Neutrons (and Neutrinos) from the Galactic Center

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Abstract. The AGASA and SUGAR extensive air shower cosmic ray detectors both find tantalizing evidence of an anisotropic overabundance of cosmic rays towards the Galactic Center (GC) region that "turns on" around 10^{18} eV. I demonstrate that the anisotropy can be explained by extremely high energy neutrons created near the GC through charge-exchange in proton-proton collisions (where the incident, high energy protons obey a $\sim E^{-2}$ power law). The Galactic center gamma ray detections by several instruments, most recently and significantly HESS, provide strong corroborative evidence for this mechanism. This scenario will be tested in the future through direct detection of the neutrons by AUGER and, indirectly, by GC neutrino detection by km^3-scale neutrino telescopes including IceCube. Finally, I argue that the required shock acceleration is probably occuring in the shell of Sagittarius A East, an unusual supernova remnant located very close to the GC.

1. Introduction

In this talk I discuss research which has been presented recently in two Astrophysical Journal articles [**?**, **?**]. The work described here has been conducted in collaboration with Marco Fatuzzo of Xavier University; Randy Jokipii and Fulvio Melia, of the University of Arizona; and Ray Volkas, University of Melbourne.

To begin, I remark that the Galactic center (GC) is apparently "brighter" in extremely high energies (EHE) cosmic rays than an average patch of sky. The evidence for this statement comes from two extensive air shower cosmic ray detectors, the AGASA and SUGAR devices, which both see an overabundance of cosmic rays towards the GC direction at EHE, $\sim 10^{18}$ eV. This anisotropy is, moreover, observed to "turn on" and then "turn off" at well-defined energies

A natural explanation of this phenomenon is that it is due to neutrons generated at the GC: the Lorentz-boosted decay length of a neutron becomes equal to the distance to the GC in exactly the energy range at which the anisotropy turns on. In other words, a neutron at 10^{18} eV experiences a quarter of an hour in its propagation from the GC and it can reach us at the Earth before it decays into a proton (that will be deflected by the Galactic magnetic field).

By relating γ-ray observations of the GC with the CR anisotropy data I have investigated – and found plausible – a conventional astrophysical explanation for the production of these putative EHE neutrons, viz. that they are produced in proton-proton collisions in the GC environment, with the parent protons most likely supplied by the supernova remnant Sgr A East located near the GC (within $\sim$ 10 pc). The research I describe here thus very tentatively identifies a definite Galactic object as a strong source of cosmic rays between the knee and the ankle.

2. Evidence for EHE CR Anisotropy

(i) The giant Japanese air-shower array AGASA finds an *extended* anisotropy ($\sim$ 25 % over-abundance) at the 4 σ level towards the GC over a 20° diameter circle for 17.9 $<$ log[E/eV] $<$ 18.3. The AGASA data were taken over a 20 year period and amount to 200 000 $> 10^{17}$ eV CR showers [?]. New AGASA data only strengthens the case for the anisotropy: the instrumental collaboration now obtains a better than a 4.5 σ result for 18.0 $<$ log[E/eV] $<$ 18.4 [?]. In passing we note that the AGASA instrument also sees an enhancement towards Cygnus (with 3 σ confidence) and a deficit towards the Galactic anti-center (with 3.7 σ confidence).

(ii) Re-analysis [?] of data from the SUGAR detector, which operated outside Sydney, Australia from 1968-1979 and had a direct view of the GC, also uncovers a *point* source near the GC (4000 events within a priori restricted energy range: [?]).

(iii) The old Fly's Eye detector saw a Galactic Plane enhancement at 3.2 σ [?] for 17.3 $<$ log[E/eV] $<$ 18.5. Fly's Eye's broad-scale analysis is consistent with the SUGAR and AGASA results, though its analysis was not able to show up more regionalized overabundances in the pertinent energy range with any statistical confidence.

(iv) From the HiRes instrument there are data consistent with an *isotropic* source distribution for log[E/eV] $>$ 18.5. Given this energy restriction, these data do not exclude the AGASA GC anisotropy result (though they may possibly in the future with more statistics).

3. Issues for CR Anisotropy Analysis

There are a number of points to keep in mind when considering the anisotropy analysis, viz:

- AGASA cannot see the GC directly (it is below the instrument's effective horizon).
- As noted above, SUGAR *can* see the GC but its point source is off-set from the GC by $(7.5 \pm 3.0)°$.
- The SUGAR GC source is in the field of view of AGASA and, therefore, should be seen by AGASA but it is *not*.
- There are no particularly compelling astrophysical object in the direction of the SUGAR source (though it is close to Galactic Plane).

- We proceed under the hypothesis, therefore, that the SUGAR directional determination is in error. Our scenario hangs on this simple point for which I have, as a theoretician, no independent rationale.

4. Modeling of GC CR Propagation

The broad features of the observed anisotropies have been successfully reproduced by Bossa et al. [**?**] with a model that assumes a point-source of neutrons injected at the GC and governed by a spectral index of 2.2.

Bossa et al.'s model incorporates the combined signal from neutrons and neutron-decay protons (with the latter's paths modeled to bend in an assumed configuration of the Galactic **B** field so as to form a "halo" around the point source on the sky). Note that neutrons and protons are indistinguishable in air shower arrays at these energies.

The model produces the following phenomenology: the anisotropy becomes increasingly point-like with increasing energy as neutrons reach closer and closer to the Earth before they decay and the resulting protons are deflected less and less far from the direction of the GC (until, at some sufficiently high energy near 10^{18} eV essentially all injected particles remain as neutrons all the way to the Earth). We thus have a neat explanation of the disappearance of the AGASA anisotropy at a certain energy: above this energy one gets a point source of neutrons in the direction of the GC, but this, as remarked above, is below AGASA's effective horizon and cannot be seen by the instrument.

Bossa et al. find that the AGASA and SUGAR fluxes are consistent with each other in the neutron decay picture given, in broad terms, AGASA is seeing the halo protons and SUGAR the neutron point source.

5. EHE Neutron Production

In terms of the microphysics, there are three basic high-energy, astrophysical neutron production scenarios: (i) dissociation (on target photons or protons) of heavy ions into component protons and neutrons; (ii) Charge exchange in p-γ, i.e., p $\gamma \to nX$; and charge exchange in p-p, i.e., $pp \to nX$. In the preceding, "X" is mostly pions (10's thereof in p p, significantly fewer in p γ)

6. Identifying the Neutron Source Process

We would like to decide which of the processes listed above best matches the observations. Certainly, dissociation *may* operate, but there is no attendant GeV-TeV photon signal produced by this process (and we therefore cannot normalize the expectation for the GC neutron flux – see below). We can neither rule this process in nor out, therefore. On the other hand, the p-γ process does not become effective until the parent proton is accelerated well above 10^{18} eV (at which energy scale, ambient

NIR photons are Lorentz-boosted above the threshold for Δ production in the parent proton's rest frame). Even then, the GC is pervaded by too small an ambient density of such photon targets to make this process effective and we can, therefore, rule out neutrons sourced by p γ interactions with some confidence. Finally, let us consider the p-p process. This is, in fact, our best bet: charge exchange can occur for parent proton energies above a GeV or so and there are many target protons in the GC environment. Furthermore, and very significantly, from this process result many neutral pions which decay to produce a concomitant gamma-ray signal. The significance of this fact I explain below.

7. Proton-Proton Collisions

From experiments conducted at CERN (ISR) and Fermilab in the 1970's, it is known that in p-p collisions: (i) charge exchange occurs, on average, in $\sim$ 40 of interactions, i.e., the average (leading) neutron multiplicity of 0.4. and (ii) the neutron produced in charge exchange gets, on average, about 25 % of incoming proton's energy, i.e., the average leading neutron elasticity is 0.25. Note here that direct data on multiplicity and elasticity are at much lower E_{CMS} (where CMS denotes "center of momentum system") energies than we are concerned with (60 GeV rather than 60 TeV) and that modeling is, therefore required to extrapolate into this region (cf. the situation for the p-γ interaction). Such modeling indicates, however, that the (average) fractions given above are approximately energy-independent [?] and we take this to be the case in our analysis.

As far as the total p-p cross-section goes, at relevant energies this is extracted from cosmic ray data. These require a scaling-violating but slow growth of the cross-section (from $\sim$ 40 mb to 120 mb over the energy span of concern). Our analysis takes this growth into account.

8. Gamma Rays: Independent Evidence for p-p Interactions at the GC

A GC γ-ray signal has been seen at both $\sim$GeV (EGRET: [?] and $\sim$TeV energies (Whipple, CANGAROO, HESS: see [?], [?], respectively) and, what is more, this signal can be convincingly ascribed to neutral pion decay with the pions originating in p-p interactions. [?, ?]. The GC γ-ray signal thus independently suggests the existence of a population of HE, shock-accelerated protons in the GC region.

Beyond this qualitative statement, in fact, one realizes the following: the normalization supplied by the (p-p) gamma-ray signal (at either $\sim$GeV or $\sim$TeV energies) **plus** the expectation from shock acceleration theory (an $\sim E^{-2}$ spectrum) **plus** the relevant particle physics (spectrum-weighted moments allowing for slow cross-section growth, constant multiplicity and inelasticity) together give us a prediction for the expected (p-p) GC neutron flux at EHE (provided, of course, that the parent proton population extends to $\sim 10^{19}$ eV).

9. Gamma-ray and Neutron Signals Compatible

Following this logic, one is able to determine the following: with a spectral index (in agreement with that supplied by observations *separately* of GC γ-rays and of the CR anisotropy and in good agreement with the expectation from acceleration at a strong shock) of 2.2-2.3 the (GeV) EGRET gamma-ray signal predicts the right neutron flux to explain the anisotropy *at nine orders of magnitude higher in energy.* The (TeV) HESS signal with a spectral index of 2.0 is also well compatible with the neutron signal. The results of these numerical considerations are displayed in figs 1 and 2 below.

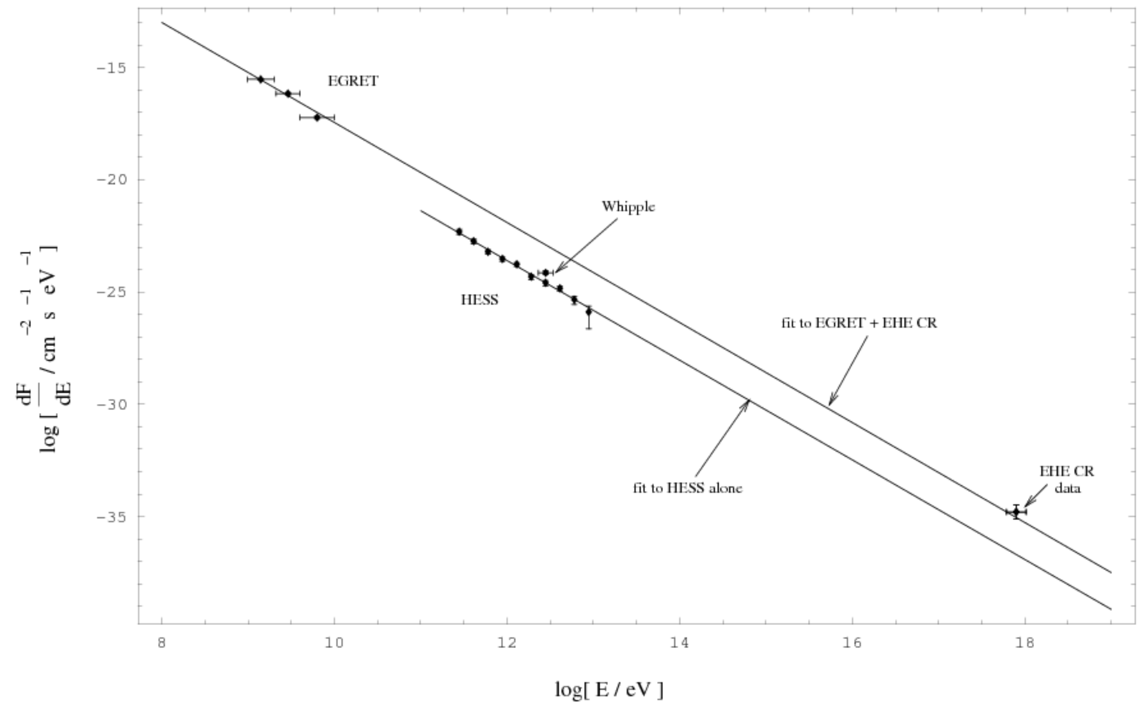

Figure 1. γ-ray and neutron differential fluxes together with fitted curves. The three points on the left of the figure are from EGRET [?]. The 11 data points in the middle of the figure are GC, γ-ray differential fluxes measured by atmospheric cerenkov telescopes. Amongst these, the single point with marked error bars sitting proud of the fitted line is due to Whipple [?], the other 10 points are from the recent HESS July/August 2003 data set [?]. The right data point gives the neutron flux which, on the basis of the EHE cosmic ray data, I have taken to be $1.0^{+1.0}_{-0.5} \times 10^{-17}$ cm^{-2} s^{-1} above $10^{17.9}$ eV. The upper line gives the best-fit photon differential flux obtained from a simulataneous fit to the EGRET and EHE cosmic ray data. This is given by a power law with a spectral index of 2.23 (the curve would be inaccurate at EHE because it does not take into account the growth of the total pp cross-section). Obscured by (i.e., in excellent agreement with) the right data point is a triangle indicating the position of the neutron differential flux at $10^{17.9}$ eV as determined by the best-fit power law (that this point is apparently on top of the γ-ray flux curve is coincidental). The lower curve – with a spectral index of 2.22 – has been found by fitting a power law to the HESS data alone. Note how extremely closely the spectral indices match.

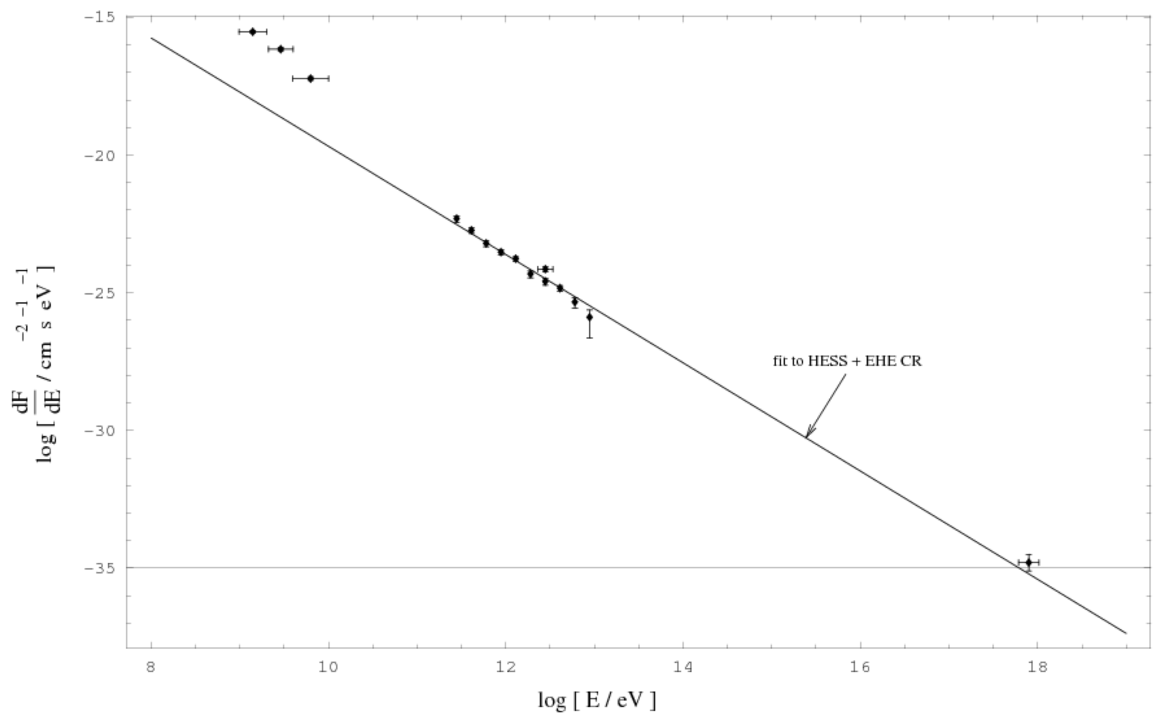

Figure 2. γ-ray and neutron differential fluxes together with another fitted curve. The data are as given in the previous figure. The curve is obtained from a power law fit (simulataneously) to the HESS $\sim$ TeV γ-ray data (but not the Whipple data point) and the EHE cosmic ray data (again, note that the curve would be inaccurate at EHE because it does not take into account the growth of the total pp cross-section). The best-fit spectral index is 1.97. The EGRET data points have *not* been used in this fit. On the right is illustrated both the EHE CR data point and (again obscured by the former) a triangle indicating the position of the neutron differential flux at $10^{17.9}$ eV as determined by the best-fit power law.

10. Considerations

The analysis presented above glosses over many serious questions and concerns. Primary amongst there are:

- Are total power requirements reasonable?
- How might p's be accelerated to such high energies?
- From fig. 1, the HESS and EGRET results are apparently incompatible: EGRET *predicts* 20 times more flux at $\sim TeV$ energies than is actually seen by HESS.
- The results from CANGAROO and HESS in the TeV energy regime are incompatible with, in particular, the different instruments detecting GC sources with very different spectral indices. (In passing. note that there is no evidence for variability of the GC source from any one instrument, only between instruments, so explaining the difference between these observations by postulation of variability between observing runs requires quite some fine-tuning).

11. Total Power

We can deal with the first concern above immediately. In fact, power requirements in our scenario are completely reasonable. In the case of the normalization to the EGRET data we require $\sim 4 \times 10^{38}$ erg/s in interacting protons This implies 1.3×10^{50} erg over 10^4 years (the relevance of this timescale is explained in the section on Sgr A East below), or about 10% of the kinematic power of a supernova explosion. In the case of the HESS normalization, power is even less of a concern: we require $\sim 4 \times 10^{36}$ erg/s in interacting protons. This implies 1.3×10^{48} erg over 10^4 years.

12. Possible resolutions of the EGRET-HESS "Disagreement"

The "disagreement" between the HESS and EGRET instruments alluded to above could have a number of resolutions. These include:

(i) Energy-independent mis-calibration of one or more instruments? This is a *logical* possibility – there are certainly big problems in observing noisy regions like the GC at ∼TeV energies – but EGRET predicts 20 × the HESS flux at ∼TeV and, therefore, this explanation would not seem to be tenable. Even a theoretican can recognize this.

(ii) Pair production on NIR-optical (~ 1 eV) photons attenuating TeV+ photons (cf. the situation in some X-ray binaries)? This mechanism *can* result in effectively energy-independent attenuation of photons over a limited range in energy (off a thermal distribution of photon targets) but the photon column density to the GC is too small given the low emission of the GC (cf. other galactic nuclei) to render this mechanism effecacious.

(iii) Are there, effectively, two sources? This is definitely plausible: firstly, there is evidence that the EGRET and HESS sources are angularly-separated. Hooper and Dingus [**?**] find the GC EGRET source center of gravity ~ 12 arcminutes from the actual GC, whereas the HESS source lies within 1 arcminute of the GC (i.e., on the GC to experimental resolution). Pohl (2004) in his recent analysis confirms this offset. Secondly, in the general SNR population, speaking very broadly, flux levels and energy cut-offs are observed to go in opposite directions (because the same process of interaction with ambient particles that renders the SNR bright at lower energies tends to act to cool the accelerated particle populations and prevent it from reaching high energies).

It should be noted, however, that the two-source idea does not explain the very similar spectral indices in Fit 1 and it also requires 7 orders of magnitude difference in maximum energies at two sites (the EGRET source must cut-off around 10^{ll} eV so as not to pollute the HESS signal, the HESS source must go to much higher energies to explain the EHE CR ansisotropy).

13. Plausible Sources of EHE Neutrons: 1. Sgr A*

In the context of the above phenomenology, the astrophysical source one would immediately suspect is the supermassive blackhole (labelled Sgr A* in the radio) or, more precisely, shock(s) in the accretion disk surrounding this object at 40-120 Schwarzschild radii. Previous modeling [?] has determined, however, that the maximum proton energy for this acceleration site is 4×10^{17} eV (given maximum shock size and magnetic field), i.e., too low to produce the required neutrons. Furthermore, the synchrotron emissivity of secondary leptons (from the decay of charged pions also, unavoidably, created in large numbers by the p-p collisions invoked to explain the γ-ray and neutron signals) in the inferred 10 G+ fields near central BH would far exceed Sgr A*'s observed radio flux. Also, the lack of variability seen in $\sim$ GeV and $\sim$ TeV data tells against such a compact source and, lastly, this mechanism is highly inefficient: given relevant length and magnetic field scales, most accelerated p's escape from this source before interacting placing a very tough energy demand. We can, therefore, probably rule out this object as the source of the neutrons required to explain the CR anisotropy.

14. Plausible Sources of EHE Neutrons: 2. Sgr A East

Sgr A East is a supernova remnant located close (shell located from 10 pc to within 1 pc) to the GC. There is good evidence for association between this SNR and the EGRET GC source (3EG J1746-2851: [?, ?]). Interestingly, this object has a γ-ray luminosity two orders of magnitude larger than other EGRET-detected SNRs and one must ask why this should be the case. The answer here is that, near the GC are to be found unusually-high magnetic field strengths of $\mathcal{O}$[mG] and ambient particle densities of at least 10^4 cm^{-3} (with $10^5 - 10^6$ cm^{-3} in nearby molecular clouds) – such unusual conditions allow us to explain this high luminosity.

15. Unusually High Maximum Proton Energies at Sgr A East

The strong magnetic fields near the GC also mean that we can reasonably expect particle acceleration up to the very high energies we require (thus addressing one of the concerns raised above). In fact, with a 4mG field, the Sgr A East shock can accelerate particles to $10^{19}(R/10\text{pc})Z$ eV in a *perpendicular* shock configuration [?, ?].

Cooling by the p-p process does not further constrain this cut-off energy, not does the finite age of the remnant (the p-p cooling-limited p energy is $\sim 10^{21}$ eV and the time-limited p energy is $\sim 10^{20}$ eV). Note that a fiducial 10 000 year age of the remnant is assumed here (hence the timescale in the section on power requirements above).

16. Sgr A East and the Two Source Model

Sgr A East is a natural fit to the two source idea: this remnant's shell subtends regions of widely varying particle density and magnetic field strength (and orientation). One could, reasonably, have the following: for the EGRET source arising from interaction in one particulat region of the remnant's shell, a 0.1 mG field to accelerate protons and create secondary leptons which then gyrate – self-consistently – to produce observed radio emission (6 and 20 cm). For the HESS source, a 4 mG field is required to produce the observed radio signal from the position of γ-ray source – and this is a good match with the field required to produce the required 10^{19} eV protons for neutron production (as explained above) and also good match with direct polarimeter measurements of GC field [**?**]. Plausibly these different sources may arise in various of the interaction sites between the shell and various surrounding molecular clouds.

17. Extension: GC Neutrino Flux

Given the particle physics we have invoked above to explain the required neutrons and the observed GC γ-rays, we also now expect a substantial neutrino flux from the GC from charged pion and muon decays (charged pions are also produced copiously in the required p-p collisions as noted above)[**?**]. Given the particle physics is well-constrained, the neutrino flux can be normalized to the γ-ray and neutron signals (note that β-decay $\overline{\nu_e}$'s are an insignificant component of the total neutrino flux). This signal should be visible fairly quickly (in the technical sense that it can be revealed with a specified degree of statistical confidence) in a future Northern Hemisphere km^3 neutrino detector (1.5 years is expected to give a detection with 2 σ statisitcal confidence for the HESS normalization case) in ν_μ-induced muons. More significantly, the signal should also be visible to the IceCube detector despite it Southern location (1.6 years is expected to give a detection with 2 σ statisitcal confidence for the HESS normalization case) in down-going ν_e and ν_τ-induced showers. HE neutrinos $\overline{\nu_e}$'s can also be detected through the Glashow process: $\overline{\nu_e}e- \rightarrow W^-$ in IceCube.

18. Summary

From the observed anisotropy in the EHE CR spectrum, there appear to be neutrons coming from the GC. These neutrons can be explained as arising from charge exchange in p-p interactions. I have shown that conventional astrophysics can explain the neutrons (and, therefore, the anisotropy): shock acceleration in the unusual SNR Sgr A East can produce the required population of extremely energetic protons (provided a perpendicular shock geometry is realized). The GC γ-ray signals are fully compatible with – in fact, predict – the EHE neutron flux required to explain the EHE CR anisotropy, but they are not (simply) compatible with each other.

19. The Future

We need observations with better statistics and higher resolution at all energy regimes. In this context, we note the following:

- **Auger**. This will be the first Southern Hemisphere extensive air shower array since SUGAR. It promises a massive increase in EHE CR data down to $\sim 10^{18}$ eV. It should see a strong, GC point source of CRs and halo. It will either confirm or rule-out our scenario.
- **GLAST**: should establish definitively which GC object is supplying the $\sim$ GeV gamma-rays seen by EGRET.
- **TeV energies**: we need continued monitoring of the GC with air Cerenkov telescopes at $\sim$ TeV energies with Whipple, HESS, and CANGAROO. Results from the Whipple upgrade (VERITAS) are eagerly awaited.

20. Continuing Work

One fascinating extension of the work described here is encapsulated in the following question: What about the protons that get away (i.e., those that leave the GC environment without interacting to produce an indirect photon, neutron or neutrino signal)? Might the GC actually be a dominant CR source (the "Source B" alluded to a number of times in this conference) in a restricted energy regime above the knee? A tentative piece of evidence in support of this idea is the dipole-like data from AGASA: not only an overabundance towards the GC but, apparently a deficit towards the anti-GC are there with quite some statisitcal confidence in the data.

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