*OG.3.3.19*

# Cosmic Ray Acceleration in the Galactic Center Region II: Neutrinos

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**Abstract**

The measured Galactic cosmic ray spectrum can be explained as a superposition of injection from supernovae exploding into the interstellar medium and injection from supernovae that explode into their own stellar winds. This leads not only to predictions for the energy spectrum and chemical composition of the charged cosmic rays, but also to predictions for the observed or soon-to-be observed gamma-ray fluxes. Using a model which appears compatible with the existing gamma ray data from EGRET and CASA-MIA, we present here the calculations of what the various neutrino detectors should expect to see. It appears that the thin strip of the inner Galaxy may be detectable in neutrinos around TeV energies. This would confirm one the most basic interpretations of the physics of cosmic rays, and may finally confirm where cosmic rays come from at all energies, and how they propagate.

## 1 Introduction:

Cosmic rays have provided many riddles to science since their discovery, and now with detections at energies far greater than what is reproducible with experiments, the challenge has only intensified. However, the origin of cosmic rays at even moderate energy (around GeV to TeV range) is not certain, and our understanding of the physics involved in their propagation is even less so. In this paper we wish to use a model built to account for the the EGRET and CASA-MIA $\gamma$-ray data in the context of cosmic ray interactions, and to investigate whether these cosmic ray interactions will provide a detectable neutrino signal. Detecting such a signal will be a strong boost to neutrino and cosmic ray astrophysics.

In the standard model for cosmic ray propagation, the average spectrum interacts with the interstellar medium (ISM), consisting of both matter and radiation, thus producing $\gamma$-ray emission via a combination of meson decays, inverse Compton (IC) upscattering of the ambient radiation field and bremsstrahlung. For photons above $\sim 1-10$ GeV, the spectrum is dominated by the meson (mainly pions and kaons) decay component and the spectrum will reflect the observed parent cosmic ray spectrum. Meson decay will usually also produce neutrino emission at a rate basically equal to that of the photon rate, averaging over the various interaction channels.

We then need to distinguish the various possibilities for the cosmic ray spectrum which is relevant for the interaction. The average spectrum in the conventional model has an injection spectrum of $E^{-2.1}$ near the source regions, which then decreases to $E^{-2.7}$ as the distribution undergoes diffusive losses in traveling away from the source. However, as shown in both (Hunter et al. 1997) and (Mori 1997), it is impossible to fit the EGRET inner Galaxy diffuse $\gamma$-ray data using the observed cosmic ray spectrum, which is too steep. An additional constraint comes from the CASA-MIA experiment (Borione et al. 1998), which measured the diffuse emission of the Galactic plane and set a very low upper limit in the $100-1000$ TeV range. (Ong 1998) demonstrates that any straight extrapolation of fits to the inner Galaxy EGRET data overshoots the CASA-MIA $\gamma$-ray limits by a fair margin.

The question then remains, what realistic models exist which can simultaneously satisfy both sets of data? What we have found using the gamma ray data, is that a model with the following properties still manages to fulfill the constraints:

- The interaction region is near the sources of cosmic rays.
- The source spectrum is near $E^{-2.3}$ up to a knee near $700Z$ TeV, and then steepens by about $0.4$.
- The spectrum extends to a particle energy close to $3\,10^{18}$ eV.
- The chemical composition is heavily enriched, since it derives from massive stars, which have lost of their envelope already. The bend at the knee is due to a reduced acceleration efficiency in the shock at an energy where the curvature drifts begin to fail. Beyond the knee medium to heavy elements dominate completely.

No other model involving mesonic decay managed to come even close to the data constraints.

Such a model predicts fairly substantial fluxes of gamma rays from the inner Galaxy around TeV energies, and so may be refuted or confirmed soon by the MILAGRO experiment. Here we address the corresponding neutrino fluxes.

## 2 The neutrino experiments:

Neutrino experiments are expected to detect first the atmospheric neutrinos - they have been seen in abundance by detectors designed for the GeV energy range like IMB, Kamiokande, Fréjus, Soudan, MACRO, and finally Super-Kamiokande. The Baikal and AMANDA experiments have also a certain number of events in the 100 GeV range, which are presumably due to atmospheric interactions.

As has been discussed in various reviews, especially by R. Protheroe, K. Mannheim, and F, Halzen, we do expect neutrinos from a cosmological isotropic background, from gamma ray bursts, from cascading from topological defects, from cosmic ray interactions, and of course also due to active galactic nuclei. This latter component is based on a particular model for the the main emission mechanisms in active galactic nuclei and their relativistic jets. Active galactic nuclei, their jets and hot spots may provide the most energetic cosmic rays, and so their neutrino emission is intimately linked to the production of energetic particles.

Here we wish to argue about a source much closer to home, our own Galaxy. There can be no doubt that our Galaxy has a strong population of cosmic rays, which interact. The models explored heretofore (Berezinsky et al. 1993) always used the average cosmic ray spectrum as the spectrum to be used for interaction. However, the gamma ray data suggest that we may need the spectrum of cosmic rays much closer to the source, so a flatter spectrum, which produces a much higher flux of neutrinos. This makes our calculation interesting.

There are four neutrino experiments operating or under construction which can be expected to detect neutrino events near TeV and at higher energies soon: AMANDA, ANTARES, Baikal, and NESTOR.

**Baikal:** The first muon neutrinos using natural (lake) water as interaction and Cherenkov light propagation medium were detected by an experiment in the Lake Baikal in Siberia. The detector has gradually been enlarged to its present size of 196 photomultipliers (NT-200). It is planned to extend this detector by one order of magnitude (NT-2000). The effective area, then would stay one order of magnitude below the canonical requirement of 1km$^2$ needed to detect extraterrestrial neutrinos (Spiering 1998), but with a sufficient energy resolution in the TeV range neutrinos from the inner Galaxy could be detected.

**AMANDA:** The AMANDA detector is located exactly at the geographical South Pole in a depth above 1500 m using ice as sensitive medium. The detector consists presently of 302 photomultipliers at 13 strings and has a typical effective area of $10^4\ \mathrm{m}^2$. By next year a outer ring of strings around the detector will be completed. AMANDA II then will be a 21 string detector with 800 photomultipliers and an effective area of $3 \cdot 10^4\ \mathrm{m}^2$. It is planned to construct within the following years ICECUBE, a km$^3$ array (Halzen 1995, Barwick 1998). Since we are considering the inner Galaxy, which is at -28 degrees declination, the AMANDA experiment sees it mostly above the local horizon, and so will have a severe background from muons from cosmic ray interactions in the atmosphere from the direction of the inner Galaxy.

**ANTARES:** ANTARES is one of two experiments, which intend to use the open Mediterranean sea as a detector medium. Presently string deployment, retrieval and maintenance in the open sea and the optical properties of water are studied at a 2400 m deep site close to Toulon (France). Based on these experiences, it is intended to construct soon a particle detector, which finally also should reach the size of $1\ \mathrm{km}^3$ (Feinstein 1998). For Antares as for Baikal the inner Galaxy is below their horizon, they are therfore both in a good position to detect neutrinos from this source. Especially the $\mathrm{km}^3$-size of Antares makes it for this purpose to an extremely sensitive experiment.

**NESTOR:** The same holds for the second Mediterranean experiment, NESTOR, which is planned to be located close to the Greek island of Pylos. This site was chosen to take advantage of a sharp fall off (to 4500 m) near the shoreline yielding the possibility to deploy strings at a depth of up to 4000 m. If realized, an experiment at this location would have an atmospheric background of 50 to 100 times smaller than at the other sites. (Sotiriou 1998)

## 3 Results and Discussion:

Using then the best remaining mesonic interaction model to account for the gamma ray data we immediately deduce an implied neutrino flux and spectrum. This spectrum is similar to some of the existing extragalactic models, but of course the emission from the inner Galaxy is localized along a thin strip in the sky, and neither isotropic nor localized in point sources. Of course the Galactic Center region itself may give a peak in emission.

In terms of detector statistics we would expect a few hundred neutrino induced muon events above 1 TeV per 10 years localized in the sky along a strip maybe 120 degrees long and a 10 to 20 degrees wide, centered on the Center of our Galaxy. This estimation takes the uncertainties due to the superposition ansatz for the high energy heavy particles already into account.

Confirming this prediction would finally settle several key questions in cosmic ray physics:

- Do hadronic interactions really dominate for the gamma ray emission of the Galaxy? Here we have made this assumption, but we need to check. The MILAGRO gamma ray data may settle this question one way or the other before the neutrinos get there.
- Are these hadronic interactions then a good tracer of cosmic ray source environments up to $3\,10^{18}$ eV? If so, they would give a useful baseline for any study of what happens in active galactic nuclei.
- Confirming the neutrinos close to expectation in spectrum and flux would finally confirm where cosmic rays come from. And we may then expect to learn this not only for cosmic rays below 100 TeV, where there is little controversy, but also all across the knee, linking up to the presumably extragalactic cosmic rays. This will be a critical and independent confirmation for all the direct air shower and Cherenkov cosmic ray experiments, as well as the high energy gamma ray experiments.
- This will also give information on the propagation of cosmic rays, since we may expect to be able to compare source and average cosmic rays.

Combining the direct cosmic ray experiments, the Gamma ray experiments, with the neutrino experiments we may expect to be able to solve the question of where cosmic rays come from, and so start using cosmic rays as a tool to do high energy physics, probing the inner structure of matter in a way very different from ground based accelerators and at much higher energies.

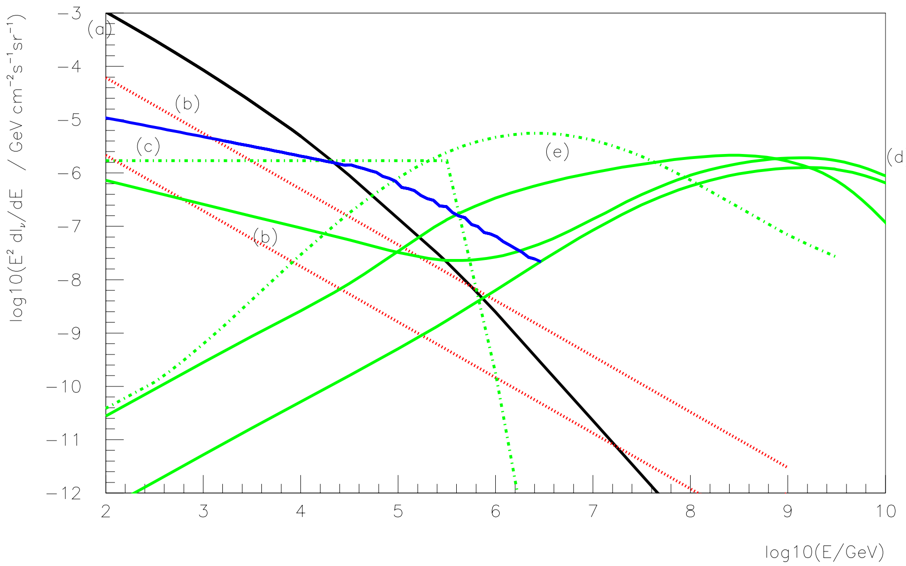


Figure 1: Comparison between different sources for neutrino induced muons: (a) atmospheric induced muons, (b) interactions with the interstellar medium (upper curve for $l = 0°$, $b = 0°$, lower curve for $b = 90°$) (Domokos 1993) (c) this calculation (d) AGN jet models: (Mannheim 1995) and (Protheroe 1996), (e: dashed dotted) AGN disk models: (Nellen et al. 1993) left and (Stecker 1993) right.

## 4 Acknowledgements

We wish to thank many colleagues, here especially Karsten Eggert, Francis Halzen, Stan Hunter, Jim Matthews, Hinrich Meyer, Buford Price, Ray Protheroe, Todor Stanev, Samvel Ter-Antoyan for discussions on these topics.

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