THE ASTROPHYSICAL JOURNAL, 461:L33–L36, 1996 April 10

THE X-RAY HALO OF THE LOCAL GROUP AND ITS IMPLICATIONS FOR MICROWAVE AND SOFT X-RAY BACKGROUNDS

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Received 1995 December 26; accepted 1996 January 31

ABSTRACT

Since recent X-ray observations have revealed that most clusters of galaxies are surrounded by an X-ray–emitting gaseous halo, it is reasonable to expect that the Local Group of galaxies has its own X-ray halo. We show that such a halo, with temperature ∼1 keV and column density $\sim O(10^{21})$ cm^{-2}, is a possible source for the excess low-energy component in the X-ray background. The halo should also generate temperature anisotropies in the microwave background via the Sunyaev-Zeldovich effect. Assuming an isothermal spherical halo with the above temperature and density, the amplitude of the induced quadrupole turns out to be comparable to the *COBE* data without violating the upper limit on the *y*-parameter. The induced dipole is negligible compared to the peculiar velocity of the Local Group, and multipoles higher than quadrupole are generally much smaller than the observed ones. However, nonsphericity and/or clumpiness of the halo will produce a stronger effect. Therefore the gaseous halo of the Local Group, if it exists, will affect the estimate of the primordial spectral index *n* and the amplitude of the density fluctuations deduced from the *COBE* data.

Subject headings: cosmic microwave background — cosmology: theory — diffuse radiation — Local Group

1. INTRODUCTION

The origin of the X-ray background (XRB) remains one of the most challenging problems in X-ray astrophysics. Figure 1 summarizes the current results on the XRB energy spectra, $I(\varepsilon)$ below 10 keV observed with different satellites. As is known (McCammon & Sanders 1990; Fabian & Barcons 1992), $I(\varepsilon) \sim 10\varepsilon^{-0.4}$ keV s^{-1} sr^{-1} keV^{-1} is a good empirical fit over the range 3–10 keV, where ε denotes X-ray energy in units of keV. Both the *Einstein* imaging proportional counter (IPC) (Wu et al. 1991; *plotted in diamonds*) and *ROSAT* (Hasinger 1992; Shanks et al. 1991; *upper-left lines*) data suggest a large excess below 2 keV. More recently the Japanese X-ray satellite *ASCA* (*crosses*) reported a modest but significant excess soft component below 1 keV relative to the extrapolation of the above power-law fit in the higher energy band (Gendreau et al. 1995). Thus the existence of the soft excess is well established, although its amplitude is still somewhat controversial.

Since Galactic absorption becomes important in the soft X-ray energy band, the origin of this excess component allows several possibilities, including Galactic sources, extragalactic pointlike sources (Hasinger 1992; Shanks et al. 1991), a diffuse thermal component (Wang & McCray 1993), and the accumulation of the thermal bremsstrahlung emission from distant clusters of galaxies (Kitayama & Suto 1996). Cen et al. (1995) found an excess of soft X-ray background below 1 keV from their hydrodynamical simulations, which properly incorporate the line emissions as well as the thermal bremsstrahlung emission; the excess originates mainly from the low-temperature and low-density plasma surrounding distant clusters of galaxies, since cooler background gas produces much stronger line emissions. Yet another possibility which we propose here is the emission from an X-ray halo of the Local Group (LG). Since the gaseous halos of clusters of galaxies are known to be strong sources of X-rays, it is reasonable to assume that the LG has its own X-ray halo.

2. SUNYAEV-ZELDOVICH EFFECT DUE TO THE HALO OF THE LOCAL GROUP

To be more specific, suppose that the LG is associated with a spherical isothermal plasma whose electron number density is given by

$$n_e(r) = n_0 \frac{r_c^2}{r^2 + r_c^2}, \tag{1}$$

where n_0 is the central density and r_c is the core radius. If we are located at distance x_0 off the LG center (Fig. 2), the electron column density at angular separation θ from the direction to the center is

$$N_e(\mu) = \int_0^\infty \frac{n_0 r_c^2\, d\xi}{\xi^2 - 2x_0\mu\xi + x_0^2 + r_c^2} = \frac{n_0 r_c^2}{x_0} \frac{1}{\sqrt{a^2 - \mu^2}} \left[\frac{\pi}{2} + \sin^{-1}\left(\frac{\mu}{a}\right)\right], \tag{2}$$

where $\mu \equiv \cos\theta$ and $a \equiv [1 + (r_c/x_0)^2]^{1/2}$. In Figure 1 the LG halo contribution to the XRB spectra simulated with the Raymond-Smith model, assuming an isothermal plasma temperature $T = 1$ keV, $r_c = 0.15$ Mpc, $x_0 = 0$, $n_0 = 10^{-4}$ cm^{-3}, and 0.3 times solar abundances, is also plotted (*histogram at lower left*). If we add this component to $I(\varepsilon) = 9.6\varepsilon^{-0.4}$ keV s^{-1} sr^{-1} keV^{-1}, the soft excess around 1 keV is explained. Note that it is not our primary purpose here to find the best-fit parameters because the single power-law component is simply an extrapolation from the higher energy band and also because the possible Galactic absorption is not taken into account

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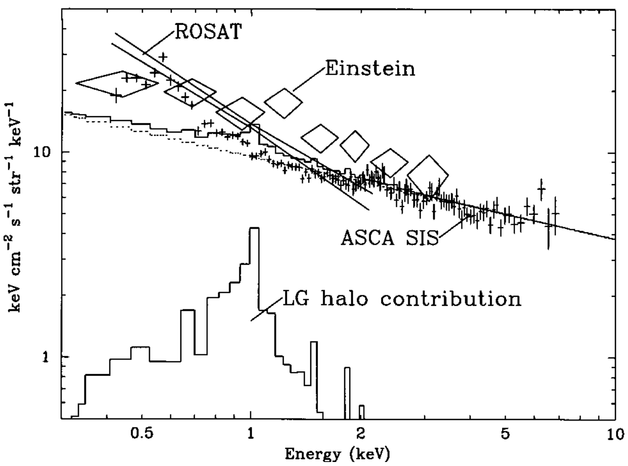

FIG. 1.—XRB spectra observed with different X-ray satellites. The size of the symbols denotes the error bars for *ASCA* (Gendreau et al. 1995; *crosses*) and *Einstein* (Wu et al. 1991; *diamonds*). The *ROSAT* data (Hasinger 1992) are indicated by the region between the two lines in the upper left. The histogram at lower left indicates the emission from the X-ray halo of the Local Group with $T = 1$ keV, $r_c = 0.15$ Mpc, $n_0 = 10^{-4}$ cm^{-3}, and 0.3 times solar abundances observed at the center of the Local Group (computed with the Raymond-Smith model). This Local Group halo model has a total X-ray luminosity of 10^{41} ergs s^{-1} between 0.5 and 4 keV, and an electron column density of 6×10^{20} cm^{-2}. The single power-law component extrapolated from the higher energy band, $I(\varepsilon) = 9.6\varepsilon^{-0.4}$ keV s^{-1} sr^{-1} keV^{-1}, is plotted in the dotted line, while the overall prediction (the Local Group emission plus the power-law component) is plotted in the solid line. Galactic absorption is not taken into account.

here. Nevertheless, it is interesting to see that the LG halo can be a possible origin for the soft excess.

If the X-ray halo of the LG really exists and accounts for the soft excess component in the XRB, it should also produce temperature anisotropies in the cosmic microwave background (CMB) via the Sunyaev-Zeldovich (SZ) effect (Zeldovich & Sunyaev 1969; Cole & Kaiser 1988; Makino & Suto 1993; Persi et al. 1995). In the Rayleigh-Jeans regime, the SZ temperature decrement is given by

$$\left(\frac{\delta T}{T}\right)_{\rm SZ}(\mu) = -2\frac{kT}{mc^2}\sigma_{\rm T} N_e(\mu), \tag{3}$$

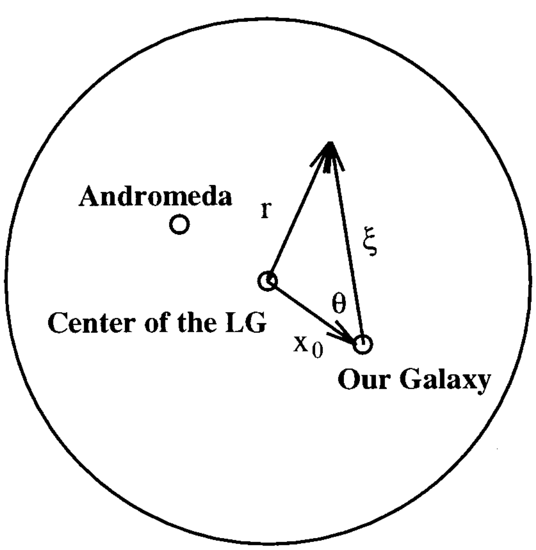

FIG. 2.—Assumed geometry of the X-ray halo of the Local Group

where k is the Boltzmann constant, m is the electron mass, c is the velocity of light, and $\sigma_{\rm T}$ is the Thomson scattering cross section. We compute the multipoles expanded in spherical harmonics:

$$\left(\frac{\delta T}{T}\right)(\theta, \varphi) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} a_l^m Y_l^m(\theta, \varphi). \tag{4}$$

With equations (2) and (4), one obtains

$$(a_l^0)_{\rm SZ} = -2\sqrt{(2l+1)\pi}\,\frac{kT}{mc^2}\sigma_{\rm T}\int_{-1}^{1} N_e(\mu)P_l(\mu)\,d\mu, \tag{5}$$

where $P_l(\mu)$ are the Legendre polynomials. Averaging over the sky, the above SZ anisotropies are expected to contribute in quadrature to the CMB anisotropies as

$$\left\langle\left(\frac{\delta T}{T}\right)^2\right\rangle = \frac{1}{4\pi}\sum_{l=0}^{\infty}(2l+1)\langle|a_l^m|^2\rangle = \frac{1}{4\pi}\sum_{l=0}^{\infty}(a_l^0)^2_{\rm SZ} \equiv \sum_{l=0}^{\infty}(T_{l,\,\rm SZ})^2. \tag{6}$$

The corresponding monopole, dipole, and quadrupole anisotropies reduce to

$$T_{0,\,\rm SZ} = \pi\theta_c\sigma_{\rm T}\frac{kT}{mc^2}\frac{n_0 r_c^2}{x_0}, \tag{7}$$

$$T_{1,\,\rm SZ} = 2\sqrt{3}\left(1 - \frac{r_c}{x_0}\,\theta_c\right)\sigma_{\rm T}\frac{kT}{mc^2}\frac{n_0 r_c^2}{x_0}, \tag{8}$$

$$T_{2,\,\rm SZ} = \frac{\sqrt{5\pi}}{4}\left[\theta_c - 3\frac{r_c}{x_0} + 3\left(\frac{r_c}{x_0}\right)^2\theta_c\right]\sigma_{\rm T}\frac{kT}{mc^2}\frac{n_0 r_c^2}{x_0}, \tag{9}$$

where $\theta_c \equiv \tan^{-1}(x_0/r_c)$.

The *COBE* FIRAS data (Mather et al. 1994) imply that the Compton y-parameter should be less than 2.5×10^{-5} (95% confidence level). With equation (7), this upper limit is translated to

$$n_0 r_c^2/x_0 < 1.1 \times 10^{22}\left(\frac{1.17}{\theta_c}\right)\left(\frac{y}{2.5\times 10^{-5}}\right)\left(\frac{1\ {\rm keV}}{T}\right){\rm cm}^{-2}. \tag{10}$$

For example, taking $r_c = 0.15$ Mpc and $x_0 = 0.35$ Mpc, the constraint (10) indicates that

$$T_{1,\,\rm SZ} < 3 \times 10^{-5}\left(\frac{y}{2.5\times 10^{-5}}\right), \tag{11}$$

$$T_{2,\,\rm SZ} < 1.3 \times 10^{-5}\left(\frac{y}{2.5\times 10^{-5}}\right). \tag{12}$$

The analysis of the first 2 years' *COBE* DMR data (Górski 1994; Górski et al. 1994; Bennett et al. 1994; Wright et al. 1994), on the other hand, yields $T_{1,\,\rm COBE} = (1.23 \pm 0.09) \times 10^{-3}$, and $T_{2,\,\rm COBE} = (2.2 \pm 1.1) \times 10^{-6}$. Therefore, the LG X-ray halo can potentially have a significant effect on the quadrupole of the CMB anisotropies, while its effect on the dipole is totally negligible compared to the peculiar velocity of the LG with respect to the CMB rest frame.

3. IMPLICATIONS

Primordial density fluctuations with power spectrum $P(k) \propto k^n$ induce CMB anisotropies via the Sachs-Wolfe effect with multipoles (e.g., Peebles 1993)

$$C_l \equiv \langle|a_l^m|^2\rangle \propto \frac{\Gamma(l + n/2 - 1/2)}{\Gamma(l - n/2 + 5/2)}, \tag{13}$$

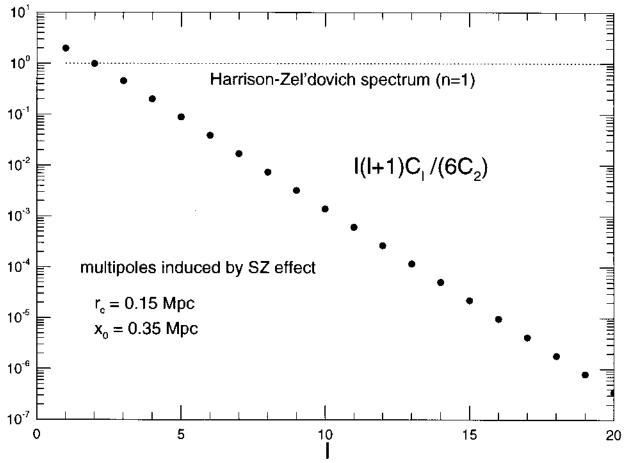

FIG. 3.—Multipoles induced by the Sunyaev-Zeldovich effect of the Local Group halo. The primordial Harrison-Zeldovich spectrum prediction $l(l+1)C_l/(6C_2) = 1$ is plotted in the dotted line.

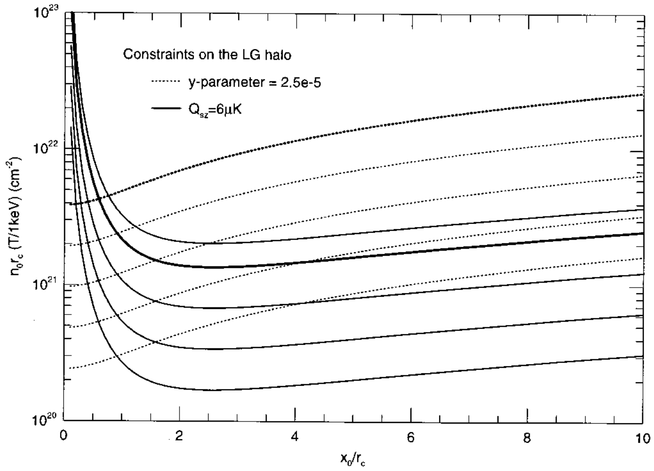

FIG. 4.—Constraints on the density and size of the halo of the Local Group from CMB anisotropies. Dotted curves correspond to $y = 2.5 \times 10^{-5}$ (*heavy dots*) $2.5 \times 10^{-5}/2$, $2.5 \times 10^{-5}/4$, $2.5 \times 10^{-5}/8$, and $2.5 \times 10^{-5}/16$. Solid curves correspond to $Q_{\rm SZ} = 9$, 6 (*heavy line*), 3, 1.5, and 0.75 μK.

where $\Gamma(\nu)$ is the gamma function. Therefore, the standard Harrison-Zeldovich ($n = 1$) spectrum predicts that

$$\frac{l(l+1)C_l}{6C_2} = 1. \tag{14}$$

The analytic expressions for the higher multipoles (eq. [5]) are quite complicated. Instead we have numerically computed $(C_l)_{\rm SZ} \equiv (a_l^0)^2_{\rm SZ}/(2l+1)$, which are plotted in Figure 3. Clearly the higher multipoles decrease very rapidly with l. Thus, even if the CMB quadrupole were contaminated by the SZ effect described here, the higher moments would be relatively free from such an effect and can be interpreted to reflect the true cosmological signature (the octopole may be affected to some extent). Although the contribution of a distant cluster of galaxies to the multipoles is small, its cumulative effect over the high redshift may be observable in the small-scale CMB anisotropies (Bennett et al. 1993; Makino & Suto 1993; Persi et al. 1995).

In this context it is interesting to note that the rms quadrupole amplitude from the 2 years' *COBE* data, $Q_{\rm rms} = (6 \pm 3)$ μK, is significantly smaller than that expected from the higher multipoles (Górski 1994; Górski et al. 1994; Bennett et al. 1994; Wright et al. 1994); if one fixes $n = 1$, for instance, the power-spectrum fitting using equation (1) requires that the most likely amplitude should be $Q_{\rm rms-PS} = (18.2 \pm 1.5)$ μK. It is somewhat common to ascribe the difference to cosmic variance. It is possible, however, to account for it in terms of our model described here, depending on the actual pattern of the primordial temperature fluctuations.

In turn, we can constrain the properties of the possible LG halo from the *COBE* data. This is summarized in Figure 4. In fact, the parameter range which is required for the LG halo to provide the excess soft component is largely consistent with the current *COBE* data. In addition, the LG X-ray halo should produce a dipole signature (toward M31 and the opposite direction) in the soft excess component; the flux f plotted in Figure 1 corresponds to what should be observed at the center of the halo. If we adopt $x_0 = 0.35$ Mpc, the flux toward M31 should be $1.27f$ while it should be $0.73f$ for the opposite direction. Such a level of XRB variation is detectable with careful data analysis of, for instance, the *ASCA* GIS observation. It should be noted that the cooling time of the X-ray halo at the center due to the thermal bremsstrahlung emission is roughly estimated as

$$t_{\rm cool} \equiv \frac{3n_0kT}{\varepsilon_{\rm ff}} \sim 3 \times 10^{11}\left(\frac{10^{-4}\ {\rm cm}^{-3}}{n_0}\right)\sqrt{\frac{T}{1\ {\rm keV}}}\ {\rm yr}, \tag{15}$$

where $\varepsilon_{\rm ff}$ is the thermal bremsstrahlung emission rate per unit volume for the primordial gas. Since $t_{\rm cool}$ is significantly larger than the age of the universe for the parameters that we are interested in here, such a LG halo is expected to survive for long once it is formed.

Our model described above assumes a fairly idealistic density profile (eq. [1]). A more realistic profile of the halo including nonsphericity and spatial inhomogeneity in temperature and density will have a stronger effect on the higher multipoles ($l \geq 3$). Therefore, one might even probe the properties of the LG halo through the multipoles of the CMB map. The direct X-ray detection of, or constraints on, the LG halo component is of great importance in deriving the primordial spectral index n and the amplitude of the density fluctuations from the *COBE* data. It is also important to search for the signature of, and/or put constraints on, the LG halo from the direct analysis of the *ROSAT* and *COBE* data.

We are grateful to the referee, Renyue Cen, for his pertinent comments on the earlier manuscript of the present Letter. We also thank Naoshi Sugiyama for discussions, and Ewan Stewart for a careful reading of the manuscript. This research was supported in part by Ministry of Education, Science and Culture of Japan Grants-in-Aid 07740183, 07CE2002.

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