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ON THE SIGNIFICANCE OF THE OBSERVED CLUSTERING OF ULTRA–HIGH-ENERGY COSMIC RAYS

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ABSTRACT

Three pairs of possibly correlated ultra–high-energy cosmic-ray events were reported by Hayashida et al. Three different numerical models are combined to study the propagation of the corresponding particles through both the intergalactic and Galactic magnetic fields. The spatial dependences of fields and galaxies are accounted for. The results suggest that the pairs are chance clusterings.

Subject headings: cosmic rays — large-scale structure of universe — magnetic fields

1. INTRODUCTION

Recently, Hayashida et al. (1996) reported the possible clustering of some of the ultra–high-energy events of the Akeno Giant Air Shower Array (AGASA) experiment. If these ultra–high-energy cosmic rays (UHECRs) are charged particles, or protons, which is more likely, then these pairs impose severe constraints on the characteristics of the propagation region and/or their sources (e.g., Cronin 1996; Sigl et al. 1997). Catastrophic extragalactic events, like gamma-ray bursts or the decay of topological defects, which are able to produce the particles over a very short period of time, should be consistent with the data only for a suitable combination of low intergalactic magnetic field (IGMF) and distance to the source. Nevertheless, the stirring of the intergalactic medium (IGM) by large agglomerates of galaxies, shocks excited in binary collisions of galaxies, or the bow shocks preceding fast-moving galaxies in dense IGM environments are examples of quiescent sources that could produce chance pairings of UHECR events on the sky. If these quiescent sources are traced by the distribution of luminous matter in the nearby universe, which is known, then the probability of the corresponding chance pairing can be estimated and compared with the observations.

In this Letter, the results of three different calculations are presented. First, the trajectories of the individual particles through the Galactic magnetic field (GMF) are calculated for each pair under different assumptions for the GMF (Medina Tanco, de Gouveia Dal Pino, & Horvath 1998; Medina Tanco 1997a). In the case of catastrophic events (i.e., an almost simultaneous particle emission), this constrains the amount of time delay due to intergalactic propagation alone and, consequently, the range of IGMF values and source distances allowed. The separation angle between the momenta of the particles at their arrival at the border of the halo, θ_{HALO}, can also be estimated. This is a matching condition that must be satisfied by the particle trajectories at the border of the halo. Second, the same numerical scheme of Medina Tanco, de Gouveia Dal Pino, & Horvath (1997) is used to estimate the arrival relative-deflection distribution function for some allowed combinations of IGMF and distance to the source. The comparison of this distribution function with the previously calculated θ_{HALO} gives a quantitative idea of the likelihood of the observed events being the result of pointlike catastrophic sources. Third, the actual distribution of extragalactic objects, as given by the CfA catalog (Huchra et al. 1995), is assumed to track the UHECR sources and to modulate the intensity of the IGMF. Consequently, with the aid of numerical, three-dimensional simulations, an all-sky arrival probability distribution function of UHECRs is built (Medina Tanco 1997b, 1997c) and compared with the observations.

2. NUMERICAL MODELS AND DISCUSSION OF RESULTS

Three different codes are used in the present work. The first one allows the calculation of the trajectory of an UHECR particle of known mass and charge between the border of the Galactic halo and the detector at Earth. A complete description of the model can be found in Medina Tanco et al. (1998) and Medina Tanco (1997a). The results depend, of course, on the model used to describe the large-scale Galactic magnetic field. This is certainly a largely unexplored area. However, we expect that a rough description, satisfactory for the present treatment, can be attained by the models of Stanev (1997). We adopt the same two extreme combinations of Stanev (1997) (see also Sofue, Fujimoto, & Wielebinski 1986 and Beck et al. 1996): (1) a bisymmetric GMF model with field reversals and odd parity (BSS-A) and (2) an axisymmetric GMF model without reversals and with even parity (ASS-S). The effects of a small $B_z = 0.1\ \mu$G component are also studied in each case.

Table 1, adapted from Hayashida et al. (1996), lists the proposed clusters of events; Δt_{arr} is the arrival time delay. The pairs were classified as type A and type B, according to the arrival order of the highest energy particle. Only type A events, where the highest energy particle arrives first, can originate in a bursting source in which the particles are released simultaneously. In type B events, either the source is quiescent or there is a finite acceleration time involved that delays the production of the high-energy particle.

Table 2 summarizes the results for pair 1 under different GMF configurations. For an almost simultaneous release of the particles at the sources, all the GMF configurations but one imply that the source of pair 1 should lie inside the Galactic halo. The maximum distance to the source for each one of these GMF models is indicated in the third column. Only the ASS-S model without a B_z component allows an extragalactic (EG) source. In the later case, a maximum arrival time delay $\Delta t_{\mathrm{IGM}} \sim 0.6$ yr is left for the intergalactic portion of the trajectories of both particles.

The arrival time delay between a proton of energy E and a

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TABLE 1
POSSIBLE CLUSTERS OF UHECRS OBSERVED BY AGASA EXPERIMENT[a]

Pair Number	Date	$\Delta t_{\rm arr}$ (yr)	Energy (EeV)	Type	$l_{\rm gal}$	$b_{\rm gal}$
1	1993 Dec 3	1.90	210	A	131.2	−41.1
	1995 Oct 29	...	51	...	130.2	−42.3
2	1992 Aug 1	2.49	55	B	143.5	56.9
	1995 Jan 26	...	78	...	145.8	55.3
3	1991 Apr 20	3.21	43	B	77.9	18.6
	1994 Jul 6	...	110	...	77.6	21.1

[a] Adapted from Hayashida et al. 1996.

photon can be estimated as

$$t_{p\gamma} \sim 9 \times 10^4 \left(\frac{B}{10^{-9}\ \mathrm{G}}\right)^2 \left(\frac{D}{30\ \mathrm{Mpc}}\right)^2 \times \left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^{-2} \left(\frac{L_c}{1\ \mathrm{Mpc}}\right) \quad (1)$$

in years (cf. Waxman & Coppi 1996), where B, L_c, and D are the intensity of the IGMF, its correlation length, and the distance to the source, respectively. If the correlation length is known, equation (1) can be used to estimate the maximum IGMF for a given D and $\Delta t_{\rm arr}$ between two protons. Two fiducial distances have been selected for quantification purposes: $D = 3$ and $D = 30$ Mpc. The maximum values of the IGMF for these distances are listed in Table 2 for $L_c = 1$ Mpc (Kronberg 1994, 1996). These are the constraints set on the intergalactic propagation region and UHECR bursting sources by the observed pair 1, after considering the propagation of the particles through the GMF. However, another constraint must be satisfied: the angle between the momenta of the particles arriving at the border of the halo from the IGM should be equal to the calculated $\theta_{\rm HALO}$ in Table 2.

To this end, numerical simulations (Medina Tanco et al. 1997) were carried out that emulated the intergalactic propagation of the components of pair 1. $L_c \sim 1$ Mpc is assumed, while IGMF values and distances to the sources are those of Table 2. Protons are injected at the sources with an E^{-2} spectrum, and the energy losses included are redshift, pair production, and photo-pion production (Berezinsky & Grigor'eva 1988). The resulting distribution functions for the relative time delay and the arrival angle between the proton components of pair 1 are shown in Figures 1 and 2. The average time delay between both protons, as given by the simulations (Fig. 1), is consistent with equation (1), although there is a considerable dispersion. Furthermore, Figure 2 shows that a $\theta_{\rm HALO} = 2°$ separation, as inferred for pair 1 at the border of the halo, is at the wing of the distribution. Therefore, if a bursting source were responsible for this pair, a very low probability event was indeed observed.

Pairs 2 and 3 are type B events. This means that a point source could not have emitted the UHECRs simultaneously.

TABLE 2
PAIR 1: CONSTRAINTS FROM GALACTIC AND INTERGALACTIC PROPAGATION

$B_{\rm gal}$	B_z	$D_{\max}$ (kpc)	$\Delta t_{\rm IGM}$ (yr)	$\theta t_{\rm HALO}$ (deg)	$B_{\rm IGM}^{\max}$ (3 Mpc)	$B_{\rm IGM}^{\max}$ (30 Mpc)
ASS-S	=0	EG	0.6	2	10^{-11}	10^{-12}
	≠0	7	...	4.5	...	...
BSS-A	=0	8	...	2	...	...
	≠0	13	...	0.5	...	...

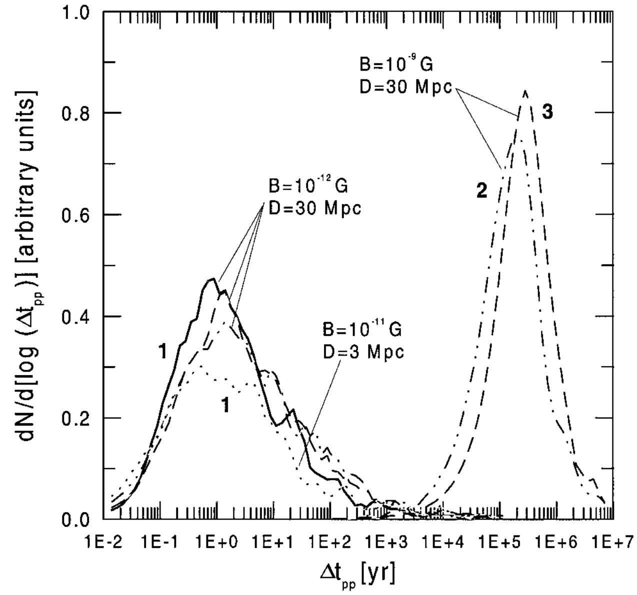

FIG. 1.—Distribution function of arrival time delays between the observed pair of protons in clusters 1, 2, and 3 that is due to propagation in the IGMF alone (i.e., at the external border of the Galactic halo). The simulations for pair 1 correspond to the two fiducial scenarios of Table 2 and match the constraint in time delay imposed by the Galactic portion of the tracks: $B_{\rm IGM} = 10^{-11}$ G and $D = 3$ Mpc (*dotted line*) and $B_{\rm IGM} = 10^{-12}$ G and $D =$ 30 Mpc (*solid line*). For pairs 2 (*dash-dotted line*) and 3 (*dashed line*) two possible scenarios are explored: $D = 30$ Mpc and $B_{\rm IGM} = 10^{-12}$ G and $B_{\rm IGM} = 10^{-9}$ G.

Therefore, if the point-source hypothesis is to be maintained, we must assume either that the source is quiescent or, if bursting, that a finite acceleration time is involved that delays the emission of the high-energy component. In this case, the sum of the arrival time delay and the time delay due to propagation through the GMF and IGMF is a lower limit to τ_s, the lifetime

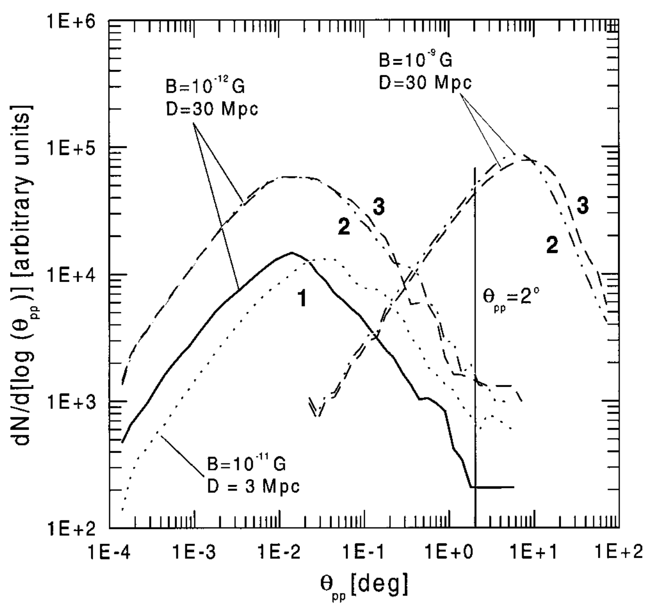

FIG. 2.—Distribution function of the angle between the momenta of the observed particles in each pair, at their arrival at the external border of the Galactic halo after propagation through the IGMF. The conditions are the same as in Fig. 1. A separation angle of 2° typically obtained from the calculations of Galactic propagation for all three pairs is also indicated.

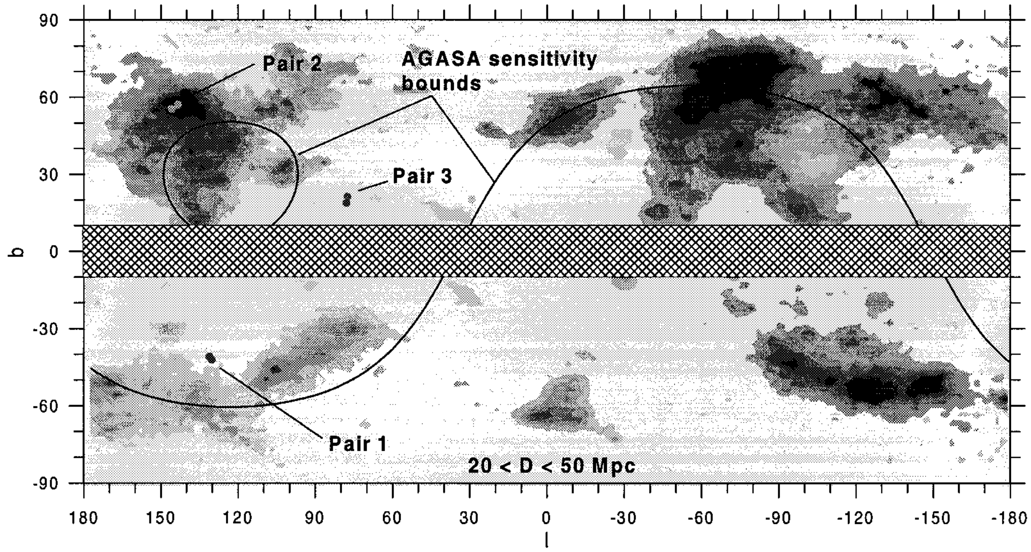

FIG. 3a

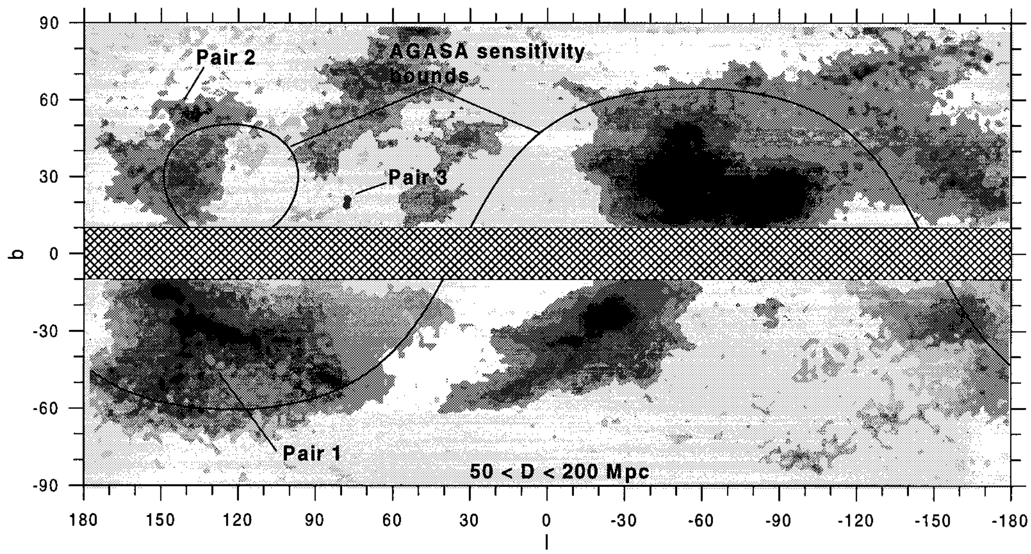

FIG. 3b

FIG. 3.—Arrival distribution of UHECRs simulated under the assumption that the luminous matter in the nearby universe tracks the distribution of the sources of UHECRs and modulates the intensity of the IGMF (see text for details). Redshift, pair production, and photo-pion production losses are included. The arrival distributions due to sources at two different depths are shown: (a) $0 < D < 50$ Mpc, (b) $50 < D < 200$ Mpc. Pairs 1 and 2 lie on top of regions of high arrival probability, strengthening the possibility of chance pairing. The solid lines bound the region of the sky actually seen by AGASA. Sensitivity is poor near these lines.

of the source. Again, the Galactic and intergalactic trajectories must verify the matching of $\theta_{\rm HALO}$ at the Galactic halo border. It is found that $\theta_{\rm HALO}$(pair 2) $\sim 2°$ and $\theta_{\rm HALO}$(pair 3) $\sim 2°$–5.°5, depending on the GMF model adopted. Numerical simulations for the IGM propagation of the proton components of pairs 2 and 3 are also shown in Figures 1 and 2. $D = 30$ Mpc and $B_{\rm IGM} = 10^{-12}$ and 10^{-9} G were used. The lower value of the IGMF is the one imposed by a bursting pair 1, and the second is the current upper limit for the IGMF. It can be seen from Figures 1 and 2 that, as for pair 1, a 10^{-12} G IGMF leads to a very low probability for an event with $\theta_{\rm HALO}$ on the order of a few degrees. Taking into account the Galactic propagation, the lower limits for the lifetime of single sources for pairs 2 and 3, with $B_{\rm IGM} \sim 10^{-12}$ G, are ∼10 and ∼100 yr, respectively. On the other hand, from the point of view of $\theta_{\rm HALO}$, a consistent picture can be obtained for a higher value of the IGMF, say, near 10^{-9} G. However, $\tau_s > 10^5$ yr, and so a single source should be quiescent and probably extended, perhaps enclosing more than one galaxy in order to confine $\sim 10^{20}$ eV particles.

The previous results seem to point to a chance clustering of the three pairs of events, despite the chance probability for the pairs quoted by Hayashida et al. (1996) being only 2.9%. We note, however, that this chance probability was derived under the assumption that the arrival direction distribution is uniform over the sky. This is arguable. Several classes of potential extragalactic sources have been proposed (e.g., Kewley, Clay, & Dawson 1996; Protheroe & Johnson 1996; Biermann, Kang, & Ryu 1996; Halzen 1997), and these are not uniformly distributed over the sky. The inhomogeneity of the sources' distribution should be more noticeable because the interaction of

UHECRs with the cosmic microwave background imposes an upper limit $D_{max} \sim 10^2$ Mpc. Even if the actual sources are unknown, we can naively assume that they follow the distribution of galaxies (i.e., luminous matter) in the nearby universe. This is compatible with isolated galaxies, interacting galaxies, galactic bow shocks in high-density IGMs, and extended sources in turbulent IGMs powered by concentrations of galaxies.

Except for a few observational determinations and upper limits (e.g., Arp 1988; Kim et al. 1989; Kronberg 1994), or numerical simulations of cosmological structure formation (Biermann et al. 1996 and references therein), we know very little about the IGMF. These constraints, however, point to an IGMF structure that follows the distribution of matter (galaxies). Therefore, a high degree of inhomogeneity can be expected, with relatively high values of B_{IGM} over small regions (~1 Mpc) of high matter density (cf. Arp 1988; Kim et al. 1989), pervading vast low-density/low-B_{IGM} regions with $B_{IGM} < 10^{-9}$ G.

Following Medina Tanco et al. (1997), it is assumed that the UHECRs are protons and that their sources are extragalactic and hosted by, or associated with, normal galaxies. It is further assumed that the magnetic field scales as $n_{gal}^{2/3}$, where n_{gal} is the local density of galaxies as derived from the CfA redshift catalog (Huchra et al. 1995). The IGMF is considered to be organized in cells of size L_c of a homogeneous field, such that the orientation of B_{IGM} between adjacent cells is uncorrelated. L_c relates to the IGMF through the expression $L_c(r) \propto [B_{IGM}(r)]^{-2}$, and the normalization condition $L_c \sim 1$ Mpc for $B_{IGM} \sim 10^{-9}$ G is adopted. UHECR protons are injected at the galaxies with an energy spectrum proportional to E^{-2} and propagated nondiffusively through the above scenario while losing energy via redshift, pair production, and photo-meson production (Berezinsky & Grigor'eva 1988).

The results are displayed in the form of all-sky UHECR images of the celestial sphere for galaxies located at $20 < D < 50$ Mpc (Fig. 3*a*) and $50 < D < 200$ Mpc (Fig. 3*b*) for arriving protons with $E > 4 \times 10^{19}$ eV. These surfaces should be representative of the arrival probability of UHECRs at the Earth's position in the Galaxy. The curved lines bound the region of the sky where AGASA is believed to be sensitive (Uchihori et al. 1996).

We can see that the arrival probability is by no means isotropic. Furthermore, pair 2 is on top of a maximum of the arrival probability for sources located between 20 and 50 Mpc, while pair 1 is also located on a high arrival probability region for sources at more than 50 Mpc. This is in contrast with the chance probability estimated by Hayashida et al. (1996) and points either to different uncorrelated sources of the components of each pair or to very extended quiescent sources involving several galaxies. We also note that the sensitivity of AGASA is rather low in the vicinity of pairs 1 and 2. Therefore, an instrument with more uniform coverage (like the proposed Auger project) should probably detect an extended region of excess UHECR flux at the position of the pairs.

The third pair comes from a region of space where no large clustering of galaxies exists up to the depths considered. Since the components could not have originated simultaneously at the same extragalactic source because of Galactic propagation constraints, they must have come from isolated sources. This seems to indicate that very large agglomerates of galaxies, large enough to give a signature in Figure 3, are not needed in order to accelerate UHECRs.

3. CONCLUSIONS

The constraints deduced from the propagation of the components of the pairs of UHECR events proposed by Hayashida et al. (1996) through the Galactic and intergalactic medium have been analyzed.

In the case of pair 1, the low value of the IGMF, imposed by the arrival time delay between the protons, is inconsistent with the deflection angle between the momenta of the particles at the border of the halo, inferred from their Galactic propagation. This makes a single, bursting source very unlikely.

If the components of pairs 2 and 3 originate in common sources, then the lifetimes of the sources are probably larger than a few times 10^5 yr and, therefore, extended. This picture is consistent with an IGMF value not much smaller than the presently accepted upper limit of 10^{-9} G (Kronberg 1996) and a distance to the sources of ~30 Mpc. In fact, the actual distribution of galaxies (Huchra et al. 1995) presents a local maximum at about that distance in the direction of pair 2. Furthermore, our simulations point to a maximum in the arrival distribution of UHECRs at exactly the same position as that of pair 2, when sources between 20 and 50 Mpc are considered. Pair 1 is also located inside a maximum of the arrival distribution, favoring chance pairing between the components.

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REFERENCES

Arp, H. 1988, Phys. Lett. A, 129, 135

Beck, R., Brandenburg, A., Moss, D., Shukurov, A., & Sokoloff, D. 1996, ARA&A, 34, 155

Berezinsky, V. S., & Grigor'eva, S. I. 1988, A&A, 199, 1

Biermann, P. L., Kang, H., & Ryu D. 1996, in Proc. Int. Symp. on EHECR: Astrophys. and Future Obs., ed. M. Nagano (Tokyo: ICRR), 79

Cronin, J. W. 1996, in Proc. Int. Symp. on EHECR: Astrophys. and Future Obs., ed. M. Nagano (Tokyo: ICRR), 2

Halzen, F. 1997, in Talk Presented at Int. Workshop, New Worlds in Astropart. Phys., Faro, Portugal, 1996 Sep. 8–10 (astro-ph/9704020)

Hayashida, et al. 1996, Phys. Rev. Lett., 77, 1000

Huchra, J. P., Geller, M. J., Clemens, C. M., Tokarz, S. P., & Michel, A. 1995, Redshift Catalog (Cambridge: CfA)

Kewley, L. J., Clay, R. W., & Dawson, B. R. 1996, Astropart. Phys., 5, 69

Kim, K.-T., et al. 1989, Nature, 341, 720

Kronberg, P. P. 1994, Rep. Prog. Phys., 57, 325

Kronberg, P. P. 1996, in Proc. Int. Symp. on EHECR: Astrophys. and Future Obs., ed. M. Nagano (Tokyo: ICRR), 89

Medina Tanco, G. A. 1997a, 25th Int. Cosmic Ray Conf. (Durban), 4, 485

———. 1997b, 25th Int. Cosmic Ray Conf. (Durban), 4, 477

———. 1997c, 25th Int. Cosmic Ray Conf. (Durban), 4, 481

Medina Tanco, G. A., de Gouveia Dal Pino, E. M., & Horvath, J. E. 1997, Astropart. Phys., 6, 337

———. 1998, ApJ, 492, 200

Protheroe, R. J., & Johnson, P. A. 1996, Astropart. Phys., 4, 253

Sigl, G., Schramm, D. N., Lee, S., & Hill, C. T. 1997, Proc. Natl. Acad. Sci., 94, 10501

Sofue, Y., Fujimoto, M., & Wielebinski, R. 1986, ARA&A, 24, 459

Stanev, T. 1997, ApJ, 479, 290

Uchihori, Y., et al. 1996, in Proc. Int. Symp. on EHECR: Astrophys. and Future Obs., ed. M. Nagano (Tokyo: ICRR), 50

Waxman, E., & Coppi, P. 1996, ApJ, 464, L75