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LETTERS

The X-ray Background from the Warm Gas of the Galactic Halo

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Abstract Within the framework of the hierarchical scenario of galaxy formation, spiral galaxies like our own Galaxy are still growing at present. This opens a possibility that one might be able to see X-ray galactic halos from gravitationally heated gas with temperatures of $\sim 10^6$ K as a result of bremsstrahlung. An interesting issue is whether the X-ray background produced by the warm gas in the halo of our Galaxy is detectable. We present a simple estimate of the strength and spectrum of the X-ray background from the Galactic halo and compare with the recent findings of a spatially variable soft X-ray component seen towards the north Galactic polar cap by Kuntz et al. (2001). It is shown that a good agreement, regardless of cosmological models, can be achieved if the gas fraction is as low as ~ 0.01. This requirement seems to be consistent with the extrapolated result from a number of independent observational and theoretical constraints established for groups and clusters of galaxies. In particular, the expected soft X-ray background from the warm gas of the Galactic halo is comparable to, or even exceeds that produced by the warm-hot gas in massive groups, and it may constitute the major source of contamination in the search for missing baryons through the detection of their soft X-ray emission, unless we can work out a way to properly remove the X-ray background (e.g., from anisotropy) from the halo of our Galaxy.

Key words: cosmology: diffuse radiation — Galaxy: formation — Galaxy: halo — X-rays: galaxies

1 INTRODUCTION

In the hierarchical scenario of structure formation, massive dark halos form by gravitational aggregation of individual low-mass objects, while the stellar disks of spiral galaxies like the Milky Way form by accretion of gas which cools and falls onto the galaxies from an extended surrounding reservoir. For a massive galaxy of $M \sim 10^{12} M_{\odot}$, the surrounding gas can be heated to temperature of $T \sim 10^6$ K by gravitationally-driven shocks, the dominant cooling is thus due to thermal bremsstrahlung emission. If the radiative cooling time of the warm gas is relatively

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large, one would be able to detect soft diffuse X-ray emission extending out to large radii and even beyond the virial radii of the galaxies. This has motivated a direct search for extended X-ray emission from the warm gas associated with galactic halos in recent years. For example, Benson et al. (2000) studied three nearby, isolated, late-type galaxies observed with ROSAT, but reached an essentially negative result. Their 95% upper limits on the X-ray luminosity of warm gas in galactic halos are one order of magnitude below the theoretical expectation. However, as was pointed out by the same authors, their results should be considered to be preliminary in the sense that besides confusion of background subtraction, their reconstruction of X-ray halos was model-dependent. Using the broad band data from the ROSAT All-Sky Survey, Kuntz, Snowden & Mushotzky (2001) have recently obtained the spectrum of the soft X-ray background in the 0.1–1.0 keV band towards the north Galactic polar cap. After the contributions from unresolved Galactic stars, from unresolved extragalactic point sources and from the Local Hot Bubble are properly removed, there are primarily two components remaining: a spatially variable soft component and a uniform hard component. The former may have the Galactic origin while the latter is most likely due to extragalactic emission. Of course, whether or not this soft component really arises from the warm gas in the Galactic halo still remains an open question.

Indeed, if our current knowledge of the hierarchical clustering model is correct, namely, spiral galaxies (e.g., the Milky Way) are still growing today, one would expect to see a diffuse X-ray emission from the warm gas associated with the halo of our own Galaxy, which should exist as a soft X-ray background around us and with some angular variation across the sky. A direct detection of the X-ray Galactic halo is certainly a challenging issue for X-ray astronomy. More importantly, it constitutes a critical test for the prevailing models of galaxy formation. Alternatively, the diffuse X-ray emission arising from the halo of our Galaxy, if any, might contribute a non-negligible fraction to the soft X-ray background, and hence might be the major source of contamination in the search for the missing baryons of the Universe. The latter is believed to be in the form of warm-hot gas residing in large filamentary structures, also seen as the soft X-ray background, although such an extragalactic X-ray background would show no angular variation across the sky (Cen & Ostriker 1999). Therefore, a quantitative estimate of the X-ray emission from the warm gas in the halo of our Galaxy is desirable in order to clarify the issue. We wish to undertake this task in this Letter and find out how large the strength of the soft X-ray background from the halo of our Galaxy would be. While the answer to such a question seems straightforward, it has not yet been explicitly given in the literature.

2 EXPECTATION FOR THE X-RAY BACKGROUND

Since our goal is to provide a crude estimate of the strength of the X-ray emission from the Galactic halo, we avoid the sophisticated models for the distributions of dark matter and gas in the halo. For the dark halo, we use the model S of Alcock et al. (1997):

$$\rho_{\rm DM}(r) = \rho_0 \frac{R_0^2 + a^2}{r^2 + a^2}\,, \tag{1}$$

where $\rho_0 = 0.0079\,M_\odot$ pc^{-3} is the local dark matter density, r is Galactocentric radius, $R_0 =$ 8.5 kpc is the Galactocentric radius of the Sun, and $a = 5$ kpc is the halo core radius. This model yields a total halo mass of $8.9 \times 10^{11}\,M_\odot$ out to 100 kpc. We assume that the gas is dissipationless, and hence traces the dark matter density profile:

$$\rho_{\rm gas} = f_{\rm gas}\,\rho_{\rm DM}, \tag{2}$$

where $f_{\rm gas}$ is the gas fraction in the Galactic halo. In principle, the temperature profile of the gas can be uniquely determined by the equation of hydrostatic equilibrium. Here, we would rather take a less rigorous treatment and use the virial temperature of the Galaxy instead, which reads (e.g. Bryan & Norman 1998)

$$kT = 0.081\ {\rm keV}\ h^{2/3}\left(\frac{\Delta}{200}\right)^{1/3}\left(\frac{M}{10^{12}M_\odot}\right)^{2/3}, \tag{3}$$

where $H_0 = 100h$ km s^{-1} Mpc^{-1} is the Hubble constant, and Δ is the overdensity of dark matter with respect to the critical density of the Universe and will be taken to be 178. Now, the X-ray flux per unit energy band per unit solid angle emitted as thermal bremsstrahlung from a warm gas at ℓ is

$$\frac{{\rm d}F}{{\rm d}Ed\Omega} = \frac{2^4e^6}{3\hbar m_{\rm e}c^2}\left(\frac{2\pi kT}{3m_{\rm e}c^2}\right)^{1/2}\mu_{\rm e}g(T,E)\frac{1}{4\pi}\int n_{\rm e}^2(r){\rm d}\ell\,, \tag{4}$$

where the integral is taken along the line of sight ℓ, $n_{\rm e} = \rho_{\rm gas}/\mu_e m_p$ is the electron number density, $\mu_{\rm e} = 2/(1+X)$, and $X = 0.768$ is the hydrogen mass fraction in the primordial abundances of hydrogen and helium. The function $g(T,E)$ is defined by

$$g(T,E) = \frac{2\pi\hbar}{kT}\, g_{\rm c}\ \exp(-E/kT), \tag{5}$$

where $g_{\rm c}$ is the average total Gaunt factor, which is calculated using the Raymond & Smith (1977) model with a metallicity of $Z = 0.3Z_\odot$. Numerical computations can be made straightforwardly once the direction is specified. We focus on the X-ray flux distribution seen within the Galactic plane, which represents the maximum variation of the X-ray background across the sky. We perform the integral of Equation (4) along the line of sight with the simple geometric restriction $r^2 = R_0^2 + \ell^2 - 2R_0\ell\cos(\pi-\theta)$, where θ is the angle in polar coordinate centered on the Sun with $\theta = 0$ in the outward Galactocentric direction from the Sun. We truncate the halo at $r_{\rm out} = 200$ kpc, which corresponds to $kT = 0.074$ keV for $h = 0.5$. We adopt a gas fraction of $f_{\rm gas} = 0.01$ in our computation below and the result scales simply as $(f_{\rm gas}/0.01)^2$. We display in Figure 1 the resulting X-ray background versus the viewing angle θ for the 0.1–2.4 keV and 0.5–2.0 keV bands and for the entire energy band. We also calculated the flux for a smaller cutoff radius of $r_{\rm out} = 100$ kpc, and found that the flux decreased only slightly.

We now compare the X-ray background from the Galactic halo with the extragalactic X-ray background from the warm-hot gas associated with groups and clusters distributed at cosmological distances. The latter can be estimated essentially by three approaches: cosmological hydrodynamic simulations (e.g. Cen & Ostriker 1999; Phillips, Ostriker & Cen 2000), semi-analytic models based on the Press-Schechter formalism (e.g. Kitayama, Sasaki & Suto 1998; Pen 1999) and the utilization of the observed X-luminosity function along with the X-ray luminosity-temperature relation (Wu & Xue 2001). It appears that these three different approaches yield a consistent X-ray background spectrum over the 0.1–10 keV range if the observed X-ray luminosity-temperature relations of groups and clusters are incorporated into the semi-analytic models. This arises because the X-ray luminosity-temperature relation acts as a good indicator of the heating processes by both gravitational and nongravitational effects. In Figure 1, we display the expected extragalactic X-ray background in the 0.1–2.4 keV and 0.5–2.0 keV bands from groups and clusters with $L_{x,0.5-2.0\ {\rm keV}} \geq 1\times10^{42}$ erg s^{-1}, using a non-evolving X-ray luminosity function by Ebeling et al. (1997). Putting aside the results towards the lower Galactic latitudes where absorption due to neutral hydrogen gas and the X-ray emission from interstellar gas may complicate our expectations, we note, at the higher Galactic latitudes the extragalactic X-ray background from the warm-hot gas in groups and clusters significantly exceeds that from the X-ray halo in the 0.5–2.0 keV band but the opposite is the case for the 0.1–2.4 keV band. This can be easily understood because the gas associated with the Galactic halo is cooler than the intragroup and intracluster gas, and so the X-ray emission from the Galactic halo is mainly concentrated in the lower energy band. Recall that we have neglected all possible soft X-ray emission from other galaxies. We conclude that the soft X-ray emission below 0.5 keV from the halo of our Galaxy is at least comparable to that from groups and clusters. Of course, unlike the X-ray background from the Galactic halo, the extragalactic component exhibits no angular variation across the sky.

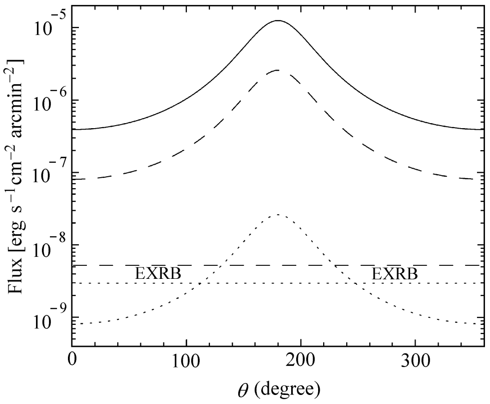

Fig. 1 The expected X-ray background from the warm gas in the Galactic halo at three energy bands: 0.5–2.0 keV (dotted line), 0.1–2.4 keV (dashed line) and bolometric luminosity (solid line). For comparison, the extragalactic X-ray background (EXRB) from groups and clusters characterized by their X-ray luminosity functions is also shown.

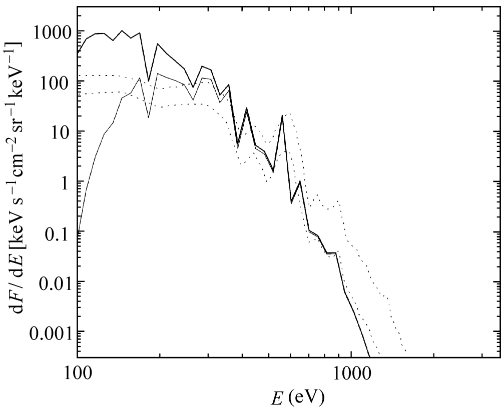

Fig. 2 The soft X-ray background spectra towards the Galactic pole produced by the warm gas in the Galactic halo with (thin solid line) and without (thick solid line) the inclusion of absorption by neutral hydrogen gas. Dotted lines are the spatially variable soft component detected by Kuntz et al. (2001).

The soft X-ray background spectrum from the Galactic halo towards the Galactic polar cap ($\theta = 90°$) is plotted in Figure 2, along with the 'remaining' soft component from Kuntz et al. (2001) seen towards the north Galactic polar cap after the contributions of the unresolved Galactic stars, of the unresolved extragalactic points and of the Local Hot Bubble are removed. Here, the largest uncertainty in the theoretical prediction is due to the absorption of neutral hydrogen gas along the line of sight. This is because the actual distribution of hydrogen column densities within our Galaxy is unknown, which hinders us from an accurate estimate of the Galactic absorption. An estimate of the maximum absorption effect may be obtained if we adopt a single value of $N_{\rm H} = 1.5 \times 10^{20}$ cm^{-2}, which is typical column density for extragalactic sources towards the Galactic polar cap. In other words, this is equivalent to putting all the warm gas to the outskirts of the Galactic halo. Consequently, an upper and a lower limit on the expected X-ray background towards the higher Galactic latitudes from the Galactic halo can be obtained by setting $N_{\rm H} = 0$ and $N_{\rm H} = 1.5 \times 10^{20}$ cm^{-2}, respectively. It appears from Figure 2 that the effect of absorption becomes significant only below 0.2 keV and the flux at the higher energy band is almost unaffected by the Galactic absorption. Meanwhile, above 0.2 keV there is a good agreement between our predicted X-ray background spectrum from the Galactic halo and the 'remaining' soft component detected by Kuntz et al. (2001), and even below 0.2 keV the measured soft component is well within our upper and lower limits.

3 DISCUSSION AND CONCLUSIONS

The recent detection of a spatially variable soft X-ray component towards the north Galactic polar cap with ROSAT All-Sky Survey (Kuntz et al. 2001) seems to favor the Galactic halo origin. Nevertheless, the strength of the X-ray emission reported by Kuntz et al. (2001) for the 'remaining' soft component indicates a small gas fraction of $f_{\rm gas} = 0.01$ for the Galactic halo. Recall that for the current popular cosmological model of $\Omega_b = 0.056$, $\Omega_{\rm M} = 0.35$, $\Omega_\Lambda = 0.65$ and a Hubble constant $h = 0.65$, the universal baryon fraction is $f_b = 0.16$. Indeed, Benson et al. (2000) have also arrived at a similar conclusion that the X-ray luminosities of the warm gas in galactic halos should be one order of magnitude below the theoretical argument. Nonetheless, this seems to agree with a number of independent observational constraints on massive scales: First, a direct measurement of the gas fraction in clusters of galaxies shows that $f_{\rm gas}$ is a decreasing function of the X-ray temperature (e.g. Mohr, Mathiesen & Evrard 1999), indicating that in the present Universe low-mass systems contains proportionately less gas than do high-mass systems. Second, the observed X-ray luminosity - temperature relations of elliptical galaxies, groups and clusters are significantly steeper than the scaling law predicted by self-similar evolution (David et al. 1993; Xue & Wu 2000; Mahdavi & Geller 2001), and other mechanisms (e.g. preheating) should be invoked to reduce the X-ray emission especially in groups. That is, it is unlikely that a significant fraction of gas can be gravitationally bound within the virial radii of less massive systems. Third, it is argued that most of the warm gas associated with groups must reside outside of the systems. Otherwise the X-ray emission produced by the gravitationally heated and bound gas in groups will greatly exceed the upper limits set by current X-ray observations (Pen 1999; Wu, Fabian & Nulsen 2001; Phillips et al. 2000; Wu & Xue 2001). Finally, we have neglected the effect of star formation in our computations. Bryan (2001) has recently collected several pieces of evidence from optical and X-ray observations and argued for a higher efficiency of star formation in groups than in clusters. In terms of his crude fitting formula for stellar mass fraction $f_{\rm star} = 0.042(T/10{\rm keV})^{-0.35}$, all the warm gas in low-mass systems like spiral galaxies has converted into stars, which may explain the observational facts listed above including the small gas fraction of the Milky Way required to explain the reported soft X-ray component if it indeed has the Galactic origin.

The present prediction of the X-ray background from the Galactic halo is subject to several uncertainties. The major problem perhaps arises from the unknown distribution of the gas around the Galaxy. We adopt an oversimplified model in which gas traces dark matter. The latter has the form of the so-called isothermal profile with a finite core radius. As a result, the gas density profile varies as r^{-2} at large radii. If the Galactic halo is instead described by the universal density profile as suggested by numerical simulations (Navarro, Frenk & White 1995), the asymptotic behavior of the gas at large radii under the gas-traces-mass assumption would decrease much faster. Recall that the X-ray emission is very sensitive to the structure of the gas. This may lead to a significant modification to our current prediction of the X-ray halo. Another uncertainty is the extensions of the Galactic halo and the associated gas. We have arbitrarily truncated the halo at $r_{\rm out} = 200$ kpc. This may be a reasonable approximation for the dark halo, but whether or not the putative gas is entirely confined within the Galactic halo remains unclear. The question is further complicated if absorption effect is included. Our computation without the consideration of absorption demonstrates a significant soft X-ray emission in the direction of the Galactic center, implying that a measurement of the multiple components at soft energy band may help to disentangle the Galactic X-ray background from the extragalactic one. However, this is possible only after a thorough, quantitative analysis of the absorption due to neutral hydrogen gas of our Galaxy is made.

Generally speaking, the X-ray emission from the warm gas associated with the Galactic halo can account for the recent findings of the spatially variable soft component by Kuntz et al. (2001), provided that the gas fraction is significantly smaller than the universal value. The latter is, nevertheless, consistent with a number of independent observational and theoretical constraints established on massive scales. An immediate consequence is that such an X-ray background produced by the Galactic halo is comparable to, or even exceeds that predicted by the warm-hot gas in groups and clusters which are further embedded in large-scale structures of the Universe. This may constitute the major source of contamination in the search for the missing baryons through the detection of their soft X-ray emission. However, one should in principle be able to remove the contribution of the X-ray halo of our Galaxy if the spatially variable pattern of the X-ray background can be precisely measured.

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