A New Method to Use Chandra Data to Resolve the X-Ray Halos Around Point Sources and Its Application to Cygnus X-1

Y. Yao, S. Nan Zhang, X. L. Zhang, Y. X. Feng

Physics Department, University of Alabama in Huntsville, Huntsville, AL 35899
National Space Science and Technology Center, 320 Sparkman DR., SD50, Huntsville, AL 35805

yaoy@email.uah.edu, zhangsn@email.uah.edu, xizhang@jet.uah.edu, fengyx@jet.uah.edu

ABSTRACT

The excellent angular resolution, good energy resolution and broad energy band make Chandra ACIS the best instrument for studying the X-ray halos around some galactic X-ray point sources caused by the dust scattering of X-rays in the interstellar medium, but the direct images of bright sources obtained with ACIS usually suffer from severe pile-up. Making use of the fact that an isotropic image could be reconstructed from its projection on any direction, we can reconstruct the images of the X-ray halos from the data obtained with the regular HETGS and/or the CC mode. These data are nearly or totally pile-up free and enable us to take full advantage of the excellent angular resolution of Chandra. With the reconstructed high resolution images, we can probe the X-ray halos as close as 1'' to their associated point sources. Applying this method to Cygnus X-1 observed with Chandra HETGS in CC mode, we derive an energy dependent radial halo flux distribution and conclude that, for a 1' region around the point source: (1) relative to the total intensity, the fractional halo intensity in Cygnus X-1 is about 35% at about 1 keV and drops to about 10% at around 6 keV; (2) about 50% of the halo photons is within less than 30'' region; and (3) the spectrum of the point source is distorted by the halo contamination, especially in the soft energy band below 3 keV.

Subject headings: dust, extinction — X-rays: ISM — X-rays: binaries — X-rays: individual (Cygnus X-1)
1. Introduction

Small-angle scatterings between X-rays and dust grains in the interstellar medium (ISM) form halos of diffuse emission around X-ray point sources. The spectrum and the intensity distribution of an X-ray halo depend on the properties of the ISM along the line-of-sight, i.e., density distribution of the dust, the dust grain size and the chemical composition of the grains (Overbeck 1965; Hayakawa 1970; Martin & Sciama 1970; Mathis, Rumpl & Nordsieck 1977; Predehl & Klose 1996). Because of the ISM absorption and scattering, the X-ray energy band provides advantages over other wave bands in studying the interstellar dusts.

The existence of the dust scattering halos was first discussed by Overbeck (1965) and was first observationally confirmed by Rolf (1983) using the data of GX339-4 with the Einstein Observatory. Using the High Resolution Imager (HRI) aboard on Einstein Observatory, Catura (1983) and Bode et al. (1985) also confirmed the existence of X-scattering halos around point sources GX 3+1, GX 9+1, GX 13+1, GX 17+2 and Cygnus X-1. The recent main results on X-ray halo studies were reported by Predehl & Schmitt (1995) by systematically examining 25 point sources and 4 supernova remnants with the ROSAT observations, and by Smith, Edgar & Shafer (2002) by studying the data of GX 13+1 with Chandra.

The conventional method to get the X-ray halo image is subtracting the point source image predicted by the point source flux and the point spread function (PSF or point response function) of the instrument from the observed X-ray image. However, the relatively poor angular resolutions of previous instruments (1' for IPC/Einstein and 25'' for PSPC/ROSAT) limit the estimation accuracy of the halo flux close to the point source. The Advanced CCD Imaging Spectrometer (ACIS) aboard on Chandra X-ray Observatory, with its excellent angular resolution (0.5'' FWHM in PSF), broad energy band (0.2 – 10.0 keV) and reasonably good energy resolution ($E/\Delta E = 10 – 60$), is the most promising instrument to date in the X-ray halo study. However, the regular timed exposure (TE) mode of ACIS, which is the mode with two-dimensional (2-D) imagery, often suffers from severe pile-up, because of the 3.2 second exposure time per frame (pile-up is caused by two or more photons impact one or more adjacent pixels in a single frame time). Therefore bright X-ray point sources will “burn” a hole at the source position and most photons from the source will be lost. In this case, we are not able to estimate the source flux, nor the halo profile near the point source (see, e.g., Smith et al. 2002).

The pile-up problem is non-existent or much less serious in the data of regular transmission grating observations and the data from the Continuous Clocking (CC) mode observations. However, the CC mode data only provide one-dimensional (1-D) intensity distribution. The grating data, though provide 2-D information, are already dispersed by the grating instruments in an energy dependent way. In this letter, we propose a new method
to reconstruct the X-ray scattering halos associated with X-ray point sources from the CC mode data and/or the transmission grating data. This method enables us to probe the halo intensity distribution in a broad energy band as close as 1" to the point source. After testing it with the MARX simulation, we apply this method to Cygnus X-1 observed with Chandra in CC mode.

2. METHODOLOGY AND SIMULATION

The operation principle of Chandra transmission grating is that, X-rays reflected by the High Resolution Mirror Assembly (HRMA), will be diffracted by the transmission grating (in one dimension) by an angle $\beta$ according to the grating equation,

$$p \sin \beta = m \lambda,$$

where $p$ is the spatial period of the grating lines, $\beta$ is the dispersion angle, $m$ is the grating order number ($0, \pm 1, \pm 2, \pm 3, \cdots$), and $\lambda$ is the photon wavelength in angstrom $^1$. The zeroth order image ($m = 0$) is the same as the direct image, except for a smaller flux due to the diffracted photons. For a mono-energy point source, Chandra transmission grating will detect exactly the same halo intensity distribution in its higher order grating images as in its zeroth order image, as long as the halo size is not too large (for instance, less than 3"), as shown in Fig. 1. If we project the secondary and higher order photons to a line perpendicular to the grating arm, the projected 1-D image will be the same as the projection of the zeroth order image, except for a scaling factor caused by the different effective areas. Because the grating only diffracts photons along the direction of the grating arm, the above projection is also valid for a source with a continuum spectrum. Usually the none-zeroth order grating images are free from pile-up, so are the CC mode data. Therefore we can use either the 1-D zeroth order data from CC mode or the 2-D higher order grating data to reconstruct the original image.

If the flux of a point source plus its X-ray halo is isotropically distributed and centered in the point source as $F(r)$, and the projection process described above can be represented by a matrix operator $M(r, d)$, the projected flux distribution $P(d)$ is therefore related to $F(r)$ and $M(r, d)$ through the following equation,

$$P(d) = F(r) \times M(r, d),$$

$^1$http://cxc.harvard.edu/proposer/POG/html/HETG.html
where $r$ is the distance from the centroid source position and $d$ is the distance from the projection center (refer to Fig. 1). If the inverse matrix $M^{-1}(r,d)$ of the operator $M(r,d)$ exists, the original distribution can be easily resolved by the equation,

$$F(r) = P(d) \times M^{-1}(r,d).$$  \hspace{1cm} (3)

We then use the numerical integration to approach the above projection process and build a matrix to approximate the integration. Fortunately, the matrix has a triangular shape and its inverse matrix can be easily calculated.

To test our method, we use MARX 3.0 simulator\(^2\) to simulate a point source and two disk sources to mimic the real point source associated with an X-ray halo observed with Chandra High Energy Transmission Grating Spectrometer (HETGS) in regular TE data mode. Using the intrinsic CCD energy resolution, we extract the photons at the energy range 1.0-1.5 keV and demonstrate our test in this energy band. To mimic the CC operating mode, we simply project the photons in the zeroth order image along any direction to get a 1-D image. We also obtain projected 1-D images from the 2-D grating data. We then apply our method to these 1-D images to resolve the flux distributions of the point source plus its halo. For the CC mode data, we use the flux distribution of the simulated point source (without halo) as the PSF. For the grating data, we perform the same resolving procedure to the grating data to get the flux distribution of the simulated point source (without halo) and take it as the PSF of the grating. The halo flux can be obtained by subtracting the corresponding PSFs from the flux of source plus halo. Because HETGS produces four different grating arms (positive/negative MEG/HEG) and results inferred from the data of these arms are quite similar to each other, we only report the results from the negative MEG arm. The projections and reconstruction results are shown in Fig. 2.

From Fig. 2, we can see that the halo flux distribution inferred both from mimicked CC mode data and from data of negative MEG arm are reasonably consistent with the distribution directly calculated from the zeroth order image, which implies that the method we proposed is a feasible way to resolve the intensity distribution of X-ray halos associated with point sources. In the following section, we will apply the method to Cygnus X-1 observed with Chandra CC operation mode.

\(^2\)http://space.mit.edu/ASC/MARX
3. APPLICATION TO CYGNUS X-1

Cygnus X-1 is the first dynamically determined X-ray binary system to harbor a black hole and has been observed with Chandra for seven times to date (2003 February 14). Four of these observations were operated with TE data mode, and during all of these four observations, the source is so bright that it causes pile-up not only in the zeroth order image but also in the grating images. The only short-frame observation (1999 October 19) is almost pile-up free in its grating image, but the statistical quality of the data is poor. The other three observations use the CC mode. We apply our method to the one with the highest statistical quality, which was observed on 2000 January 12 with effective exposure 12.7 kiloseconds and is nearly pile-up free. To avoid crossing with the MEG arm, we limit our halo study within 1′ from the source position. The results are reported in Fig. 3. The halo can be clearly resolved as close as 1″ to the point source. The fractional halo intensity as a function of photon energy is shown in Fig. 4(a); the fraction drops from about 35% at around 1 keV to about 10% at about 6 keV. We define the half-flux radius of the halo as the radius within which the halo includes 50% of the total halo photons. The half-flux size of the halo as a function of energy is shown in Fig. 4(b); for a region of 1′ around the point source, 50% of the halo photons are concentrated within 30″. We also investigate how the halo affects the source spectrum in Cygnus X-1 system and the results are reported in Fig. 4(c) and Fig. 4(d). The halo spectrum is softer than the point source spectrum, especially in the soft energy band (below 3 keV), which makes the source plus halo spectrum different from the original point source spectrum not only in total flux but also in the spectral shape.

To avoid underestimating the wings of Chandra PSF by the MARX simulator, we follow the step of Smith et al. (2002) and use Her X-1 to make a check (Her X-1 is a “real” point source and almost halo free). We did a quick analysis of the calibration observation of Her X-1 on 2002 July 1 with effective exposure about 50 kilo-seconds and found that beyond 15″, pile-up is not noticeable. We then calculate the energy dependent radial flux of Her X-1 and use them to replace our simulated PSFs at off-axis angle 15″ to 60″. The difference of our results between using of different PSFs is negligible.

4. CONCLUSION AND DISCUSSION

In this letter, we propose a new method to reconstruct the image from the CC mode data and/or grating data, and then use the reconstructed image to resolve the X-ray halos associated with point sources. With this method, the high angular resolution of the Chandra Observatory allows us to probe the intensity distribution of the X-ray halos as close as 1″ to their associated point sources. This method is tested with the MARX simulation and
applied to Cygnus X-1.

The fractional halo intensity in Cygnus X-1 is energy dependent, but does not seem to follow the $E^{-2}$ relationship reported by Predehl et al. (1995). In the soft energy band, the fractional halo intensities we obtained are much higher than the previous report by Predehl et al. (1995) (11% at the ROSAT energy range 0.1-2.4 keV), even though we limit our calculation to a 1′ region around the point source (it is expected to be even higher at outer region, e.g., at 2′, $\sim$ 70% at the HRI energy range 0.15-3.0 keV (Bode et al. 1985)). This discrepancy, we believe, is caused by the different angular resolution of different instruments.

According to our results, for a region about 1′ in Cygnus X-1 system, 50% of the total halo photons is within 30″ around the point source, and if the angular resolution of an instrument is no much better than 30″, the accuracy of the halo estimation will be limited.

The existence of the halo around a point source distorts the spectrum of the point source. Because cross-section of the scattering process in the ISM is energy dependent, the halo spectrum is different from the point source spectrum (Fig. 4(c)). Therefore if the instrument is unable to resolve the point source from the halo, the source spectrum will be contaminated; this is the case for most X-ray instruments prior to Chandra. Many of the previous measurements of the continuum X-ray spectra of galactic X-ray sources with significant X-ray scattering halo may suffer from this problem. More detailed work is needed to quantitatively describe the spectrum distortion in Cygnus X-1 system, and systematic studies of the X-ray halo distribution in the broad band should be carried out for other X-ray sources with significant X-ray scattering halos, before we can draw any conclusion on the significance of the halo introduced distortion to their X-ray continuum spectra.

In this letter, we did not fit the energy dependent behavior of the halo with any halo model to constrain the physical properties of the dust grains, such as the dust grain size and chemical abundance. The broad energy band of the Chandra ACIS compared with ROSAT PSPC will allow detailed studies of the dust chemical abundance. We will address this issue in our future work.

This work was supported in part by NASA Marshall Space Flight Center under contract NCC8-200 and by NASA Long Term Space Astrophysics Program under grants NAG5-7927 and NAG5-8523.

REFERENCES

Bode, M. F., Priedhorsky, W. C., Norwell, G. A. & Evans, A. 1985, ApJ, 299, 845
Catura, R. C. 1983, ApJ, 275, 645
Hayakawa, S. 1970, Progr. Theor. Phys., 43, 1224
Martin, P. G. & Sciama, D. W. 1970, Ap. Letters, 5, 193
Mathis, J. S., Rumpl, W. & Nordsieck, K. H. 1977, ApJ, 217, 425
Overbeck, J. W. 1965, ApJ, 141, 864
Predehl, P. & Schmitt, J. H. M. M. 1995, A&A, 293 889
Predehl, P. & Klose, S. 1996, A&A, 306, 283
Rolf, D. P. 1983, Nature, 302, 46
Smith, R. K. & Edgar, R. J. 2002, ApJ, 581, 562
Fig. 1.— Projection of the photons along the grating arm and the photons in zeroth order image. See text for explanation.
Fig. 2.— The reconstruction of the intensity distribution of a simulated X-ray point source with halo in the energy band 1.0–1.5 keV. Panel (a): from the projected zeroth order image. Panel (b): from MEG negative orders. The curve with the diamond symbols and the dashed line are the projected photon distribution (cts/sec). The triangle symbols are for the reconstructed halo distribution, after subtracting the PSF of the source (cts/sec/arcsec$^2$). The solid line is the halo distribution from the zeroth order image of the simulated halo (no pile-up in the simulation).
Fig. 3.— The flux distribution of Cygnus X-1 with its halo and the PSF at different energy bands. In each panel, the dashed line indicates the projected flux distributions calculated directly from the observation (cts/sec), the dotted line is the resolved flux distributions of the source with halo (cts/sec/arcsec$^2$), the dash-dot line is the corresponding PSF at that energy range (cts/sec/arcsec$^2$), scaled to the first point of the resolved intensity distribution, the solid line is the corresponding radial flux profile of Her X-1 (cts/sec/arcsec$^2$) and the turn-off in the central region is due to pile-up.
Fig. 4.— Panel (a): fractional halo intensity relative to the total intensity, as a function of energy. The dotted line indicates the best fit $I(E) = (31.2 \pm 0.6)(E/1 \text{ keV})^{-0.54 \pm 0.02}$. Panel (b): the half-flux size of the halo as a function of energy. Panel (c) and (d) show the spectrum of Cygnus X-1 in unit of cts/s/keV/cm$^2$. Panel (c), from top to bottom, the spectrum of the source with halo contamination, the point source spectrum and the halo spectrum. Panel (d), the ratio of the spectra between the source with halo contamination and the point source (dotted line), the ratio between the halo and the pure point source (dashed line).