The Astrophysical Journal, 597:L129–L131, 2003 November 10

DETECTION OF THE HIGH-ENERGY COSMIC RAYS FROM THE MONOGEM RING

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Received 2003 August 25; accepted 2003 September 30; published 2003 October 21

ABSTRACT

The MAKET-ANI detector reveals significant excess of extensive air showers with arrival directions pointed to the Monogem ring, a supernova remnant located at a distance of ≈300 pc from the Sun with ≈100 kyr old radio pulsar PSR B0656+14 near the center. The chances that this excess is due to the fluctuations of an isotropic flux is 2 per million. For the search of the cosmic-ray source, we use the MAKET-ANI detector data from years 1997 to 2003. The best signal bin coordinates, right ascension $7^{\rm h}.5$, declination 14° (750+14), significantly deviate from the ring morphological center, shifted in the direction of the most intensive X-ray emission from the supernova remnant's limb, now located 66 pc from the supernova remnant center and 27 pc from the candidate source.

Subject headings: acceleration of particles — cosmic rays — supernova remnants

1. INTRODUCTION

The most exciting problem connected with cosmic rays is the exploration of a particular accelerating astrophysical source. Unfortunately, owing to the bending in Galactic magnetic fields, charged particles lose information about parent sites during the long travel and arrive at Earth highly isotropic. The supernova (SN) explosions are the most popular candidates for acceleration sites. The problem is in understanding how the Galactic "ensemble" of SNe maintains the cosmic-ray flux in the vicinity of Earth. The fine structure of all-particle spectra at the "knee" suggests the hypothesis that one or several recent nearby SNe are responsible for the observed spectra structures (Erlykin & Wolfendale 1997, 1998). Therefore, identifying such an SN and measuring the flux of particles from its direction will be the best proofs of the most popular model of hadron acceleration.

Very long baseline interferometric measurements of the ≈100 Kyr old pulsar PSR 656+14 (Brisken et al. 2003) locate the pulsar near the center of the supernova remnant (SNR) called the Monogem ring at ≈300 pc from the Sun. It was logical to assume that the Monogem ring, the shell of debris from an SN explosion, was the remnant of the blast that created the pulsar (Thorsett et al. 2003). The position and age of the SNR perfectly fit the single source (SS) model (Erlykin & Wolfendale 2003), and following the recommendation in Thorsett et al. (2003), we "scanned" the Monogem ring with high-energy cosmic rays detected by the MAKET-ANI detector (Chilingarian et al. 1999) at Mount Aragats in Armenia (N40°30′, E44°10′).

We choose high-energy particles, not deflected significantly by the Galactic magnetic fields. More than 2,000,000 extensive air showers detected by the MAKET-ANI experiment with size greater than $N_e > 10^5$ [primary energy >(3–4) × 10^{14} eV] were selected for the search of the cosmic-ray point source. Two-dimensional grids were generated in equatorial coordinates with the bin center tuned in the direction of the Monogem ring center (circle of $9^\circ.2$). The best signal was obtained with bin center coordinates of 750+14 and bin size 3° × 3°. The selected direction corresponds to the detector looking at the zenith coordinates of ≈28°, where the MAKET-ANI zenith angular accuracy is ≈$1^\circ.5$ and azimuth angle estimation accuracy is about 3° (Chilingarian et al. 2001). Shower cores were collected from an area of 18 × 36 m^2 around the rectangular central area of the detector. The shower age parameter was selected in the range of 0.3–1.7.

2. SIGNAL FINDING AND SIGNIFICANCE TESTS

After analyzing more than 2 million events with $N_e > 10^5$, we test different locations of the source within the Monogem ring using different cuts on shower size. Results are summarized in Figures 1 and 2 and Tables 1 and 2. From the analyses, we determine the declination band where the candidate source is located ($\delta_j = 12^\circ.5$–$15^\circ.5$). In the right ascension (R.A.) bin distribution (Fig. 1), we see a large peak corresponding to the R.A. bin of 7.4–7.6 hr.

We use the R.A. scan method for confirming the existence of the cosmic-ray point source. The background events were taken from the mean value of other R.A. bins in the same declination band (in our case, 120 rectangular R.A. bins in each of 20 declination bands of 3°). The significance of the source was calculated by

$$\sigma_{i,j} = \frac{N_{i,j} - \bar{N}_j}{\sqrt{N_j}}, \quad i = 1,\ N_\alpha,\ 3, \quad j = N_{\delta 1},\ N_{\delta 2},\ 3, \qquad (1)$$

where $N_{i,j}$ is the number of events in the equatorial coordinates bin (window), $N_\alpha = 360$ is the range of R.A., $N_{\delta 1} = 6$ is the first declination, and $N_{\delta 2} = 66$ is the last declination, for a total of 20 declination "bands;" N_j is the band-averaged number of events in the bin.

We are looking for SS candidates in the two-dimensional $\Delta\alpha \times \Delta\delta$ (3° × 3°) grid, covering a 360° × 60° equatorial coordinate range with 2400 bins. We assume that for jth declination belt, the number of events that fall in each R.A. bin is a random variable obeying the Gaussian distribution with parameters $N[N_j,\ (N_j)^{1/2}]$. We calculated the R.A. bin average (over 120 bins) and used its square root as a measure of the background variance for this particular declination. To integrate information from all declination bands, we perform normalization transformation (eq. [1]) and obtain joint distribution for all declination bins. As is usual in statistical hypothesis testing, the main hypothesis we want to check (named H_0) exists in opposition to the hypotheses in which we are interested; i.e., we will check the hypothesis that the arrival of the particles detected by the MAKET-ANI detector is isotropic ("no-signal"

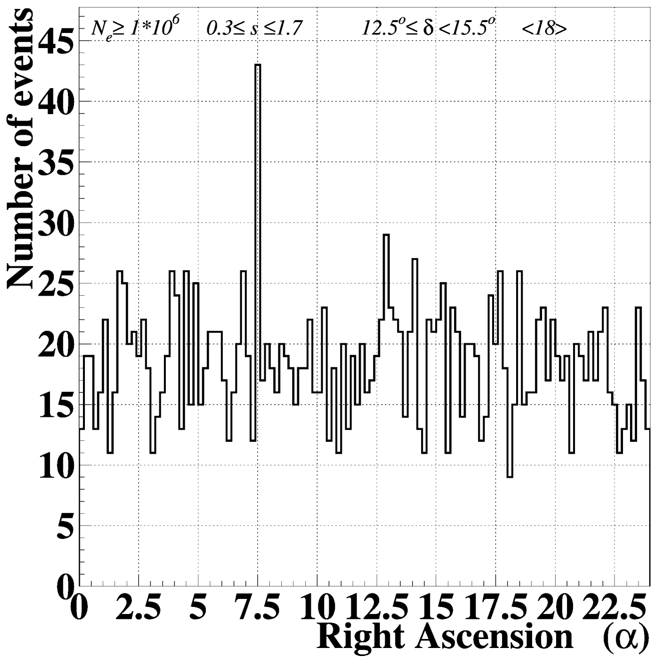

FIG. 1.—Distribution of the number of events in each of 120 R.A. bins for the declination band of 12°.5–15°.5.

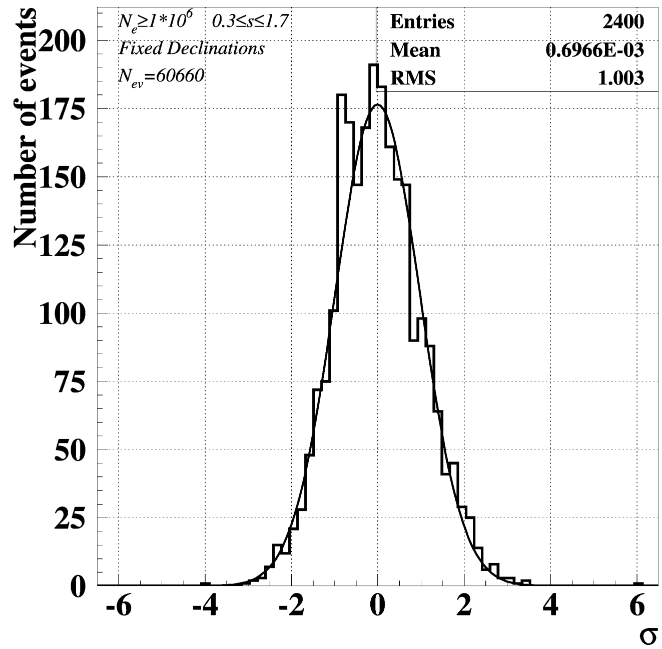

FIG. 2.—Signal significance test with full equatorial coverage with 2400 3° × 3° bins; $N_e > 10^6$.

hypothesis) and, therefore, that the detected enhancement in the "signal bin" is simple random fluctuation of the isotropic background. We are interested in the rejection of H_0 with the maximal possible confidence. Detecting a large peak, we estimate a very low probability of H_0 being true, but, of course, it does not imply that the opposite hypothesis is automatically valid. As was mentioned by Astone & D'Agostini (1999), behind the logic of standard hypothesis testing is hidden a revised version of the classical proof by contradiction. "In standard dialectics, one assumes a hypothesis to be true, then looks for a logical consequence which is manifestly false, in order to reject the hypothesis. The slight difference introduced in classical statistical tests is that the false consequence is replaced by an improbable one." If the experimental histogram will not differ significantly from test distribution, we will have no reason to reject H_0 and, therefore, our results will support the hypothesis that the detected peak is statistical fluctuation only. If the experimental histogram significantly deviates from the test distribution, we will be able to reject H_0 and accept with a high level of confidence that detected enhancement is due to the additional cosmic rays from the Monogem ring. According to the logic described above, we calculate the test statistics by applying equation (1) to the experimentally detected showers and using the equatorial grid covering all directions seen by the MAKET-ANI detector. As we can see from Figure 2, the shape of the cumulative distribution is very close to the standard Gaussian distribution $N(0, 1)$; the χ^2 test value is 1.5 per degree of freedom. Only one point from 2400 (corresponding to the Monogem ring direction) deviates from the $N(0, 1)$ distribution. Proceeding from this experimental result, we adopt the hypothesis of isotropic background in 2399 bins and signal mixed with background in one bin. From the obtained value of $\sigma = 6.04$ for this particular signal bin, we calculate the corresponding probability of obtaining this value under the H_0 hypothesis to be 2×10^{-6}. The null hypothesis could be true only in two cases out of a million; therefore, we have good reason to reject the null hypothesis and conclude that the MAKET-ANI detector detected high-energy cosmic rays from the direction of the Monogem ring.

For more details about signal dependence on shower size, we calculate the number of events that fall in the signal bin for different N_e cuts. The best estimate of the number of signal events equals the difference between the number of events in the signal bin and the mean number of events in the considered declination band ($N_s \approx N_{750+14} - N_{\mathrm{background}}$). This estimate is a random variable with variance controlled by the variance of the background. Table 1 demonstrates that the estimated number of signal events remains approximately constant after shower size cuts from $N_e > 5 \times 10^5$ up to $N_e = 10^6$ and fades rapidly thereafter.

TABLE 1
DEPENDENCE OF THE SIGNAL VALUE ON SHOWER SIZE CUT

N_e	Number of Events in Declination Band δ_j = 12°.5–15°.5	Mean Number of Events in R.A. = 3° Bin (Background)	Number of Events in R.A. = 7ʰ.4–7ʰ.6 Signal Bin	Number of Signal Events
$>10^5$	73382	611	663	52 ± 35
$>5 \times 10^5$	7123	58	84	26 ± 11
$>8 \times 10^5$	3282	26	57	31 ± 7
$>10^6$	2225	18	43	25 ± 6
$>2 \times 10^6$	573	4	13	9 ± 3

TABLE 2
Cosmic-Ray Source Localization around the Center of the Signal Bin

Bin Size ($\alpha \times \delta$)	Number of Events in the Chosen Declination Band	Mean Number of Events in R.A. = 3° Bin (Background)	Number of Events in Signal Bin	Number of Signal Events
1 × 1	744	2	11	9 ± 2
2 × 2	1468	7	22	15 ± 4
3 × 3	2225	18	43	25 ± 6
4 × 4	2952	32	48	16 ± 8
5 × 5	3739	51	71	20 ± 10

Another test concerns the influence of the chosen bin size on the signal significance. From Table 2, we can conclude that the 3° × 3° bin size provides the best coverage of the signal domain. Enlarging the bin size leads to the reduction of the signal due to the enlarged fluctuations of background, but the number of signal events remains approximately constant. The statistical errors in Table 2 illustrate that the number of signal events obtained in the "best confidence" bin and equal to 25 is consistent with both enlarging the bins and lowering the shower size cut. Nevertheless, we did not claim that 25 is the best estimate of the signal; for checking the statistical hypothesis on the best signal value we need to tune more precisely the shape of the signal domain using neural network techniques described in Chilingarian (1995).

3. CONCLUSIONS

The MAKET-ANI experiment detects significant excess of particles from the direction of the Monogem ring with a chance fluctuation probability of 2 per million. Position of the cosmic-ray source, 750+14, is consistent with the SN shock propagation. These conclusions lead us to accept the Monogem ring SNR as the universal source of particles with energy up to at least 3×10^{15} eV. For estimating the source energy spectra, we need a more precise estimation of the type and energy of the SS particles, now underway with methodology proposed in Chilingarian (1989) and Chilingarian & Zazian (1991).

The data collected by the MAKET-ANI detector from 1997 to 2003 are the property of the ANI collaboration. This publication primarily reflects the opinion of its authors. We thank ANI collaboration members for multiyear fruitful cooperation and scientific discussion. The authors also thank Gagik Hovsepyan for numerous cross-checks of the reported results. Work was supported by the Armenian government grants, by grant ISTC A216, and by grant INTAS IA-2000-01.

REFERENCES

Astone, P., & D'Agostini, G. 1999, preprint (hep-ex/9909047)
Brisken, W. F., Thorsett, S. E., Golden, A., & Goss, W. M. 2003, ApJ, 593, L89
Chilingarian, A. A. 1989, Comput. Phys. Commun., 54, 381
———. 1995, Pattern Recognition Lett., 16, 333
Chilingarian, A. A., & Zazian, H. Z. 1991, Nuovo Cimento C, 14, 555
Chilingarian, A. A., et al. 1999, Proc. 26th Int. Cosmic Ray Conf. (Salt Lake City), 1, 240
Chilingarian, A. A., et al. 2001, Proc. 27th Int. Cosmic Ray Conf. (Hamburg), 2, 540
Erlykin, A. D., & Wolfendale, E. W. 1997, J. Phys. G, 23, 979
———. 1998, Astropart. Phys., 8, 265
———. 2003, Proc. 28th Int. Cosmic Ray Conf. (Tsukuba), 2349
Thorsett, S. E., Benjamin, R. A., Brisken, W. F., Golden, A., & Goss, W. M. 2003, ApJ, 592, L71