4 August 1994

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 333 (1994) 555–560

# The limit to the UHE extraterrestrial neutrino flux from the observations of horizontal air showers at *EAS–TOP*

M. Aglietta [a,b], B. Alessandro [b], P. Antonioli [b], F. Arneodo [d,e], V.S. Berezinsky [e], L. Bergamasco [a,c], C. Castagnoli [a,b], A. Castellina [a,b], A. Chiavassa [a,c], G. Cini [a,c], B. D'Ettorre Piazzoli [f], G. Di Sciascio [f], W. Fulgione [a,b], P. Galeotti [a,c], A.Z. Gazizov [g], P.L. Ghia [a,b], M. Iacovacci [f], G. Mannocchi [a,b], C. Melagrana [a,c], C. Morello [a,b], G. Navarra [b,c], L. Riccati [b], O. Saavedra [a,c], G.C. Trinchero [a,b], P. Vallania [a,b], S. Vernetto [a,b]

[a] *Istituto di Cosmo-Geofisica del CNR, Torino, Italy*
[b] *INFN, Sezione di Torino, Italy*
[c] *Istituto di Fisica dell'Università di Torino, Italy*
[d] *Dipartimento di Fisica dell'Università de L'Aquila, Italy*
[e] *INFN, Laboratorio Nazionale del Gran Sasso, Assergi, L'Aquila, Italy*
[f] *Dipartimento di Scienze Fisiche dell'Università di Napoli, INFN, Sezione di Napoli, Italy*
[g] *Institute of Physics of the Belarussian Academy of Sciences, Belarus*

Received 5 May 1994
Editor: K. Winter

**Abstract**

Extensive Air Showers at large zenith angles $\theta > 70°$ (Horizontal Air Showers, HAS) are observed at the *EAS–TOP* array at Campo Imperatore (Gran Sasso Laboratories). The rate of these events exceeds the one due to primary cosmic rays (at this angles) and therefore these showers have to be generated by penetrating particles. Assuming that they are produced by atmospheric muons we derived the muon flux as $F_\mu(> 30 \text{ TeV}) = 1.1 \times 10^{-11}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$, in good agreement with the underground measurements. The upper limits for diffuse neutrino radiation from these measurements is $I_\nu(> 10^5 \text{ GeV}) < 1.5 \times 10^{-8}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for "all-flavour" neutrinos and $dI_{\bar\nu_e}(E_0)/dE_{\bar\nu_e} < 7.6 \times 10^{-18}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^{-1}$, for the resonant ($E_0 = m_W^2/2m_e = 6.4 \times 10^6$ GeV) neutrinos.

## 1. Introduction

The near horizontal directions in the study of Extensive Air Showers (EAS) provide a remarkable low-background channel for the detection of penetrating particles such as high energy atmospheric muons, cosmic neutrinos and some suggested hypothetical high-energy particles, which can be produced in the cosmic sources or from the decays of cosmological superheavy relic particles.

The low background at large zenith angles is provided by large depth of the atmosphere ($x \sim 3000$ gr/cm$^2$ at $\theta > 75°$) and by the exponential (with $\Lambda \sim 220$ gr/ cm$^2$) decrease of the rate of nuclear-electromagnetic showers (see Fig. 1). Fig. 2a gives a scheme of the muon-produced showers. A high energy muon is produced in the shower near the top of the atmosphere. Due to bremsstrahlung,

Elsevier Science B.V.
*SSDI* 0370-2693(94)00814-N

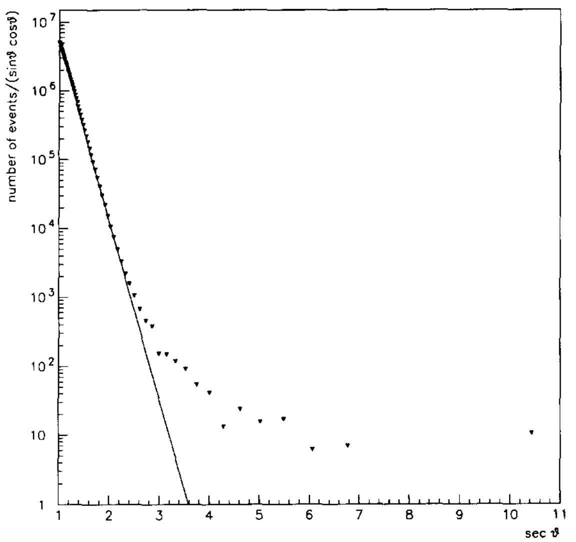


Fig. 1. The measured zenith angle distribution of the detected EAS. The solid line shows the exponential behaviour of the angular distribution of primary cosmic rays.

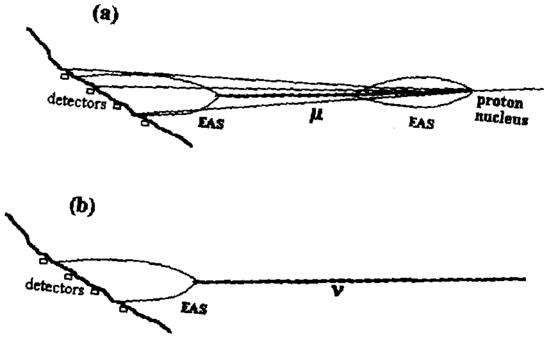


Fig. 2. A typical picture of horizontal air shower production: a) HAS produced by UHE muon (shown by thick line). The remnant low energy muons from the nucleon produced shower are shown by the thin lines. b) HAS produced by neutrino.

$\mu + Z \longrightarrow Z + \mu + \gamma$, or deep-inelastic scattering, $\mu + N \longrightarrow \mu + hadrons$, it can initiate a shower at the depth appropriate for the detection. In case of *EAS–TOP* [1-5] we can detect two components of these events: the e.m. shower produced by the high-energy muon and the "remnant" low-energy muons from the initial shower.

UHE neutrinos can produce showers detectable by EAS arrays too (see Fig. 2b). This channel for the detection of high energy cosmic neutrinos is one of the oldest suggestions for UHE neutrino astronomy [6]. More recently it was developed numerically in Ref. [7] and [8].

Neutrinos produce showers through the CC-interactions:

$$(\bar{\nu}_l)\nu_l + N \Rightarrow l^{\pm} + \text{hadrons}, \quad \text{CC–events} \qquad (1)$$

through NC-interactions

$$(\bar{\nu}_l)\nu_l + N \Rightarrow (\bar{\nu}_l)\nu_l + \text{hadrons}, \quad \text{NC–events} \qquad (2)$$

where $l = e$ or $\mu$, and through resonance production

$$\bar{\nu}_e + e^- \Rightarrow W^- \Rightarrow \text{hadrons} \qquad (3)$$

where the resonant neutrino energy is

$$E_0 = m_W^2/2m_e = 6.4 \times 10^6 \ \text{GeV} \qquad (4)$$

Electron neutrinos are more effective for the generation of showers since in the process (1) the total neutrino energy is transferred to the cascade, while for muon neutrinos with $E_\nu \sim 10 \div 100$ TeV the fraction of energy transferred amounts to only $\sim 30\%$. Reaction (3) is analogue of the Glashow resonance [9] $\bar{\nu}_e + e^- \longrightarrow \mu^- + \bar{\nu}_\mu$. For high-energy neutrino astronomy for the case of heavy $W$-boson it was first discussed in Ref. [10].

From the experimental point of view only accurate measurements of arrival directions can allow to extract the neutrino-produced showers from the large background due to primary protons and nuclei. Such problem of background is illustrated by the fact that the electromagnetic detector of *EAS–TOP* is recording events above 70° at a rate of $\sim 1$ event/day against a total number of triggers of $1.5 \times 10^5$ events/day.

Detection and first interpretation of HAS was made early in seventies by Böhm and Nagano [11] (see also more recently [12]).

In this paper we discuss the rate of HAS selected only on arrival direction measurements. We show that this rate provides a good measurement of the UHE muon flux, and we derive the upper limit to the extraterrestrial neutrino flux (a detailed discussion of the phenomenology of HAS and of the interpretation of the $\mu$ flux is not within the aims of this paper and will be presented elsewhere).

## 2. The array

The *EAS–TOP* array [1] is located at Campo Imperatore (2000 m a.s.l., National *GRAN SASSO* Laboratories). It consists of detectors of UHE cosmic rays ($E_0 = 10^{13} \div 10^{16}$ eV) through different EAS components, namely:

**i)** electromagnetic: 35 modules of plastic scintillators (10 $m^2$ each) distributed over an area of $\sim 10^5$ $m^2$ [2] on the slope of *Mount Aquila* (average slope $\simeq 15°$, that guarantees even for zenith angles $\theta = 75°$ a significant internal area for a range of azimuth angles $\Delta\phi \sim 180°$);

**ii)** muon-hadron: 140 $m^2$ calorimeter, 920 g/ $cm^2$ thick, made of 9 iron layers, seen by limited-streamer and quasi-proportional tubes for muon tracking and hadron calorimetry [3];

**iii)** Čerenkov telescopes [4], and radio antennas [5].

We will essentially discuss, here, the results of the electromagnetic, and partially of the muon detectors.

Relevant to the present analysis are the triggering requirements and the accuracies in the measurements of the arrival directions of the EAS.

Concerning the electromagnetic detector, the triggering condition for the events under discussion is provided by the firing of a subarray made of 6 (or 7) contiguous modules, the central one recording the largest number of particles. The energy threshold is set at 30 % of energy loss of a vertical minimum ionizing particle (*m.i.p.*). In the following, events will be discriminated by cuts on the energy losses in the triggering modules ($\Delta E_{\min}$). Arrival directions are measured from the time of flight technique; the angular resolution of the array is measured from the self-consistency of data, and checked from the measurement of the shadowing effect of the moon on the flux of primary cosmic rays [2]. For the quoted trigger conditions such resolution, confirmed by the two techniques, is $\sigma_{\theta_{\rm e.m.}} = 0.83°$. For very inclined directions ($\theta > 60°$), the angular resolution, obtained from the self-consistency of data, is $\sigma_{\theta_{\rm e.m.}} = 1.5°$.

The muon detector is triggered by the electromagnetic one; its acceptance for $\theta \simeq 75°$ is $A_\mu \approx 40$ $m^2$. Arrival directions are obtained from the muon tracking; the angular resolution is $\sigma_{\theta_\mu} < 1°$, obtained from self-consistency of data [13].

## 3. The data

At zenith angles $\theta > 70°$ an excess of events is observed above the rates of EAS as expected from their attenuation length in the atmosphere (Fig. 1) [11,14].

In this analysis we use only events with $\theta_{\rm e.m.} > 75°$, for which the contamination from cosmic ray hadron showers is $\approx 1$ %, and the contaminations from events with $\theta < 75°$ (obtained from the shape of the angular distribution and the detector angular resolution) is $\approx 20\%$. We therefore subtract from the sample the 20% events with worse angular reconstruction ($\chi^2 > 2$/degree of freedom).

After such procedure, in 326 observation days we obtain 36 events with $\theta_{\rm e.m.} > 75°$: 21, 15 and 7 of them with energy losses in the 6 (or 7) triggering scintillators larger respectively than $\Delta E_{\min} = 8.2$, 16.4 and 32.8 MeV (corresponding to 1, 2, 4 vertical *m.i.p.*).

In a previous paper [14] we have shown that the "anomalous" arrival direction of such fraction of showers is confirmed by different approaches, namely:

- the quoted measured arrival direction accuracy for the very inclined events ($\sigma_{\theta_{\rm em}} = 1.5°$ for $\theta > 60°$);
- the absence of events from the direction of the sky shaded by the top of the mountain on which the array is located (0 events detected against 12 calculated on the basis of a uniform distribution, that would be expected if they were originated by random error measurements);
- the agreement between the arrival directions as reconstructed by the electromagnetic and the muon detectors. For the events in which at least one $\mu$ is present in the calorimeter we have (for $\theta_{\rm em} > 70°$ and $\chi^2 < 2/dgf$): $\sigma_{(\theta_{\rm em}-\theta_\mu)} = 4.7°$, which is smaller than the same quantity measured for the hadron showers recorded with $\theta < 15°$ and $\chi^2 < 2/dgf$: $\sigma_{(\theta_{\rm em}-\theta_\mu)} = 9.5°$.

The acceptance of the EAS array is calculated as a function of the EAS primary energy ($E_{EAS}$), the production height above the observation level ($x$), the triggering requirement ($\Delta E_{\min}$), and the zenith angle ($\theta$). The acceptance area has been evaluated by a simulation. Cascades are calculated following the *HEMAS* code [15], and a shape of longitudinal development as parameterized in Ref. [16] both for electromagnetic and hadron primaries. The fluctuations in the shower development (total number of ionizing particles: $Ne = Ne(E_{EAS}, x)$) have been included [17], and the transition effect in the scintillators has been obtained using the EGS code [18]. We obtain for the effective areas:

$$A_{em}(\Delta E_{min} = 8.2\ \text{MeV}) \simeq 10^5(\cos\theta/\cos 70°)^{1.6}(Ne/10^5)^2\cos\theta\ \text{m}^2.$$

$$A_{em}(\Delta E_{min} = 32.8\ \text{MeV}) \simeq 10^5(\cos\theta/\cos 76°)^{2.2}(Ne/10^5)^{2.8}\cos\theta\ \text{m}^2.$$

## 4. The muon flux

If we assume that all observed events are produced by muon interactions, which is their most natural interpretation, then from the event rate $f_{exp}$ we can derive the UHE muon flux $S\ (> E_{\mu 0})$.

For a power law muon spectrum $\propto E_\mu^{-\gamma}$ we have:

$$S_\mu(> E_{\mu 0}) = \frac{f_{exp}}{f_b + f_{ph}} E_{\mu 0}^{-(\gamma-1)} \frac{1}{\gamma - 1} \quad (5)$$

where:

$$f_{b,ph} = \int d\Omega \int dE_\mu \int dE_{EAS} \int dx \times \frac{E_\mu^{-\gamma}}{\cos\theta} \sigma_{b,ph}(E_\mu, E_{EAS}) A_{em}(E_{EAS}, x, \theta, \Delta E_{min}), \quad (6)$$

are the calculated rates of showers produced by bremsstrahlung and photoproduction, respectively.

For $\gamma = 3.70$, $E_0 = 30$ TeV (mean muon calculated energy), and by using the rate of events with $\Delta E_{min} =$ 8.2 MeV ($f_{exp} = 21/326\ \text{d}^{-1}$), we obtain:

$$S_\mu(> 30\ \text{TeV}) = 1.1 \times 10^{-11}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1} \quad (7)$$

with statistical error 22% and systematic errors 10% and 6% due to the calculations of the effective area and the uncertainties in $\gamma$ ($\pm 0.05$), respectively. This is well consistent, within the experimental errors, with the extrapolation of *MUTRON* spectrum [19], the underground measurements [20], and calculations [21].

From the flux (7) the expected number of events with $\Delta E_{min} = 32.8$ MeV in the triggering modules is 11 while the measured one is 7, which shows that the rate of the larger size showers is also explained by the muon interaction rate.

## 5. Upper limits to the diffuse neutrino fluxes

Since all the events with threshold $\Delta E_{min} =$ 32.8 MeV can be explained by the muon interactions, we can derive upper limits to the flux of other penetrating particles as neutrinos.

The event rate, for a neutrino flux $I_\nu$ and processes (1) and (2) is given by

$$f_\nu = \int d\Omega \int dx \int dE_{EAS} A_{em}(E_{EAS}, x, \theta, \Delta E_{min}) \times \sum_{\nu,k} \int dE_\nu I_\nu \frac{d\sigma_{ik}(E_\nu, E_{EAS})}{dE_{EAS}dx} \quad (8)$$

where $E_{EAS}$ here is the energy transferred to a shower in $\nu$N interactions, index $\nu$ indicates summation over all $\nu$ flavors ($\nu = \nu_e, \bar\nu_e, \nu_\mu, \bar\nu_\mu$), and $k$ over CC and NC interactions ($k$=CC,NC).

For the shape of neutrino spectrum $I_\nu(E_\nu)$ we used the calculations of Ref. [22] of the $\nu_\mu + \bar\nu_\mu$ fluxes from AGNs. These fluxes must be accompanied by $\nu_e$ and $\bar\nu_e$–fluxes of the same origin. As an approximation, we used the asymptotic flavor ratios for $p\gamma$–neutrino production of Ref. [23], i.e. $I_{\nu_e+\bar\nu_e} = 0.45\ I_{\nu_\mu+\bar\nu_\mu}$

The differential $\nu N$–cross-sections were calculated using the *Eichten et al.* [24] parameterization of the quark distributions in nucleon with the extrapolation for very small $x$, described in Ref. [7].

The maximum contribution to the showers rate ($\sim$ 80%) comes from the energy interval $E_\nu = 10^5 \div 10^6$ GeV. With the assumed spectrum, the detection of one event per year corresponds to $I_\nu(> 10^5\ \text{GeV}) = 5.9 \times 10^{-9}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$, while the expected rate for the intensity calculated in Ref. [22] is $f_\nu = 2.9 \times 10^{-4}$ events/day.

For the resonant events $\bar\nu_e + e^- \Rightarrow W^- \Rightarrow$ hadrons, i.e. process (3), the calculation of the event rate is analogous to (8) with the following expression for the production rate of the showers with the resonant energy $E_0$ per one electron in the atmosphere [25]:

$$\nu_{res}(E_0) = 2\pi\sigma_{eff} E_{\bar\nu_e} I_{\bar\nu_e}(E_0), \quad (9)$$

where $\sigma_{eff} = (3\pi/\sqrt{2})G_F = 3.0 \times 10^{-32}\ \text{cm}^2$ is the effective cross-section.

Comparing the calculated rates with the upper limits to the number of observed events, 2.3 for 90% confidence level, we obtain the following upper limits

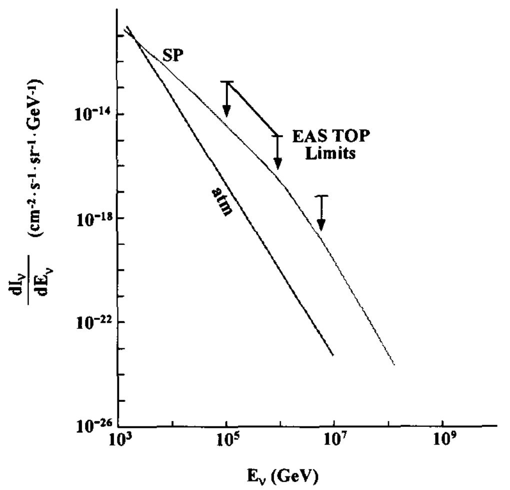


Fig. 3. Comparison of the present upper limits with the calculated diffuse $\nu_\mu + \bar{\nu}_\mu$-fluxes from AGNs. Notations: atm – atmospheric neutrinos flux; SP – Szabo & Protheroe [22].

to the diffuse neutrino fluxes. For "low" neutrino energies $10^5 \div 10^6$ GeV, where processes (1) and (2) dominate, the limits to the integral flux is:

$$I_\nu(> 10^5\,\mathrm{GeV}) < 1.5 \times 10^{-8}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}. \quad (10)$$

For the differential flux in the same energy interval $10^5 \div 10^6$ GeV and for a spectrum $\propto E_\nu^{-2}$, valid for AGN models, we obtain:

$$\frac{dI_\nu}{dE_\nu}(E_\nu) < 1.5 \times 10^{-13} \left(\frac{10^5}{E_\nu}\right)^{-2} \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{GeV}^{-1}. \quad (11)$$

For the resonant process (3) at $E_{\bar{\nu}_e} = E_0 = 6.4 \times 10^6$ GeV the limit is:

$$\frac{dI_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}}(E_{\bar{\nu}_e}) < 7.6 \times 10^{-18}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{GeV}^{-1} \quad (12)$$

These limits are shown in Fig. 3 together with the expected atmospheric neutrino flux and the one calculated by Szabo & Protheroe for neutrinos produced in AGNs [22]. For muon neutrinos a global constraint to the models predicting a diffuse flux from AGNs, obtained by deep underground measurements, is reported in Ref. [26].

We have searched also for the events from the Galactic Center, Cyg X-3, Sco X-1 and 3C273 inside angular bins of size 17.6 degrees$^2$. No events from these bins were detected. The corresponding upper limits (at 90% c.l.) are:

$$\frac{dI_\nu}{dE_\nu}(E_\nu) < 1.6 \times 10^{-12} \left(\frac{10^5}{E_\nu}\right)^{-2} \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{GeV}^{-1} \quad (13)$$

for the energy interval $10^5 < E_\nu < 10^6$ GeV.

Data (11), (12) represent, in the energy range $10^4 \div 10^7$, GeV new limits to the extraterrestrial diffuse neutrino flux. Although these limits are one-two orders of magnitude higher than the fluxes predicted from AGNs and other extraterrestrial sources [22, 27–30], these results demonstrate the potential effectivity of the HAS technique for UHE neutrino astronomy.

## Acknowledgements

The continuous cooperation of the director and of the staff of the Gran Sasso National Laboratories as well as the technical assistance of C. Barattia, R. Bertoni, M. Canonico, G. Giuliani, A. Giuliano and G. Pirali are gratefully acknowledged.

## References

[1] M. Aglietta et al., (EAS-TOP Collab.), Il Nuovo Cimento C 9 (1986) 262
[2] M. Aglietta et al., (EAS-TOP Collab.), Nuclear Instruments and Methods A 277 (1989) 23; A 336 (1993) 310
[3] M. Aglietta et al., (EAS-TOP Collab.), Il Nuovo Cimento C 15 (1992) 735
[4] M. Aglietta et al., (EAS-TOP Collab.), Il Nuovo Cimento C 15 (1992) 357
[5] C. Castagnoli et al., Proc. 23rd ICRC, 1 (Calgary, 1993) 233
[6] V.S. Berezinsky and A.Yu. Smirnov, Astrophys. Space Sci. 32 (1975) 461
[7] V.S. Berezinsky et al., Sov. J. Nucl. Phys. 43 (1986) 406
[8] E. Zas, F. Halzen and R.A. Vazquez, Astroparticle Physics, 1 (1993) 297
[9] S.L. Glashow, Phys. Rev. 118 (1960) 316
[10] V.S. Berezinsky and A.Z. Gazizov, JETP Lett. 25 (1977) 254
[11] E. Böhm and M. Nagano, J. Phys. A 6 (1973) 1262
[12] M. Nagano et al., J. Phys. G 12 (1989) 69
[13] EAS-TOP Collab., Proc. 23rd ICRC, 4 (Calgary 1993) 251
[14] EAS-TOP Collab., Proc. 23rd ICRC, 4 (Calgary, 1993) 255
[15] C. Forti et al., Phys. Rev. D 42 (1990) 3668
[16] E.J. Fenyves et al., Phys. Rev. D 37 (1988) 649

[17] B. D'Ettorre Piazzoli and G. Di Sciascio, Submitted to Astroparticle Physics, (1993)
[18] W.R. Nelson et al., report SLAC-265 (1985)
[19] S. Matsuno et al., Phys. Rev. D 29 (1984) 1
[20] Yu.M. Andreyev et al., Proc. 21st ICRC 9 (Adelaide, 1991) 301
[21] L.V. Volkova et al., Nucl. Phys. 29 (1979) 1252
[22] A.P. Szabo and R.J. Protheroe, Proc. of TAUP-93 Conf., Gran Sasso, Italy
[23] V.S. Berezinsky and A.Z. Gazizov, Phys. Rev. D 47 (1993) 4206
[24] E. Eichten et al., Rev. Mod. Phys. 58 (1986) 1065
[25] V.S. Berezinsky et al., Astrophysics of Cosmic Rays (North-Holland, Amsterdam, 1990)
[26] H. Meyer, Proc. 4th Int. Workshop Neutrino Telescopes (Venezia, 1992) 213
[27] F.W. Stecker et al., Proc. Workshop High Energy Neutrino Astrophysics (Honolulu, 1992) 1
[28] M. Sikora and M.C. Begelman, ib., 114
[29] P.L. Biermann, ib., 86
[30] V.S. Berezinsky, In Proc. Neutrino 77 Conf. (Baksan, 1977) 177