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NON-LTE ASTROPHYSICS AND THE ORIGIN OF HIGH ENERGY COSMIC RAYS

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ABSTRACT

The most startling aspects of the universe are the departures from the nonuniform, nonthermodynamic equilibrium state. Mass concentrations and high energy electromagnetic quanta and particles are the primary examples. Of these various departures the extremum of nonexplained phenomena is still the acceleration of cosmic rays. The usual explanations involving multiple mechanisms contributing to various regions of the spectrum is suggested as most unlikely. In particular, the suggestion of the acceleration of the very highest energy cosmic rays in distant active galactic nuclei is shown to be untenable because of photon particle interactions.

INTRODUCTION

The simplest state of affairs for our universe would be uniform, homogeneous, isotropic, local thermodynamic equilibrium matter. It is the departures from this benign state that are interesting astrophysics. The extremum of these departures are both the mass distributions of the universe, clusters, galaxies, and stars, and the extrema of energy such as cosmic rays, quasars, supernovae, gamma bursts, and masers. The explanation of these phenomena, using the known laws of physics is the essence of astrophysics. There are very many puzzles; it is surprising how old many of these problems are and how such depressingly small progress has been made in their resolution. On the other hand, it is heartening that astrophysics universally restricts itself to the laws of physics tested here on earth and so far has refrained from attempting to invoke new laws of physics to explain its greatest confrontations. I will select one of these topics, the ultrahigh energy part of the cosmic ray spectrum and attempt to make the puzzle still more difficult for astrophysics to explain, yet I note in passing that the radiation mechanisms of quasars, Seyfert galaxies, and active galactic nuclei are as challenging, or as little understood as ever and that supernova consistently either marginally work or marginally don't work and that gamma bursts are still a high energy phenomenon that await an explanation.

ULTRA-HIGH ENERGY COSMIC RAYS

Cosmic rays are the extremum of nonthermal particles. A quasi power law spectrum extends up to 10^{20} eV, or for protons $E = 1/\sqrt{1-\beta^2} = 10^{11}$. Measurements of variations in this power law as a function of energy have been continuously refined but nowhere is there allowed the possibility of a departure from a monotonic spectrum of

particles from the very lowest energies to the very highest. There is nowhere in the spectrum a clear cut evidence for a peak and thus a contribution from an entirely different mechanism for a given group of particles. The special circumstance that any given mechanism should more or less serendipitously overlap another in just such a fashion as to produce a monotonic spectrum would seem highly unlikely. This is unlikely not only because of the lack of a secondary peak, but also because a second acceleration mechanism should produce more lower energy particles than the presumed primary mechanism.

STOCHASTIC PROPERTY OF ACCELERATION

Acceleration is a progressive departure from thermal and hence low energy particles are nearly always overabundant. The general property of an acceleration mechanism is that the probability of producing a high-energy particle decreases as a function of energy simply because the high-energy particle requires a greater coherence or lifetime within the acceleration region. This is inherently true for all proposed mechanisms. It is not true for a laboratory accelerator because of a perfection of construction whose a priori probability is of measure zero.

DIFFUSION ACCELERATION

It has been suggested that energy diffusion accompanying spacial diffusion within the galaxy should lead to a monotonic distribution from several different energy sources. A diffusion in energy, however, is equivalent to a heating or acceleration of the few particles that drift to high energy. A first order Fermi acceleration across supernova induced shock waves in the galactic medium is now well recognized as a possible primary acceleration mechanism. Particles are scattered back and forth across the expanding shock wave by Alfvén wave turbulence induced in turn by the the particle diffusion. The limit to this process is generally recognized to be roughly 10^{13} eV due to the ratio of particle Larmor orbit to the maximum (strong) shock diameter induced by the supernova.

HYPOTHETICAL SECONDARY ACCELERATION

If a second mechanism exists to produce high energy cosmic rays, it must become predominant within a factor of 2 in energy and 2 in magnitude of the value where the primary mechanism fails, otherwise there will either be a peak in the spectrum or too large a negative step in flux to be consistent with the near constant power law slope $\pm .5$ from the measured spectrum from $N(> E) \propto E^{-1.7 \pm 0.5}$. Diffusion must spread this secondary source in energy so as not to leave a spectral "bump". Such an energy diffusion will spread the secondary source to higher energies, i.e., a tertiary mechanism. Then why not dispense with the secondary acceleration and just diffuse the upper energy limit of the primary mechanism to still

higher energy by the tertiary mechanism? If there were such a diffusion to high energy, this would be the primary mechanism. Instead it is generally believed that galactic diffusion removes energy from the high energy CR's $> 10^{13}$ eV and lets high energy particles preferentially escape.² Hence the requirement to develop the supernova interstellar medium shock mechanism to energize the turbulent diffusion, but this energization leads to a modest upper energy limit.

The second unlikely circumstance is that the proposed high energy mechanism should not produce more low energy particles than the proposed primary mechanism. When one considers the immense scientific effort spent on the problem of the origin of CR's it would seem far less likely to accept the existence of any serendipitous high energy source $E > 10^{13}$ eV of just the right source strength, energy, and lack of low energy acceleration than to start from scratch and say I am going to find an entirely new mechanism for the full monotonic spectrum. In other words, a good theory of a low energy source is less likely to be true just because it demands a special high energy one to complete the picture. Whatever may be the high energy source, this source is then more likely to dominate the originally proposed low energy one.

EXTRAGALACTIC ACCELERATION

The problem of multiple acceleration mechanisms is recognized and taken seriously for energies less than galactic confinement, $E_p < 10^{18}$ eV, but above this energy, it has been assumed that cosmic rays must be accelerated in extra galactic space, more particularly in exotic energetic objects like quasars and active galactic nuclei.^{3,4}

Besides the difficulty of serendipitous matching in energy flux, and lack of low energy particles, further difficulties can be found.

The very highest energy cosmic rays were inferred from air shower measurements, 10^{19} to 10^{20} eV, and confirmed among various experiments.⁵ Greisen⁶ pointed out that such high energy particles in the extragalactic environment would lose their energy in a Hubble expansion time due to Doppler shifted collisions with the blackbody radiation. The predicted cutoff around 10^{20} eV is definitely not seen and indeed the spectrum becomes flatter above 10^{18} eV, the exact converse of the expectation. Very detailed calculations of spallation of nuclei due to infrared and star light, pair production and pion⁷ production were performed by Puget, Stecker, and Bredekamp. Figure 1, reproduced from their article shows the energy loss time due to the blackbody photons alone. The full radiation spectrum used for the spallation analysis is shown in Fig. 2. Even with the very weak photon flux in the infrared and optical, the Doppler shifted spallation of iron nuclei limits this possible explanation of these ultrahigh energy cosmic rays to either protons or iron nuclei within the local supercluster.

Fig. 1. From Puget et al (1976). The energy loss time and attenuation length for protons from pair production, redshift, and photo-pion production losses. Also shown is the attenuation length for ^{56}Fe from pair production losses. Also, separate scales have been added for the equivalent process in the near radiation field of an active galactic nucleus (AGN). The diagonal line added is the approximation appropriate to these added scales.

What we now wish to point out is that the frequent assumption of acceleration in active galactic nuclei in the local supercluster has far worse limitations due to the same radiation damping.

ACCELERATION IN ACTIVE GALACTIC NUCLEI

The assumption of the acceleration of cosmic rays in Quasars, BL lac objects, Seyfert galaxies, AGN (active galactic nuclei) suffers in the extreme from the same problem of photon damping. The damping or deceleration occurs within the photon energy density of the emission by which we recognize the objects in the first place. A particle can be accelerated inside or outside such an object

Inside and outside corresponds to an emission surface. In general the most energetic phenomenon should occur inside, but it would be possible for a particle to be accelerated outside in a magnetically confined orbit. Therefore the following assumptions are made as applying to any reasonable mechanism of acceleration in any AGN.

1. The acceleration of a particle must take place within, and the particle traverse, at least one radius of the object where the radius corresponds to an emission surface inside of which the photon flux is quasi-isotropic.

Fig. 2. From Puget et al (1976). Computed background radiation fields from quasars, Seyfert and related galaxies, and normal galaxies. Separate scales and an extension of the graph has been added appropriate to the near radiation field of AGN.

2. Acceleration outside an emission surface must require at least one or it around the object in a presumed magnetic field strong enough to confine the high energy particle.

Both circumstances lead to impossible loss of the cosmic ray energy due to the two processes of pair production and pion production. In the first case of purely radial traversal of the emission nebula, the photons are quasi-isotropic in the rest frame and in the second case the photon streaming will lead to a primarily orthogonal flux, both of which lead to photon collision energies in the frame of the cosmic ray particle essentially the same as calculated by Puget et al. It should be noted that one cannot use the radial photon flux external to the surface to significantly accelerate the particles further because of red shift and photon drag.

Under these circumstances we can scale the photon damping or cosmic ray energy loss to a standard AGN. Let the standard luminosity be

$$L_{46} = 10^{46} \text{ erg s}^{-1}$$

and radius for 10-day fluctuation period be

$$R_{16} = 10^{16} \text{ cm}$$

so that the photon energy flux at the surface becomes

$$\phi = 10^{13} L_{46} R_{16}^{-2} \text{ ergs cm}^{-2} \text{ s}^{-1}.$$

Some AGN's have a peak in the emission spectrum in the long wavelength IR, $\lambda \cong 100$ microns about a factor of 10 shorter than the cosmic black body radiation. Others like Seyfert galaxies have their peak in emission in the x-ray region. In general the fluctuation time decreases for shorter wavelength, being months to years in the IR and as short as hours in the x rays for low luminosity Seyferts. The average energy flux per logarithmic band width, $d\phi/d \log(h\nu)$, is conservatively 1/10 the total luminosity so that the average flux at the surface becomes

$$d\phi \cong 10^{12} L_{46} (h\nu_{\text{eV}}) d(\log h\nu) \text{ ergs cm}^2 \text{ s}^{-1}$$

where $h\nu_{\text{eV}}$ is the mean photon energy in eV in a band $d(\log h\nu)$ wide and where the fluctuation time has been approximated as being

$$\Delta t \cong 10^6 (h\nu_{\text{eV}})^{-1/2} \text{ s so that } R_{16} = (c/3) \Delta t = (h\nu_{\text{eV}})^{-1/2}$$

corresponding to a fluctuation time of an hour for 10 keV x rays and a year at $\lambda = 1$ mm. With this fluctuation time and $L = 10^{46}$ ergs s^{-1} , the photon emission is superluminal below $h\nu = 1$ eV.

This spectral flux is shown as a separate scale and a line on Fig. 2 from Puget et al and also as a time on the CR photon loss curve, Fig. 1.

Here the rate per particle of pair or pion production is taken as proportional to the photon number density at the relative energy $\Gamma(h\nu)$ necessary to create pairs or pions. Since $n(h\nu) \propto d\phi/(h\nu)$, the loss time becomes independent of photon energy. Since this time is 10^{15} seconds for the black body flux of 10^{-3} ergs $\text{cm}^2 \text{ s}^{-1}$, the AGN deceleration time becomes

$$\Delta t_{\text{loss}} = \Delta t_{\text{bb}} (\phi_{\text{bb}}/\phi_{\text{AGN}}) = L_{46}^{-1} \text{ s}.$$

The fluctuation time and hence radius of the surface of an AGN is 10^4 times larger than this energy loss time even for the hard x-ray upper limit of the spectrum $\cong 10$ keV for Seyfert galaxies. The cosmic rays accelerated in such an object would therefore likely be truncated for energies above

$$\Gamma(h\nu_{\text{x ray}}) > 2 \times 10^8 \text{ eV},$$

the pion threshold, or

$$\Gamma > 2 \times 10^4, \text{ or cosmic ray energy } E > 2 \times 10^{13} \text{ eV}.$$

The spallation of heavy nuclei such as Fe would of course extend to the energy of the photo-nuclear threshold or a factor of 20 lower energy.

The large photon damping of the acceleration of high energy cosmic rays is strongest for the highest energy particles in the most energetic quasars where the emission peaks at 10-100 microns at $L = 10^{47}$ ergs s^{-1} and the luminosity fluctuation time is a year. Here the damping time is 3×10^{-9} of the particle escape time at an energy of 10^{18} to 10^{19} eV. Hence it seems unreasonable to expect ultra high energy cosmic ray acceleration in AGN.

REMAINING ACCELERATION IN IGM

Currently we recognize the universe external to the Galaxy as being filled with other galaxies, the intergalactic medium (IGM), inter cluster medium, ICM, and AGN. The medium between galaxies and between cluster members is similar in the sense that the magnetic field, plasma energy density and particle density is less than that within galaxies.

The cosmic ray energy limitation to shock wave acceleration in the interstellar medium (ISM) applies also to the IGM, or ICM. The much weaker fields $\sim 10^{-2}$ of the ISM means the field times distance (galaxy spacing) or likely maximum larmor orbit size is not much larger than within the galaxies - at most $\times 10$ so that it is unlikely that a factor of 10^7 (10^{13} eV to 10^{20} eV) higher acceleration energy can be achieved by any of the presently proposed shock and turbulence acceleration mechanisms.

The only remaining space is galaxies themselves. Ours is a good example. I believe we must still look for the one singular mechanism for cosmic ray acceleration within our own galaxy.

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