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EUV AND SOFT X-RAY EMISSION IN CLUSTERS OF GALAXIES

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ABSTRACT

Observations with EUVE, ROSAT, and BeepoSAX have shown that some clusters of galaxies produce intense EUV emission. These findings have produced considerable interest; over 100 papers have been published on this topic in the refereed literature. A notable suggestion as to the source of this radiation is that it is a "warm" (10^6 K) intracluster medium which, if present, would constitute the major baryonic component of the universe. A more recent variation of this theme is that this material is "warm-hot" intergalactic material condensing onto clusters. Alternatively, inverse Compton scattering of low energy cosmic rays against cosmic microwave background photons has been proposed as the source of this emission. Various origins of these particles have been posited, including an old (~Giga year) population of cluster cosmic rays; particles associated with relativistic jets in the cluster; and cascading particles produced by shocks from sub-cluster merging. The observational situation has been quite uncertain with many reports of detections which have been subsequently contradicted by analyses carried out by other groups. Evidence supporting a thermal and a non-thermal origin has been reported. The existing EUV, FUV, and optical data will be briefly reviewed and clarified. Direct observational evidence from a number of different satellites now rules out a thermal origin for this radiation. A new examination of subtle details of the EUV data suggests a new source mechanism: inverse Compton scattered emission from secondary electrons in the cluster. This suggestion will be discussed in the context of the data.

Key words : clusters of galaxies – UV – X-ray

I. INTRODUCTION

Observations with the Extreme Ultraviolet Explorer (EUVE) provided evidence that a number of clusters of galaxies emit excess EUV emission in the cores of the clusters. The first clusters reported to have EUV excesses were the Virgo cluster (Lieu et al. 1996b; Bowyer et al. 1996) and the Coma Cluster (Lieu et al. 1996a). Thereafter EUV emission was reported for Abell 1795 (Mittaz, Lieu & Lockman 1998) and Abell 2199 (Lieu et al. 1999).

These early works employed a variety of data analysis schemes that were later found to be incorrect (Bowyer, Berghoefer, & Korpela 1999), primarily because incorrect methods were used to account for the sensitivity profile, or exposure map, of the telescope. The only clusters that have been determined to have an EUV excess using uncontested data analysis procedures are the Virgo cluster (Berghoefer et al. 2000) and the Coma Cluster (Bowyer et al. 1999). In this paper we discuss the possibilities for the underlying source mechanism for the production of this flux.

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II. THE SOURCE OF THE EUV EXCESS EMISSION IN COMA AND VIRGO

(a) Thermal

In principle, the EUV excess in these clusters could be either thermal or nonthermal emission. However, observational evidence for the Coma Cluster has been obtained by Arnaud et al. 2001 and by Vikhlinin et al. 2001 that rules out thermal emission. Both of these groups studied the Coma cluster in detail. Arnaud et al. analyzed *XMM-Newton* data and determined temperatures in 3.5 x 3.5 arcmin regions in the 20 arcmin core of the cluster. The temperatures in these regions ranged from 7 to 8.5 keV (with a few outliers) with no evidence for lower temperature gas. Vikhlinin et al. used *Chandra* observations to search for lower temperature gas in very small regions over the entire core of the cluster. They found only high temperature (9 keV) gas throughout the entire cluster. The only exceptions were small regions of 1 to 2 keV gas within a 700 radius of NGC 4874 and NGC 4889 which they attributed to emission from the halos of these individual galaxies. Several modifications to the *Chandra* calibration have been made subsequent to the calibration used in this paper; when all of the updates are included, the *Chandra* spectrum in the core of the Coma cluster excludes any soft component which contributes more than 5% of the total flux above 0.6 keV. (Vikhlinin, private communication)

Kaastra, Lieu et al. 2003 claimed to have found "warm" thermal emission within the central 12 arcmin core of the Coma Cluster with *XMM-Newton.* However, their claim was based on the (marginal) detection of a diffuse soft X-ray excess in the cluster and is contradicted by the work of Arnaud et al. 2001 and Vihklinin et al. 2001.

Finoguenov et al. 2003 summed *XMM-Newton* data in 20 arcmin diameter bins and detected OVII and OVIII emission 30 arcmin off from the center of the cluster. These lines would be produced by a 0.2 keV (or 2×10^6 K) gas. They claimed to have shown that this emission came from a filament in front of the Coma Cluster that was seen in projection against the cluster. However, these data are in conflict with ROSAT data taken of this region, and the *XMM-Newton* data are suspect, at a minimum (see the paper by Bowyer & Vikhlinin, these Proceedings, for details).

(b) Nonthermal

A number of nonthermal mechanisms have been proposed as the source of the EUV excess in clusters. The most thoroughly explored possibility is that this emission is cosmic microwave background photons that have been inverse Compton (IC) scattered by a population of cosmic ray electrons. A wide variety of suggestions have been made as to the source of these cosmic ray electrons, but virtually all of these studies assumed the electrons are *primary cosmic rays.*

Bowyer et al. 2004 carried out an analysis of EUVE data on the Coma Cluster using new techniques. They demonstrated that the EUV emission in that cluster is cosmic microwave background radiation that has been IC scattered by cosmic ray electrons in the cluster, as has been assumed in many previous studies. However, they showed that the emission was produced by secondary electrons, not primary electrons. They argued that these secondary electrons had been produced in hadronic interactions between a population of cosmic ray protons in the cluster and the thermal gas protons in the cluster.

Miniati has modeled the nonthermal emission from clusters (Miniati, 2003). In this work, he showed results only above 10 keV. However, he has now extended his work to lower energies and has calculated the EUV flux with the specific parameters of the Coma Cluster (F. Miniati, 2004, private communication). He finds that the IC EUV emission from electrons produced in hadronic interactions is consistent at the 20% level with the measured EUV flux in the Coma Cluster. Further, the spatial distribution of this emission is concentrated in the inner region of the cluster.

III. NEW RESULTS ON THE EUV EMISSION IN THE VIRGO CLUSTER

We have examined the EUVE data on the Virgo Cluster using the new analysis procedures of Bowyer et al. 2004 in an attempt to determine the source of the EUV emission in this cluster (Bowyer, Kuo, and Korpela, in preparation). We have found solid evidence that the source of the EUV emission in the Virgo Cluster is also IC scattered cosmic microwave background photons scattered by secondary electrons and positrons. We again suggest that these secondary electrons are produced in hadronic interactions between a cosmic ray proton population in the cluster and the thermal gas in the cluster. We find that the required underlying cosmic ray protons could reasonably have been produced in large scale structure shocks accompanying the formation of the cluster.

IV. CONCLUSIONS

The EUV data obtained on the Coma and Virgo Clusters with the EUVE spacecraft have been examined using the new analysis procedures described by Bowyer et al. 2004. We find that the EUV emission in both clusters is produced by cosmic microwave background photons that have been IC scattered by secondary electrons. This hypothesis is consistent with all aspects of the EUV data, and it is consistent with constraints imposed by radio observations. The proposal that the secondary electrons are produced by a population of cosmic ray protons in the clusters undergoing hadronic interactions with the thermal gas in the cluster is consistent with constraints imposed by current gamma-ray observations.

We believe the longstanding question of the source of the excess EUV emission in the Virgo and Coma Clusters has now been answered.

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