Southern Hemisphere Observations of a 10^{18}eV Cosmic Ray Source Near the Direction of the Galactic Centre

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Abstract

We report on an analysis of data from the southern hemisphere SUGAR cosmic ray detector. We confirm the existence of an excess of 10^{18}eV cosmic rays from a direction close to the Galactic Centre, first reported by the AGASA group. We find that the signal is consistent with that from a point source, and we find no evidence for an excess of cosmic rays coming from the direction of the Galactic Centre itself.

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1 Introduction

It is generally accepted that the majority of cosmic rays observed on Earth are accelerated within our galaxy. However, apart from our Sun at low energies, no specific acceleration site has previously been confidently identified for hadronic cosmic rays. Various mechanisms have been proposed for their acceleration, including the very efficient shock acceleration in supernova explosions. All proposed galactic mechanisms have difficulty explaining the highest energy cosmic rays, and the lack of any likely candidates has led to a search for extragalactic sources for these particles. The energy at which galactic sources might be overtaken by extragalactic sources is not at all clear but is of considerable interest. The situation is complicated by the galactic magnetic field which is thought to be strong enough (of order 1μG) to scramble the directions of charged cosmic rays at energies up to at least 10^{18}eV [1]. It is only at 10^{19}eV, when the Larmor radius of a cosmic ray proton becomes comparable with the galactic scale, that one can confidently expect a clear galactic anisotropy if galactic protons exist at these energies. No strong cosmic ray anisotropy had been detected from galactic directions until very recently.

In 1999 the AGASA group reported a study of data collected with their $20\,\mathrm{km}^2$ and $100\,\mathrm{km}^2$ extensive air shower arrays over the period from 1984 to mid-1995 [2]. With such a large data set they were able to systematically perform harmonic analyses in right ascension as a function of energy, from 10^{17}eV to 10^{20}eV. They discovered a large first harmonic anisotropy (amplitude 4%) over the narrow energy range from $10^{17.9}$ to $10^{18.3}$eV. A sky map of the cosmic ray density showed that this anisotropy was apparently caused by an excess in a direction close to the Galactic Centre, with a possible smaller excess from the direction of the Cygnus region of the galactic plane. When producing the sky map, the AGASA group tried 4 different assumptions for the signal beam size, and found that the near-Galactic Centre excess was most significant when a beam size of radius 20° was assumed. That excess was a 4.1σ deviation above the expected isotropic flux.

This very important analysis was complicated by the number of trials in energy and beam size used to produce the final result. More recently the group has completed an analysis of AGASA data up to April 1999 [3]. This extra time has resulted in almost a doubling in the number of events in the energy region around 10^{18}eV. A new analysis was performed on the entire data set from 1984 to 1999, and the results of the original study were confirmed. The group selected a slightly different energy range, from $10^{18.0}$ to $10^{18.4}$eV, and produced a sky map assuming a beam size of radius 20°. They found a 4.5σ excess near the Galactic Centre (506 events with a background of 413.6 events), with a smaller 3.9σ excess (3401 events with a background of 3148) seen in the Cygnus region.

Some evidence for a galactic plane excess was also seen in data from the Fly's Eye experiment over a similar energy range [4]. This was a broad-scale study, and no attempt was made to identify whether any particular galactic longitudes were responsible for the excess. As pointed out by the AGASA group, other experiments such as Haverah Park and Yakutsk are too northerly to see the excess region identified by AGASA near the Galactic Centre.

The energy dependence of the anisotropy may offer a clue to the nature of the signal particles. At an energy of 10^{18}eV a neutron will have a decay length of approximately 10 kpc, roughly the distance to the Galactic Centre [5]. At energies lower than this, neutrons from the distance of the Galactic Centre would decay before reaching Earth. The appearance of the anisotropy at around 10^{18}eV could be explained by this effect. Its disappearance at 3×10^{18} might then be explained by the source reaching its energy limit. Other clues to the nature of the signal particles would include the scale of the anisotropy on the sky (point source-like or broad) and the response of different detector arrays to the signal events (a possible discriminant between hadronic and non-hadronic primary cosmic rays).

2 The SUGAR Air Shower Detector

Because of the detector latitude and a shower zenith angle cut (60°), the AGASA sky map cuts off at a declination of $-24.2°$, some 4.7° north of the Galactic Centre $(\alpha, \delta) = (266.4°, -28.9°)$ (J2000.0). Their most significant excess, near the Galactic Centre, is on the edge of the sky map. In order to study this region and more southerly declinations, we have used data collected by a large southern air shower array, using the AGASA results to define *a priori* cuts and thus avoiding statistical penalties.

The SUGAR array was located in the Pilliga State Forest in New South Wales, Australia (array latitude 30.53°S , longitude 149.60°E) and was operated between 1968 and 1979. It enclosed an area of up to 70 km^2, and was designed to detect showers produced by the highest energy cosmic rays [6]. The array had an energy threshold of about 2×10^{17}eV, and in its final configuration consisted of 47 independent stations. Each station contained two buried liquid scintillator counters separated by a distance of 50 m. The shielding over each detector was (1.5 ± 0.3)m of earth, and hence these detectors were sensitive to the penetrating muon component of extensive air showers (with a muon energy threshold 0.75 GeV for vertical showers).

The typical detector station spacing in the array was 1.6 km, since the main purpose of the array was to study very large showers with energies above 10^{19}eV. However, a small (approximately 1 km^2) sub-array with detector spacing of 500 m was operated with sensitivity to showers around 10^{18}eV.

3 Analysis

Our intention was to study the Galactic Centre region highlighted by the AGASA analysis, and we have used their results to set *a priori* the energy range to be used in this SUGAR analysis. The SUGAR group determined the primary particle energy from a shower's equivalent vertical muon size by applying a conversion factor determined by early simulations of Hillas (see [6]). We have found that the SUGAR integral energy spectrum derived with this technique is in good agreement with the AGASA spectrum [7] around 10^{18}eV. We have chosen (*a priori*) an energy range of $10^{17.9}$ to $10^{18.5}$eV for our study. This is slightly wider than the optimal AGASA range because we recognise that the SUGAR energy resolution is likely to be poorer than that of AGASA.

The SUGAR data set yielded 3732 events within this energy range. We produced a shower density sky map using the following technique. Each event was assumed to have a directional uncertainty of $3^\circ \sec\theta$, where θ is the zenith angle of the event. This uncertainty is based on a study of events triggering more than three SUGAR stations [6]. We have applied it to all events in our sample (54% of which triggered more than three detector stations) as the best available estimate of the uncertainty.

We represented each event by a gaussian probability function surrounding its nominal direction on the sky, with the gaussian's standard deviation equal to the directional uncertainty.

The volume of the gaussian was normalized to one. All events were added to the map in this way, resulting in a shower density map (Figure 1).

We next compare this map with the expectation based on an isotropic flux of cosmic rays. That expectation must take into account the exposure of the array in right ascension and declination. It was determined using the "shuffling" technique [8]. Here, a number of shuffled data sets are derived from the real data set, with each shuffled data set containing the same number of events as the real one. A real arrival time (Julian date) from one event is randomly paired with a local arrival direction (zenith angle, azimuth angle) from another event in the real data set. This is repeated until a new data set is filled. The new data set has the same arrival time distribution and the same zenith and azimuth angle distributions as the real data set. However, because the pairings have been randomized, all celestial directions have been randomized producing an isotropic event flux. Many shuffled data sets can be generated. For each of those, an event density map can be generated (like Figure 1) using gaussian point-spread functions. Figure 2 shows the isotropic background shower density map, derived from an average of 1000 shuffled maps.

Comparing the real density map with the isotropic expectation, we derive a map showing the fractional excess of event densities across the sky, shown in Figure 3. We show this map to emphasise that regions of excess are rare. Only two regions of interesting excess are apparent, with one of them near-coincident with the strongest AGASA excess. The other excess is quite likely to be a statistical fluctuation, given the number of unique directions represented on the map. This second region is not of interest to us as it was not part of our analysis strategy derived *a priori* which related to the region of the AGASA excess. The interesting SUGAR excess is centered at $(\alpha, \delta) = (274^\circ, -22^\circ)$ (B1950.0), close to the position of the AGASA excess (see below).

We next calculate the statistical significance of the SUGAR excess. To do this we again use the shuffled data sets. We grid the original shower density map (Figure 1) into 0.5° bins, and ask how many of the 1000 shuffled data sets have a shower density in the bin equal to or larger than the real bin density. Given that each shuffled map is a representation of an isotropic cosmic ray flux, this gives us a bin-by-bin probability that the real map density has occurred by chance.

We show the significance map for the signal region in Figure 4. The contours represent chance probabilities, with the signal region peaking at a chance probability of 0.005. (On this map, regions of excess will have chance probabilities less than 0.5, and regions of deficit will have chance probabilities greater than 0.5).

4 Discussion

Figure 4 shows at least two interesting features. First, there is no hint of a signal from the true centre of the galaxy, even though SUGAR (unlike AGASA) had a clear view of this region. The peak of the signal region is 7.5° from the Galactic Centre. Secondly, the signal region is no larger than would be expected for a point source of cosmic rays. The size of the region is consistent with the detector's angular precision. This would suggest that the particle source is not an extended region, and that the particles have not experienced large direction deviations during propagation.

In Figure 5 we compare our result with the AGASA map, using the 2,3 and 4σ contours from reference [3]. The peaks of the signals are displaced by about 6°, and the size of the signal region is clearly different with AGASA seeing a much broader enhancement. There are several possible reasons for the differences, including

- The SUGAR data is, simply by chance, tightly clustered and offset from the AGASA signal.
- The SUGAR peak could be offset due to a systematic pointing error in local coordinates. This question has been thoroughly investigated by the SUGAR group [9]. Possible sources of systematic errors in pointing were investigated (array survey, curvature of the Earth, electronics, propagation of radio timing signals through a refractive atmosphere and vegetation, the effect of ghosting of these signals etc) and it was concluded that likely systematic errors were small compared with random errors. In any case, a systematic pointing error of reasonable magnitude would also cause a significant smearing of the signal in right ascension and declination.
- The AGASA angular resolution is poorer than expected at large zenith angles, and/or

AGASA suffers from a systematic pointing error which manifests itself as a smearing and offset of the signal in right ascension and declination.

- The AGASA analysis technique, which uses signal averaging over 20° radius circles, has smeared out an otherwise point-like feature.

- Apparent excesses on the AGASA map further north along the galactic plane might have systematically shifted the peak of their main excess northward. No similar bias would have an opportunity to act southward, given their cutoff in declination at $\delta = -24^\circ$.

We encourage the AGASA group to consider performing an analysis of their data with a technique similar to ours. This technique requires an estimate of arrival direction uncertainty for each event, but it removes the need to search for an optimal beam size and it uses the data themselves to estimate the background.

We calculate the SUGAR source flux in the following way. Given our assumption that the size of the signal region is consistent with point-spread function, we count the number of events inside a circle of radius 5.5° centered on $(\alpha, \delta) = (274^\circ, -22^\circ)$. (The average zenith angle for events at this declination is approximately 30°, so the typical direction uncertainty would be $3^\circ \sec(30^\circ)$. We multiply this radius by 1.59 in order to maximize the signal-to-noise ratio of our flux estimate). We find that this region of the density map contains 21.8 equivalent events. This is compared with the background expectation of 11.8, the average number of events inside 27 circles of the same size arranged around same declination band. Thus the signal region is populated by approximately 10 signal events above an expectation of 11.8 background events. This is consistent with the chance probability of 0.005 derived above using shuffling and the sky maps. (The Poisson probability of observing 22 or more events when the expectation is 11.8 is 0.0050). Using the AGASA energy spectrum [7] as normalization, and assuming that the signal events have the same triggering efficiency as the background cosmic rays, this excess is equivalent to a point-source flux of $(9 \pm 3) \times 10^{-14}$ $\mathrm{m}^{-2}\mathrm{s}^{-1}$ or (2.7 ± 0.9) $\mathrm{km}^{-2}\mathrm{yr}^{-1}$ between $10^{17.9}$ and $10^{18.5}$eV. We cannot compare this flux with the AGASA result [3], since no flux is quoted and we do not know the procedure used by the AGASA group to estimate the signal and background counts within the large (20° radius) error circle used in their analysis. In particular, such a circle centred on the excess extends beyond the southern limit of the AGASA map.

The excess shown in Figure 4 is clearly not coincident with the Galactic Centre. At the declination of the Galactic Centre, the expected number of events between $10^{17.9}$ and $10^{18.5}$eV arriving within a circle of radius 5.5° is 13.4. The actual number of events within 5.5° of the Galactic Centre is 12.5. Thus, we calculate a 95% upper limit [10] on the point source flux from the Galactic Centre of 2.2 $\mathrm{km}^{-2}\mathrm{yr}^{-1}$ (or roughly 70% of the cosmic ray flux) over this energy range.

The peak of the SUGAR excess does not appear to be centered on the galactic plane itself. However, at a galactic latitude of only about 3° south, it is still within the SUGAR angular uncertainty of the plane.

We have examined astronomical data in the direction of the SUGAR peak to determine whether there might be any coincident objects of interest. The direction is on the border of galactic plane surveys and many surveys have only statistically poor information. However, an 11cm Effelsberg 100m single dish radio survey (sensitive to broad scale structure) [11] and data from the COMPTEL gamma-ray telescope [12] do seem to be useful, based on their angular coverage and the apparent quality of the data.

The 10-30 MeV COMPTEL dataset shows a large feature which arcs south of the galactic plane, from the Galactic Centre to an unidentified bright source in the galactic plane at 18° galactic longitude. That arc, with a radius of about seven degrees, is apparently centred on the direction of the SUGAR peak. The radio data show a bright region with a radius of about one degree in the direction of the peak and this appears to be surrounded by a roughly circular feature of much reduced radio intensity, again centred on the peak. There may be a brighter radio region outside that feature and coincident with the COMPTEL arc. The central radio source is polarised but there is no sign in the data for radio polarisation associated with the COMPTEL arc. If this feature was at the distance of the Galactic Centre, it would have a diameter of about 800pc.

We emphasise that these other astronomical data are within the SUGAR angular resolution and their apparently coincident directions may be a statistical artefact.

5 Conclusion

Data from the SUGAR array confirm the existence of an excess flux of cosmic rays from a direction near the Galactic Centre. While this result is not as statistically strong as that reported by the AGASA group, it is interesting in a number of ways. First, the SUGAR array consisted of buried scintillator detectors, with a muon energy threshold of 0.75 GeV for vertical showers. If the SUGAR flux we calculated above proves to be consistent with that measured by AGASA, it would imply that the signal particles are unlikely to be gamma-rays, unless our understanding of muon production in photon cascades is severely incomplete.

Secondly, the SUGAR array had a near overhead view of the true Galactic Centre, and found no signal from that direction. This, coupled with the observation that the SUGAR signal is point-like in character, raises the possibility that the source of these particles is unrelated to the centre of our galaxy. For example, it is conventional to think of the galactic magnetic field as a superposition of regular and turbulent components. It would be difficult to conceive of a field structure which would take a source of charged cosmic rays at the Galactic Centre and make it appear like a point source offset by 7.5° from the true source direction. Clay [13] has discussed propagation from such a source and has shown that a large diffuse region would result, a region much larger than the point spread dimensions observed with SUGAR.

The possibility of neutron primary particles cannot be ignored, especially as this could account for the turn-on of the signal at around 10^{18}eV (e.g. [5]) if the source were at a distance close to that of the galactic centre. It would also account for the point-like character of the excess as seen by SUGAR.

6 Acknowledgements

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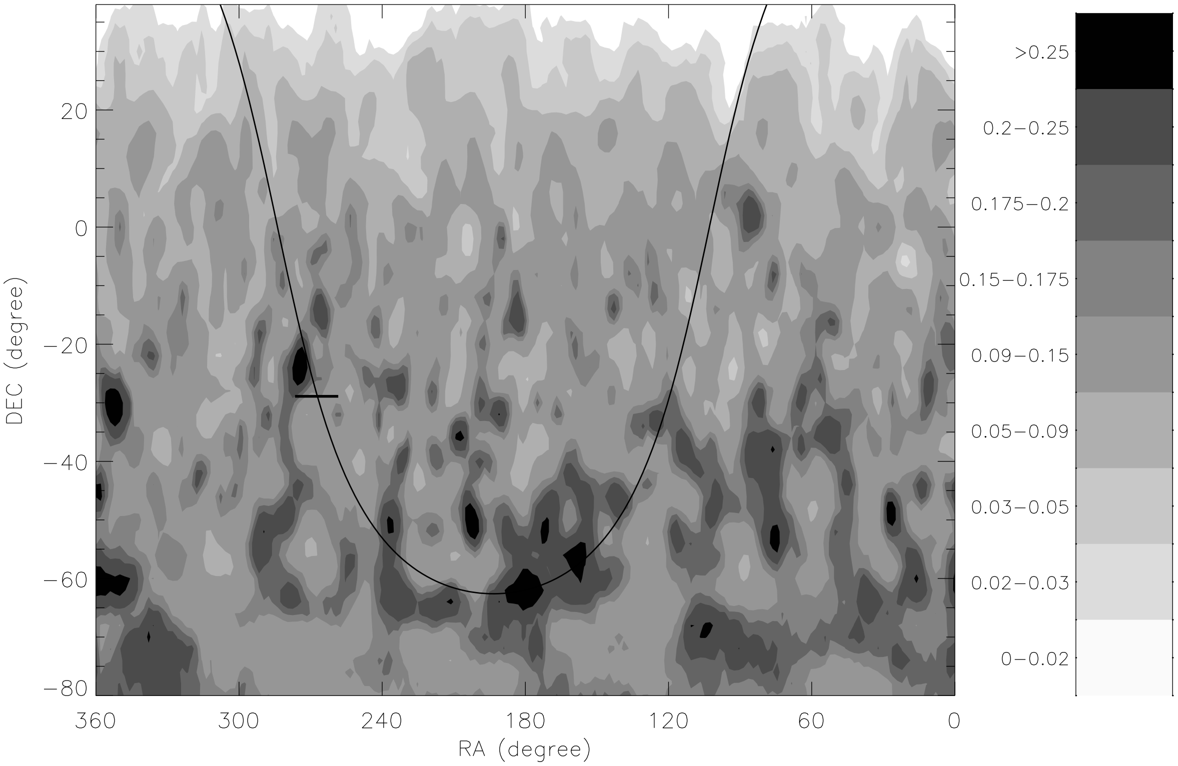

Figure 1: Cosmic ray event density over the sky viewed by the SUGAR array for the 3732 events between $10^{17.9}$eV and $10^{18.5}$eV. The density scale represents the number of events viewed per true square degree of sky, where a true square degree is defined as being 1 degree in declination $(\delta) \times 1^\circ \sec\delta$ in right ascension. A point spread function has been applied to every event to represent the angular uncertainty in their arrival directions. The galactic plane and Galactic Centre are indicated with the solid line and cross respectively. The 1950 epoch has been assumed for the equatorial coordinates displayed here and in other plots.

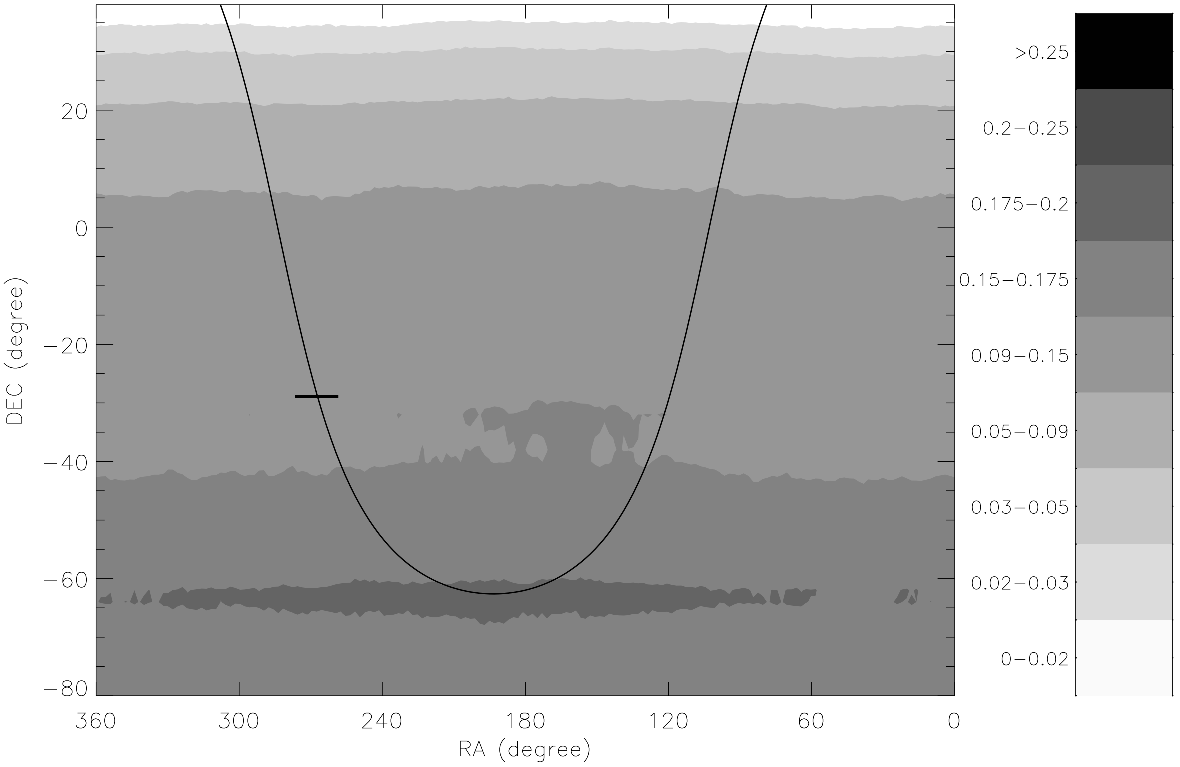

Figure 2: The expected density of events for an isotropic flux of cosmic rays as viewed by SUGAR between $10^{17.9}$eV to $10^{18.5}$eV. Again, the density is given in units of events per true square degree (see caption to Figure 1).

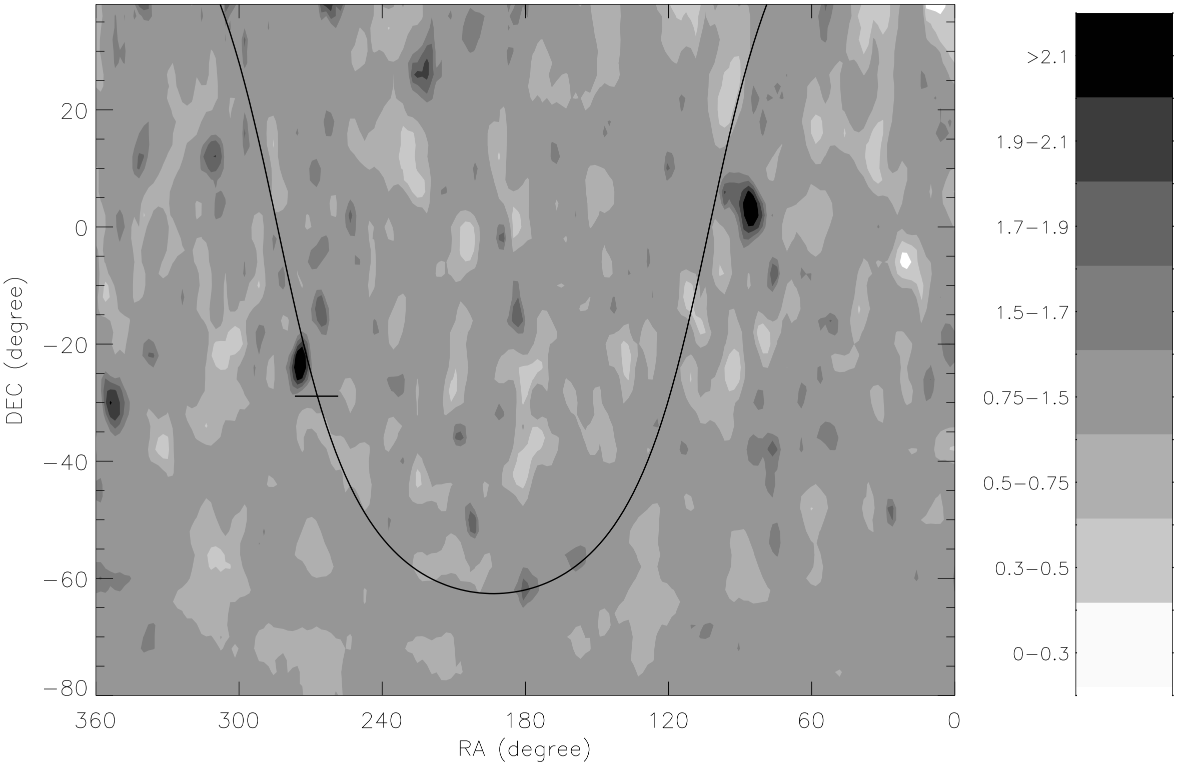

Figure 3: We compare Figures 1 and 2 and derive the fractional excess (or deficit) of the event density over the sky viewed by SUGAR. A value of 1 indicates that the measured density is in agreement with the expected density.

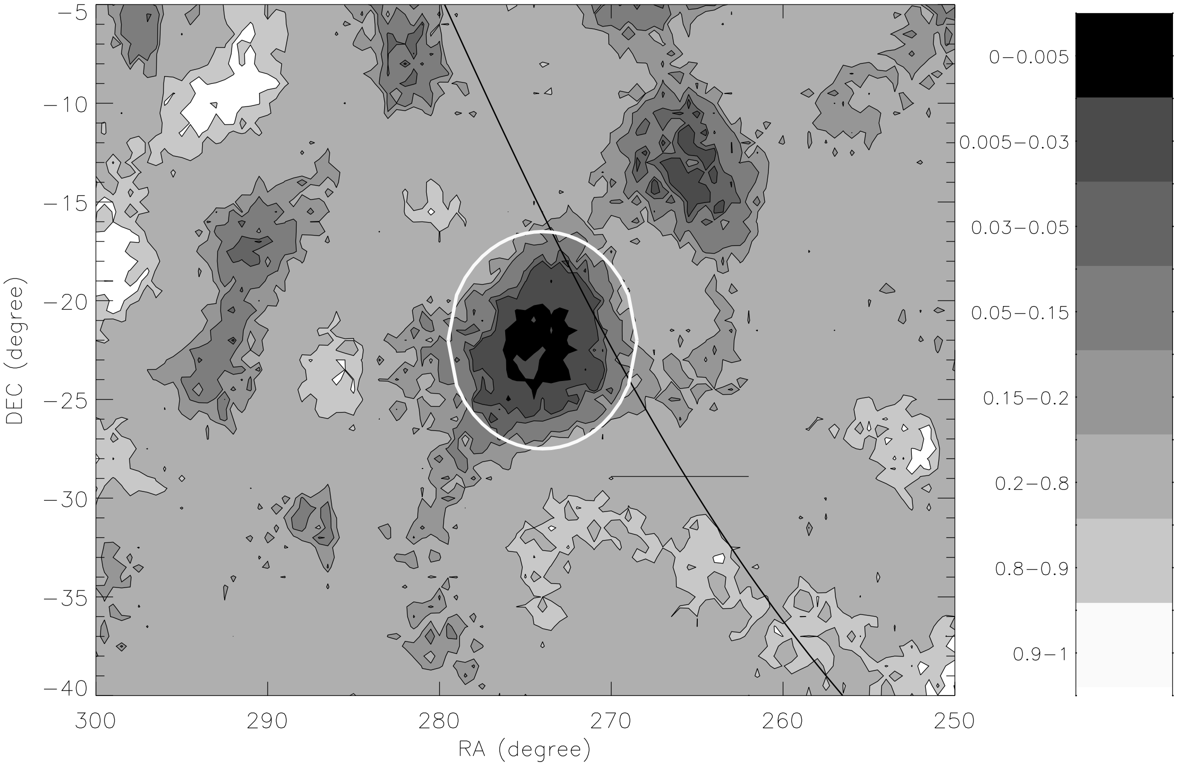

Figure 4: The significance of the excess detected in the Galactic Centre region, as calculated using shuffled data sets. The contours represent the chance probability of SUGAR detecting the observed density or greater. Thus, a contour level of 0.5 represents a measured density which is consistent with expectation. The peak of the signal region has a chance probability of 0.005. The galactic plane and Galactic Centre are indicated by the solid line and cross respectively. The white circle of radius 5.5° represents the typical error circle for SUGAR events. The excess therefore appears to be consistent with that from a point source.

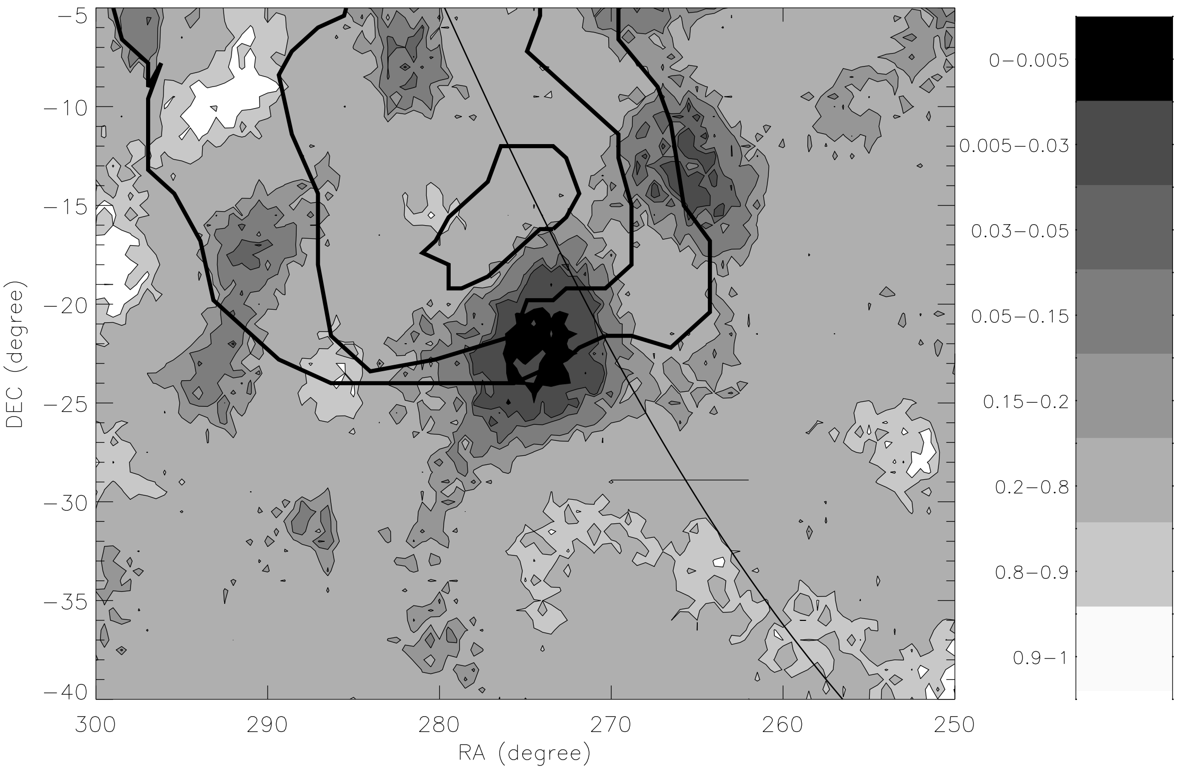

Figure 5: A comparison of the AGASA and SUGAR results. The SUGAR map from Figure 4 is overlaid with 2σ, 3σ and 4σ contours from reference [3]. Note that the limit of AGASA's view is close to $\delta = -24°$, indicated by the horizontal portion of the 2σ contour. The AGASA signal region size is significantly larger than seen by SUGAR. See the text for a discussion.