# X-Ray Halos with Chandra: Results from GX13+1

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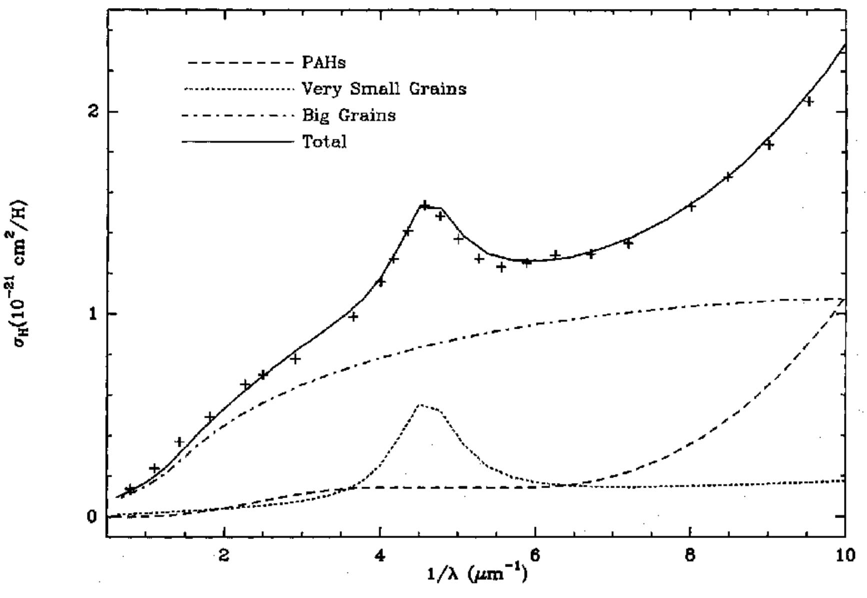
Data on dust grain distributions comes largely from observing the extinction of optical and UV light:

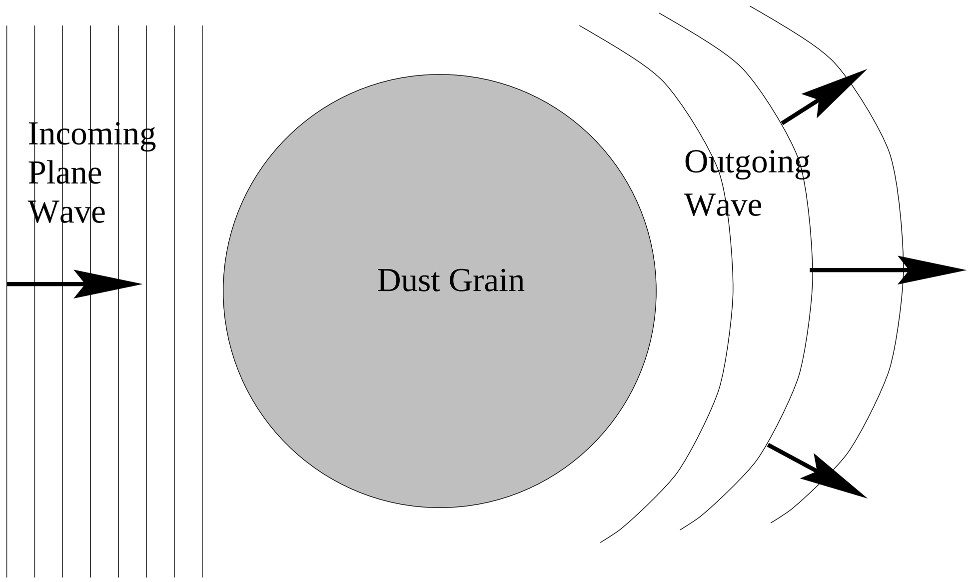



These observations can be fit using Mie scattering theory with some distribution of dust grains. Shown here is a model including very small graphite (VSG) grains to fit the bump, as well as big grains $\sim 0.1\mu$m (BG) and polycyclic aromatic hydrocarbons (PAH) to fit the rest of the extinction.

However, the extinction becomes gray (size-independent) for large ($>$ 0.1 $\mu$m) dust grains.

*Very little is known about large dust grains, although they have most of the mass*

What causes the scattering?




The X-ray photon sees the dust particle as a cloud of free electrons, each one a scattering site. Assuming each electron "sees" the wave (photon), it will oscillate like a dipole at the wave frequency–ie, Rayleigh scattering.

A photon with wavenumber $k$ scatters from a sphere of radius $a$ and index of refraction $m$ as

$$I(r,\theta) = \frac{(1+\cos^2\theta)k^4|\alpha|^2}{2r^2} I_0 \tag{1}$$

where for a sphere

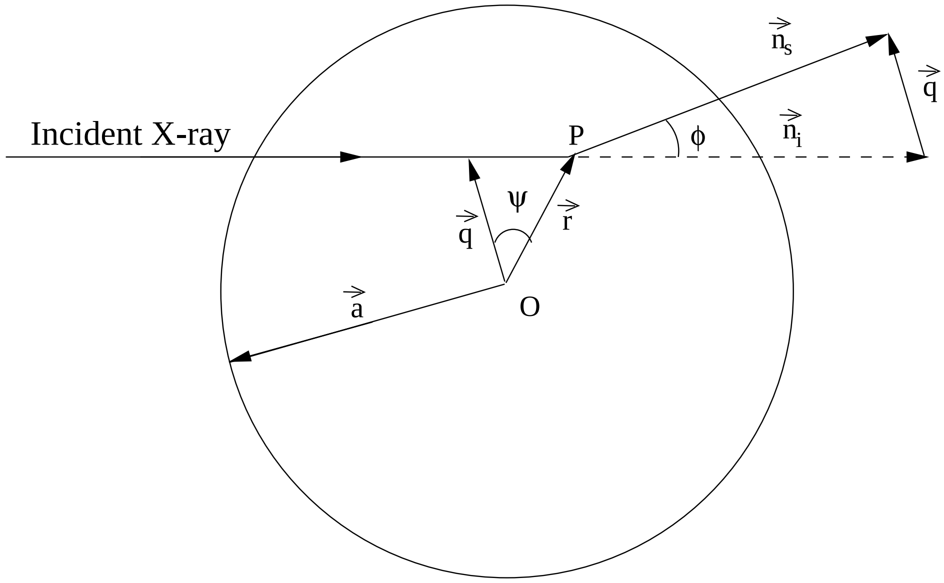
$$\alpha = \frac{m^2-1}{m^2+2} a^3 \tag{2}$$

How can we model the observed halo intensity from an x-ray source?

If dust grains are spherical, then Mie scattering theory always works (but it's a pain). The Rayleigh-Gans approximation will hold if we assume that the *phase* and *amplitude* of the wave inside the dust is close to the incident values:

$$\begin{aligned} |m-1| &\ll 1 \\ ka|m-1| &\ll 1 \end{aligned}$$

For X-rays in normal matter, the first requirement is always met. The second requirement is equivalent to $E_{keV} \gg a_{\mu m}$.




Scattering through small angles means small values of $\vec{q}$, which implies $\vec{q} \cdot \vec{r} \to 0$

When the scattered waves add coherently, the scattering amplitude is $\propto N^2$. Otherwise, the amplitude is only $\propto N$.

The final answer:

$$(\frac{d\sigma}{d\Omega})(E, a, \phi) = 2a^2(\frac{2\pi a}{\lambda})^4|m-1|^2(\frac{j_1(y)}{y})^2(1+\cos^2\phi)$$

where $y = 4\pi a/\lambda \sin(\phi/2)$, and $j_1$ is the first bessel function.

*This is not particularly convenient.*

However, this equation can be well-approximated by a Gaussian. In addition, the index of refraction $m$ has a simple analytic form for high-energy photons:

$$|m-1| \propto \rho/E^2$$

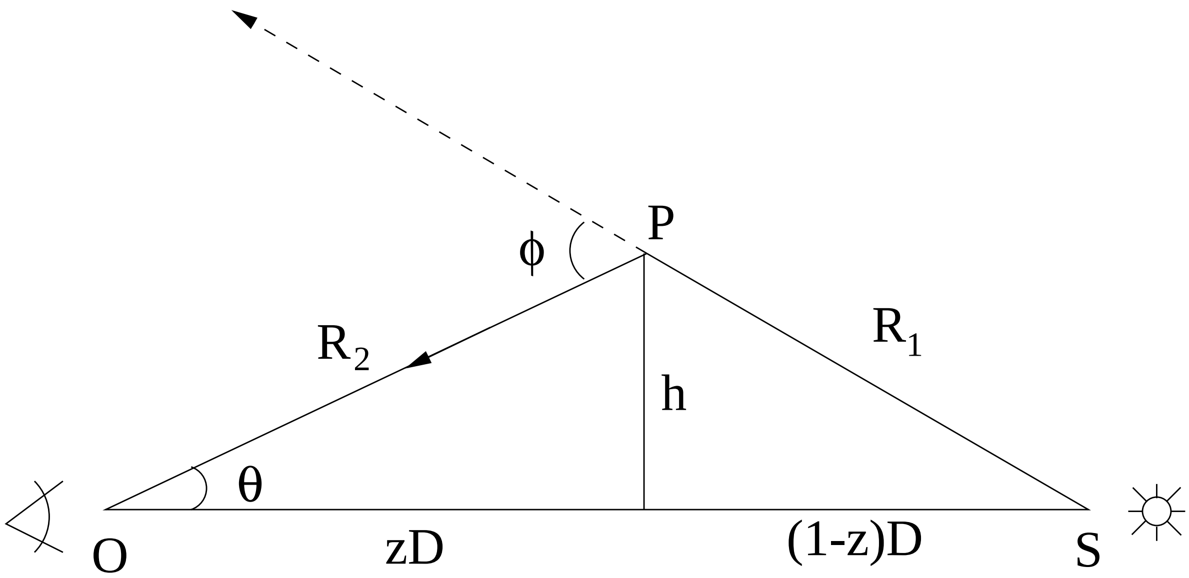
Using these approximations, the above becomes

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

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

The scattering intensity is $\propto N_e^2 \propto \rho^2\, a^6$, as long as the Rayleigh-Gans requirement ($E_{\mathrm{keV}} \gg a_{\mu m}$) is met.

We have $(\frac{d\sigma}{d\Omega})(E, a, \phi)$. We need $I_{\text{halo}}(\theta)$, the observed halo intensity.




For small angles $\theta \approx (1 - z)\,\phi$.

If D = 10 kpc and $\phi = 60''$, the maximum value of h is 1.5 pc.

Since the scattered X-rays travel along nearly the same line of sight as the direct photons,

$$I_{\text{halo}} \propto F_X$$

where $F_X$ is the x-ray flux from the source.

In addition, we'll assume that the individual dust grain parameters (density, size distribution) is independent of position.

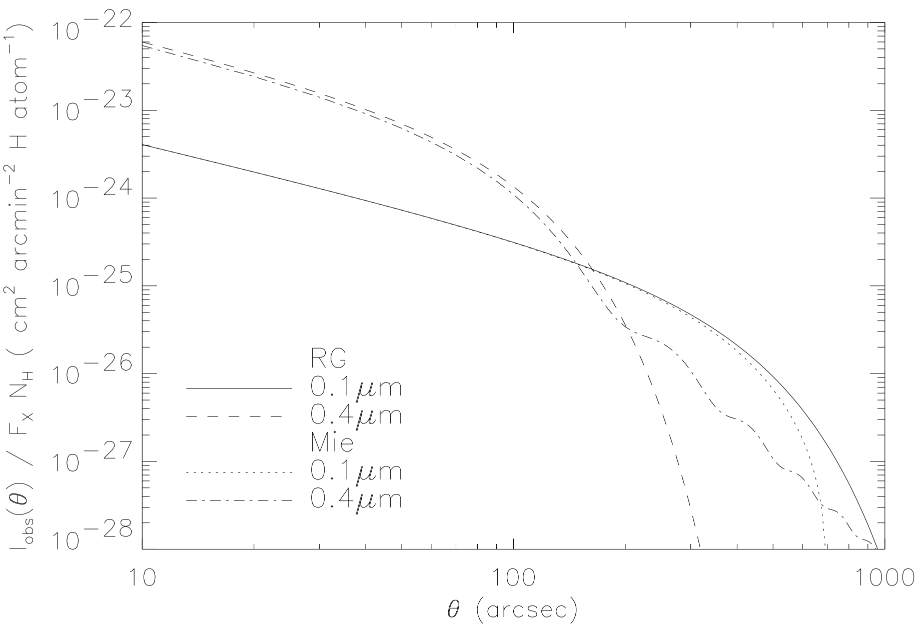
And the final answer is:

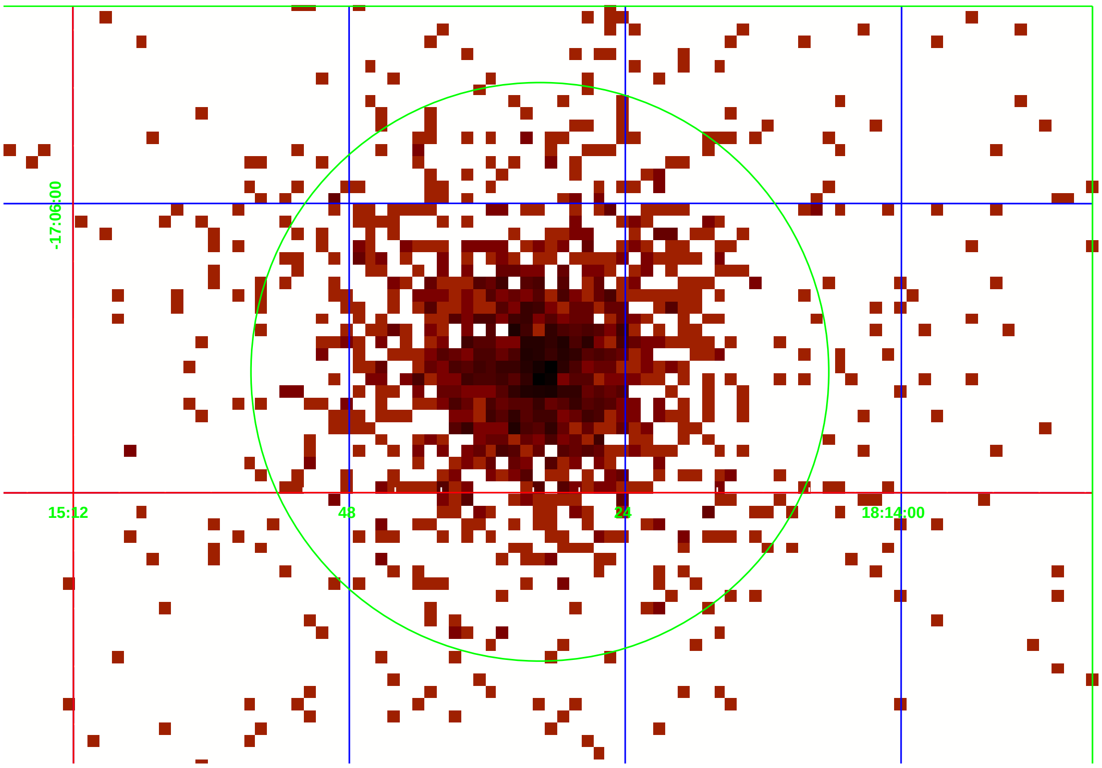
$$I_{sca}(\theta) = N_H F_X \int dE\, S(E) \int da\, n(a) \int \frac{f(z)}{(1-z)^2} \frac{d\sigma}{d\Omega}(E, a, \frac{\theta}{1-z}) dz$$

The halo strength depends upon the following parameters:

- $S(E)$ : Spectrum of the X-rays
- $n(a)$ : Size distribution of the dust grains
- $\rho$ : Density of the dust grains
- $f(z)$ : Distribution of dust along the line of sight

The observed scattering for two single dust grain sizes, smoothly distributed:






X-ray observations of point sources have “halos” due to scattering from large dust grains. Shown here is the halo of GX 13+1, observed with the ROSAT PSPC. The green circle is centered on the source with a radius of 6’.

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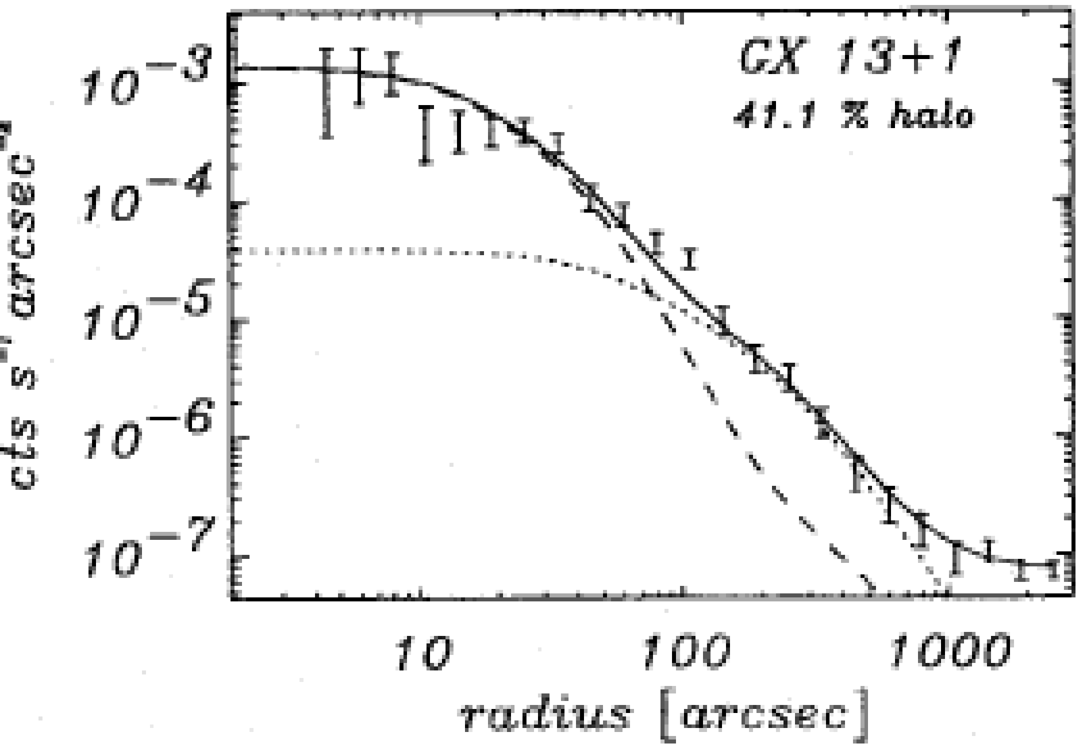
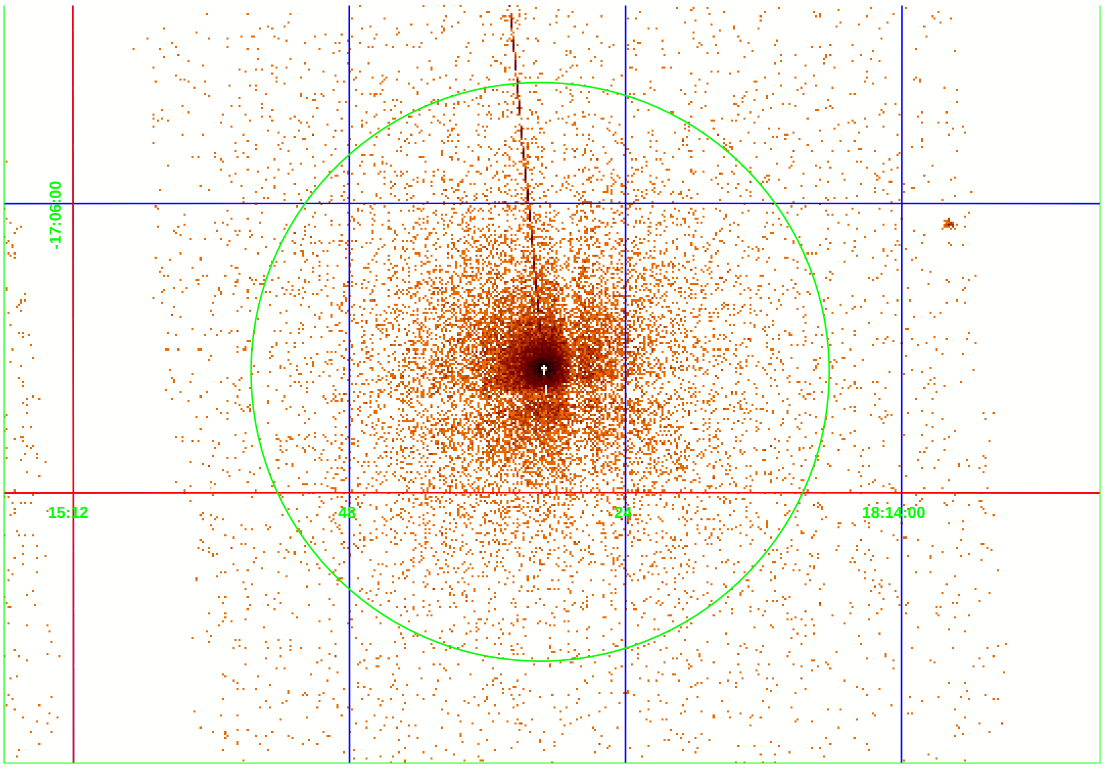



(from Predehl & Schmitt 1995)

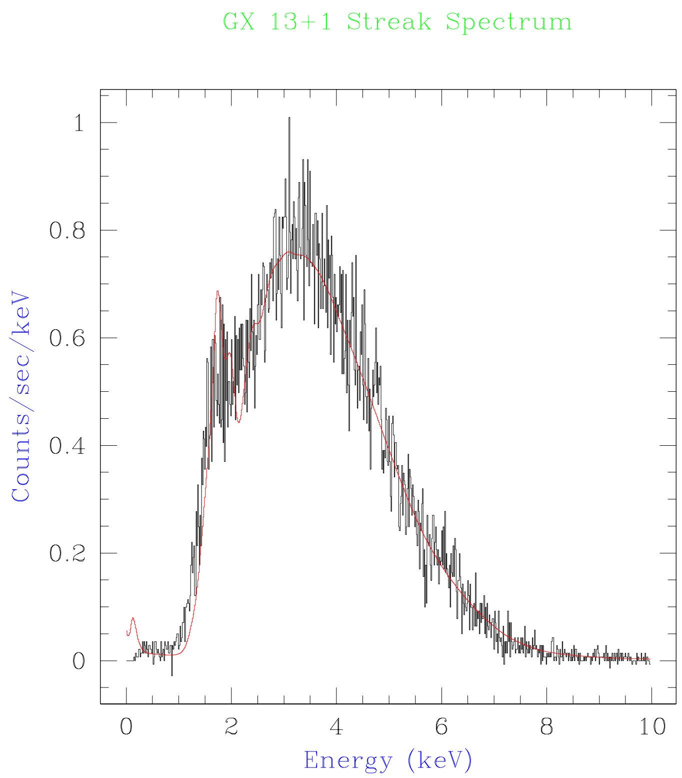
In this case, the halo emission well exceeds the amount expected from the point spread function of the PSPC (solid line) and the background emission (dashed line).

*The radial intensity of an x-ray halo strongly depends upon the size, position, and density of large dust grains, none of which can be otherwise easily measured.*




A 10 ksec exposure of GX13+1 with the Chandra X-ray observatory, with the same circle plotted. A total of $\sim 700,000$ counts were detected, so the source had massive pile-up but the halo was well-determined.

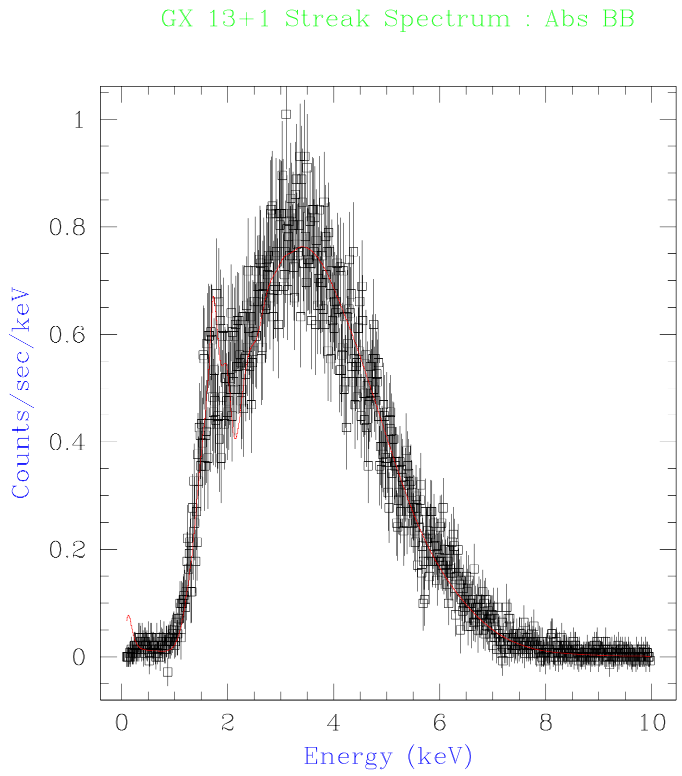
Extracting the spectrum on-axis is impossible, due to pile-up. So we used the transfer streak, which has only 1.25% of the observing time but still had plenty of photons.




We fit the spectrum to an absorbed bremsstrahlung model, getting the results :

- $\mathrm{N_H} = 4.02 \pm 0.09 \times 10^{22}\,\mathrm{cm}^2$
- $kT = 5.4 \pm 0.3\,\mathrm{keV}$
- Normalization $= 3.30 \pm 0.13 \times 10^{-2}$

This column density is slightly in excess of results in the IR, which find $A_V$ in the range $\sim 13.2 - -17.6$ (Charles & Naylor 1992) corresonding to $\mathrm{N_H} \sim 2.5 - 3.3 \times 10^{22}$.



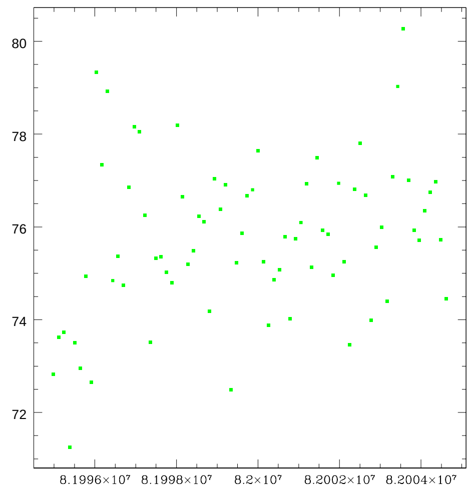

We fit the spectrum to an absorbed blackbody model, getting the results :

- $\mathrm{N_H} = 2.18 \pm 0.07 \times 10^{22}\,\mathrm{cm}^2$
- $kT = 1.15 \pm 0.02\,\mathrm{keV}$
- Normalization $= 4.22 \pm 0.24 \times 10^{-3}$

This column density is slightly less than the value found in the IR.

Despite the very different column densities, the fluxes (except in the lowest-energy channel) are nearly identical

We began by examining the lightcurve for flares (none seen):




Exposure maps were then generated at full resolution for each chip at 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 keV. The data was then cut into 0.5 keV bins centered at those energies. **`funcnts`** was used to calculate the radial profile of the data (after removing sources) and the exposure maps, with 2" and 4" annuli. Then the radial profile of the data was divided by the radial profile of the exposure maps.

Finally, 3C273 was used to estimate Chandra's PSF using the same energy cuts as were used for the data.

Lightcurve analysis can be made particularly easy using S-lang:

```
chips> evalfile("/home/rsmith/slang/analyze_ltcrv.sl")
chips> analyze_ltcrv("3c273_ltcrv.fits")
((time > 77379659.74) && (time < 77381272.03)) ; 1.61 ksec
((time > 77381387.19) && (time < 77399583.03)) ; 18.20 ksec
((time > 77403786.50) && (time < 77404016.83)) ; 0.23 ksec
((time > 77404765.39) && (time < 77405341.21)) ; 0.58 ksec
((time > 77405398.79) && (time < 77406780.75)) ; 1.38 ksec
((time > 77407241.41) && (time < 77407414.15)) ; 0.17 ksec
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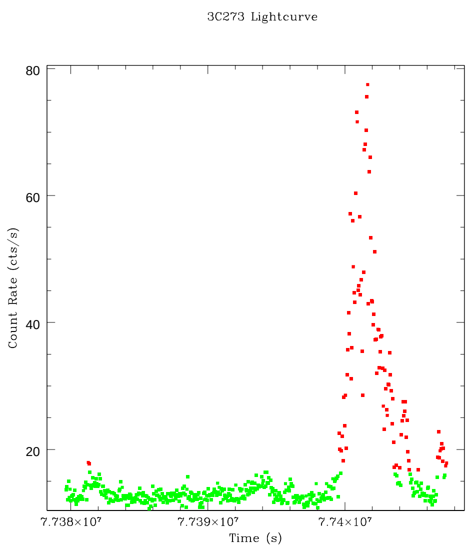
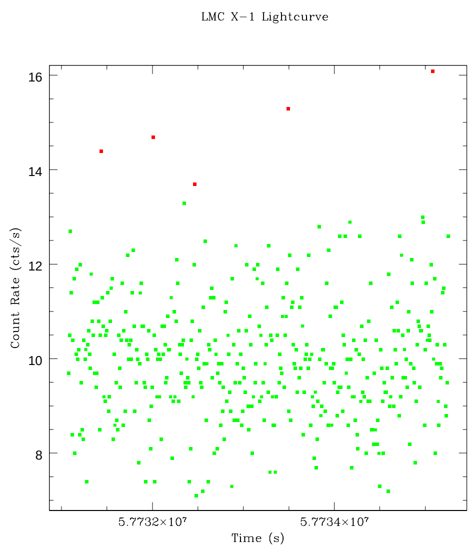
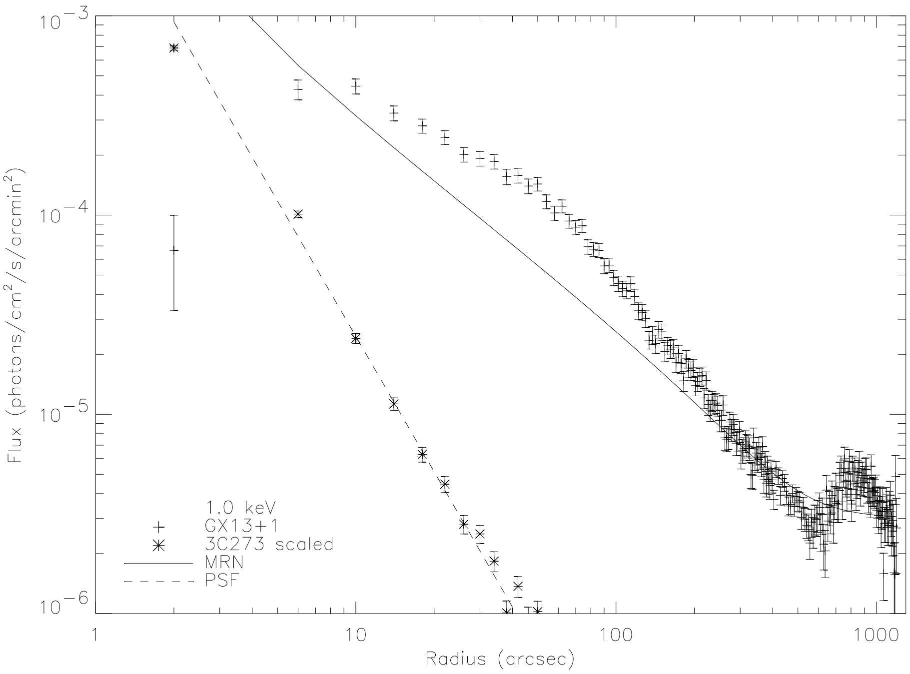
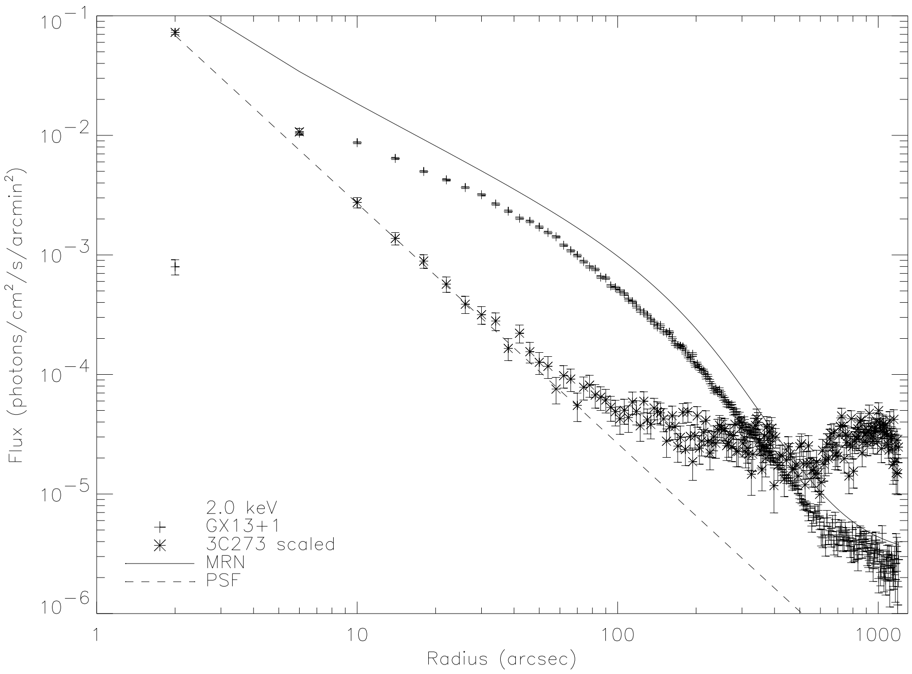




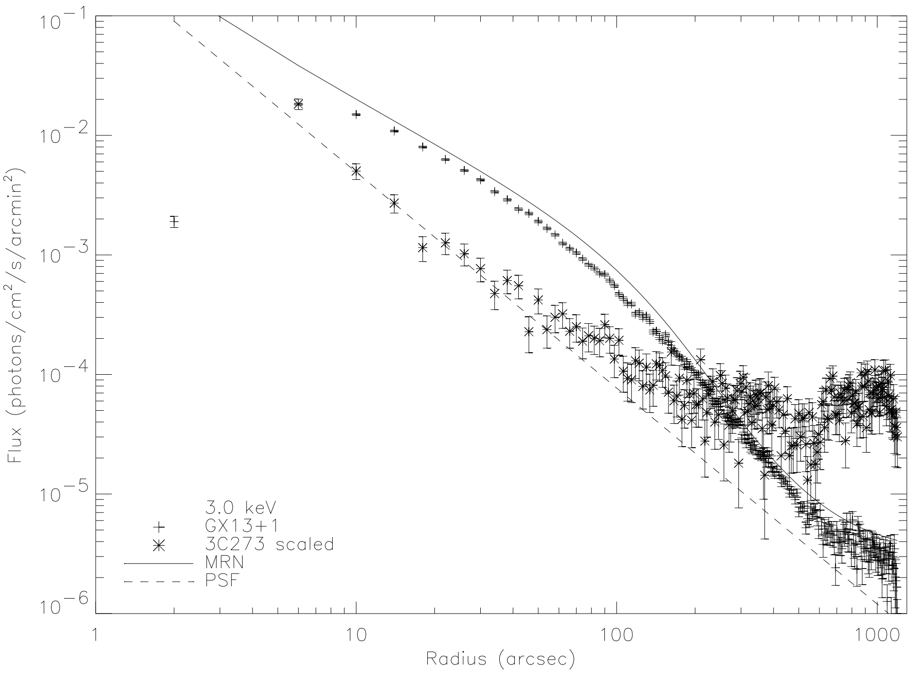

At 1.0 keV, the requirements of the Rayleigh-Gans (RG) approximation are not met, although the halo is usually strongest here. Instead, a full-bore Mie method is required. However, the RG model should *over*predict the data; the result shown here is very strange ($N_H = 4 \times 10^{22}\,\mathrm{cm}^{-2}$ was used). The excess beyond 10' is due to the S3 chip data, and is not yet understood.

The 3C273 data was fit using a simple power-law plus flat background for point $> 10''$ from the source. At 1.0 keV, the fit is quite good with a power-law index of 2.26.

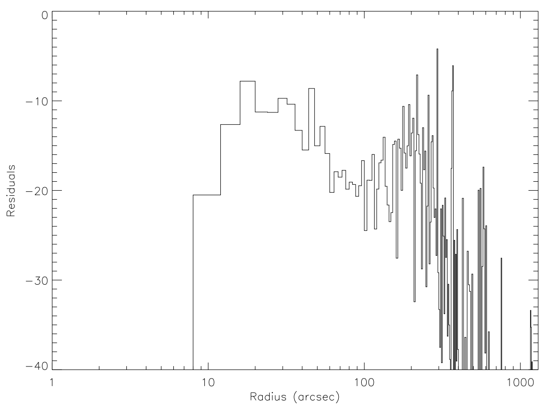



At 2.0 keV, the Rayleigh-Gans approximation should be accurate (so long as the dust grains are spherical). Shown here is a comparison to the Mathis, Rumpl & Nordsieck (1977) (MRN) dust grain model, which has $n(a) \propto a^{-3.5}$ with $a = 0.005 - 0.25\mu$m. In the MRN model, 92% of all silicon and 80% of all carbon is in dust grains. However, new results (Sofia *et al.* 1997) show that the gas-phase abundance of carbon in the ISM is larger than 20% of the total.

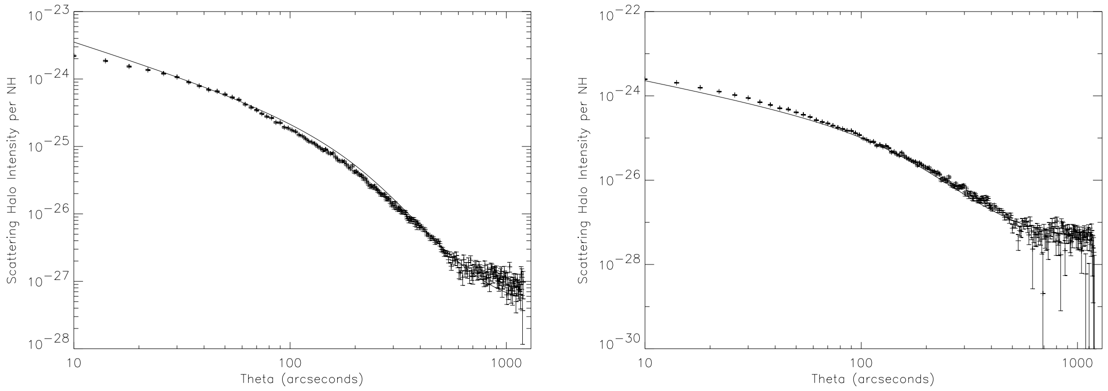
Since the halo is proportional to $\rho^2$, this result allows for so-called "fluffy dust," which has been suggested as a solution to this problem–but only for the $\mathrm{N_H} = 4 \times 10^{22}\,\mathrm{cm}^{-2}$ case.



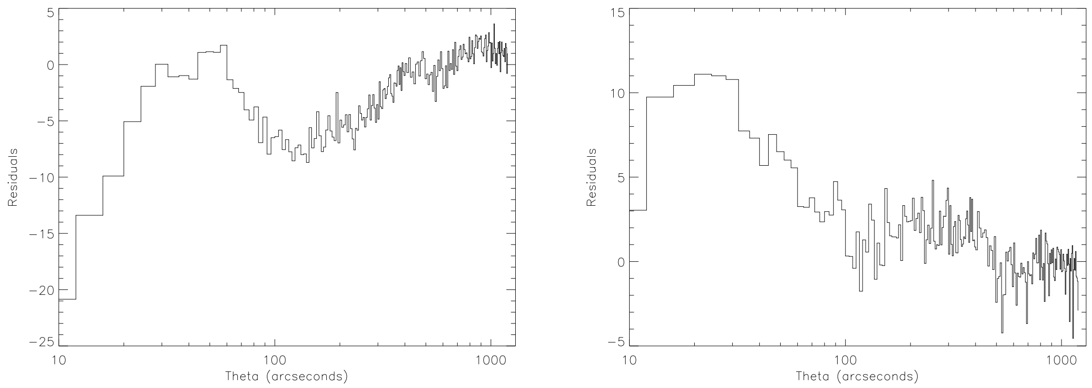

At 3.0 keV, the MRN model qualitatively appears to do a good job with $N_H = 4 \times 10^{22}\,cm^{-2}$, unlike the previous cases. However, the residual plot shows that the fit is really not all that good:



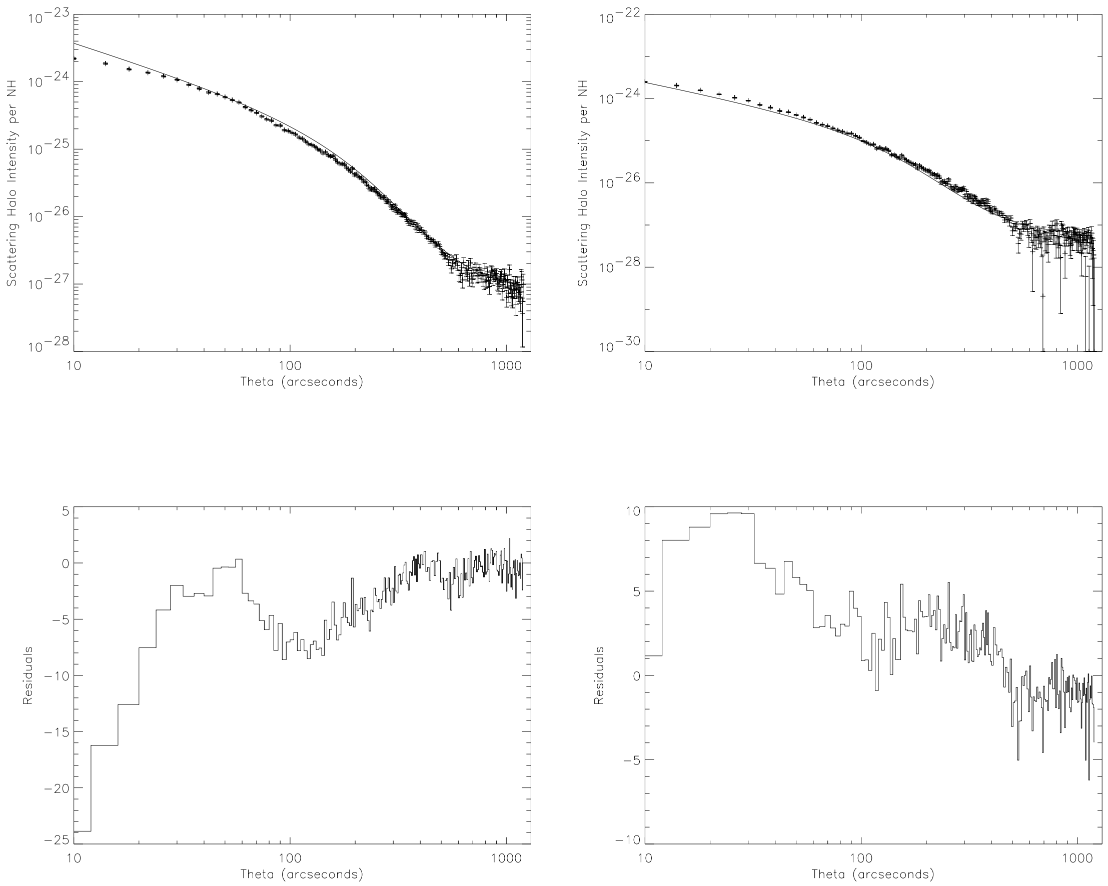
If we simply allow the overall normalization to float (and ignore the lowest two energies, 1.0 and 1.5 keV), we get a good, but not great fit overall with $N_H = 2.44 \times 10^{22}\,\mathrm{cm}^2$. At 2.0 and 3.0 keV, the results look quite good to the eye:



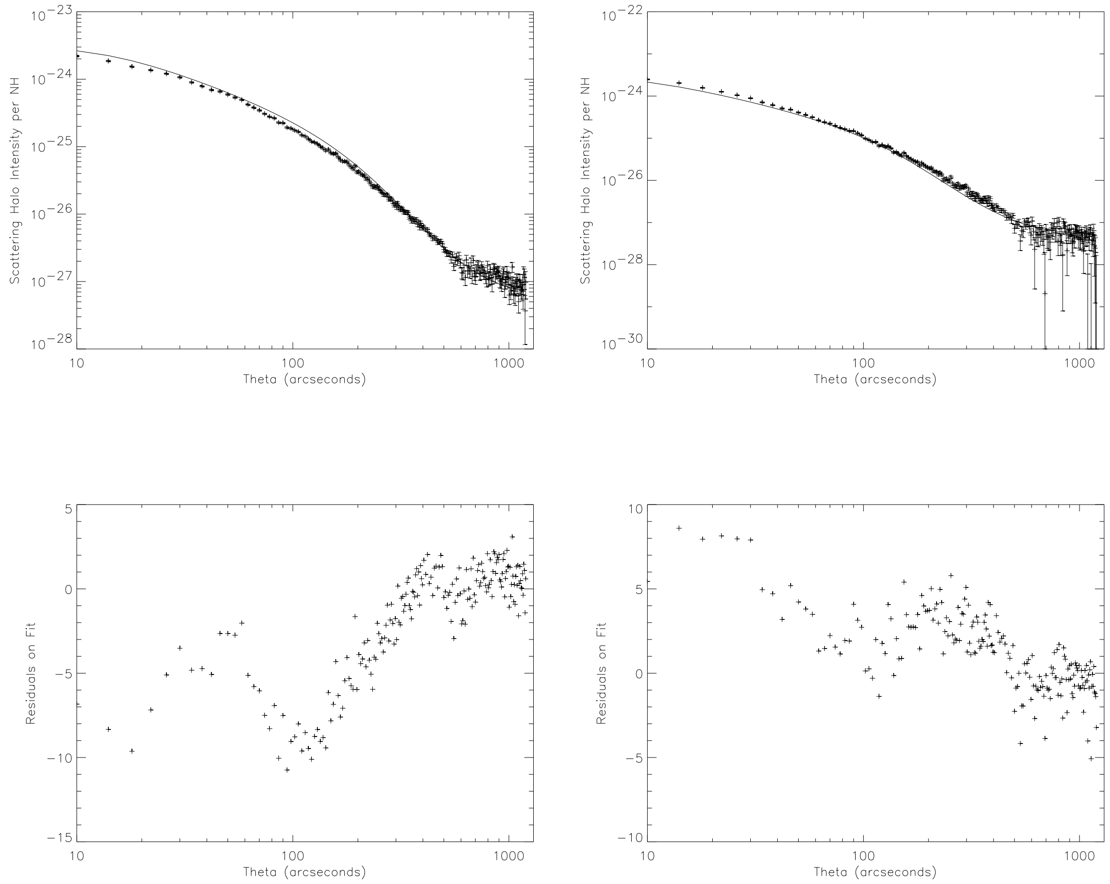

but the residuals tell a different story:



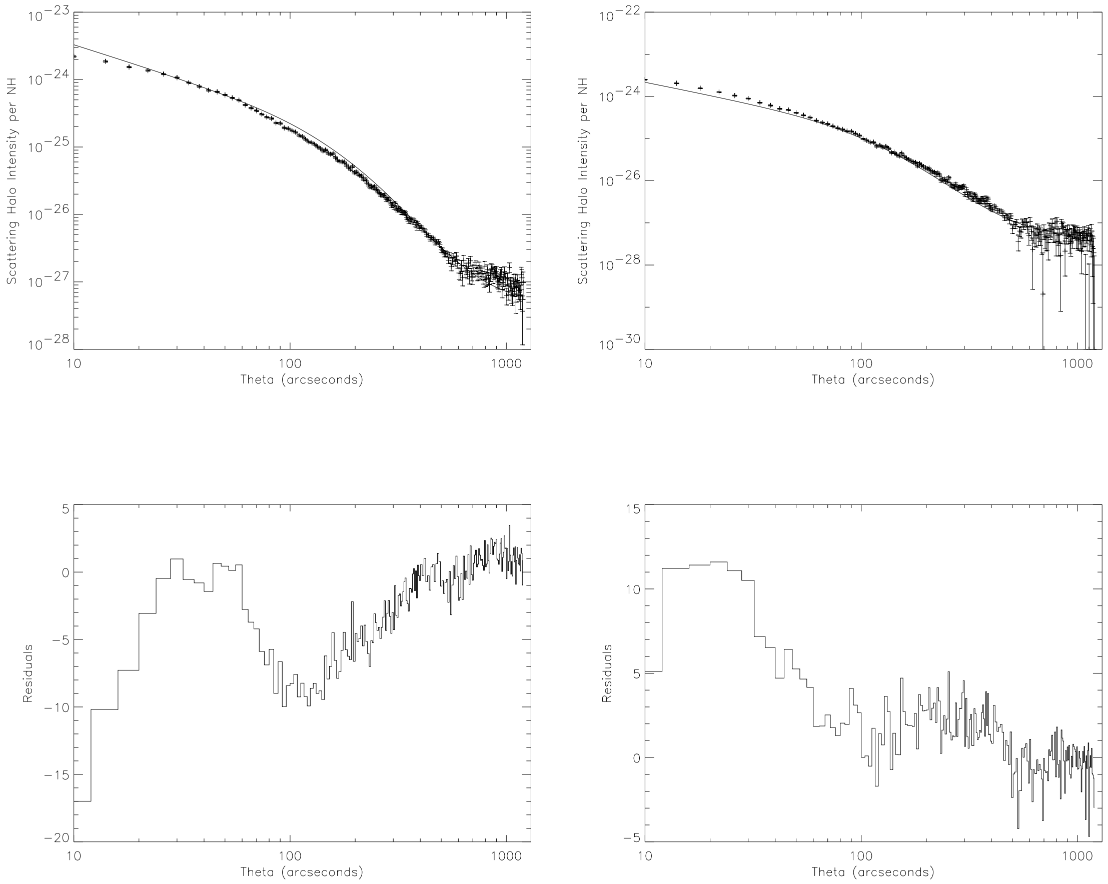
Since the X-ray scattering cross section is $\propto a^6$ larger dust grains are better at scattering X-rays. Allowing $a_{\rm max}$ to float but requiring the same mass in dust, we get a poor fit with $a_{\rm max} = 0.291 \pm 0.002\,\mu$m (forcing $\mathrm{N_H} = 4 \times 10^{22}\,\mathrm{cm}^{-2}$). Allowing it to float, we get $\mathrm{N_H} = 2.26 \times 10^{22}\,\mathrm{cm}^2$, and $a_{\rm max} = 0.268 \pm 0.001\,\mu$m the following fits at 2.0 keV and 3.0 keV:



The position of the dust grains along the line of sight can also be allowed to vary; in this case the result is $N_H = 2.35 \times 10^{22}\,\mathrm{cm}^{-2}$, and dust grains evenly distributed in the range $0.11 - 0.95$D, where D is the distance to GX 13+1. The fit, however, is not particularly good.

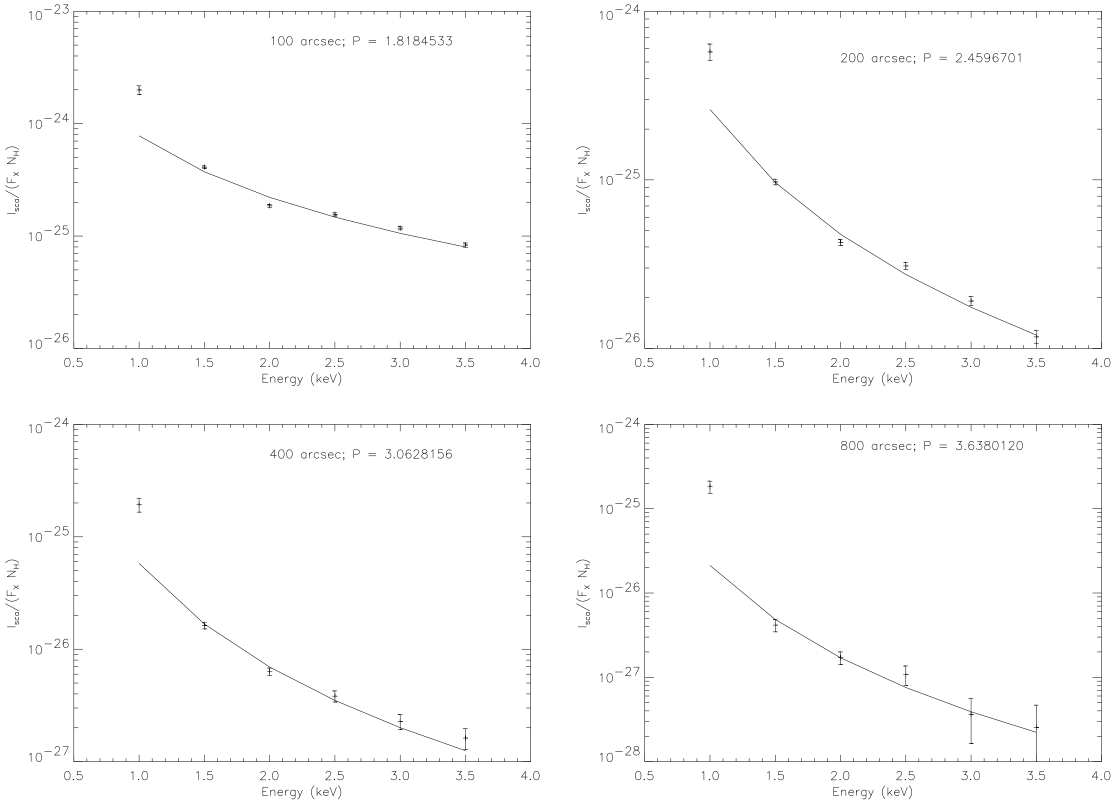


Allowing an additional molecular cloud to add scattering at a particular position helps somewhat, but does not fully answer the problems. This fit adds a cloud with $N_H = 3.8 \times 10^{21}\,\mathrm{cm}^{-2}$ at about 40% of the distance to the cloud.



## Energy Profile

So far, we've seen good qualitative fits to the radial profile at particular energies, but they fail quantitatively. We can also look at the data as a function of energy for particular halo angles, such as 100″, 200″,400″, and 800″. If the RG model holds, these should show an $E^{-2}$ dependence:

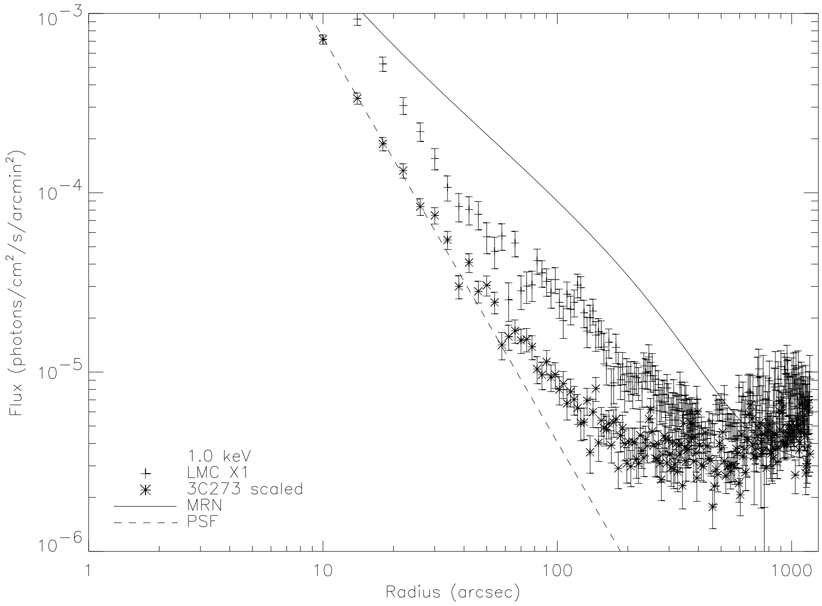


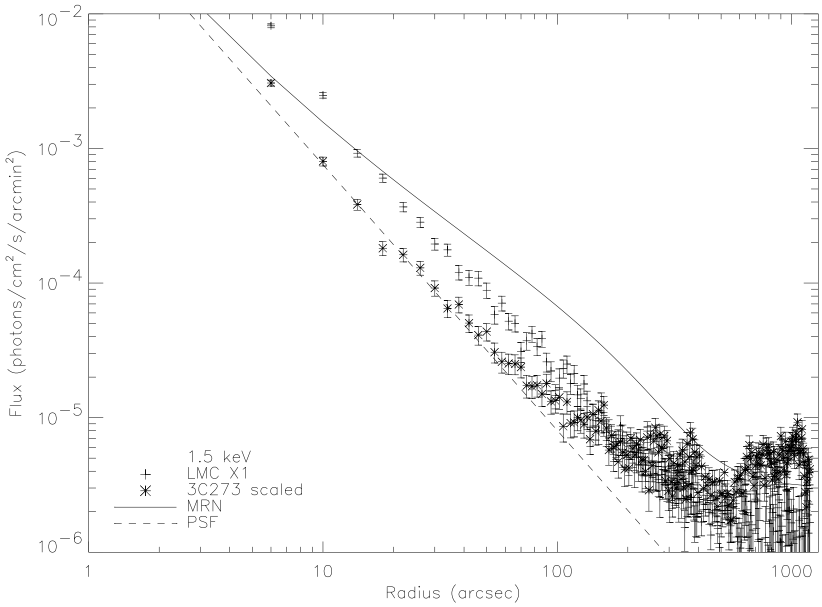

The $E^{-2}$ comes from an approximation of the dust grains as bundles of free electrons; this relatively poor fit suggests either that details of the ACIS response are not being handled well, or that the binding energy of the electrons is playing a role in the scattering.

This is a work in progress; few real conclusions can be made at this point:

- At 2.0 keV and higher energies, the RG approximation seems to work well–although the energy dependence must be examined more closely.
- Understanding the source spectrum is key, since the dust density can play directly off the absorbing column density.
- The MRN model fits the data in its gross features quite well.
- Even after allowing the maximum dust size to float, it returns to $\sim 0.25\,\mu$m.
- The dust grain position along the line of sight appears to be quite smooth.
- Despite their near-equal probability, the blackbody fit gives an $N_H$ value which agrees much better with the halo data than the bremsstrahlung.

At 1.0 and 1.5 keV:



At 2.0 and 2.5 keV: