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A possible heating mechanism for the X-ray-emitting plasma within clusters of galaxies

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Abstract. X-ray and extreme ultraviolet emission from galaxy clusters can be interpreted as thermal emission from a hot plasma gravitationally bound to the cluster and constituting a significant amount of the mass of the cluster. The origin of this plasma and its thermal energy content can be linked to the formation process through the theory of self-organization of these structures.

1. Introduction

Observations of large-scale structures in the Universe have been made for over 50 years. With the advent of new, large-area, digital cameras, several major surveys are now starting to take data and significant advances will undoubtedly be made in the next few years. The first result that emerged from the original studies of the two-dimensional structures of the Universe was that galaxies are not randomly distributed across the sky. Instead, galaxies form a hierarchical structure of groups, clusters and superclusters. Groups and clusters contain from two to three up to, perhaps, ten thousand individual galaxies ('groups' become 'clusters' at about 30 galaxies). Several clusters together make a supercluster.

Clusters of galaxies are the largest recognizable organizations of matter in the Universe. They form stable, gravitationally bound, dynamically evolving structures. Thousands of clusters have been found in optical and X-ray surveys. The very fact that clusters are X-ray sources was one of the very earliest results to emerge from the 'new' subject of X-ray astronomy more than thirty years ago (although it has taken many years to fully realize what those early results were hinting at). The X-ray emission from clusters of galaxies is largely produced by diffuse, hot plasma contained within the gravitational potential well of the clusters. Dynamically, this plasma is far more important than the optical galaxies of the cluster. Clusters of galaxies are usually classified by their 'richness'. This is a measure of the number of galaxies found within some standard 'core' radius at the centre of the cluster. The Abell definition of the core radius is 1.5 ${h_{100}}^{-1}$ Mpc, where h_{100} is $H_0/100$ and H_0 is Hubble's constant in km s^{-1} Mpc^{-1}. The more galaxies within 1 core radius, the richer is the cluster. The Coma cluster is a good example of a nearby rich cluster.

The X-ray plasma within a cluster is expected to be very close to hydrostatic equilibrium. Only major perturbations, such as galaxy cluster mergers, are likely to disrupt the plasma from its thermal equilibrium. Such mergers will produce shocks within the X-ray plasma and generate local heating, thus producing thermal inhomogeneities within the cluster plasma. However, these shocks should thermalize relatively quickly, typically within a sound crossing timescale of about 2–3×10^9 yr for typical cluster core quantities. From the properties of this plasma, i.e. its temperature of the order of 2−14 KeV and density 10^{-4}−10^{-3} cm^{-3}, we can estimate the number of particles in the Debye sphere to be of the order of 10^{17}. This makes the intracluster medium (ICM) plasma about the most perfect plasma in the Universe. Such a plasma cannot be treated using simple gas dynamics, but must be treated using the full collisionless Vlasov equation where the self-consistent electromagnetic fields are used to determine its behaviour.

For clusters that are in or close to hydrostatic equilibrium, X-ray observations are an excellent way of determining physically useful descriptions of the cluster. The X-ray images provide a very good means of determining the distribution of mass within the cluster, and when the X-ray temperature is also known, the total (gravitational) binding mass of the cluster can also be estimated. Some X-ray clusters are also known to contain gravitational lensed images of background galaxies. These tend to be seen as 'arcs' in optical pictures of the cluster. The high concentration of gravitational mass within the cluster is acting as a gravitational lens. This provides a completely independent method of obtaining the mass distribution and total mass of the cluster. Providing the X-ray images is 'smooth', indicating that the cluster is in hydrostatic equilibrium and the galaxies within the cluster are therefore 'relaxed', the agreement between the two mass estimates (X-ray derived and gravitationally lensed derived) is excellent (e.g. Allen et al. 1996). The mass of the optically emitting mass, 2%−7% of the total mass, and the X-ray-emitting plasma, 10%−30% of the total mass, still leaves a large mass deficit relative to the total binding mass of the cluster. This excess is generally known as the 'dark matter' content of clusters and typically accounts for 60%–80% of the total cluster mass budget.

One of the main puzzles concerning the X-ray plasma in clusters of galaxies is its origin. A second important question to be answered concerns the high temperature of this plasma; in some cases this is in excess of 10^8 K. In this paper, we would like to suggest that these two problems are actually related and could provide a fundamental link back to the very initial formation of the cluster itself and also of the individual galaxy formation processes.

2. Background observations

The first X-ray astronomy satellite, *Uhuru* (Kellogg et al. 1973; Kellogg 1975), demonstrated that clusters of galaxies were the commonest bright, extragalactic, X-ray sources. *Uhuru* also showed that the X-ray emission was not time variable and that the X-ray spectrum showed no evidence for low energy absorption. However, it was the advent of imaging X-ray telescopes that revealed the true importance of the X-ray emission from clusters of galaxies.

X-ray images from the *Einstein* satellite typically revealed very smooth, regular spatial distributions with central emission peaks. For clusters with central dominant galaxies, the X-ray peak would generally coincide with this galaxy. For clusters that are known to have a low central concentration of galaxies (i.e. 'poor' clusters), the X-ray emission was found to be somewhat irregular. These clusters were also observed to have low X-ray luminosities and temperatures. By contrast, the 'regular' clusters were associated with the richer (optical) clusters, which show a higher central density of galaxies and which were also found to be more X-ray luminous and have higher X-ray temperatures. This can be very easily seen in the recent cluster observations made by the *Rosat* satellite. X-ray images are essential for mapping the physical extent of the X-ray plasma within clusters of galaxies.

However, perhaps the most important properties of the plasma are revealed by detailed X-ray spectral observations. In particular, the discovery of 6.67-keV line emission from the He-like ion of highly ionized iron was very significant (Mitchell et al. 1977; Serlemitsos et al. 1977; Mushotzky et al. 1978a, b). This emission line is now detectable from virtually every cluster of galaxies. Its importance derives from the fact that it implies that a significant fraction of the intracluster plasma must have been processed in stars, since the most likely source of this iron (Fe) is the ejecta from Type II supernovae (SNe). From large samples of clusters, it is found that the mean Fe abundance is fairly narrowly distributed around a value of ∼0.3 of the solar Fe abundance. More recent measurements that were sensitive enough to do spatial mapping of the Fe abundance reveal that iron is fairly uniformly distributed out to radii of ∼1 Mpc and in the case of the Coma cluster perhaps even out to ∼2 Mpc. Given the fact that the ICM plasma mass is some 2–10 times the total mass in the form of stars in the clusters, the implied mass of Fe is very considerable. Since the Fe almost certainly originated in Type II SN, this very large amount of Fe places very severe constraints on virtually every model of galaxy formation and subsequent cluster evolution.

Arnaud et al. (1992a) showed that the total Fe mass of clusters correlated with the total light from elliptical galaxies in the same clusters. This lends support to the hypothesis that it is SNe in elliptical galaxies that produced the metal enrichment of the ICM, the SN ejecta being driven out of the galaxies when they pass through the denser core of the clusters by the ICM pressure. Mushotzky et al. (1996) have measured the abundances of other elements in four rich clusters (e.g. O, Ne, Mg, Si and S). These trace elements are very important for distinguishing the origin of Fe, since only Type II SNe produce significant quantities of these other elements, in addition to Fe. They found that the relative elemental abundances observed in the four clusters are consistent with the expected values for Type II SNe. This would then suggest either a very flat initial mass function (IMF) (i.e. a relative excess of higher mass stars) or a bimodal star formation rate during the evolutionary phase when most of the metals were created in these clusters.

Another result was the observation of a very good correlation between the observed X-ray temperature and the cluster core radius (Arnaud et al. 1992b). This result does not apply to very poor groups and clusters of galaxies, but once the core radius exceeds about 1.5 Mpc, the correlation becomes very strong. This result demonstrates that if more galaxies are packed into a given volume, more net plasma heating is produced (i.e. the plasma temperature rises).

3. Analysis

The main physical problem that has to be addressed is the mechanism of plasma heating and why there is so much of it, i.e. it far exceeds the visible matter. The fact that it is so hot raises another interesting problem about the early history of galaxy formation. Did galaxies form after recombination and is this plasma a result of ionization by stellar radiation? To ionize this amount of matter would need an enormous amount of energy and with the only source being thermonuclear it is difficult to

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reach the present energy balance. If galaxies formed from dense hot plasma, then we would only require enough energy to overcome radiation cooling i.e. bremsstrahlung radiation losses.

Starting with a model of galaxy formation as a gravitationally collapsing plasma not in thermodynamic equilibrium, then the formation of structures leads to a decrease of entropy locally which is balanced by an overall increase in entropy globally. The physical process that describes this type of behaviour is self-organization introduced by Nicolis and Prigogine (1977) in discussing the dynamical behaviour of complex systems far from thermodynamic equilibrium. The theory of self-organization explains the formation of ordered structures formed in a complex system of many interacting particles. The formation of a galaxy containing 1000 billion stars is such a system. One of the main results from this theory is that the entropy overall increases by dissipating energy into the surroundings. The gravitational energy released in galaxy formation is a possible source, which is of the order of kilovolts per hydrogen ion excluding the energy released by the formation of a massive black hole at the galaxy's centre. The theory of self-organization can be applied to galaxy formation by explaining how gravitational energy released during contraction and formation of ordered structures is dissipated in the surrounding plasma, keeping it hot. We believe that the hot plasma halo is the manifestation of this general law of self-organization.

The exact physical mechanism by which the plasma heats up is not explicitly defined by the self-organization theory that only nature will always find a suitable path to dissipate the energy, in this case the excess gravitational energy, released. This is in fact a requirement for the self-organization to take place.

The dissipation mechanism could be of a collective nature typical for plasmas with many possible instabilities, for example collisionless shocks. The main point to be stressed is that the self-organization process should be independent of the exact collective process. Many examples are known, such as collisionless shocks, collisionless wave absorption, anomalous dissipation of magnetic field energy. The gravitational energy gain provides a rate of dissipation for the formation of a dissipative self-organized structure. The plasma should adjust and develop an appropriate mechanism to absorb this released energy at the appropriate rate. Such effects are seen in computer simulations of such things as phase space vortexes associated with the two-stream instability; in fact, this instability is analogous to gravitating material. Thus, the argument we put forward above is independent of the precise details of the appropriate dissipation process but obviously a collective mechanism is needed in the collisionless plasma within the cluster.

Since the plasma within and surrounding the galaxy cluster contains most of the mass, about 30 times more mass than is in the luminous stars, and contains most of the energy, more than that produced by the stars, there is a major problem in identifying the energy source necessary for ionizing this matter from neutral form. If, however, this was always in the plasma state, we only require enough energy to prevent recombination. We call this the percolation theory, whereby the rate of cooling is balanced by the rate of heating. Our aim is to identify a heating mechanism.

If we take the alternative point of view and assume that matter had indeed recombined before the onset of galaxy formation, then the theory of self-organization requires that the rate of heating should be equal to the rate of energy gain due to gravitational contraction. We can easily estimate the gravitational energy at the present time. The question that we need to answer is at what time in the galaxy formation did the plasma halo exist. If we assume that the galaxy formation time is of the order of 10^9 years and that the gravitational energy released goes into the heating processes, this provides us with an estimate of the probable energy gain for heating in the range 10^{50} erg s^{-1}. Structure formation through self-organization requires that most of the energy released goes into kinetic energy of the plasma. We thus come to the conclusion that gravity contraction and plasma dissipative processes are not separable in the formation of galaxies. There are many ways in which gravitational energy can be converted into heat, for example SN explosions convert gravitational energy into particle energy, most of it coming out in the form of energetic neutrinos but a fraction going into shock waves that provide the heating through various plasma instabilities. Cosmic rays are another component of SNe and these can be created within the shock structure.

Cosmic rays are a natural source of energy since they exist throughout the galaxy. Cosmic rays can heat the background plasma directly through Coulomb collisions with a heating rate given by

$$P_{\mathrm{Cosmicrays}} = 4\pi n_e n_c c \left(\frac{Z e^4}{m_e v^2}\right) \times \ell n\left(n_e \lambda_{\mathrm{De}}^3\right) \mathrm{erg\,cm^{-3}\,s^{-1}}, \qquad (1)$$

where n_e is the electron density, n_c is the cosmic-ray density, Z is the charge on the cosmic rays, v is the electron velocity, λ_{De} is the Debye wavelength and c is the speed of light.

The bremsstrahlung losses of the heated plasma result in X-ray emission in the keV energy range with a power per unit volume given by

$$P_{\mathrm{Brem}} = 9.3 \times 10^{-26} n_e^2 Z_i T_e^{\frac{1}{2}} \left[1 + 2\left(\frac{T_e}{mc^2}\right)\right] \times \mathrm{erg\,cm^{-3}\,s^{-1}}, \qquad (2)$$

where Z_i is the charge on the ions, T_e is the electron temperature and m is the electron mass.

For the galactic halo, we take the plasma density to be $n_e = 10^{-4}$–10^{-3} cm^{-3} and the cosmic-ray density to be 10^{-9} cm^{-3}.

From (1) and (2), we then find that the cosmic-ray heating of the galactic halo is about an order of magnitude larger than the bremsstrahlung radiation rate. Taking the radius of the halo to be 10^{27}cm (10^6 light years) and the total volume of the halo to be 10^{72} cm^3, the total radiation is $10^{40}-10^{42}$ erg s^{-1}. Cosmic-ray production in our galaxy is of the order of $10^{41}-10^{42}$ erg s^{-1} corresponding to particles with energies greater than 2 GeV. Sub-cosmic rays also exist, i.e. with energies less than 1 GeV, and the rate of production is greater for sub-cosmic rays, but these tend to remain close to their source such as supernova remnants and stellar objects. An estimate of the power per galaxy available for heating in cosmic rays is about $10^{43}-10^{44}$ erg s^{-1}. Apart from cosmic rays, other energy deposition processes also exist, for example, collisionless shocks, Alfvén waves, magnetic reconnection, turbulent wave generation and damping. From (1) and (2), we see that the bremsstrahlung emission rate and hence cooling rate is orders of magnitude less than available in cosmic rays.

4. Discussion

In this paper, we describe a possible scenario for explaining the X-ray emission from galaxy clusters. The process of galaxy formation follows from the theory of self-organization where the formation of structures locally results in a local decrease of entropy that results in a global increase of entropy. This global increase manifests as a heating mechanism for the plasma within and surrounding the cluster of galaxies. This plasma is also responsible for star-forming material in regions where filaments, clumps or shock waves form. The hot plasma is a natural consequence of the theory of self-organization applied to gravitational collapse.

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