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High-energy emission from the galaxy cluster Abell 3376

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Abstract. Cluster of galaxies are extremely powerful X-ray sources, with luminosities $L_{\rm X} \sim 10^{43-45}$ erg s^{-1}. Some galaxy clusters also show radio emission. The radio luminosity is interpreted as synchrotron radiation produced by relativistic particles accelerated by strong large-scale shocks present in clusters. The interaction of relativistic particles with photons and matter produce high-energy emission. We investigate the particular case of the Abell 3376 cluster of galaxies. The resulting spectral energy distribution obtained from the most relevant non-thermal processes indicates that this cluster might be detected at gamma-rays by future planned Cherenkov arrays.

Resumen. Los cúmulos de galaxias son fuentes extremadamente potentes de rayos X, con luminosidades $L_{\rm X} \sim 10^{43} - 10^{45}$ erg s^{-1}. Algunos cúmulos también muestran emisión en la banda de radio. La luminosidad en radio es interpretada como radiación sincrotrón producida por partículas relativistas que han sido aceleradas por ondas de choques de gran escala existentes en los cúmulos. La interacción de partículas relativistas con fotones y materia produce emisión a altas energías. Investigamos el caso particular del cúmulo de galaxias Abell 3376. La distribución espectral de energía que resulta de los procesos no-térmicos más relevantes indica que este cúmulo podría ser detectado por futuros arreglos de telescopios Cherenkov ya planeados.

1. Introduction

Clusters of galaxies are the largest virialized structures in the Universe. They contain a large number of galaxies, but the dominant baryonic component is the diffuse and hot ($T_X \sim 3 - 10$ keV) intracluster medium (ICM). This ionized gas radiates energy through thermal Bremsstrahlung, which is detected in the X-ray band of the electromagnetic spectrum, with luminosities $L_X \sim 10^{43} - 10^{45}$ erg s^{-1}. The formation of cosmic structures is successfully described by the ΛCDM cosmogony. Within this framework, large scale shocks in clusters of galaxies can be produced by mergers and accretion of smaller objects. These shocks might accelerate particles up to relativistic velocities via a diffusive acceleration mechanism, such as the first-order Fermi process. Evidence for the presence of such a population of accelerated particles is given by the synchrotron

emission detected in some clusters. Two different morphologies can be distinguished in the observed radio emission: radio-halos (emission co-spatial with the X-ray radiation) and radio-relics (irregular emission observed at the outskirts of the clusters).
The recent detection of radio-relics in the outskirts of the nearby ($z = 0.046$) cluster of galaxies Abell 3376 (Bagchi et al. 2006) suggest that there are non-thermal electrons which produce the observed radio emission. Protons could be also accelerated, thus producing gamma-ray emission via neutral-pion decay in proton-proton (pp) interactions. Using the information available for this cluster, we calculate the electromagnetic radiation at high energies produced by the most relevant non-thermal radiative processes.

2. The cluster Abell 3376

The southern source Abell 3376 is a rich cluster of galaxies. It has an X-ray luminosity $L_X = 2 \times 10^{44}$ erg s^{-1} as measured by *XMM*-Newton, corresponding to a temperature $T_X = 5.8 \times 10^7$ K. The estimated virial radius is $R_{\rm vir} \sim 1.5$ Mpc. Radio observations made by Bagchi et al. (2006) with the VLA instrument show that two radio-relics are present at the edge of the cluster, within a distance of ~ 1 Mpc from the center of the cluster. The observed radio flux at frequency $\nu = 1.4$ GHz is $F_\nu = 302$ mJy. The configuration of radio-relics are inside a volume $V = 3.6\,{\rm Mpc}^3$; in our calculations, we have considered a filling-factor of 30% for the radio emitting relativistic particles.
Those parameters of the cluster not provided by the observations but relevant for the purpose of this work were obtained from a simulated cluster. We consider resimulations of galaxy clusters that have been initially selected from a dark matter simulation for a standard ΛCDM cosmology with $\Omega_0 = 0.3$, $h = 0.7$, $\sigma_8 = 0.9$ and $\Omega_b = 0.04$ (Dolag et al. 2005). We chose a cluster with similar virial mass ($1.3 \times 10^{15}\, h^{-1}\, M_\odot$), and dynamical state as the observed one. The presence of radio relics in Abell 3376 might be interpreted as the result of an on-going merger of subclusters (Ensslin et al. 1998). From the analysis of this simulation we have adopted $n_{\rm H} = 2 \times 10^{-5}\,{\rm cm}^{-3}$ for the ambient medium density at the location of the relics, and a gas velocity of the order of $600\,{\rm km\,s}^{-1}$.

3. Acceleration of particles and spectral energy distribution

We assume that both electrons and protons are accelerated in the accretion and merger shocks present in the cluster through the Fermi mechanism which leads to a particle injection rate with a power-law energy distribution. For our calculations, we adopt an spectral index $\Gamma = 2.1$. The energy distribution of these primary particles evolve as a result of leptonic and hadronic radiative losses. The main channel of losses for relativistic protons are inelastic pp collisions with the intracluster gas; the energy loss rate can be estimated by (Mannheim & Schlickeiser 1994):

$$\dot{\gamma}_{pp} = -4.5 \times 10^{-16}\, n_{\rm H} \left[0.95 + 0.06 \ln\left(\frac{\gamma}{1.1}\right)\right] \gamma \ {\rm s}^{-1}, \tag{1}$$

where γ is the Lorentz factor for protons, and $n_{\rm H}$ is the density of target nuclei given by the simulated cluster. Part of the energy lost by relativistic protons is used to create neutral pions which subsequently decay into γ-rays. The rest is used in the creation of charged pions that will decay into secondary $e^{\pm}$ pairs. These leptons will be cooled by the same radiative process as that of the primary electrons.

Energy losses of electrons are estimated taking into account relativistic Bremsstrahlung, inverse Compton (IC) interactions and synchrotron radiation. According to the ambient conditions described in the previous section, radiative losses due to IC interactions with the field of X-ray photons, and relativistic Bremsstrahlung are negligible. However, the energy loss rate produced by IC interactions with the cosmic microwave background (CMB) radiation field becomes relevant; it is given by:

$$\dot{\gamma}_{\rm IC}({\rm CMB}) = -3.20 \times 10^{-8}\, U_{\rm CMB}\, \gamma^2 \;\; {\rm s}^{-1}, \qquad (2)$$

where γ is the Lorentz factor for electrons, and $U_{\rm CMB} = 1.2 \times 10^{-13}\,{\rm erg\,cm}^{-3}$ is the energy density of the photon field at the cluster redshift.

Calculation of synchrotron losses requires the knowledge the magnitude of the magnetic field, B, which can be estimated by assuming equipartition between the energy density of the field B and the particles: $B^2/(8\pi) = u_{\rm e_1} + u_{\rm p} + u_{\rm e_2}$, where $u_{\rm e_1}$ and $u_{\rm e_2}$ are the energy densities of primary electrons and secondary pairs, respectively, and $u_{\rm p}$ is the energy density of protons. For each case $(i = e_1, p, e_2)$, we have $u_i = \int E_i n(E_i) dE_i$, where $n(E_i) = K_i\, E_i^{-\Gamma_i}\, \exp(-E_i/E_i^{\rm max})$ is the particle density distribution. The number of accelerated protons is unknown; for the present calculations we consider $u_{\rm p} = u_{\rm e_1}$, and thus it is possible to estimate u_{e_2}. Applying the constraint of the radio flux observed for Abell 3376, we find $B = 4.2 \times 10^{-7}$ G, $K_e = 1.4 \times 10^{-16}$ ${\rm erg}^{\Gamma-1}$ ${\rm cm}^{-3}$, and $K_p = 1.8 \times 10^{-16}$ ${\rm erg}^{\Gamma-1}$ ${\rm cm}^{-3}$ for the magnetic field and the normalization constants of the primary accelerated electrons and protons, respectively. The synchrotron losses are given by

$$\dot{\gamma}_{\rm synch} = -1.94 \times 10^{-9}\, B^2\, \gamma^2 \;\; {\rm s}^{-1}. \qquad (3)$$

Main electron losses and the acceleration rate are shown in Figure 1 (left panel). In order to obtain the maximum energy of primary particles, we have to balance the energy gain and loss rates, taking into account the diffusive escape of particles to the acceleration region. We have obtained $E_e^{\rm max} = 7 \times 10^{13}$ eV and $E_p^{\rm max} = 1.9 \times 10^{20}$ eV, for electrons and protons, respectively. Finally, we have studied the time-evolution of the three kind of particles presents in the relic: primary electrons, secondary pairs and protons. All these particles reach the steady-state within a time of ~ 1 Gyr.

From these steady distributions of particles, we have calculated the spectral energy distribution (SED). The luminosity produced through π^0-decay has been estimated by applying the δ-function approximation given in Aharonian & Atoyan (2000) and the new parametrization of the corresponding cross-section (Kelner et al. 2006). On the other hand, the emissivities produced by the leptonic interactions have been calculated using the standard formulae given in Blumenthal & Gould (1970) and in Pacholczyk (1970). The results of our calculations are shown in the right panel of Figure 1. The SED is dominated by the IC

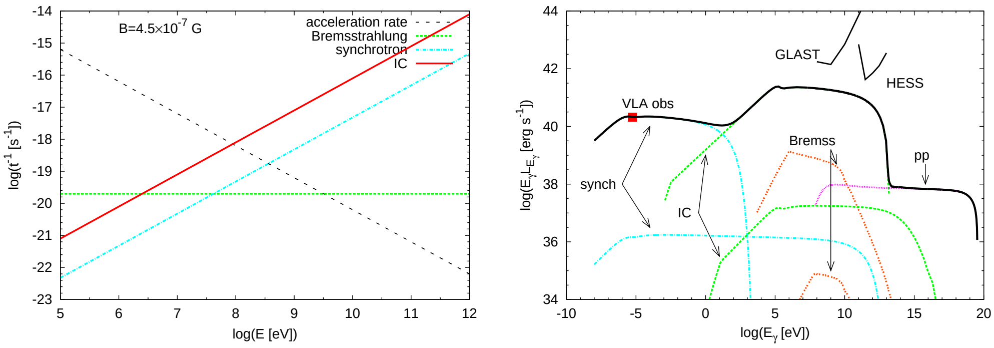

Figure 1. *Left panel*: Losses and acceleration rate for leptons. *Right panel*: Spectral energy distribution. The contribution of primary and secondary electrons to the leptonic losses are represented by the highest and lowest curves for each considered process, respectively.

interactions, with a luminosity $L \sim 5 \times 10^{41}$ erg s^{-1}, from $E_\gamma = 0.1$ MeV to $E_\gamma = 100$ TeV. The emission at highest energies is generated by neutral pion decay, reaching $L_{pp} \sim 5 \times 10^{39}$ erg s^{-1} and with a cut-off at $E_\gamma \sim 10^{19}$ eV. From the results obtained for the particular case of the cluster Abell 3376, we can consider that galaxy clusters are potential sources of γ-rays. However, observations of the clusters Coma and Abell 496 made by Domainko et al. (2007) with the array of Cherenkov telescopes HESS, have not detected significant signal in exposure times of $\sim 10-20$ hours. The proximity of the cluster studied in this work, and its high content of relativistic particles in the radio-relics, located at its edge, make Abell 3376 an interesting potential target for the investigation of γ-ray emission in this type of objects. Probably, this source might be detected at γ-rays by the future Cherenkov telescope HESS II.

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