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Nuclear Physics B (Proc. Suppl.) 113 (2002) 95–102

NUCLEAR PHYSICS B
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High Energy Cosmic Ray Composition

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Cosmic rays are understood to result from energetic processes in the galaxy, probably from supernova explosions. However, cosmic ray energies extend several orders of magnitude beyond the limit thought possible for supernova blast waves. Over the past decade several ground-based and space-based investigations were initiated to look for evidence of a limit to supernova acceleration in the cosmic-ray chemical composition at high energies. These high-energy measurements are difficult because of the very low particle fluxes in the most interesting regions. The space-based detectors must be large enough to collect adequate statistics, yet stay within the weight limit for space flight. Innovative approaches now promise high quality measurements over an energy range that was not previously possible. The current status of high energy cosmic-ray composition measurements and planned future missions are discussed in this paper.

1. INTRODUCTION

Cosmic rays are the product of energetic processes in the universe, and their interactions with matter and fields are the source of much of the diffuse gamma-ray, x-ray, and radio emissions, as well as most of antiprotons that we observe [1]. We have good reason to believe they are intimately connected with the enormous release of energy in supernova explosion, and we know of no other process in the Galaxy that could provide the energy required to sustain the galactic cosmic-ray intensity. The most compelling evidence that supernova remnants are common sites for shock acceleration of electrons comes from recent observations of non-thermal X-ray spectra from several shell-type remnants [2]. However, no firm observation of supernova remnants has yet been made that gives evidence for the acceleration of protons and nuclei. Furthermore, the overall energy spectrum of cosmic rays follows a power law in energy that continues more than 5 orders of magnitude beyond the highest energies thought possible for production in supernova. The observed overall intensity of cosmic rays is shown in Fig. 1 [3], which covers the range from 10^9 eV to at least 10^{20} eV.

Due to their high flux, low energy cosmic rays have become relatively well understood. Most cosmic rays are the protons and helium nuclei (>90%), but there are also heavy nuclei (essentially

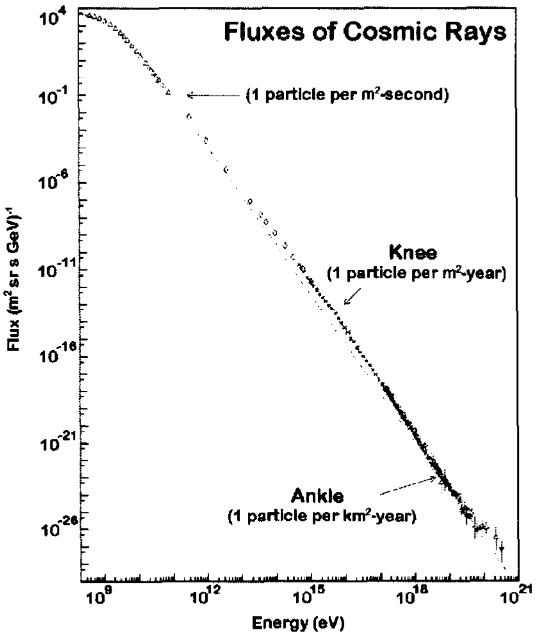

Figure 1. The flux of all cosmic rays vs. the total energy per particle [3].

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PII S0920-5632(02)01827-3

all the elements in the periodic table) and electron components. With notable exceptions, the cosmic ray composition is similar to that measured in the solar system.

2. COSMIC RAY ACCELERATION

Over the past two decades, theorists have developed a convincing theory of diffusive shock acceleration by supernova blast waves that naturally accounts for the essential features of most relativistic particles in the Galaxy. Shock waves are observed to be the dominant particle acceleration process within the heliosphere, and they are believed to be prevalent in astrophysical plasmas on all scales throughout the universe. It is characteristic of diffusive shock acceleration that the resulting particle energy spectrum is much the same for a wide range of parameters, or shock properties. This spectrum, when corrected for leakage from the galaxy, is consistent with the observed spectrum of galactic cosmic rays.

The shock-accelerated particles pick up a small increment of energy each time they cross a shock in a diffusive, random-walk process. The maximum particle energy depends on the magnetic field associated with the shock and on how long the acceleration mechanism acts. For a supernova shock the time and distance scales greatly exceed the scales encountered in the heliosphere, so much higher particle energies are attained. However, supernova acceleration is limited by the time taken for the blast wave to propagate outward and weaken to the point that it is no longer an efficient mechanism. The nominal energy limit is about Z x 10^{14} eV, where Z is the particle charge. This implies that the elemental composition would begin to change beyond about 10^{14} eV, the limiting energy for protons, with heavier nuclei having correspondingly higher energy limits. The iron nuclei spectrum would reflect this change at an energy 26 times higher than for protons. This is nowhere near the maximum energy shown in Fig. 1, but it is intriguingly close the "knee" feature observed by many air shower experiments around 10^{15} eV. The limit to the supernova acceleration process would be reflected by a characteristic change in the elemental composition between the limiting energies for protons and iron, i.e., between ~10^{14} eV and 2.6 x10^{15} eV. It has long been known that the all-particle cosmic-ray energy spectrum is somewhat steeper above 10^{16} eV than it is below 10^{14} eV. In Figure 2 this spectral-steepening, the so-called "knee" around 3 x 10^{15} eV is emphasized by multiplying the flux by an energy power law. Whether and how the knee structure is related to the mechanisms of acceleration, propagation, and confinement are among the major current questions in particle astrophysics.

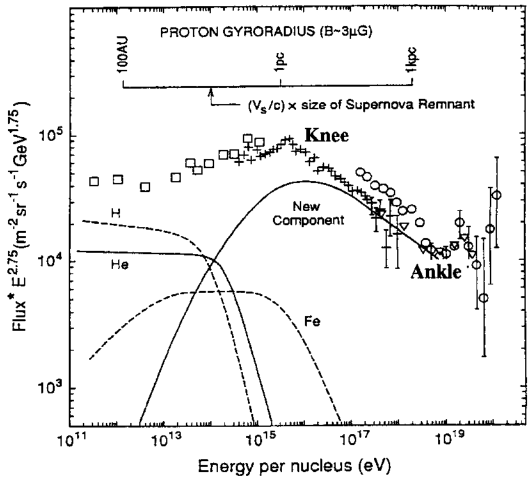

Figure 2. The spectral "knee" and "ankle" in the all-particle spectrum [4].

3. GROUND-BASED DATA

The data shown in Fig. 2 are mainly obtained from ground level observations of air showers, which measure the energies of the incident cosmic rays but do not determine their elemental identity. The ground based cosmic ray studies are hampered by insufficient knowledge of the hadronic interaction properties of the cosmic-ray particles with air nuclei and the production of secondary particles at energies above the available collider energies. Various assumptions and phenomenological models are devised to extrapolate quantities such as interaction cross-sections and pseudo-rapidity distributions to the relevant energies. Modern air-shower arrays are also equipped with complementary sets of detectors, such as arrays of scintillators, air Cherenkov detectors etc., to measure simultaneously as many air-shower parameters as possible, in order to reduce the model dependence in the energy reconstruction. Some of the methods that used to determine the shape of the differential energy spectrum are dependent on an accurate knowledge of the mass composition. The composition-sensitive shower observables (e.g., shower maximum location) are analyzed in an attempt to infer the mean primary mass as a function of energy near the knee region. Figure 3 [5], which summarizes various analyses, illustrates the wide range of answers that result due to all the uncertainties inherent in these techniques. Note that the iron-dominant mass composition above the knee, which is predicted from the super nova shock acceleration model, is not evident in these data.

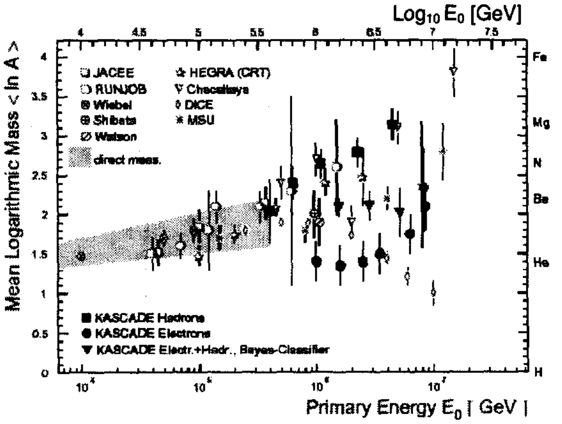

Figure 3. The mean mass of cosmic rays inferred from air shower measurements. The shaded area indicates direct measurements [5].

4. SPACE-BASED DATA

By flying particle detectors on spacecraft or high altitude balloons, cosmic rays can be measured directly. In this case, both the primary cosmic ray particle energy and its identity can be determined unambiguously. However, the energy reach with this measurement technique is much lower than the ground based indirect measurement, because the collecting power is limited due to the limited detector size and exposure time. Figures 4 and 5 show currently available composition data from direct measurements. The statistics are low and the uncertainties are large (in addition to the shown statistical uncertainties there are systematic uncertainties), but if we take the data at the face value, Fig. 4 shows a rather unexpected behavior: The H spectrum is almost flat (i.e., $E^{-2.75}$ spectrum), while the He continues to increase (i.e., about $E^{-2.65}$ spectrum). If the spectrum of He and heavier ions is flatter than that of H, as is suggested by current data, then there is serious disagreement with the simple theory of cosmic-ray acceleration in SNR shocks. This behavior could be interpreted as evidence for two different types of sources or acceleration mechanisms for H and He [6].

At the highest energies in Fig. 4, near 40 TeV, the proton spectrum from a certain data set appears to roll-off or bend, but at an energy that is about a factor of 2 below the expected cut-off for supernova remnant shock acceleration discussed above. Note that He shows no tendency to change slope, within the limited statistics, to the highest energies shown. A bend in the proton spectrum had been reported previously [7] to occur above ~2 TeV, which is likely to be due to the backscatter effect in the charge measurement [8].

If the proton spectral bend is real, it is likely

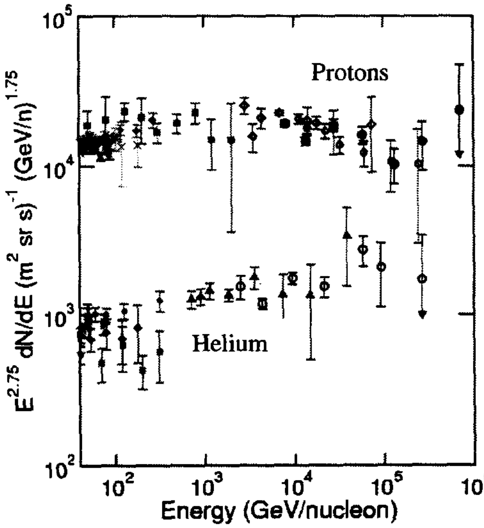

Figure 4. Compilation of proton and helium data from direct measurements.

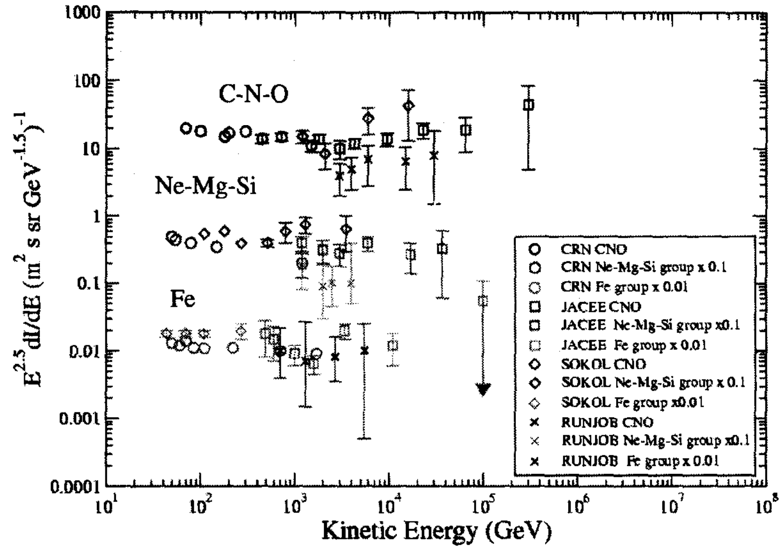

Figure 5. Compilation of heavy ion data from direct measurements.

due to some "cutoff", and it may well be related to the "knee" feature. However, the roll-off energy of protons in Fig. 4 is an order of magnitude below the "knee" seen in the all-particle spectrum. Recent data from magnet spectrometers (AMS [9], BESS [10], CAPRICE [11] etc.) confirmed the proton flux is about a factor of 2 lower than the previous calorimeter based measurement [12] at about 100 GeV. The extrapolation of this flux to higher energy is much lower than the high energy flux (JACEE [13] etc.) unless the spectral shape is much flatter than previously measured. Above 2 TeV, most data are attributed to emulsion-based, passive calorimetry. In this energy region, previous and current data are in some disagreement: JACEE [13] has reported a difference in the spectral indices for H and He, but RUNJOB [14] does not see such a difference. Both composition measurements are limited to charge groups using the emulsion and x-ray film techniques. These passive techniques limit the exposures because of the integrating effects of background. Studies of long space-based exposures using these techniques require frequent replacement of the emulsion plates and x-ray films.

It is clear from Fig. 5 that there is an overall trend for the spectra of the groups of heavier elements to be flatter than the proton spectrum. They also appear to become flatter with increasing energy. Specifically, the spectral slopes at higher energies seem to be close to values around 2.5 to 2.6, i.e., significantly flatter than the lower energy values reported by CRN [15] and HEAO [16]. It has been suggested that the flattening of all the heavier nuclei spectra could be explained by a less severe decline in the escape length above 1 TeV/nucleon.

The detailed energy dependence of the elemental spectra, measured to as high an energy as possible, holds the "key" to understanding the acceleration (and galactic propagation) for the bulk of the cosmic rays, i.e., those at energies below the knee in the all-particle spectrum. Note even the most dominant (> 90%) components, H and He nuclei, have statistics that could only detect a bend below about 20 TeV. All the plots show only statistical uncertainties. There are additional systematic errors not shown that make it difficult to prove the Supernova acceleration theory of cosmic rays with the current data.

5. MEASUREMENT TECHNIQUE

Direct measurements of high-energy cosmic-ray composition are difficult because of the very low particle fluxes. The detectors must be large enough to collect adequate statistics, yet stay within the weight limit for space flight. Innovative approaches now promise high quality measurements over an energy range that was not previously possible. The only practical method of energy determination for cosmic-ray nuclei (H – Fe) from 10^{12} to 10^{15} eV is ionization calorimetry, a high energy particle physics analog to the traditional measurement of heat energy with a calorimeter. In an ionization calorimeter a particle's energy is deposited inside an absorber via a cascade of nuclear and electromagnetic interactions. At each step of the cascade the energy of the primary particle is sub-divided among many secondary particles. Ultimately, the primary energy of an incident hadron is dissipated via ionization and excitation of the absorbing material. This cascade is much like a compressed air shower.

The most desirable material for an electron calorimeter would be one with a short radiation length (Xo), in contrast with a hadron calorimeter which should have a short interaction length (λ_I) to force hadronic interactions near the top of the instrument, and, in addition, sufficient material to absorb the cascades. Most commonly used electromagnetic calorimeter materials with high density (e.g. W, Pb) have a short radiation length, but their interaction lengths are long. Therefore, the best electron calorimeter wouldn't necessarily be the best choice for hadron shower measurements. To meet the weight constraint for space experiments, a good hadron calorimeter can be made by adding a light target material, such as carbon, upstream of a good electron calorimeter.

Practical calorimeters for space applications must necessarily be limited in absorber thickness, in order to have a reasonable cross-sectional area, i.e., geometrical factor for collecting the particles. The minimum depth depends on the energy resolution required for a particular experiment. A thin calorimeter to measure the spectra of galactic cosmic rays must meet two basic requirements: (1) the primary nucleus must undergo at least one inelastic interaction; and (2) following this interaction, the resulting electromagnetic energy must be measured with good resolution. Generally, this means that the electromagnetic shower should develop past its maximum within the calorimeter. Obviously, it is important to have the first interaction high enough in the instrument that the electromagnetic cascade will develop. For this reason the calorimeter has two distinct parts, a target section where the number of nuclear interaction mean free paths are maximized and a calorimeter portion where the number of radiation lengths (Xo) is maximized. In order to maximize the geometrical factor, the total thickness of the target plus calorimeter should be thin in physical dimensions, and the cross-sectional area should be as large as possible.

Another key factor with calorimetry is an accurate charge measurement of the incoming particle. The identification of the incident particle charge is hampered by albedo from the calorimeter. Albedo particles from the shower interactions can reach the charge detector and provide additional ionization loss signal, which can result in misidentification of some H as He nuclei. Since the shower albedo increases with particle energy the fraction of misidentified protons is likely to increase at higher energies. Spatial segmentation in the charge detector can be combined with the tracking provided by the calorimeter to help mitigate this problem. The drawback of this approach is a large number of channels. Another approach takes advantage of the fact that the incident particle traverses the charge detector before impacting the calorimeter, and that the albedo returns to the charge detector several nanoseconds later. This timing charge detector technique [17] is to be tested with a balloon experiment described in Sec. 4. Another approach involves the use of Cherenkov counters to discriminate upward moving particles from downward moving ones. This latter approach tends to decrease the geometry factor by increasing the height of the detector.

6. CURRENT AND FUTURE SPACE-BASED EXPERIMENTS

The high-energy cosmic-ray composition experiments based on ionization calorimetry to address the supernova acceleration limit are (1) Advanced Thin Ionization Calorimeter (ATIC), which utilizes the existing Long Duration Balloon (LDB) flight capability to achieve 10 - 20 days of exposure per flight; (2) Cosmic Ray Energetics And Mass (CREAM), which will utilize the new

Ultra Long Duration Balloon (ULDB) flight capability being developed to achieve 60 - 100 days of exposure per flight; and (3) Advanced Cosmic-ray Composition Experiment for the Space Station (ACCESS), which is proposed to utilize the International Space Station to achieve about 1000 days of exposure.

6.1 ATIC

The ATIC instrument [18] consists of a Si matrix for charge measurements, a carbon target to force nuclear interactions, scintillator strip hodoscopes for triggering and assisting in trajectory measurements, and a BGO calorimeter to measure the energy of incoming particles. It takes advantage of NASA's long-duration balloon flight capability to investigate the shapes of the cosmic ray differential energy spectra of the individual elements. ATIC was designed for a series of LDB flights from, principally, McMurdo, Antarctica. A balloon launched during the austral summer from McMurdo travels in the polar wind vortex, which carries it around the continent and back to near the launch site in 10-15 days, thereby providing a long exposure. About 50 days of exposure is needed for ATIC to reach 10^{14} eV. ATIC was launched as a test flight on 12/28/00 local time from McMurdo, Antarctica. After flying successfully for about 16 days the payload was recovered in excellent condition. Absolute calibration of the detector response was made using cosmic-ray muons. The data analysis algorithm, which was developed with Monte Carlo simulations and validated with CERN beam test, is being used for the flight data analysis. Currently we are refining and completing the calibration of data from ATIC's first flight. During the upcoming year we will produce energy spectra of various elements with further analysis. Simultaneously, we have been preparing for another LDB flight around Antarctica during December, 2002 – January, 2003.

6.2 CREAM

The CREAM [19] investigation is designed to measure cosmic ray composition to the supernova energy scale of 10^{15} eV in a series of ULDB flights. The objective is to observe cosmic ray spectral features and/or abundance changes that might signify a limit to supernova acceleration. The measurements will be made with an instrument that consists of a sampling tungsten/scintillator calorimeter, a transition radiation detector (TRD), and a segmented timing-based particle-charge detector. A key feature of the instrument is its ability to obtain simultaneous measurements of the energy by the complementary calorimeter and TRD techniques, thereby allowing in-flight inter-calibration of their energy scales.

In August 2001, the CREAM proto-flight calorimeter module as well as a TRD layer was shipped to CERN, Switzerland for a beam test. Preliminary results show good agreement between the beam test data and our simulations [20]. Further refinements of the calibration, event reconstruction and data analysis are underway.

Currently, mass production of all the components needed to assemble the full instrument is being completed. Using the finalized design, electronics boards are being fabricated and assembled. The integrated instrument will be tested in high-energy proton, electron and pion beams at CERN in August 2002, and in a Pb beam at CERN in October, 2002. The electron beam will provide the critical calibration for the calorimeter, while the heavy ion beam is critical for both the charge detector and the hodoscopes.

CREAM will be integrated and tested in April 2003 and be reviewed for mission readiness in August 2003. Subsequently, the payload will be shipped to Antarctica to be ready for the first ULDB demonstration flight in early December 2003.

6.3 ACCESS

ACCESS [21] has been studied for an attached payload on the International Space Station (ISS) to be launched about 2007 – 2008. Like ATIC and CREAM, it is intended to measure the cosmic-ray elemental energy spectra at the limiting energies expected from Supernova shock waves. Like CREAM, ACCESS has two major instruments: a Hadron Calorimeter and a Transition Radiation Detector (TRD). ACCESS will measure every element from H to Fe with unprecedented sensitivity for the four key elements, H, He, O, and Fe. The data will inherently determine the energy dependence of the secondary-to-primary element flux ratios, such as the Boron/Carbon ratio. These ratios must be known to understand the cosmic-ray propagation history, including possible reacceleration processes and energy loss mechanisms experienced by particles in traversing the galaxy and, ultimately, to understand the fluxes at the source.

ACCESS can achieve these exciting science goals with three years exposure as an external attached payload on the International Space Station (ISS). With its capability for 0.1e charge resolution and large dynamic range for measuring energies with two complementary, cross-calibrating instruments, the ACCESS mission can fully achieve the objective of precise measurements of individual $Z = 1 - 26$ elements in the cosmic radiation over the range from 10^{12} to 10^{15} eV, which was identified as a high priority "space-based small initiative," in the NAS/NRC decadal-study report [22].

7. SUMMARY

Existing composition data from both ground-based indirect measurements and space-based direct measurements are not sufficient to confirm or deny the supernova acceleration limit. There are several ongoing/planned experiments that will extend direct measurements of cosmic ray composition to higher energies, where the present idea about the supernova acceleration begins to fail. The ATIC/CREAM/ACCESS mission set provides the bridge to connect the voluminous, high quality satellite data at energies 3 – 4 decades below the knee with the ground-based air shower measurements extending at least 5 orders of magnitude above the knee.

At the low-energy end, the ATIC threshold energy overlaps data from the Advanced Composition Explorer (ACE), which was launched in August 1997 into a halo orbit at the L1 Lagrangian point and is still providing unprecedented isotopic resolution of $Z = 3 - 30$ cosmic rays and solar energetic particles. The Heavy Nuclei Explorer (HNX) mission, currently awaiting the outcome of its Phase A study as a candidate SMEX mission to study low-energy cosmic rays with atomic numbers greater than 30, would determine whether the cosmic ray source material is predominantly ionized particles from stellar atmospheres or interstellar material bound up in grains. Using the actinides, HNX would provide the first radioactive dating of the heaviest cosmic rays since their nucleosynthesis, analogous to using C^{14} for radioactive dating of rocks on Earth. The ATIC threshold will also overlap cosmic-ray data from the Alpha Magnetic Spectrometer (AMS), which is to be deployed by 2006 on the ISS for ~ 3 years to conduct searches for antimatter and signatures of dark matter in the cosmic particle radiation.

At the high energy end, Extensive air shower measurements from below 10^{15} eV to above 10^{20} eV have established the existence of the "knee," as well as violations of the Greisen-Zatsepin-Kuzman (GZK) cutoff around 5×10^{19} eV. The process that can accelerate particles beyond 10^{20} eV is completely unknown. Such extremely energetic particles, presumably protons and/or neutrinos, are unlikely to originate in our Galaxy, but protons cannot reach us from far-distant extra-galactic sources because of the GZK (p, gamma) energy loss processes. At such high energies, the radius of curvature for protons in the extragalactic magnetic field is probably large compared to their distance away, so their trajectories should point to their origin. This opens up the possibility of charged-particle astronomy. Observations of these extremely rare, extreme-energy events are truly exploration at the frontiers of cosmic-ray physics/astrophysics, fundamental particle physics, and early universe cosmology. The high level of interest in this topic has resulted in the recent development of a very-large-area (> 3000 km^2) ground-based experiment (Auger), and it is driving concepts for even more sensitive space missions such as the Extreme Universe Space Observatory (EUSO) on the ISS and the stereo Orbiting Wide-angle Light-collector (OWL).

ACKNOWLEDGEMENTS

This work is supported by NASA grants NAG5-5249, NAG 5-5308, and NAG5-5204.

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