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Ultrahigh energy cosmic rays as heavy nuclei from cluster accretion shocks

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Abstract: Large-scale accretion shocks around massive clusters of galaxies, generically expected in hierarchical scenarios of cosmological structure formation, are shown to be plausible sources of the observed ultrahigh energy cosmic rays (UHECRs) by accelerating a mixture of heavy nuclei including the iron group elements. Current observations can be explained if the source composition at injection for the heavier nuclei is somewhat enhanced from simple expectations for the accreting gas. The proposed picture should be clearly testable by current and upcoming facilities in the near future through characteristic features in the UHECR spectrum, composition and anisotropy, in particular the rapid increase of the average mass composition with energy from 10^{19} to 10^{20} eV. The associated X-ray and gamma-ray signatures are also briefly discussed.

Introduction

The origin of UHECRs with energies 10^{18}-10^{20} eV and above remains one of the biggest mysteries in physics and astrophysics [1]. Only a few types of astrophysical objects appear capable of accelerating UHECRs to the highest observed energies, such as the jets of radio-loud active galactic nuclei or gamma-ray bursts [2, 3]. However, no unambiguous identification with any kind of source has been achieved so far.

In the currently favored picture of hierarchical structure formation in the CDM cosmology, all massive clusters of galaxies should be surrounded by strong accretion shocks, as a consequence of continuing infall of dark matter and baryonic gas [4]. Such shocks should be interesting sites of particle acceleration, and have also been proposed as sources of UHECRs [5]. Here we summarize our recent work on this subject invoking UHECR nuclei; more details can be found in Ref. [6].

Model

For clusters of mass M, the rate of gas kinetic energy dissipation through accretion shocks can be estimated as $L_{\rm acc} \simeq 9 \times 10^{45}(M/10^{15}M_\odot)^{5/3}{\rm erg\,s^{-1}}$ [7]. This can be combined with the expected mass function of dark matter halos [8] to evaluate the total energy output from cluster accretion in the universe. Note that due to the hierarchical nature of structure formation together with the nonlinear nature of gravity, the maximum energy dissipation is reached at $z = 0$, with ample room to supply the UHECR energy budget [3].

However, estimates of the maximum energy $E_{\rm max}$ for protons seem to fall short of 10^{20} eV by 1-2 orders of magnitude [9, 10]. A fiducial cluster of $M = 2\times10^{15}M_\odot$ has shock radius $R_s \simeq 3.2$ Mpc and shock velocity $V_s = (4/3)(GM/R_s)^{1/2} \simeq$ 2200 km/s. The shock magnetic field is taken to be $B_s = 1\mu$G, as suggested by some recent observations [11]. The timescale for shock acceleration of particles with energy E and charge Z is $t_{\rm acc} = 20\kappa(E)/V_s^2 = (20/3)(Ec/ZeB_sV_s^2)$, assuming the Bohm limit for the diffusion coefficient $\kappa(E)$ as inferred for supernova remnant shocks [12] and possibly induced by the CRs themselves [13]. To be compared are the energy loss timescales for photopair and photopion interactions with the cosmic microwave background (CMB), the escape time from the acceleration region $t_{\rm esc} \sim R_s^2/5\kappa(E)$ [14], and the Hubble time t_H. As is clear in Fig.1, for protons $E_{\rm max} \sim 10^{18}$-10^{19} eV, confirming previous findings.

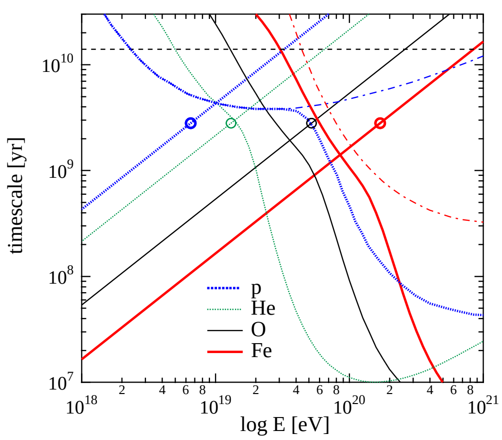

Figure 1: Comparison of timescales at cluster accretion shocks for shock acceleration $t_{\rm acc}$ (diagnonal lines), and energy losses from interactions with background radiation fields (curves), for protons (thick dotted), He (thin dotted), O (thin solid) and Fe nuclei (thick solid). The photopair timescales are denoted separately for p and Fe (dot-dashed). Also indicated are the Hubble time t_H (dashed) and the escape-limited $E_{\rm max}$ (circles).

On the other hand, heavy nuclei with higher Z have correspondingly shorter t_{acc}, and Fe may be accelerated up to 10^{20} eV in the same conditions, notwithstanding energy losses by photodisintegration and photopair interactions with the far infrared background (FIRB) and CMB (Fig.1). In order to explore whether nuclei from cluster accretion shocks can provide a viable picture of UHECR origin, detailed propagation calculations of UHE nuclei above 10^{19} eV are undertaken, following energy losses in the CMB and FIRB [15] and deflections in extragalactic magnetic fields (EGMF) for all particles including secondary nuclei arising from photodisintegration. We consider EGMF models that trace large-scale structure [16], as well as the case of negligible EGMF, although Galactic fields [17] are not included. The source density is $n_s = 2 \times 10^{-6}{\rm Mpc}^{-3}$, appropriate for massive clusters with $M \gtrsim 10^{15} M_\odot$ [8]. A fraction $f_{\rm CR}$ of the accretion luminosity $L_{\rm acc}$ is converted to cosmic rays with energy distributions $\propto E^{-\alpha}\exp(-E/E_{\rm max})$, and we set $E_{\rm max}/Z = 5 \times 10^{18}$ eV, a fair approximation to estimates for each species obtained by comparing timescales as in Fig.1. For the elemental composition at injection, the He/p ratio is taken to be 0.042. All heavier elements are assumed to have the same relative abundances at fixed energy/nucleon as that of Galactic CR sources at GeV energies [18], and scaled with respect to protons by the metallicity ζ of the accreting gas. We take $\zeta = 0.2$ as suggested by both observations and theory for the gas flowing in from large-scale filaments [19]. An additional factor A^β for the injected abundance of nuclei with mass number A is introduced to take account of possible enhancement of heavier nuclei due to nonlinear modification of shock structure by CRs [20], which may possibly be stronger here than for Galactic CRs due to the acceleration to much higher energies.

Results and Discussion

Fig.2 shows our results for the observed spectrum and composition for $\alpha = 1.7$ and $\beta = 0.5$, which are consistent with the current data for HiRes [21] and Auger [22] (and possibly AGASA [23] as well [6]). Values of $\alpha < 2$ are naturally expected at the high energy end for nonlinear shock acceleration that accounts for the dynamical back reaction from CRs [24]. The spectral steepening at $\gtrsim 10^{20}$ eV is due both to propagation losses and the $E_{\rm max}$ limit at the source. Normalization to the observed flux and comparison with the available accretion power for $M > 10^{15} M_\odot$ fixes $f_{\rm CR}$, which is $\simeq 0.01-0.6$ for cases with EGMF and $\simeq 0.004$ for the case without. Low values of f_{CR} may reflect inefficient escape of CRs from the system, which is conceivable in view of the converging nature of the accretion flow. CR escape may be mediated mainly during episodic merging events that partially dis-

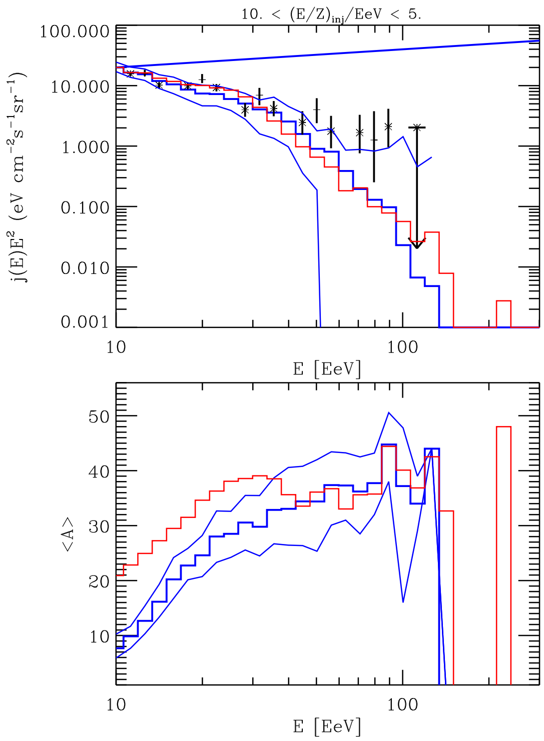

Figure 2: Observed UHECR spectrum (top) and mean mass composition (bottom) versus energy E (1 EeV $\equiv 10^{18}$ eV) from cluster accretion shocks for $\alpha = 1.7$ and $\beta = 0.5$, compared with the current data for HiRes (bars) and Auger (stars). The histograms are the average result over different model realizations for the cases with (thick) and without (thin) EGMF, and the thin curves outline the cosmic variance for the former case only. The straight line in the top panel denotes α.

rupt the shock and drive outflows of some of the downstream gas [25].

The mass composition at $\lesssim 3 \times 10^{19}$ eV is predominantly light and consistent with HiRes reports [26], while the rapid increase of the average mass at higher energies is a clear prediction of the scenario to be tested by the new generation experiments (and is in line with the latest Auger results [27]).

Despite the relative rarity of massive clusters in the local universe, strong deflections of the highly charged nuclei in EGMF allow consistency with the currently observed global isotropy (Fig. 3). On the other hand, with a sufficient number of accumulated events, clear anistropies toward a small number of individual sources should appear, although this prediction is subject to uncertainties in the EGMF and Galactic fields.

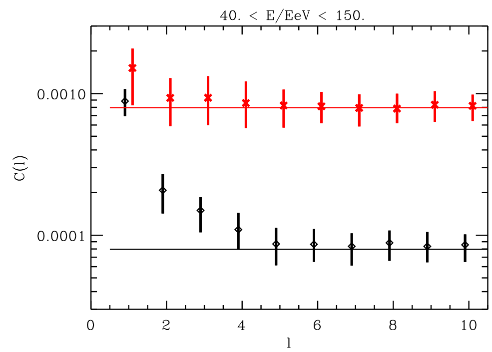

Figure 3: Angular power spectrum $C(l)$ of UHECR arrival directions above 4×10^{19} eV versus multipole l, for a realization with EGMF and a single, dominant cluster at $D \sim 50$ Mpc. The crosses are for 100 events with AGASA + SUGAR exposure and diamonds for 1000 events with Auger North + South exposure. Vertical bars indicate statistical errors.

An aspect of this scenario that warrants further study is the spectral domain $< 10^{19}$ eV and the implications for the Galactic-extragalactic transition region [18].

X-ray and Gamma-ray Signatures

If cluster accretion shocks are indeed accelerators of UHE particles, we may look forward to very unique X-ray and gamma-ray emission that can serve as valuable multimessenger signals. Protons accelerated to 10^{18}-10^{19} eV in cluster accretion shocks should efficiently channel energy into pairs of energy 10^{15}-10^{16} eV through interactions with the CMB, which then emit synchrotron radiation peaking in hard X-rays and inverse Compton radiation in TeV gamma-rays. Fig.4 displays the predicted spectra for a Coma-like cluster, conservatively assuming that UHE proton injection continued only for a dynamical time $\simeq 2$ Gyr (see Ref. [10] for more details). The detection prospects are very promising for Cerenkov telescopes such as

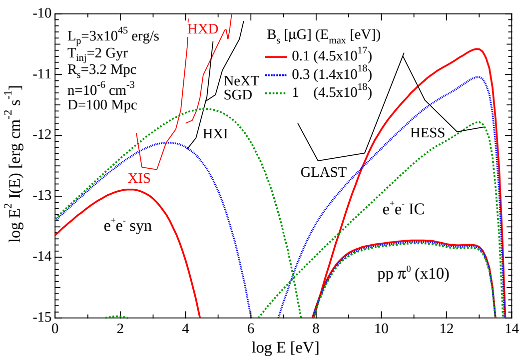

Figure 4: Spectra of UHE proton-induced photopair emission from the accretion shock of a Coma-like cluster, for B_s =0.1, 0.3 and 1 μG. The sensitivities for a 1 degree extended source are overlayed for HESS, GLAST, Suzaku XIS+HXD, and NeXT HXI+SGD.

HESS, VERITAS, CANGAROO III and MAGIC, and hard X-ray observatories such as Suzaku and the future NeXT mission. Photopair production by nuclei may also be efficient and induce further interesting signals that are worth investigating.

Combined with such complementary information from X-ray and gamma-rays, detailed measurements of UHECR composition and anisotropy with facilities such as the Pierre Auger Observatory, the Telescope Array, and the future Extreme Universe Space Observatory should provide a clear test of whether the largest bound structures in the universe are also the largest and most powerful particle accelerators.

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