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On the possible galactic sources of the ultra-high energy cosmic ray anisotropy at 1 EeV

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Abstract. There have been many attempts to look for anisotropies in the arrival directions of cosmic rays in the expectation that the source of the particles might be revealed directly. Such prospects are more realistic when the energies of the particles are such that their Larmor radii are comparable to the thickness of the galactic disk. Recently, the AGASA group reported the analysis of a total of $216,000$ showers above 10^{17} eV observed over 15 years. They discovered a first harmonic signature in right ascension of amplitude $\sim$ 4% around 1 EeV. Remarkably, this is confirmed in two independent data set of 18274 and 10933 events between 1 and 2 EeV respectively. This corresponds to a 4.5σ excesses of events from directions close to the galactic center (GC). The AGASA array is sited too far north to cover the galactic center itself; however, the Sydney array, located at latitude 30.5 S has also claimed recently a point like excess region at $(\alpha, \delta) = (274, -22)$, i.e., close to (but not at) the Galactic center in the energy range $10^{17.9}$ to $10^{18.5}$ eV. In this paper we discuss these data and discuss possible interpretations of them. In particular we explore the possibility that protons accelerated to a high energy ($\sim$ 1 EeV) in some source(s) create high-energy neutrons via photopion production. We find that some of the characteristics of the experimental data can be explained under this hypothesis. Based on numerical simulations of particle propagation, we also set constraints to the location of a potential Galactic source.

1 The Experimental Data

Anisotropy searches were the main motivation behind the construction of the giant air shower arrays which were operated before the discovery of the CMB radiation and the subsequent prediction by Greisen, Zatsepin and Kuzmin in 1966 (Greisen (1966)) that there might be a cut-off in the cosmic ray spectrum at energies above 4×10^{19} eV. However the claims for anisotropy that have been made have rarely been substantiated when further data have been accumulated. Recently a very interesting result has been reported by the AGASA group Hayashida N. et al. (1999a) and an exploration of a similar sky region has been made by the Adelaide group Bellido et al. (2001) using data recorded by the Sydney array many years ago.

The AGASA group Hayashida N. et al. (1999a) reported the analysis of a total of $216,000$ showers above 10^{17} eV observed over 15 years. For their first report Hayashida N. et al. (1999b) they searched a data base of $114,000$ events and discovered a first harmonic in right ascension of about 4% around 1 EeV. Taking into account trials, this amplitude was reported as having a chance probability of occurrence of about 0.2%. Analysis in right ascension and declination showed that there were significant excesses of events from directions close to the galactic centre and the Cygnus region. The most significant excess in the near-galactic centre region was found when a beam size of 20^o was assumed. This beam size is very much larger than the angular resolution of the AGASA array, which is only a few degrees. As long as showers with zenith angles less than 60^o are used, the AGASA array cannot observe events with declination below -25^o, too far north to cover the galactic centre itself. Nevertheless, what is most important about the claim, is that the sample in the range 1.0 to 2.0 EeV has recently been increased from 18274 events Hayashida N. et al. (1999b) to 29207 events Hayashida N. et al. (1999a). For the additional 10933 events the overall amplitude in right ascension is 4.4% with a chance probability of 5.2×10^{-3}. This is the first time, at these energies, that a claimed anisotropy has been confirmed with an independent data set at a reasonable level of significance. The excess near the galactic centre that is the matter of interest in this paper can be summarized as a 4.5σ excess with 506 events in a region having an expected background of 413.6 events.

In an effort to confirm the AGASA result, the Adelaide group Bellido et al. (2001) have used data recorded many years ago by the Sydney University shower array Winn et all

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(1986). The Sydney array was located at latitude 30.5 S and was operated between 1968 and 1979. This array probably had a rather inferior energy resolution compared to that of the AGASA instrument so the Adelaide group chose a priori the range $10^{17.9}$ to $10^{18.5}$ eV for their study. For the 54% of events that triggered more than three stations, the angular accuracy is taken from Winn et all (1986) to be $3 \sec q$, where q is the zenith of the event. This angular uncertainty was used to define a Gaussian point spread function and a shuffling technique adopted to compare the probability density distribution for the real data with that expected for an isotropic distribution. Two regions of excess were found, one of which at $(\alpha, \delta) = (274, -22)$, or $(l, b) = (9.8, -3.1)$, is close to the AGASA *galactic centre signal*. This signal is ~ 10 degrees from the galactic centre and from a region of sky consistent with the angular resolution of the detector: the signal peaks with a probability of 0.005. Within a circle of radius 5.5 , centred on the *Sydney source* there are 21.8 events in the probability density map as compared with a background expectation of 11.8. However the point source nature of the Adelaide/Sydney signal is different from the broad span of intensity enhancement found by the AGASA team.

At present it is not clear whether these two apparently significant signals from similar regions of the sky are consistent and could therefore originate in the same way. However a common suggestion Bellido et al. (2001); Hayashida N. et al. (1999b) has been that the signals might be due to neutrons, as suggested soon after the first report of the AGASA excess at the Durban International Cosmic Ray Conference Hayashida N. et al. (1997); Watson (1997). We explore this idea below.

2 The neutron hypothesis

It is well known that a neutron of 10^{18} eV has a mean lifetime comparable to the rectilinear travel time from the galactic centre to the Earth. In their detailed paper Hayashida N. et al. (1999b) the AGASA group postulate a neutron source in the galactic center region produced by the interaction of heavy nuclei with photons or matter in the region around the source. They claim that this scenario is consistent with the dominantly heavy composition below 1 EeV claimed from Fly's Eye data Gaisser (1993) and with the lack of anisotropy below $10^{17.9}$ eV. They point out that below 1 EeV the neutron energy spectrum strongly depends on the source distance while at larger energies it depends on the energy spectrum at the source. They find that the experimental data on the amplitude of the anisotropy can be reasonably well fitted with a neutron spectrum at the source having a power law slope $\gamma = -2.5$, a source distance of 10 kpc and a cut-off energy for the neutrons of $E_{cut} = 10^{18.5}$ eV. Below we discuss the origin of the neutrons proposed and the plausibility of this "post hoc" fit to the data in the context of the AGASA result and that from the Sydney analysis reported by the Adelaide group.

We consider that interactions of high energy protons with ambient protons or IR photons are a more likely way of generating a high energy neutron flux than the interaction of heavy nuclei with either ambient photons or ambient gas. The point is that the energy carried away by a neutron produced after spallation or photodisintegration of a heavy nucleus will, to a good approximation, have an energy equal to the energy per nucleon of the nucleus. Thus to create a neutron of 1 EeV with an iron nucleus as primary would require that it had an energy some 56 times as great. Mechanisms involving high energy protons producing neutrons are inherently more energy efficient.

There are two mechanisms for neutron production to consider: these can be represented by the reaction equations

$$p + p \longrightarrow n + p + N\pi \tag{1}$$

and

$$p + \gamma_{IR} \longrightarrow \Delta^{+} \longrightarrow n + \pi^{+} \tag{2}$$

where in each case the proton on the left hand side is the particle with an initial energy of ~ 1 EeV. Reaction (1) will certainly produce neutrons that will carry away about 50% of the energy of the initiating primary. However the mean free path for a p-p collision is about 40 g cm^{-2} at 1 EeV so that even in 30 g cm^{-2} only 50% of the protons will interact. This is equivalent to a column density of $\sim 2 \times 10^{25}$ cm^{-2} or, e.g. 6×10^{5} M$_\odot$ inside a 1 pc scale region. This is a large amount of matter to surround a source and can only be found in very few astrophysical environments inside the Galaxy, like the central cores of giant molecular clouds and, perhaps, the neighborhood of its central supermassive black hole.

Reaction (2), photopion production, is also a promising, and perhaps less demanding, route for generating a neutron beam.

The photon energy for photopion production can be roughly estimated from the well-known relationship for a photon to be above threshold in a head-on collision with a photon:

$$E_{th} = 2\Gamma E_g \tag{3}$$

where Γ is the Lorentz factor of the proton and E_{th} and E_g are the threshold energy and an energy characteristic of the ambient photon field, respectively. Thus if the threshold is 200 MeV and the proton has $\Gamma = 109$ then the characteristic photon energy is 0.1 eV, i.e. the infra-red region of the spectrum. Using the method outlined by Stecker Stecker (1968) in the context of photopion production on the cosmic microwave background radiation, a mean free path $\lambda \sim 1.1 \times 10^{20}$ cm ~ 37 pc can be obtained for the interaction with an IR photon background at ~ 100 K in the inner regions of the GC.

3 The location of the source

The AGASA result points to the possible existence of a source of EeV CR in the direction of the GC. Common sense then seems to indicate the GC itself as the very source of these particles; for the first time at high energies, the distance scale to the source would be known: 8.5 kpc. The latter is quite satisfactory in principle, since our Galaxy is known to have a central supermassive black hole: $M_{BH} \sim 2.5 \times 10^6$ M$_\odot$. Furthermore, as demonstrated by Levinson and Boldt (2000), the maximum energy achievable in Sgr A*, due to the electric potential difference generated by spinning of the BH, is of the order of 1 EeV which would naturally explain the absence of an excess of events at higher energies in AGASA and Sydney data.

However, inconsistencies arise within this picture. First, while AGASA does not have the GC inside its field of view, its signature suggests the general direction the GC; Sydney, on the other hand, had a good view of the GC, but its signature is off center by $\sim 10^o$, which amounts to an offset of ~ 1.5 kpc at a distance of 8.5 kpc. This is not a trivial bending. Second, the nature of the images detected by both experiments are different. AGASA's signal is maximal for a beam size of 20^o and their published significance map shows an extended source; but Sydney sees a point like source.

We have performed particle propagation simulations for neutrons and their decay products (protons) inside the magnetic field of our galaxy (GMF). We performed a comprehensive study of propagation in the vicinity of 1 EeV for axisymmetric and bisymmetric regular GMF models with and without a random component (Kolmogorov spectrum). Two different models were assumed for the random field: (a) one in which the amplitudes of the regular and irregular field scale in the same way along the Galactic plane, which gives place to regions in which the total field goes to zero and (b) an alternative model (inspired in Beck et al. (1996)) in which the total field increases smoothly towards the inner galaxy despite the radial oscillations of the regular component.

If neutrons are injected at the GC, our simulations show that most neutrons fly in a straight line from source to Earth forming a point image centered on the source coordinates. Those neutrons that decay into protons while traveling radially outward from the galactic center, have their trajectories scrambled by intervening magnetic fields and lose directional information when arriving at Earth. In the absence of a random field, the latter proton component propagates along the spiral arms arriving at Earth from $0^o < l < 180^o$ (see Figure 1). Much the same happens if model (a) of the random field is included, while a uniform background is formed for random field model (b). In any case, the total signature, neutral plus charged, is never the same as the point (Sydney) plus extended halo (AGASA) observed by both experiments (see figure 2). Furthermore, a point source of neutrons in the GC would never produce a point image at $\sim 10^o$ from its true location.

A direct conclusion of this is that a neutron source cannot be located in the GC and be responsible for both observations. To lose this option means to lose the distance scale to the particle source, as now it might be located anywhere in the Galaxy along the line of sight.

A point to note is that, if there were a GMF topology able reconcile AGASA and Sydney results, the hypothetical GC source should be stable for $\sim 10^6$ yr, since protons arriving from a neutron source are much older than the neutrons, typically several 10^5 yr (see figure 1).

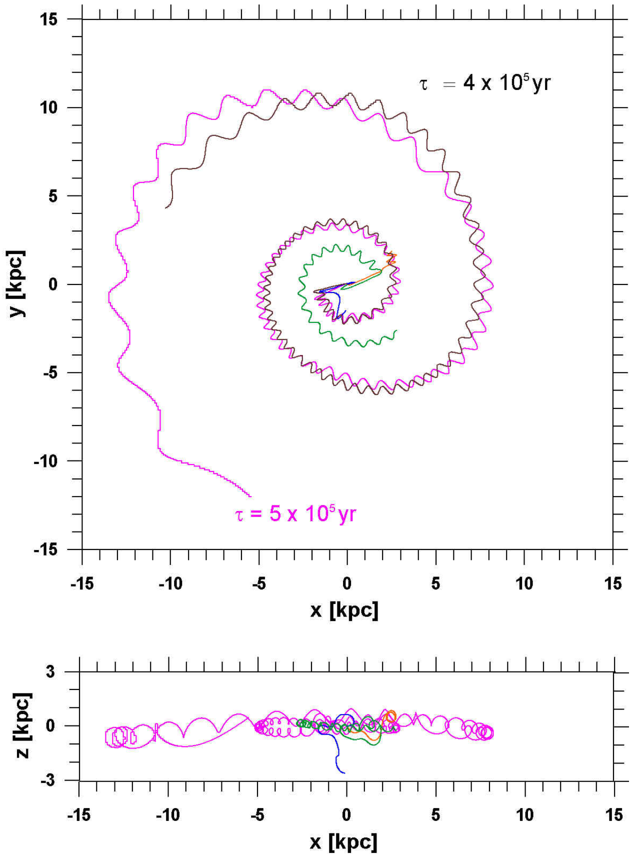

Fig. 1. Proton trajectories at 1 EeV in the regular (no random) GMF. At 1 EeV particles are restricted to propagate along the spiral arms. When the random component is included are scrambled, but still tend to arrive at Earth from positive galactic longitudes. The latter tendency disappears for random field model (b). The numbers in the upper box are the ages of the protons originated at the GC at the end of the plotted tracks. Note that these ages are much larger than the flying time of neutrons, $\sim 2.7 \times 10^7$ yr.

An alternative way to produce a peaked source surrounded by an extended halo and, therefore, to be able to combine AGASA and Sydney results is a source accelerating protons up to $E \sim 10^{18}$ eV roughly along the line of sight defined by Sydney, but much nearer than the GC. In figure 3 we show the results of several simulations of proton sources located at distances between 1.2 and 2 kpc, inside the galactic plane, $b = 0^o$, and galactic longitudes $l = 12, 18^o$. In a model like this, the position of the source would be rather well constrained ($d \sim 1.6$ kpc, and $(l, b) \sim (15^o, 0^o)$) in the case that AGASA and Sydney anisotropy observations are correct and correspond to the same point source; which, at this stage, is probably premature to say.

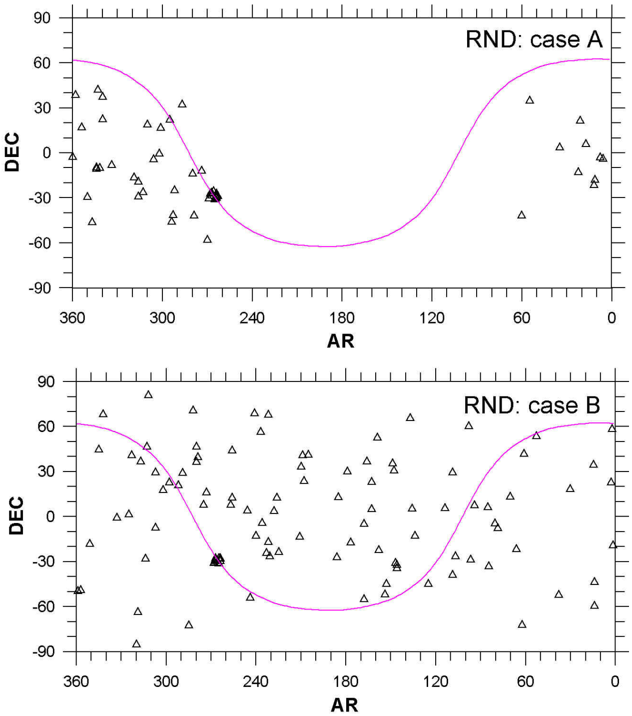

Fig. 2. Arrival directions at Earth for a neutron source located at the GC. Neutrons are injected at 1 EeV and decay while traveling through the Galaxy. The spot at the position of the GC is formed by neutrons; all other points are protons that decayed from neutrons and had their trajectories deflected by the GMF. Results are shown for two different models of the random component (see text).

4 Conclusions

A priori, neutrons seem to provide a natural explanation for the AGASA anisotropy signal in the direction of the GC. Neutrons can be plausibly produced from EeV protons interacting with a very high column density of matter or a background of IR photons in the GC. Also, a viable acceleration candidate exists in the region in the form of a supermassive black hole which has just enough power to produce the maximum energy observed coming from that region, but not more, providing a natural upper cut-off consistent with observations. However, neutrons should point exactly (within the angular error box of the experiment - few degrees) towards Sgr A* in the GC. Some of the neutrons traveling radially through the Galaxy should also decay inside the solar circle, giving some proton background signal at Earth. They are the primary candidates in this model for the production of the halo-like signal detected by AGASA extending up to several tens of degrees from the GC. Unfortunately, based on numerical simulations of particle propagation, it seems unlikely that such a halo appears in the required position for any of the possible GMF models considered. Furthermore, the detection by Sydney, if correct, is off the GC by $\sim 10^o$. If the latter signal is due to neutrons, then their source cannot be the GC. Moreover, if this is the same source observed by AGASA, then AGASA's source is not located in the GC

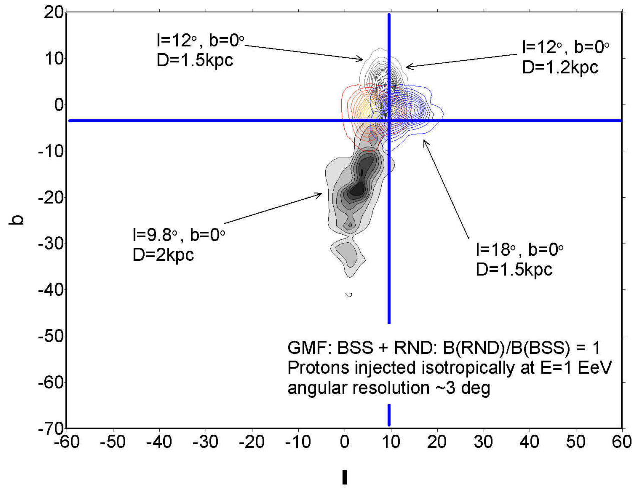

Fig. 3. A source of protons at different positions in the galaxy. This shows that an isotropic source of protons located at $d \sim 1.6$ kpc, and $(l, b) \sim (15, 0)$ could be compatible with both AGASA and Sydney data.

either.

An alternative possibility is that the excess observed by both experiments is due to protons, but the source is relatively near Earth, ~ 1.6 kpc, inside the Galactic plane at $l \sim 15^o$.

At any rate, it is fundamental at this stage that more data is obtained at 10^{18} eV, specially from the Southern hemisphere, to solve this most significant problem.

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