A Possible Intracluster Origin for the Excess Soft X-ray Component in Some Clusters

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The soft x-ray spectra of the Virgo and Coma clusters cannot be modeled by emission from the well-known hot intracluster medium attenuated by photoelectric absorption along the line of sight in our galaxy. If the excess soft emission is due to thermal emission in the clusters from gas at about 1 million kelvin, then the gas should be rapidly cooling. The high rate of cooling poses problems for the origin of the gas and its sink. A model in which the component is due to turbulent mixing layers around clouds scattered throughout the intracluster medium may explain the excess emission. The gas in the mixing layer is reheated after cooling, so that the total mass remains relatively small.

Lieu *et al.* (*1*) report excess soft x-ray emission in the Virgo and Coma clusters, greater than that expected from the known hot intracluster medium in those clusters. The excess is apparent in data from the Extreme Ultraviolet Explorer (EUVE), with which they discovered this effect, and in archival data from the Position Sensitive Proportional Counter (PSPC) on ROSAT. Although a smaller galactic column density along the line of sight to the clusters (which absorbs the soft x-ray emission) can eliminate the excess, the correction is greater than the uncertainty of the measurements. Moreover, possibilities that the effect is due to subtleties in the absorption corrections (*2*) are considered unlikely (*3*). If the excess component is due to soft x-ray emission from gas at $\sim 5 \times 10^5$ to 1×10^6 K, then the gas is cooling radiatively at a rate of hundreds to thousands of solar masses ($M_\odot$) per year for the Virgo and Coma clusters, respectively (*1*). Although the accumulation of cooled gas at these rates might evade detection at other wavelengths (*4*), it would be more than 10^{12} to 10^{13} $M_\odot$ after 10 billion years. The cooling rate exceeds any cooling flow inferred from higher energy x-ray data for the clusters by one (Virgo) to two (Coma) orders of magnitude. Therefore, the source of the cooling gas cannot be the hotter intracluster medium. However, turbulent mixing layers of mass $\lesssim 10^{11} M_\odot$ at the edges of cold clouds distributed throughout a cluster can provide a viable explanation for a gas component at a temperature of about 10^6 K.

A mixing layer occurs at the interface of cold gas and turbulent hot gas (*5*). Consider a cold gas cloud tumbling through the hot intracluster medium. Turbulent motions in the hotter gas tear up shreds of cold gas around the cloud which then mix with the hot gas to produce gas at a temperature near the geometric mean of the two temperatures. (The momentum flux dictates the relative masses of hot and cold gas that mix.) Gas at about 10^6 K can thus be produced by the mixing of gases at 10^8 and 10^4 K. The mixed gas is near the peak of the radiative cooling curve, so it cools back down to join the bulk of the cold cloud. This process repeats continuously. There is only a small accumulation of cooled gas from the entrained hot gas because most gas is reused over and over again. The overall energy source is the thermal energy of the hot gas. Moreover, rapid mixing creates gas at 10^6 K without needing gas at intermediate higher temperatures.

Quantitatively, the surface emissivity of a mixing layer (*5*) is about $\frac{5}{2}pv$ per unit area, where p is the gas pressure (in kelvin per cubic centimeter) and v is a typical velocity (in kilometers per second) within the hot gas [I assume that the efficiency of mixing (*5*) is ~ 1]. Taking $p = 10^5\ k$ dyne cm^{-2} (k, Boltzmann constant), which is the minimum value in the EUVE-observed regions of the Virgo and Coma clusters, and a velocity $v = 100$ km s^{-1}, the area of cold clouds required is less than $\sim 3 \times 10^{46}$ cm^2 for a luminosity of 10^{43} erg s^{-1}. For the luminosities of the excess components in the Virgo and Coma clusters estimated from the cooling rates (*1*), the areas correspond to 30 kpc by 30 kpc and 150 kpc by 150 kpc, respectively. These areas are less than 10% of the total observed regions (the total fraction of the hot gas covered by the clouds is then also less than 10%). The mass of cold gas in the underlying clouds depends on thickness but is 10^{10} to $10^{11} M_\odot$ for a column density of 10^{21} cm^{-2}. This value is not much more than the mass of the interstellar medium of a spiral galaxy and is several orders of magnitude less than that which would have accumulated over the lifetime of the cluster without continuous mixing.

The size of a cloud must exceed the depth of its mixing layer, which is $l \sim vt_{cool}$, where t_{cool} is the cooling time of the mixed gas. At the assumed pressure, $l \sim 100$ pc, so clouds (which may be sheet- or filament-like) must have at least one dimension exceeding 100 pc. Such clouds could be still be less than an arc second in size at the distance of the Coma cluster, whereas at the Virgo cluster, they would subtend a few arc seconds. Irradiation of a cloud by the cooling mixed gas will produce line emission (*6*, *7*). Assuming that half of the power is absorbed by the cloud and an efficiency of 1% for the production of Hα line emission, the surface brightness of that line is about 10^{-17} ergs cm^{-2} s^{-1} (arc sec)$^{-2}$ for both clusters. This line strength is at least an order of magnitude less than that of the emission-line filaments seen (*8*) at the centers of cooling flows (where the gas pressure is perhaps 100 times greater) but may be detectable in dedicated observations.

No emission lines due to highly ionized oxygen, O VI, have been detected from these clusters by the Hopkins Ultraviolet Telescope (*9*). This observation gives an emission-profile–dependent limit on the mass of warm gas that, if centrally peaked, may be inconsistent with gas cooling at the inferred rate. However, the lack of ionization equilibrium in mixing layers [the surface brightness in O VI should only be comparable to that of Hα (*7*)] and possible dust in the cold clouds, particularly at the center of the cluster, reduce the O VI emission that is detectable and so lower that limit. Note that the low covering fraction of the clouds means that no clear absorption signal need be found in searches for dust in clusters (*10*). Such clouds and mixing layers do have implications, however, for the intervening absorption lines seen in quasars.

The scenario presented here consists of many thousands of cold clouds distributed throughout the cluster, each with a size of a few hundred parsecs. Such clouds may be remnants of the formation of the cluster, gas that was never efficiently heated or from early cooling flows, or gas stripped from member galaxies. Conduction has to be suppressed for the clouds to be long-lived. This can occur if the clouds have a magnetic structure separate from that of the intracluster medium. Provided that the clouds are only a few hundred parsecs across, the excess emission from their mixing layers can give a smooth, soft x-ray profile at the resolution of the ROSAT PSPC. The shape of the profile depends on the pressure of the hot gas and the distribution of the clouds themselves. A difference between the soft excess profile and that of the harder x-ray emission would favor a mixing-layer origin over any explanation based on galactic absorption. Many of the factors involved in the mixing-layer model are uncertain, and the above estimates may be equally uncertain. If mixing layers are the source of the

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excess emission in clusters, then the intracluster medium must be multiphase on a large scale, with a component of long-lived cold clouds.

REFERENCES AND NOTES

1. R. Lieu *et al.*, *Astrophys. J.* **458**, L5 (1996); R. Lieu *et al.*, *Science* **274**, 1335 (1996).
2. A. C. Fabian, *Science* **271**, 1244 (1996).
3. S. Bowyer, M. Lampton, R. Lieu, *ibid.* **274**, 1338 (1996).
4. A. C. Fabian, *Annu. Rev. Astron. Astrophys.* **32**, 277 (1994).
5. M. C. Begelman and A. C. Fabian, *Mon. Not. R. Astron. Soc.* **244**, 26 (1990).
6. C. S. Crawford and A. C. Fabian, *ibid.* **259**, 265 (1992).
7. J. D. Slavin, J. M. Shull, M. C. Begelman, *Astrophys. J.* **407**, 83 (1993).
8. L. L. Cowie, E. M. Hu, E. B. Jenkins, D. G. York, *ibid.* **272**, 29 (1983); W. B. Sparks, H. C. Ford, A. L. Kinney, *ibid.* **413**, 531 (1993).
9. W. V. D. Dixon, M. Hurwitz, H. C. Ferguson, *ibid.* **469**, L77 (1996).
10. H. C. Ferguson, *Mon. Not. R. Astron. Soc.* **263**, 343 (1993).

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Generation of X-rays from Comet C/Hyakutake 1996 B2

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The instability resulting from the relative motion of newly picked-up cometary photoions and the solar wind generates lower hybrid waves that are capable of accelerating electrons to the keV range of energies. These electrons may be responsible for the x-rays from comet C/Hyakutake 1996 B2 seen by the Röntgen X-ray Satellite. The inferred x-ray photon power depends on the electron energy, with keV electrons providing values of photon power two orders of magnitude greater than 100 eV electrons. These observations and in particular, spectral resolution of the x-rays, should provide more insight into the composition of the comet.

Observations by the Röntgen X-ray Satellite (ROSAT) on 26 to 28 March 1996 of x-ray emission from comet C/Hyakutake 1996 B2 (*1*) appear to have been a surprise to most comet researchers. However, plasma data taken by the Vega spacecraft (*2*, *3*) from the encounter with comet P/Halley suggests that this observation can be explained by wave-particle interactions producing keV electrons, which are necessary for x-ray emission. Observations of strong plasma wave turbulence (*2*) together with energetic electrons (*3*) in the keV energy range observed in the sunward mantle region separating the solar wind and the interior cometary ionosphere of Halley corresponds to the same region where the x-rays were observed from Hyakutake. Halley's plasma wave turbulence is in the range 4 to 40 Hz corresponding to frequencies between the ion and electron gyro-frequencies and is close to the lower hybrid frequency which is the geometric mean of the electron and ion gyro-frequencies of the order of tens of hertz. Lower hybrid waves (*4*) are effective in energizing electrons, therefore it is not surprising that an energetic electron population up to several keV was also observed at Halley (*3*) in the same region as the lower hybrid wave activity (*2*). Hyakutake's gas production rate (*5*) (2×10^{29} molecules per second at 1 AU) is similar to Halley's (7×10^{29} molecules per second at 1 AU) (*6*) so it is possible that the electron population at Hyakutake might have the appropriate energies to produce the observed x-ray emission. A previous attempt to take an x-ray image of comet Bradfield 1979X (*7*) yielded an upper limit $\sim 10^{14}$ erg s^{-1} for the total x-ray power emitted at the comet. It was assumed that x-rays would result from the precipitation of auroral type keV electrons following the cometary analogy of a terrestrial substorm. This process implies that the emission, should it occur, is sporadic.

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Here we will demonstrate that the interaction of the cometary plasma and the solar wind produces waves in the lower hybrid frequency range that are responsible for the production of suprathermal electrons with energies in the range of 100 eV up to several keV, which are necessary for bremsstrahlung and cometary gas K-shell radiation of x-rays. Close to the sun ($\sim$1 AU) every cometary nucleus is surrounded by an expanding gas cloud that consists mostly of water with some carbon dioxide and other molecules that is ionized largely by photoionization. These ions, created in the solar wind, immediately see the $\mathbf{v}_{SW} \times \mathbf{B}_{SW}$ electric field which accelerates them to high energies. ($\mathbf{v}_{SW}$ and $\mathbf{B}_{SW}$ are the solar wind velocity and magnetic field vectors, respectively). These ions, called pick-up ions, form in the solar wind frame an ion beam gyrating in the solar wind magnetic field. The energy source for this process is the relative motion between the solar wind and newly created cometary ions that results in the modified two stream instability (*8*) of an ion beam. The excitation of waves in the lower hybrid frequency range by this instability and subsequent absorption of the wave energy by electrons is the main mechanism for converting energy from the solar wind flow into plasma electrons, and then accelerating them parallel to the magnetic field forming a suprathermal electron component.

We obtained simple approximate formula for the characteristic energy and density of the suprathermal electrons using the conservation equations between the flux of energy from the ions into wave turbulence and absorption of the turbulent wave energy by the electrons. The cometary ion flux F_i at a distance r from the surface of the comet can be estimated by equating the photoionized part of the cometary gas outflow to the flow of the cometary ions picked up by the solar wind such that

$$F_i = 4\pi r^2 n_{ci} u = Q_s - Q_s \exp(-r/v_g \tau) = \frac{Q_s r}{v_g \tau} \quad (1)$$

where Q_s is the initial flux of gas molecules at the comet surface (*5*) (2×10^{29} molecules per second at 1 AU), τ^{-1} is the rate of photoionization ($\tau = 10^6$ s), v_g is the initial gas velocity at 1 AU ($v_g = 10^5$ cm s^{-1}), and n_{ci} is the cometary ion density (*9*). From Eq. 1 we can estimate the density of the cometary ions, n_{ci}, to be ≈ 10 cm^{-3} for $u = 3 \times 10^6$ cm s^{-1} corresponding to the downstream shocked solar wind velocity (*10*) at the distance $r = 50{,}000$ km which is close to the position where x-ray emission is being generated. These cometary photoions picked up by the solar wind excite the lower hybrid waves which in turn are absorbed by the suprathermal electrons through Cherenkov resonance with the waves.

In steady state, the energy flux lost by the pick-up ions is equal to the energy flux carried away by the suprathermal electrons. This leads to the energy flux balance equation

$$\alpha n_{ci} m_{ci} u^3 \simeq n_{Te} \varepsilon_e \left(\frac{\varepsilon_e}{m_e}\right)^{1/2} \quad (2)$$

where α is the transfer efficiency from the cometary ions of mass m_{ci} and n_{Te} is the