1. INTRODUCTION

X-rays are not only absorbed but are also scattered by dust grains when they travel through the interstellar medium (ISM). This scattering of X-rays from a source behind a dust-containing cloud in the ISM will lead to the formation of an X-ray scattering halo surrounding the X-ray source. The properties of the halo depend on the size distribution and density of the dust grains, and on the relative geometry of dust, X-ray source, and observer.

Such dust scattering halos were first discussed by Overbeck (1965), but they were not observationally confirmed until Rolf (1983) observed the X-ray binary GX 339—4 with the Einstein X-ray Observatory. Since then, X-ray halos have been studied via observations facilitated by X-ray satellites which include Einstein, ROSAT, BeppoSAX, Chandra, and XMM-Newton. Thus far, the most complete samples of these studies have been presented by Predehl & Schmitt (1995), based on ROSAT data, and by Xiang et al. (2005), based on observations with the Chandra ACIS-S/HETGS, with the method presented by Yao et al. (2003). Of additional note, Draine & Tan (2003) have analyzed ROSAT observations of the halo associated with the X-ray nova V1974 Cygni 1992 to confirm that the interstellar dust model of Weingartner & Draine (2001, hereafter WD01) is consistent with the observed extinction. The theoretical calculations governing the observed halo suggest that a large fraction of the dust grains when they travel through the interstellar medium (ISM) can adequately reproduce its halo radial profile.

X-ray halos are not limited to the aforementioned binaries. Most bright X-ray sources are surrounded by X-ray halos (Predehl & Schmitt 1995), including one of the most extreme of the dipping sources, the Big Dipper 4U 1624—490, which is an atoll source (Lommen et al. 2005) with an IR counterpart of magnitude $K_s = 18.3$ (Wachter et al. 2005). The presence of a halo in 4U 1624—490 has been surmised via BeppoSAX observations, which exhibit a soft excess above its several arcminute PSF (Balucinska-Church et al. 2000). The poor angular resolution of BeppoSAX, however, prevents the direct extraction of the halo radial profile at radii less than $100''$, where the halo is much more prominent.

In this paper, we present a focused study of the X-ray halo associated with 4U 1624—490, using the highest resolution (angular and energy) data to date, as afforded by the Chandra ACIS-S/HETGS. The ~3 hr long duration of the dips (Watson et al. 1985; Smale et al. 2001; Balucinska-Church et al. 2001) and large obscuration of this compact object offer us the unique opportunity to use the time delay of photons arriving from the halo to determine the distance to 4U 1624—490 (§ 2 for theory and § 4.2 for data analysis) and to compare with dust grain models to assess composition and density along the line of sight (LOS; § 4.3). (The large obscuration may be due to the accretion disk stream impacting the disk. A ~75% obscuration has been reported by Watson et al. (1985) and Church & Balucinska-Church (1995); the superior angular resolution of Chandra allows us to detect a 90% obscuration; § 4.2.) We also present a new method for assessing the Chandra point-spread function (PSF) at large angles ($\gtrsim 50''$) and compare the PSF measured by our technique with Chandra Ray Tracing (ChaRT) predictions between $9''$—$160''$ (§ 4.3.1).

2. THEORETICAL AND HISTORICAL BACKGROUND

The theoretical calculations governing the observed halo surface brightness and the time delay of a scattered photon with respect to an unscattered one have been discussed extensively (e.g., Mauche & Gorenstein 1986; Mathis & Lee 1991; Trümper & Schönfelder 1973). Here, we briefly describe the main points.

As discussed by Mauche & Gorenstein (1986), the differential cross section in the Rayleigh-Gans approximation, coupled with
the Gaussian approximation for a spherical particle of radius \(a\), can be described by

\[
S(a, E, \theta_{\text{sca}}) = \frac{d\sigma_{\text{sca}}(a, E, \theta_{\text{sca}})}{d\Omega} = 1.1 \times 10^{-12} \left(\frac{2Z}{M}\right)^2 
\times \left(\frac{\rho}{2}\right) \left(\frac{a}{\mu m}\right)^6 \left|\frac{F(E)}{Z}\right|^2 \exp(-K^2 \theta_{\text{sca}}^2),
\]

where \(K = 0.4575(E/\text{keV})/(a/\mu m)^2\) and \(\theta_{\text{sca}}\) is the angle of scattering. The mean atomic charge (\(Z\)), molecular weight (\(M\), in amu), mass density (\(\rho\)), and atomic scattering factor \([F(E);\text{from Henke 1981}]\) also factor into the calculation. A photon of wavelength \(\lambda\) will be scattered to a typical angle

\[
\theta = \lambda/\pi a \propto E^{-1}.
\]

For small angles (several arcminutes), we can approximate the observed angle by \(\theta \approx (1-x)\theta_{\text{sca}}\), where \(x = d/D\) is the relative distance defined to be the ratio of the distance from scattering grain to observer \((d)\) over the distance between source and observer \((D)\); see Figure 1.

The intensity of the observed first-order scattering halo, \(I_{\text{sca}}^{(1)}(\theta, E)\), depends on the X-ray flux \(F_X(E)\) of the point source \((4U 1624-490\text{ in our case})\) and is a function of both the observed angle \(\theta\) and the energy \(E\). The form of this equation, as initially derived by Mathis & Lee (1991), is expressed as

\[
I_{\text{sca}}^{(1)}(\theta, E) = F_X(E)N_H \int_{a_{\text{min}}}^{a_{\text{max}}} da n(a) \int_0^1 dx f(x)(1-x)^{-2} S\left(a, E, \frac{\theta}{1-x}\right),
\]

where \(N_H\) is the total hydrogen column density between the observer and the X-ray source, \(n(a)\) is the size distribution of the dust grains, and \(f(x)\) is the relative hydrogen density to the average total hydrogen density along the LOS at \(xD\). For uniformly distributed dust, \(f(x) \equiv 1\), and equation (3) can take on the more explicit form

\[
I_{\text{sca}}^{(1)}(\theta, E) \propto F_X(E)N_H \int_{a_{\text{min}}}^{a_{\text{max}}} da n(a) \left(\frac{a}{\mu m}\right)^6 \text{erfc}(R) \frac{R}{(1-x)^2},
\]

where \(R = K\theta_{\text{sca}} = K(\theta/1-x)\) and \(\text{erfc}(R) = (2/\sqrt{\pi}) \int_R^\infty dt \times \exp(-t^2)\).

Mathis & Lee (1991) further established that multiple scattering is likely important if there is enough scattering optical depth to see an appreciable halo. As discussed by those authors, as well as by Predehl & Klose (1996), for a fixed energy \(E\), doubly scattered radiation at the position of the observer can be described via

\[
I_{\text{sca}}^{(2)}(\theta, E) = F_X(E)N_H \int_0^1 dx f(x) \int_0^1 dx' f(x') \frac{1}{(1-x')^2} \times \int_0^{\theta_{\text{sca}}} \theta'd\theta' \int_0^{2\pi} d\phi \int_{a_{\text{min}}}^{a_{\text{max}}} dn(a) S(a, E, \theta_{\text{sca}}) 
\times \int_{a_{\text{min}}}^{a_{\text{max}}} da' n(a') S(a', E, \theta_{\text{sca}}'),
\]

where

\[
\theta_{\text{sca}} = \theta^2 + 2\theta' \sin \phi \frac{\theta}{1-x} + \theta'^2 \left(1-(1-x)^2\right),
\]

\[
\theta_{\text{sca}}^2 = \theta^2 \frac{1-x}{1-x'},
\]

For a typical scattering optical depth of \(\tau_{\text{sca}} \approx 0.5\), the doubly scattered radiation dominates the multiple scattering terms at several arcminutes, such that higher order (>2) scatterings can be largely neglected.

Other factors, in particular the ISM dust composition and grain size distribution, affect our overall determination of the halo properties. Several different models exist for describing the composition and size distribution of ISM dust grains. The two most commonly used are the grain models of WD01 and the “classical” one of MRN77. The details of these two models are different, although they are both based on IR observations. The MRN77 model assumes both graphite and silicate grains with size distributions \(n(a) \propto a^{-3.5}\), for \(a_{\text{min}} < a < a_{\text{max}}\), where \(a_{\text{min}} = 0.005\ \mu m\) is the same for both grain types, while \(a_{\text{max}} = 0.25\ \mu m\) for silicate grains and \(a_{\text{max}} \approx 0.25-1\ \mu m\) for graphite grains. In contrast, the WD01 model, which includes very small carbonaceous grains (\(a < 0.005\ \mu m\)) and larger grains (\(a > 1\ \mu m\)), is comparatively more complex than the MRN77 model. To illustrate, the size of the carbonaceous grains extends to more than 1 \(\mu m\), while the number of grains decreases sharply with size; see Weingartner & Draine (2001) for details.

3. OBSERVATION

We observed 4U 1624-490 on 2004 June 4 (MJD 53160.26813, ObsID 4559) with the Chandra High Energy Transmission Grating Spectrometer (HETGS) for 76 ks, covering one binary orbit. To reduce pileup, the observation was performed using a reduced 1.7 s frame time and one-half subarray corresponding to 512 columns per CCD. Figure 2 shows that our observation encompasses \~2.7 hr total of dipping periods (3 dipping events with durations, respectively, of about 3.5, 2.3, and 4.0 ks).

4. DATA ANALYSIS

We used CIAO 3.3 with ca1d4b 3.2 to extract HETGS spectra of the source for the persistent (nondipping) and dipping periods.
The 2–6 keV halo light curve between 3" and 20" is extracted from the CCD S3 zeroth-order data, while the point-source light curve in the same energy band is extracted from the dispersed data of the gratings (first-order data). We note that the halo light curve, between 3" and 20", will have ~40% contamination from the bright point-source photons scattered into the wings of the PSF. CIAO 3.3 is also used to extract the surface brightness of the zeroth-order data for the persistent and dipping periods. (Note that in order to ensure that neither the halo nor the PSF radial profiles are contaminated by the dispersed spectra of the HETGS, we have, throughout, excluded pie slices of the regions from the zeroth-order image that contain the medium-energy grating [MEG] and high-energy grating [HEG] arms.) Our analysis technique for the results presented in §§ 4.2 and 4.3 are best illustrated by the flowcharts of Figures 3 and 4, respectively.

4.1. The Broadband Spectrum as Determined from First-Order HETGS Data

In order to determine the distance (§ 4.2) and distributed hydrogen column (§ 4.3) along the LOS to 4U 1624–490, it is necessary that its light curve, and the total flux covering the entire ~ 76 ks spectrum, the dipping phase (~12 ks), and persistent phases (persistent 1 + persistent 2, ~59 ks), are estimated over the same energy bands. (This corresponds to 2–6 keV over 200 eV incremental bandpasses.)

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**Fig. 2.**—The 2–6 keV halo and point-source light curves. The topmost dotted line is the point-source light curve for 4U 1624–490. The combined halo and PSF light curve between 3" and 20" is shown, with error bars, in the middle. The overplotted solid line is the “best fit” (χ² statistics) for the halo light curve based on LC WD01(t) (dashed line) convolved with the PSF light curve. To facilitate clearer viewing, we multiply the observed halo plus PSF light curve by a factor 4, the LC WD01(t) from model WD01 by a factor of 3, and the LC MRN(t) from model MRN77 by a factor of 2.

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**Fig. 3.**—Flowchart showing the data analysis process for determining the distance to 4U 1624–490.
steps for this paper; see § 4.2 for details.) Furthermore, because there is a direct proportionality between the source spectrum and the X-ray halo intensity such that any uncertainties associated with the spectral analysis will map onto the halo analysis, we take care to use spectra which suffer from the least amount of pileup in our continuum modeling.

4.1.1. The Time-Averaged Continuum Covering the Binary Cycle

The best-fit model based on HEG ± 1 fits to the time-averaged ~76 ks spectrum between 1.5–10.0 keV is $1.37^{+0.05}_{-0.05}$ keV blackbody plus $\Gamma = 1.0^{+0.6}_{-0.6}$ power law modified by $N_{H} = 7.6^{+0.6}_{-0.6} \times 10^{22}$ cm$^{-2}$. Not surprisingly, these parameters are similar to that derived from the persistent period which is discussed in more depth below.

4.1.2. The Persistent-Phase Continuum

The maximal count rate for the HEG ± 1 spectra during this phase is $7.8 \times 10^{-3}$ counts per pixel per frame time, corresponding to a maximal pileup ~2% at ~5 keV. The maximal count rate per pixel in the MEG ± 1 is about 2 times that of HEG ± 1, indicating a maximal pileup of ~4%. Therefore, we have taken care to use the nearly pileup free HEG ± 1 spectra to derive the flux for the different bands used in our analysis in §§ 4.2 and 4.3. The halo intensity is proportional to $E^{-2}$, such that it decreases sharply with increasing energy. We therefore retain as many low-energy (~2 keV) halo photons as possible for our halo studies. We further note that we derive broadband spectral parameters based on the 1.5–10 keV spectral region, while only the 2–6 keV flux (measured in 200 eV steps) is used in order to match our halo studies of § 4.3.

Using XSPEC 12.2.1 (Arnaud 1996), we fit the broadband source continuum HEG ± 1 spectrum of the persistent phase with various combinations of power law, blackbody, diskbb, and thermal bremsstrahlung modified by the Tuebingen-Boulder ISM absorption model (Wilms et al. 2000). (Because of the high count rate of the source spectrum, the data were binned to require at least 400 counts in each energy bin.) The fitting results are listed in Table 1. We find that both model 1, absorption×(blackbody+power law), and model 2, absorption×(diskbb+power law), fit the data well. However, the latter gives an unreasonable photon index of $\Gamma = 12^{+8}_{-4}$, while the former agrees better with the parameters reported by Balucinska-Church et al. (2000), based on BeppoSAX data; by Smale et al. (2001), based on RXTE data; and by Parmar et al. (2002), based on XMM-Newton data, barring a flatter photon index in our fitting. The steepness of $\Gamma$ appears strangely tied to choice of cold absorption model (i.e., wabs vs. tbabs), which we will explore in more depth in our forthcoming paper on the high-resolution Chandra spectrum of 4U 1624–490. For present purposes, it suffices that model 1 describes the broadband continuum spectrum well (see Fig. 5), such that we can confidently extract flux values over the incremental 200 eV steps between 2–6 keV for our calculations of § 4.3.

4.1.3. The Dip-Phase Continuum

We also fit the MEG ± 1 and HEG ± 1 spectrum of the dip phase with many of the same models. Due to the lower overall
count rate during this phase, we were only able to rebin these data to require S/N $\approx 8$ bin$^{-1}$. Both the MEG $\pm 1$ and HEG $\pm 1$ dip spectra are pileup free. We find the best fit for this broadband dip continuum spectrum to be a $\Gamma = 0.7 \pm 0.5$ power law modified by $N_{\text{H}} = 9.05^{+0.25}_{-0.19} \times 10^{22}$ cm$^{-2}$ cold absorption. Fluxes in 200 eV steps were also obtained in the same 2–6 keV energy band to compare with the persistent periods.

4.2. Using the Halo and Point-Source Light Curves to Determine Distances

The scattering photon travels longer distances than the unscattered one. The delay time $dt$ is given by

$$dt = 1.15 \, h \left( \frac{D}{1 \, \text{kpc}} \right) \left( \frac{\theta}{1''} \right)^2 \left[ \frac{x}{(1 - x)} \right].$$  \hspace{1cm} (8)

Thus, measurement of a time delay between the point source and the halo yields direct information about the distance to the dust cloud and the source. The $\sim 3$ hr long dipping of 4U 1624–490 provides an excellent opportunity to search for such a delay. Trümper & Schönfelder (1973), Hu et al. (2004), and Xu et al. (1986) proposed methods for using this behavior to measure the distance to variable X-ray sources, and Predehl et al. (2000) presented a successful geometric distance determination to Cyg X-3 based on Chandra ACIS-S/HETGS observations.

The time delay $dt$ is only dependent on the location of scattering, but the halo surface brightness is determined by the size, position, and composition of the dust grains, as well as the source flux and scattering hydrogen column. Therefore, the spectrum of the source, the dust grains model and the spatial distribution of the grains is implicitly factored into equation (8).

The halo intensity is proportional to $E^{-2}$, such that it decreases dramatically at the very high energies. Figure 5 shows that the majority of the 4U 1624–490 counts are contained within the 2–6 keV energy band. Therefore, we restrict our comparative analysis of the halo and point-source light curve exclusively to this band, where fluxes are estimated over 200 eV steps based on the continuum model described in  \hspace{1cm} § 4.1.1.

In order to avoid pileup effects, the bright point-source light curve is extracted directly from the dispersed first-order data of the HETGS, where the count rate is a factor of $\sim 4$ lower than that of the nondispersed zeroth-order data. In contrast, we extract the (lower flux) halo light curve between 3'' and 20'' from the zeroth-order data, where the minimum angle is restricted to 3'', in order to mitigate pileup. We estimate that while pileup at 3'' is less than 2%, between 3'' and 20'', it is $\ll 1\%$, so that we can safely neglect it for our analysis. The maximum angle restriction of 20'' was chosen to reduce multiple scattering effects, which if not factored in properly can lead to overpredictions of the time delay. Alternatively, we could have restricted the energy band to 3–6 keV, for example. However, this would not have reduced the degree of multiple scatterings, it would have greatly decreased the halo intensity, which scales as $E^{-2}$. Thus, we opted for the angular restriction with an energy that covers the observable point-source continuum well. We estimate that the total halo intensity between

![Fig. 5.—Best-fit models overplotted on the broadband spectra of 4U 1624–490 during the persistent phase (HEG $\pm 1$; left) and dipping periods (HEG $\pm 1$ and MEG $\pm 1$; right).](image-url)
3'' and 20'' associated with the second-order scattering is less than 5% that of the first-order scattering in the 2–6 keV energy band of interest. While we account for second-order scattering effects in our analysis, we wanted to make sure that it would not play a major role in affecting our final results.

A comparison of the halo and point-source light curve (Fig. 2) reveals a mean delay of ~1.6 ks for source photons arriving from the halo that is at 3''–20'' from 4U 1624–490. It is interesting to note that the dips we detect show as much as ≥90% blockage of the compact object (Fig. 2), compared, for example, to the 75% reported previously in EXOSAT (Watson et al. 1985), Ginga (Jones & Watson 1989), BeppoSAX (Balucinska-Church et al. 2000), and RXTE (Smale et al. 2001) observations. This is attributed to the fact that the superior imaging capabilities of Chandra can better separate the source light curve from contaminated light from the halo. Using the time delay, and equation (8), a simple estimate for the distance derived from the MRN77 model is somewhat sensitive to errors. In a recent reanalysis of GX 13+1, based on a new Chandra calibration, Smith finds that the WD01 model may be preferred (although the differences between the WD01 and MRN77 models are still small).

Therefore, for our distance determinations, we are still inclined to accept the value of $D_{4U1624} = 15.0^{+2.9}_{-3.9}$ kpc, based on fits using the WD01 model. This is consistent with the 10–20 kpc value derived by Christian & Swank (1997), based on a method which compared the hydrogen column densities from their spectral fitting to an exponential distribution model of hydrogen in the Galaxy.

Furthermore, since dust grains between us and the point source are unlikely to be uniformly distributed, we check whether and to what extent our distance determinations are affected by unevenly distributed dust. Accordingly, in our modeling, we vary the dust placement in additional fits, e.g., $x = 0.5$–1, 0.4–1, etc., where $x = 0$ and 1 correspond, respectively, to our position and that of the source (see Fig. 6). We find our distance estimates to be robust to these changes, as long as the dust is uniformly distributed near the source. This is because the distance estimates are based primarily on small-angle scatterings, where the observed halo is attributed primarily to dust near the source (see, e.g., Fig. 4 of Mathis & Lee 1991). This finding is consistent with our results based on fits to the halo profile for determining column densities in § 4.3.

### 4.3. Using the Halo Radial Profile to Determine the $N_\text{H}$ Spatial Distribution

Fits to the halo light curve show that ~40% of the photons come from the point source as far out as 20''. While Chandra has very good imaging resolution, the halo brightness is not much greater than the PSF (see Fig. 7, right). Therefore, a good understanding of the telescope PSF is necessary for optimal results.

#### 4.3.1. The Chandra PSF and Halo of 4U 1624–490

As discussed by Smith et al. (2002) the CIAO tool mkpsf and the Chandra ray trace model SAOAC reproduce the observed core of the PSF well but underestimate the wings of the PSF.

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**Fig. 6.—** Spiral arm structure of the Milky Way Galaxy and the position of 4U 1624–490. This figure is adapted with permission from Caswell & Haynes (A&A, 171, 261 [1987]), but using a Sun–Galactic center distance of 8.0 kpc. The positioning and the source is based on the distance of 15 kpc derived in § 4.2.
The same is true of the tool ChaRT since it also uses SAOSAC. Column (5) of Table 2 lists the comparison between the PSF (PSF\textsubscript{Ch}) from the ChaRT simulation and the one (PSF\textsubscript{Her}) derived from the Chandra ACIS-S/HETGS observation of the almost halo-free source, Her X-1 (ObsID 6149). Parameters derived from the Her X-1 observation are used in its ChaRT simulation. As such, we can confidently use ChaRT to assess the PSF behavior at small (\(\leq 50^\circ\)) angles. For angles larger than 50\(^\circ\), we subsequently present a new method for assessing the Chandra PSF by using the observed dips in 4U 1624–490.

Figure 8 shows the WD01 halo model light curve over different angular distances compared with the point-source light curve. It is clear that at increasingly larger angles, the flux behavior of the point source is reflected less in the halo light curve (Table 2). This is in part due to a “smearing” effect at large angles, as well as the increased delay between the photons arriving from the point source and those arriving from the halo. Capitalizing on this observed effect of the dipping phenomenon on the halo light curve, we discuss a prescription for assessing the Chandra PSF for 4U 1624–490 at large angles. First we define

\[
\text{PSF}(r) = \frac{I_{\text{per}}(r) - I_{\text{dip}}(r)}{F_{\text{per}} - F_{\text{dip}}},
\]

where \(I_{\text{dip}}(r)\) and \(I_{\text{per}}(r)\) are, respectively, the surface brightness over different radii during the time periods when 4U 1624–490

### TABLE 2

**ESTIMATION OF THE SYSTEMATIC ERROR OF PSF AND HALO**

| Radius (arcsec) | \(I_{\text{halo}}^{\text{WD01}}(r) - I_{\text{halo}}^{\text{WD01-dip}}(r)\) | PSF\textsubscript{data}(r)\textsubscript{h} | \(\Delta \text{PSF}_{\text{data}}(r)\textsubscript{h}/\text{PSF}_{\text{data}}(r)\textsubscript{h}\) | PSF\textsubscript{Her}(r) - PSF\textsubscript{Ch}(r)\textsubscript{d} | PSF\textsubscript{CS}(r)\textsubscript{h} | \(\Delta \text{PSF}_{\text{CS}}(r)\textsubscript{h}/\text{PSF}_{\text{CS}}(r)\textsubscript{h}\) |
|----------------|-------------------------------------------------|-----------------|-----------------------------------|---------------------------------|-----------------|-----------------------------------|
| 09–20 .......... | -0.12                                           | 0.77            | 0.18                              | 0.02                            | 0.36            |
| 20–30 .......... | -0.07                                           | 0.51            | 0.16                              | 0.08                            | 0.23            |
| 30–40 .......... | -0.05                                           | 0.46            | 0.13                              | 0.13                            | 0.20            |
| 40–50 .......... | -0.04                                           | 0.39            | 0.11                              | 0.13                            | 0.19            |
| 50–60 .......... | -0.03                                           | 0.32            | 0.09                              | 0.24                            | 0.16            |
| 60–70 .......... | -0.02                                           | 0.24            | 0.09                              | 0.30                            | 0.13            |
| 70–80 .......... | -0.01                                           | 0.36            | 0.04                              | 0.32                            | 0.11            |
| 80–90 .......... | 0.01                                            | 0.25            | 0.04                              | 0.38                            | 0.11            |
| 90–100 .......... | -0.03                                           | 0.16            | 0.02                              | 0.46                            | <0.10           |
| 100–160 .......... | <0.03                                           | ~0.30           | <0.01                             | <0.40                           | <0.10           |

**Notes**—The data in this table are used solely to discern the relative accuracy of our PSF estimates and are not used in the calculation of either the PSF or halo radial profiles.

a \(I_{\text{halo}}^{\text{WD01}}(r)\) and \(I_{\text{halo}}^{\text{WD01-dip}}(r)\) mean the halo intensity for the persistent and (averaged) dip phases, respectively, derived from fitting the energy-dependent light curves with the WD01 model.

b PSF\textsubscript{data}(r)\textsubscript{h} is the PSF intensity derived from eq. (10), while \(I_{\text{halo}}(r)\) is the halo intensity derived from eq. (11).

c \(\Delta \text{PSF}_{\text{data}}(r)\) is an estimate of systematic error in the (persistent phase) PSF due to the underestimate of the derived halo intensity (i.e., \(r_{\text{halo}}^{\text{WD01}}(r)\) radial profile of 4U 1624–490.

\[
\text{PSF}(r) = \frac{I_{\text{per}}(r) - I_{\text{dip}}(r)}{F_{\text{per}} - F_{\text{dip}}},
\]

\d(PSF_{\text{CS}} - PSF_{\text{Ch}})/PSF_{\text{CS}}\) means the systematic error of PSF intensity from ChaRT simulations compared with the Her X-1 observational data.

\(I_{\text{halo}}^{\text{CS}}(r) = I_{\text{per}}(r) - PSF_{\text{Ch}}(r)\) is the halo intensity with the ChaRT simulation PSF.
is dipping and when it is persistent. Similarly, \( F_{\text{dip}} \) and \( F_{\text{per}} \) refer to the point-source flux during these periods. Based on this, we can then define the surface brightness of the halo

\[
I_{\text{halo}}(r) = I_{\text{per}}(r) - \text{PSF}(r) = \frac{I_{\text{dip}}(r)F_{\text{per}} - I_{\text{per}}(r)F_{\text{dip}}}{F_{\text{per}} - F_{\text{dip}}}. \tag{11}
\]

To properly track the spectra of the dip and persistent periods and determine how these spectra are reflected in the behavior of the energy dependent PSF, we use equation (10) to calculate the PSF over the energy range 2–6 keV in 200 eV steps. Note that this equation implicitly assumes no time dependence of the halo flux. This is, of course, inaccurate, especially at small angular distances from the source. It becomes more accurate, however, at large angular distances, where the dipping behavior is “smeared out” in the halo light curves (see Fig. 8). Thus, we expect equation (10) to be less dominated by systematic uncertainties at larger angular distances. Large angular distances are also where ChaRT estimates of the PSF become more problematic.

To assess the systematic errors in our determination of the PSF radial profile, we use equations (3) and (8) to calculate the theoretical halo light curves \( \text{LC}_{\text{mod}}(r) \) at different ranges of angular distances, as shown in Figure 8. Specifically, as described in § 4.2, we used the light curve of the persistent source with different presumed models for the source distance and dust distribution and chose a model that minimizes the \( \chi^2 \) for the fit to the halo light curves. The halo intensity averaged over the dip phases (i.e., essentially the estimate embodied in eq. [11]) can then be compared to the halo intensity in the persistent phases (i.e., the “true” steady state halo flux). This estimate is presented in column (2) of Table 2. As expected, for radii near the point source, selecting the periods during the dips slightly understimates the persistent halo flux and hence leads to a systematic overestimation at small angular radii of the PSF as calculated via equation (10) (col. [c] of Table 2).

As shown in Table 2, for radii <50', ChaRT yields less than 13% uncertainties for the PSF, while for radii >50', using equation (10) yields uncertainties <10% for the PSF. The relative uncertainty in the halo flux is approximately given by the fractional uncertainty in the PSF multiplied by the ratio of the PSF flux to the halo flux (i.e., col. [4] multiplied by col. [3] or col. [5] multiplied by col. [6] from Table 2). Thus, by using the ChaRT PSF estimate for radii <50', and equation (10) for radii >50', the systematic uncertainty in the halo profile should be <3% everywhere.

4.3.2. Fits to the Halo Radial Profile

Having gained some understanding of the PSF behavior, we use the WD01 and MRN77 models to fit the halo radial profile using the fitting codes developed by Smith et al. (2002) as also applied to the Chandra halo studies presented in Xiang et al. (2005). See also Figure 4 for a flow chart of the analysis process. We confine our halo fitting to angular distributions corresponding to radii 9°–160°, where the extreme of pileup effect is <0.5% at ≥9° and decreases with angular distance. Therefore, we can assume a pileup-free halo for our analysis.

In order to assess dust properties and distribution, for our initial fitting, we assume uniformly distributed dust between \( x = 0 \) (us) and \( x = 1 \) (4U 1624–490; see Fig. 6; as recreated from Caswell & Haynes 1987 and annotated to show the distance of 4U 1624–490 from us). Based on this scenario, we find that neither the MRN77 model [with \( a_{\text{max}}(\text{graphite}) = 0.42 \) \( \mu \text{m} \); \( \chi^2/\text{dof} = 141/49 \) for a best-fit \( N_{\text{H}} = 4.44^{+0.08}_{-0.08} \times 10^{22} \text{ cm}^{-2} \)] nor the WD01 model \( (\chi^2/\text{dof} = 171/49) \) with \( N_{\text{H}} = 3.40^{+0.06}_{-0.08} \times 10^{22} \text{ cm}^{-2} \) provides a good fit to the halo profile. Both models underpredict the halo surface brightness at >80° by ~50%. We also fit the halo radial profile to include the second-order scattering and find a 50% substantial improvement in our fits. (We remind the reader that the angular regions probed in this study are much larger than the distance determination study of § 4.2, where multiple scattering effects were found to be negligible.) While the fits improved somewhat, they are still statistically unacceptable, with \( \chi^2/\text{dof} \sim 91/49 \) for the WD01 model and \( \chi^2/\text{dof} \sim 89/49 \) for the MRN77 model of \( a_{\text{max}}(\text{graphite}) = 0.42 \) \( \mu \text{m} \).

Having determined that the uniformly distributed dust between us and the point source 4U 1624–490 is an unlikely scenario, we investigate whether the models are sensitive to patchy distributions. Accordingly, based on Figure 6, we roughly divide the dust distribution along our LOS into three parts: \( x = 0.0–0.20 \) (Region 1: R1), 0.20–0.40 (R2), and 0.40–1.0 (R3), corresponding to a distance \( d \) relative to us of, respectively, 0–3.0 kpc (R1), 3.0–6.0 kpc (R2), and 6.0–15.0 kpc (R3), as seen in Figure 9. While dust is assumed to be smoothly distributed in each of these regions, the quantity is allowed to vary independently. Based on this, fits to the halo radial profile using the WD01 model yield hydrogen column densities for each region (Table 3). Compared to fits assuming uniformly distributed dust between \( x = 0 \) and 1, \( \Delta \chi^2 = 26 \) for 47 dof (\( \chi^2_u = 1.38 \)), i.e., >99% confidence for two additional parameters, according to the F-test. Similarly, fits based on three parts with the MRN77 model give \( \Delta \chi^2 = 24 \) for 47 dof (\( \chi^2_u = 1.38 \)), i.e., again >99% confidence for two additional parameters. The second-order scattering is accounted for in these fits by adding the numerically integrated value of the second-order scattering to the first-order scattering value during fitting of the halo radial profile. The scattering hydrogen column density \( N_{\text{H}(\text{Scatt})} = 4.8 \times 10^{22} \text{ cm}^{-2} \) derived from the MRN77 model is consistent with the result (\( N_{\text{H}} = 5.0 \times 10^{22} \text{ cm}^{-2} \)) corresponding to \( \tau = 2.4 \) obtained by Balucinska-Church et al. (2000). We also notice, however, that
the average density along the entire LOS to 4U 1624–490. The best halo radial profile fits are shown in Figure 9.

While the absorption hydrogen column density includes both the Galactic ISM and the gas nearby the source, the scattering hydrogen column density only comes from the Galactic interstellar medium. Therefore, our finding that the scattering $N_H$ derived independently from the WD01 and MRN77 models is much less than the absorption $N_H$ derived from spectral fitting implies that there is significant absorption intrinsic to the source. If we naively take the difference between the best-fit value $N_{abs}^H \approx 8 \times 10^{22}$ cm$^{-2}$ of the broadband HETGS spectra due to Galactic and source ISM and $N_{H}^{\text{tot}} \approx 4 \times 10^{22}$ cm$^{-2}$ derived from our halo studies, a $N_H \leq 4 \times 10^{22}$ cm$^{-2}$ can conceivably be local to the source, possibly put there by the stellar wind of the companion.

5. SUMMARY

1. We improve on previous distance estimates for 4U 1624–490 by making use of the delay time of the halo photons relative to the bright point-source photons to obtain $D_{4U1624} = 15.0^{+3.9}_{-2.6}$ kpc. This is consistent within the errors of the 10–20 kpc estimates by Christian & Swank (1997) using a different technique.

2. We find that varying dust distributions will not affect our distance determination to 4U 1624–490, except possibly for a scenario where there is no dust within $\sim 7.5$ kpc of the source ($x = 0.5–1.0$). This extreme scenario does not match the $N_H$ derived from our halo fitting results, so it can be ignored as potentially problematic for our distance estimates.

3. Using the extreme dipping behavior of 4U 1624–490, we discuss a new method for estimating the Chandra PSF at large angles ($>50^\circ$). In a comparison with ChaRT estimates for the PSF, we find that if we estimate the PSF using ChaRT at $<50^\circ$, and our method at $>50^\circ$, we can limit the errors associated with our halo analysis to $\lesssim 3\%$ over the angular $9^\circ$–$160^\circ$ region.

4. Varying dust distribution does affect the derived column densities. A simple estimate based on our halo fits imply the hydrogen particle density in the spiral arms is $n_R \sim 1.7$ cm$^{-3}$, and the one between two spiral arms is $n_R \lesssim 0.2$ cm$^{-3}$.

5. For the future, larger field of view and high throughput observations combined with ongoing Chandra studies will allow us to better diagnose the scattering of dust near and far from us, to reveal more detailed spatial information.

Note: After submission of this paper, Iaria et al. (2006) posted a preprint presenting the spectral analysis of our HETGS data for 4U 1624–490 which is currently public. Our complete analysis of these data will be presented in a forthcoming publication.

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**TABLE 3**

| Model       | $N_{H1}^{R1}$ (10$^{22}$ cm$^{-2}$) | $N_{H2}^{R2}$ (10$^{22}$ cm$^{-2}$) | $N_{H1}^{R3}$ (10$^{22}$ cm$^{-2}$) | $N_{H1}^{\text{tot}}$ (10$^{22}$ cm$^{-2}$) | $\chi^2$/dof |
|-------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|--------------|
| WD01        | 1.58 ± 0.15                     | 0.00 ± 0.10                     | 2.04 ± 0.08                    | 3.62 ± 0.06                    | 65/47        |
| MRN77       | 2.08 ± 0.20                     | 0.00 ± 0.10                     | 2.73 ± 0.05                    | 4.81 ± 0.08                    | 65/47        |
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