Chandra Observations of Dust Grains

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Theory

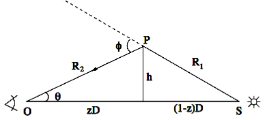
When an X-ray passes through a dense cloud of effectively free electrons (i.e., a dust grain), the electrons oscillate in response. For sufficiently small grains ($a_{\mu m} \leq E_{keV}$), the electrons act coherently and the scattering cross section at small ($1'/(a_{\mu m}E_{keV})$) angles is a N_e^2. This effect creates "halos" around absorbed X-ray sources (Overbeck 1965).

The scattering can be calculated in detail using the exact Mie solution (e.g. Smith & Dwek 1998), or if $a_{\mu m} \ll E_{keV}$ the "Rayleigh-Gans" (RG) approximation, calculated by assuming coherent Rayleigh scattering throughout the dust grain and integrating over the volume (shown here for a spherical grain):

$$\left(\frac{d\sigma}{d\Omega}\right)(E,a,\phi) \approx 1.1\left(\frac{\rho}{3\text{ g cm}^{-3}}\right)^2 a_{\mu m}^6 E_{keV}^{-2} \exp\left(-\frac{\phi^2}{2\sigma^2}\right) \text{ cm}^2\text{ sr}^{-1}$$

where $\sigma \approx 62.4'' E_{keV}^{-1} a_{\mu m}^{-1}$.

The observed halo can then be calculated by integrating the scattering cross section over the line of sight, for an assumed distribution of dust grain positions and properties.



Then the observed surface brightness at position θ from the source is:

$$I_{sca}(\theta) = F_X N_H \int dE\, S(E) \int da\, n(a) \int_0^1 dx\, \frac{f(x)}{(1-x)^2}\frac{d\sigma}{d\Omega},$$

where F_X is the source flux, S(E) the spectrum in the chosen bandpass, f(x) the normalized space density of grains along the line of sight, and n(a) the dust grain size distribution. The total scattering cross section (assuming an MRN dust model) is $\tau = 0.686 \times 10^{-22} N_H / E_{keV}$

Mathis & Lee (1991) and Predehl & Klose (1996) both noted that for $\tau > 1$, the halo will be dominated by multiple scattering, which tends to broaden the halo. Even for $\tau > 0.5$, the effect is not insignificant. Calculating even double scattering is non-trivial, as can be seen from the equation below:

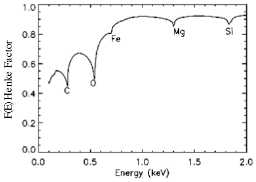
$$I^{(2)}(\theta) \propto F_X N_H^2 \int_0^1 dx \int_x^1 \frac{dx'}{(1-x')^2} \int d\Omega' \times$$
$$\int da\, n(a) a^6 \exp[-cE^2a^2(\theta'^2 + \frac{2\theta'\theta}{1-x}\sin\phi' + (\frac{\theta}{1-x})^2] \times$$
$$\int da'\, a'^6 n(a') \exp[-cE^2a^2\theta^2(\frac{1-x}{1-x'})^2] \exp[-\tau_{sca}(x'-x)]$$

Before Chandra, X-ray telescopes could measure either the surface brightness or the spectrum, but not both with useful resolution. Chandra and XMM-Newton can do spatially-resolved spectroscopy with E/ΔE~10 resolution; for X-ray halos, which vary as E-2, this is adequate to measure the total surface brightness in the halo relative to the source flux, Hf(Q,E) in arcmin-2. This can be directly compared to a model of the dust density r, size distribution, and composition (which enters via F(E), the Henke atomic factor):

$$I(E) = \int H_f(\theta, E, \Delta E) 2\pi\theta\, d\theta$$
$$\approx 0.2\left(\frac{2Z}{M}\right)^2 \left(\frac{\rho}{3\text{ g cm}^{-3}}\right)^2 \left[\frac{F(E)}{Z}\right]^2 D_{\rm kpc} E_{\rm keV}^{-2} \int da\, n(a) \left(\frac{a}{0.1\ \mu\rm m}\right)^4 \left[\frac{n_{\rm gr}(a)}{10^{-12}\text{ cm}^{-3}}\right]$$
$$= 80.7 \left(\frac{N_{\rm H}}{10^{22}\text{ cm}^{-2}}\right) \left(\frac{\rho}{3\text{ g cm}^{-3}}\right) E_{\rm keV}^{-2} \int da\, n(a) \left(\frac{a}{0.1\ \mu\rm m}\right) \frac{m_{\rm gr}(a)}{m_{\rm H}}$$

Future X-ray Halo Observations

With sufficient energy resolution and effective area, it will be possible to diagnose dust abundances directly:

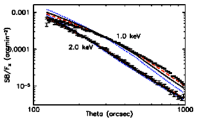


Measuring halos with sufficient energy resolution to see the absorption features (due to K-shell absorption in the dust grains) will require Constellation-X, the next major NASA X-ray mission.

The Crab Nebula: Extended Sources

The Crab Nebula was observed with *Chandra* in a search for the outer shock wave, which was not discovered (Seward et al. 2005). The data did show the halo around the Crab Nebula (which, as expected, confused the search for a shock front). The column density towards the Crab is relatively low: N_H~3.5x10^{21} cm^{-2}, so a strong halo is not expected. We fit the data using our standard three models and found again relatively poor fits, although again the ZDA04 model was the best fit [Below, Right]. Unusually, the halo column densities were all lower than 3.5x10^{21} cm^{-2}.

We also tried a two component model. In this case, using the ZDA04 model, we found a reasonable fit (formally χ^2=2.2, but no systematic offsets) with a small cloud ~100 pc distant. If true, this could be the swept-up dust from the creation of the Local Bubble!



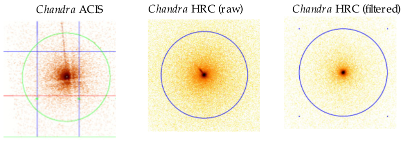
Note: The Crab Nebula is extended (~1'), and so a simple point-source approximate is inadequate. However, we point out that a convenient analytic expression exists which calculates the halo from a circular source of size φ from the point halo models:

$$I(\theta,\phi) = 2\int_{\theta-\phi}^{\theta+\phi} d\psi\, \psi \arccos\left(\frac{\theta^2 - \phi^2 + \psi^2}{2\theta\psi}\right) I(\psi)$$

Abstract

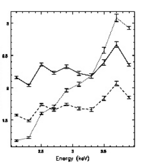
X-ray halos created by interstellar dust grains have been observed with *Einstein*, *ROSAT*, and *ASCA*. Data from *Chandra* and *XMM-Newton*, however, qualitatively change the analysis that can be done. The variation in the halo intensity with energy and angle is strongly dependent on the composition, size, and position of the dust grains, and can be directly compared to the absorbing column density measured via the X-ray spectrum. Prior observations allowed at best rough estimates of the dust properties. I present results from GX13+1, GX5-1, X1724-307, and the Crab Nebula to determine the parameters of the dust along the line of sight.

Results from Initial Sources in Survey: GX13+1

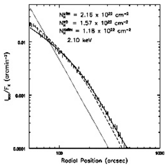

Chandra ACIS *Chandra* HRC (raw) *Chandra* HRC (filtered)

Images of GX13+1; the circle has 5' radius in the ACIS image, and 1' for the HRC images. Note the transfer streak in the *Chandra* ACIS data, and the "jet" in the raw HRC data. Aggressive filtering is necessary to remove this feature, which is normally removed by pipeline filtering and appears here only due to the high count rate from GX13+1. GX13+1 is one of the brightest sources observed without a grating by either ACIS-I or the HRC.

The LMXB GX13+1 has a poorly measured column density. Its position (only 0.1° out of the Galactic plane, despite the name) and unknown distance make any CO emission measurements inconclusive. Infrared observations suggested a limit on $A_V \leq 14.4$ (Garcia *et al.* 1989), corresponding to $N_H \leq 2.2$x10^{22} cm^{-2} assuming blackbody emission. X-ray spectral fits to CCD data suggest $N_H \sim 2.9$x10^{22} cm^{-2} (Ueda et al. 2001). Ueda et al. (2004) used HETG data to determine a value of $N_H \sim 3.2\pm0.2$x1022 cm^{-2}, which is probably the most robust measurement available.

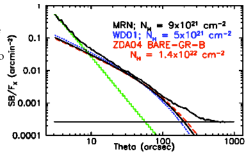


We (Smith, Edgar & Shafer 2001) analyzed the X-ray halo seen by ACIS around GX13+1 between 50" to 600" [Right], finding that the data excluded a hypothetical model with very large dust grains. The MRN and WD01 models both fit, although with very different best-fit N_H values [Left]. **A low NH was found for the WD01 model, along with slightly inferior fits compared to MRN.**

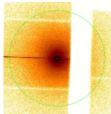


Draine (2003) noted that these oddly low N_H values found for the WD01 above might be explained by dust near the source, to which the ACIS observations were insensitive. Xiang et al. (2005) analyzed the halo of GX13+1 along with 16 other sources from the zero-order HETG image. In all cases, they found that the majority of dust along the line of sight is very near the source, and proposed that all or most XRBs are surrounded by molecular clouds. **To test this, we obtained 9 ksec of HRC-I data (without a grating) on Feb 8, 2005.** This data allows us to measure the halo (albeit without any spectral data) to 3" of the source. Since GX13+1's spectrum is variable, we also obtained simultaneous RXTE data to measure it. We also used HRC-I observations of AR Lac to measure the PSF; this is the same data used to calibrate the *Chandra* PSF generally.

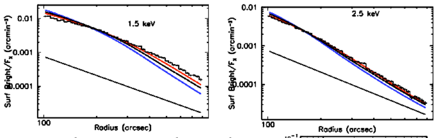
Our initial analysis simply fit a smooth dust distribution using an flux-weighted halo model. We found generally poor fits (χ^2 >6 in all cases), and, curiously, relatively **low** values of N_H compared to the ACIS results [Right]. Since this data is at small angles, it naturally weights dust near the source higher than distant dust. These low values suggest there is less, not more, dust near the source. However, this crucially depends on what is used for the *Chandra* PSF (the green curve at Right), and more work is needed.



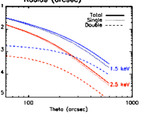
GX5-1: Bright and Highly Absorbed


Chandra ACIS

The HMXB GX 5-1 was observed by *Chandra* for 6.8 ksec on August 6, 2000. The above circles are 6' in radius. Ueda et al. (2004) used a *Chandra* HETG observation to measure N_H=2.8x10^{22} cm^{-2}, with relatively large systematic errors. We begin with a smoothly distributed dust model, shown below at 1.5 and 2.5 keV for the MRN (black), WD01 (blue), and ZDA04 BARE-GR-B (red) models along with the Chandra PSF (dashed). Again the ZDA04 model is the best fit, especially at 2.5 keV (N_H=4.2x10^{22} cm-2, within the limits of Ueda et al (2004)). However, none of the fits at 1.5 keV are acceptable.



Clearly, something is missing from the model. The general shape from 100-200" is reasonable, but there is a consistent excess beyond 200". This could be due to multiple scattering and/or molecular clouds along the line of sight. The scattering cross section, assuming a MRN dust model, is τ=0.686x10^{-22}N_H/E^2_{keV}; at 1.5 keV, $\tau \sim 1.3$, so multiple scattering is the likely cause, at least at this energy [Right].

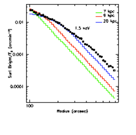


At a Galactic latitude of -1^0, we can use CO observations to measure the position and thickness of any clouds, and further reduce the parameters in the model. The best distance estimate for GX5-1, based on the Eddington luminosity, is 9kpc, putting it potentially in front of, behind, or in clouds 3 and 4.

Cloud	Velocity	W_{CO}	2xN(H_2)	N(HI)	Position
	(km/s)	(K km/s)	(10^{20} cm^2)	(10^{20} cm^2)	(kpc)
1	-15	24.4	88	34	5.5
2	23	40.4	146	34	4.7
3,4	184,208	21.7	78	11	8.47
Total		86.5	310	83	

Using these values for the cloud positions and column densities (summing the H_2 and HI columns) we considered three possible distances for the source, 7, 9, and 20 kpc [Below, Right]. None of these models was an adequate fit, although it is possible that including double scattering would significantly improve the 9 kpc model. In this fit we considered only single scattering, for simplicity.

We also tried using a single cloud model, allowing both the position and column density of the cloud to vary. Our best fit had NH = 2.8x10^{22} cm^{-2}, and a cloud about 1/5 of the distance from the source. However, the fit underestimated the data at low energies, suggesting substantially more dust was required.

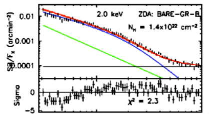


Can X-ray halos actually distinguish between rival dust models? Three major dust models in current use are the venerable Mathis, Rumpl & Nordsieck (1977; MRN) model, the Weingartner & Draine (2001; WD01) model, and the family of models created by Zubko, Dwek & Arendt (2004; ZDA04). The goal of MRN was to fit the observed UV/optical extinction, which it did with a power-law distribution of graphite and silicate grains. The total carbon required to be in the dust, however, exceeds what is now thought to be available. WD01 expanded the requirements to include fitting the IR emissivity and staying within a tighter set of abundance constraints, using a more complex size distribution. ZDA04 showed that a large family of grain models could fit the existing restrictions, and suggested X-ray halo observations would be necessary to distinguish between the models.

X1724-307

X1724-307 (l,b = 356.3, 2.3) is an XRB in the globular cluster Terzan 2, thought to be near the Galactic center. It was observed by *Chandra* for 14 ksec on July 7, 2005. The total hydrogen column density along the line of sight, from CO and HI data, is 1.35x10^{22} cm^{-2}; at 8 kpc the source is 100 pc from the plane, so most of this is likely foreground. X1724-307 has also been observed with the LETG/HRC on March 9, 2000 for 10 ksec. A good fit is found with an absorbed bremsstrahlung model with N_H=1.37x10^{22} cm^{-2}, in good agreement with the CO and HI data.

A simple fit (shown Right) using smoothly-distributed dust and the BARE-GR-B model from ZDA04 gives a relatively poor fit (χ^2 = 2.3), albeit with a plausible N_H. Fits with the WD01 or MRN models are significantly worse (χ^2 = 6.9, 3.7); the WD01 fit also has an implausible N_H=5.6x10^{21} cm^{-2}. The residuals show that the problem is in the overall shape, suggesting a second dust component, perhaps clumped in a cloud along the line of sight.

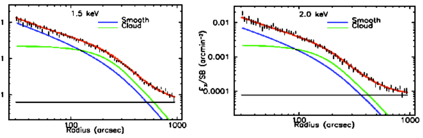


The blue curve shows the halo profile; green is the Chandra PSF and the flat line shows the background.

We refit the radial profiles between 1.5-2.5 keV with the ZDA04 BARE-GR-B model, using a two component model with some dust smoothly-distributed along the line of sight and a second component found in a clump. We allowed the background to vary at each energy., but fixed the column densities of the two components to be the same at each energy.

The resulting fit is overall reasonably good (χ^2 = 1.4) with plausible parameter values. The total column density is 1.39±0.21x10^{22} cm^{-2}, and that the clump is 30% of the distance to the source; assuming d=8 kpc, this is 2.4 kpc distant, possibly a component of the Crux spiral arm (although it is normally thought to be ~4 kpc distant).

Comp	NH	Position
	10^{21} cm^{-2}	%
Smooth	6.7±1.6	–
Clump	7.2±1.3	0.3±0.01



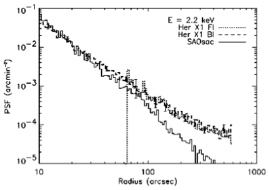
Fitting the same model using the WD01 dust model leads to a slightly worse fit (χ^2=1.6), but with utterly implausible values: the total column density is only 6.3x10^{21} cm^{-2}, and the dust clump (with column density 4.8x10^{21} cm^{-2}) must be within 200 pc of the Sun. The MRN fit also has χ^2=1.6, with only slightly more plausible parameters: a total column density 9.8x10^{21} cm^{-2} and a dust clump at 800 pc.

Although not conclusive, these results strongly suggest that at least one of the ZDA04 models (BARE-GR-B) fits the data significantly better than either the MRN or WD01 models, and with plausible values.

Calibration

X-ray halos appear as radially symmetric enhancements in the surface brightness around an absorbed X-ray source. Typically, the total flux in the halo is in the range of 10%-100% of the directly observed source flux, depending on the energy, radii of extraction, and the dust column density. Unfortunately, X-ray halos have an ever-present background: the point-spread-function (PSF) of the mirrors along with any instrumental background. Despite the tiny size of *Chandra* core PSF, the combination of CCD pileup and background cause problems when measuring the far-off-axis PSF. The PSF must be modeled and removed with great care, since it is often of the same magnitude as the X-ray halo; small errors in calibration translate into substantial effects in the model.

To measure X-ray halos, the PSF must be known as a function of energy between 10" - 1000" from the source, where (in the case of Chandra) the PSF drops by 3 orders of magnitude. This can be done using a bright, lightly-absorbed (i.e. no halo) source as a calibrator.



However, the PSF is also a function of the source's position on the detector; ideally we want to know

$$SB_{PSF}(\Theta,p,E)/S(E)$$

where S(E) is the source flux, Θ is the angular distance from the source, p the source position on the detector, and X-ray energy E. Since accurate measurements spanning 3 orders of magnitude are time-consuming, this can only be done using simulation. In the case of Chandra, this is inadequate as can be seen at left.

The PSF (= $SB_{PSF}(\Theta,p,E)/S(E)$) for Chandra/ACIS for Her X-1 observed onaxis at 2.1-2.3 keV. Her X-1 is an HMXB with an absorbing column of $N_H \sim 10^{20}$ cm^{-2}. The lower curve shows the predicted PSF calculated using the Chandra raytrace code ***SAOsac***, which agrees well for Θ < 20" but obviously is inadequate for halo studies. Using the ***SAOsac***-calculated PSF for halo studies leads to overstrong halos with unphysical tails.