HIGH ENERGY COSMIC RAY ELECTRONS
SCIENTIFIC OBJECTIVES AND PERSPECTIVES

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Fundamental Questions for the Next Decade:

- **What high-energy cosmic particle accelerators are nearby?**
- **What constraints do high-energy electrons place on dark matter theories?**

Discovery Potential

Direct observation of cosmic-ray electrons up to energies above 10 TeV has an unmatched potential to identify, for the first time, the signature of high-energy particles accelerated in a local astrophysical engine and subsequently released into the Galaxy. High-energy electrons and positrons may also be produced by dark-matter annihilation. ***Together with measurements at the Large Hadron Collider, details of the spectra of high-energy cosmic-ray electrons and positrons may hold the key to revealing the nature of the ubiquitous, but little understood, dark matter.***

Introduction: Electrons provide a unique probe of local cosmic accelerators because they lose energy rapidly by synchrotron and inverse Compton processes. The electron spectrum from the superposition of distant sources is expected to be relatively featureless, falling as approximately as E^{-3} and softening rapidly above 1 TeV. Electrons with TeV energy must have been accelerated within about 10^5 yrs of their detection and can have diffused at most a few hundred pc [1, 2]. The electron lifetime and the diffusion distance decrease rapidly with energy. Thus, detection of electrons with energy significantly above 1 TeV would indicate the presence of a nearby source. The electrons from such a source would experience little deflection by the galactic magnetic field and their arrival directions should show significant anisotropy. As measured energies increase, electron measurements are restricted to progressively nearer sources and both spectra and arrival directions sample only the local neighborhood. At energies above 1 TeV, features from discrete sources may be evident in the high-energy cosmic-ray electron (HECRE) spectrum as illustrated in Figure 1. A significant feature in the electron spectrum below 1 TeV, superimposed on the otherwise featureless distant-source spectrum, might also indicate a nearby source of electrons, a pulsar or perhaps a dark-matter clump. Recent results from PAMELA, ATIC, and HESS indicate that the HECRE spectrum likely has features and extends to well above 1 TeV. Understanding these features and their implications requires direct measurements of high-energy electron spectra, with excellent energy resolution and background rejection, along with measurements of electron arrival directions.

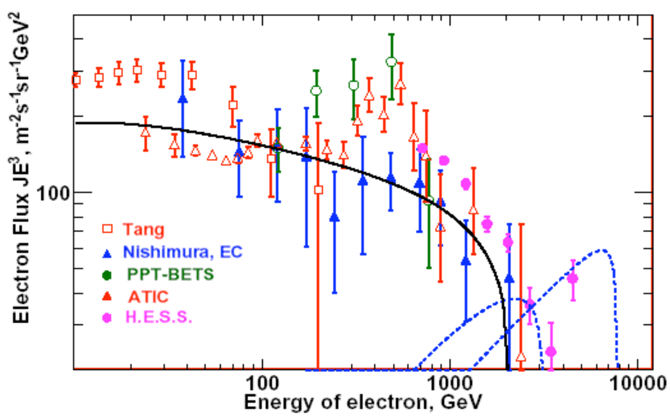

Figure 1. Current results on high energy electrons above 100 GeV. Solid line spectrum from distant sources; dotted line possible spectral features from nearby galactic sources.

Local cosmic particle accelerators can be expected to manifest themselves both in the spectra and arrival directions of HECRE [3]. Candidate nearby sources of particle acceleration include supernova remnants (SNR) and pulsars. The detection of non-thermal X-rays and TeV gamma rays from these objects gives strong evidence of the acceleration of electrons to over TeV energies and injection of high-energy electrons and positrons accelerated in pulsars into pulsar wind nebulae (PWN). However, there is no direct evidence that these particles escape the accelerator. Identification of a local acceleration engine via HECRE measurements will thus provide a benchmark to understand the details of high-energy particle acceleration in astrophysical environments and can illuminate the operation of particle accelerators in other regions of the Universe. This is crucial to understanding the origin of all cosmic rays since it is expected that some of these processes are also responsible for the acceleration of hadronic cosmic rays. It is also important to understanding galaxies, as it is increasingly evident that high-energy processes, including supernova explosions, pulsar jets, active galactic nuclei, and black hole accretion, are central forces in their evolution.

In addition to electron and positron origins in conventional astrophysical sources, it is possible that significant flux may result from the annihilation of candidate dark matter (DM) particles. These include the weakly interacting massive particles (WIMP) predicted by supersymmetric (SUSY) theories, such as neutralinos, as well as particles resulting from theories involving compactified extra dimensions, such as Kaluza-Klein (KK) particles. A DM source contributing to the electron spectrum would manifest itself as excess flux up to the mass of the DM particle. The spectral shape that might result from this excess differs considerably depending on the candidate particle and its annihilation channels. WIMP annihilation is expected to give a smooth feature softening toward the DM particle mass while KK annihilation is expected to give a feature with a sharp cutoff at the DM mass.

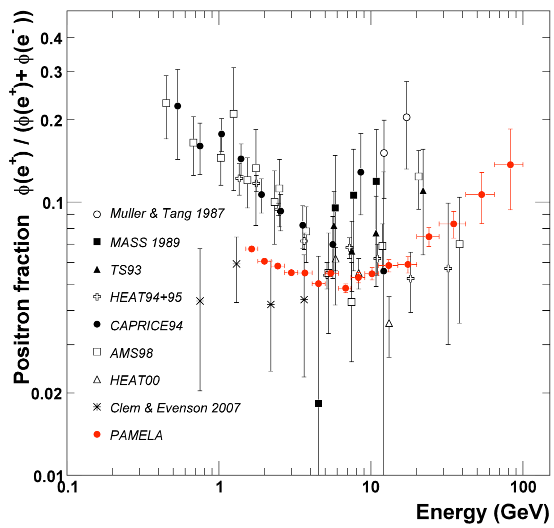

Figure 2. Results on the positron to electron ratio reported by the PAMELA group [11]

High-Energy Electron Origins: Cosmic ray electrons, both negatrons (e^-) and positrons (e^+), are produced mainly in two processes: "primary" production in astrophysical sources, believed to be SNR or pulsars, and "secondary" production by interactions of hadronic cosmic rays with interstellar matter. Supernova explosions are generally accepted as the most likely source of the majority of cosmic rays. Radio observations and evidence of non-thermal X-ray emission from SNRs indicate that high-energy electrons are accelerated in SNR and recent measurements of TeV gamma rays provide evidence that particles are accelerated to trans-TeV energies. SNR are expected to accelerate cosmic rays by diffusive shock acceleration. Some of the details, such as possible magnetic field amplification, are unclear so SNR may accelerate electrons to energies above 10 TeV. Detection of such electrons, particularly if associated with SNR by arrival direction, can provide crucial tests of models for the acceleration of cosmic rays. Similarly, although the mechanism for gamma ray production by pulsars is not fully understood, there is ample evidence that e^- and e^+ pairs are produced by primary e^- accelerated within pulsars and that the e^- and e^+ are subsequently accelerated to ultra-relativistic velocities. This process is self-limiting to energies of around 6 TeV, as the e^- and e^+ current screens the local magnetic field. However, the e^- and e^+ may be injected into a PWN and re-accelerated by diffusive shock acceleration to the same limits as in SNR. If nearby, pulsars could produce the features in the HECRE spectrum suggested by recent measurements. Secondary cosmic ray electrons and positrons are almost equally produced in the interactions of hadronic cosmic rays with interstellar matter and the smooth hadronic spectrum results in an equally smooth contribution to the HECRE spectrum.

In addition to e^- and e^+ origins in conventional astrophysical sources, they might result from the annihilation of candidate DM particles as discussed above. The possible signatures of DM candidates differ considerably. WIMPs do not have a direct annihilation channel into e^- and e^+ pairs. Instead they annihilate into non-leptonic final states, primarily quarks and gauge bosons. The gauge bosons then decay to produce electrons and positrons. SUSY theory also suggests the possible existence of ~1 TeV heavy higgsinos and ~2 TeV heavy winos. Both should annihilate abundantly into gauge bosons, which in turn produce energetic e^+ and e^- pairs. Because the direct production channel is suppressed, the e^- and e^+ produced by gauge boson decay are distributed in energy below the SUSY particle mass and their spectra are further spread in transport. Thus the contribution of SUSY particles is likely a relatively broad feature up to the particle mass. In contrast, KK particles can annihilate directly to e^- and e^+ pairs. This gives an initial delta function spectrum which, when modified by propagation, results in a contribution to the spectra with a sharp cutoff at the KK mass. Inhomogeneities in the distribution of dark matter could lead to an enhanced annihilation rate with a subsequent "boost" in the flux of e^+ and e^-. Theories explaining e^+ and e^- origins from dark matter annihilation are strongly constrained by measurements of cosmic-ray antiprotons. Most models of dark matter annihilation predict an excess of antiprotons over those expected as secondary products of nuclear interactions of primary cosmic-ray nuclei with the interstellar medium. High statistics antiproton measurements by BESS [4] and PAMELA [5] show no apparent antiproton excess above 1 GeV. Some recent suggestions to resolve this include annihilation preferentially into leptonic channels [6] and an extra universal spatial dimension [7].

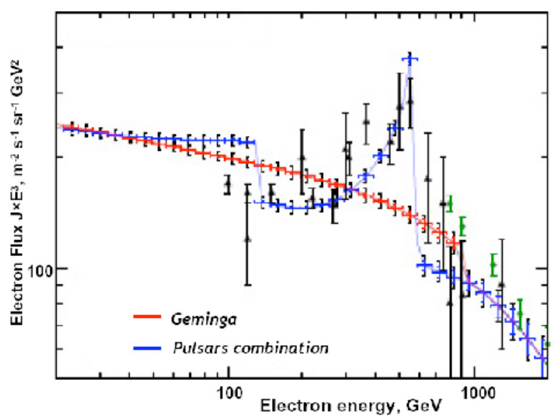

Figure 3. Anticipated spectrum for one bright source (Geminga) and a combination of more distant pulsars, accounting for both the Pamela and the ATIC data [19])

The contribution from distant sources should result in a smooth electron spectrum rolling off to both low and high energy. The lifetime of cosmic ray electrons is determined by the leakage from the Galaxy for low energy and by radiation losses and inverse Compton on starlight and the 2.7K background radiation at higher energy. These differential processes produce a bend in the electron spectrum, and the spectral indices are directly connected with the confinement time of electrons in the Galaxy, diffusion coefficient and galactic halo size. The lifetime of electrons against radiation and inverse Compton energy losses in the ISM can be estimated as $t_{rad} \approx 3\times10^5\times(1\text{TeV}/E)$ yr for B = 4 μG and photon density of 1 eV/cm^3 . For a diffusion coefficient $D = 3\times10^{28}\times(E/7\text{ GeV})^{0.3}$ cm^2/s the maximum distance from which 1 TeV electrons can reach Earth during their lifetime is ≈350 pc. Figure 1 shows the experimental results above 100 GeV along with the spectral shape from distant sources, modeled with the comprehensive GALPROP simulation package, and possible structural "bumps' at higher energy due to nearby sources [8]. Experimental evidence for such features would imply the existence of nearby source(s).

Although there is universal agreement that cosmic rays propagate by diffusion, the model and energy-dependent diffusion coefficient for particle transport is uncertain to about a factor of 3-5 and has never been measured directly. Recent results from MILAGRO [9], have indicated anisotropy in the arrival directions of 10-TeV hadronic cosmic rays with a scale size of about 10°. This is an unexpectedly low energy to see localized excesses, suggesting that the diffusion coefficient may not be isotropic. If a nearby HECRE source can be observed and identified by arrival direction, then an accurate value of D can be inferred in that direction. Several such sources would test the isotropy of diffusion. Even if no sources are seen, the shape of the cutoff can constrain the diffusion coefficient.

In addition to the structure of the HECRE spectrum, extremely important and critical information can be obtained from measurements of electron flux directionality. Anisotropy in the electron flux at a level of 10-20% is possible [10]. High statistics measurements of HECRE arrival directions may allow spectral features to be connected directly with celestial objects. If the preferred direction does not include known local pulsars, this may favor dark matter origin, or may indicate the presence of unknown pulsars.

Recent Observations: Recent results reported by PAMELA, ATIC and HESS suggest that the e^- and e^+ spectra may reflect a nearby source or sources. PAMELA [11] reports a significant increase with energy in the e^+ fraction of the electron flux in the 10-100 GeV range (Figure 2). This is inconsistent with standard secondary e^+ models. If secondary production dominates, the e^+ fraction is expected to fall as a smooth function of increasing energy. There were indications of this excess in previous works [12-15] with lower statistics. ATIC [16] recently reported a "bump" in the total electron (e^- + e^+) spectrum at ~ 600 GeV (see Figure 1). Outside this feature, the ATIC data is in good agreement with previous measurements. A similar bump was reported by PPT-BETS[17], but with less statistical significance. The first ground-based measurement of cosmic ray electrons was reported by HESS [18]. They reported a steep spectrum with index of 3.9 above 800 GeV. These data are well reproduced by an exponential cutoff power law at 2.1 TeV, which may indicate the existence of at least one source of HECRE within 1 kpc.

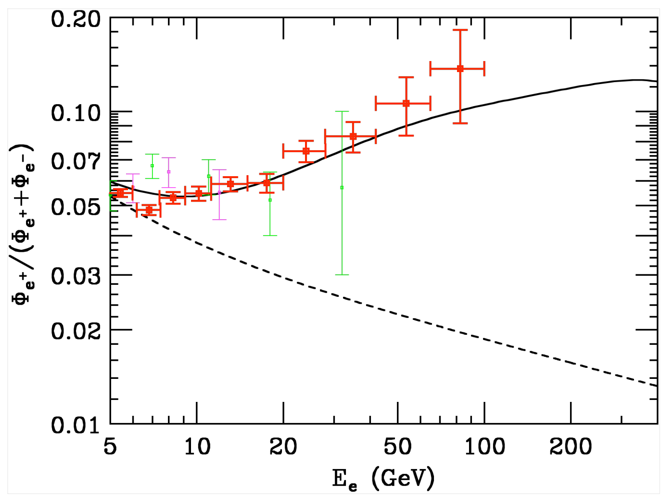

Figure 4. Positron fraction from the sum of contributions from B0656+14, Geminga, and all pulsars further than 500 pc (solid line), fitting the Pamela data. Dashed line – expected positron fraction from secondary production [20]

Interpretation of Current Data: Many recent papers have offered explanations for the ATIC and PAMELA results. Two general classes of explanation have been offered for the e+ excess observed by PAMELA and the feature in the ATIC electron spectrum: the signature of a nearby pulsar, or group of pulsars, and annihilation radiation from a dark matter clump. Profumo [19] has modeled both the PAMELA excess and ATIC bump and suggests that both can be explained by multiple, more distant (around 1 kpc), mature pulsars (Figure 3). Hooper, Blasi and Serpico [20] consider pulsars as sources of high energy positrons (Figure 4). Cholis et al [6] discuss a WIMP annihilation source and argue that both PAMELA and ATIC results can be well explained by dark matter annihilations in leptonic modes, either directly or through a new light boson (Figure 5). Hooper, Stebbins, and Zurek [21] argue that both the PAMELA and ATIC excesses can be explained by emission from a nearby clump of neutralino dark matter, although they note that a large boost factor is needed. Hooper and Zurek [7] show that the PAMELA and ATIC results can be reproduced, without violating antiproton measurement constraints, by a KK model with one extra universal spatial dimension.

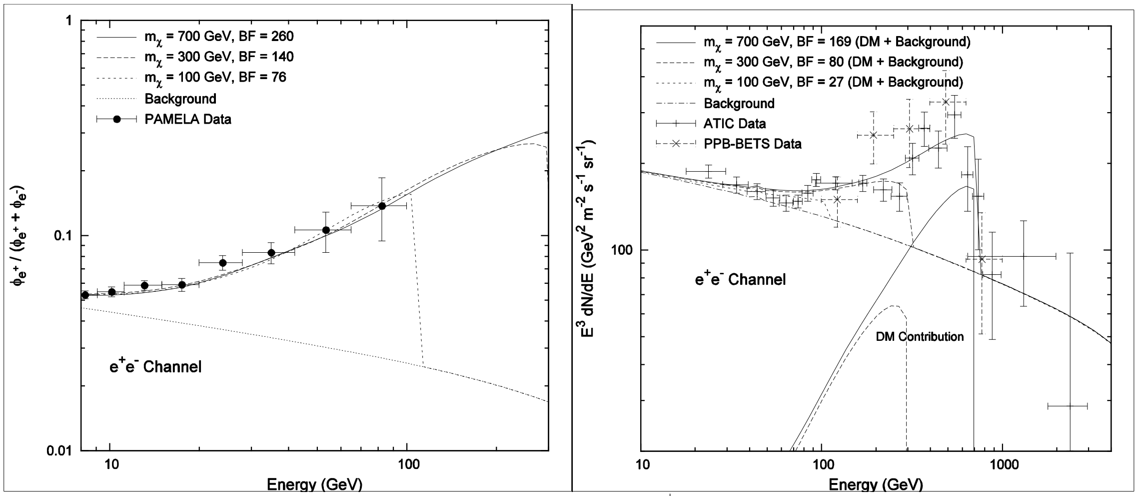

Figure 5. The cosmic ray signals from DM annihilation $\chi\chi\text{->}e^+e^-$ for m_χ = 700 GeV and boost factor 260. Left panel – fit to Pamela positron fraction; right panel – fit to ATIC spectral bump [6]

Key Instrumental Advances Needed: Three important papers on high energy electrons and positrons were published in 2008 (PAMELA [11], ATIC [16], HESS [18]). The joint effect of these experiments is to demonstrate the importance of electron and positron measurements. Measurements using these instruments, however, cannot determine with full confidence the origin of the HECRE. Measurements with far better statistics are needed. To search for astrophysical sources, in particular, higher electron energies must be observed. Accurate mapping of the arrival directions of HECRE associated with spectral features will be crucial, particularly above 1 TeV.

High statistics electron results from the Fermi Large Area Telescope [22] will cover the energy range up to 1 TeV. Up about 300 GeV, detailed spectra of e^+ may be provided by the Alpha Magnetic Spectrometer (AMS). Above this energy, AMS cannot distinguish e^+ from the far more abundant protons. However, it can distinguish e^- up to the ~1 TeV effective limit of the magnetic spectrometer set by its ability to distinguish negative particles from proton spillover. If high-statistics total electron spectra are available from Fermi-LAT or later instruments, the e^+

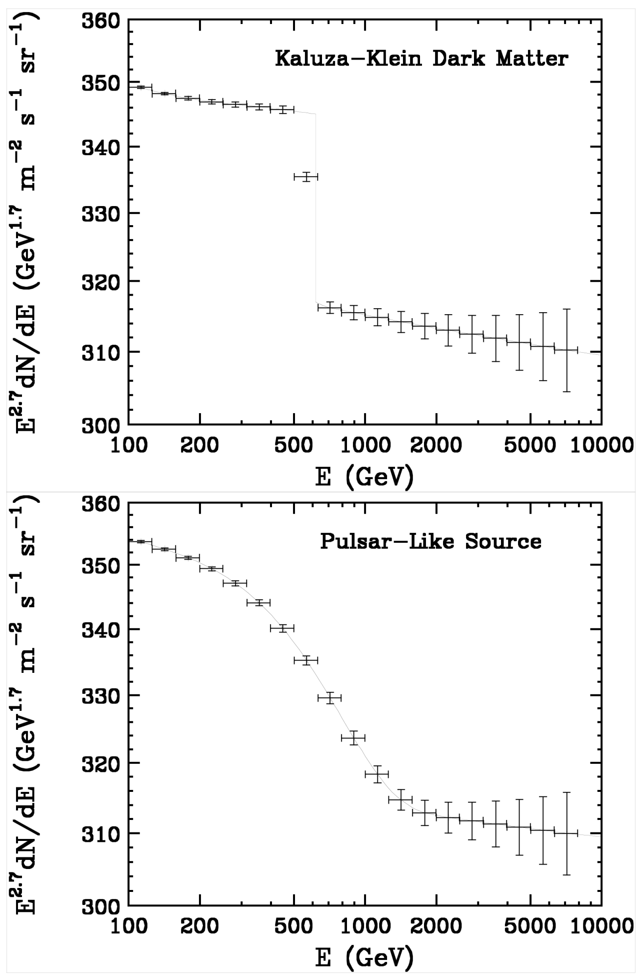

Figure 6. The expected upper edge of the electron feature in the case of 620 GeV KKDM (upper) or a pulsar-like source corresponding to the same energy (lower) [23])

flux can be derived by subtraction.

Hall and Hooper [23], argue that Atmospheric Cherenkov Telescopes (ACT) including Magic, HESS, VERITAS, and proposed ACT arrays such as AGIS or CTA can provide the information to distinguish between dark matter and pulsar origin of the ATIC result by performing accurate measurements of the upper energy end of the feature (Figure 6) where a DM annihilation signal should have sharper edge than one of astrophysical origin. From 1 TeV to a few tens of TeV, ACT can provide useful measurements with high statistics, but they cannot distinguish between electrons and gamma rays and their measurements have to be taken as upper limits. Contamination by hadronic cosmic rays is also a concern.

To fully investigate the region above 1 TeV, where spectral features are most likely to point definitively to local HECRE sources, direct measurements by a large-area orbiting instrument are needed. This should be configured to accurately measure electron spectra and arrival directions up to the SNR and pulsar acceleration limits.

Such an instrument must be able to clearly distinguish electrons from gamma rays and to eliminate background from cosmic-ray hadrons. This is especially important since the expected electron flux at high energies is very small. High-energy gamma rays can come both from Galactic and extragalactic sources. The most likely potential site for DM is the galactic center, and electrons from that direction must be detected in the presence of high intensity gamma-ray flux. Also, it is likely that extragalactic diffuse gamma-ray spectrum is harder than that for electrons, so for high energy the background from diffuse gamma rays may become significant. The danger of hadron contamination is even more significant. The proton spectrum is certainly harder than the electron spectrum, so the ratio of hadrons to electrons increases with the energy, making the proton rejection requirement more stringent.

No current instrument, including Fermi-LAT and AMS measures electrons above 1 TeV. The Calorimetric Electron Telescope (CALET) [24], proposed for flight on the ISS Kibo (Japanese Experiment Module) Exposed Facility, could extend electron measurements to ~10-20 TeV using a combination of imaging and absorption calorimeters. The High Energy Particle Calorimeter Telescope (HEPCaT) is the subject of a formal NASA study as part of the Orbiting Astrophysical Spectrometer in Space (OASIS) mission, funded as an Astrophysics Strategic Mission Concept, and would extend measurements to about 30 TeV.

HEPCaT has much greater collecting power than any other planned HECRE instrument and has optimized ability to identify incident hadrons coupled with excellent energy resolution. HEPCaT uses a Si-W imaging-sampling calorimeter. Powerful hadron identification is achieved by imaging the longitudinal development and lateral distribution of particle cascades within the calorimeter. A neutron/penetration detector provides additional hadron identification by identifying penetrating particles and measuring the neutron flux from cascades. A silicon pixel detector measures the charge of incident particles and provides gamma rejection. The instrument techniques used in HEPCaT have extensive heritage in accelerator experiments as well as in balloon and space instruments. HEPCaT does not require new detectors to be developed.

Supporting Theory and Phenomenology: In addition to the needed HECRE observations, there must be continued theoretical work to improve models for the acceleration and injection of cosmic rays from astrophysical sources, models of electron generation in dark matter annihilation, and galactic cosmic ray transport. Advancing the basic phenomenology needed to interpret the new data is equally critical. Computationally tractable descriptions of primary and secondary electron and positron acceleration, interaction, and propagation are to a large degree available and in many cases (e.g., GALPROP) integrated into a comprehensive framework that also includes the cosmic-ray hadronic processes. In some of these descriptions, however, there remain model-dependent estimates with uncertainties that must be reduced before the new data and improved phenomenology can be used to test existing or new theories.

Corollary Observations: Firm conclusions about the origin of HECRE cannot be drawn strictly from electron experiments either directly or by ACT. Corollary observations in the radio, X-ray, and gamma-ray ranges will be required to search for potential local sources and to understand the electron injection spectra of those sources. In particular, the structure of gamma pulses from pulsars can provide strong constraints on potential sources and on their electron emission spectra. The gamma-ray data from Fermi-LAT and from the ACT will be crucial to understanding HECRE measurements. Data from other large gamma-ray instruments including HAWC and ARGO-YBJ will be important to understand both the gamma-ray sources and to search for anisotropy in multi-TeV hadrons. The direct electron measurements from CALET or HEPCaT will provide important information for ACT as well. The ACT are very narrow FOV instruments. Direct measurements can identify spectral features and their locations for examination by the ACT.

Conclusion: High-energy electron measurements have a unique potential to identify and characterize local cosmic particle accelerators. Recent measurements from PAMELA, ATIC [18] HESS have begun this work. Soon additional high-statistics measurements can be expected from Fermi-LAT and perhaps from AMS and CALET. Realizing the full potential of these measurements will require an instrument such as OASIS-HEPCaT.

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