Balloon and Space based Cosmic Ray Astrophysics

White Paper for 2010 Decadal Survey

Submitted to Science Frontier Panels:
Stars and Stellar Evolution (SSE)
The Galactic Neighborhood (GAN)
Cosmology and Fundamental Physics (CFP)

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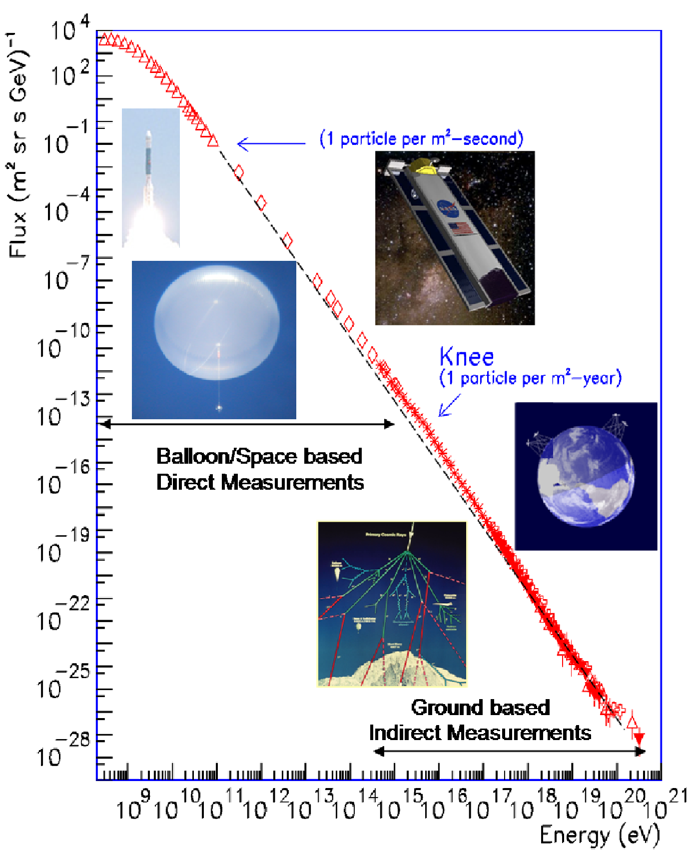

Balloon and Space based Cosmic Ray Astrophysics

Lying at the intersection of particle physics, cosmology, and astronomy, cosmic-ray astrophysics probes some of the most exotic objects in the universe. While much of traditional astronomy is concerned strictly with photons produced in fairly tranquil thermal processes, the cosmos is also filled with highly relativistic particles -- cosmic rays -- producing non-thermal radiation over a vast range of wavelengths. Cosmic-ray astrophysics concerns itself with the study of these particles, the radiation they generate, and the extreme, non-equilibrium environments (e.g., supernova explosions, gamma-ray bursts, and/or active galactic nuclei) in which they are produced.

In many cases, the most profound and ground-breaking results of cosmic-ray astrophysics have come via instrumentation on balloon and space-based platforms that avoid the obscuring and interfering effects of the atmosphere. These missions have achieved unprecedented precision and accuracy in their measurements, which are at the forefront of particle astrophysics. Observing cosmic rays and connecting their properties observed at Earth to the production and radiation of highly energetic particles in exotic environments has led to a better understanding of our local solar environment and the high-energy universe in general. These activities lie at the leading edge of all astrophysical research.

The broad reach of cosmic-ray astrophysics becomes evident when considering the Astro2010 Science Frontier Panels. **Planetary Systems and Star Formation (PSF)**: The collapse of molecular clouds is influenced by ionization produced by cosmic rays, so they have an important influence on both the star formation rate and galactic chemical evolution. **Stars and Stellar Evolution (SSE)**: Cosmic rays observed at Earth (particularly isotope ratios) provide direct information on nucleosynthesis, and their production substantially influences the evolution of supernova remnants. The highest energy cosmic rays may be produced in gamma-ray bursts. **The Galactic Neighborhood (GAN)**: Cosmic rays exert a pressure comparable to that of starlight and galactic magnetic fields so they influence galactic structure and the state of interstellar media. Furthermore, cosmic-ray interactions with interstellar gas and radiation are a source of intense diffuse gamma-ray emission, which is a background for observations of point sources and indirect dark matter searches. It is also a foreground for extragalactic diffuse gamma-ray emission which may contain signatures of exotic physics. **Galaxies across Cosmic Time (GCT)**: Some fraction of the highest energy cosmic rays may be produced in active galaxies and galaxy clusters, and the radio emission produced by the electron component provides much of the information we have on active galaxies, QSO's, etc. **Cosmology and Fundamental Physics (CFP)**: Cosmic rays are, and will long be, a source of particles with energies unreachable with man-made accelerators: the highest energy cosmic rays probe physics at PeV center-of-mass energies. Cosmic-ray production may be important during large-scale structure formation. Recent observations indicate that they may also contain the signature of Dark Matter annihilation.

The last decade has been very productive for cosmic-ray astrophysics with discoveries in a number of areas. These include proof from TeV gamma-ray observations that cosmic-ray electrons are produced in young supernova remnants; the discovery of magnetic field amplification at supernova shocks; and the correlation of the highest energy cosmic rays with AGNs. Steady progress has been made in measuring spectra of individual elements to extend the energy reach to ~10^{14} eV (see Fig. 1). The value of long-duration balloon flights has also been demonstrated with massive cosmic-ray payloads flying multiple circumnavigations of the

Antarctic continent. During the past two austral summers five large aperture cosmic-ray instruments were collectively flown successfully for about 130 days. During the 2008–2009 season a prototype of NASA's new "super-pressure" Ultra Long Duration Balloon (ULDB) was flown for >45 days (see NatureNews 2009).* Its performance confirms the promise of 100-day balloon flights during the coming decade, which would significantly enhance the measurement ability of balloon-borne instruments.

The American Institute of Physics recently listed "COSMIC RAYS" as one of the Top Ten Stories of 2008 in its Physics News Update. This recognition is based on four observations of features scattered across the cosmic-ray energy spectrum. The cosmic-ray flux covers a range of more than 32 orders of magnitude, with particles reaching energies of 10^{20} eV or more. These high-energy particles (protons, nuclei, and electrons) are accelerated by sources in the Galaxy and beyond. The flux reaching Earth decreases with energy according to the approximate power law $dN/dE{\sim}E^{-\alpha}$ with an energy-dependent spectral index $\alpha{\sim}3$. The spectrum in the lower half of the energy range has been determined by direct measurements using relatively small aperture satellites at the lowest energies and larger aperture balloon-borne instruments to explore the 10^{11} - 10^{15} eV region. The upper half has been determined exclusively by indirect measurements using ground-based detectors of extensive air showers, or particles produced by them. We can learn much about the sources of cosmic rays and their propagation by measuring the spectra of individual elements and analyzing their spectral features.

Identified below are four central questions that we believe are answerable in the next decade with balloon-borne and space-based observations in conjunction with theoretical understanding.

1) How are the elements created and distributed?

All elements heavier than boron are understood to be produced in stars, during supernova explosions, and possibly during gamma-ray bursts. Understanding this nucleosynthesis is one of the great quests of science and critical evidence comes from measurements of cosmic rays at Earth. There are two general types of supernovae; massive stars that undergo core-collapse explosions, and white dwarf stars that undergo thermonuclear explosions. These two general types produce elements and isotopes that can be distinguished from each other

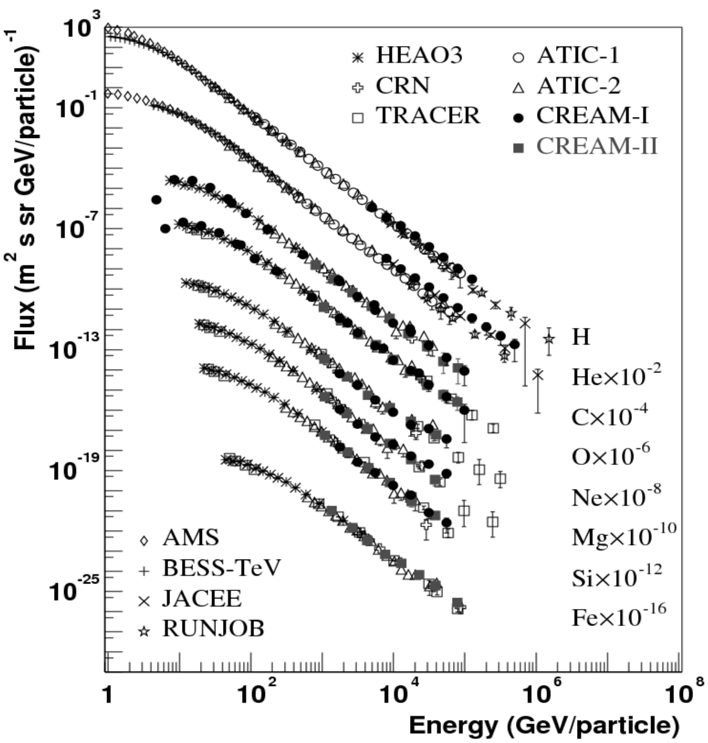

Fig. 1. Cosmic ray energy spectra of individual elements from proton to iron. Figure is adapted from references found in ***Link to figure references.***

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* As this paper is being prepared, the ULDB is in its third revolution around Antarctica and is still flying!

and from elements produced in normal stellar evolution by their abundances. The freshly synthesized elements are distributed throughout the interstellar medium by stellar winds and by supernova explosions. The cosmic rays we observe at Earth are accelerated from some mix of this material.

A key mystery concerning this scenario is that, while most supernovae are believed to be core-collapse ones that occur primarily in massive-star (i.e., OB) associations, the cosmic-ray elemental composition is dominated by well-mixed interstellar material. From measurements of ^{22}Ne and several other isotopes, and elemental abundances of heavy nuclei, evidence exists for a large contribution from massive Wolf-Rayet stars. More sensitive observations are needed to test the OB-association origin of cosmic rays and determine the core-collapse supernova vs. thermonuclear supernova vs. normal stellar evolution mix in cosmic rays. Definitive observation of actinide nuclei (i.e., $_{90}$Th, $_{92}$U, $_{94}$Pu, and $_{96}$Cm) will give unique information on the age of cosmic rays and nucleosynthesis in our Galaxy. The more sensitive the measurements, the more information obtained on the relative abundances of elements produced; on the *r*-process vs. *s*-process fraction; on how freshly synthesized elements are distributed in the galaxy; on the physical state of the supernova explosion when the elements are produced; and on the role OB-associations play in cosmic-ray origin. The isotopic and actinide abundances are particularly important and, among other things, are critical for understanding the supernova explosion mechanism.

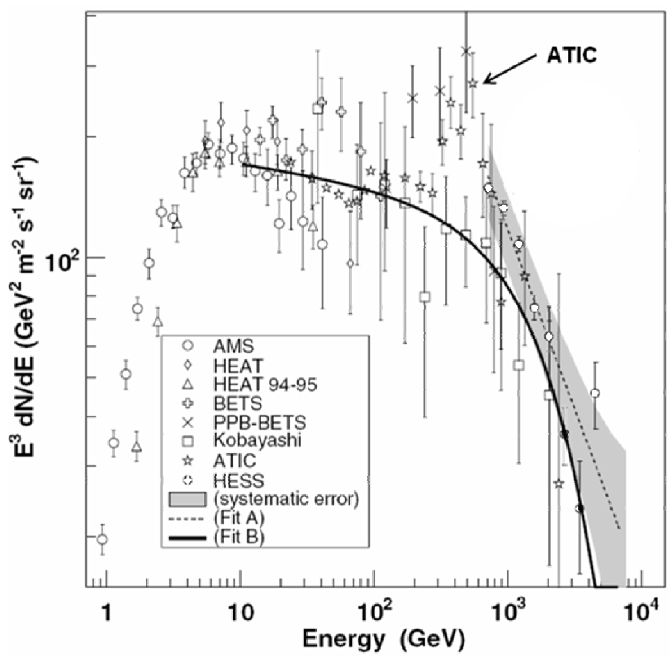

Fig. 2. Cosmic ray electron data indicating an excess between 100 GeV and 1000 GeV. This excess, if real, might be from a discrete, nearby source or be an annihilation signature of Dark Matter. Figure is adapted from Aharonian et al. (2008).

2) What are the nearest sources of cosmic rays?

Except for the highest energy cosmic rays, the meandering nature of cosmic-ray transport in tangled galactic magnetic fields spreads out arrival directions and prevents us from directly pointing back to the sources. However, recent observations suggest that local sources of cosmic rays may be identified as features in cosmic-ray spectra (see the ATIC points in Fig. 2 as an example). If future observations with improved spectral sensitivity confirm these suggestions, a new era of cosmic-ray astronomy could emerge that would simultaneously inform us about the origin of cosmic rays, their diffusion in the interstellar medium, and about our local galactic environment.

High-energy electrons moving through the galactic magnetic field lose energy rapidly due to inverse Compton and synchrotron emission. For the typical energy density of Galactic radiation and magnetic fields of ~1 eV cm^{-3}, the energy loss timescale is ~3x10^5 yr at 10^{12} eV, and this becomes as short as ~3000 yr at 10^{14} eV. The direct observation of cosmic-ray electrons with energies above 10^{12} eV at Earth would mean that there are sources near us in space and time. If nearby sources produce electrons, they may produce nuclei as well. There have been reports of small-scale cosmic-ray anisotropy from MILAGRO at $>10^{13}$ eV energies (Abdo et al., 2008), which indicates a nearby source that could produce a feature in the elemental spectra. To illustrate this, we have superimposed two symbolic spectra (green and blue curves) on the proton spectrum in Fig. 3 to point out three effects: (1) different SNRs may produce spectra with different maximum energy and normalizations; (2) the observed spectrum may show features where the hard spectra of nearby sources dominate the softer galactic component; and (3) features from young SNRs may be present at energies well below the cosmic-ray "knee" near 10^{15} eV. It is critically important to reduce the statistical and systematic uncertainties in the data with improved balloon and space-based observations. Firm identification of features in cosmic-ray spectra would be paradigm breaking, and would represent an advance at least as significant as the recent detection of $>10^{12}$ eV photons from young SNRs.

Ultra heavy nuclides (i.e., $Z > 29$) are another invaluable source of information about nearby sources. These neutron-rich nuclides are synthesized in endothermic reactions occurring predominantly in the final stages of stellar evolution. Since most heavy elements are ejected into the interstellar medium (ISM) by supernovae clustered in space and time, the relative abundance ratios will differ between these fresh ejecta and the well-mixed ISM. These heavy elements have large disintegration cross sections when they are accelerated to cosmic-ray energies, and they only reach us from < 2000 light years away. The composition of these cosmic rays is a direct measure of the solar environment, including the local superbubble which started to form about 5×10^{7} years ago. Cosmic rays shown to come from nearby OB-associations carry information on the composition of material out of which stars are currently being formed.

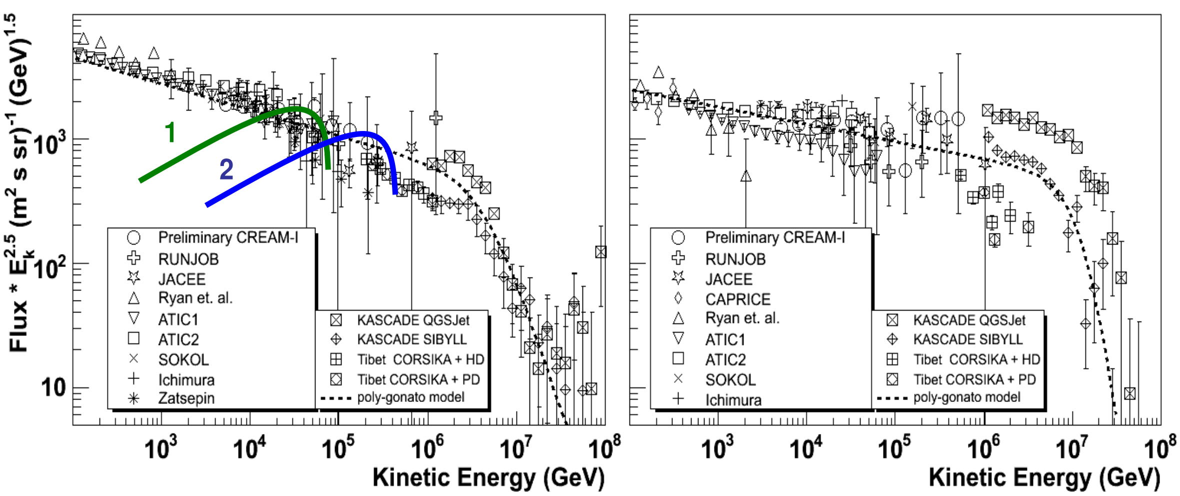

Fig. 3. Cosmic-ray proton (left) and helium (right) spectra in energy per particle are compared with Hörandel's (2003) empirical model (dotted curve) and ground based indirect measurements. The latter are based on the interpretation of air shower measurements using various hadronic interaction models. The green and blue curves, labeled 1 and 2, indicate how hard spectra from individual sources might appear (e.g., Zatsepin & Sokolskaya 2006). Figure is adapted from references given in ***Link to figure references.***

3) How do cosmic ray accelerators work?

Understanding how the highest energy cosmic rays are accelerated is arguably one of the most fascinating questions in all of science. The main clues we have are the total energy going into cosmic rays, their energy spectra at Earth, and their maximum energy. The most likely accelerators of cosmic rays below the "knee" near 10^{15} eV are shock waves in supernova remnants (SNRs), although other sources such as pulsars and stellar winds may contribute. Extending accurate measurements of the elemental spectra shown in Fig. 1 by just one order of magnitude in energy to a few times 10^{15} eV would help answer the question of how Galactic accelerators work. The most likely mechanism at these energies is diffusive shock acceleration, which has undergone intense study because collisionless shocks in the heliosphere accelerate particles, and such shocks exist throughout the Universe.

The sources of the highest energy cosmic rays are much less certain, but they must originate from beyond the Milky Way Galaxy. Great progress in determining their origin has been made by the Auger and HiRes telescopes, which show that cosmic rays beyond about 10^{19} eV obey the so-called Greisen-Zatsepin-Kuzmin (GZK) cutoff. Their flux falls sharply above this energy due to photo-pion production on cosmic microwave background photons. This means that cosmic rays above the GZK cutoff must originate from a region within ~300 million light years from the Earth. The GZK interactions transfer a large fraction of the cosmic-ray energy to ultra-high energy neutrinos and gamma rays. The detection of these neutrinos and gamma-rays would greatly help the understanding of the highest energy cosmic rays. Exotic "top-down" sources become less probable when the GZK cutoff is added to evidence from Auger for a correlation between arrival directions and matter distribution in the local universe, as traced by nearby active galactic nuclei (AGNs). Limits imposed by the long-duration balloon-borne ANITA experiment (Gorham et al. 2008) further disfavor "top-down" scenarios, which also predict hard neutrino spectra at the highest energies.

Thus, the physical processes accelerating the highest energy cosmic rays in AGNs may not be much different from the processes that produce galactic cosmic rays below 10^{15} eV, which are directly observable with balloon-borne and space-based missions. Making those direct observations is essential for understanding the underlying astrophysical processes, including those involved in the more exotic highest energy cosmic rays. The path to understanding cosmic-ray acceleration connects much of high-energy astrophysics, which requires analytical work in several areas. For example, nonlinear plasma physics theory must be coupled to large-scale computer simulations, and photon observations of thermal and non-thermal radiation from young SNRs must be reconciled with nonlinear acceleration models, cosmic-ray propagation models, and direct cosmic-ray observations at Earth.

4) What is the nature of Dark Matter?

Identifying the nature of Dark Matter is one of the most exciting and important problems in astrophysics. The balloon-borne Advanced Thin Ionization Calorimeter (ATIC) experiment recently reported an excess of high-energy cosmic-ray electrons that might indicate an annihilation signature of Kaluza-Klein dark matter (Chang et al. 2008). However, this is extremely tentative since a ~200 'boost factor' associated with non-uniform clumps in the dark matter distribution would be needed to support this explanation. The electron excess shown in Fig. 2 might instead come from a less exotic source relatively close to the Earth, such as a previously unidentified pulsar, mini-quasar, or supernova remnant.

The PAMELA satellite recently reported a significant enhancement in positrons up to ~ 100 GeV (see figure 3 in Adriani et al., 2008). Secondary positrons are produced as cosmic rays interact with normal interstellar material, but the ratio of secondary positrons to electrons is expected to decrease above a few GeV. The observed increase may signify annihilation products of WIMPs (e.g., Physics Today, 2008), but less exotic, nearby sources may be responsible. Only more sensitive observations of spectra and composition using magnetic rigidity spectrometers such as the Alpha Magnetic Spectrometer (AMS) can determine this. The AMS was designed and developed for flight on the International Space Station to address such questions.

The detection of Dark Matter implies "new physics," and the results of any single experiment will require confirmation using instrumentation based on different techniques. Cosmic ray probes of Dark Matter offer an entirely different experimental channel from photon measurements, so they are invaluable for Dark Matter searches.

Discovery Potential: Definitive measurements of cosmic rays to the knee and beyond

The cosmic-ray flux is one of the most amazing data sets in physics (see figure on cover page) and contains the highest energy particles known. The vast range of this flux means that several different detection techniques utilizing ground, balloon-based, and space-based instruments, must be used. Correctly normalizing these techniques to each other is challenging, since the flux falls off extremely rapidly with energy. Nevertheless, matching direct measurements below the knee to the indirect ground-based measurements above the knee is essential for understanding the entire galactic cosmic-ray spectrum, and the extragalactic spectrum above ~10^{18} eV. Figure 3 shows that considerable uncertainty exists in observations above 1000 GeV energies, well below the "knee" near 10^6 GeV. This figure also indicates how hard spectra from individual sources might appear. More sensitive observations are the key to determining whether such spectral features actually exist. The critical transition between galactic cosmic rays above the knee and extragalactic cosmic rays is even more uncertain. Different models for the highest energy cosmic rays make very different predictions for this transition region.

What is needed is a combined program of ground-, balloon- and space-based measurements covering the entire cosmic-ray spectrum. Satellites typically cover the lower energy range, and AMS would provide precision data to 10^{12} eV. This energy overlaps balloon measurements, which can yield direct data on individual elements up to 10^{15} eV with ultra-long-duration (i.e., 100-day) flights in the next decade. Extending accurate measurements of the elemental spectra shown in Fig. 1 by just one order of magnitude would provide information on how the accelerators work, and on the nature of their sources. Good statistics near 10^{15} eV from direct measurements are also required to calibrate the model dependent air shower measurements that extend the spectrum to 10^{19-20} eV.

The Advanced Cosmic-ray Composition Experiment for the Space Station (ACCESS) was designed to measure cosmic-ray composition from protons through iron at very high energies approaching the spectral knee near 10^{15} eV. It was second highest among the six *Prioritized Space-Based Small Initiatives* recommended in the most recent Decadal Study. It seems unlikely that ACCESS can be flown on the International Space Station, given NASA's decision to terminate the Space Shuttle in order to implement the U.S. Space Exploration Policy. It should be noted, however, that a "Free-Flyer" mission could accomplish the scientific goals of ACCESS, and a similar one is under study as an Astrophysics Strategic Mission concept.

A space-based mission with 10-100 times larger aperture than ground-based observations at 10^{19-20} eV would provide the exposure and sensitivity needed to bring the field of charged particle astronomy into reality. The technology necessary for this space mission should be further developed during the coming decade.

Concluding Remarks:

The detection of matter, as opposed to photons, allows cosmic-ray astrophysics to investigate unique problems. Cosmic rays impact, more or less directly, all Astro2010 Science Frontier areas. Questions such as the creation of the elements, the production of the highest energy particles ever observed, and the apparent universality of energetic particle production across the Universe are among the most fascinating in Science. The vast spread of cosmic-ray energies presents observational challenges but it also mandates interactions across many areas of astronomy and astrophysics. Specific examples include heliospheric physics, thermal X-ray emission, all of high-energy astrophysics, particle physics at energies beyond those accessible with man-made machines, exotic physics associated with Dark Matter, and hazards for manned spaceflight.

If we are to remain a vibrant nation, we must maintain our scientific infrastructure, and no element addressed in this Decadal Survey is better suited for this than cosmic-ray astrophysics. Space-based and balloon-borne particle astrophysics experiments uniquely probe fundamental astrophysical questions. Furthermore, balloon-borne experiments are an extremely cost-effective way to explore new ideas and new instrumentation. As has been amply demonstrated in the past, these relatively low-cost missions lead to new discoveries and rapid publication, and they attract and train outstanding young scientists who will contribute to future American strength in Science. The availability of ultra-long duration (~100 day) balloon flights coupled with the well-developed particle detector technology proven on balloon-borne instruments defines a solid path to these scientific goals.

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