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MACHOS AND THE DIFFUSE X-RAY BACKGROUND

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ABSTRACT

The possible contribution of X-ray emission from massive compact objects in the Galactic Halo (MACHOs) to the diffuse X-ray background is explored. We show that such emission cannot be responsible for the shadowing seen in soft X-ray observations by *ROSAT*, but that these objects may indeed contribute significantly (at levels $> 10\%$) to the diffuse background at higher ($\gtrsim 0.5$ keV) energies. Thus, X-ray observations may well be able to significantly constrain the spatial distribution of MACHOs.

Subject headings: stars: low-mass – stars: luminosity function, mass function – Galaxy: halo – Galaxy: stellar content – X-rays: general – X-rays: stars – X-rays: ISM

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1. INTRODUCTION

Detection of shadowing of the diffuse soft X-ray background by interstellar clouds beyond the local supernova bubble (Burrows & Mendenhall 1991; Snowden et al. 1991; also see Snowden et al. 1993) has raised the possibility that a major fraction of this diffuse background arises beyond the Local Interstellar Medium. Further, auto-correlation analysis of the photon counts observed in the *ROSAT* PSPC has led to the identification of a non-local, non-QSO component in the diffuse X-ray background (DXBG; Wang & McCray 1993; Carrera & Barcons 1993). The recent detection of gravitational microlensing of stars in the Large Magellanic Cloud (Alcock et al. 1993; Auborg et al. 1993) implying that the Galactic Halo may be composed of MACHOs (MAssive Compact Halo Objects), with a likely mass of $\lesssim 0.12 M_\odot$, suggests a possible new class of sources which can contribute to this component of the DXBG. Hence, we have investigated the possible contribution of X-ray emission from MACHOs to the DXBG: Using a simple model to describe this X-ray emission, we have explored the parameter space of possible MACHO contributions to the X-ray fluxes at Earth in various passbands, and have compared them to observations.

The first question to answer is why we would expect MACHOs to be X-ray–emitting objects. Observations of field stars by *Einstein* and *ROSAT* have shown (Barbera et al. 1993; Fleming et al. 1993) that low-mass stars are also "active," i.e., have coronal emissions (albeit at rather lower levels than those from the Sun) characterized by $L_x(m_*)/m_* \sim 10^{26} - 10^{28}$ergs s^{-1} M$_\odot^{-1}$, where $L_x(m_*)$ is the mean total X-ray luminosity of stars of mass m_* (the contribution from lower-mass objects, such as Jupiter-sized planets is ignorable, due to the low $L_x(m)/m \sim 10^{19} - 10^{20}$ ergs s^{-1} M$_\odot^{-1}$); no dependence of X-ray emission levels on metallicity has been detected to date. To the extent that MACHOs are nothing but rather old, very low-mass, stars, we expect that they should have X-ray coronae. Thus, on the reasonable assumption that MACHOs *are* X-ray sources, we proceed to compute the X-ray flux at Earth from these objects. We describe the model we have adopted in §2, discuss our results in §3, and summarize in §4.

2. MODEL

The X-ray flux at Earth in the energy range $[E, E+dE]$ due to MACHOs at a distance $[r, r+dr]$ from Earth, and in the mass range $[m, m+dm]$ is given by

$$f(E,r,m;l,b)\;dE\;dm\;dr\;d\Omega = \frac{L_x(E,m;Z)}{4\pi r^2}\;e^{-\tau(E,r;l,b)}\;N_0(r;l,b)\phi(m)\;dE\;dm\;dr\;d\Omega\,. \quad (1)$$

Here (l,b) refer to the pointing direction in Galactic coordinates, $d\Omega$ is the solid angle of observation, $L_x(E,m;Z)\;dE$ is the mean total X-ray luminosity of objects of mass m with metallicity Z in the energy range $[E, E+dE]$, $\tau(E,r;l,b) \equiv \sigma_E N_H(r;l,b)$ is the optical depth at energy E, σ_E is the interstellar absorption cross-section at energy E, N_H is the hydrogen column density in the direction (l,b) to distance r, $\phi(m,r;l,b) = \phi(m)$ is the stellar mass function (assumed to be independent of position and direction, and normalized as in Eq. 4 below), and $N_0(r;l,b)$ is the number density of MACHOs, normalized such that

$$N_0(r;l,b) = \frac{\rho(r;l,b)}{\mu} r^2\,. \quad (2)$$

Here $\rho(r;l,b)$ is the mass density of the Galactic Halo, and μ is the mean MACHO mass, where

$$\mu \equiv \int_{m_{\rm min}}^{m_{\rm max}} m\;\phi(m)\;dm\;, \qquad \int_{m_{\rm min}}^{m_{\rm max}} \phi(m)\;dm\; = 1\,. \quad (3)$$

The X-ray flux in a given passband is then computed by adopting a specific mechanism for the stellar X-ray emission of MACHOS and a specific model for the Milky Way halo mass distribution. Here, we assume that all X-ray emission due to MACHOs arises as a result of optically thin thermal emission (Raymond & Smith 1977; Raymond 1988) from coronal plasma at temperatures $> 10^6$ K (see Drake 1992). Consequently, the total X-ray flux at Earth per unit solid angle, in the passband $(E_1 - E_2)$, due to MACHOs in the direction (l,b) is

$$f_x(E_1 - E_2, l, b) = \frac{1}{4\pi\mu}\int_0^{r_{\rm max}} dr \int_{m_{\rm min}}^{m_{\rm max}} dm \int_{E_1}^{E_2} dE\; e^{-\tau(E,r;l,b)}\;L_x(E,m;Z)\;\phi(m)\;\rho(r;l,b)\,. \quad (4)$$

Here we have parametrized the MACHO X-ray luminosity by the relative stellar metal abundance, i.e., $L_x(E, m; Z)\, dE$ is the mean X-ray luminosity of MACHOs of mass m and relative metal abundance Z, in the energy range $[E, E + dE]$; in the following, we shall use $Z = 10^{-2}\, Z_\odot$ unless otherwise stated.[1]

In the following, it will prove to be useful to define the mean X-ray luminosity of MACHOs,

$$\mathcal{L} \equiv \int_{m_{\rm min}}^{m_{\rm max}} dm \int_0^\infty dE\ L_x(E, m; Z)\ \phi(m)\ . \tag{5}$$

Note that in the context of our model for stellar X-ray emission, we have assumed (as discussed above) that the energy input necessary to heat these stellar coronae is independent of Z. Now, the flux computed toward a given direction varies linearly as the X-ray luminosity per unit mass of the Halo, $\mathcal{L}/\mu$, which unfortunately is the least well-determined of the parameters in Eq. (5). We therefore compute the X-ray fluxes for a range of Halo model parameters and plasma temperatures by adopting a nominal value for $\mathcal{L}/\mu = 10^{27}$ ergs s^{-1} M$_\odot^{-1}$ (obtained by assuming that the Halo is composed entirely of objects of mass $m = 0.1$ M$_\odot$ and $L_x(m) = 10^{26}$ ergs s^{-1}), and later scaling the flux to match the possible range of $\mathcal{L}/\mu$. More complicated models for both $\phi(m)$ and $L_x(m)$ can be constructed, and are found to result in values of $\mathcal{L}/\mu$ ranging from $\sim 2 \times 10^{28}$ to $\sim 10^{25}$ ergs s^{-1} M$_\odot^{-1}$. The higher values result from models where power-law forms of the mass function $\phi(m)$ extend

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[1] Emission from bound-bound and free-bound transitions dominate stellar coronal X-ray emission at $T \lesssim 10^{7.5}$ K (Raymond & Smith 1977), and is therefore sensitive to metallicity. Although we take this effect into account, we ignore metallicity effects in the outer layers of stellar convection zones (D'Antona 1987; Burrows et al. 1993; Dearborn 1994; Saumon et al. 1994), especially as they impact photospheric magnetic field dynamics. Indeed, it seems that the most scientifically productive course may be to turn the argument around, and to use observations of very low metallicity stars as a probe of the physics of energy transmission to stellar coronae.

to $m \approx 1$, and $L_x(m)$ is allowed to vary, increasing from $L_x(0.1) \sim 10^{26}$ to $L_x(1) \sim 10^{28}$ ergs s^{-1}; the lower values result from extending the range of the initial mass function to very small masses without simultaneously extending $L_x(m)$ over the same range. Since we cannot further constrain the value of $\mathcal{L}/\mu$ at this point, we adopt the values quoted above as realistic bounds on the ratio.

We use a piecewise polynomial fit to the interstellar absorption cross-section (Morrison & McCammon 1983) to compute σ_E, and a 3-component model of the distribution of neutral and molecular Hydrogen in the Galaxy (Bloemen 1987; Kashyap et al. 1992) to compute the absorption column density N_H along a given line-of-sight.

Finally, for definiteness, we adopt a mass density for the Halo consistent with the observed rotation curve of the Galaxy (Bahcall, Schmidt, & Soneira 1982),

$$\rho(R) = \rho(R_\odot)\frac{a^{1.2} + R_\odot^{1.2}}{a^{1.2} + R^{1.2}}(R/R_s)^\gamma\,, \tag{6}$$

where R is the distance from the Galactic Center, $\gamma = 0$ for $R \leq R_s$ and $\gamma = -1.5$ for $R > R_s$, $R_\odot = 8.5$ kpc is the distance of the Sun from the Galactic Center, $\rho(R_\odot) \sim 0.013$ $\mathrm{M}_\odot$ pc^{-3} is the Halo mass density in the Solar neighborhood, $a \sim 2$ kpc is the core radius, and $R_s \sim 30$ kpc is the distance beyond which the mass density falls as $R^{-2.7}$. This model for the Halo mass density predicts a total mass of $\sim 2.5 \times 10^{12}$ $\mathrm{M}_\odot$ within 100 kpc, consistent with current measurements (Ashman 1992). However, both the total Halo mass as well as the actual mass distribution are poorly determined. Hence, we compute fluxes for a variety of values of the model parameters (see Table 1) in order to explore the sensitivity of our results to the Halo mass distribution. The models are arranged in the order of a highly centrally condensed low-mass halo to a diffuse high-mass halo.

The X-ray flux at Earth in a specific passband due to MACHOs is then obtained by integrating Eq. (5) numerically to $r = 100$ kpc in a nominal direction $(l, b) = (90^o, 45^o)$; our studies indicate that at high latitudes, i.e., far from the plane of the Galaxy, the modulation in the flux at Earth due to a latitudinal variation in the absorption column density is much less than an order of magnitude even for fluxes in the low energy (0.15-0.28 keV) passband.

3. RESULTS

3.1 C Band (0.15–0.28 keV)

The observed count rates in the *ROSAT* PSPC in the C band (0.15 - 0.28 keV; "1/4" keV) due to emission originating beyond the local interstellar medium (Burrows & Mendenhall 1991; Snowden et al. 1991; Snowden et al. 1993) lie in the range $6 - 30 \times 10^{-4}$ ct s^{-1} $arcmin^{-2}$. We find that only under rather optimistic circumstances does the X-ray flux due to MACHOs form a significant fraction of the observed flux (cf. Figure 1a). For example, for standard galactic absorption characteristics, it is only at values of $\mathcal{L}/\mu \sim 10^{30}$ ergs s^{-1} $M_\odot^{-1}$ that the flux due to MACHOs approach the observed flux; such large values of $\mathcal{L}/\mu$ are physically unjustifiable (see above). Similarly, if the MACHO X-ray flux is minimally absorbed (for example, if the ISM is extensively clumped), then more plausible values of $\mathcal{L}/\mu$ (down to 10^{28} ergs s^{-1} $M_\odot^{-1}$) will account for a substantial portion of the C-band DXBG; however, the magnitude of the clumping necessary for this to occur (cloud column densities $\gtrsim 10^{20}$ cm^{-2}) appears to be very unlikely (Jacobsen & Kahn 1986; Diamond et al. 1989). We therefore rule out MACHOs as a significant contributor to the non-local C-band DXBG.

3.2 M Band (0.5–0.9 keV)

Auto-correlation analyses of photon distributions in deep *ROSAT* PSPC exposures (Wang & McCray 1993; Carrera & Barcons 1993) show that $\sim 40\%$ of the total diffuse flux in the M band (0.5 - 0.9 keV; "3/4" keV) is due to a diffuse thermal component at a temperature of $2.2^{+0.6}_{-0.4} \times 10^6$ K (or from point sources with similar emission characteristics, and with a surface density $> 10^4$ deg^{-2}, as is consistent for Halo objects), and that the contribution from QSOs can be at most 60%. We now show (cf. Figure 1b) that X-ray emission from MACHOs could account for this difference. The count rate in the PSPC in the M band due to the residual background (Snowden et al. 1993; Wang & McCray 1993) is $\approx 10^{-4}$ ct s^{-1} $arcmin^{-2}$, and the expected MACHO flux would be 4×10^{-5} ct s^{-1} $arcmin^{-2}$. We find that at the suggested temperature, the plausible MACHO flux lies in the range $\sim 1-3 \times 10^{-6}$ ct s^{-1} $arcmin^{-2}$ for the nominal $\mathcal{L}/\mu$ value of 10^{27} ergs s^{-1} $M_{\odot}^{-1}$. Thus, the range of MACHO X-ray fluxes allowed by the variation in $\mathcal{L}/\mu$ lies within the range of diffuse flux levels which must be contributed by a non-QSO source (or sources).

This conclusion is not changed if the X-ray emission arises from plasma at a higher temperature ($T > 10^7$ K), or if MACHOs can be characterized by *two* dominant emission components at two different temperatures; in all these cases, we find that the X-ray flux at Earth is not significantly changed. Finally, we need to know how these results depend upon the assumed metal abundances. If the abundances in the emitting plasma are identical to solar abundances, we find that the M-band fluxes can be enhanced by factors of $2-5$ for temperatures T below $\sim 10^7$ K; indeed, at $T \sim 4 \times 10^6$ K, the MACHO flux for the nominal Halo model (# 3; cf. Table 1) is 10% of the observed total diffuse flux in the M-band. On the other hand, if the assumed metal abundances are much smaller than $Z_{\odot}$, then the atomic line and continuum contributions become negligible, but the MACHO X-ray flux remains similar in magnitude (in this passband) to the corresponding flux for the $Z = 10^{-2} Z_{\odot}$ case. We therefore conclude that MACHOs can constitute a very significant component of the DXBG in the M band — they could well constitute the entire non-QSO portion of the M-band DXBG.

3.3 H Band (2–6 keV)

Rocket observations (McCammon et al. 1983) of the X-ray sky in the H band (2-6 keV) show the existence of diffuse isotropic emission well-characterized by a photon spectrum of the form $11E^{-1.4}$ ph s^{-1} cm^{-2} keV^{-1} sr^{-1}, corresponding to an average all-sky flux $\sim 1.3 \times 10^{-11}$ ergs s^{-1} cm^{-2} deg^{-2}. As above, we computed the X-ray flux from MACHOs in this passband for various plasma temperatures, mass distributions, and metal abundances (Figure 1c). For the nominal value of $\mathcal{L}/\mu \sim 10^{27}$ ergs s^{-1} M$_\odot^{-1}$, the H-band flux contributed by MACHOs constitutes $\approx 1-5\%$ of the total diffuse flux in this passband at high temperatures ($\gg 10^7$ K), and hence may constitute a significant component of the residual H-band flux for larger values of $\mathcal{L}/\mu$. However, at lower plasma temperatures ($T < 10^7$ K), the MACHO X-ray flux contribution is miniscule, as is expected from the nature of the thermal spectrum. These results are not sensitive to the adopted metal abundances for a fixed value of $\mathcal{L}/\mu$, unlike the case of the M band: At lower temperatures ($T < 10^7$ K), where the fractional luminosity in the H band is low due to the large line emission contribution in the M band, the MACHO X-ray flux is insignificant, while at higher temperatures ($T > 10^7$ K) line emission contributions are smaller.

4. SUMMARY

In summary, we find that a significant contribution by MACHOs to the DXBG is possible in either the M (0.5-0.9 keV) or the H (2-6 keV) X-ray passbands. (Results in other high energy passbands such as the J band [1.15 - 2 keV] are similar to that in the H band: A flux $\sim 1-3 \times 10^{-13}$ ergs s^{-1} cm^{-2} deg^{-2} is obtained for the plausible halo mass models [$\mathcal{L}/\mu = 10^{27}$ ergs s^{-1} M$_\odot^{-1}$], which forms $\sim 5-10\%$ of the DXBG flux in the J band; cf. McCammon et al. 1983.) Since the temperature structure of the emitting plasma is likely to be complex, we cannot rule out the possibility that MACHOs can contribute significantly in all high energy passbands simultaneously. In contrast, the likely contribution of MACHOs to the DXBG in the C (0.15-0.28 keV) passband is very small, and hence these objects cannot be the originators of the non-local soft X-ray flux detected with *ROSAT*.

Can X-ray observations by *ROSAT*, *ASCA* or the forthcoming *AXAF* constrain the parameters in Eq. (5) better? First, we note that systematic observations of low-metallicity low-mass stars would certainly allow better estimates of the stellar X-ray luminosity function as a function of stellar mass. Second, more extensive searches for X-ray shadowing in various passbands by interstellar clouds at various distances would lead to a better understanding of the contribution of the non-local flux comprising the DXBG, and hence place direct limits on $f_x(E_1 - E_2, l, b)$. Finally, we note that if MACHOs are a new class of X-ray sources, then they would also contribute to the X-ray emission of other galaxies. In this case, Eq. (5) can be modified to predict the X-ray flux from a spheroidal MACHO distribution around a distant galaxy: The flux at Earth from a spheroidal MACHO component is then

$$f_{x_H} \approx 1.3 \times 10^{-13} \left(\frac{\alpha}{0.5}\right) \left(\frac{\mathcal{L}/\mu}{10^{27}\ \mathrm{ergs\ s^{-1}\ M_\odot^{-1}}}\right) \left(\frac{\rho_H}{0.01\ \mathrm{M_\odot\ pc^{-3}}}\right) \left(\frac{\Delta r}{10\ \mathrm{kpc}}\right) \mathrm{ergs\ s^{-1}\ cm^{-2}\ deg^{-2}},$$

where α is a correction factor (< 1) which takes into account both the finite bandpass and attenuation due to absorption, ρ_H is the mass density, and Δr is the effective pathlength through the spheroid. Thus, the surface brightness of the MACHO component for nominal values of the model parameters is more than 5% of the total diffuse flux in the M band ($\alpha \approx 0.225$, predicted $f_{x_H} \sim 6 \times 10^{-6}$ ct s^{-1} arcmin^{-2} for *ROSAT*), and about 1% of the total flux in the H band. Thus, a careful analysis of the large-scale variation in X-ray surface brightness *around* a relatively isolated galaxy may allow the detection of (or an upper limit on) this excess flux due to MACHOs; and can therefore also directly constrain the spatial distribution of MACHOs in such galaxies.

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TABLE 1

Halo Model Parameters

Model	$\rho_\odot$ [$M_\odot$ pc^{-3}]	a [kpc]	R_s [kpc]	Halo Mass [$M_\odot$]
1	0.001	0.1	10	4.3×10^{10}
2	0.013	2	10	6.8×10^{11}
3	0.013	2	30	2.5×10^{12}
4	0.025	2	30	4.8×10^{12}
5	0.03	5	50	1.2×10^{13}

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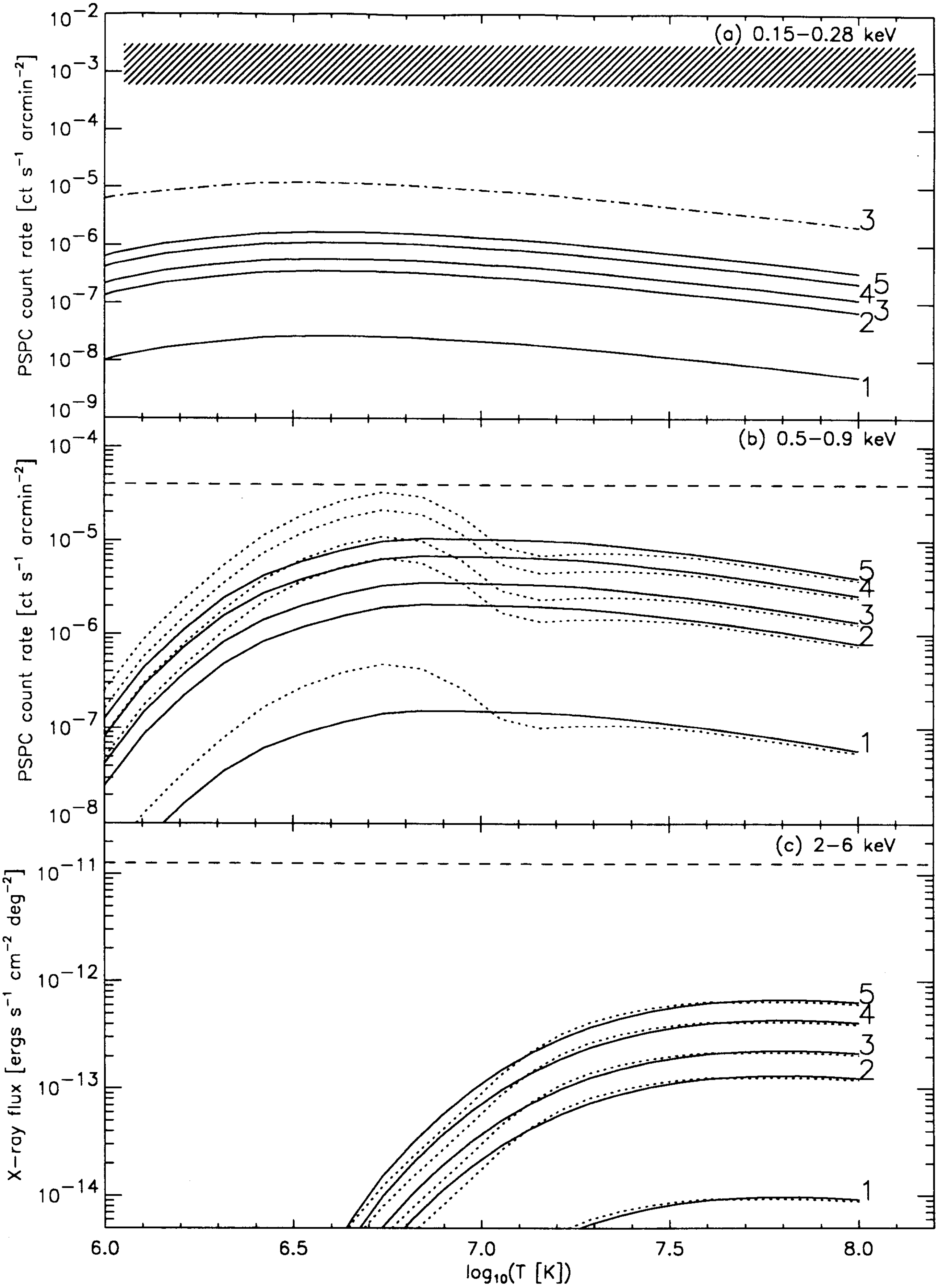
Figure Captions

Figure 1 : The X-ray flux at Earth due to MACHOs for various Galactic halo mass distributions and coronal plasma temperatures. The solid lines denote the fluxes computed using $Z = 10^{-2} Z_{\odot}$; dotted curves in panels (b) and (c) are fluxes for $Z = Z_{\odot}$. The different Halo mass distributions used are identified by the corresponding model number in Table 1; note that fluxes at a given temperature increase monotonically with model number. All curves are characterized by $\mathcal{L}/\mu = 10^{27}$ ergs s^{-1} M$_{\odot}^{-1}$, while possible values for $\mathcal{L}/\mu$ lie in the range 10^{26} - 2×10^{28} ergs s^{-1} M$_{\odot}^{-1}$ (see §2).

a) The count rates expected in the *ROSAT* PSPC in the C (0.15-0.28 keV) passband. The dash-dotted line corresponds to fluxes computed assuming no absorption for Halo model 3. Some labels are offset for clarity. The shaded region represents the range of count rates estimated for the non-local component of the C-band DXBG. We have used a constant energy-to-count conversion factor (*ecf*) of 3×10^{-12} ergs cm^{-2} ct^{-1} for all temperatures.

b) The count rates expected in the *ROSAT* PSPC in the M (0.5-0.9 keV) passband. For a given Halo model, the fluxes computed with the two abundances are nearly identical at high temperatures. The horizontal dashed line represents 40% of the total diffuse flux in the M band. We have used an *ecf* of 8×10^{-12} ergs cm^{-2} ct^{-1} in all cases.

c) The X-ray flux at Earth in the H (2-6 keV) passband. The flux values obtained for the different abundances are nearly identical for a given mass distribution. The horizontal dashed line represents the total diffuse flux observed in this band.


(a) 0.15–0.28 keV
PSPC count rate [ct s^{-1} arcmin^{-2}]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
3
5
4
3
2
1
(b) 0.5–0.9 keV
PSPC count rate [ct s^{-1} arcmin^{-2}]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
5
4
3
2
1
(c) 2–6 keV
X-ray flux [ergs s^{-1} cm^{-2} deg^{-2}]
10^{-11}
10^{-12}
10^{-13}
10^{-14}
5
4
3
2
1
6.0
6.5
7.0
7.5
8.0
$\log_{10}$(T [K])