PREDICTIONS ON THE HIGH-ENERGY EMISSION FROM THE COMA CLUSTER

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ABSTRACT

The Coma galaxy cluster exhibits evidence for the existence of a high-energetic non-thermal particle populations. At frequencies $>$ 1 GHz observations of Coma's radio halo indicate a significant spectral steepening of the volume-integrated emission from Coma which comprise important information on the electron spectrum. We calculate the volume-averaged high-energy spectrum due to inverse Compton scattering off the cosmic microwave background radiation field and non-thermal bremsstrahlung taking into account an exponential cutoff in the electron spectrum. This particle distribution was deduced from the radio observations. The synchrotron radiation from the secondary pairs, created from the decay of charged mesons produced in hadronic *pp*-interactions, is found to set significant limits on the hadronic energy component in Coma when compared to the steepening radio spectrum. This leads to further constraints for the maximum flux that can be expected in the high-energy range. In particular we predict that Coma cannot be detected with INTEGRAL's ISGRI above a few 100 keV (based on the AO-2 continuum sensitivity) nor with the current generation atmospheric Cherenkov telescopes unless significantly more than 10^6 sec or $>$ 50 hrs of observations are accummulated, respectively.

Key words: Galaxies: clusters: Coma – Gamma rays: theory – Radiation mechanisms: non-thermal.

1. INTRODUCTION

One of the controversially discussed properties of cluster of galaxies are their non-thermal components (i.e. cosmic rays, magnetic field, turbulence, etc.). The non-thermal pressure has important impact in the evolution of galaxy clusters.

Radiation from radio halos and relics interpreted as synchrotron radiation signals the existence of relativistic electrons in the intercluster medium. The most prominent cluster which possess a radio halo is the Coma Cluster (Abell 1656) at redshift z=0.0232 ($\sim$ 90 Mpc, H_0=75 km s^{-1} Mpc^{-1}). While at frequencies $<$ 1 GHz its integrated spectrum follows a power law, at larger radio frequencies observations are now accumulating that point towards a significant spectral steepening of the integrated emission from the radio halo Coma C (Schlickeiser et al. (1987), recently confirmed and extended to higher frequencies by Thierbach et al. (2003) (=TH03)).

This work investigates the consequences of this steepening in the electron spectrum for the expected flux from Coma C at high energies, and its detectibility by current/near future γ-ray instruments.

2. NON-THERMAL RADIATION PROCESSES

2.1. Leptonic radiation processes

We restrict our considerations to the size of the radio halo ($\sim 10' \times 30'$ (TH03)) and its volume-averaged emission. For the volume-averaged magnetic field $\langle B \rangle$ a range from 0.1μG (suitable to explain the detected non-thermal hard X-ray (HXR) excess (Fusco-Femiano et al. (2004), Rephaeli et al. (1999)) by inverse Compton (IC) scattering off cosmic microwave background (CMB) photons) to 6μG, the central field strength in Coma C (Feretti et al. (1995))), is considered. The multifrequency spectrum of Fig. 1 shows the volume-averaged radio continuum spectrum of the radio halo source Coma C as published in TH03 together with the best fit model. Schlickeiser et al. (1987) showed that among the three basic models for cluster halos (primary electron model: e.g. Jaffe (1977); secondary pair model: Dennison (1980); in-situ acceleration model: e.g. Schlickeiser et al. (1987)) the in-situ acceleration model fits the observed steepening of the synchrotron spectrum best.

For the calculations we used an exponential shape electron momentum distribution with a cutoff momentum that is suitable to explain the volume-averaged synchrotron spectrum. This phenomenological ansatz is useful to constrain the high-energy component arising from this leptonic particle population independent of the precise model. IC scattering off CMB photons by these electrons is restricted to the Thomson regime, and is calculated in the δ-approximation. Non-thermal bremsstrahlung is calculated in the relativistic limit for a mean gas density in Coma of 10^{-3}cm^{-3} and a primordial ^{4}He mass fraction. For a more detailled description see Reimer et al. (2004).

The steepening of the electron spectrum at $10^{3...4}$ MeV causes the IC component to decline at ~1-10 MeV, while the non-thermal bremsstrahlung dominates till its decline at a few GeV (see Fig. 1). This is in contrast to works where the primary electron spectrum extends to several 10^7 MeV (e.g. Atoyan & Völk (2000), Miniati (2003)).

2.2. Nuclear cosmic ray – gas interactions

For a high relativistic hadron content γ-rays from the decay of π^0 (produced in hadronic pp-interactions) are expected to determine the energy range > 1 GeV. For the purpose of this work the assumption of the collision rate to be time-independent is appropriate. Because cosmic ray protons (p) are stored efficiently in galaxy clusters for cosmological times the radiation from the secondary pairs reflects the injected proton spectrum, and the global p spectrum should be not significantly different from the injected one if reacceleration can be neglected and uniform injection throughout the cluster is assumed. The p injection spectrum $N_p \propto E_p^{-\alpha_p}$ may range from $\alpha_p \sim 2.0 \ldots 2.5$ (in structure formation scenarios; Miniati (2003)) to $\alpha_p \sim 2 \ldots 5$ (in merger shock scenarios; Berrington & Dermer (2003)). We consider here $N_p \propto E_p^{-2.1\ldots-2.5}$, $E_p < 10^6$ GeV.

The normalization of the p component is limited by:

- π^0-decay γ-rays must not be overproduced in order not to violate the EGRET upper limit (Reimer et al. (2003)),
- IC scattering off CMB photons by the secondary pairs ($e^{\pm}$) produced in pp-interactions leads to a further radiation component from ~ 5 eV... a few GeV, and is observationally constrained by the HXR flux and EGRET upper limit (UL),
- the synchrotron radiation from the secondary $e^{\pm}$ must be consistent with the radio observations.

The resulting π^0-decay γ-ray component and the corresponding IC and synchrotron emission from the secondary pairs are shown in Fig. 1, together with the leptonic components for $\langle B \rangle = 0.1\mu$G, which simultanously gives the most optimistic flux predictions at high energies.

Proton energy densities are calculated from the stationary p spectrum above the threshold for pp-interactions, and compared to Coma's thermal energy density $u_{\text{therm}} \approx 3.8 \cdot 10^{-11}\text{erg/cm}^{-3}$.

3. RESULTS AND CONCLUSIONS

- The high frequency radio data place the most stringent constraint on the proton energy content in the Coma Cluster.
- The resulting ULs for the relativistic hadronic energy density of $u_p/u_{\text{therm}} < 3 \ldots 0.009\%$, $u_p/u_{\text{therm}} < 8 \ldots 0.01\%$ and $u_p/u_{\text{therm}} < 28 \ldots 0.07\%$ ($\langle B \rangle = 0.1 \ldots 2\mu$G) for $\alpha_p = 2.1$, 2.3 and 2.5, respectively, are significantly lower than anticipated from previous works (e.g. Miniati (2003),Atoyan & Völk (2000),Dolag & Enßlin (2000)). The lower cosmic ray pressure may reduce the efficiency requirements acceleration scenarios in galaxy clusters, and may have consequences for their evolution.
- For $\alpha_p = 2.1$, $\langle B \rangle = 0.68\mu$G we find approximative equipartition between particles and fields with $u_p/u_{\text{therm}} \approx 0.05\%$.
- A turnover from primaries' to secondaries' dominated IC below the soft X-ray band may occur depending on α_p and u_p. This is in agreement with the suggestions of Bowyer & Berghöfer (1998) that the nonthermal halo component detected with the EUVE may stem from an additional population of low-energy cosmic ray electrons which we interpret here as the secondary pair component. Independent hints for a EUV emission of secondary pair origin has just been given by Bowyer et al. (2004) on the basis of a spatial correlation analysis between the EUVE excess and ROSAT thermal hard X-ray flux.
- The point source minimum flux after 50 hrs on-source observations[1] reached by new generation northern hemisphere Cherenkov telescopes is above the most optimistic predicted flux limit in the sub-GeV/TeV energy range, and even worse for extended sources, while GLAST-LAT might be able to detect Coma if the magnetic field and/or Coma's hadronic energy content is favorable.
- The continuum sensitivity of INTEGRAL's ISGRI at $>$ a few 100 keV for a 10^6 sec observation based on the revised instrumental performance as described in the AO-2[2] is insufficient to detect even the most optimistic predicted flux from Coma, it is even worse for PICsIT and SPI.

A more detailled discussion of our results, in particular in comparison to other works, is given in Reimer et al. (2004).

[1] with statistics exceeding 10 photons and a signal detection at a level of at least 5σ

[2] http://astro.estec.esa.nl/Integral/AO2/

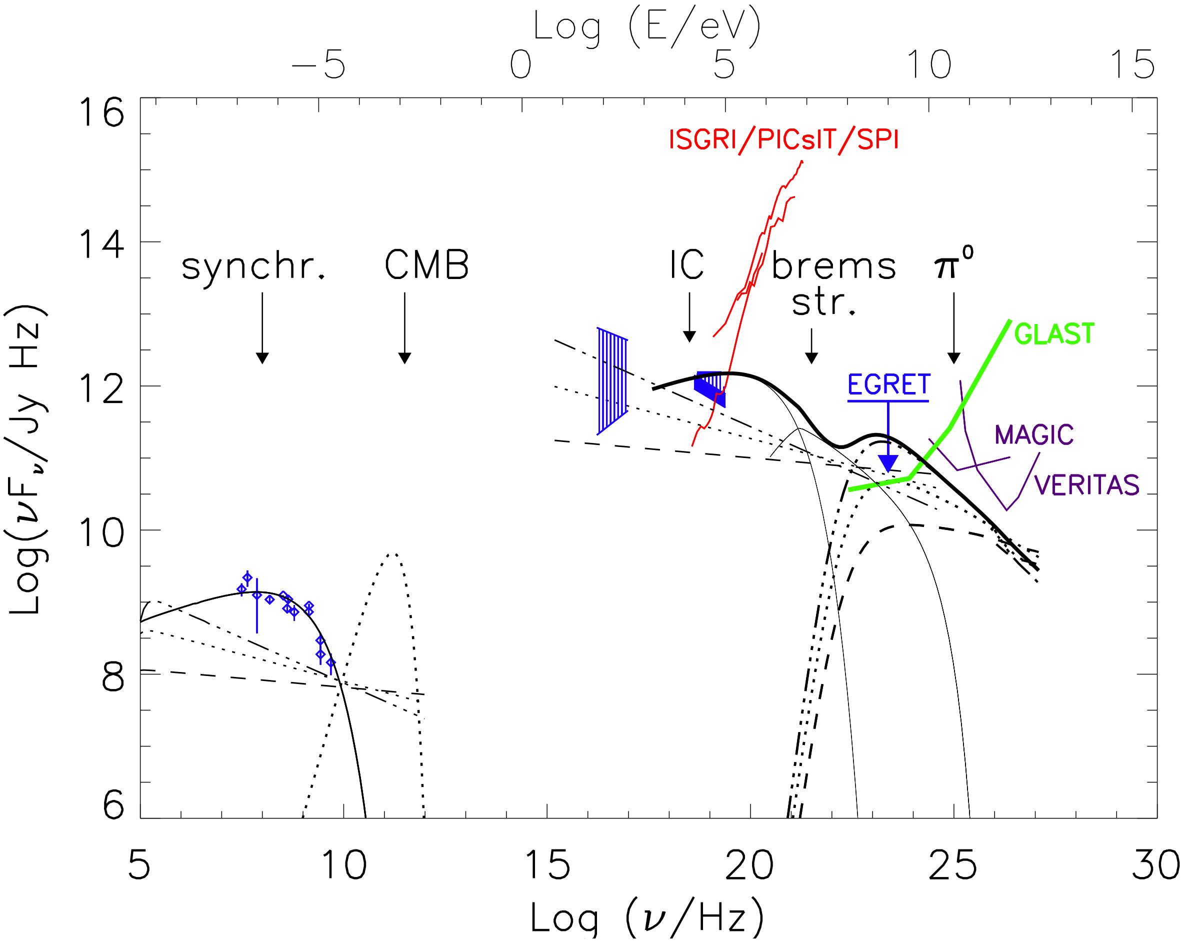

Figure 1. Broad band continuum spectrum of Coma. The radio data and the best-fit function (corrected for self-absorption) are taken from TH03. The dotted line represents the CMB field (corrected for the thermal Sunyaev-Zeldovich effect with $y = 0.75 \cdot 10^{-4}$; see Enßlin (2002)). The IC and nonthermal bremsstrahlung fluxes are shown for a field strength $\langle B \rangle = 0.1\mu G$ using an exponential electron distribution (with adjusted normalization and cutoff momentum to fit the radio data), and $n_i = 10^{-3} cm^{-3}$. They are extended to lower energies assuming the synchrotron spectrum follows a power law down to at least $10^{-9} eV$. The π^0-decay γ-ray spectra (most right curves) are calculated for a $\alpha_p = 2.1$ (dashed line), 2.3 (dotted line), 2.5 (dashed-dotted line) proton spectrum and the normalization of the particle spectra are adjusted to avoid violating the EGRET upper limit as well as the integral fluxes in the HXR and radio domain (see text). The required relativistic proton energy densities are 3%, 8% and 28% of the thermal energy content in the system for $\alpha_p = 2.1$, 2.3 and 2.5, respectively. The corresponding IC and synchrotron fluxes from the secondary pairs are shown as dashed/dotted lines. The hatched regions in the X-ray domain represent the data from PDS/BeppoSAX (Fusco-Femiano et al. (2004)), HEXTE/RXTE (Rephaeli et al. (1999)) and EUVE (Lieu et al. (1999)).

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