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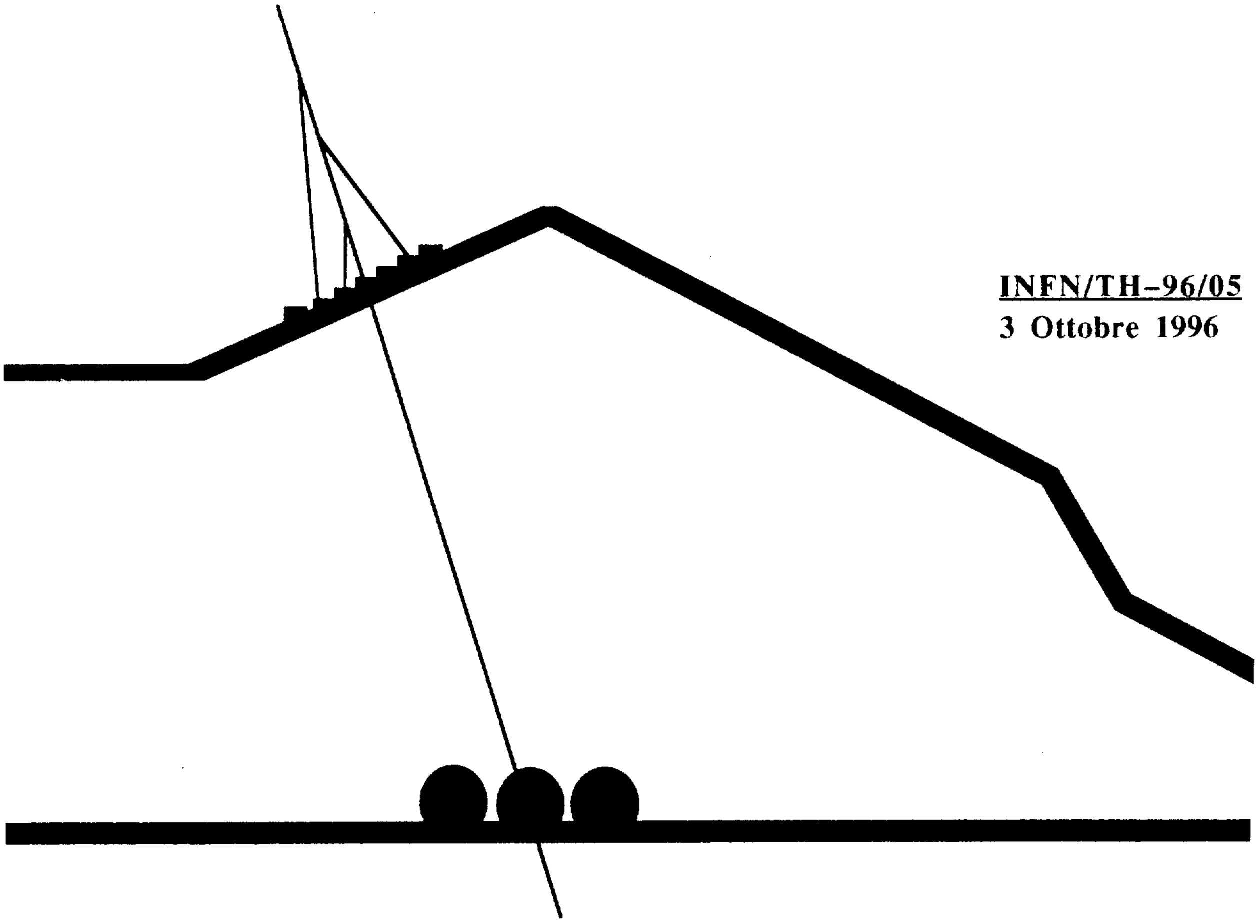

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COSMOLOGICAL DENSITY OF BARYONS AND HIGH ENERGY RADIATION FROM CLUSTERS OF GALAXIES

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Abstract

We calculated the diffuse high energy gamma and neutrino radiations produced by the *pp* collisions between cosmic rays confined in clusters of galaxies and intracluster gas. Our expressions for such diffuse fluxes depend on a very restricted set of parameters namely the cosmological baryon fraction Ω_b, the cosmic ray spectrum due to sources inside clusters and the radius of a typical cluster of galaxies.

Several possibilities of sources of cosmic rays in clusters have been studied (normal galaxies, AGN, accretion shocks) but none of them can account for the observed diffuse gamma radiation above 100 MeV.

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1 Introduction

X-ray observations of the sky give evidence of a large baryon content in the intracluster gas (White and Frenk 1991, White et al. 1993, White and Fabian 1995) so that the baryon fraction in clusters, $\Omega_b^{cl} \simeq 0.05h^{3/2}$ results to be close to the value of Ω_b found from nucleosynthesis: $0.009 \leq \Omega_b h^2 \leq 0.024$ (Copi, Schramm and Turner 1995).

Recently Dar and Shaviv (1995a,b) used this consideration in order to calculate the contribution of the clusters of galaxies to the diffuse gamma and neutrino radiation produced by the nuclear interactions between cosmic rays (CR) and the intracluster gas, making the *ad hoc* assumption that the CR energy density in clusters is the same as in our galaxy. In spite of this assumption we considered here all possible sources of CR in clusters and calculated a more realistic contribution to the diffuse flux of gamma's and neutrinos.

The basical ingredient of our calculation is the confinement capability that a cluster shows in keeping the CR produced along its lifetime inside the cluster radius. In other words clusters behave as storage rooms for CR.

We consider here normal galaxies, AGN and accretion shocks as the sources of CR in clusters and calculate the correspondent contribution to the diffuse backgrounds due to nucleus-nucleus collisions in the intracluster gas.

2 Cosmic Ray confinement

The confinement of CR in clusters of galaxies has been recently recognized by Volk, Aharonian and Breitschwerdt (1996). The main point in the proof of such confinement comes from radio observations, which show the presence of tangled magnetic fields in clusters, with typical value $H = 1 - 3\ \mu G$ and typical scale of homogeneity $l \sim 20\ pc$ (Jaffe 1980). In the following we shall take $H = 1\ \mu G$. The diffusion coefficient for CR having energy smaller than $E_0 \simeq 2 \times 10^7\ GeV$, correspondent to protons with larmor radius $r_h \simeq l$, can be taken as $D_0 = \frac{1}{3}cl \simeq 6 \times 10^{29} cm^2/s$, while for $E > E_0$ we write $D(E) = D_0(E/E_0)^2$. The escape time of protons with $E \leq E_0$ is:

$$\tau = \frac{R_{cl}^2}{6D_0} \simeq 3 \times 10^{11} yrs > t_0 \tag{1}$$

where R_{cl} is the cluster radius and $t_0 = 2.06 \times 10^{17} h^{-1} s$ is the age of Universe. This means that particles with energy $E \leq E_0$ are confined inside clusters, needing for escaping times larger than the age of the cluster itself. More precisely, by using the equation for $D(E)$ given above, it is clear that the confinement mechanism works up to $E \simeq 10^8 GeV$.

Very similar results are obtained if the Bohm diffusion coefficient $D(E) = r_H c$ is used for any energy E of the CR.

We shall consider here only CR with energy smaller than $E_{max} \simeq 10^8 GeV$; the origin of these CR is more or less understood: in fact diffusive acceleration at SN shock can give CR up to $10^5 - 10^6 GeV$, but this value can reach $10^8 GeV$ in the region near a SN filled by the presupernova stellar wind (Volk and Biermann 1988).

Particles with energy $E > 10^8 GeV$ escape from the clusters on time scales shorter than the age of the clusters, being thus inefficient in the gamma and neutrino production (see section 3).

3 Spectrum of the radiation from one cluster

In this section we shall study the spectrum of the gamma and neutrino radiation produced by the CR interactions in one cluster of galaxies. Let us first consider a single source (e.g. a galaxy) from which CR diffuse away. The generation spectrum of the source is $Q_{source}(E) \propto E^{-\gamma_g}$ and the diffusion coefficient is $D(E) \propto E^{\eta}$.

In the formalism of the i-yields (Berezinsky et al. 1990) the number density of secondaries of type i ($i = \gamma, \nu$) per unit time at distance r from the source is given by

$$q_i(E,r) = Y_i \sigma_{pp} n_H c n_{CR}(E,r) \tag{2}$$

where $\sigma_{pp} = 3.2 \times 10^{-26}\ cm^2$ is the typical cross section for high energy pp collisions, n_H is the number density of the baryons in the intracluster gas and $n_{CR}(E,r)$ is the number density of CR with energy E at distance r from the source, that from the diffusion equation results to be:

$$n_{CR}(E,r) = \frac{1}{4\pi r}\frac{Q_{source}(E)}{D(E)}. \tag{3}$$

The total flux is obtained by integration of eq. (2) over volume:

$$Q_i(E) = \int_0^{r_{max}} q_i(E,r) 4\pi r^2 dr, \tag{4}$$

with $r_{max} = min(R_{cl}, R_{diff})$, where R_{cl} is the cluster radius and $R_{diff} = \sqrt{6D(E)\tau_{cl}}$ is the maximum diffusion distance from the source during the cluster age τ_{cl}. It is clear that $r_{max} = R_{cl}$ for $E > E_{max}$ introduced in the previous section, and $r_{max} = R_{diff}$ for energy $E < E_{max}$. On this basis it is easy to show that for the latter case the i-secondary spectrum is

$$Q_i(E) = Y_i Q_{source}(E) \sigma_{pp} n_H c \tau_{cl} \propto E^{-\gamma_g} \tag{5}$$

while for the opposite case

$$Q_i(E) = Y_i Q_{source}(E) \sigma_{pp} n_H c \frac{R_{cl}^2}{6D(E)} \propto E^{-(\gamma_g+\eta)}. \tag{6}$$

Physically these two equations mean that for confined CR ($E < E_{max}$) the probability of interaction in the intracluster gas does not depend upon energy, while this dependence exists for not confined CR ($E > E_{max}$) and causes the reduced efficiency in the secondary production.

If more that one CR source is in the cluster, it will be enough to sum all the contributions from the other sources in order to have the flux from the whole cluster.

4 Diffuse fluxes of gamma rays and neutrinos

In the previous section we studied the spectrum of the radiation due to the CR produced by one cluster. The diffuse flux of i-secondaries with energy E per unit time per unit surface per unit solid angle can be written as

$$I_i(E) = \frac{3}{32\pi^2} Y_i \sigma_{pp} \frac{(ct_0)^2}{m_H R_{cl}^3} Q_p^{tot}(E) \xi \Omega_b \rho_{cr} \tag{7}$$

where a fraction ξ of all the baryons is accumulated in clusters of galaxies; this is equivalent to say that $n_{cl} M_{gas}^{cl} = \xi \Omega_b \rho_{cr}$, if n_{cl} is the number density of clusters in the Universe, M_{gas}^{cl} is the gas mass of a cluster and $\rho_{cr} = 1.88 \times 10^{-29} h^2 g/cm^3$ is the critical density. The important feature of our expression for the diffuse radiation is that it depends only on very general parameters: the CR spectrum $Q_p^{tot}(E)$ of the sources, the cosmological baryon fraction Ω_b and the radius of a cluster, taken to be $R_{cl} = 1.5 h^{-1} Mpc$. Y_i in eq. (7) are the yields, listed in table 1.

What are the sources of CR in a cluster of galaxies?

In the following we shall consider the contribution due to normal galaxies, AGN and accretion shocks and we shall compare the correspondent gamma ray flux with the observed extragalactic diffuse value (Osborne et al. 1994)

$$I_\gamma^{obs}(E) = 9.6 \times 10^{-7} E_{GeV}^{-2.11} \; cm^{-2} s^{-1} sr{-}1 GeV^{-1}, \tag{8}$$

and the neutrino flux with the atmospheric neutrino background.

- **Normal galaxies**

  We shall assume that a typical galaxy in a cluster has the same CR luminosity as our galaxy, $L_p = 3 \times 10^{40} erg/s$, and consider a cluster as made on average of $N_g \simeq 100$ galaxies. Using $\xi = 0.5$, $Y_\gamma = 0.116$ (see table 1) and $\gamma_g = 2.11$ we obtain for the diffuse gamma ray flux:

  $$I_\gamma^{gal}(E) = 3.4 \times 10^{-10} E_{GeV}^{-2.11} h_{80} \frac{\Omega_b h^2}{0.025} \; cm^{-2} s^{-1} sr{-}1 GeV^{-1} \tag{9}$$

  which is 3×10^{-4} times smaller than the observed value (we took here $h = 0.8$). The correspondent neutrino flux is shown in fig. 1 and compared with the atmospheric neutrino flux (the prompt neutrinos are taken into account by the calculations of Gondolo, Ingelman and Thunman (1995)). It is clear that no observable contribution can be due to normal galaxies.

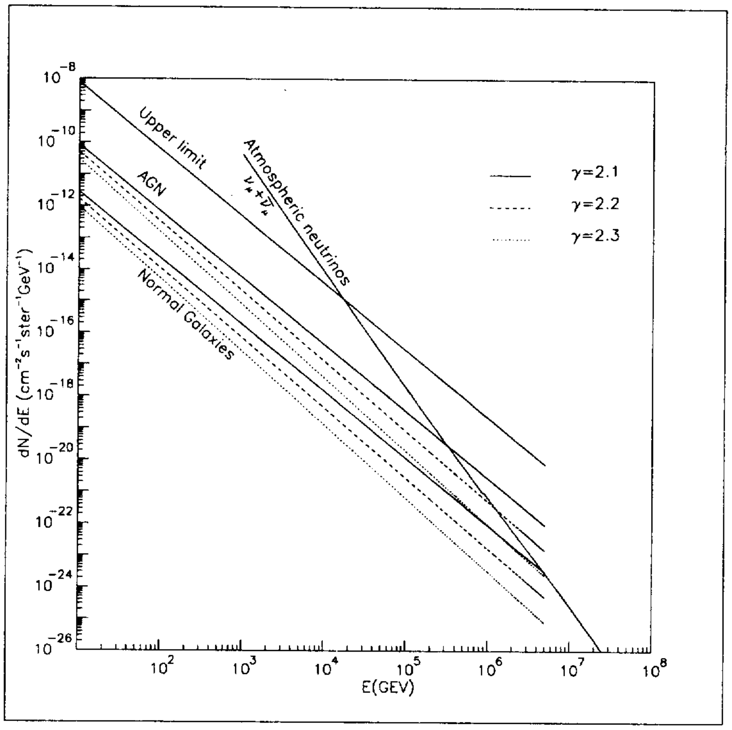

Figure 1: *The diffuse neutrino flux due to the interactions of the CR produced by normal galaxies and AGN with the intracluster gas. The upper limit referes to the maximum neutrino flux correspondent to the observed diffuse gamma ray flux as produced in clusters. As a comparison the atmospheric neutrino flux is plotted with the prompt neutrinos taken into account.*

The upper limit on the neutrino flux shown in fig. 1 is obtained from the condition that the diffuse gamma ray flux observed (see eq. (8)) is produced by clusters. It results in

$$I_{\nu_\mu+\bar{\nu}_\mu} = \frac{Y_{\nu_\mu} + Y_{\bar{\nu}_\mu}}{Y_\gamma} I_\gamma^{obs}(E) \qquad (10)$$

where the neutrino yields are taken from table 1.

- **AGN**

About 1% of all galaxies are AGN. Thus we can expect ~ 1 AGN per cluster if the average richness is $N_g = 100$. We shall take $L_{CR} \simeq 10^{44} erg/s$ as the typical CR luminosity of an AGN (see (Blandford 1976, Biermann and Streitmatter 1987, Quenby and Lieu 1989, for possible acceleration mechanisms in AGN). Such luminosity is ~ 30 times larger than that due to the normal galaxies. Thus we can expect a diffuse flux of gamma rays and neutrinos larger by the same factor as compared to that due to normal galaxies. This factor is not enough for describing the observed value. As shown in fig. 1 the neutrino flux should be seen above $10^6 GeV$ as a bump over the atmospheric neutrino flux.

- **Accretion shocks**

  We considered the accretion of baryonic matter onto a cluster of galaxies on the background of the expansion of Universe. A rough estimate of the accretion rate can be obtained by averaging over the age of Universe:

$$< \dot{M} > \simeq \frac{M_{gas}}{t_0}. \tag{11}$$

  A detailed analysis of the accretion flow of baryons onto a cluster of galaxies is given in (Bertschinger 1985). In that work a self-similar solution for the accretion flow is found, the basic parameter being the turn-around radius R_{ta}, defined as the distance from the gravitational center where the expansion of Universe is balanced by the gravitation, or equivalently where the velocity of expansion of Universe, $v_H = H_0 r$, is approximately equal to the free fall one $\sqrt{2GM_{grav}/r}$, where M_{grav} is the gravitational mass inside such radius.

  The Bertschinger analysis shows the formation of a shock at a distance $R_{sh} \simeq 0.347\ R_{ta}$. The study of the ability of this shock to accelerate CR has been made finding that the CR luminosity due to the shock is comparable with that obtained by AGN in clusters.

Table 1: The values of the yields

γ	2.1	2.2	2.3	2.4	2.5	2.6	2.7
$\gamma - rays$	116	88.8	69.0	54.2	43.0	34.5	
$\nu_\mu + \bar{\nu}_\mu$	126.2	94.6	69.8	51.9	39.1	29.7	22.8
$\nu_e + \bar{\nu}_e$	58.7	44	32.3	23.81	17.87	13.46	10.25

5 Conclusions

We calculated the diffuse fluxes of high energy gamma rays and neutrinos if they are produced in *pp* collisions in clusters of galaxies. We found that the expressions for such diffuse fluxes depend only on general parameters: the cosmological baryon fraction Ω_b, the typical radius of a cluster and the spectrum of the CR sources inside clusters. The main physical basis in such calculations is the confinement of the bulk of CR inside the cluster radius for times larger than the age of Universe.

We first considered as sources of CR in clusters normal galaxies, AGN and accretion shocks (Bertschinger 1985).

For normal galaxies the diffuse gamma ray flux above 100 MeV is 3×10^{-4} times the observed one (Osborne et al. 1994), if an average richness of $\sim$ 100 galaxies per cluster is assumed. On the other hand on statistical grounds it is plausible to assume that ~ 1 AGN per cluster is present, with typical CR luminosity $10^{44} erg/s$. In this case the result for gamma rays is ~ 30 times larger than for normal galaxies, but still less than the observed value. However the neutrino flux in this case overcomes the atmospheric neutrino background above $\sim 10^6 GeV$. The situation is similar as far as shocks in the accretion flow onto clusters are considered as CR accelerators. Thus in all cases the *ad hoc* assumption used by Dar and Shaviv (1995a,b) of CR energy density in clusters equal to the one in our galaxy has not been confirmed, as far as *usual CR sources* are concerned.

On the other hand all our estimates neglect the evolution of the sources inside clusters of galaxies; thus we want here to speculate about the possible effect that this evolution could cause. As we stressed from the very beginning, the basic point of this calculation is the confinement of CR inside clusters for times larger than their age. This means that clusters retain informations about all times of their CR history, included the possibility of an enhanced CR production in the past due to source evolution. In fact Partridge and Peebles (1967) by first proposed that a *bright phase* in the galaxy evolution could have caused an enormous increase in the total luminosity and correspondingly in the CR luminosity.

This early phase of enhanced activity of galaxies should be mainly due to the fact that first generation stars, produced by the non-linear growth of the fluctuations in the baryonic gas, had a spectrum strongly dominated by large masses (the fundamental mass scale being the Jeans mass $M_J \sim 10^5\ M_\odot$); most of these massive short-lived first generation stars finished their life as SNeII. If we believe that the bulk of CR is produced by acceleration at SN shock fronts, this enhanced rate of SNeII explosions, inevitably implies a corresponding enhancement in the CR energy density. The duration of this bright phase has been estimated to be $10^7 - 10^8\ yrs$, with a total energy release of $3 \times 10^{61}\ erg$ per galaxy according with Partridge and Peebles (1967) or $10^{61} - 10^{62}\ erg$ per galaxy according with Schwartz, Ostriker and Yahil (1975). In the latter work the bright phase has been taken to be located at red shift $2 < z < 10$.

The enhanced rate of SN explosions during bright phase produces a strong enrichment of the interstellar medium by heavy elements. Moreover a strong galactic wind should develope from the galaxies in their bright phase, so that most of the heavy elements should be ejected in the intergalactic medium. On this basis Volk et al. (1996) used the measured Iron abundance in the intracluster gas in order to estimate the total number of SNII events in Perseus cluster, and they found that this number is much larger than if each of the 500 galaxies has produced SNeII with the usual rate of one per 30 yrs.

In conclusion we think that there is room for speculating about a strong increase in the CR energy density in clusters when evolution of galaxies and more specifically a bright phase is included in the calculations. As a consequence a detectable effect on the diffuse gamma and neutrino flux, or at least from single gas-rich clusters of galaxies, could be expected.

6 References

Berezinsky, V. S. et al., 'Astrophysics of Cosmic Rays' (North Holland 1990).
Bertschinger, E. 1985, ApJS, **58**, p. 39.
Biermann, P. L. & Streitmatter, P. A. 1987, ApJ, **322**, p. 643.
Blandford R. D. 1976, MNRAS, **176**, p. 465.
Copi, C.J., Schramm, D.N. & Turner, M.S. 1995, Science, **267**, p. 192.
Dar, A. & Shaviv, N. J. 1995a, Phys. Rev. Lett., **75**, p. 3052.
Dar, A. & Shaviv, N. J. 1995b, PREPRINT, to be published in Astroparticle Physics.
Gondolo, P., Ingelman, G. & Thunman, M. 1995, Accepted for publication in Astrop. Phys.
Jaffe, W. 1980, ApJ, **241**, p. 925.
Osborne, J. L. et al. 1994, J. Phys. G, **20**, p. 1089.
Partridge, R.B. & Peebles, P.J.E.,1967, ApJ, **147**, p. 868.
Quenby, J. A. & Lieu, R. 1989, Nature, **342**, p. 654.
Schwartz, J., Ostriker, J. P. & Yahil, A. 1975, ApJ, **202**, p. 1.
Volk, H. J., Aharonian, F. A. & Breitschwerdt, D. 1996, Scape Sci. Rev., **75**, p. 279.
Volk, H. J. & Biermann, P. L. 1988, ApJ, **333**, p. L65.
White, S.D.M. et al. 1993, Nature **366**, p. 429.
White, S.D.M. & Fabian, A.C., 1995, MNRAS, **273**, p. 72.
White, S.D.M. & Frenk, C.S. 1991, ApJ, **379**, p. 52.