INTERSTELLAR AND INTRACLUSTER TUNNELS AND ACCELERATION OF HIGH-ENERGY COSMIC RAYS

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The present evidence about the origin of high-energy cosmic rays is that two ranges exist: one below 10^{18} eV related with galactic sources, and one up to 10^{20} eV, corresponding to extragalactic processes (Kiràly et al. 1979). However the continuity of the spectrum indicates that the physical mechanisms must be correlated. In the global energetics the spectral range above 10^{12} eV is irrelevant and the bulk of CR energy is actually provided by supernovae, pulsars, X-ray binaries, etc. in the Galaxy. Nevertheless none of these objects seems capable of producing CR above 10^{15} eV/nucleon. We have investigated the possibility that the acceleration at higher energies is statistical, taking place over a hierarchy of scales. A model has been developed in terms of the quasi-linear theory of particle acceleration by MHD turbulence (Kulsrud and Ferrari 1971). Cosmic rays with $\lesssim 10^{15}$ eV/nucleon injected by single sources into interstellar space undergo momentum diffusion by stochastic interaction with long wavelength MHD perturbations; small wavelength modes provide pitch-angle scatterings. These MHD perturbations, Alfvèn and fast magnetosonic waves, are generated by the dynamic interaction of supernova remnants with the interstellar medium. From observations (Jokipii 1977), the range of possible wavelengths extends from the proton gyroradius to the size of the so-called "superbubbles", up to 100 pc, with a power-law spectrum. Correspondingly acceleration is efficient up to 10^{18} eV/nucleon; in fact for $B = 10^{-3} \div 10^{-5}$ G, $n = 0.01 \div 1\ \mathrm{cm}^{-3}$ and $L = 0.1 \div 100$ pc, we find that the acceleration timescale

$$\tau_{acc} = (B/\delta B)^2 (c/v_A)^2 L/c\ (\varepsilon/eBL)^{4-\alpha}$$

($\varepsilon = eBL$ is the maximum allowed energy) is always shorter than the time scales of losses and turbulent structure lifetimes; $\alpha = 3.5 \div 4$ is the spectral index of turbulent modes. Contrary to the original Fermi mechanism, in this theory the time scale for acceleration up to any energy ε is fixed by the final phase, previous steps being negligible.

A similar scenario can be envisaged in the extragalactic range, simply assuming that galaxies, especially those with active nuclei, are the localized sources injecting particles with energies $\varepsilon \lesssim 10^{18}$ eV. Magnetic inhomogeneities can be produced by: (1) protruding SN cavities, (2) galactic winds, (3) galactic wakes due to Kelvin-Helmholtz instabilities for the relative motion in

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the intergalactic medium. It is not possible at present to measure a spectrum of MHD perturbations in IGM and their filling factor in clusters is also difficult to estimate; data will come from radio and X-ray observations. For instance we already know that in the Abell cluster 1367 a 300 kpc radio halo has been detected (Gavazzi 1978) neither connected with radio galaxies, nor with the cluster centre. It likely indicates the occurrence of particle acceleration in IGM.

For the acceleration to energies above 10^{18} eV, a rate of energy supply $\sim 10^{41}$ erg/s is required in a volume equal to the Virgo cluster. Referring for instance to the case of galactic wakes, the energy released in turbulence by a streaming galaxy can be estimated to be

$$\dot{E}_g = 10^{44}\ \eta\ (M_{11}\ v^3_{g,8}\ D^{-1}_{24})\ \text{erg/s},$$

assuming a typical dispersion velocity $v_g = 10^3$ km/s and a stopping distance D = 1 Mpc; η is an efficiency factor. With 10^3 galaxies in a cluster, the energetic supply is quite adequate (this is also true for not rich clusters as our Local Group). Eventually in a stationary situation the power-law spectrum should not differ from that measured in the ISM. Acceleration of stochastic origin of particles leaking from galaxies is then possible.

Scattering from MHD inhomogeneities has been similarly used by Wdoczyk and Wolfendale (1979) in a model of CR propagation in the Virgo cluster.

The acceleration time scale must be here confronted essentially with that for γ p losses against the cosmic background radiation. For B $\cong 10^{-6}$ G, n $\cong 10^{-6}$ cm^{-3}, L = 0.1 ÷ 1 Mpc, acceleration is faster up to a few times 10^{20} eV/nucleon. This continuous acceleration allows also to explain the flattening of the energy spectrum above 10^{19} eV as a piling up of CR when balance is reached between stochastic acceleration and γp losses; at higher energies the spectrum should then drop rapidly. An alternative explanation of this flattening, also compatible with our model, has been forwarded by Wdoczyk and Wolfendale in terms of propagation effects in turbulent IGM.

Finally we find that in this scenario measurements of arrival direction anisotropies in the range $10^{16} \div 10^{17}$ eV can be fitted with the large scale structures of the ISM; correspondingly anisotropies above 10^{19} eV could provide an indirect tool for studying the structure of IGM in our Local Supercluster.

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