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Extreme ultra-violet and soft X-ray extinction by dust in clusters of galaxies

M. Bonamente

University of Alabama in Huntsville, Huntsville, AL, U.S.A.
e-mail: bonamem@email.uah.edu

Abstract. Intergalactig dust in galaxy clusters, recently detected in the central Coma cluster by *ISO* far infra-red observations, may present substantial opacity to extreme ultraviolet (EUV) and soft X-ray photons. Low-energy X-ray photons in clusters of galaxies are produced by a hot intra-cluster medium (ICM) and oftentimes, in addition, by a yet unidentified *soft excess* source. EUV and soft X-ray radiation from the central regions of many galaxy clusters is often depleted with respect to the predictions from the hot ICM alone, while at large radii *soft excess* emission is detected above the hot ICM radiation. A scenario is here proposed whereby in the centers of some galaxy clusters intergalactic dust is responsible for intrinsic EUV and soft X-ray extinction, or for the lack or lesser soft excess emission with respect to outer cluster regions.

Key words. EUV and soft X-ray emission – dust extinction – galaxy clusters

1. Extreme ultraviolet and soft X-rays from galaxy clusters and the cluster soft excess phenomenon

Clusters of galaxies are strong emitters of X-rays, which originate from a very diffuse ($n \sim 10^{-3}$ cm^{-3}) and hot (T$\sim 10^8$ K) phase of the intra-cluster medium (ICM) with overall mass budgets of $\sim 10^{13} - 10^{14}$ M$_{sun}$. The hot ICM emission is mainly free-free bremsstrahlung, as nearly all species are fully ionized at such temperatures, and it is more suitably detected above ~ 1 keV. The extreme ultraviolet (EUV) and soft X-ray bands around 0.1-0.4 keV offers a unique window to investigate the presence of other emitting/absorbing phases of the ICM.

Recently, pointed observations with the *Extreme Ultraviolet Explorer (EUVE)*, *ROSAT* and *BeppoSAX* missions detected excess EUV and soft X-ray radiation, above the contribution from the hot phase of the ICM, from several galaxy clusters (Sérsic 159-03, Bonamente et al. 2001a; Coma and Virgo, Lieu et al. 1996a,b; Bonamente et al. 2001b; A1795, Mittaz et al. 1998; A2199, Lieu et al. 1999; Kaastra et al. 1999; A3571 and A3558, Bonamente et al. 2001c), indicating that the *cluster soft excess* phenomenon may be a common feature of clusters. In Fig. 1 it is shown the soft excess emission of A2199 from a deep

Send offprint requests to: M. Bonamente

EUVE observation, plotted as fractional excess above the hot ICM predictions. It is clear that the central regions do not show the excess, in reality excess *absorption* is found. The excess *emission* is confined to large distances from the cluster's center (Lieu et al. 2000), and similar distribution of the soft excess is also found in other sources like Virgo (Fig. 2), where the center has now only a modest excess, and significantly larger fractional excess is found at larger distances from the cluster's center (e.g., Bonamente et al. 2001b).

The excess EUV and soft X-ray radiation is explained as either a second thermal phase of the ICM at lower temperatures (a 'warm' phase at T$\sim 10^6$ K), or as a non-thermal Inverse-Compton emission due to scattering of microwave background photons with a population of relativistic electrons (e.g., Lieu et al. 1999; Bonamente et al. 2001a). These findings on EUV and soft X-ray emission from galaxy clusters call for an interpretation of the lack or lesser soft excess emission near the cluster center found in many sources (as, e.g., in Virgo or A2199, see Fig. 1; similar results are also displayed by other sources). As the hot ICM distribution has its density peak near the cluster's center, the radiative cooling time may oftentimes become shorter than the cluster's age, and there significant cooling of the hot phase may be expected (e.g., Fabian 1988). Presence of 'cold' gas (T $\leq 10^4$ K) may then be responsible for the central absorption of EUV and soft X-ray radiation, although definitive proof of its presence has not yet been found, despite a more than decade-long search (Fabian et al. 2001). In this paper it is investigated the alternative possibility of EUV and soft X-ray extinction by intra-cluster dust, whose presence is revealed by its far infra-red thermal emission.

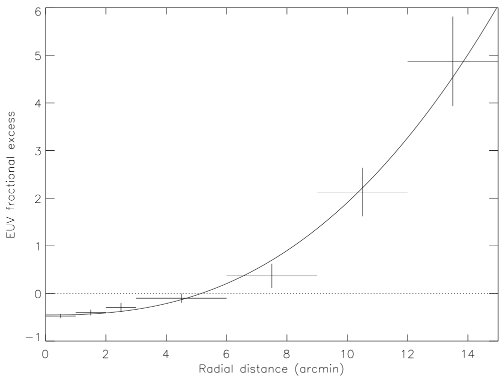

Fig. 1. EUV ($\sim$ 65-190 eV) fractional excess emission of A2199 from a *EUVE*/DS observation. Fractional excess is defined as $\eta = (p-q)/q$, where p is detected EUV flux, and q is predicted EUV flux from the hot ICM. Excess is found at large distances from the center.

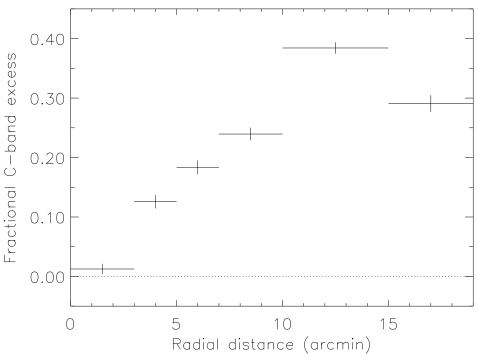

Fig. 2. Soft X-ray ($\sim$ 0.2-0.4 keV) fractional excess emission of the Virgo cluster form a *ROSAT*/PSPC observation.

2. Infra-red emission from intra-cluster dust

Intergalactic dust at T $\sim$ 20 K (Dwek et al. 1990) has the peak of its black-body emission at $\sim 150\ \mu$m. Extended far infrared emission from the central Coma cluster was detected by ISOPHOT at 120 and 185 μm (Stickel et al. 1998), implying that $\sim 10^8 - 10^9$ M$_{sun}$ of intergalactic dust is present within a ≤ 0.4 Mpc diameter. Earlier, presence of intracluster dust was surmised by the extinction of ultraviolet objects behind Coma (Boyle et al. 1998; Dwek et al. 1990), although *IRAS* had failed to detect any FIR emission. Similarly, upper limits on the dust mass near the center of other galaxy clusters are found to be typically $\leq 10^8$ M_{sun} by optical, infrared and sub-mm observations (Maoz 1995; Annis & Jewitt 1993), and IR emission associated with central galaxies in clusters was reported for a significant fraction of the observed clusters (Cox et al. 1995; Bregman et al. 1990).

3. EUV and soft X-ray extinction by dust grains

The details of scattering and absorption properties of dust grains strongly depend on their size and chemical composition (e.g., Spitzer 1978). Mie theory calculations of EUV and soft X-ray opacities of C, Fe and Si grains (Cruise 1993) show that the scattering cross sections of $\sim 1-0.1\mu$m grains can be as large as ~ 2 times their geometrical cross section. Considering a total mass of M=10^9 M_{sun} of dust grains with an average radius of a=0.2 μm and a grain density of ρ=1 g cm^{-3}, distributed over a volume of diameter 0.4 Mpc and with a scattering cross section $\sigma = \pi a^2$, it is readily found that a EUV/soft X-ray photon has a mean free path of $\sim$ 0.1 Mpc when crossing such volume of space. In addition, absorption will also contribute significantly to the extinction, especially for grains whose composition includes elements (like C) with strong absorption properties of EUV and soft X-ray radiation. Dust grains may be ejected in the intergalactic space by galactic winds or other mass loss process with an approximate power law distribution of sizes (a^{-k}), the size a ranging from 1 μm to a few Å (e.g., Dwek et al. 1990). Survival of dust grains in the harsh intergalactic environment is controlled by the efficiency of sputtering by the hot gas. For gas temperatures above 10^7 K, Draine & Salpeter (1979a,b) showed that sputtering is a function of gas density n and grain size a,

$$\tau_{sputt} \sim \frac{10^6 a(\mu m)}{n(cm^{-3})}.$$

For $a \sim 0.2$ μm and $n \sim 10^{-3} - 10^{-4}$ cm^{-3}, $\tau_{sputt} \sim 10^8 - 10^9$ years, typically shorter than the cluster's age. This implies that the dust must be periodically or continuously injected in the cluster environment, although presently the mechanism of dust formation itself is not completely understood. Clearly dust particles with very small sizes are very rapidly distroyed by the interaction with the hot gas, and are not expected to survive for long periods of time.

4. Discussion and conclusions

Combined observations of galaxy clusters in the far infra-red and EUV/soft X-ray bands indicate that dust masses of the order of $10^8 - 10^9$ M_{sun} in the central few 100 kpc may result in substantial extinction of the low energy X-ray emission. This phenomenon may on one hand explain deficit EUV and soft X-ray fluxes with respect to the hot ICM predictions observed in some cases, and on the other explain the increasing trend of the *cluster soft excess* of other galaxy clusters. In fact, excess EUV and soft X-ray radiation is seldom present in the centers of clusters, and the excess component is more often visible at large distances ($\geq$ 200 kpc) from the center. Evidence for soft X-ray dust absorption was found by Arnaud & Mushotzky (1998) through analysis of *BBXRT* X-ray data, where the complex spectrum of the Perseus cluster seemed to be best explained with a dust absorption model.

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