

THE ORIGINS OF COSMIC RAYS AND QUANTUM EFFECTS ON GRAVITY*

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The energy spectrum of primary cosmic rays is explained by particles emitted during a thermal expansion of explosive objects inside and near the galaxy, remnants of which may be supernova and/or active galaxies, or even stars or galaxies that disappeared from our sight after the explosion. A power law energy spectrum for cosmic rays, $E^{-\alpha-1}$, is obtained from an expansion rate $t \propto R^\alpha$. Using the solution of the Einstein equation, we obtain a spectrum which agrees very well with experimental data. The implication of an inflationary early universe on the cosmic ray spectrum is also discussed. It is also suggested that the conflict between this model and the singularity theorem in classical general relativity may be eliminated by quantum effects.

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Since the discovery of cosmic rays early this century, an impressive amount of experimental data has been accumulated. Yet, the origin of cosmic rays defies the understanding of physicists. Several important questions are: What is the fraction of galactic and extragalactic components of primary cosmic rays? How can one understand the power law energy spectrum ($\sim E^{-2.5} - E^{-3}$ for the energy range $10^9 \text{ eV} < E < 10^{20} \text{ eV}$)? How do they attain such high energies? Despite various attempts in the past to answer these questions, we are still left in the dark.¹ In this article, we present a model which explains some of the features of cosmic rays described above.

The following are the assumptions which we propose to make:

- (a) The sources of primary cosmic rays are supernova, galaxies and/or clusters of galaxies which have exploded in the past, after the gravitational contraction. Active galaxies such as radio- or X-ray galaxies, Seifert galaxies, or QSO's may be the remnants of such an explosion. Or some of them might have disappeared completely from our sight after the explosion.
- (b) The explosion of such an object is a replica of the expansion of the universe at a smaller scale. It goes from expansion in a radiation dominated era at extremely high temperature to that in a matter dominated era at lower temperature. It may even undergo a phase like that of an inflationary early universe.
- (c) In the course of expansion, high energy particles of various kinds are emitted because of nonequilibrium processes. The energy distribution of the emitted particles reflects the black body radiation law at the temperature T at which the particles are emitted. The number of such

particles is not large and the system is approximately in equilibrium at each instant since the collision time is much smaller than the expansion time.

Under the assumptions, the number of particles of type x emitted with energy E is given by

$$f_x(E) = \frac{(2s+1)}{2\pi^2} \int \eta_x(E/kT) \frac{E^2 V_S dt}{e^{E/kT - \mu/kT \pm 1}}, \quad (1)$$

where V_S is the effective volume around the surface of the system which emits the particles, $\eta_x(E/kT)dt$ is the fraction of particles x emitted in time interval dt and μ and s are the chemical potential (zero) and the spin for fermions (bosons) of type x . The $+(-)$ sign in the denominator is for fermions (bosons). The volume V_S is taken to be

$$V_S = 4\pi R^2 d = 4\pi \frac{a^2}{(kT)^3} \quad (2)$$

since the surface of the particle distribution is defined with uncertainty $\Delta x = d = 1/kT$, where a is a constant defined by $R = a/kT$. For an expanding system

$$t = bR^\alpha, \quad (3)$$

where b is constant and²

$$\alpha=2 \quad \text{for the radiation dominated era} \quad (4a)$$

and

$$\alpha=3/2 \quad \text{for the matter dominated era} \quad (4b)$$

(the Einstein-deSitter flat space)

The function $\eta_x(E/kT)$ is unknown, but is assumed to scale as a function of E/kT . The result is essentially the same if the E (or T) dependence of $\eta_x(E/kT, E \text{ (or } T))$ is slowly varying except in E/kT . The chemical potential for fermions is obtained by the condition

$$\frac{N}{V} = \frac{(2s+1)}{2\pi^2} (kT)^3 \int_0^{\infty} \frac{x^2 dx}{e^x - \mu/kT + 1} \quad (5)$$

or equivalently

$$\mu_0 \equiv \mu/kT = g\left(\frac{N}{V(kT)^3} \frac{2\pi^2}{(2s+1)}\right), \quad (6)$$

where N is the total number of particles in the system and V is the volume given by

$$V = \frac{4\pi}{3} R^3 = \frac{4\pi}{3} \frac{a^3}{(kT)^3} \quad (7)$$

(At high temperature, $g(x) = \ln(x/2)$.) Obviously, μ_0 is independent of temperature since VT^3 is constant during the course of the expansion. ($\mu_0=0$ for bosons, as was stated earlier.) Using eqs.(1)-(4), we obtain

$$f_X(E) = \frac{A_{X,\alpha}}{E^{\alpha+1}}, \quad (8)$$

where

$$A_{X,\alpha} = \frac{2(2s+1)\alpha b(a)^{2+\alpha}}{\pi} \int_0^{\infty} \frac{n_X(s) s^{\alpha+2} ds}{e^{s-\mu_0} \pm 1} \quad (9)$$

is a constant. Then, the total energy spectrum is given by

$$f(E) = \frac{A_\alpha}{E^{\alpha+1}} \quad (10)$$

where

$$A_\alpha = \sum_X A_{X,\alpha}. \quad (11)$$

The power law energy spectrum (8) and (10) with the values of α in eq.(4), is