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Expectation for the X-ray Galactic Halo

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Abstract We present an estimate of the strength and spectrum of the X-ray background from the warm gas associated with the Galactic halo. This investigation is motivated primarily by the recent detection of a spatially variable soft X-ray component towards the north Galactic polar cap by Kuntz et al. (2001), suggesting that the warm gas heated by gravitational shocks of the Galactic halo may produce a significant contribution to the soft X-ray sky. Another purpose of the study is to refine the recent theoretical prediction of the X-ray spectrum from the Galactic halo by Xue (2001) who adopted an ideal and simple isothermal model for the gas and dark matter distributions of the Galactic halo. We use the universal density profile for the dark matter distributions of the Galactic halo to evaluate the X-ray properties of the warm gas either in hydrostatic equilibrium with, or tracing the underlying gravitational potential of the Galaxy. It has been shown that our prediction is consistent with the measured soft X-ray component towards the north Galactic polar cap if the gas fraction is taken to be ~ 0.005.

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

1 INTRODUCTION

In the hierarchical clustering model, massive objects form by gravitational aggregation of lower-mass objects, and the disks in spiral galaxies like our Galaxy form by a late accretion of gas from an extended reservoir around the galactic halos. According to this scenario, spiral galaxies are still growing at present.

At the virial temperature of galactic halos, $T \sim 10^5 - 10^6\,\mathrm{K}$, the dominant cooling mechanism is X-ray bremsstrahlung. If the cooling rate is significant, the flux may be visible as a component of diffuse X-ray emission extending well beyond the optical radius of the galaxy. Yet, the question is: is the X-ray emission produced by the warm gas associated with galactic halos observable with current detectors? A particularly interesting question is: can we see the diffuse X-ray background from the Milk Way? Recently, Kuntz et al. (2001) have obtained the spectrum of the soft X-ray background in the 0.1–1.0 keV band towards the north Galactic

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polar cap from the ROSAT All-Sky Survey. When the contribution of unresolved Galactic stars, unresolved extragalactic point sources and the Local Hot Bubble are removed, two components still remained: a spatially non-uniform soft component and a uniform hard component. The former may have a Galactic origin while the latter is most likely due to extragalactic emission. The detection of the X-ray Galactic halo, if confirmed, would be of significance for testing the theories of galaxy formation. Moreover, this may help to resolve the puzzle of missing baryons in the universe.

Using a simple, isothermal model for the Galactic halo, Xue (2001) recently made an estimate of the strength and spectrum of the X-ray emission from the warm gas associated with the Galactic halo, and found that the non-uniform soft X-ray component detected by Kuntz et al. (2001) can be naturally explained, provided the gas fraction is as low as ~ 0.01. This last value is significantly smaller than the universal baryon fraction of $f_{\rm b} \sim 0.3$ for a density parameter of $\Omega_{\rm M} = 0.3$. In this paper, we conduct a new calculation of the X-ray emission from the X-ray Galactic halo based on a more realistic model for the dark matter distribution in the halo, namely, the universal density profile (Navarro, Frenk & White 1995; NFW) suggested by high-resolution N-body simulations in different cosmological models. This density profile has a very different asymptotic behavior at large radii (r^{-3}) from the isothermal model (r^{-2}), which may significantly suppress the X-ray emission generated in the outer region. Moreover, both the isothermal and adiabatic models for the Galactic gas will be tested. It is hoped that our new theoretical calculation will be helpful for a better understanding of the origin of the X-ray Galactic halo.

2 THE STRENGTH AND SPECTRUM OF THE X-RAY GALACTIC HALO

We use the NFW profile to describe the dark matter distribution of the Galactic halo

$$\rho_{\rm DM}(r) = \frac{\delta_{\rm c}\rho_{\rm c}}{(r/r_{\rm s})(1+r/r_{\rm s})^2}, \tag{1}$$

where $\delta_{\rm c}$ and $r_{\rm s}$ are the characteristic density and length, and $\rho_{\rm c}$ is the critical density of the universe. We first assume that the gas is dissipationless, and follows the dark matter density profile

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

where $f_{\rm gas}$ is the gas fraction in the Galactic halo. We will consider another situation in which the gas is isothermal and in hydrostatic equilibrium with the NFW potential. In this case, the gas distribution reads (Markino, Sasaki & Suto 1997)

$$\rho_{\rm gas}(r) = \rho_{\rm g0} e^{-27b/2}(1+r/r_{\rm s})^{27b/(2r/r_{\rm s})}, \tag{3}$$

in which

$$b(M) \equiv \frac{8\pi G\mu m_{\rm p}\delta_{\rm c}(M)\rho_{\rm c0}r_{\rm s}^2}{27kT_{\rm X}}. \tag{4}$$

The gas temperature $T_{\rm X}$ can be related with the total galactic mass via the virial theorem (e.g. Bryan et al. 1998)

$$kT = 0.081\ {\rm keV}\ h^{2/3}\left(\frac{\triangle}{200}\right)^{1/3}\left(\frac{M}{10^{12}M_{\odot}}\right)^{2/3}, \tag{5}$$

where $H_0 = 100\ h\ {\rm km\,s^{-1}\ Mpc^{-1}}$ is the Hubble constant, and $\triangle$ is the overdensity of dark matter with respect to the critical density of the universe and will be taken to be 178 in the following computation. The virial radius $R_{\rm vir}$ is defined by $M_{\rm vir} = \frac{4}{3}\pi R_{\rm vir}^3 \bigtriangleup \rho_{\rm c}$. We assume that the virial mass of the Galaxy is $M_{\rm vir} = 10^{12}\ M_{\odot}$, and use the prescription of Navarro, Frenk & White (1997) to specify the parameters $\delta_{\rm c}$ and $r_{\rm s}$ in the NFW profile. Now, the central value $\rho_{\rm g0}$ can be fixed by introducing the gas fraction $f_{\rm gas} = M_{\rm gas}/M$, and

$$M_{\rm gas} = \int_0^{R_{\rm vir}} \rho_{\rm g0} e^{(-27b/2)} \left(1 + \frac{r}{r_{\rm s}}\right)^{27b/(2r/r_{\rm s})} 4\pi r^2 {\rm d}r\,. \qquad (6)$$

The X-ray flux per unit energy per unit solid angle emitted as thermal bremsstrahlung from the warm gas is

$$\frac{dF}{dEd\Omega} = \frac{2^4 e^6}{3\hbar m_{\rm e} c^2} \left(\frac{2\pi kT}{3m_{\rm e}c^2}\right)^{1/2} \mu_{\rm e} g \frac{1}{4\pi} \int n_{\rm e}^2(r) {\rm d}\ell\,, \qquad (7)$$

where the integral is performed along the line of sight ℓ, $n_{\rm e} = \rho_{\rm gas}/\mu_{\rm e} m_{\rm p}$ 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, and $g = \int_{E_1}^{E_2} \overline{g}_{\rm ff}(T, h\nu) e^{-h\nu/kT} {\rm d}(h\nu/kT)$ is the Gaunt factor over the energy range $(E_1,\ E_2)$, and $\overline{g}_{\rm ff}$ is the Gaunt factor of the free-free emission.

For simplicity, we only calculate the X-ray flux distribution seen within the Galactic plane, which exhibits the maximum variation of the X-ray background across the sky. We perform the integral of Equation (7) along the line of sight with the simple geometrical restriction $r^2 = R_0^2 + \ell^2 - 2R_0\ell\cos(\pi - \theta)$, where θ measures the angle in the polar coordinate centered on the sun with $\theta = 0$ in the outward Galactocentric direction to the sun. We truncate the halo at $R_{\rm vir}$, and adopt a gas fraction of $f_{\rm gas} = 0.005$, and we display in Figure 1 the resulting X-ray background at 0.1–2.4 keV versus the viewing angle θ.

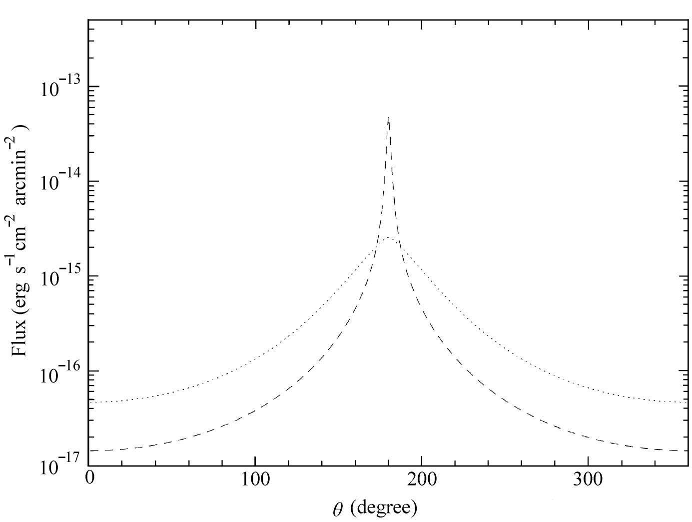

Fig. 1 Expected X-ray background from the warm gas in the Galactic halo in the energy band: 0.1–2.4 keV for the adiabatic (dotted line) and isothermal models (dashed line).

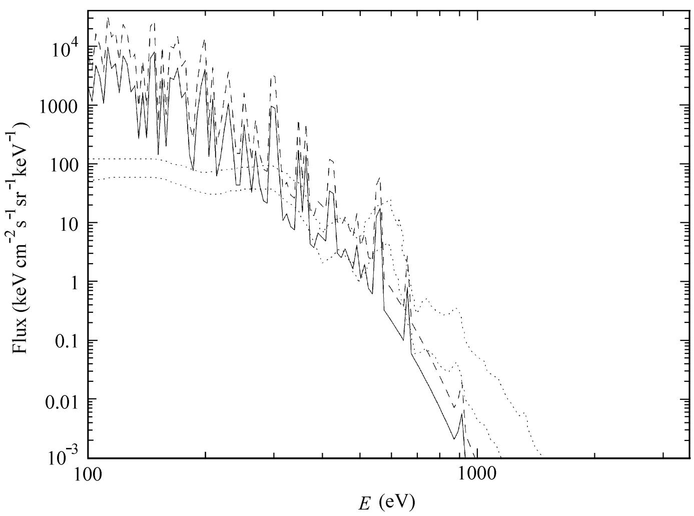

Fig. 2 Soft X-ray background spectra towards the Galactic pole produced by the warm gas in the Galactic halo from the adiabatic (solid line) and isothermal models (dashed line). Dotted lines are the spatially variable soft component detected by Kuntz et al. (2001).

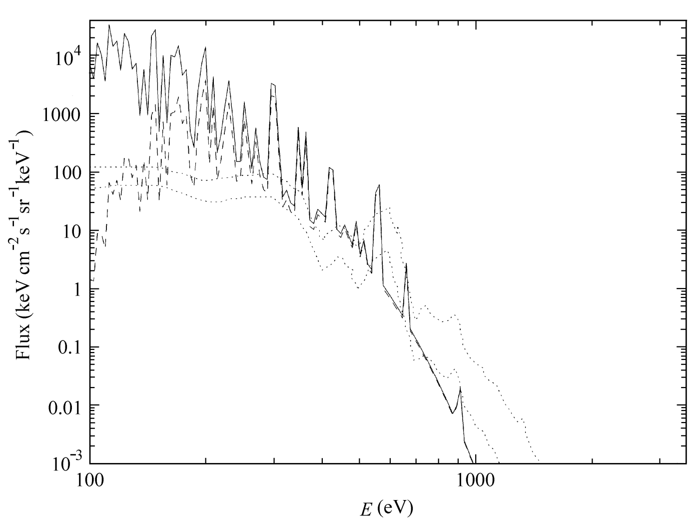

Fig. 3 Soft X-ray background spectra (isothermal models) towards the Galactic pole produced by the warm gas with (dashed line) and without (solid line) the correction for neutral hydrogen gas. Dotted lines are the spatially variable soft component detected by Kuntz et al. (2001).

We then calculate the soft X-ray background spectrum from the Galactic halo towards the Galactic polar cap ($\theta = 90°$) for both the adiabatic and isothermal models, using the Raymond & Smith code (Raymond & Smith 1977). The results are shown in Figure 2, along with the "remaining" soft component observed by Kuntz et al. (2001) after the contributions of unresolved Galactic stars and extragalactic points and the Local Hot Bubble are removed. It is obvious from Figure 2 that the spectra given by the two models are roughly similar to each other. So far, Galactic absorption has not been included. In order to obtain a crude estimate of the effect, we adopt a single value of $N_{\rm H} = 1.5 \times 10^{20}\,{\rm cm}^{-2}$, for the Galactic polar cap, and modify the above estimates by a factor of $e^{-N_{\rm H}\sigma}$. In Figure 3 we compare the two spectra towards the Galactic pole produced by the warm gas in the Galactic halo with and without the absorption by neutral hydrogen gas. It turns out that the absorption effect is significant below 0.2 keV, and the "remaining" soft component detected by Kuntz et al. (2001) is well within our predictions.

3 DISCUSSION AND CONCLUSIONS

In the prevailing model of galaxy formation, spiral galaxies like our own Galaxy are still growing at present. Yet, there is no convincing evidence found so far for the presence of warm gas around galactic halos. Kuntz et al. (2001) have recently detected a spatially variable soft X-ray component towards the north Galactic pole with ROAST All-Sky Survey, and their result seems to favor the Galactic halo origin. In this paper, we have conducted a theoretical investigation of whether the strength and spectrum produced by the warm gas tracing the universal dark halo model can be reconciled with the observational limit. A positive result has been found when the gas fraction is assumed to be $f_{\rm gas} = 0.005$. This last value turns to be even smaller than the requirement of $f_{\rm gas} = 0.01$ claimed by Xue (2001) based on a singular isothermal gas distribution.

However, the present prediction has essentially the same uncertainty as in the discussion by Xue (2001), though we have not used one of their free parameter, the truncated radius. It should also be emphasized that no exotic assumptions for either the dark matter or warm gas distributions have been made in our calculation. Therefore, the consistency between the theoretical prediction and the observational limit may imply an extremely small value of the gas fraction for spiral galaxies. It will be interesting to find whether the remaining gas has been converted into stars or has never collapsed into the shallow gravitational potential of the galaxy.

References

Bryan G. L., Norman M. L., 1998, ApJ, 495, 80
Kuntz K. D., Snowden S. L., Mushotzky R. F., 2001, ApJ, 548, L119
Navarro J. F., Frenk C. S., White S. D. M., 1995, MNRAS, 275, 720 (NFW)
Navarro J. F., Frenk C. S., White S. D. M., 1997, MNRAS, 490, 493
Makino N., Sasaki S., Suto Y., 1998, ApJ, 497, 555
Raymond J. C., Smith B. W., 1977, ApJS, 35, 419
Xue Y. J., 2001, Chin. J. Astron. Astrophs., 1, 5, 383