On the ICS interpretation of the Hard X-Ray Excesses in Galaxy Clusters: the case of Ophiuchus

S. Colafrancesco\textsuperscript{1,2} and P. Marchegiani\textsuperscript{2,3}

\textsuperscript{1} ASI-ASDC c/o ESRIN, Via G. Galilei snc, I-00040 Frascati, Italy Email: sergio.colafrancesco@asi.it
\textsuperscript{2} INAF - Osservatorio Astronomico di Roma via Frascati 33, I-00040 Monteporzio, Italy. Email: cola@mporzio.astro.it
\textsuperscript{3} Dipartimento di Fisica, Università di Roma La Sapienza, P.le A. Moro 2, Roma, Italy Email: marchegiani@mporzio.astro.it

Received 13 February 2009 / Accepted 14 April 2009

ABSTRACT

\textbf{Context.} High energy electrons can produce Hard X-Ray (HXR) emission in galaxy clusters via Inverse Compton Scattering (ICS) of CMB photons.

\textbf{Aims.} We discuss here the consequences of the presence of such high energy particles for the multi-frequency emissivity of the same clusters and for the structure of their atmospheres.

\textbf{Methods.} We derive predictions for the ICS HXR emission in the specific case of the Ophiuchus cluster under three main scenarios for producing high-E electrons: primary cosmic ray model, secondary cosmic rays model and neutralino DM annihilation scenario. We further discuss the predictions of the Warming Ray model for the cluster atmosphere. Under the assumption to fit the HXR emission observed in Ophiuchus, we explore the consequences that these electron populations induce on the cluster atmosphere.

\textbf{Results.} We find that: i) primary electrons can be marginally consistent with the available data provided that the electron spectrum is cutoff at $E \sim 30$ (90) MeV for electron spectral index values of 3.5 (4.4); ii) secondary electron models from pp collisions are inconsistent with the viable gamma-ray limits, cosmic ray protons produce too much heating of the intra cluster (IC) gas and their pressure at the cluster center largely exceeds the thermal one; iii) secondary electron models from DM annihilation are inconsistent with the gamma-ray and radio limits, and produce too much heating of the IC gas at the cluster center, unless the neutralino annihilation cross section is much lower than the proposed value. In that case, however, such models no longer reproduce the HXR excess in Ophiuchus.

\textbf{Conclusions.} We conclude that ICS by secondary electrons from both neutralino DM annihilation and pp collisions cannot be the mechanism responsible for the HXR excess emission; primary electrons are still a marginally viable solution provided that their spectrum has a low-energy cutoff at $E \sim 30 - 90$ MeV. We also find that diffuse radio emission localized at the cluster center is expected in all these models and requires quite low values of the average magnetic field ($B \sim 0.1 - 0.2 \mu G$ in primary and secondary-pp models; $B \sim 0.055 - 0.39 \mu G$ in secondary-DM models) to agree with the observations. Finally, the WR model (with $B \sim 0.4 - 2.0 \mu G$) offers, so far, the best description of the cluster in terms of the temperature distribution, heating and pressure and multi-frequency spectral energy distribution. Fermi observations of Ophiuchus will set further constraints to this model.

Key words. Cosmology; Galaxies: clusters: theory; Dark Matter, Cosmic Rays

1. Introduction

Hard X-Ray (HXR) excess emission in galaxy clusters has been observed in the direction of several nearby systems (see \cite{Nevalainen et al. 2004}) but its origin is still disputed. It has been proposed that such HXR emission is due to inverse Compton scattering (ICS) of relativistic electrons with the cosmic microwave background (CMB) (Blasi & Colafrancesco 1999, Atoyan & Volk 2000, Ensslin & Biermann 1998, Sarazin 1999, Brunetti 2004, Profumo 2008, see Petrov et al. 2008 for a recent review), to bremsstrahlung emission from a supra-thermal electron population (Dogiel et al. 2007, see Petrov et al. 2008 for a recent review) or to a population of PeV electrons that would radiate in hard X-rays through synchrotron emission (Timokhin, Aharonian & Neronov 2004; Inoue, Aharonian & Sugiyama 2005). None of these models has been definitely proven or rejected, so far, due to the lack of instrumental sensitivity (spatial and spectral) of the available experiments operating in the HXR band.

In such a context, the Ophiuchus cluster ($z=0.028$, Johnston et al. 1981) has been recently at the center of an interesting dispute concerning the combination of new
observational evidence for the HXR emission and various theoretical considerations on its origin. The Ophiuchus cluster seems to have a high plasma temperature $kT \sim 10$ keV (Johnston et al. 1981). Measurements of the IC gas temperature vary from $8.5 \pm 0.5$ keV (INTEGRAL; Eckert et al. 2008) up to $9.5^{+1.4}_{-1.1}$ keV (Swift/BAT; Ajello et al. 2009). Watanabe et al. (2001) also found a large $(20' \times 30')$, hot $(kT > 13$ keV) region, $20$ arcmin west of the cluster center, from which they concluded that the cluster is not dynamically relaxed, and suggested that it experienced a major merging event in the recent past ($t < 1$ Gyr).

Eckert et al. (2008) have recently reported a tentatively resolved ($\sim 5'$) X-ray source at the cluster center, and indicated the presence of a non-thermal emission tail with a flux $(10.1 \pm 2.5) \cdot 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in the $20–60$ keV energy band. These authors interpreted the non-thermal hard X-ray emission as due to ICS emission from relativistic electrons scattered off the CMB in the intra-cluster (IC) medium. Suzaku observations of the Ophiuchus cluster by Fujita et al. (2008) have, however, failed to detect the non-thermal component detected by Eckert et al. (2008), although their quoted upper limit of $2.8 \cdot 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the $20–60$ keV energy band is still compatible with the INTEGRAL detection. Ajello et al. (2009) have found, using Swift/BAT spectra (with a IC gas temperature of $kT = 9.5$ keV), an upper limit on the Ophiuchus non-thermal X-ray emission in the $20–60$ keV band, of $7.2 \cdot 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (90% c.l.). We notice that the INTEGRAL detection and the Swift-BAT upper limit are consistent, at the same 90% confidence level, in the flux range $(6.1 – 7.2) \cdot 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. This is the flux range in which the HXR excess detected from Ophiuchus is consistent with both Swift-BAT and INTEGRAL observations. In our study of the origin of such HXR excess, we refer to the value $F_{20–60keV} = 7.2 \cdot 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ as the maximum value of its flux and we discuss how our results change by considering also the minimum flux of the HXR, $F_{20–60keV} = 6.1 \cdot 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, that is $\sim 15\%$ less than the previous maximum value.

The possible presence of an ICS tail of HXR emission in Ophiuchus was previously related to the identification of the steep-spectrum radio source MSH 17-203 (also dubbed Cul 1709-231) as a radio mini halo (Johnston et al. 1981), that would thus imply the presence of relativistic electrons, and hence the relative ICS emission emerging from the thermal bremsstrahlung emission in the X-ray band at $E \gtrsim 20$ keV.

However, a recent high resolution study (Perez-Torres et al. 2008) made with 240 and 607 MHz GMRT radio observations of the Ophiuchus cluster of galaxies, along with archival 74 and 1400 MHz VLA data, indicates that there is no significant diffuse radio emission in the core of the Ophiuchus, and that the previous measurements of radio flux from the MSH 17-203 source (Slee & Higgins 1975, Slee 1977) do not refer to the radio halo of the cluster: these authors present new upper limits to the integrated, diffuse non-thermal radio emission from the cluster core. More recently, Govoni et al. (2009) pointed out that there is indeed a diffuse radio mini-halo located at the center of the Ophiuchus cluster, with angular size of $\sim 9 \times 12$ arcmin$^2$; the flux of the mini halo is $\sim$ 8 times lower than the old measurement of Johnston et al. (1981), which had a resolution of $80$ arcmin (see details in Perez-Torres et al. 2008).

There is no other information on non-thermal emission from Ophiuchus: gamma-ray emission from this cluster has been not detected and therefore the only information we have directly on the high-E particle population of Ophiuchus is an upper limit obtained by EGRET $F(> 100$ MeV) $= 5 \cdot 10^{-8}$ cm$^{-2}$ s$^{-1}$ (Reimer et al. 2003).

In such an observational scenario (that is similar to other clusters where an HXR emission detection has been claimed) the HXR emission excess from Ophiuchus has been recently interpreted as ICS emission from either a population of primary cosmic ray electrons (Eckert et al. 2008) or secondary electrons produced in neutralino DM annihilation (Profumo 2008). In particular, Profumo (2008) proposed that a combination of three different neutralino DM models $[M_\chi = 81(W^+W^-), 40(bb) and 10(\tau^+\tau^-)$GeV] is consistent with all non-thermal emission data for Ophiuchus, from radio to HXR and gamma-rays. The available data on diffuse radio emission in the core of Ophiuchus and the overall analysis of its multi-frequency SED further led Perez-Torres et al. (2008) to conclude that i) a synchrotron+ICS model from primary cosmic ray electrons is in marginal agreement with the the available data, with a range of magnetic field values $B \sim 0.02 – 0.3 \mu$G; ii) that a pure neutralino annihilation scenario cannot reproduce both radio and HXR emission, unless extremely low magnetic field values $(10^{-2}$ to $10^{-3}$ $\mu$G) are assumed; iii) a scenario in which synchrotron and ICS arise from PeV electron-positron pairs (via interactions with the CMB), can also be ruled out, as it predicts a non-thermal soft X-ray emission that largely exceeds the thermal bremsstrahlung emission measured by INTEGRAL.

In this paper we take a more radical approach to the problem of the HXR emission of Ophiuchus and we consider not only the SED properties of synchrotron plus ICS scenarios (from both primary and secondary electrons) but also the physical consequences of the ICS origin of the HXR emission in all models so far viable: primary electron model (Sect.2.1), secondary electron models from pp collisions (Sect.2.2) and from DM annihilation (Sect.2.3) and finally a Warming Ray model (Sect.3). We will discuss our conclusions in Sect.4.

Throughout the paper, we use a flat, vacuum-dominated cosmological model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.7$. 


2. Modeling the electron populations in Ophiuchus

The spatial distribution of the intra cluster (IC) thermal plasma in the Ophiuchus cluster can be represented by:

\[ n_{th}(r) = n_{th,0} \left[ 1 + \left( \frac{r}{r_c} \right)^2 \right]^{-q_{th}} \]  

(1)

with \( r_c = 108 h_{70}^{-1} \) kpc and \( q_{th} = 0.96 \) (Watanabe et al. 2001), and \( n_{th,0} = 1.77 \times 10^{-2} h_{70}^{1/2} \, \text{cm}^{-3} \) (Johnston et al. 1981). The available data for this cluster indicate, out to a reasonable extent, an isothermal temperature profile with a temperature \( kT \approx 9.9 \) keV (Watanabe et al. 2001, Ajello et al. 2009); the virial radius of the cluster is \( R \approx 1.7 h_{70}^{-1} \) Mpc (Mohr et al. 1999).

Non-thermal electrons that can be able to produce the cluster HXR emission by ICS on CMB photons must have energies \( E_e \approx 0.35 \) GeV/(E/keV)$^{1/2}$ in the range \( 1.6 \) – \( 2.7 \) GeV, in the case of the HXR emission observed in the \( 20 \)–\( 60 \) keV range (see, e.g., Colafrancesco et al. 2005).

In this section we discuss the predictions of various models for the origin of the high-E electrons: i) primary electron model (PEM) (see, e.g., Colafrancesco, Marchegiani & Perola 2005 and references therein); ii) secondary electron model produced by proton-proton (pp) collisions in the cluster atmosphere (SEM-pp) (see, e.g., Colafrancesco & Blasi 1998, Blasi & Colafrancesco 1999, Marchegiani et al. 2007); iii) secondary electron models produced by neutralino Dark Matter annihilation (SEMDM) (see e.g. Colafrancesco et al. 2006, Profumo 2008). The electron spectra expected in the previous models are normalized by assuming that the produced ICS HXR emission equals the Swift-BAT/INTEGRAL data.

In addition to the previous models, we also consider in the next Sect.3 a self-consistent warming-ray (WR) electron model (see e.g. Colafrancesco & Marchegiani 2008; Colafrancesco et al. 2004) in which the cluster atmosphere is heated - in a quasi stationary equilibrium condition between heating and cooling - by the interactions of non-thermal cosmic-ray protons with the IC gas. Note that this WR model reproduces the X-ray properties of the thermal IC gas (namely its temperature and density profiles) and, therefore, we use this constraint to predict the cluster ICS HXR emission.

2.1. Primary Electron Model (PEM)

The high-E electron spectrum is usually best constrained by using the radio halo synchrotron spectrum that provides direct information on the electron spectral shape (see e.g. Colafrancesco et al. 2005 for a discussion). However, the upper limits on the Ophiuchus radio halo (see Perez-Torres et al. 2008) and the measurement at 1.4 GHz made byGovoni et al. (2009) are not sufficient to determine precisely the electron spectrum. Therefore, we choose to adopt here a simple power-law model

\[ N_e(E, r) = N_{e,0}(E/\text{GeV})^{-p} \cdot g(r) \]  

(2)

with \( p = 3.5 \), which corresponds to a radio spectral index of \( \alpha_R = 1.25 \), typical of radio halos in galaxy clusters and consistent with the available radio data on Ophiuchus; we also consider the case with \( p = 4.4 \), which provides \( \alpha_R = 1.7 \), which is, at 1σ level, the maximum value of the spectral index allowed by radio data (see, e.g., Fig.I). The radial function \( g(r) \) should be constrained, in principle, by measuring the radial shape of the ICS emission of the relativistic electrons (the radio measures are not sufficient to constrain this shape; see discussion in Colafrancesco et al. 2005); since the available HXR measures of the Ophiuchus cluster have no sufficient spatial resolution, we assume in the following that the radial distribution function of the non-thermal electrons has the same shape of the thermal gas radial distribution (see Eq.I). Under such assumption, we consistently assume that the relativistic electrons extend out to the virial radius of the cluster, like the IC plasma.

The value of the normalization of the electron spectrum \( N_{e,0} \) can be derived by reproducing the value of the HXR flux set by the Swift-BAT and INTEGRAL experiments: for the previous spectral index, we obtain the value \( N_{e,0} = 1.1 \times 10^{-10} \) GeV$^{-1}$ cm$^{-3}$ for \( p = 3.5 \), and \( N_{e,0} = 2.1 \times 10^{-10} \) GeV$^{-1}$ cm$^{-3}$ for \( p = 4.4 \).

All the previous information can be derived, strictly speaking, only for the range of the electron energies that produce the HXR emission via ICS. To obtain information on other energy ranges of the electron spectrum one must consider other constraints.

The only other constraint that can be set on the electron spectrum comes from the requirement that the heating rate of the IC gas produced by non-thermal electron Coulomb collisions does not exceed the bremsstrahlung cooling rate of the IC gas. The heating rate produced by an electron with Lorentz factor \( \gamma \) and velocity \( v = \beta c \) is given by

\[ \frac{dE}{dt} \approx K Z^2 \frac{2}{\beta} \ln \left( \frac{2mc^2\beta^2\gamma^2}{I_p} \right) \]  

(3)

where \( Z^2 \) is the (suitably averaged) squared charge of the plasma’s nuclei, \( K = 4 \pi n_{th} r_e^2 m_e c^3 \), with \( r_e = e^2/m_e c^2 \approx 2.82 \) fm, and \( I_p = \hbar \omega_p \), with \( \omega_p = [4\pi n_e e^2/m_e c]^1/2 \) the plasma frequency (see Colafrancesco et al. 2004, Colafrancesco & Marchegiani 2008).

As a consequence, the heating rate induced by the electrons with the spectrum assumed in Eq.2 is given by:

\[ \frac{dE}{dt}_{\text{WR}} \bigg|_{E_{min}}^{E_{max}} N_e(E, r) \left( \frac{dE}{dt} \right) dE \]  

(4)

while the cooling rate is given by

\[ \frac{dE}{dt}_{\text{x}} \bigg|_{E_{min}}^{E_{max}} = a \left[ n_{th}(r)^2 \right] \sqrt{\frac{1}{T(r, r')}} \]  

with

\[ a = \sqrt{\frac{2\pi^3}{3^3} \frac{e^6 \sqrt{m_e}}{h m_e^2 c^3} \frac{G}{z^3}} \]  

\[ \sim 4.8 \times 10^{-24} \frac{1}{\sqrt{\text{keV}}} \text{erg cm}^2 \text{ s}^{-1}, \]  

(5)
where $\bar{z}$ is an average charge of the IC plasma (we have approximated here the Gaunt factor $G$ by unity).

The two expressions in Eqs. (4) and (5) equal (to the value $\frac{d\epsilon}{dt} \sim 4.7 \times 10^{-27}$ erg cm$^{-3}$ s$^{-1}$) for the energy $E_{\text{min}} \sim 33$ MeV for $p = 3.5$, and for $E_{\text{min}} \sim 91$ MeV for $p = 4.4$; therefore, we assume these energy values as the minimum energy of the primary electron spectra. As for the maximum electron energy we can safely choose $E_{\text{max}} \rightarrow \infty$ since its specific value is irrelevant for the assumed spectral index.

Under such assumptions, it is possible to calculate the overall radiation emission via the various emission mechanisms in different frequency ranges.

The synchrotron emission spectrum produced at radio frequencies by primary electrons is shown in Fig. 1 for different values of the magnetic field (the B-field has been assumed to be constant in the emission region, and this corresponds, approximately, to consider a volume averaged value of the magnetic field). From the radio emission, we can derive a value of the average magnetic field of $\sim 0.1 \, \mu$G for $p = 3.5$ and $\sim 0.2 \, \mu$G for $p = 4.4$, in agreement with that derived by Ajello et al. (2009) and Perez-Torres et al. (2008).

In the gamma-ray frequency range, these primary electrons emit via non-thermal bremsstrahlung and ICS against CMB radiation field if their energy spectrum, as we assume in this case, extends up to high energies (at least up to $E \sim 100 - 1000$ GeV in order to produce ICS emission in the energy range 0.1–10 GeV). Fig. 2 shows that the EGRET upper limit on Ophiuchus, $F(100 \, \text{MeV}) \leq 5 \times 10^{-8} \, \text{cm}^{-2} \, \text{s}^{-1}$ (Reimer et al. 2003), is not exceeded in the $p = 3.5$ case, while it is marginally exceeded in the $p = 4.4$ case. In the first case, we can conclude that the HXR observation of Ophiuchus cluster sets a constraint on the ICS emission from relativistic electrons that is stronger than the analogous limit set by EGRET; in the second case, the EGRET limit is stronger than the HXR limit. The signals we derive here for the gamma-ray emission of Ophiuchus in the PEm, and in particular the one derived from non-thermal bremsstrahlung emission, are sensibly larger than the Fermi sensitivity at $E \lesssim 300$ MeV; therefore, such an experiment could be able either to detect the bremsstrahlung gamma-ray emission from Ophiuchus or set even stronger limits on the non-thermal electron density.

It is important to stress here that the HXR data sets also indirectly a lower cut-off of $E_{\text{min}} \sim 33$ and 90 MeV for the two models considered on the electron spectrum in order to have an heating rate not larger than the cooling rate.

### 2.2. Secondary Electron Model from pp collisions (SEM-pp)

To calculate the overall radiation emission from secondary electrons produced by collisions of cosmic ray (CR) non-thermal protons and the thermal protons of the IC gas (see Marchegiani et al. 2007 for details), we assume that the non-thermal protons have the following spectrum

$$N_p(E, r) = N_{p,0}(E/\text{GeV})^{-s} g(r) ,$$

and we further assume, also in this case, that their spatial distribution is the same of the thermal IC gas out to the virial radius.

Similarly to the PEm model, we assume proton spectral indices $s = 2.5$ and $s = 3.4$, which provide again radio spectral indices of $\alpha_R = 1.25$ and 1.7 respectively.
hadronic collisions) induced by non-thermal protons in the cluster center is \( \frac{dN}{dt} \sim 1.1 \times 10^{-25} \text{ erg cm}^{-3} \text{ s}^{-1} \) for \( s = 2.5 \), and \( \frac{dN}{dt} \sim 1.4 \times 10^{-24} \text{ erg cm}^{-3} \text{ s}^{-1} \) for \( s = 3.4 \); these values are about 23 and 298 times larger than the cooling rate. This fact would imply a quite fast heating of the cluster, \( \frac{d(\Delta T)}{dt} \sim 41 \text{ keV Gyr}^{-1} \) and \( \frac{d(\Delta T)}{dt} \sim 531 \text{ keV Gyr}^{-1} \), that will bring in a short time the whole IC gas to a temperature sensitively different (larger) from the observed one;

ii) finally, the gamma-ray emission produced by both secondary electrons and by neutral pion decay (see Fig. 3) exceeds the EGRET upper limit on Ophiuchus by a factor \( \sim 18 \) and 170, for \( s = 2.5 \) and 3.4 respectively.

Thus, we must conclude that the HXR emission of Ophiuchus as set by Swift and INTEGRAL, cannot be produced by secondary SEM-pp electrons. We notice that such a conclusion is analogous to that found in the case of other clusters we already studied like Coma, A2199, A2163 and Perseus (Colafrancesco & Marchegiani 2008).

### 2.3. Secondary Electron Model from DM annihilation (SEM-DM)

We consider here three neutralino DM models (similarly to the analysis of Profumo 2008) with neutralino masses:

\[ M_{\chi} = 81(W^+W^-), \quad 40(b\bar{b}) \quad \text{and} \quad 10(\tau^+\tau^-) \text{ GeV}. \]

For each neutralino model we consider a radial DM density profile as given by

\[ g_{DM}(r) = \exp[-(2/\alpha)((r/r_c)^\alpha - 1)] \]

(Navarro et al. 2004), with \( \alpha = 0.17 \) and \( r_c \) equal to the core radius of the thermal gas density distribution. We assume that this DM radial profile extends out to the virial radius. The spectrum of the DM source function for the secondary electrons has, consequently, a radial distribution \( \propto g_{DM}^2(r) \).

To derive the equilibrium spectrum of these secondary electrons in Ophiuchus we consider the role of the dominant energy loss mechanisms. These are ICS losses against CMB photons and synchrotron losses for electrons with energy larger than a few hundreds MeV (notice that synchrotron losses for magnetic fields less than 3 \( \mu G \), are negligible with respect to the ICS losses), while at low energies (\( \lesssim 150 \text{ MeV} \)) the dominant energy loss mechanisms are Coulombian interactions with the IC gas particles.

For this reason the final spatial distribution of secondary electrons is proportional to \( g_{DM}^2(r) \) at high energies (\( > 150 \text{ MeV} \)) and proportional to \( g_{DM}^2(r)/n_{th}(r) \) at low energies (\( < 150 \text{ MeV} \)).

The DM-produced secondary electron density is fixed, also in this case, by requiring that their ICS emission fits the observed HXR emission; such a constraint corresponds to set the value of the neutralino annihilation cross section, \( \langle \sigma V \rangle \), because both the neutralino mass and its composition have been fixed by the chosen model.

Also this SEM-DM model has serious implications for the Ophiuchus cluster.
Fig. 3. The gamma-ray spectrum of Ophiuchus with $s = 2.5$ (upper panel) and $s = 3.4$ (lower panel) as produced by ICS (dashes) and bremsstrahlung (dot-dashes) of secondary electrons and by neutral pion decay (long dashes). We compare the predictions of the SEM-pp model with the sensitivity curves of EGRET and Fermi ($5\sigma$, 1 year observation).

i) The heating rate at the cluster center as produced by the secondary SEM-DM electrons is very high; Fig. 4 shows the secondary electrons heating rate at different radii compared to the cooling rate of the thermal IC gas. In fact, the heating rate largely exceeds the cooling rate in the cluster core at $r < 30$ kpc. This result would imply a fast over-heating of the Ophiuchus core, even though the volume integral of the heating rate is always lower than the volume integral of the cooling rate (this last quantity is $4.6 \times 10^{42}$ erg/s, $7.4 \times 10^{42}$ erg/s and $3.6 \times 10^{42}$ erg/s for $M_\chi = 81, 40$ and 10 GeV, respectively).

Fig. 4. The heating rate induced by secondary electrons produced by DM annihilation is shown at different radii for different neutralino models: $M_\chi = 81$ GeV (dashed), 40 GeV (dot-dashed) and 10 GeV (dot-dot dashed). The intracluster gas cooling rate (solid) is also shown for comparison.

ii) We show in Fig. 5 the gamma-ray emission spectra as produced by the DM composite model worked out here via the three main mechanisms of gamma-ray emission: ICS and bremsstrahlung from secondary electrons and neutral pion decay. All the three DM models considered in this composite DM model for Ophiuchus produce a gamma-ray flux that exceeds the EGRET limit, $F(> 100$ MeV) $= 5.0 \times 10^{-8}$ cm$^{-2}$ s$^{-1}$ (the low mass neutralino model with $M_\chi = 10$ GeV is marginally consistent with the EGRET limit). The gamma-ray flux of Ophiuchus at $E > 100$ MeV produced under the assumption that the same DM model reproduce the HXR data are $7.4 \times 10^{-8}$, $1.3 \times 10^{-7}$ and $4.3 \times 10^{-8}$ cm$^{-2}$ s$^{-1}$ for neutralino masses of 81, 40 and 10 GeV. A direct prediction of this DM model is that the gamma-ray flux produced by the three neutralino models considered here should be easily detectable by the Fermi experiment whose results will be able, therefore, to validate or rule out this model for the origin of the HXR emission of Ophiuchus.

iii) Fig. 6 shows the diffuse synchrotron radio spectra produced by the same secondary SEM-DM electrons under the assumption of a reference value of the average intracluster magnetic field in Ophiuchus of 0.1 $\mu$G. This figure shows that, for this value of magnetic field, a model with low neutralino mass between 40 and 80 GeV can reproduce the radio data.

We also searched for the value of the magnetic field that, for each of the models we considered, reproduces the
the 81 GeV (M fit magnetic field values of 0.055, 0.18 and 0.39 radio spectrum produced by SEM-DM electrons for best-
Ophiuchus radio halo flux at 1.4 GHz. Fig. 7 shows the are shown for comparison.

The overall gamma-ray spectrum produced by the 10 GeV (ICS and bremsstrahlung) and of the neutral pion decay for the three neutralino models here considered. The sen-
sitivity curves of EGRET and Fermi (5σ, 1 year observation) are shown for comparison.

Ophiuchus radio halo flux at 1.4 GHz. Fig 7 shows the radio spectrum produced by SEM-DM electrons for best-fit magnetic field values of 0.055, 0.18 and 0.39 µG, for \( M_\chi = 81, 40 \) and 10 GeV, respectively. We can conclude that the 81 GeV (\( W^+W^- \)) model is consistent with radio data, while the 10 GeV (\( \tau^+\tau^- \)) model is not consistent. The 40 GeV (\( bb \)) model is a border-line situation: we find, in fact, that for a slightly lower magnetic field of 0.17 µG the radio spectrum is marginally consistent with the point at 1.4 GHz and the upper limit at 74 MHz.

3. Warming Ray Model

In this Section we abandon the strategy of fitting the ICS emission produced by high-E electrons to the HXR data of Swift and INTEGRAL because we evaluate – in the frame-
work of the Warming Ray (WR) model (see Colafrancesco & Marchegiani 2008, Colafrancesco et al. 2004) – the spectral and spatial characteristics of the WR proton population that produce through their heating action the tem-
perature structure of the Ophiuchus cluster, namely a con-
stant temperature radial profile at the observed value of \( kT \approx 9.9 \) keV.

The proton spectrum is written as in Eq. 6, with the values \( s = 2.5 \) and \( s = 3.4 \), and assuming a radial distribution given by \( g(r) \propto r^{-\alpha} \), where the value of \( \alpha \) is found by fitting the radial temperature profile of the cluster (see Colafrancesco & Marchegiani 2008 for technical details). The best fit analysis of the temperature profile of Ophiuchus provides the value \( \alpha = 1 \), in analogy to what is found for other isothermal clusters (see dis-
cussion in Colafrancesco & Marchegiani 2008), while the central WR density is \( N_\rho_{th} = 4.9 \times 10^{-8} \) cm\(^{-3} \) GeV\(^{-1} \) and \( N_\rho_{th} = 9.4 \times 10^{-8} \) cm\(^{-3} \) GeV\(^{-1} \) for \( s = 2.5 \) and \( s = 3.4 \) respectively, i.e. a factor \( \approx 31 \) and 362 lower than that required to reproduce, in this model, the Swift BAT/INTEGRAL HXR data. Consequently, the pressure ratio of the WR to the thermal gas at the cluster center is \( P_{CR}/P_{th} \approx 0.17 \) for \( s = 2.5 \) and \( P_{CR}/P_{th} \approx 1.0 \) for \( s = 3.4 \): the first value does not give any problem to the overall stability of the cluster, while the second one is a problematic situation.

The diffuse radio emission produced by the secondary electron in this WR model is shown in Fig. 8 for various values of the uniform magnetic field; our results indicate that a uniform B-field of the order of \( \sim 0.4 \) µG is required to fit the available data for \( s = 2.5 \), and \( B \sim 2.0 \) µG for \( s = 3.4 \).

Fig. 8 shows the diffuse gamma-ray emission from Ophiuchus as expected in the WR model: this emis-

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{fig5}
\caption{The overall gamma-ray spectrum produced by the composition of the contributions of the secondary SEM-DM electrons (ICS and bremsstrahlung) and of the neutral pion decay for the three neutralino models here considered. The sensitivity curves of EGRET and Fermi (5σ, 1 year observation) are shown for comparison.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{fig6}
\caption{The radio halo spectrum produced from secondary SEM-DM electrons via synchrotron emission in a constant magnetic field of 0.1 µG. Data are from Perez-Torres et al. (2008) (upper limits) and Govoni et al. (2009) (point at 1.4 GHz).}
\end{figure}
Fig. 7. The radio halo spectrum produced from secondary SEM-DM electrons via synchrotron emission in a constant magnetic field of 0.055, 0.18 and 0.39 \( \mu \)G for \( M_\chi = 81, 40 \) and 10 GeV, respectively. Data are from Perez-Torres et al. (2008) (upper limits) and Govoni et al. (2009) (point at 1.4 GHz).

4. Discussion and conclusions

We have show in this paper that various and serious problems stand out with the ICS interpretation of the HXR excess emission of the Ophiuchus cluster and, in general, of galaxy clusters for which an HXR emission excess has been detected. These problems are:

i) the actual level of the HXR emission flux: the derivation of an HXR emission excess in clusters seems to depend strongly on the precise determination of the background thermal bremsstrahlung emission. Eckert et al. (2008) derived from INTEGRAL data an HXR flux in the 20–60 keV band of \( F_{HXR} = (10.1 \pm 2.5) \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\), with an IC gas temperature of 8.56\( ^{+0.37}_{-0.35} \) keV. Ajello et al. (2009), using Swift BAT data, derived an upper limit (90\% c.l.) \( F_{HXR} \leq 7.2 \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\), with a different IC gas temperature of 9.5\( ^{+1.4}_{-1.1} \) keV; it must be noticed that the same authors (Ajello et al. 2009) derived the upper limit for the HXR flux of \( F_{HXR} \leq 4.5 \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\) by using an higher value of the temperature 9.93\( ^{+0.24}_{-0.24} \) keV, as obtained by using a combination of Chandra and Swift-BAT data.

In conclusion, it is clear that a crucial input quantity to determine the value of the HXR excess flux is the detailed modeling of the thermal emission of the IC gas, because different values assumed for the IC gas temperature lead to different conclusions on the amount of the HXR excess flux (see, e.g. the long standing discussion on the evidence and counter evidence of the HXR excess in Coma, Fusco-Femiano et al. 1999, 2004, 2007, 2008; Rossetti & Molendi 2004, 2007; see also Petrosian et al. 2008 for a review). For this reason, it would be extremely important to estimate the temperature of the IC gas through measurements that are independent from those obtained in the X-ray band. We notice, in this context, that a reliable method to measure IC gas temperatures can be found by using Sunyaev-Zel’dovich observations over a wide spectral band (from \( \sim 100 \) to \( \sim 400 \) GHz) reaching high frequencies where the sensitivity of the SZE to the cluster temperature is maximum (we have discussed in details this issue in a dedicated paper, Colafrancesco & Marchegiani 2009; see

Fig. 8. The radio halo spectrum produced by secondary electrons with \( s = 2.5 \) (upper panel) and \( s = 3.4 \) (lower panel) in the WR model is shown for different values of a constant IC magnetic field (as labeled) in units of \( \mu \)G. Data are from Perez-Torres et al. (2008) (upper limits) and Govoni et al. (2009) (point at 1.4 GHz).
S. Colafrancesco and P. Marchegiani: Consequences of HXR excesses in Clusters

Fig. 9. The gamma-ray spectrum produced by secondary electrons with $s = 2.5$ (upper panel) and $s = 3.4$ (lower panel) via ICS (dashes) and bremsstrahlung (dot-dashes) and neutral pion decay (solid) in the WR model that is set up by the requirement to reproduce the observed temperature structures of the IC gas in Ophiuchus. The sensitivity curves of EGRET and Fermi (5σ, 1 year observation) are shown for comparison.

also Colafrancesco et al. 2003 and Colafrancesco 2007 for a review;

ii) the ICS HXR scenario: the hypothesis that high-$E$ electrons are responsible for an ICS HXR emission at the level found by the combination of Swift-BAT and INTEGRAL observations leads to some important consequences.

First, in order to reconcile the HXR excess value with the relative diffuse synchrotron radio emission (from the same electron population) at the level observed in the same cluster, the value of the average magnetic field must be quite low and of the order of $\sim 0.1 \, \mu G$ for $p = 3.5$ and $\sim 0.2 \, \mu G$ for $p = 4.4$ (see Fig. 1). The result found for Ophiuchus is analogous to what is derived for other clusters (see also our previous results discussed in Colafrancesco, Marchegiani & Perola 2005, Marchegiani, Perola & Colafrancesco 2007): Specifically, we found that the data are consistent with an IC magnetic field of order of $\sim 0.7$ and $1.2 \, \mu G$ at the cluster center with a decreasing radial profile similar to that of the IC gas, for $p = 3.5$ and $4.4$ respectively.

Secondly, there is a strong relation between the ICS HXR emission level and the relative gamma-ray emission and the consequences on the physics of the cluster, i.e. the heating of the IC gas and the ratio between non-thermal and thermal pressures:

- if the electrons that produce the HXR emission are primaries, their gamma-ray emission (dominated at $E < 1$ GeV by non-thermal bremsstrahlung) is slightly lower than the EGRET upper limit in the $p = 3.5$ model, and slightly higher than this limit in the $p = 4.4$ model, but certainly detectable by Fermi (see Fig. 2). If Fermi will not detect such gamma-ray emission, one should conclude that the ICS HXR emission is much lower than the Swift-INTEGRAL HXR detection and that the relativistic electron content of Ophiuchus is consequently much lower. The HXR data set, in addition, a lower cut-off of $E_{\text{min}} \sim 33$ and $93 \, \text{MeV}$ (for $p = 3.5$ and $4.4$) on the electron spectrum in order to have an heating rate not larger than the cooling rate;

- if the electrons responsible for the ICS HXR emission are secondary particles produced in the decay of charged pions generated by cosmic-ray proton collisions with the IC gas protons (SEM-pp), then an ICS flux set at the HXR observations has unacceptable consequences. Specifically we find that: in the $s = 2.5$ case, the pressure exerted by relativistic protons at the cluster center is $\sim 5$ times larger than the thermal gas one; the heating rate induced by the same relativistic protons at the cluster center is $\sim 23$ times larger than the IC gas cooling rate; and the gamma-ray emission produced by neutral pion decay exceeds the EGRET limit by a factor $\sim 18$; in the $s = 3.4$ case, these quantities rise respectively to $\sim 367$, $298$ and $170$ (see Fig. 3). For all these reasons, we conclude that if electrons produce an ICS HXR emission in the observed range, they cannot be secondary (in the SEM-pp). This conclusion is analogous to what has been found also in other clusters like Coma, A2199, A2163 and Perseus (see Colafrancesco & Marchegiani 2008);

- if electrons are produced by neutralino DM annihilation, we have found that: the heating rate they induce at the cluster center is quite high (see Fig. 4); the relative gamma-ray emission exceeds the EGRET limit by a factor $\sim 18$; in the $s = 3.4$ case, these quantities rise respectively to $\sim 367$, $298$ and $170$ (see Fig. 3). For all these reasons, we conclude that if electrons produce an ICS HXR emission in the observed range, they cannot be secondary (in the SEM-pp). This conclusion is analogous to what has been found also in other clusters like Coma, A2199, A2163 and Perseus (see Colafrancesco & Marchegiani 2008);
ferred by gamma and radio data are not compatible, and we conclude that it is not possible to conceive that the ICS HXR emission of secondary SEM-DM electrons has a flux close to the available observation (i.e., the maximum allowed flux set by Swift and INTEGRAL, see Sect.1), and thus their annihilation cross section must be much lower than the values used by Profumo (2008).

Even normalizing these models to the lower allowed flux value of the HXR excess of Ophiuchus (see our discussion in Sect.1), all the previous results vary (decrease) by ~15%, leaving unchanged our basic conclusions.

iii) Relaxed the assumption to recover the observed HXR excess and assuming that non-thermal protons act as warming rays (see Colafrancesco & Marchegiani 2008) it is possible to paint a much more acceptable scenario in which the unacceptable pressure ratios derived in SEM models do not hold since the ratio $P_{\text{non-th}}/P_{th} \approx 0.17$ and 1.0 for, respectively, $s = 2.5$ and $3.4$ and it is constant throughout all the cluster (this is because non-thermal protons must have the same spatial distribution of the thermal IC gas to recover the spatial temperature distribution of the cluster). In addition, the WR model has other positive aspects for the cluster structure: i) it does not induce excess heating effects, since a quasi-stationary balance between heating and cooling is the working assumption of the WR model; ii) we found that the diffuse radio emission produced in this case requires, for $s = 2.5$ and $s = 3.4$ respectively, a value of the average magnetic field of $\sim 0.4$ and $2 \mu$G (see Fig. 3) and a central value of $\sim 1.1$ and $6 \mu$G with a radial profile similar to that of the IC gas, consistently with the general findings for clusters through Faraday Rotation measurements (see, e.g., Carilli & Taylor 2002, Govoni & Feretti 2004); iii) the gamma-ray emission produced in this model is quite lower than the EGRET limit but definitely detectable by Fermi (see Fig. 4). The Fermi detection of such gamma-ray emission from Ophiuchus will have a crucial impact for proving or disproving this model.

In such a WR model, the HXR ICS flux of Ophiuchus is much lower (by a factor ~30 and 362 for $s = 2.5$ and $s = 3.4$ respectively) than the limit set by the present observations (by INTEGRAL and Swift-BAT) and could only be detectable by using long exposure observations with the next generation HXR instruments like NeXT (see e.g. Takahashi et al. 2004).

To conclude, models of high-E electrons in clusters that can be adjusted to reproduce their ICS HXR emission at the level indicated by the available observations fail to work because they would imply unacceptable levels of heating and gamma-ray emission. On the contrary, models of high-energy particles that are able to reproduce the IC gas temperature structure (i.e. that WR model) predict a level of non-thermal HXR ICS emission that is far below the current limits obtained with INTEGRAL and Swift-BAT, and provide an overall Spectral Energy Distribution that is consistent with all the available data – from radio to gamma-rays – on Ophiuchus as well as on other clusters.

Acknowledgements. We thank P.Ullio for providing detailed source spectra of the neutralino annihilation models considered in this paper. We also thank the Referee, M.A. Perez-Torres, for his comments and suggestions that allowed to improve the presentation of our results.

References

Ajello, M. et al. 2009, ApJ, 690, 367
Atoyan, A. & Volk, H. 2000, ApJ, 535, 45
Blasi, P. & Colafrancesco, S., 1999, Astroparticle Physics, 12, 169
Brunetti, G., 2004, JKAS, 37, 493
Carilli, C.L. & Taylor, G.B., 2002, ARA&A, 40, 319
Colafrancesco, S. 2007, New Astron. Rev., 51, 394
Colafrancesco, S. & Blasi, P., 1998, Astroparticle Physics, 9, 227
Colafrancesco, S., Marchegiani, P. & Palladino, E., 2003, A&A, 397, 27
Colafrancesco, S., Dar, A. & De Ruijula, A., 2004, A&A, 413, 441
Colafrancesco, S., Marchegiani, P. & Perola, G.C., 2005, A&A, 443, 1
Colafrancesco, S., profumo, S. & Ullio, P., 2006, A&A, 455, 21
Colafrancesco, S. & Marchegiani, P. 2008, A&A, 484, 51
Colafrancesco, S. & Marchegiani, P. 2009, preprint
Dogiel, V. et al. 2007, A&A, 461, 433
Eckert, D., Produit, N., Paltani, S., Neronov, A. & Courvoisier, T. J.-L., 2008, A&A, 479, 27
Ensslin, T. & Biermann, P. 1998, A&A, 330, 90
Fujita, Y. et al. 2008, PASJ, 60, 1133
Fusco-Femiano, R., et al. 1999, ApJ, 513, L21
Fusco-Femiano R., et al. 2004, ApJ, 602, L73
Fusco-Femiano R., Landi R. & Orlando M. 2007, arXiv:astro-ph/0702576
Fusco-Femiano, R. & Orlando M. 2008, arXiv:0802.1817
Govoni, F. & Feretti, L., 2004, International Journal of Modern Physics D, 13, 1549
Govoni, F. et al. 2009, arXiv:0901.1941
Inoue, S., Aharonian F.A., Sugiyama N., 2005, ApJ, 628, L9
Johnston, M. D., Bradt, H. V., Dossey, R. E., Marshall, F. E., Schwartz, D. A. & Margon, B., 1981, ApJ, 245, 799
Marchegiani, P., Perola, G.C. & Colafrancesco, S., 2007, A&A, 465, 41
Mohr, J. J., Mathiesen, B. & Evrard, A. E., 1999, ApJ, 517, 627
Navarro, J. et al. 2004, MNRAS, 349, 1039.
Nevalainen, J., Oosterbroek, T., Bonamente, M. & Colafrancesco, S., 2004, ApJ, 608, 166
Perez-Torres et al. 2008, arXiv:0812.3598
Petrosian, V. et al. 2008, arXiv:0801.1016
Profumo, S. 2008, arXiv:0801.0740
Reimer, O., Pohl, M., Sreekumar, P. & Mattox, J.R., 2003, ApJ, 588, 155
Rossetti, M. & Molendi, S. 2004, A&A, 414, L41
Rossetti, M. & Molendi, S. 2007, arXiv:astro-ph/0702417
Sarazin, C. 1999, ApJ, 520, 529
Slee, O.B. & Higgins C.S. 1975, ApJ, 36, 1
Slee O.B. & Higgins C.S. 1975, ApJ, 36, 1
Takahashi, T. et al. 2004, New AR, 48, 269
Timokhin, A. N., Aharonian, F. A. & Neronov, A. Yu, 2004, A&A, 417, 391
Watanabe, M., Yamashita, K., Furuzawa, A., Kunieda, H. & Tawara, Y., 2001, PASJ, 53 605