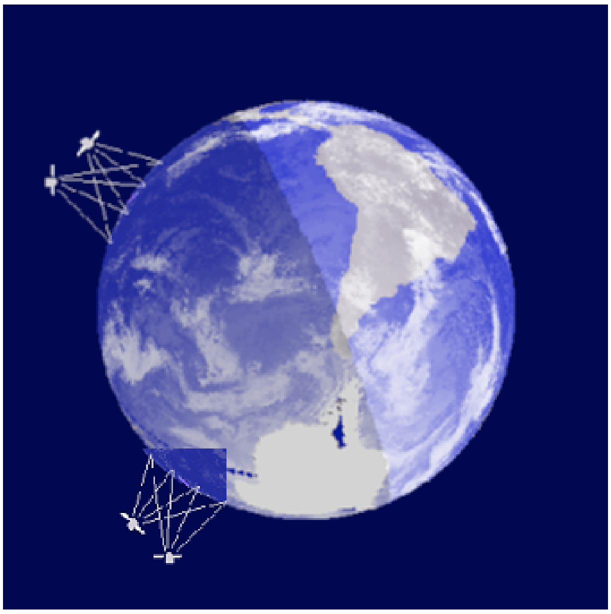

Fig. 6. Artist concept of two pairs of telescopes viewing Earths atmosphere.

eV. The Particle Astronomy Telescope (PATEL) introduced at the 2007 cosmic ray workshop proposed several pairs of orbiting telescopes to observe a large fraction of the Earth's surface.[22] See the schematic illustration in Fig. 6. While the idea of using an array of satellites to observe the Earths atmosphere is not new, the PATEL concept also suggested using the rapid slewing capability of Micro Electro Mechanical Systems (MEMS) technology for the mirrors.

5.3 Concluding Remarks

The NASA cosmic ray astrophysics program is vital, active, and producing new ideas, although more space missions are needed. Balloon-borne experiments are currently at the heart of progress in the field, and they provide the test bed for new ideas and instrumentation that can lead to new space missions. Balloon investigations are cheap compared to satellites missions but relatively expensive compared to typical grants in the Supporting Research and Technology (SR&T) program where they are competed. Partnerships become increasingly important as the investigations become more sophisticated and expensive. The NASA Science Mission Directorate (SMD) states as one of its principles: "*Partnerships are essential to achieving NASA's science objectives. Other nations and agencies are engaged in space and Earth science. NASA and SMD will partner with other national and international organizations to leverage NASA's investment and achieve national goals.*" The international community should keep this principle in mind as new projects are conceived, as indeed it already does. An excellent example presented at this conference is the Japanese-led Calorimetric Electron Telescope (CALET) being studied for ISS/JEM utilization.

The U.S. National Research Council (NRC) has emphasized the importance of observing the highest energy cosmic rays and neutrinos. *How do cosmic accelerators work and what are they accelerating is one of the Eleven Science Questions for the New Century and Determine the origin of the highest-energy gamma rays, neutrinos, and cosmic rays* is one of the recommendations of NRC Committee on Physics of the Universe.[23]

The importance of very high-energy cosmic-ray investigations is also recognized in the Science Program for NASA's Astronomy and Physics Division:[24] "*A future mission designed to measure the composition of cosmic rays up to energies of a few hundred trillion electron volts would explore their connection to supernovae. At still higher energies, we detect cosmic rays that cannot be confined by the magnetic field of our Galaxy and probably come from great distances. Although ground-based observatories are currently used to detect huge showers of particles produced by these very energetic particles, space instruments looking back down on Earth would be more effective, creating a detector as wide as the entire Earth. They would allow us to learn more about astrophysical particle accelerators that can produce energies far beyond those we can achieve on Earth, accelerators involving the intense gravity around black holes and neutron stars and the largest electromagnetic fields known.*"

Concurrence from the Decadal Study for 2010-2020 would provide the basis for implementing an exciting future program in cosmic ray research.

Acknowledgments

Special thanks are due to Jonathan F. Ormes for organizing the Cosmic Ray Community Workshop and to the working group helping him prepare a discipline roadmap; to Martin H. Israel and the Scientific Ballooning Planning Team for updating its roadmap to guide the NASA Balloon Program. Deep appreciation is extended to the staffs of the NASA Balloon Program Office, Columbia Scientific Balloon Facility, and Aerostar, Inc. for major advancements in balloons and balloon systems that benefit the science community. These improvements coupled with the crucial contributions of the U.S. National Science Foundation Office of Polar Programs and Raytheon Polar Services Company enabled the outstanding accomplishments of the 2007-2008 Antarctic balloon campaign and hold promise for comparable future achievements.

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