Balloon and Space based Cosmic Ray Astrophysics

2010 Decadal Survey: Request for Information (RFI)

Submitted to Program Prioritization Panel (PPP)

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Summary (1 page)

The purpose of this RFI response is to outline some of the most important science questions cosmic-ray observations can address in the next decade, and to make the case that renewed investment in the discipline is not only justified, but vital. Rather than proposing a specific mission, we focus on particle astrophysics research, in general, that can be performed at the edge of space and beyond with balloons and spacecraft.

Lying at the intersection of particle physics, cosmology, and astronomy, cosmic-ray astrophysics probes some of the most exotic objects and phenomena in the universe. While much of traditional astronomy is concerned mainly with photons produced in fairly tranquil thermal processes, cosmic-ray science focuses on highly relativistic particles produced in the most extreme non-equilibrium environments in nature (e.g., supernova explosions, gamma-ray bursts, or active galactic nuclei). Measuring cosmic rays and connecting their properties to the production and radiation of highly energetic particles in these locations is an unique key to understanding the high-energy universe in general, and our local solar environment in particular.

In many cases, the most profound and ground-breaking results of the field have come via instrumentation on balloon and space-based platforms. By avoiding the obscuring effects of the atmosphere, balloon and space-based missions have made unprecedented measurements and are at the forefront of particle astrophysics. Despite this success, however, balloon and space-based cosmic-ray research is relatively under-funded compared to disciplines of equal impact, and there is a dearth of space missions. The last particle-focused mission was launched in 1997, but high-altitude balloons have sustained the field with a supply of new data. The key science goals we identify for this RFI are:

1. Nucleosynthesis: The origin of the elements. Measurements of cosmic rays, particularly the actinide elements and isotopic abundances of lower-Z nuclei, provide unique information on elemental yields from various types of supernovae, on particular nuclear processes, and on how freshly created elements are distributed throughout the Galaxy.

2. The nearest sources of cosmic rays. Observations of TeV electrons at Earth mean that nearby sources of cosmic rays exist. Improved sensitivity may confirm “features” in the cosmic-ray spectrum that reveal these sources and open a new era of “cosmic-ray astronomy.”

3. How do cosmic particle accelerators work? Relativistic particles exist throughout the Universe and cosmic rays contain the highest energy particles ever observed. Understanding how particle accelerators work is basic to understanding high-energy astrophysics.

4. What is the nature of Dark Matter? The detection of Dark Matter implies “new physics” and will require confirmation using different techniques. Cosmic rays explore a different channel from photon measurements and can play a critical role in addressing this great puzzle.

New technologies are emerging to help achieve these goals (and many others), the most significant being Ultra-Long Duration Ballooning (ULDB). The stable altitude and ~100-day flight durations of this new capability open doors to previously unrealized scientific opportunities. They also help mitigate the loss of the intended spacecraft for the Advanced Cosmic-ray Composition Experiment for the Space Station (ACCESS) prioritized in the 2001 Decadal Study. The technologies needed to complete ULDB would benefit greatly from a timely, modest investment that promises substantial scientific return in areas extending well beyond cosmic rays. The ultimate fruit of this new technology will be realized only if a parallel investment is made in the science instruments to use them.
Key Science Goals (5 pages)

Cosmic-ray astrophysics is on the verge of a period of great discovery. There is now convincing evidence from TeV γ-ray and X-ray synchrotron observations that cosmic-ray electrons are produced in young supernova remnants (SNRs) and the indication for cosmic-ray ion production in SNRs may soon come with Fermi (a.k.a. GLAST) and/or air-Cherenkov telescope observations. The sources of the highest energy cosmic rays are less certain, other than that they must originate from beyond the Milky Way Galaxy, but great progress in determining their origin has been made by the Auger and HiRes telescopes. These telescopes have shown that cosmic rays with energies above ~$10^{19}$ eV obey the Greisen-Zatsepin-Kuzmin (GZK) cutoff and may well be correlated with active galactic nuclei (AGNs). At lower energies, progress has been made in measuring the spectra of individual elements (e.g., Fig. 1), and long-duration balloon flights achieving multiple circumnavigations of the Antarctic continent (see Fig. 4), promise to extend these measurements to ~$10^{15}$ eV, close to the cosmic-ray “knee.” If sufficient resources are available in the next decade, the study of cosmic rays can address questions as important as any in astrophysics such as determining how the elements are created and distributed, identifying the nearest sources of cosmic rays, determining how cosmic-ray accelerators work, and contributing unique constraints in the search for “Dark Matter.”

While much of traditional astronomy is concerned with photons produced in fairly tranquil thermal processes, cosmic-ray astrophysics studies ultra-relativistic particles and the radiation they generate. These particles come from extreme, non-equilibrium environments such as supernova explosions, gamma-ray bursts, and AGNs.

Observing cosmic rays and connecting their properties 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 cutting edge activities are connected to many areas of astronomy and astrophysics, as described in our White Paper. In many cases, the most profound and ground-breaking results have come via instrumentation on balloon and space-based platforms that avoid the obscuring effects of the atmosphere. These missions have achieved unprecedented precision and accuracy in their measurements and we propose here a range of Science Goals where balloon and space-based exploration will have the largest impact.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Cosmic-ray energy spectra of individual elements from proton to iron. Figure is adapted from references found in Link to figure references.}
\end{figure}

1 Submitted to three Science Frontier Panels: Stars and Stellar Evolution (SSE); The Galactic Neighborhood (GAN); and Cosmology and Fundamental Physics (CFP).
1. **Nucleosynthesis: How are the elements created and distributed?** All elements heavier than boron are understood to be produced in stars, in 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. There are different types of supernovae; massive stars that undergo core-collapse explosions, white dwarf stars that undergo thermonuclear explosions, and perhaps coalescing binary neutron stars and/or black holes. These types produce elements and isotopes that can be distinguished from each other and from elements produced in normal stellar evolution. 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 events 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 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. The missions ACCESS, OASIS, CREAM, and Super-TIGER, discussed in the Technical Overview section, will provide unprecedented composition measurements and help reach this science goal.

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 randomizes arrival directions and prevents us from directly observing sources. However, recent observations suggest that local sources of cosmic rays may be identified as “features” in cosmic-ray spectra (e.g., the ATIC points in Fig. 2). 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.

   ![Fig. 2: Cosmic-ray electrons 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 from Aharonian et al. (2008).](image)
High-energy electrons moving through the galactic magnetic field lose energy rapidly due to inverse Compton and synchrotron emission. The observation of cosmic-ray electrons with energies above $10^{12}$ eV at Earth (e.g., Fig. 2) means there are sources near us in space and time. These nearby sources of electrons may produce nuclei as well. There have been reports of a 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 sources (e.g., SNRs) may produce spectra with different maximum energy and normalizations; (2) the observed total 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, such as ACCESS and CREAM discussed below. Firm identification of features in cosmic-ray spectra would be paradigm breaking, and it would represent an advance at least as significant as the recent detection of $>10^{12}$ eV photons from young SNRs by air-Cherenkov telescopes.

Ultra heavy nuclides (i.e., $Z > 29$) are another invaluable source of information about nearby sources. These neutron-rich nuclides are synthesized 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 $5 \times 10^7$ 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. CREAM and Super-TIGER are designed to provide this knowledge.
3. How do cosmic particle accelerators work? Understanding how nature’s highest energy particles are accelerated is one of the most fascinating questions in science. One of the main clues we have is the cosmic-ray energy spectrum measured at Earth. The most likely accelerators of cosmic rays below the “knee” near $10^{15}$ eV are shock waves in SNRs, although other sources such as pulsars and stellar winds will contribute. Extending accurate measurements of the elemental spectra shown in Fig. 1 by just one order of magnitude to $\sim 10^{15}$ eV, will help determine how Galactic accelerators work. The most likely mechanism at these energies is diffusive shock acceleration, which has undergone intense study because collisionless shocks are known to exist throughout the Universe and have been seen to accelerate particles in the heliosphere. However, other mechanisms, such as second-order Fermi acceleration operating in strong magnetic turbulence, or pulsar acceleration, are not excluded. These mechanisms make distinct predictions for spectral shapes and composition and these differences are most pronounced in the turnover region near the cosmic-ray knee. A critical component to unraveling the details of the source behavior is a sound understanding of the propagation effects which modify the particle spectra prior to their detection at earth. Only detailed, high-precision measurements of the secondary-to-primary ratios of cosmic-ray species can provide this information, and ULDB or space-based missions are the ideal platform for making them.

The Auger and HiRes investigations have shown that the highest energy cosmic rays beyond $\sim 10^{19}$ 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 $\sim 300$ 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 GZK neutrinos and gamma-rays would greatly help the understanding of the highest energy cosmic rays since they point back directly to where they were created. 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 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. The confirmed detection of GZK neutrinos by ANITA will further add to our understanding of the highest energy particles in the universe.

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 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? Dark Matter is one of the most exciting and important puzzles in all of physics. Cosmic rays explore a different channel from photon measurements and can play a critical role in addressing this puzzle, by providing the astrophysical context needed to complement accelerator measurements, or indeed, by outright discovery. The balloon-borne Advanced Thin Ionization Calorimeter (ATIC) experiment recently reported an excess of high-
energy cosmic-ray electrons (see Fig. 2) that might indicate an annihilation signature of Kaluza-Klein dark matter [Chang et al. 2008]. However, this is extremely tentative since a ‘boost factor’ of ~200 associated with non-uniform clumps in the dark matter distribution would be needed to support this explanation. This intriguing electron excess might instead come from a less exotic source, relatively close to the Earth, such as a previously unidentified pulsar, miniquasar, or supernova remnant. A related measurement was recently reported by the PAMELA satellite experiment: a significant enhancement in positrons up to ~ 100 GeV (see Fig. 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.

In both cases, only more sensitive observations of energy spectra and composition can determine whether the signals are of astrophysical or exotic origin. Indeed, the detection of Dark Matter implies “new physics,” and the results of any single experiment will require confirmation using instrumentation based on different techniques. In particular, magnetic spectrometers and experiments with redundant methods for rejecting overwhelming hadronic backgrounds are needed to provide the evidence necessary for extraordinary claims. Missions on long-duration balloon flights are essential for addressing this science. Further, if electron anisotropies are to be investigated over the entire sky, multiple flights covering different latitudes are also needed.

What needs to be done? Definitive measurements of cosmic rays to the knee and beyond: The vast range of cosmic-ray flux (see cover page) means that different detection techniques utilizing ground, balloon, and space-based instruments, must be used. Normalizing these techniques to each other is challenging but 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 large uncertainties exist in observations above 1000 GeV, but 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 exist and for reducing uncertainties in the critical transition region between galactic and extragalactic cosmic rays.

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 the Alpha Magnetic Spectrometer (AMS) will provide precision data to $10^{12}$ eV. This energy reach overlaps the threshold of ACCESS, which was studied extensively at the time of the last decadal survey [Astronomy and Astrophysics in the New Millennium (2001)] and endorsed as a “small initiative.” Many of its central goals, however, could be realized by a series of direct measurements with payloads on Ultra Long Duration Balloon (ULDB) flights. High-precision measurements of secondary-to-primary ratios, for instance, could have a dramatic impact at ~$10^{13}$ eV. For primary element spectra, the region around $10^{15}$ eV is the most critical and also the hardest energy to explore. Direct space and near-space measurements run out of statistics, whereas indirect ground-based measurements have difficulty resolving individual elements, and they have serious systematic problems caused by uncertainties in modeling hadronic interactions in the atmosphere. While direct air-Cerenkov methods may improve charge resolution in ground-based arrays (Kieda et al. 2001), good statistics near $10^{15}$ eV from direct measurements are required to calibrate the model dependent air-shower measurements that extend the spectrum to $10^{19-20}$ eV.
Technical Overview (5 pages)

This report details cosmic-ray measurement opportunities in the next decade, with a focus on practical approaches to making precise, direct measurements up to $\sim 10^{15}$ eV with satellites and balloons.\(^2\) Proposals to the 2010 Decadal Survey for addressing Ultra-high-energy cosmic rays with both ground-based and space-based instruments are being prepared separately. Balloon and space-based instruments can make direct measurements up to $\sim 10^{15}$ eV with accuracy limited only by the collection power, i.e., exposure time and aperture of the instruments. Such instruments are routinely configured with redundant and complementary detectors for particle-by-particle measurements of elemental charge and energy and pointing is not required. These technologies are ripe for tackling the Science Goals discussed above.

1. **Space Based Missions:** Two proposals to implement the ACCESS (Advanced Cosmic-ray Composition Experiment for the Space Station) mission were submitted to the most recent (2001) MIDEX Announcement of Opportunity (AO). One proposed the mission as planned by the ACCESS Formulation Study, i.e., launch on the Space Shuttle to the International Space Station (ISS) for three years of operation. The other proposed launching a comparable instrument on a Delta rocket. Both proposals were highly rated scientifically and technically, but neither was selected. In view of the NASA decision to phase out the Space Shuttle by the end of 2010, only the free-flyer version of this highest priority recommendation of the Cosmic Ray Assessment Group is viable in the next decade. No other mission under study would accomplish the ACCESS science goals in their entirety.\(^3\) We are not aware of any submission of ACCESS to the 2010 Decadal Study. ACCESS would address Science Goals 1, 2 and 3.

The Orbiting Astrophysical Spectrometer in Space (OASIS) is being studied as a medium class Astrophysics Strategic Mission. One of the conditions for its selection was that its study results would be submitted to the 2010 Decadal Study. OASIS would measure the composition of trans-iron elements and the spectra of electrons, both being cosmic rays produced within several thousand light-years of the solar system. The study was to determine the feasibility and cost of a mission comprised of the Energetic Trans-Iron Composition Experiment (ENTICE) to identify local acceleration sites of ultra-heavy cosmic rays and the High Energy Particle Calorimeter Telescope (HEPCaT) to identify local sources of electrons. Even with their focus on electrons, both HEPCaT and the Japanese CALorimetric Electron Telescope (CALET) planned (Torii et al. 2007) for the Japanese Experiment Module (JEM-EF) on the ISS would accomplish some of the ACCESS primary objectives by measuring elemental composition. But, neither has the collection power required to measure all $Z = 1$ - 26 elements up to $10^{15}$ eV with the statistics enabled by payloads employing transition radiation detectors (e.g., ACCESS). OASIS would address most of the Science Goals we list here.

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\(^2\) We note that the Alpha Magnetic Spectrometer (AMS) observatory is almost built, and it is on the NASA Space Shuttle Manifest for launch in September 2010 to the International Space Station. It will make detailed measurements of cosmic-ray nuclei ($Z = 1$ – 30), electrons and positrons, and antiprotons up to $\sim 10^{12}$ eV. Signatures of dark matter could be reflected by structure in its precision spectra of positrons and antiprotons, and its searches for anti-deuterium and anti-helium nuclei will be 10 to 100 times more sensitive than heretofore possible. The additional measurements needed beyond AMS require large payloads and investments beyond current Research and Analysis (R&A) grants.

\(^3\) It seems likely that a free-flyer mission to pursue the ACCESS Category A primary science objectives would be proposed in response to the next MIDEX AO, perhaps as early as 2010.
2. Ultra Long Duration Balloon (ULDB) missions: Long-duration balloon (LDB) flights, and ultra-long-duration balloon (ULDB) flights, when they become available, offer a proven, 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 MCF (million cubic feet) super-pressure balloon test flight launched in December 2008 and terminated in February 2009 after 54 days aloft, while on its third circumnavigation of Antarctica, shows the promise of this entirely new launch vehicle (Fig. 4). 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 important and cost effective observations of cosmic rays and in other areas as well including infrared and hard X-ray astronomy.

The frequent access to space provided by smaller space missions (e.g., Small Explorers-SMEX) has 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 at the top of the stratosphere per flight is now imminent.

2.1 CREAM (Cosmic Ray Energetics And Mass): The CREAM instrument was designed as a quarter-scale version of ACCESS to measure cosmic-ray elemental spectra using a series of balloon-borne experiments (Fig. 5). The goal was to extend direct measurements of cosmic-ray composition to the highest energies practical with long-duration and ultra-long duration balloon flights in Antarctica. The instrument meets the challenging and conflicting requirements of having a large enough geometry factor to collect adequate statistics for the low flux of high-energy particles, and yet stay within the 1000 kg mass limit for ULDB (~100-day) flights. It has charge identification and energy measurement systems capable of precise measurements of elemental spectra for Z = 1 - 26 nuclei over the energy range \(10^{11} - 10^{15}\) eV. It includes double layers of finely segmented Silicon detectors, scintillator based timing detectors, and an imaging Cherenkov camera for charge measurements. An ionization calorimeter and a transition radiation detector (TRD) are used for energy measurements. The silicon pixel detectors implement one of the two technological advances identified for ACCESS in the 2000 Space Science Enterprise Strategic Plan. New readout electronics for the gas-filled tubes in the CREAM TRD accomplish the other.

Fig. 4: A photograph of the 7 MCF super pressure balloon at float (upper) and its 54 day flight trajectory in Antarctica showing the turnaround of the polar vortex (lower). [http://sites.wff.nasa.gov/code820/uldb.html](http://sites.wff.nasa.gov/code820/uldb.html)
CREAM has achieved an exposure of 119 days in four flights, including the record-breaking 42-day flight of 2004-2005. This is the longest exposure ever achieved by a single balloon project, and it exceeds the original 100-day design goal for a single ULDB flight. The CREAM payloads have flown with all ULDB systems except for the super-pressure balloon. Each additional CREAM flight extends the reach of composition measurements to energies not previously possible, and ~10 ULDB flights would:

1. Test the validity of SNR shock models of cosmic-ray acceleration;
2. Determine parameters governing cosmic-ray confinement in the Galaxy;
3. Measure directly the composition and flux of ~10^{15} eV cosmic rays allowing calibration of energy overlapping indirect (air-shower) measurements.

The science objectives require spectral measurements of H and He for energies 10^{12} - 10^{15} eV and Li through Ni from 10^{12} eV/nucleon to as high in energy as their fluxes would allow, with an exposure great enough to measure spectra of C, O, and Fe to 10^{15} eV per nucleus. Like ACCESS, CREAM combines a calorimeter capable of measuring Z = 1 - 28 particles and a TRD capable of measuring Z = 3 - 28 particles to span the broadest possible range of atomic numbers and energies (Ahn et al. 2007). Only the calorimeter is capable of measuring the most abundant H and He at the highest energies, but its area must be limited to stay within an acceptable mass. The relatively low mass TRD can have a large collecting area, enabling it to see adequate numbers of elements heavier than helium. A substantial fraction of the cosmic rays can be measured in both detectors, thereby providing a direct inter-calibration for Z ≥ 3 particles.

For each of the primary elements, H, He, C, O, and Fe, it is necessary to detect at least ten events with energies greater than 10^{15} eV (if the energy spectra of these elements continue unbroken from the spectra that have been measured at lower energies). The energy resolution σ_{E}/E should be ~40% or better. It will be necessary to resolve boron (Z = 5) from carbon (Z = 6) when the B/C ratio is as low as 1%. This requires charge resolution of ≤ 0.2 charge units. Systematic errors in flux determination must be less than 20% to provide a definitive calibration of air-shower measurements. Since the flux varies steeply with energy, it is necessary to have systematic errors in energy determination < 10%. [Mass 1000 kg, Power 400 W.]

2.2. Super-TIGER (Super-Trans-Iron Galactic Element Recorder): Super-TIGER is a large-area instrument being developed to measure the abundances of 30 ≤ Z ≤ 42 elements with unprecedented individual-element resolution. It will test the emerging model of cosmic-ray origin in massive (i.e., OB) star associations, and models for atomic processes by which nuclei are selected for acceleration to cosmic-ray energies. This model is supported by the observed $^{22}$Ne/$^{20}$Ne and $^{58}$Fe/$^{56}$Fe overabundances in cosmic rays measured by the CRIS instrument on ACE (Binns et al. 2005), and by the ordering of the source abundances of refractory and volatile elements in cosmic rays measured by TIGER (e.g., Rauch 2008). These data indicate a cosmic-ray source with approximately 80% of the mass having the composition characteristic of the
Material of our Solar System, and 20% having a composition characteristic of outflow from massive stars in OB associations.

Super-TIGER will also accurately measure energy spectra of the more abundant elements of $14 \leq Z \leq 28$ at energies $0.8 \leq E \leq 10$ GeV/nucleon. These spectra will permit a sensitive test of the hypothesis that microquasars or other phenomena could superpose spectral features on the otherwise smooth energy spectra previously measured with less statistical accuracy.

Super-TIGER builds on the success of the smaller TIGER, successfully flown twice in Antarctica in 2001 and 2003, yielding a total of 50 days of data and producing the first well-resolved measurements of elemental abundances of the elements Ga, Ge, and Se. The interpretation of the TIGER data is limited, however, by the small number of events detected. Super-TIGER utilizes the same detectors and techniques as TIGER; plastic scintillator dE/dx detectors, Cherenkov counters with two different refractive indices, and scintillating fiber hodoscopes. Two Antarctic flights with a total of 60 days at float would obtain approximately an order of magnitude increase over TIGER in number of events detected.

Super-TIGER is also planned as a forerunner of the Energetic Trans-Iron Composition Experiment (ENTICE), currently being studied as part of OASIS, one of the NASA Astrophysics Strategic Mission Concept Studies. ENTICE would have sufficient exposure and resolution to measure even the rarest individual elements including the actinides, Th, U, Pu, and Cm.

**Mass 1800 Kg, Power 200 W.**

2.3. ANITA (Antarctic Impulsive Transient Antenna): The ANITA project seeks to observe neutrinos produced when ultra-high-energy cosmic rays interact with microwave background photons. It makes use of the very large target volume (several million km$^3$) of extremely radio transparent ice (attenuation lengths >1 km) to look deep into the ice sheet for neutrino interactions (see Fig. 6). Strong radio impulses are produced by coherent radio Cherenkov emission from the charge asymmetry in the particle cascades associated with the interactions: the Askaryan effect. Neutrinos above $\sim 10^{18}$ eV interacting anywhere within $\sim 700$ km of the balloon-borne ANITA payload can be detected. The neutrino signature would reflect the spatial and $z$-distribution of ultra-high-energy cosmic rays arising from exotic processes such as acceleration in $\gamma$-ray bursts, more conventional dynamo acceleration near AGN black holes, or exotic possibilities such as the top-down decay of early universe relics. ANITA completed its first science flight with 35 days aloft in January 2007 and its second flight of 30 days in January 2009.

Although the Greisen-Zatsepin-Kuzmin (GZK) cutoff may have been observed, the mystery surrounding the highest energy cosmic rays has not diminished, since there is no conclusive data on the nature of the sources. We may never directly detect their sources via charged-particle astronomy if they are accelerated in $\gamma$-ray bursts or close to the central engines in cosmologically distributed AGN. Neutrino measurements are critical in attacking this part of the problem.
problem, because every GZK neutrino detected must point back to a parent cosmic-ray source. Since the daughter neutrino momenta closely match that of the parent particles in the lab frame, their arrival direction is nearly identical to the source direction as observed from earth.

The ANITA payload is among the largest ever flown in the balloon program, measuring over 25 ft (8 m) high and about 18 ft (6 m) wide at the base. The flight weight, including the NASA-supplied supporting hardware, is about 2 metric tons, and power requirements are about 550 Watts. This power level supports the primary function of the payload electronics: the digitization of 80 high-speed radio receiver channels at 2.6 Giga samples per second whenever any radio impulse more than ~4 standard deviations above thermal background noise is detected. This low-power achievement is one of the enabling technologies for ANITA, since commercially-available data digitizers running at such high speeds would likely require several kilowatts of power to operate in this fashion. Once detected, the radio impulses measured by the entire antenna array are stored in onboard solid-state drives, and later analysis then reconstructs the direction of the impulse using techniques of radio-pulse-phase interferometry, yielding good angular resolution of about ~15 arcmin in elevation and ~50 arcmin in azimuth.

2.4. Examples of Future Missions: The ULDB platform would support investigations across astronomy and astrophysics, and other areas of science as well. Below are a couple of high priority cosmic-ray astrophysics measurements that would benefit greatly from ULDB flights.

**Precision Secondary Mission:** The spectrum of cosmic rays measured at earth is not the same as the spectrum produced at the sources. As cosmic rays propagate through the galaxy, their spectrum steepens and secondary elements are produced by collisions with the background gas. The effects of propagation must be determined to relate the measured cosmic-ray flux to the properties of the sources, and the best tools for this are accurate measurements of secondary to primary nuclei. A dedicated “Precision Secondary Mission” comprised of a low-energy-optimized transition radiation detector and multiple Cerenkov detectors with high-resolution charge detectors would be an ideal ULDB mission. Such a mission could focus on deep measurements over a smaller energy range since mapping the secondary/primary ratios with high-statistics measurements at lower energies can be more constraining than lower statistics measurements at higher energies. [ULDB flight time ~ 100 days]

**High-Energy Electron/Positron Mission:** Recent results from PAMELA and ATIC have highlighted the need for background-free measurements of electrons and positrons at high energies. Magnetic spectrometers are ideal instruments for such a mission, and a balloon-borne payload flying in either hemisphere could make an immediate impact on Dark Matter searches. Even a relatively simple configuration employing a permanent magnet with high-resolution tracking would provide good electron spectral measurements to 1 TeV, with positron fractions to 30 GeV. The importance of Dark Matter demands multiple observations and the statistics and energy range obtainable with balloons are high enough to test the conclusions drawn from previous measurements. A magnet spectrometer could also yield high-quality measurements of antiprotons at ~100 GeV and possibly even of $^3$He/$^4$He in the ~100 GeV/n range, much higher than previously measured. [LDB or ULDB, 7-100 Days]
1. Trajectory Modification System for Ultra-Long-Duration Balloon Missions

While orbital platforms are still the optimum place for many measurements, building and launching space instruments is far too costly to afford the full range of needed scientific investigations and/or development of new instrument technologies. The ability to fly high-altitude super-pressure balloons for months at a time offers a multitude of opportunities for high priority science investigations. Balloons are particularly suitable for research areas such as cosmic microwave background, X-ray, gamma-ray, and cosmic-ray investigations, where being above 99.5% of the Earth's atmosphere is essentially as good as being in space. Experiments in these areas generally need to measure very low photon or particle fluxes, so the product of detector-area and flight-duration is often critical. Balloons meet this requirement by accommodating relatively large detector masses and/or areas, as well as flight times up to several weeks, and eventually even months when super-pressure ballooning becomes operational.

It has been realized since the inception of ultra-long-duration ballooning (ULDB) that some level of trajectory modification would be required to realize its full potential. This technology, which is currently only at the very conceptual design stage, is important for several reasons. In particular, payloads need to be recovered on dry land in accessible locations, and heavily populated regions must be avoided due to safety concerns. Geopolitical concerns about over-flights of sovereign territories are of special concern for global ULDB flights. In latitude corridor maintenance mode, the trajectory modification system would need to impart a relative wind velocity of no less than 1.3 m/s (approximately 1° of latitude per day), in addition to providing an acceptable level of control authority on demand.

Two concepts that have undergone initial feasibility studies are: (1) The StratoSail balloon guidance concept of Global Aerospace Corporation based on a light weight “Wing & Rudder” suspended below the balloon on a long (2 – 3 miles) tether to achieve a balloon velocity change from different wind speeds/directions at different altitudes; and (2) a solar-powered electric-motor-propeller system to generate enough thrust for operational control authority within the constraints on launch size and power consumption. While technological challenges exist for both the passive and active system concepts, it is widely recognized in the scientific ballooning community that there is a high priority need for modest trajectory modification, which would greatly expand the value of balloon science by enabling ~100-day flights with many circumnavigations of the Earth.
2. ULDB-Radio Antenna For Balloon Based Ultrahigh Energy Neutrino Observations

The Antarctic Impulsive Transient Antenna (ANITA) mission has established the baseline goal of ultra-high-energy neutrino observations: detecting and characterizing the cosmogenic neutrinos that arise from the Greisen-Zatsepin-Kuzmin (GZK) absorption of the ultra-high-energy cosmic rays throughout the universe. ANITA has demonstrated that radio methodologies that exploit Askaryan’s coherent Cherenkov radiation from ultra-high-energy showers in Antarctic ice are a powerful approach toward this goal. Synoptic viewing of the ice sheets from balloon altitudes, combined with precision location of the interaction vertices in the ice through pulse-phase interferometry, has defined the state-of-the-art in this field. However, the current ANITA payload is fundamentally limited in its radio collecting area by the size of the payload envelope, which sets the effective energy threshold for observing GZK neutrinos. Improvement in neutrino sensitivity, as measured by an increase in the detected neutrino rate, scales roughly as the square of any lowering of this energy threshold. Thus, the primary science and technology driver for ultra-high-energy neutrino observations from balloon payloads is the need to increase the effective aperture size of the antennas.

A range of techniques has been explored to accomplish this goal, e.g., large phased arrays of low-gain antennas that could be deployed or unfolded on orbit, thereby creating large synthesized apertures once they are digitally combined. However, the improvement in such cases goes only as the square root of N, the total number of antennas that “see” a particular direction. The current ANITA aperture is of order 1.5 square meters for the 4-5 antennas that share any given arrival direction for a neutrino impulse. To improve the energy threshold by a factor of 10, placing it in the heart of the expected GZK neutrino spectrum, would require ~100 times the collecting area, i.e., about 20,000 phased low-gain antennas. Adapting such an enormous array to the size, weight, and power requirements of a balloon payload is indeed a daunting challenge.

A more promising approach would take advantage of the largest possible space available in a balloon system: the balloon itself. If a balloon can be modified to support reflective elements at radio frequencies, along with subsystems that provide support for feed array elements, the natural quasi-spherical geometry of the balloon may be utilized to provide directed focusing. The corresponding high-gain systems would not require digital phasing, so they would not pay a penalty in the number of antennas. Reflective elements have been incorporated into balloons via so-called “radar-tape” in the past, but the technology to extend such reflective elements to a significant portion of the balloon must still be developed. In addition, an even greater challenge is the positioning of the feed array for such a reflector. Since the foci for balloon-surface reflective regions are in the interior of the balloon, the technology for positioning, powering, and obtaining signals from receiver elements within the balloon would be required. A possible alternative would be to find a way of redirecting the radio radiation to the external surface or base of the system using interior sub-reflectors. Each of these ideas, while they are being delineated as concepts and even modeled at some level, is currently beyond the state-of-the-art.

The scientific payoff for development of this technology is the possibility of creating a balloon-borne radio telescope with an aperture of several thousand square meters to survey more than a million square kilometers of Antarctic ice continuously for as much as 100 days using ultra-long-duration balloons. This could in turn enable as much as a hundred-fold increase in the net sensitivity of next-generation ultra-high-energy neutrino detectors.
3. Arc Second Pointing System for Balloon Missions

NASA’s Scientific Balloon Program affords researchers the opportunity to conduct research in a near-space environment. Flight altitudes of 120k feet are typical, which place the balloons above more than 99.5% of the earth’s atmosphere. There is significant interest from the science community in a reliable balloon-borne fine pointing system. Potential science efforts include the areas of extra-solar planetary finders, cosmic background exploration, astronomy at a variety of wavelengths, high-energy astrophysics, upper atmospheric science, and ultra-high-energy neutrinos.

In order to successfully utilize balloons as platforms for such science investigations, a means of pointing the instrument at the intended target within the required accuracy and jitter limits is required. A fine pointing system that can accept a wide range of payloads is needed, including sub-arcsecond stability of a balloon-borne telescope viewing a celestial target. Suspension of these heavy instruments from a balloon subjects them to torques that create significant challenges to fine pointing.

Laboratory feasibility work already completed by the Balloon Program (e.g., DeWeese & Ward 2006) indicates that a system capable of adequately rejecting disturbances can be made robustly stable with significant design margins. With modest resources a sub-arcsecond pointing stability for a large balloon-borne instrument pointing at an inertial target can be achieved.

References:
DeWeese, K. & Ward, P., 36th COSPAR (Beijing), 2006

Cosmic-Ray Astrophysics web site: http://cosmicray.umd.edu/vision2020/
Activity Organization, Partnerships, and Current Status (1 page)

The NASA Astrophysics Division manages the Balloon Program on behalf of the Science Mission Directorate. The Balloon Program Office (BPO) at the Goddard Space Flight Center (GSFC) Wallops Flight Facility (WFF) manages flight operations through a competitively selected contract to operate the Columbia Scientific Balloon Facility (CSBF) in Palestine, Texas. New Mexico State University Physical Science Laboratory holds the current contract. A Balloon Working Group (BWG) chaired by the GSFC Balloon Project Scientist and comprised of representatives from the user disciplines advises the BPO on implementation matters. NASA supports both conventional balloon flights and long duration balloon campaigns. The former are launched from the CSBF home site or from the semi-permanent launch site in Fort Sumner, New Mexico. Long-duration campaigns are conducted in Antarctica, the Arctic region (e.g., Sweden to Canada), and at mid-latitudes (e.g., Australia to/from South America). The NSF Office of Polar Programs provides logistical support for the Antarctic campaigns.

Scientific ballooning has made important contributions to NASA’s science program, both directly with science from measurements using balloon-borne instruments and indirectly by serving as a test platform for instruments being developed for subsequent use on spacecraft. Balloons provide access to the space radiation environment, above 99.99% of the water vapor in the atmosphere, to conduct scientific experiments and/or test flight instrumentation in a wide range of scientific disciplines. They frequently offer the only flight opportunity for investigations that require large-aperture, heavy payloads, due to the lack of other suitable launch vehicles and/or cost considerations. The primary users of NASA’s balloon carriers are members of the astrophysics community, with solar and geo-space communities being occasional users. Proposals are solicited in annual Research Opportunities in Space and Earth Science (ROSES) announcements. Long-duration balloon investigations have also been solicited as Missions of Opportunity in Explorer (UNEX, SMEX, MIDEX) Announcements of Opportunity (AO). Several hundred PhD degrees have been awarded for balloon-borne investigations.

Current technology development is focused on the first new balloon since the conventional polyethylene balloon with integral load tapes was patented in 1950. Balloons that have been used to date for both conventional and long-duration balloon (LDB) flights are “zero-pressure,” meaning that they are vented near the bottom to the outside so the balloon pressure is in equilibrium with the atmospheric pressure at that point (zero differential pressure). The super pressure, ultra long duration balloon (ULDB) stabilizes the float altitude and extends the flight duration to 100 days or more. An effective balloon trajectory modification system is needed to facilitate the extended flights, avoid no-fly zones, and aid in recovery of the payloads. Other Technological studies underway include an arc-second pointing system to accommodate scientists wanting, for example, to conduct balloon-borne searches for extra-terrestrial planets.

The following quotes were taken from the June 2008 BWG report: “Congratulations for great advances: Solution to chute shock problem, Rip stitch decelerator, and the problem of dragging payloads! The development of the mini-SIP will enable many new small science investigations. There has been a major step forward in solving the deployment problem for the lobed design (super pressure balloon). Big improvements in fabrication and QA at Aerostar, and the three flight capability in Antarctica! We saw excellent video data and other instrumentation data from recent test flights. We cannot remember a meeting with so much positive news!”

4 An average of ~30 balloon missions/year were flown in the 1990’s, with ~15 missions/year flown in the 2000’s.
Activity Schedule (2 pages)

Space and balloon-borne experiments have produced a steady stream of cosmic-ray science results. Low-energy particles have been studied with satellite detectors since the dawn of the space age, while stratospheric balloons have provided all of the direct information we have on higher energy cosmic rays. Larger aperture space missions with long exposures to observe the lower fluxes of the rarer and/or higher energy particles are needed for major advances in the field, both from the standpoint of new data and from the perspective of priority within the funding agencies. The AMS observatory scheduled for launch to the Space Station in September 2010 will make detailed measurements of electrons, positrons, antiprotons, as well as Z = 1 – 30 nuclei (with isotopic resolution for the more abundant elements) up to ~10^{12} eV. Its precision spectra of positrons and antiprotons could reflect signatures of dark matter, and its sensitivity to anti-deuterium and anti-helium will be 10 to 100 times better than previous searches. A free-flyer version of the ACCESS mission may be proposed in response to the next MIDEX AO that would have a threshold that overlaps AMS data and an energy reach up to ~10^{15} eV. The OASIS Astrophysics strategic mission concept, one of 19 selected in early 2008, has been submitted to the Astro2010 Decadal Survey to explore nearby origins of ultra-heavy nuclei and electrons in cosmic rays.

In contrast to the near-dominance of cosmic-ray instruments on early space missions, e.g., the Pioneers, Voyagers, and Ulysses, there is currently a dearth of cosmic-ray space missions. The Advanced Composition Explorer (ACE) launched to the L1 LaGrange point in 1997 was the last particle-focused mission selected and developed by NASA. 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: only the latter is included in the current astrophysics portfolio. Cosmic-ray astrophysics has benefited greatly from NASA-supported balloon missions selected competitively via annual ROSES/APRA solicitations, as well as selections by other countries and other agencies in the U.S. The term “balloon mission” is indeed appropriate for most of the cosmic-ray investigations supported within APRA, because they are similar in size and many other respects to space flight missions. Most missions are carried out by Principal Investigators that lead collaborations of 2 - 7 institutions. They are typically reviewed every three years, although the average lifetime for an individual balloon mission is approximately 6 – 11 years.

Cosmic-ray data extending beyond 10^{14} eV from long-duration balloon (LDB) missions in Antarctica now overlap the indirect ground based observations extending to the highest energies beyond 5 x 10^{19} eV. Cosmic-ray instruments on super-pressure balloons could make direct observations up to the spectral “knee” region during the coming decade. It would take ~10 ULDB flights of CREAM to reach that goal, i.e., a decade at one flight per year. A specially designed support system to provide power, telecommunications, command and data handling, mechanical structures, thermal management, and solar array pointing has flown successfully for ~120 days on four LDB flights of the CREAM instrument, which was developed as the ULDB-Demonstration payload. The outstanding success of these LDB missions is attributed to their use of all ULDB systems except for the balloon vehicle.

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5 The next MIDEX AO is expected in 2010-2011, but it should be noted that the Explorer schedule has been unpredictable and unreliable for a number of years. Selections for the last MIDEX AO occurred in 2002. The AO for the current SMEX cycle was released in late 2007, down-selections are currently in progress, and selections are expected in mid-2009. The last SMEX selections occurred in 2004.

6 Research Opportunities in Space and Earth Science / Astronomy and Astrophysics Research and Analysis.
Given the recent rate of progress and budget outlook, demonstration of the ULDB vehicle with the 1000 kg CREAM payload on the 22 million-cubic-feet (MCF) balloon is expected in 2011-2012. Successful demonstration of the ULDB capability will place world-class science within reach of a large community of scientists in a wide range of disciplines. Some level of trajectory modification will be required to realize the full ULDB potential, and the feasibility of a trajectory modification system is under investigation. Payloads need to be recovered on dry land in accessible locations, and heavily populated regions must be avoided due to safety concerns. Geopolitical concerns about over-flights of sovereign territories are of special concern for global flights. As illustrated in Table 1, this new capability is expected by 2015, and it would allow sophisticated payloads to be flown for long periods at virtually any latitude and at nearly constant float altitude, thereby enabling science investigations not possible on current balloon platforms. In the meantime, science flights could occur on the smaller 7, 14, and 22 MCF balloons fabricated and tested in the stepwise development of this new capability.

<table>
<thead>
<tr>
<th>Fiscal Years</th>
<th>14 MCF Operational</th>
<th>22 MCF Operational</th>
<th>125 KFT Operational</th>
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</thead>
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<tr>
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<td>22 MCF Test Flight</td>
<td>125 KFT Test Flight</td>
</tr>
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<td>FY 2010</td>
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<td>22 MCF Test Flight w/ Science</td>
<td>125 KFT Test Flight w/ Traj Ctrl</td>
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<td>FY 2011</td>
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<td>22 MCF Science Demo Flight</td>
<td>125 KFT Test Flight</td>
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<td>FY 2012</td>
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</table>

Table 1: Current schedule for ULDB development. Here, MCF stands for million cubic feet and KFT stands 1000 feet altitude. The table is courtesy of Balloon Program Office, NASA Wallops Flight Facility.
Cost Estimates (3 pages)

With its current annual budget of ~$25M, the Balloon Program Office (BPO) supports ~15 conventional flights of about one-day duration from Palestine, TX or Ft. Sumner, NM, one polar Long-Duration Balloon (LDB) campaign to Antarctica, and a LDB campaign to either Kiruna, Sweden or Alice Springs, Australia. Each of these LDB campaigns has the capability for two to three balloon flights. The BPO also carries out a research and development program to advance the capabilities of scientific ballooning. This includes the phased development of super-pressure ballooning, starting with relatively small balloons leading to a balloon large enough to carry a 1-ton science instrument to 33.5 km by 2011-2012. The current BPO budget is inadequate for sustaining this program. Enhanced funding will be required to bring the super-pressure ballooning technology to fruition to support an appropriately enhanced science program.

The scientific instruments flown by the BPO are funded by grants to investigators in competition with other users of NASA’s Supporting Research and Technology (SR&T) program, also known as the Research and Analysis program. The investigations are selected by peer review of proposals submitted in response to annual ROSES solicitations. There is no specific allocation for balloon investigations, but the current year funding for development of balloon instruments and analysis of data is ~$15M across all disciplines, and it has been at approximately that level for several years. The typical time from selection of a new instrument to its first flight is three to five years, depending on its complexity. This relatively short time required for development of balloon-flight instruments makes ballooning an ideal place for training graduate students and young scientists. A significant strength of the balloon program is that the science is selected by peer review, thereby providing opportunity for new ideas to be developed that were not foreseen in long-range strategic plans or roadmaps. A serious weakness is that the SR&T funding levels for payloads are inadequate for developing some of the sophisticated balloon-borne missions most capable of advancing key elements of strategic plans.

Reliable Funding Source Needed for Balloon-Borne Instruments

The LDB capabilities opened a new era in scientific ballooning as they matured over the past two decades into a reliable platform for achieving significant amounts of observing time in a near-space environment. The LDB platform is particularly cost-effective for its science return. But, in spite of the substantial number of highly rated investigations proposed, there has been a significant decrease in the number of instruments funded. This has threatened the viability of the balloon program, which depends on there being a steady stream of orders to the balloon manufacturer and flights for the CSBF launch crew.

Significant scientific opportunities are enabled by the increased ballooning capabilities, and the natural evolution is toward increasingly more sophisticated and more expensive instruments. Supporting enough payloads to satisfy the proposal pressure is already beyond the scope of the current SR&T budget. Furthermore, some proposed LDB instruments are ambitious enough to be treated like small space missions rather than SR&T investigations. There is no viable means for funding such payloads, due to the large gap between funding levels in the SR&T program and the Explorer program. The University Class Explorer (UNE X) program, for example, would offer an intermediate range, competitive approach to address this large gap. It would allow NASA to utilize fully the mature LDB launch capability, while growing the ULDB capability for maximum science returns.

Table 2 shows that the budget for science instruments would need to ramp up to about $18M - $20M per year to start one new UNEX-equivalent balloon mission per year. The numbers used in this table are based on the actual costs for six balloon payloads proposed as LDB Missions of
Opportunity to the UNEX, SMEX, and/or a MIDEX AO.\textsuperscript{7} They were proposed as full-cost missions, including incremental costs for mission management by the Balloon Program Office (BPO); balloon flight support equipment; and balloon flight operations. Given the BPO management, flight support equipment, and operations from the Balloon Program, these estimated costs should be more-or-less valid also for ULDB science instruments. The BPO costs have been deducted from the proposed costs to get a realistic estimate of the average costs to build a new instrument and fly that average payload, followed by analysis and publication of the data. The budget model assumes three years of instrument development from selection to the first flight, with one new mission start each year. A re-flight of the instrument could occur about two years after the first flight, but the cost for that re-flight is not included in the table. Re-flights opportunities could be selected competitively via the SR&T/R&A program.

<table>
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<td>4th Mission</td>
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Table 2: Budget model to select one new LDB/ULDB payload annually. All numbers are in millions of dollars.

Super-Pressure Balloons: The Path to Future Science

In virtually every scientific area the scientific return is greatly enhanced by increased flight duration, which provides longer-integration time for observation of weak sources, the ability to survey more sources, the ability to observe temporal variations, etc. The extension from conventional flights of one or two days to LDB flights of two to six weeks opened doors to previously unrealized scientific capability. Likewise, the extension from LDB flights of a few weeks to ULDB flights of a few months using super-pressure balloons will greatly expand scientific opportunities for a fraction of the cost of a space mission. As recognized and recommended by the 2001 Astronomy and Astrophysics Decadal Survey, this capability would make balloon science truly competitive to orbital missions for some areas of investigation.

NASA has recently achieved promising breakthroughs in understanding the requirements for successful fabrication and deployment of super-pressure balloons. Tests in airship hangers, followed by deployment tests at float altitude have clarified the technology needs. Enhanced

\textsuperscript{7} The numbers in this table were derived from a NASA Headquarters presentation to the February 24-25, 2005 Structure and Evolution of the Universe Subcommittee meeting. They have been inflated by 25% to convert them from 2004 dollars to current-year dollars.
funding could now bring this new technology to fruition. First, and foremost, it would enable LDB flights at “mid-latitudes,” in addition to the Antarctic and Arctic flights. The current super-pressure technology makes it likely that one-ton science payloads could be flown for ~15 days from South America to Australia or vice versa without encountering over-flight safety issues. The capability for modest trajectory control to avoid latitude drifts over major population areas would greatly expand the science return by enabling 100-day flights with multiple circum-Earth “orbits.”

**Trajectory Modification**

The ability to modify the trajectory of a balloon, even if limited to steering it a few degrees off the direction that the winds are carrying it, will be necessary to utilize fully the capabilities of both super-pressure balloons and conventional zero-pressure balloons. Both LDB and ULDB flights face the possibility of premature cut-down if winds are carrying the balloon toward a heavily populated area, where safety requirements prohibit over flight. Flight controllers could steer flights away from such areas if they have the ability to modify a balloon’s trajectory.

Long-duration flights of zero-pressure balloons over Antarctica take advantage of the stratospheric winds that carry the balloons around the South Pole in about 10 to 15 days. There have now been several Antarctic flights of approximately thirty-day duration in two rounds of the Pole, and one traveled three times around the Pole in 42 days. Most of the instruments flown over Antarctica would benefit from the longer flights offered by two, three, or more revolutions. However, some flights are not permitted to fly around more than once, because a northerly component to the (generally westward) winds at float altitude make it likely that the balloon would drift off the continent, thereby making instrument recovery impossible. Given the ability to steer a flight trajectory by a few degrees could ensure at least two or three revolutions.

Table 3 shows the anticipated costs by fiscal year to complete the ULDB development, including completion of the 22 MCF balloon for the ULDB Demonstration flight at 110,000 ft, increasing the altitude to 125,000 ft, and incorporating trajectory modification.

<table>
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<tr>
<th></th>
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</tr>
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<td>Subtotal SP Balloons</td>
<td>4.7</td>
<td>7.3</td>
<td>10.1</td>
<td>10.1</td>
<td>8.7</td>
<td>4.0</td>
<td>4.0</td>
<td>4.1</td>
<td>4.0</td>
<td>4.0</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Table 3: Anticipated costs (in millions of dollars) by fiscal year to complete the ULDB development. Table courtesy of Balloon Program Office, NASA Wallops Flight Facility.

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8 Mid-latitude LDB flights are essential to ensure nighttime and/or full sky coverage for several science programs directly in support of the Beyond Einstein Program, e.g., the Inflation Probe and Black Hole Finder Probe.