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THE LAST GAMMA-RAY BURST IN OUR GALAXY? ON THE OBSERVED COSMIC-RAY EXCESS AT PARTICLE ENERGY 10^{18} eV

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ABSTRACT

Here we propose that the excess flux of particle events of energy near 10^{18} eV from the direction of the Galactic center region is due to the production of cosmic rays by the last few gamma-ray bursts in our Galaxy. The basic idea is that protons get accelerated inside gamma-ray bursts, then get ejected as neutrons, decay and so turn back into protons, meander around the inner Galaxy for some time, and then interact again, turning back to neutrons to be observed at our distance from the Galactic center region, where most star formation is happening in our Galaxy. We demonstrate that this suggestion leads to a successful interpretation of the data, within the uncertainties of cosmic-ray transport timescales in the inner Galaxy, and in conjunction with many arguments in the literature.

Subject headings: cosmic rays — gamma rays: bursts — ISM: magnetic fields

On-line material: color figures

1. INTRODUCTION

For some time now, the detection of an excess in 10^{18} eV cosmic rays from the general direction of the Galactic center (GC) by the Akeno Giant Air Shower Array (AGASA; Hayashida et al. 1999) has been a special riddle in Galactic cosmic-ray research. The angular region of the excess observed by AGASA and the Sydney University Giant Air Shower Recorder (SUGAR) is illustrated in Figure 1.

Gamma-ray bursts (GRBs) have long been argued to produce high-energy cosmic rays. In this Letter we show what the observational signature should be and try to demonstrate that the AGASA excess can be attributed to the last one or last few GRBs in our inner Galaxy. After defining the basic conditions for acceleration of protons to very high energy by Hillas (1984), Biermann & Strittmatter (1987) showed in a detailed analysis the limiting conditions due to proton-proton collisions, including the conversion of protons to neutrons in powerful shocks in radio galaxies; the analogy between active galactic nuclei and GRBs was noted in Biermann (1994a, 1994b). A quantitative application to GRBs was suggested by Milgrom & Usov (1995, 1996), Vietri (1995, 1996), and Waxman (1995), Miralda-Escude & Waxman (1996), and Waxman & Bahcall (1997), with a very recent review on GRBs by Zhang & Mészáros (2004). The AGASA excess and a similar excess in the Cygnus region were discussed also by Bednarek (2002, 2003) and Bednarz et al. (2002) using a point-source model. The propagation of protons through the Galaxy was discussed by Stanev (1997), Alvarez-Muñiz, Engel, & Stanev (2002), and others.

There is a significant excess around 10^{18} eV, seen by two different experiments, AGASA and SUGAR, of cosmic rays coming from the general direction of the GC region, that cannot be attributed to the expected gradient of cosmic-ray sources and distribution. This excess has been supported at the time by the air fluorescence detector Fly's Eye (Bird 1999). However, the sky coverage of AGASA does not include the GC, while that of SUGAR does (Clay 2001). The SUGAR data suggest a point source to within their spatial resolution, while AGASA shows an extended source.

The excess starts to be significant around 3×10^{17} eV, peaks near 10^{18} eV, and cuts off sharply at about 3×10^{18} eV (see Teshima et al. 2001). The flux of the excess particles can be turned into a luminosity of particles beyond 10^{18} eV of about 4×10^{30} ergs s^{-1}. Since AGASA cannot observe the entire region, this inferred luminosity must be a lower limit, with the true luminosity possibly being a factor of 3–10 larger.

As suggested by the AGASA Collaboration, these events may arise from neutrons (Hayashida et al. 1999); the possibility that they are due to photons was discussed and discarded by Bellido (2002) on the basis of SUGAR data. First, neutrons are not deflected because of the Galactic magnetic fields. Second, a peak at exactly 10^{18} eV corresponds to the distance to the GC region (in distance from here between 5 and 11 kpc, using the region of highest star formation rate of about 3 kpc around the GC [Güsten & Mezger 1983]), folding the neutron decay with an injected power-law spectrum. Only with neutrons would there be a lower limit in energy, above which there can be significant flux. With photons there is no such threshold. In this case the original proton must have had an energy about 3 times that observed, and so we require proton energies of at least up to 6×10^{18} eV.

There are three main mechanisms and respective sites to accelerate particles in the Galaxy: supernova explosions in the interstellar medium, in young and hot star bubbles, or in massive star winds. In any of the three cases such an energy per nucleon cannot be reached for any reasonable parameter of shock velocity and/or magnetic field (Lagage & Cesarsky 1983; Jokipii 1987; Biermann & Cassinelli 1993; Biermann & Strom 1993; Biermann 1994).

The only way to accelerate particles to such an energy per nucleon in a normal galaxy such as ours is relativistic shocks. Such relativistic shocks are produced in GRBs (Vietri 1998; Piran 1999). GRBs are believed to occur in every galaxy in some small fraction of all supernovae, of the order of 10^{-4}, arising from the final evolutionary stages of very massive stars, either in a binary

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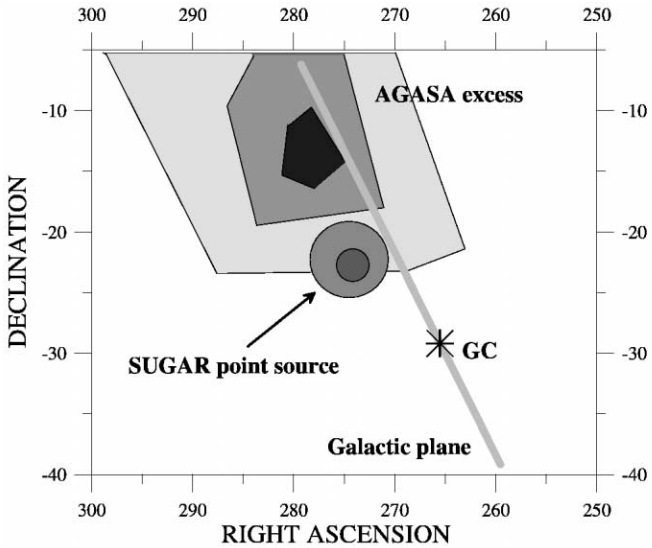

FIG. 1.—Cartoon map of AGASA and SUGAR data. Indicated are the regions from which an excess of cosmic rays is observed. In addition, the location of the GC and the Galactic plane is marked. Right ascension and declination are both given in degrees. [*See the electronic edition of the Journal for a color version of this figure.*]

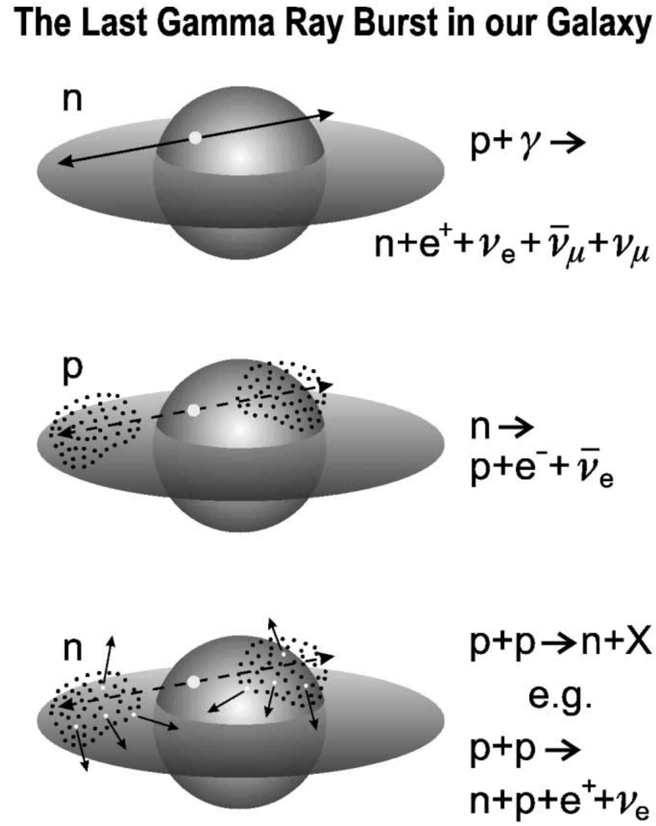

FIG. 2.—Scenario that we propose in three key time steps. First, neutron ejection, second, neutron decay, and finally, proton interaction leading to new neutrons being observable from Earth. The GRB is taken to happen in the thin disk within 3 kpc from the GC, seen here in projection together with the old stellar bulge. [*See the electronic edition of the Journal for a color version of this figure.*]

system or as a single star. Therefore we propose to ask: what are GRBs expected to produce in terms of energetic particles?

As shown in Rachen & Mészáros (1998), because of adiabatic losses, the highest energy particles that emerge from a GRB are mostly neutrons; protons are captive in the magnetic field and so suffer extensive adiabatic losses on the way out. These neutrons will decay after some distance, turning into protons, which are then caught by the magnetic field in the Galaxy and rumble around with a rather short residence timescale. There is a small but finite probability that they will produce a neutron again in interactions with the interstellar medium. These secondary neutrons then could travel undeflected to us to be observed. We try to follow the neutrons originally ejected from a GRB. Figure 2 shows our concept in three key time steps.

2. THE LAST GRB EVENT IN OUR GALAXY

In order to estimate the remaining traces of any activity of cosmic rays ejected and/or produced by GRBs, we discuss below various probabilities, the residence time for the protons resulting from the decay of the neutrons ejected, and present spectral and spatial arguments. We somewhat arbitrarily adopt here a GRB rate of 1 per 10^6 yr for the inner Galaxy (considering Piran 2001, this may seem pessimistic, but considering Frail 2001, even optimistic).

The residence timescale for energetic protons in the solar neighborhood is around (Gaisser 1990; Ferrando 1994) $\tau_{\rm res} = 2 \times 10^7$ yr $(E/10^9\ {\rm eV})^{-1/3}$ and so is about 2×10^4 yr at 10^{18} eV. Obviously, near the GC this timescale could be different. Since the magnetic field strength is higher and the path to the outer parts of the Galactic halo is also larger, it is likely that the time is longer, and so we adopt 10^5 yr. After an injection event the number of cosmic rays at some energy will decay in a three-dimensional slab diffusion approximation with $t^{-3/2}$ for times up to the diffusive reservoir time and with $t^{-5/2}$ thereafter. For the nominal injection timescale of every 10^6 yr, the expected diminution factor is about 1/300 at again the typical time to the next GRB. The decay length of a neutron at 10^{18} eV exceeds the thickness of the GC thin disklike region of high density and high star formation rate. Using a 3 kpc radius of the region of high interstellar medium density and high star formation rate in the Galactic disk about the GC and a decay length of 10 kpc, this leads to a suppression factor of about $\frac{1}{3}$. Another important aspect of the model is the probability of a proton to produce again an energetic secondary neutron in a collision with a nucleus of the interstellar medium in the inner Galaxy. Using conservatively the typical grammage inferred from the boron-to-carbon ratio in cosmic rays, with the solar neighborhood again as a reference, this probability is of the order of a few percent, estimated to 1/20 (simulated with cross sections from the Particle Data Group 2002).[5] Next we compare in the following the flux of particles above 10^{18} eV with the flux at all cosmic-ray energies combined. Assuming the injection spectrum to be around $E^{-2.2}$ at first produces a diminution of the flux beyond 10^{18} eV by a factor of about 1/100 (Rachen & Mészáros 1998; Bednarz & Ostrowski 1998). Photons are produced in decays of neutral pions, but the typical energy of secondary pions is lower than that of energetic secondary protons and neutrons. Thus the final photon energy is lower and so may become submerged in the higher cosmic-ray flux at lower energies. In Figure 3 we show a simulation for a power-law injection spectrum with an arbitrary exponential cutoff in energy at $E_{\rm cut} = 10^{18}$ eV: the differential flux is $E^{-2.2}$ for $E < E_{\rm cut}$ and $E^{-2.2} \exp[-(E - E_{\rm cut})/E_{\rm cut}]$ for $E \geq$

[5] See the CERN Web site, http://pdg.web.cern.ch/pdg.

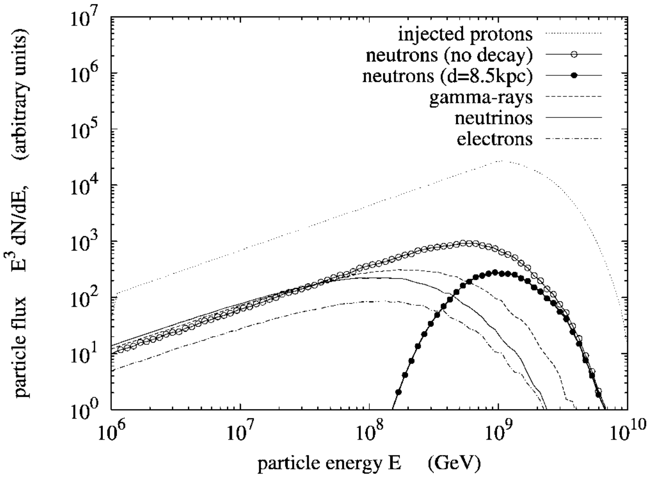

FIG. 3.—Resulting spectra of secondary particles, such as secondary neutrons/antineutrons, gamma rays, electrons/positrons, and neutrinos. For comparison, the secondary neutron spectrum near the GC (no decay) and the local one for a distance of $d = 8.5$ kpc from the production site is shown.

$E_{\rm cut}$. Down to an energy of about a factor of 10 below the cutoff energy, the effect of the cutoff is clearly visible in the ratio of the various fluxes, and below that energy, the ratio approaches a constant. What is the probability that a GRB jet points more or less along the Galactic plane? As seen from the GC region, the Galactic plane is quite thick, and so maybe half the sky has an appreciable column density—see, e.g., Zylka, Mezger, & Wink (1990)—leading to a factor of $\frac{1}{2}$. Finally, what is the total cosmic-ray production by a "typical" GRB? We adopt here the generous number of 10^{51} ergs in pure cosmic rays from Piran (1999), Pugliese et al. (2000), and Berezinsky (2002).

Therefore the expected flux today, from the last GRB occurring 10^6 yr ago, is now 10^{31} ergs s^{-1}. This is just above what is observed, and so allowing for uncertainties due mainly to the limited sky coverage of AGASA, it is a very plausible estimate to explain the data.

The observed spectrum would be completely dominated by the two-step propagation of the secondary neutrons in such a picture. Therefore, the spectrum is the folding of the production spectrum, with the decay probability inside the available space, so a hump from the minimum distance to get any neutrons (see Fig. 3) to the maximum energy possible from GRB productions.

Last, we wish to ask whether it could be that we observe the effect of a few GRBs. The most important parameters are (1) the time since the GRB event and (2) the orientation with respect to the Galactic plane. So, adopting a picket-fence model for the timing of subsequent GRBs, we note that the flux from a GRB that was twice as old is decreased by a factor of about 5 with respect to the younger one, and a GRB at 3 times the age shows a flux that is a factor of 16 down. We conclude that the observed distribution is rather likely to be the result of several GRB events in the GC region.

3. PREDICTIONS AND TESTS

Large numbers of photons, electrons, and neutrinos are produced in the collisions that give rise to the second-generation neutrons in such a picture. However, their mean energy is small relative to that of the neutrons. The fluxes of photons, electrons, and neutrinos are expected to follow an energy spectrum similar to that of the interaction protons. Furthermore, photons and neutrinos map out the spatial and angular distribution of the

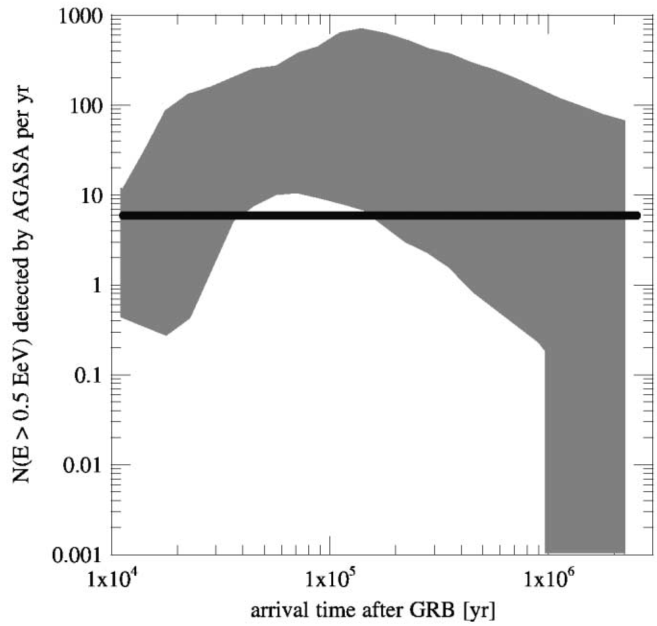

FIG. 4.—Number of neutrons due to GBRs that would be detected in excess to an isotropic background distribution. The simulation is based on 1000 random realizations of GRBs with uniformly distributed jet orientation in the inner Galaxy. The shaded band shows the 95% confidence level region for the flux of particles above 5×10^{17} eV as a function of time detected by an AGASA-like instrument (same aperture and same declination dependence of the exposure). The line indicates the excess actually observed by AGASA. [*See the electronic edition of the Journal for a color version of this figure.*]

proton interactions. It is convenient to express the secondary particle spectra in terms of the primary proton spectrum by multiplying it with appropriate reduction factors. Simulations using the Monte Carlo event generator SIBYLL 2.1 (Fletcher et al. 1994; Engel et al. 1999) predict the following reduction factors: for secondary protons and antiprotons 0.27, for neutrons and antineutrons 0.09, for photons 0.11, for electron-positron pairs 0.05, and for neutrinos (all flavors) 0.13. All these numbers are normalized to a primary proton spectrum, using a power law of $E^{-2.2}$ and the energy range 10^{17}–10^{18} eV. These numbers are the ratio of the fluxes far below the upper energy cutoff. Observable is the ratio of the uncharged components, e.g., the ratio of neutrons to gamma rays, which is here close to 1; however, as Figure 3 shows, near to the upper cutoff the photons drop off earlier than the neutrons. The curves can be shifted in energy for any other assumption of maximum energy, since they will look the same relative to maximum energy (here 10^{18} eV with a following exponential cutoff).

To see an appreciable flux of neutrons peaking near 10^{18} eV with a visible extension to 2×10^{18} eV requires that the primary proton/neutron flux extends to at least about 6×10^{18} eV. A measurement of the ratio of neutrons to photons, with a simultaneous determination of the injected power-law slope, would then allow us to estimate the real cutoff energy of the injected proton/neutrons.

In Figure 4 we show the 95% confidence level for the expected flux at an AGASA-like experiment at Earth, using 1000 random realizations of GRBs in the inner Galaxy. The horizontal line shows roughly the average value actually observed for the excess signal by AGASA. The density distributions are from J. Lepine (2003, private communication), and the magnetic field distributions are from Stanev (1995), Beck et al. (1996), Harari, Mollerach, & Roulet (1999), Beck (2001), and

Medina Tanco (2001). In these specific simulations the cross sections were taken from Particle Data Group (2002).

The spatial distribution of the neutrons should mimic roughly a folding of the decay distance at some energy of the presumed original neutron with the matter distribution. Thus it should be similar to the gamma-ray emission and the far-infrared emission along the Galactic plane. We note that the estimated residence time at 10^{18} eV energies corresponds to a real travel distance via diffusion of only about 2–3 kpc, while the propagation and interaction distance (i.e., the length along the meandering path) is 30 kpc.

It is interesting to consider the time evolution of such a neutron flux: during a first phase, protons resulting from neutron decay interact to produce new neutrons and so steadily increase the observable neutron flux. Second, we begin to use up the reservoir of protons, so the flux of neutrons decreases slowly, with $t^{-3/2}$. Third, the flux begins to decay with $t^{-5/2}$, as protons leak out from the probable interaction volume.

The spatial distribution strongly depends on the specific orientation and the exact location of the original double jet of the GRB—if that is the best model. Of course, it is very unlikely that the GRB jet would point exactly at Earth; that might be damaging to us, since this is the same power in a few seconds as the Sun gives in minutes and in a less benign form. Therefore, if we see several GRB events and their consequences superposed on each other, then the discrepancy between AGASA and SUGAR in spatial distribution might be partially explainable.

4. CONCLUSIONS

We have shown that it is plausible that the observed AGASA excess of events near 10^{18} eV energies coming to us from the GC region is due to the last few GRB events in the Galaxy. We predict a corresponding flux in photons and neutrinos.

In fact, if the predicted details can be confirmed, we will have established (1) that GRB cosmic-ray signature can be detected, (2) the cosmic-ray production of GRBs to be of the order of 10^{51} ergs, (3) that their particle energy extends to at least 6×10^{18} eV, (4) that the maximum particle energy can be estimated with a measurement of both neutrons and photons, as well as the slope of the injection spectrum, and (5) that their contribution to the overall energetics of Galactic cosmic rays is minor. To check this will be a major contribution of the Pierre Auger Observatory, whose southern part is ideally located to observe the GC region (Blümer et al. 2003). The combination of fluorescence and surface detectors of this experiment allow measurements in the energy region from several 10^{17} eV to the highest energies.

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