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Possible galactic sources of ultrahigh-energy cosmic rays and a strategy for their detection via gravitational lensing

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If decays of superheavy relic particles in the galactic halo are responsible for ultrahigh-energy cosmic rays, these particles must be clustered to account for small-scale anisotropy in the AGASA data. We show that the masses of such clusters are large enough for them to gravitationally lens stars and galaxies in the background. We propose a general strategy that can be used to detect such clusters via gravitational lensing, or to rule out the hypothesis of decaying relic particles as the origin of highest-energy cosmic rays.

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The origin of cosmic rays [1 – 3] with energies beyond the Greisen – Zatsepin – Kuzmin (GZK) cutoff [4] is unknown. One of the possible explanations invokes decays of metastable superheavy relic particles X with masses 10^{13} GeV or higher and cosmologically long lifetimes [5 – 7]. Such superheavy particles could be produced non-thermally at the end of inflation [8 – 10]. Their extremely small decay width may be due to a conservation of some topological charge [6]. Particles with the requisite properties may also arise from string theory [11].

If these particles decay into hadrons and photons, the flux of ultrahigh-energy cosmic rays (UHECR) is dominated by those particles in the halo of our galaxy [5]. This can explain the absence of the GZK cutoff. Even if the superheavy particles decay predominantly into neutrinos [12], cosmic rays with energies beyond the GZK cutoff may originate through Z-bursts [13]. In this *letter* we concentrate on the former possibility and assume that observed ultrahigh-energy events [1 – 3] come mainly from the decays of relic particles in the Milky Way halo.

The new data provide an opportunity to test this hypothesis through gravitational lensing. There is a strengthening evidence for directional clustering of events in the AGASA data [2, 3]. The latest analyses [2] show one triplet and six doublets of events, each originating from the same point in the sky, to $\pm 1.3^\circ$ accuracy. The probability of this clustering to occur by accident is less than 0.07% [2]. The only way to reconcile these data with the hypothesis of relic particle decays is to assume a non-uniform distribution of particles in the halo. If the relic particles form regions of increased density, such lumps may be responsible for the doublets in the UHECR data. To produce a doublet, a lump of particles must be of a certain size determined by the decay probability. Since the mass of the hypothetical particle is fixed by the energy of UHECR, there is a prediction for the mass of each lump that can give rise to a doublet. In addition, the celestial coordinates of the particle cluster are known to one degree accuracy. In this *letter* we propose a novel gravitational lensing technique that can be used to discover a cluster of relic particles, or to rule out such particles as the origin of ultrahigh-energy cosmic rays.

Under the assumption that UHECR are caused by the relic particle decays, the data suggest that (in addition to a possible uniform distribution), of the order of ten clusters of X-particles exist in our galactic halo. N-body simulations of dark matter halos predict some inhomogeneities that can be related to small-scale anisotropy of UHECR [14] but probably are not sufficient to produce larger clumps. However, additional interactions of the hypothetical particles can alter this picture dramatically. We assume that each doublet comes from a separate cluster of particles. Here we do not discuss the dynamics of clustering of the heavy particles. This issue will be addressed in an upcoming publication. We note in passing that clumps of dark matter with masses $10^8 M_\odot$ may resolve [15] the widely debated issue of cusps in the halo density profiles [16].

If the X-particle lifetime is $\tau_x \sim 10^{10} - 10^{22}$ yr [6], a cluster of N particles produces decays at a rate

$$P = \frac{N}{\tau_x} \sim (10^{-10} - 10^{-22}) N \text{ yr}^{-1}. \qquad (1)$$

The probability for the decay products to produce an air shower in a detector is $P \times (d/L)^2$, where $d \sim 10^6$ cm is the size of the detector and $L \sim 10^{23}$ cm is the distance to the cluster of relic particles. In order to have a doublet in a one-year data set, each cluster must have

$$N \sim \frac{\tau_X}{1\ \mathrm{yr}} \left(\frac{L}{d}\right)^2 \sim 10^{50} \left(\frac{\tau_X}{10^{16}\ \mathrm{yr}}\right) \tag{2}$$

particles. If X-particle has mass $m_X \sim 10^{13}$GeV [5, 6], the mass of the cluster is

$$M \sim 10^{63} \left(\frac{\tau_X}{10^{16}\ \mathrm{yr}}\right)\ \mathrm{GeV} = 10^6 \left(\frac{\tau_X}{10^{16}\ \mathrm{yr}}\right)\ M_\odot. \tag{3}$$

The lifetime τ_X can be in the range from 10^{10} yr (for the relic particles to survive until present) to 10^{21} yr (for the total mass of the clusters not to exceed the mass of the galaxy). Correspondingly, the masses of clusters can range from one solar mass to $10^{10} M_\odot$.

There is a remarkable possibility to discover such invisible massive objects by what we will call a "lens-chasing" technique. Although the cluster can be entirely dark, it can be detected through gravitational lensing of stars and galaxies behind it. AGASA data [1, 2] provide the celestial coordinates of the clusters with a precision of a few degrees.

The Einstein radius of a cluster with mass M is

$$R_E = 0.14\ \mathrm{pc} \left[\frac{M}{10^7 M_\odot} \frac{L}{10\,\mathrm{kpc}}\right]^{1/2}. \tag{4}$$

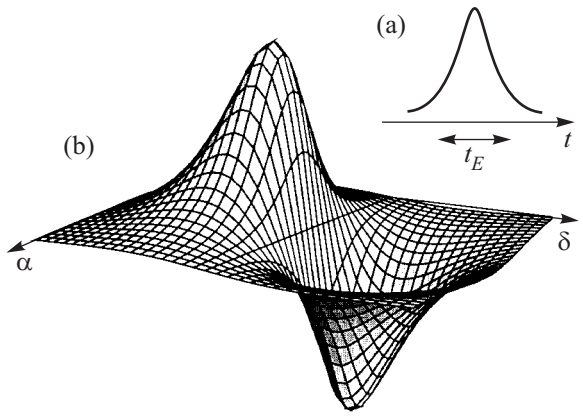
A lens of this kind has angular size

$$\theta_E = \frac{R_E}{L} = 0.0008^\circ \left[\frac{M}{10^7 M_\odot} \frac{10\,\mathrm{kpc}}{L}\right]^{1/2} \tag{5}$$

and passes the line of sight in time

$$t_E = \frac{R_E}{10^{-3} c} = 4.8 \cdot 10^2\ \mathrm{yr} \left[\frac{M}{10^7 M_\odot} \frac{L}{10\,\mathrm{kpc}}\right]^{1/2}. \tag{6}$$

We propose to use the small changes in brightness of stars and galaxies behind the lens on time scales of the order of one year. The AGASA data specify the location of the cluster to $\pm 1.3^\circ$. It is possible to scan over a large sample of remote sources in the patch specified by the UHECR data, recording the brightness of the background stars and galaxies. The scan must be repeated after a period of several months. Next, one should extract the changes in the absolute brightness of the background stars. A slowly moving lens with a single-star light curve shown in Figure (a) will produce a map of brightness differentials shown in Figure (b). By using temporal changes in the brightness of stars from a large sample, one can locate a small lens within a large, 2.5°, patch of the sky.



A typical light curve for gravitational lensing of a single source as a function of time (a), and the corresponding plot of brightness variations for a sample of stars (b) as a function of celestial coordinates, in arbitrary units. Photometric changes indicate the location of the lens

The number of background sources chosen for scanning and photometry determines the sensitivity of the proposed lens-chasing experiment. Let us consider a sample of n^2 stars with an average angular separation of $\theta_b \approx 2.5^\circ/n$. A lens that passes near one of these stars at an angular distance $\delta\theta = \theta_b/2 < \theta_E$ from the line of sight will magnify the source by a factor $(2\theta_E/\theta_b)^2$ as compared to its brightness in the absence of the lens. The change in the star's brightness over a one year period is

$$\frac{\Delta A}{A} \approx \frac{1\ \mathrm{yr}}{t_E} \left(\frac{\theta_E}{\theta_b/2}\right)^2 = \frac{1\ \mathrm{yr}}{t_E} \left(\frac{2n\theta_E}{2.5^\circ}\right)^2 =$$

$$= 0.8\% \left(\frac{n^2}{10^7}\right) \left[\frac{M}{10^7 M_\odot}\right]^{1/2} \left[\frac{10\,\mathrm{kpc}}{L}\right]^{3/2}. \tag{7}$$

Assuming a better than 1% precision photometry, a sample of 10^7 background sources allows detection of clusters with mass $10^7 M_\odot$ and higher. Smaller masses require a higher number of background sources. For comparison, MACHO project has monitored 11.9 million stars during 5.7 yr of operation [17]. Of course, lens chasing presents a very different challenge from that faced by MACHO. Unlike MACHO, which monitors bright nearby stars in Large Magellanic Cloud on a continuous basis, we want a relatively infrequent (once

a year) accurate photometry of stars in the directions of UHECR doublets.

Some of the clusters in the AGASA data lie in the supergalactic plane [2, 3]. The presence of many relatively close (and, hence, bright) background stars in these directions makes the corresponding clusters particularly appealing for lens chasing.

One can, of course, refine this technique. If the lensing cluster is discovered after several initial crude scans, one can narrow down its coordinates and perform a more detailed monitoring of closely spaced sources around the location of the lens.

We note in passing that future detectors can observe yet another signature of the same kind of sources. Decays of superheavy particles and subsequent fragmentation can produce excited hadrons. Their decays, in turn, can produce simultaneous air showers separated by thousands of kilometers. The time delay is $\delta t = t\gamma^{-2}\Delta E/E$, where t is the time of flight, $\gamma \sim 10^{11}$ is the Lorentz factor, and $\Delta E/E \sim 1$. The difference in the arrival time $\delta t \sim 10^{-11}$ s, and the distance between air showers is of the order of 10^3 km. Future space-based detectors, such as EUSO and OWL, can observe such spatially separated events in coincidence.

To summarize, a small-scale anisotropy in the AGASA data demands that, if the UHECR are due to decaying relic particles in the halo, these particles form clusters with coordinates specified by the cosmic ray events. The masses of such clusters can range from $M_\odot$ to $10^{10}M_\odot$. We have proposed a general strategy for detecting such clusters by their gravitational lensing of the background stars and galaxies.

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