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THE FEASIBILITY OF DETECTING X-RAY HALOS DUE TO INTERGALACTIC "COSMOLOGICAL" GRAY DUST

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ABSTRACT

Extinction due to large-diameter intergalactic gray (i.e., nonreddening) dust grains has been identified as a possible mechanism to explain the apparent systematic dimming of high-redshift Type Ia supernovae, an alternative hypothesis to the interpretation of this dimming as evidence of acceleration in the cosmological expansion of the universe. Detection of such dust grains could be achieved, in principle, through observations of the X-ray scattering halos surrounding high-redshift X-ray sources, produced by the intervening dust. I have calculated the expected intensity of such X-ray halos, as well as the halo intensity expected to result from Galactic dust; I find that the cosmological dust halo would be too faint to detect with current X-ray telescopes.

Subject headings: cosmology: observations — dust, extinction — X-rays: ISM

1. INTRODUCTION

The apparent systematic dimming of distant ($z \sim 0.5$) Type Ia supernovae (SNe Ia) has been interpreted as evidence of acceleration in the cosmological expansion of the universe (Riess et al. 1998; Perlmutter et al. 1999). A possible alternative mechanism to explain this dimming is extinction due to intergalactic dust (Aguirre 1999); such dust would necessarily have a shallow opacity curve, so as not to cause a significant reddening in the observed SN spectra. The requisite "gray" dust, consisting of large-diameter (>0.1 μm) grains, or perhaps needles, as discussed in detail by Aguirre (1999), plausibly could have been expelled from galaxies beginning at $z = 3$ and would have filled intergalactic space by $z = 0.5$. As discussed by Aguirre, the density of dust (i.e., the mass density relative to the critical density) required to explain the observed SN Ia extinction, e.g., ~0.2 mag at $z = 0.7$, is $\Omega_{\rm dust}$ approximately a few times 10^{-5}. Although the recent observation by Riess et al. (2001) of an SN Ia at $z = 1.7$ is evidently inconsistent with the gray dust hypothesis, I discuss here nevertheless a possible method for detecting such dust, should it exist.

Methods recently discussed for potentially detecting intergalactic dust, either through observations of the far-infrared background (Aguirre & Haiman 2000) or from extinction measurements in the X-ray versus optical spectra of gamma-ray burst afterglows (Perna & Aguirre 2000), have not yet yielded any conclusive results. In contrast, the detection of *interstellar* dust grains has been inferred directly from observations made over the past two decades of X-ray scattering halos in both Galactic and extragalactic sources (Rolf 1983; Catura 1983; Bode et al. 1985; Mauche & Gorenstein 1986, 1989; Gallagher, Cash, & Green 1995; Predehl et al. 1991; Mathis et al. 1995; Woo et al. 1994; Predehl & Schmitt 1995; Witt, Smith, & Dwek 2001). Thus, the possible detection of X-ray halos in high-redshift X-ray sources could be attributed, in principle, to intergalactic dust grains. To estimate the feasibility of such observations, I have calculated numerically the expected halo intensity, assuming the dust density necessary to explain the apparent dimming observed in SNe I, as well as the additional halo intensity expected from Galactic dust. I present below my methods, results, and conclusions.

2. METHODS

X-ray scattering halo intensities were computed following the same general methods described in detail in Windt, Cash, & Kahn (2000): following Mauche & Gorenstein (1986), I use the Rayleigh-Gans (RG) approximation for the differential scattering cross section

$$\frac{d\sigma_{\rm sca}(\theta_{\rm sca})}{d\Omega} = c_1 \left(\frac{2Z}{M}\right)^2 \left(\frac{\rho}{3\ {\rm g\ cm^{-3}}}\right)^2 a(\mu{\rm m})^6 \left[\frac{F(E)}{Z}\right]^2 \Phi^2(\theta_{\rm sca}), \tag{1}$$

where $c_1 = 1.1\ {\rm cm^2\ sr^{-1}} = 2.6 \times 10^{-11}\ {\rm cm^2\ arcsec^{-2}}$, Z is the mean atomic charge, M is the mean molecular weight (in atomic mass units), ρ is the grain mass density, $F(E) = |f_1 + if_2|$ is the grain atomic scattering factor at energy E (Henke, Gullikson, & Davis 1993), and $\Phi(\theta_{\rm sca})$ is the "form factor" to be discussed below. As discussed by Smith & Dwek (1998), as a rule of thumb the RG approximation is valid only if the photon energy in keV is significantly larger than the dust grain radius in microns, for grains of normal composition (i.e., graphite, silicates, etc.). I thus consider below the scattering of X-rays having energies above 1 keV, by graphite dust grains having radii less than 0.25 μm.

The form factor in equation (1) contains the information relating the geometrical shape of the dust grain to the angular distribution of scattered light. Previous investigations of X-ray scattering halos typically have used the form factor for spherical grains, given by

$$\Phi(\theta_{\rm sca}) = 3(\sin u - u\cos u)/u^3, \tag{2}$$

where

$$u \equiv 2\pi a\theta_{\rm sca}E/hc = 1.474 a_{\mu{\rm m}}\theta_{\rm arcmin}E_{\rm keV}/(1-x), \tag{3}$$

and x is the fractional distance to the source, with $0 < x < 1$; the observation angle is related to the scattering angle by $\theta = (1-x)\theta_{\rm sca}$. Here I consider the specific model for intergalactic dust that could explain the observed SN Ia results described by Aguirre (1999), consisting of graphite needles of diameter $d \leqslant 0.25\ \mu$m having aspect ratios in the range $4 < L/d < 32$, in which case the form factor for scattering from a finite cylinder is appropriate. The cylindrical form factor is considerably more complicated than the form factor for spherical grains, having a three-dimensional dependence on both the incidence and scattering angle of X-rays relative to the orientation of the cylinder (Bohren & Huffman 1983). However, the integrated X-ray halo brightness is only weakly dependent on the specific form factor used, and so for the purposes of estimating the halo visibility, I simply use the form factor applicable to the case when the incidence and scattering angles are both normal to the cylinder axis:

$$\Phi(\theta_{\rm sca}) = 2J_1(u)/u, \qquad (4)$$

where J_1 is the Bessel function of the first kind of order 1. Furthermore, as it turns out, comparisons made using both the spherical and cylindrical form factors (eqs. [2] and [4]) reveal that the resulting differences are essentially insignificant, particularly in light of the conclusions presented below.

In the case of scattering from interstellar dust, the halo surface brightness (assuming only single scattering events, as per the discussion in Windt et al. 2000) at an observation angle θ is determined from the scattering cross section using

$$I_{\rm sca}(\theta) = F_{\rm X} N_{\rm H} \int dE\, S(E) \int da\, n(a) \int dx\, f(x)(1-x)^{-2} \times \left[\frac{d\sigma_{\rm sca}(a, E, \theta, x)}{d\Omega}\right], \qquad (5)$$

where $F_{\rm X}$ is the observed source flux (in units of photons $\rm cm^{-2}\ s^{-1}$), $N_{\rm H}$ is the column density of hydrogen (in all forms), $S(E)$ is the (normalized) photon energy of the source, $n(a)da$ is the number of grains (per H atom) with radii between a and $a + da$, and $f(x)$ is the (normalized) distribution of hydrogen along the line of sight to the source. Equation (5) as written was used to compute the Galactic halo brightness surrounding a high-redshift X-ray source, assuming (1) the grain distribution of Mathis, Rumpl, & Nordsieck (1977), i.e., a power-law distribution of graphite and silicate grains with diameters in the range of 0.005–0.25 μm, and (2) the spatial distribution of Galactic gas and dust given by Mauche & Gorenstein (1986), where the gas density is constant in planes parallel to the galactic plane and decreases exponentially outward with a scale height of 100 pc, with the density along the line of sight to an object located a distance D (in kiloparsecs) at a galactic latitude b given by $\rho(x) = \rho_0 \exp[-10xD({\rm kpc}) \sin b]$; the function $f(x)$ in equation (5) is then $f(x) = \rho(x)/\int_{x=0}^{x=1} \rho(x)dx$.

In order to compute the halo brightness due to intergalactic dust grains, the quantity $N_{\rm H} n(a)da$ in equation (5) must be replaced by the column density of dust grains along the line of sight to the high-redshift X-ray source. The column density of grains out to some distance r is

$$N_{\rm dust} = \int_0^r \frac{\rho_{\rm dust}(r)}{M_{\rm grain}}\, dr, \qquad (6)$$

where $M_{\rm grain} = \rho_{\rm grain}\pi L d^2/4$ is the mass of a single grain of density $\rho_{\rm grain}$, and the mass density of grains as a function of r is related to the cosmological dust density $\Omega(r)$ by

$$\rho_{\rm dust}(r) = \frac{3H_0^2}{8\pi G}\,\Omega(r). \qquad (7)$$

For simplicity, I take the case of an Einstein–de Sitter (flat) universe to relate distance r to redshift z:

$$r(z) = \frac{2c}{H_0}\left(1 - \frac{1}{\sqrt{1+z}}\right). \qquad (8)$$

Adopting the specific model described by Aguirre (1999), I consider a distribution of dust that is constant out to $z = 0.5$ and then drops linearly with distance to 0 at $z = 3$:

$$\Omega(r) = \begin{cases} \Omega_{\rm dust}, & 0 \le z \le 0.5, \\ \Omega_{\rm dust}\left[\dfrac{r(3) - r(z)}{r(3) - r(0.5)}\right], & 0.5 < z \le 3. \end{cases} \qquad (9)$$

Taking $H_0 = 65\ \rm km\ s^{-1}\ Mpc^{-1}$, the column density of grains out to some redshift z is thus

$$N_{\rm dust}(z) = 0.29\,\frac{\Omega(z)}{\rho_{\rm grain} L d^2}\left(1 - \frac{1}{\sqrt{1+z}}\right). \qquad (10)$$

Furthermore, the function $f(x)$ in equation (5) is now given by

$$f(x) = \frac{\Omega(x)}{\int_{x=0}^{x=1} \Omega(x)dx},$$

with x, the fractional distance to the source, determined for a source at redshift z using equation (8).

3. RESULTS

The expected X-ray halo brightness versus observation angle is shown in Figure 1*a* for the case of graphite dust grains ($\rho = 2.3\ \rm g\ cm^{-3}$) of diameter $d = 0.1\ \mu$m (with $L/d = 5$) distributed as per equation (9) with $\Omega_{\rm dust} = 4.5 \times 10^{-5}$, for sources located at redshifts $z = 1$, 2, 3, and 4, with monoenergetic X-rays $E = 1$, 3, and 10 keV. As expected, the halo "diameter," i.e., as defined qualitatively by the "shoulder" in the brightness curve, increases with decreasing X-ray energy, from ~100″ for $E = 10$ keV to ~400″ for $E = 3$ keV to ~1000″ for $E = 1$ keV. The overall halo brightness decreases both with increasing energy and (weakly) with redshift. The brightness is small in all cases: even very close to the source, at an observation angle of ~1″, for example, the brightness is at most ~10^{-7} relative to the source flux. The integrated brightness curves (i.e., as would be obtained by summing azimuthally a two-dimensional image) are shown in Figure 1*b*, and the total halo intensities (i.e., integrated over both dimensions) are listed: the integrated intensity is only ~0.05% of the source flux, even in the most favorable case—$E = 1$ keV, $z = 1$—and is as small as ~3×10^{-6} of the source flux when $E = 10$ keV, $z = 4$. Although omitted here for brevity, comparable results were obtained in cases with grain diameters as large as 0.25 μm and larger aspect ratios; indeed, the precise halo profile depends on the details of the grain shape (and scattering form factor, as discussed above), but the peak and integrated brightness values are relatively insensitive to these parameters and scale simply with the cosmological dust density Ω.

To estimate the feasibility of detecting such a halo with one of the current generation of X-ray observatories (e.g., *Chandra*), I compare the results just presented with an estimate of the minimum detectable halo brightness, in the case of a bright, distant X-ray source. Taking the optimistic case of an active galactic nucleus (AGN) at $z = 1$ having a luminosity of

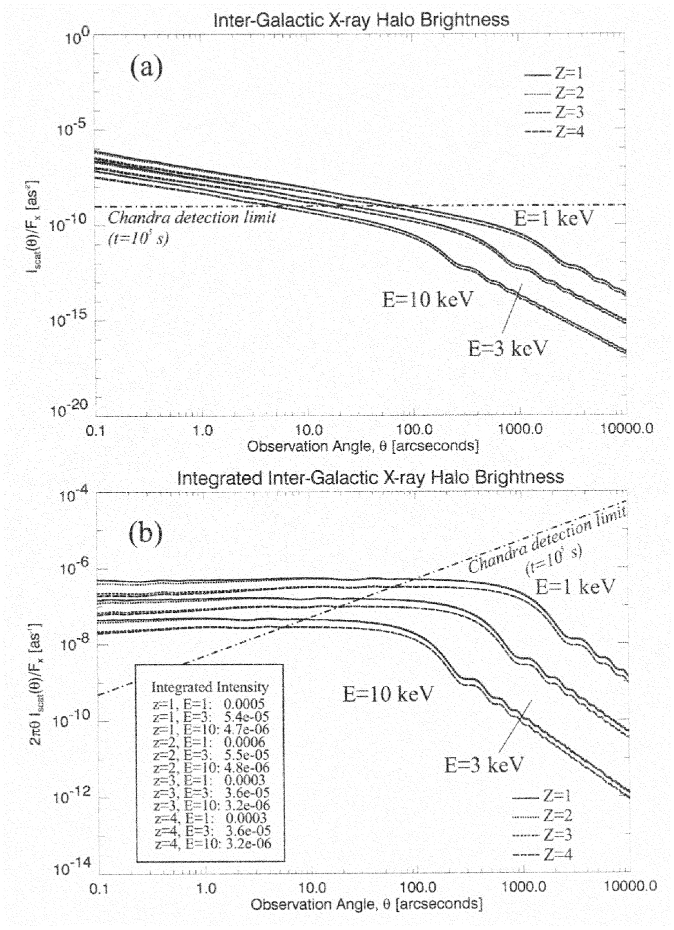

FIG. 1.—(*a*) X-ray halo brightness due to intergalactic "cosmological" gray dust, as a function of observation angle θ, for X-ray energies $E = 1$, 3, and 10 keV and source redshifts $z = 1$, 2, 3, and 4 as indicated. The dust grain parameters used for this calculation are discussed in the text. (*b*) Integrated X-ray halo brightness vs. observation angle. The total integrated halo intensities (relative to the source flux) are listed. The lines marked "*Chandra* detection limit ($t = 10^5$ s)" in both figures correspond to the minimum detectable halo brightness for the case of a bright AGN at $z = 1$, as described in the text.

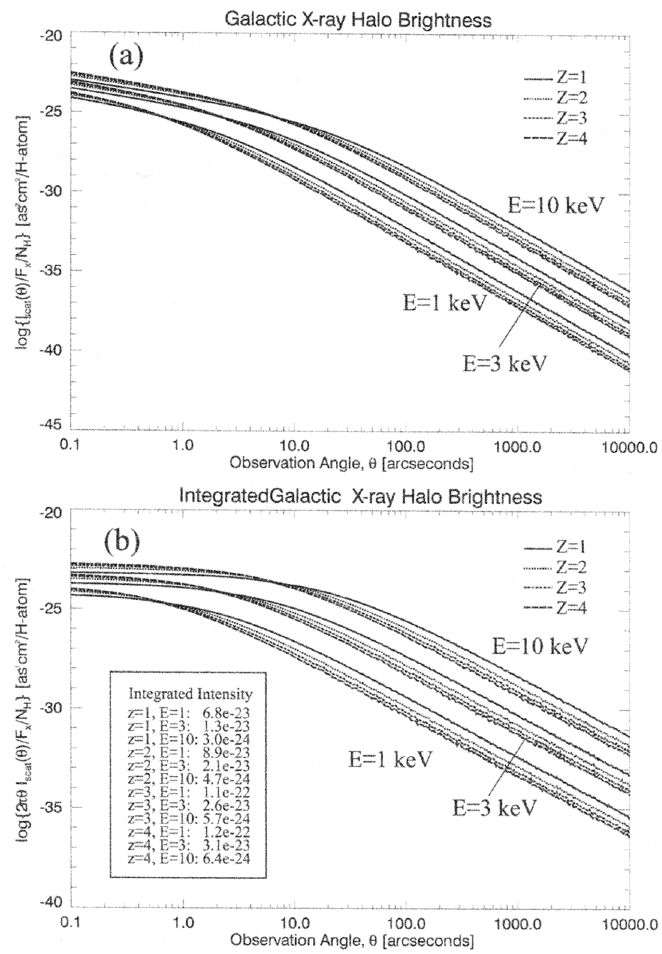

FIG. 2.—Similar to Fig. 1, but for the case of halos produced by scattering from Galactic dust. Here the halo brightnesses are computed relative to the hydrogen column density N_H along the line of sight to the source. The dust grain parameters used for this calculation are discussed in the text.

$\sim 5 \times 10^{46}$ ergs s^{-1} with a photon index of 1.4 (Boyle et al. 1993), the observed (point-source) flux is estimated to be on the order of 2×10^{-11} ergs cm^{-2} s^{-1} in the 1–3 keV band; in comparison, the source flux that would produce a detection having a unity signal-to-noise ratio when observed for 10^5 s with the *Chandra* ACIS-S instrument (2.6×10^5 arcsec^2 field) is estimated (using PIMMS) to be on the order of 3×10^{-15} ergs cm^{-2} s^{-1}. Thus, the minimum detectable relative halo brightness is $\sim 10^{-9}$ arcsec^{-2}. (Comparable detection sensitivities are estimated for *XMM-Newton* as well.) This minimum detectable brightness (i.e., integrated in the 1–3 keV band) is shown as the dot-dashed lines in Figure 1: the expected (monoenergetic) X-ray halo brightness curves exceed this estimated detection threshold only at observation angles below about 100″; the halo brightness curves integrated over energy in the 1–3 keV would exceed the minimum-detection threshold at slightly larger angles. However, as discussed below, the halo produced by intergalactic dust will be much fainter than the halo due to Galactic dust at these small angles in all cases.

Shown in Figure 2 are the halo brightness and integrated brightness curves due to scattering by Galactic dust for an object at 90° galactic latitude, at redshifts $z = 1$, 2, 3, and 4, and for energies $E = 1$, 3, and 10 keV. The shapes of the brightness curves are markedly different from those due to intergalactic cosmological dust (Fig. 1), as is expected due to the different spatial distributions of dust in the two cases. However, even for reasonably unabsorbed sources, the Galactic halo will be much brighter than the halo due to cosmological dust, except at the largest observation angles. To illustrate, shown in Figure 3 are the integrated halo brightness curves due to scattering from both Galactic and intergalactic dust for sources at $z = 1$ and $z = 4$ and X-ray energies $E = 1$ and 3 keV, taking $N_H = 10^{20}$ cm^{-2}. The Galactic halo is 3–5 orders of magnitude brighter than the cosmological dust halo for small observation angles, and the cosmological halo only becomes visible above the Galactic halo out in the large-angle wings: in the most favorable case of those considered—$E = 3$ keV, $z = 4$—the two halo integrated brightness values are equal at $\theta \sim 40''$, while in the worst case ($E = 1$ keV, $z = 1$) the Galactic halo is brighter than the cosmological halo out to $\theta \sim 200''$. The ability to distinguish Galactic from intergalactic cosmological dust halos will become even more difficult for sources along lines of sight with greater absorption. In any case, comparison of the integrated halo brightness curves with the minimum-detection threshold curve (the dot-dashed line in Fig. 3, as discussed above) indicates that even under the most favorable conditions (i.e., a long observation of a bright, distant X-ray source along an unabsorbed line of sight), at the large

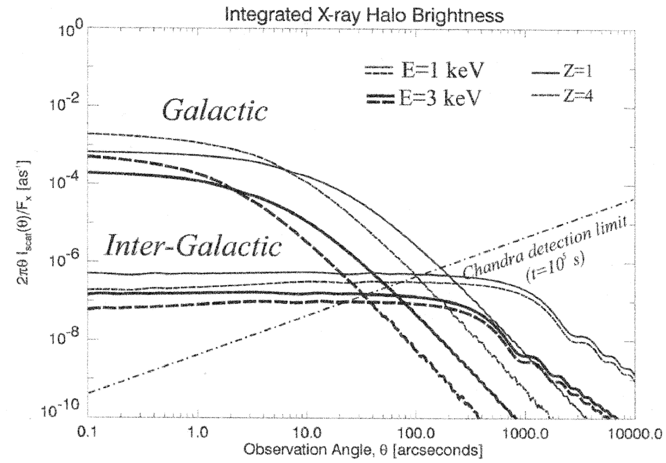

FIG. 3.—Comparison of intergalactic vs. Galactic dust halos (assuming $N_H = 10^{20}$ cm^{-2}), for X-ray energies $E = 1$ and 3 keV and source redshifts $z = 1$ and 4. The line marked "*Chandra* detection limit ($t = 10^5$ s)" corresponds to the minimum detectable halo brightness for the case of a bright AGN at $z = 1$, as described in the text.

observation angles where the intergalactic dust halo is estimated to be brighter than the Galactic dust halo, both halos are too faint for detection.

4. CONCLUSIONS

I have calculated the X-ray halo brightness that would result from the scattering of X-rays emitted from high-redshift sources by intergalactic gray dust. Assuming an intergalactic dust distribution that could plausibly explain the observed SN Ia observations, I have shown that the intensity of such halos, if they exist, would be low: the integrated halo intensity would be only a small fraction of the source flux, even under the most favorable conditions. The integrated halo brightness curves are also extended over hundreds of arcseconds, depending on the X-ray energy. Given the detection sensitivities of the current generation of X-ray observatories (i.e., *Chandra* and *XMM-Newton*), distinguishing such halos from the brighter, less extended halos produced by dust in our own Galaxy would represent a major observational challenge.

Refinements to the calculations presented here, for example, using the exact Mie scattering theory (Smith & Dwek 1998) rather than the RG approximation used presently, or perhaps using somewhat different cosmological dust distributions, will likely produce some small though significant changes in the expected halo brightness curves. Such refinements, however, should not affect any conclusions drawn above regarding the difficulty associated with detection of intergalactic cosmological dust halos. Other techniques for detecting intergalactic dust seem to be more promising, such as those cited above based on observations of the infrared background or gamma-ray burst afterglows.

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