A DIRECT UPPER LIMIT ON THE DENSITY OF COSMOLOGICAL DUST FROM THE ABSENCE OF AN X-RAY SCATTERING HALO AROUND THE z = 4.3 QUASAR QSO 1508+5714

ANDREEA PETRIC, GISELA A. TELIS, FRITS PAERELS, AND DAVID J. HELFAND
Columbia Astrophysics Laboratory and Department of Astronomy, Columbia University, 550 West 120th Street, New York, NY 10027
Received 2005 July 5; accepted 2006 July 13

ABSTRACT

We report on the results of a search for an intergalactic X-ray dust scattering halo in a deep observation of the bright, high-redshift quasar QSO 1508+5714 with the Chandra X-Ray Observatory. We do not detect such a halo. Our result implies an upper limit on the density of diffuse, large-grained intergalactic dust of $\Omega_d < 2 \times 10^{-6}$, assuming a characteristic grain size of $\sim 1 \mu$m. The result demonstrates the sensitivity of this technique for detecting very small amounts of intergalactic dust, which are very hard to detect otherwise. This will allow us to put important constraints on systematic effects induced by extinction on the interpretation of the Hubble diagram for Type Ia supernovae, as well as on the amount and properties of cosmological dust being expelled into the intergalactic medium at early ($z \geq 2$) times.

Subject headings: cosmology: observations — galaxies: active — galaxies: evolution — galaxies: nuclei — intergalactic medium — quasars: individual (QSO 1508+5714) — X-rays: general

Online material: color figure

1. INTRODUCTION

Recent discoveries of large quantities of dust at high redshifts, such as that of $\sim 7 \times 10^6 M_\odot$ of dust in the redshift $z = 6.42$ quasar QSO J1148+5251 (Bertoldi et al. 2003) and in other high-redshift ($z \geq 4$) sources (e.g., Priddey et al. 2003), suggest that substantial amounts of dust had been already produced at times as early as those corresponding to $z \sim 6$. One possible technique for detecting and quantifying the amount of dust grains produced at early times, and their dispersal into the intergalactic medium, is to search for X-ray scattering halos around bright extragalactic X-ray sources.

Dust particles will scatter X-rays, and dust scattering halos are indeed seen routinely around distant Galactic X-ray sources. The absence of detectable systematic reddening of Type Ia supernovae (SNe Ia) with increasing redshift means that any intergalactic dust extinction must be gray at optical wavelengths, and it suggests that if dust does exist in large quantities at these redshifts, the grains must be large, that is, at least larger than a wavelength of red light. This circumstance highly favors the formation of an X-ray dust scattering halo: the integrated X-ray scattering cross section per particle increases as the fourth power of the particle diameter (Mauche & Gorenstein 1986 and references therein). Consequently, sensitive X-ray observations can provide an independent measurement of the dust density, and the observations are sensitive precisely to a population of grains that would elude optical and near-infrared detection. A search for intergalactic scattering halos was first suggested by Evans et al. (1985).

The X-ray scattering is not a small effect. A rough estimate of its magnitude may be obtained from the following simple argument: The total scattering cross section (assuming spherical particles of density $\rho$ and radius $a$) scales approximately as $\sigma_{\text{scattering}} \propto \rho^2 a^4 E^{-2}$, with $E$ the photon energy, while the characteristic angular width of the cross section, $\theta$, is approximately $\theta \approx 10^5 E(1 \text{ keV})^{-1} [a/(0.1 \mu m)]^{-1}$ arcminutes (Mauche & Gorenstein 1986).

For small optical depth $\tau_{\text{scattering}}$, the fractional halo intensity $f \equiv I_{\text{halo}}/(I_{\text{halo}} + I_{\text{unscattered}})$ is approximately equal to $f \approx \tau_{\text{scattering}}$.

We can calculate the scattering optical depth through the universe by integrating

$$d\tau_{\text{scattering}} = \sigma_{\text{scattering}} \rho_{\text{dust}} dl \approx 6.5 \times 10^{-2} h_{75} \left( \frac{\Omega_d}{10^{-3}} \right) \left( \frac{\rho}{3 \text{ g cm}^{-3}} \right) \left( \frac{a}{1 \mu m} \right) \left( \frac{E}{1 \text{ keV}} \right)^{-2} (1+z)^2 \frac{dz}{E(z)} \]$$

with $\Omega_d$ the dust mass density in units of the critical density, $h_{75}$ the Hubble constant in units of 75 km s$^{-1}$ Mpc$^{-1}$, and $E(z) = \Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_{\Lambda}^{1/2}$. Here $\Omega_m$, $\Omega_k$, and $\Omega_{\Lambda}$ stand for the density of baryonic matter, curvature, and dark energy, respectively, as a fraction of the critical density. We have assumed a constant comoving dust density; a weak dependence of the optical depth on the composition of the dust has been suppressed. For $z \gg 1$, assuming $\Omega_{\Lambda} = 0$ (de Bernardis et al. 2000), we find

$$\tau_{\text{scattering}} \approx 4.3 \times 10^{-2} \Omega_m^{-1/2} [(1+z)^{3/2} - 1] h_{75} \left( \frac{\Omega_d}{10^{-3}} \right) \left( \frac{\rho}{3 \text{ g cm}^{-3}} \right) \left( \frac{a}{1 \mu m} \right) \left( \frac{E}{1 \text{ keV}} \right)^{-2},$$

so for $z \sim 4$, $f \sim 0.44 \Omega_m^{-1/2} (\Omega_d/10^{-5}) [a/(1 \mu m)][\rho/(3 \text{ g cm}^{-3})] \times [E/(1 \text{ keV})]^{-2}$. This shows that a moderately deep image of a sufficiently distant point source can place significant constraints on the dust density. The optical depth does not depend very strongly on the precise grain shape, for fixed cosmological dust density and characteristic grain radius. This is intuitively obvious: needle-shaped grains of radius $a$ can be thought of, to lowest order, as just strings of spheres of radius $a$. It is conceivable that the dust population is dominated by long, small-diameter needles, with physical dimensions such that the X-ray scattering effect is suppressed, for a given amount of optical extinction. For simplicity, in the absence of significant optical reddening and given a lack
of information on the shapes of grains in the intergalactic medium, we will perform our analysis assuming a spherical geometry for the grains.

Here we report on the analysis of a dedicated deep exposure with Chandra on the bright, distant \( z = 4.30 \) quasar QSO 1508+5714 (Moran & Helfand 1997 and references therein), designed to set constraints on the density of intergalactic dust.

### 2. DATA ANALYSIS

QSO 1508+5714 was observed with Chandra on 2001 June 10 for 88,971 s (effective exposure time), with the ACIS-S3 chip at the focus. The data were processed with CIAO 2.2.1. We reprocessed the data with the latest ACIS-S3 gain map, retaining only event grades 0, 2, 3, 4, and 6. The background was stable throughout our observation, and we retained the entire exposure for analysis. A close examination of the image of the source shows that it is definitely extended (Fig. 1). As is apparent from Figure 1, however, the extended feature contains less than 10% of the source counts and does not affect the radial profile of the source beyond \( \sim 4'' \), so it will not affect our measurement of a scattering halo. This jet, the highest-redshift X-ray jet known, is discussed elsewhere (Siemiginowska et al. 2003). In order to minimize the background, we excluded events outside the energy range from 300 to 8000 eV (the instrumental background in the S3 chip rises steeply of 0''5 on a side), vs. radial coordinate (points with error bars). Superposed are a ray-trace simulation for the core of the image (dotted line) and a radial profile for the bright source 3C 273 \( (r < 5 \) pixels \( (25'' \) is a consequence of photon pileup in the detector. The upper solid curve represents a simple dust scattering halo model corresponding to an average dust density of \( \rho_d = 2 \times 10^{-6} \) for dust particle size 1 \( \mu \) m. The flat distribution extending out to approximately 300 pixels is a model halo for particle size 0.25 \( \mu \) m and \( \rho_d = 2 \times 10^{-6} \).

Our attempt to detect a faint extended scattering halo obviously requires a careful treatment of the background. We retrieved the standard ACIS-S3 quiescent background data (acis7sD2000-12-01bkgrnd0001.fits, 330 ks exposure) and reprocessed it with the same gain map we used for the quasar image. We restricted event energies to the range 300–8000 eV and reprojected the background events using the aspect solution provided by the Chandra X-Ray Center for our observation. As a test, we subtracted a smoothed version of the resulting background image, simply scaled by exposure time, from the quasar image, and found that the residual intensities were generally of order 1% of the background image, or less. A very faint diffuse structure (roughly circular shape, diameter \( \sim 5'' \)) remains, located at position angle 70\(^\circ \) (measured east from north) at 25'' from the quasar, with a peak surface brightness of 0.2 counts arcsec\(^{-2} \). The total flux in this structure is less than 0.1% of the quasar flux, so we did not subtract it from the image. Otherwise, the smoothed, background-subtracted image appears completely dark outside a circle 20'' in radius centered on the quasar. The background is slightly spatially inhomogeneous (variations up to 10% from the mean surface brightness occur near the position of the quasar, on scales of \( \sim 1'' \)), so we chose to use the same set of annular extraction regions as we used for the quasar to extract a background histogram. This histogram was subtracted from the radial intensity profile of the quasar. The result is shown in Figure 2. We have not made corrections for the angular dependence of the telescope throughput, since these remain small (a few percent) over the angular range of interest.

The wings of the Chandra point-source response are dominated by scattering due to microroughness on the mirrors. The amplitude and angular distribution of the mirror-scattered light depend strongly on photon energy, and we therefore need to carefully model the wings in the image of the quasar. In order to investigate the intensity distribution, we compared the radial profile with the image of a low-redshift extragalactic point source with a spectrum similar to QSO 1508+5714. We selected the ACIS-S3 image of 3C 273 (ObsID 1712); at redshift \( z = 0.158 \), this source is too nearby to have a measurable intergalactic dust halo. Its Galactic interstellar column density is small (\( N_H \approx 1.7 \times 10^{20} \) atoms cm\(^{-2} \), so it does not have a Galactic dust scattering halo brighter than a few percent of the point-source flux, either; moreover, the Galactic scattering halo will be very extended and have very low surface brightness. We followed the same general procedures for the extraction of a radial intensity profile for 3C 273 as we used for QSO 1508+5714. There are no bright point sources near 3C 273,
and the object is so bright that we simply determined a constant background from a region located well away from the image of 3C 273. When we calculated the radial profile for 3C 273, we took care to exclude angular sections centered on the jet (Marshall et al. 2001; Sambruna et al. 2001) and the two detector readout streaks.

Scaling the profile for 3C 273 to that of QSO 1508+5714 requires a little care; 3C 273 is so bright that the center of the image is depressed as a result of pileup. 1 We therefore ignored the profile inside 8" as being affected by pileup. We scaled the profile of 3C 273 to that of our quasar over the angular range 9°–100°; the result is displayed in Figure 2. As can be seen, the wings of the two profiles outside a radius of ~10° coincide closely.

We performed a ray-trace simulation with MARX (Wise et al. 2003) for comparison with the core of the profile of QSO 1508+5714. We fitted the spectrum of the quasar with a power law over the range 0.3–8 keV, finding a photon index 1 = 1.53 and column density N_H = 8.4 × 10^{20} cm^{-2}. These parameters were used for input into MARX. For comparison with the 1995 Advanced Satellite for Cosmology and Astrophysics (ASCA) observation (Moran & Helfand 1997), we also record the results of a power-law fit with photon energy restricted to E > 0.5 keV; we find 1 = 1.44 ± 0.05 and N_H = (4.8 ± 1.4) × 10^{20} cm^{-2}. The power-law slope is identical to the ASCA value; the column density is somewhat larger, but this depends on the accuracy of the ASCA and ACIS-S calibrations below 0.8 keV. The flux in the observed 0.5–10 keV range in this model is (5.1 ± 0.4) × 10^{-13} erg cm^{-2} s^{-1}.

We assumed a simple point source on-axis (the actual off-axis angle of the source is 38°, small enough that it should not distort or broaden the point-spread function with respect to the on-axis performance). The resulting radial intensity profile is overlaid on the data in Figure 2. Inside 3", the quasar profile deviates from that of a point source, as noted above; we therefore scaled the simulated profile by eye to the measured profile, matching the amplitudes between 9° and 20°. At large radii, it appears that the simulation slightly underpredicts the amplitude of the scattering wings observed in 3C 273, an effect that was noted during flight calibration (Gaetz 2002). 2 The agreement between the quasar and the combined 3C 273/model profiles is good, and we conclude that there is no evidence for a substantial extended X-ray scattering halo.

3. MODELING THE HALO

We estimated the amount of scattered emission as a function of observed angle using the angular scattering cross sections derived in the Rayleigh-Gans approximation for a spherical particle of density ρ and radius a:

\[
\frac{d\sigma}{d\Omega} = 9.3 \times 10^{-14} \left( \frac{2Z}{M} \right)^2 \left( \frac{\rho}{3 \text{ g cm}^{-3}} \right)^2 \left( \frac{a}{0.1 \mu\text{m}} \right)^6 \times \left[ \frac{F(E)}{Z} \right]^2 \exp \left( -\frac{\theta_{\text{scat}}^2}{2\sigma^2} \right) \text{ cm}^2 \text{ arcmin}^{-2}
\]

(e.g., Maucole & Gorenstein 1986), where \(F(E)\) is the atomic scattering factor, Z is the atomic charge, and M is the atomic mass number. E is the energy of an incoming photon as seen by the grain, so \(E = E_0(1 + z_2)(1 + z_3)\) with \(E_0\) the photon energy at the quasar and \(z_2\) and \(z_3\) the redshifts of the source and the grain, respectively. Photons are scattered through an angle \(\theta_{\text{scat}}\), and the rms scattering angle is

\[\bar{\sigma} = \frac{10.4}{E(\text{keV})} \mu\text{m} \quad \text{arcmin}.\]

1 Chandra Proposers’ Observatory Guide ver. 5.0, § 6.16.

2 See http://asc.harvard.edu/cal/HRma/psf/ CUC–2002–01–31. TIG.ps.

The monochromatic intensity of the scattered radiation \(I_{\text{scattered}}\) as a function of angle θ on the sky is given by an integral along the line of sight:

\[
I_{\text{scattered}}(\theta) = \int_0^\infty \frac{L_0}{(1 + z_2)4\pi r^2_{\text{scat}}} d\sigma \exp \left( -\tau_{\text{scattering}} \right) n_g dl (4)
\]

Here \(n_g\) is the volume number density of grains, \(L_0\) is the monochromatic luminosity of the quasar (in ergs s^{-1} keV^{-1}), in the rest frame), and \(\tau_{\text{scattering}}\) is the scattering optical depth along the line of sight from observer to quasar. The differential cross section \(d\sigma/d\Omega\) is to be evaluated at the redshift of the grain. Finally, \(r_{\text{scat}}\) is the comoving distance between intervening grains and the quasar:

\[r_{\text{scat}} = \frac{c}{H_0} \int_{z_2}^{z_3} \frac{dz}{E(z)}. (5)\]

We evaluate the integral in equation (4) numerically. Throughout, we assume \(\Omega_m = 0.3, \Omega_\Lambda = 0.7, \text{ and } \Omega_r = 0\).

For an assumed grain size distribution, grain density and composition, and space distribution of the dust (all of which may evolve with redshift), one can in principle exactly calculate the intensity and shape of the scattering halo. Fitting such model halos to the data would yield the most constraining upper limits on the overall density of the dust. Here we report an upper limit that is robust and displays the dependence on the overall dust parameters as explicitly as possible, based on a set of simplifying assumptions.

In the first simplification, we assume that the dust has constant comoving density. This choice is motivated in part by detection of thermal dust emission from high-redshift QSOs selected from the Sloan Digital Sky Survey out to redshifts of 6 and reobserved at millimeter wavelengths (Omont et al. 2001, 2003; Carilli et al. 2001; Bertoldi & Cox 2002; Bertoldi et al. 2003). Also, Pettini et al. (2003) find that the metallicity of the LyC forest appears to show little evolution out to redshifts \(z \approx 5\). This suggests that dust is already present in significant amounts at redshifts larger than 1. Secondly, we assumed that the dust is homogeneously distributed. This is not a severe restriction, since the universe is evidently optically thin to dust scattering, so the total amount of scattered light is not sensitive to the precise distribution of the scattering medium. We will also be studying a relatively large area on the sky (on the order of a few square arcminutes), and since there should be order 10 star-forming galaxies per square arcminute out to high redshift as possible dust sources (Adelberger & Steidel 2000; Blain et al. 2002), effects of cosmic variance should not be dominant.

Given the probable blazar-like nature of the quasar (its isotropic luminosity in the rest-frame 1.5–10 keV band is \(1.0 \times 10^{47} \text{ ergs s}^{-1}\), for \(H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}\) and \(q_0 = 0\)), one might worry that the radiation is strongly beamed in our direction, and that no photons are emitted at sufficiently large angles from the line of sight to be scattered into our direction. However, the bulk Lorentz factors in X-ray jets are believed to be of order 5–10, which means that typical opening angles are on the order of several degrees, much larger than an X-ray halo; thus, beaming is unlikely to suppress the halo significantly.

Photon travel time delays could also in principle affect the shape and intensity of the halo. But typical time delays will be on the order of \(\theta_{\text{scat}}\) times the light-travel time to the quasar, so for scattering angles of ~1°, all that is required is for the quasar X-ray emission to have been stable on average for the last few thousand years, which is much shorter than the estimated average length of...
the accretion phase in the life of a quasar. The halo intensity depends on the past luminosity history of the quasar, and so the fractional halo intensity we measure with respect to the flux of the quasar does fluctuate with the instantaneous quasar flux. Between the ASCA observation in 1995 (Moran & Helfand 1997) and the present observation with Chandra, the object has declined by a factor 2 in isotropic luminosity, so we expect an uncertainty of order this factor in our final estimate for the upper limit to the intergalactic dust density. Averaging over several observations (objects or epochs) would reduce this uncertainty.

In the absence of any information on the grain size distribution, we will simply assume for now that the grains are spherical, with a characteristic radius of \( a \sim 1 \mu\text{m} \). We note that grains of this typical dimension remain optically thin to X-ray absorption for photon energies \( E \gtrsim 1 \text{keV} \).

Finally, we assumed a power-law spectral shape for the X-ray emission of the quasar, using the slope we determined from a direct fit to the measured spectrum (see § 2), and we integrated the photons arriving at the telescope over the telescope/ACIS-S effective area between 300 and 8000 eV, for direct comparison with the X-ray image. Since the halo is much wider than the telescope response, we did not convolve it with the telescope point-spread function.

Our expressions for the scattering optical depth are based on the Rayleigh-Gans approximation for the scattering cross section (Mauche & Gorenstein 1986). At low photon energies and large particle sizes, this approximation breaks down, and exact Mie theory should be used. For a characteristic particle size of 1 \( \mu\text{m} \), the Rayleigh-Gans approximation starts to fail below photon energies of \( \sim 1 \text{keV} \). This implies that in order to separate out low-energy photons, the cross section is overestimated by a factor up to a few (Smith & Dwek 1998). In view of the approximations listed above, which introduce an uncertainty of the same order, we chose to perform the calculations based on the simple Rayleigh-Gans formulation. We also note that because of the redshifting, the average photon energy at the scattering site is higher than at the observer, which tends to dilute the error introduced by the use of the Rayleigh-Gans approximation.

We compare the model halo directly with the measured angular intensity profile of our source in Figure 2. Superposed on the observed profile of the quasar is a model halo for an assumed dust density of \( \Omega_d = 2 \times 10^{-6} \) (and \( \Omega_m = 0.3, \Omega_{\Lambda} = 0.7 \), grain radius \( a = 1 \mu\text{m} \), and density of the grain material \( \rho = 3 \text{g cm}^{-3} \)). For reference, on the scale of this figure, the background level in the image was approximately a constant 0.04 counts pixel\(^{-1} \) before subtraction. A dust halo at the chosen level would have been detected significantly over the range \( \sim 10-100 \) pixels: the net source count in the image over the range 8-100 pixels is 107, while the halo model (excluding the inner 8 pixels) contains 484 counts; the expectation value for the constant background in this area is 250 counts, with an expected Poissonian fluctuation of 50 counts. We chose the dust density of \( \Omega_d = 2 \times 10^{-6} \) somewhat arbitrarily. At this level, a halo is clearly visible, while the dust density is already a factor of several below the astrophysically interesting fiducial level of \( \Omega_d = 10^{-5} \) (see below).

A more sensitive upper limit could probably be obtained by formally fitting model halos for various assumed sets of parameters, taking the point source, background, and halo photon statistics explicitly into account. However, at that point we should also properly consider the effect on the upper limit on \( \Omega_d \) of varying the physical parameters of the dust model (grain size and shape distribution, spatial distribution, composition, etc.). Given the large uncertainties in these parameters, we prefer to state the upper limit for a given fixed set of dust parameters. Of these, the dependence on dust grain size is probably the strongest. To very rough approximation, the integrated halo intensity will scale in inverse proportion to the dust grain radius. In addition, the shape of the halo changes with changing values for the radius (a smaller grain radius will produce a wider halo at lower amplitude, while a larger grain radius will produce the opposite effect). As a result, the upper limit to \( \Omega_d \) depends not only on the integrated halo intensity, but also on the background in the X-ray image. Nevertheless, for grain radii not very different from 1 \( \mu\text{m} \), the upper limit on \( \Omega_d \) will scale approximately inversely with grain radius. This is illustrated in Figure 2, where we plot a model halo for assumed grain size \( a = 0.25 \mu\text{m} \) and \( \Omega_d = 2 \times 10^{-6} \).

4. DISCUSSION

Our upper limit of \( \Omega_d < 2 \times 10^{-6} \) to the density of gray, smoothly distributed intergalactic dust has several important astrophysical implications. First, for the simplest assumptions for the properties of the dust (spherical particles of characteristic radius \( 1 \mu\text{m} \), of constant comoving density), the upper limit is about an order of magnitude below the dust density required to explain the appearance of the \( z < 1 \) SN Ia Hubble diagram (Riess et al. 1998; Perlmutter et al. 1999) solely in terms of intergalactic extinction. This information is now probably largely redundant, since evidence has become available to indicate that the apparent relative dimming of supernovae (relative to a coasting universe) for \( z < 1 \) turns into a relative brightening at large redshifts (Riess et al. 2004), and this of course very strongly suggests that dust extinction does not have a major effect. But apart from its providing independent confirmation of the relative unimportance of gray dust extinction on the overall appearance of the SN Ia Hubble diagram, the X-ray dust scattering halo technique can in principle be refined to constrain and quantify systematic effects of dust extinction on attempts to use SNe Ia to measure the equation of state of dark energy.

Second, the limit already appears to rule out the most optimistic estimates for the density of dust expelled by galaxies. Aguirre (1999) estimates, on the basis of the measured cosmic metal production rate, and the observed metallicity of galaxies and intracluster medium, that as much as \( \Omega_d \gtrsim 2 \times 10^{-5} \) could be smoothly distributed in the space between galaxies; this is not observed. Our result may thus be used to put significant constraints on the cosmic dust production rate and dispersal mechanism.

We note that our finding appears to be at variance with the conclusion reached by Windt (2002) that a dust halo would be much too faint to be detectable. Comparing the integrated intensity quoted in that paper for the benchmark case (\( \Omega_d = 4.5 \times 10^{-5}, \Omega_m = 1, a = 0.1 \mu\text{m}, E = 1 \text{keV} \)), we find that it is inconsistent with the robust estimate based on the optical depth (eq. [2]), with the optical depth argument giving a 15 times larger estimate. Also, Windt evaluated the observability of a halo for a particularly unfavorable choice of parameters (e.g., effectively no dust beyond \( z = 0.5 \), and constant physical, rather than comoving, dust density). Our estimate for the dust halo brightness based on a simple optical depth argument is robust, and we conclude that a halo should have been detected around our redshift \( z = 4 \) quasar if the dust density \( \Omega_d \) were significantly higher than a few times \( 10^{-6} \).

We gratefully acknowledge help from and conversations with Zoltan Haiman, Masao Sako, Ali Kinkhabwala, David Windt, Meg Urry, and Dani Maoz. This work was supported by Chandra X-Ray Observatory grant GO1-2144X from the Smithsonian Astrophysical Observatory.
REFERENCES

Adelberger, K. L., & Steidel, C. C. 2000, ApJ, 544, 218
Aguirre, A. N. 1999, ApJ, 525, 583
Bertoldi, F., & Cox, P. 2002, A&A, 384, L11
Bertoldi, F., et al. 2003, A&A, 409, L47
Blain, A. W., Smail, I., Ivison, R. J., Kneib, J.-P., & Frayer, D. T. 2002, Phys. Rep., 369, 111
Carilli, C. L., et al. 2001, ApJ, 555, 625
de Bernardis, P., et al. 2000, Nature, 404, 955
Evans, A., Norwell, G. A., & Bode, M. F. 1985, MNRAS, 213, 1P
Gaetz, T. 2002, Calibration of the Chandra On-Axis PSF: 2002 Chandra Users’ Committee Presentation (Cambridge: Chandra X-Ray Cent.)
Hook, I. M., McMahon, R. G., Patnaik, A. R., Browne, I. W. A., Wilkinson, P. N., Irwin, M. J., & Hazard, C. 1995, MNRAS, 273, L63
Marshall, H. L., et al. 2001, ApJ, 549, L167
Mauche, C. W., & Gorenstein, P. 1986, ApJ, 302, 371
Moran, E. C., & Helfand, D. J. 1997, ApJ, 484, L95
Omont, A., Beelen, A., Bertoldi, F., Cox, P., Carilli, C. L., Priddey, R. S., McMahon, R. G., & Isaak, K. G. 2003, A&A, 398, 857
Omont, A., Cox, P., Bertoldi, F., McMahon, R. G., Carilli, C., & Isaak, K. G. 2001, A&A, 374, 371
Perlmutter, S., et al. 1999, ApJ, 517, 565
Pettini, M., Madau, P., Bolte, M., Prochaska, J. X., Ellison, S. L., & Fan, X. 2003, ApJ, 594, 695
Priddey, R. S., Isaak, K. G., McMahon, R. G., Robson, E. I., & Pearson, C. P. 2003, MNRAS, 344, L74
Riess, A. G., et al. 1998, AJ, 116, 1009
———. 2004, ApJ, 607, 665
Sambruna, R. M., Urry, C. M., Tavecchio, F., Maraschi, L., Scarpa, R., Chartas, G., & Muxlow, T. 2001, ApJ, 549, L161
Siemiginowska, A., Smith, R. K., Aldcroft, T. L., Schwartz, D. A., Paerels, F., & Petric, A. O. 2003, ApJ, 598, L15
Smith, R. K., & Dwek, E. 1998, ApJ, 503, 831 (erratum 541, 512 [2000])
Windt, D. L. 2002, ApJ, 564, L61
Wise, M. W., Davis, J. E., Huenemoerder, D. P., Houck, J. C., & Dewey, D. 2003, MARX 4.0 Technical Manual (rev. 3.0; Cambridge: Chandra X-Ray Cent.)