FOREGROUND AND SOURCE OF A CLUSTER OF ULTRA–HIGH-ENERGY COSMIC RAYS

GLENNY R. FARRAR, ANDREAS A. BERLIND, AND DAVID W. HOGG

Center for Cosmology and Particle Physics, Department of Physics, New York University, 4 Washington Place, New York, NY 10003; gf25@nyu.edu, aberlind@cosmo.nyu.edu, david.hogg@nyu.edu

Received 2005 July 27; accepted 2006 March 30; published 2006 April 19

ABSTRACT

We investigate the origin of a nearly pointlike cluster of five ultra–high-energy cosmic rays (UHECRs) in the vicinity of R.A. ≈ 169°2 and decl. ≈ 56°8, using Sloan Digital Sky Survey and other data. No particular source candidates are found near the estimated source direction, but the direction is exceptional in having a likely merging pair of galaxy clusters at 140 h⁻¹ Mpc, with an unusually low foreground density. Large-scale shocks or another product of the merging galaxy clusters may accelerate the UHECRs, or the merging galaxy clusters may be coincidental and the UHECRs may be accelerated in a rare event of an unexceptional progenitor. Low magnetic deflections in the foreground void may explain why this is the only identified pointlike cluster of so many UHECRs.

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

Online material: color figures

1. INTRODUCTION

Recently, a cluster of five ultra–high-energy cosmic ray (UHECR) events was found in the complete published AGASA-HiRes data set, whose distribution of arrival directions is consistent with their having a common pointlike origin and little magnetic smearing (Farrar 2005). The cluster of four highest-energy events was identified in Abbasi et al. (2005), in a data set consisting of 57 AGASA events above 40 EeV and 37 HiRes events above 30 EeV. The fifth event joins the others when the full HiRes data set above 10 EeV is used, adding 214 events to the 94-event high-energy data set containing the quadruplet. The (a posteriori) probability that the quadruplet is a chance occurrence in a random isotropic data set of 94 events is 2 × 10⁻³ (Farrar 2005), motivating a search for a common source. In this Letter, we address the questions of what objects offer the greatest promise for being or containing the source, and whether the large-scale structure of the environment in the direction of the cluster gives any clue about the likely distance of the source or the reason that the magnetic dispersion among the five events is so low.

The highest-energy event in the cluster was observed by AGASA, the Akeno Giant Air Shower Array, which measured its energy to be 77.6 EeV (Hayashida et al. 2000), with an estimated ±25% statistical and ±18% systematic energy uncertainty (Takeda et al. 2003). As a consequence of energy loss during propagation, especially from photopion scattering on the cosmic microwave background, the maximum distance for the source of this UHECR cluster can be inferred to be ~210 Mpc at 99% confidence using the nominal energy of the highest-energy event, 77.6 EeV, or ~430 Mpc for a 30% lower energy of 54.3 EeV (S. Balberg 2005, private communication). The fifth event gives an essentially perfect fit to the cluster hypothesis with Gaussian magnetic dispersion ~E⁻¹, but given the large number of added events when the HiRes (High Resolution Fly’s Eye) threshold is reduced from 30 to 10 EeV, there is a one in six chance that the fifth event is a coincidental association. The source direction was reconstructed in Farrar (2005), using either just the four highest-energy events or all five events and with and without magnetic dispersion and deflection, fixing the magnetic dispersion so that the minimum χ² is 1 degree of freedom. The results differ almost not at all for the source right ascension and by less than half a degree for the source declination. For definiteness, we adopt as the nominal source direction (169°2, 56°8) with a 1°2 99% error radius. We examine below a 16° × 16° region around this direction, to better understand its large-scale properties. As a corollary, the results presented here will remain applicable even if more events or better information on the angular resolution of the present events leads to a modification of the best-estimate source location.

There are two natural explanations for why this cluster of four to five UHECRs is unique in the northern hemisphere in having a spatial dispersion consistent with being pointlike, for such a large number of events:

1. The source is the closest or most powerful one, and other sources have a lower flux at Earth.

2. Other sources have as large or a larger flux, but larger magnetic dispersion in those sources’ foregrounds prevents event clusters from these directions from being recognized.

In order to help choose between these options, we examine the observations to see if there is any inherent evidence that the magnetic field may be lower here than in other directions. Serendipitously, the cluster lies in the region covered by the Sloan Digital Sky Survey (SDSS) Data Release 3 (DR3; Abazajian et al. 2005), which we use to characterize the environment out to 300 h⁻¹ Mpc. Besides this cluster, AGASA and HiRes observed six doublets: five with AGASA alone and one that is an AGASA-HiRes pair (Abbasi et al. 2004). Unfortunately, only the quadruplet falls in the part of the sky covered by the SDSS DR3. We have tried using other surveys, such as the all-sky PSCz catalog (Saunders et al. 2000), but they are not sensitive enough to resolve the structure adequately for our purpose, so we cannot perform the analogous test for those doublets.

We investigate the large-scale structure of matter in the direction of the UHECR quadruplet using two volume-limited samples of galaxies constructed from the SDSS DR3: one is complete down to an r-band absolute magnitude of M₁₅ < −20 and goes from 45 h⁻¹ Mpc out to 300 h⁻¹ Mpc, and one is complete down to M₁₅ < −18.3 and goes from 45 h⁻¹ Mpc out to 150 h⁻¹ Mpc. Absolute magnitudes are k-corrected to a redshift of 0.1 and are

1 In conference proceedings, speakers from AGASA have also referred to a second triplet, in addition to the one that was promoted to a quadruplet by HiRes, but its coordinates are not available.
provided by the New York University Value-added Galaxy Catalog (Blanton et al. 2005). In addition to studying the overall density field, we also look for galaxy clusters, which are the largest gravitationally bound objects in the universe. We identify galaxy clusters in our larger volume, volume-limited sample using a simple friends-of-friends algorithm with perpendicular and line-of-sight linking lengths of 0.14 and 0.7 times the mean intergalaxy separation, respectively, and we only retain clusters containing 10 or more member galaxies and a minimum estimated mass of $10^{14} h^{-1} M_\odot$. We make rough mass estimates for the clusters by assuming a monotonic relation between cluster mass and luminosity, and matching the cluster luminosity function to the theoretical mass function of dark matter halos for a concordance cosmological model.

2. RESULTS AND DISCUSSION

Figure 1 (Plate 1) shows SDSS galaxies from our $M_{200, r} < -20$ volume-limited sample in a $16^\circ \times 16^\circ$ field centered on (1692, 5628). The asterisks and hatched circles show the individual UHECR events with their “1 σ” domains. Dots are SDSS galaxies in our sample. Galaxies in clusters are shown as filled circles with sizes proportional to their luminosities, gray-scale-coded (color-coded in the online version) to show their distances, with the estimated virial radii of the galaxy clusters indicated by open circles. Cluster galaxies in the $M_{200, r} < -18.3$ sample are also included in this figure, for better visualization of the clusters. The same field is shown in orthogonal slices in Figure 2. There are three striking features in these figures. First, the nominal UHECR source direction is directly aligned with a pair of galaxy clusters at $140 h^{-1} \text{ Mpc}$, whose physical proximity to each other suggests that they are either currently merging or will likely merge within a dynamical time. We return to this merging pair later. Second, the source direction is at the edge of a void and near the confluence of several high-density filaments or sheets of galaxy clusters. Third, virtually all other galaxy clusters are even more distant than the merging pair; the exception, at (173°, 49°), is $100 h^{-1} \text{ Mpc}$ away. (Being slightly more than 8° from the line of sight, it is not entirely visible in Fig. 2.)

The magnetic field strength can be expected to be highest in regions of high temperature and pressure, and lowest in voids. The luminosity density is thus a convenient, albeit approximate, surrogate for local magnetic field strength, and we adopt it as a tool to compare the environment in the direction of the cluster to that of average SDSS fields. Figure 3 reveals that in the direction of the UHECR cluster there is very little matter out to $100 h^{-1} \text{ Mpc}$. At $100 h^{-1} \text{ Mpc}$, only 11.5% of directions in the full SDSS DR3 have as low or lower cumulative r-band luminosity density as the UHECR direction. Evidently, if the source is in the density enhancement at $100 h^{-1} \text{ Mpc}$, it is plausible that the magnetic deflections experienced by UHECRs en route to Earth may be much smaller than for sources in other, more typical directions. The same conclusions hold when we compute the luminosity density in cones of $2^\circ$ radius, rather than $1^\circ$ (not shown). As can be understood from Figure 1, if the center of the cone is shifted several degrees from the nominal UHECR direction, it falls either in the direction of a void or in a direction in which the galaxy clusters are even more distant. Thus, independently of the exact UHECR direction, the density is very low along the UHECR line of sight out to at least $100 h^{-1} \text{ Mpc}$.

We now turn to the question of what the source or accelerator of the UHECRs might be, and what can be deduced about its likely distance. Some candidate UHECR sources (e.g., gamma-ray bursts) are found preferentially in star-forming regions. We can probe directly the rate of star formation in our field by repeating the analysis described above for r-band luminosity using Hα luminosity. We use the Hα luminosities computed by Quintero et al. (2004). The results are given in the right panels of Figure 3. They show that the high matter density regions along the UHECR line of sight have enhanced star formation, roughly in proportion to the matter density.

After being significantly underdense out to $100 h^{-1} \text{ Mpc}$, the luminosity column depth in the UHECR direction abruptly climbs to a level well above average, as can be seen from Figure 3. Indeed, by the far side of the merging clusters at $140 h^{-1} \text{ Mpc}$ the cumulative r-band and Hα luminosities for the 1° field are greater than in all but ∼0.6% and 2.9% of the SDSS directions, respectively, gradually decreasing at larger distances but remaining in the top ∼5% out to $300 h^{-1} \text{ Mpc}$.

Merging galaxy clusters offer multiple acceleration options. One possibility, not previously examined with UHECR data, is that the UHECRs could be accelerated in large-scale shocks produced by the merging galaxy clusters. Shock acceleration within large galaxy clusters has been identified as an acceleration mechanism for UHECRs (see Hillas 1984), and the large-scale shocks created when galaxy clusters merge would be expected to have coherence lengths and field strengths several times as large as those produced by infall onto an isolated cluster of comparable mass. Evidence for shocks created by merging galaxy clusters has been detected in the Chandra observation of the high-redshift galaxy cluster Cl J0152.7−1357 (Maughan et al. 2003). Berrington & Dermer (2003) studied shock acceleration in merger shocks. They obtained maximum proton energies of about $10^{19}$ eV with their standard parameter choice, $B = 10^{-7}$ G and shock size of 1 Mpc. However, since their limiting condition on proton energy is that the Larmor radius must be smaller than the size of the shock, larger values of field strength and scale—as we argue are plausible for the merging clusters—push the maximum energy up enough to accommodate the energies of these cosmic rays. As is evident from Figure 1, even a several Mpc spatial extent of the source region is compatible with the observed dispersion in arrival directions of the UHECR events, given the angular resolution of the events.

Or the merging clusters could merely host the source of the UHECRs. When galaxy clusters merge, the merger rate of their constituent galaxies would be expected to increase. This in turn should stimulate star formation and therefore could possibly enhance the rate of gamma-ray bursts (GRBs) and magnetar births, both proposed as UHECR accelerators (see, e.g., Waxman 2004; Arons 2003). We looked at the morphology of individual galaxies in the merging clusters to estimate the rate of galaxy mergers, but we find that an enhancement in comparison with field galaxies, if present, is not statistically significant. Galaxy merging could also activate quiescent active galactic nuclei (AGNs) by perturbing their accretion disks. By contrast, undisturbed galaxy clusters are thought to have a lower star formation rate per unit mass because their virialized gas is too hot to form stars and the process of unvirialized gas cooling and forming stars is largely complete.

Just how unusual is this likely merging pair of galaxy clusters? Roughly 20% of our galaxy clusters are candidates to be in a merging pair, defined as being separated by less than 1.1 times the sum of their estimated virial radii. With the definition of a galaxy cluster described above, there are 256 galaxy clusters, containing 8.5% of the galaxies, in the sample. The merging pair of galaxy clusters in the direction of the UHECR events
Fig. 2.—Side views of the field shown in Fig. 1. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 3.—Top left: The $r$-band luminosity density (measured using the smaller volume of our two volume-limited samples) as a function of distance in the direction of the UHECR cluster, averaged over a disk of 1° radius, out to 150 $h^{-1}$ Mpc. The shaded histogram in the bottom left panel shows the corresponding cumulative luminosity density; for comparison, the middle open histogram shows the median cumulative luminosity density in the SDSS DR3, computed from 688 independent lines of sight, while the upper and lower histograms show the values such that only 10% of the cases have higher and lower integrated luminosity, respectively. The luminosity density in all lines of sight drops to zero below 45 $h^{-1}$ Mpc because that is the lower limit of our volume-limited sample. The panels on the right are the same, using Hα rather than $r$-band luminosity.

Fig. 4.—Distribution of the cumulative foreground $r$-band luminosity density of galaxy clusters in the SDSS DR3. For each cluster of galaxies identified in the SDSS DR3 redshift survey, we measure the integrated luminosity density of galaxies out to the cluster redshift in a conical volume of radius $2°$. The histogram shows the number distribution of these values (in units of $L_\odot$). The solid and dotted arrows represent these values for the clusters that are within $2°$ of the UHECR cluster candidate.

Fig. 5.—Integrated luminosity density map (orthographically projected) in the northern Galactic region of the SDSS DR3. The luminosity density in every direction is averaged in a conical volume of radius 1°. The gray scale represents luminosity densities in the upper 5th, 25th, 50th, 75th, and 95th percentiles, respectively. The black circle shows the region of radius 2° centered on the best-fit UHECR cluster direction. [See the electronic edition of the Journal for a color version of this figure.]
has a total estimated mass of $3.1 \times 10^{14} M_\odot$; 24% of the 256 clusters have a mass at least this high, as do 90% of other candidate merging clusters. In Figure 4, we compare the cumulative $r$-band luminosity densities in the foreground of these clusters. The foreground of the merging clusters in the direction of the UHECRs has a lower integrated luminosity density than all but 17% of the clusters in our sample of 256.

Although merging galaxy clusters are unusual, they account for only a small fraction of the total baryonic mass, and this pair of merging galaxy clusters may not be the source of the UHECR events. In fact, as shown in Figure 5, the direction of the source is in the top 5% of all SDSS directions, from the point of view of total integrated luminosity out to 300 $h^{-1}$ Mpc. Also, the void, which extends to 100 $h^{-1}$ Mpc, could be a red herring: Perhaps the magnetic field is generally low in all directions, and the unique aspect of this field is just its large column density of sources. In this case, an estimate of the likely minimum distance of the source would be the distance at which the integrated luminosity density in the source direction crosses the mean for all SDSS directions, 100 $h^{-1}$ Mpc.

SDSS galaxies within 4° of the source include a few LINERs but no powerful AGNs. This does not mean there are no powerful AGNs in this field, since X-ray measurements have established that a large fraction of AGNs can evade detection in the optical because of obscuration. It has been noted that BL Lacertae objects may be preferentially correlated with UHECR directions (Gorbunov et al. 2004, Abbasi et al. 2006), but a search of the catalog of Véron-Cetty & Véron (2003), containing 876 confirmed, possible, and probable BL Lac objects, shows that the closest to our nominal source direction is RXS J10586+5628, at $z = 0.144$, which is 2% away. The closest EGRET source, 3EG J1054+5718, is over 3° away. Unless the energies of the events were mismeasured in such a way that they are much closer in energy than reported, or there is an accidental conspiracy among the measurement errors, magnetic displacement could not shift the reconstructed source location far enough for a known BL Lac object or EGRET source to have produced the UHECR cluster.

Searching the NASA/IPAC Extragalactic Database within 2° of the source directions, one finds few exceptional objects. The most interesting potential source is SN 1983w, in NGC 3625, which is 26.2 Mpc away (R.A., decl.) = (170°13, 57°78) and thus 175 from the nominal UHECR source direction. SN 1983w was almost simultaneous with GRB 831221, which appears to a corresponding enhancement in the rate of GRBs, magnetar births, and other cataclysmic events. We provisionally conclude that the most likely distance of the UHECR source is about 140–210 Mpc. We also conclude that the almost pointlike quality of this UHECR cluster may be due to exceptionally low magnetic dispersion thanks to a long foreground void in that direction. An examination of the Two Degree Field for similar conditions of void followed by very high density in the field of view of the Pierre Auger Observatory is under way.

We thank D. Branch and A. Fillippenko for the SN Ia identification, and K. Hurley for the GRB direction information. We have also benefited from information and advice from S. Balberg, M. Blanton, B. Dingus, A. Fruchter, D. Helfand, E. Pierpaoli, H.-W. Rix, and M. Shara. Funding for the creation and distribution of the SDSS has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, NASA, the NSF, the US Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The research of G. R. F. has been supported in part by grants NSF PHY 04-01232 and NASA NAG 5-9246, that of A. B. by NSF PHY 01-01738 and NASA NAG 5-9246, and that of D. H. by NASA NAG 5-11669 and NSF AST 04-28465.

This possibility will be examined in the next round of Chandra observations, by D. Helfand and G. R. F.

REFERENCES

Abazajian, K., et al. 2005, AJ, 129, 1755
Abbasi, R., et al. 2004, ApJ, 610, L73
———. 2005, ApJ, 623, 164
———. 2006, ApJ, 636, 680
Arons, J. 2003, ApJ, 589, 871
Berrington, R. C., Dermer, C. D. 2003, ApJ, 594, 709
Blanton, M. R., et al. 2005, AJ, 129, 2562
Farrar, G. R. 2005, preprint (astro-ph/0501388)
Gorbunov, D. S., Tinyakov, P. G., Tkachev, I. I., & Troitsky, S. V. 2004, JETP Lett., 80, 145
Hillas, A. M. 1984, ARA&A, 22, 425
Hayashida, N., et al. 2000, preprint (astro-ph/0008102)
Maughan, B. J., Jones, L. R., Ebeling, H., Perlman, E., Rosati, P., Frye, C., & Mullis, C. R. 2003, ApJ, 587, 589
Quintero, A. D., et al. 2004, ApJ, 602, 190
Saunders, W., et al. 2000, MNRAS, 317, 55
Takeda, M., et al. 2003, ApJ, 589, 589
Véron-Cetty, M.-P., & Véron, P. 2003, A&A, 412, 399
Waxman, E. 2004, ApJ, 606, 988

We thank D. Branch and A. Fillippenko for the SN Ia identification, and K. Hurley for the GRB direction information. We have also benefited from information and advice from S. Balberg, M. Blanton, B. Dingus, A. Fruchter, D. Helfand, E. Pierpaoli, H.-W. Rix, and M. Shara. Funding for the creation and distribution of the SDSS has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, NASA, the NSF, the US Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The research of G. R. F. has been supported in part by grants NSF PHY 04-01232 and NASA NAG 5-9246, that of A. B. by NSF PHY 01-01738 and NASA NAG 5-9246, and that of D. H. by NASA NAG 5-11669 and NSF AST 04-28465.
Fig. 1.—A 16° × 16° field centered on the best-fit UHECR cluster direction (16°2, 56°8). Asterisks show the arrival directions of the five UHECR events and hatched circles show their "1 σ" error domains, i.e., the regions expected to contain the true arrival direction in 68% of comparable measurements. The size of the asterisks is proportional to the energy of the UHECR events. Dots represent the positions of galaxies in a volume-limited sample constructed from the SDSS redshift survey (described in the text). Galaxies that are members of clusters are shown as filled circles with sizes proportional to their luminosities and grayscale-coded according to their redshift. Open circles indicate the estimated cluster virial radii. [See the electronic edition of the Journal for a color version of this figure.]