A Dust-scattering Halo of 4U 1630–47 Observed with Chandra and Swift: New Constraints on the Source Distance

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Abstract

We have observed the Galactic black hole transient 4U 1630–47 during the decay of its 2016 outburst with Chandra and Swift to investigate the properties of the dust-scattering halo created by the source. The scattering halo shows a structure that includes a bright ring between 80″ and 240″ surrounding the source, and a continuous distribution beyond 250″. An analysis of the 12CO J = 1–0 map and spectrum in the line of sight to the source indicates that a molecular cloud with a radial velocity of −79 km s⁻¹ (denoted MC −79) is the main scattering body that creates the bright ring. We found additional clouds in the line of sight, calculated their kinematic distances, and resolved the well known “near” and “far” distance ambiguity for most of the clouds. At the favored far-distance estimate of MC −79, the modeling of the surface brightness profile results in a distance to 4U 1630−47 of 11.5 ± 0.3 kpc. If MC −79 is at the near distance, then 4U 1630−47 is at 4.7 ± 0.3 kpc. Future Chandra, Swift, and submillimeter radio observations not only can resolve this ambiguity, but also would provide information regarding properties of dust and the distribution of all molecular clouds along the line of sight. Using the results of this study we also discuss the nature of this source and the reasons for the observation of an anomalously low soft state during the 2010 decay.

Key words: dust, extinction – stars: individual (4U 1630–47) – X-rays: binaries

1. Introduction

Galactic black hole transients (GBHTs) are sources that allow one to study strong gravity, accretion, and outflows, as well as the surroundings by using them as luminous probes. GBHTs undergo outbursts where the luminosity can change by a factor of ∼10⁷. The multiwavelength observational properties change during outbursts, generally obeying a general trend in their evolution (Belloni 2010). Outbursts start in the hard state with a power law that dominates the ∼1–20 keV spectrum and stays hard as the mass accretion rate from the secondary

1.1. 4U 1630–47

Among many GBHTs studied, one source stands out as peculiar: 4U 1630–47. This source has had a large number of outbursts, allowing us to compare its spectral evolution in different outbursts (see Figure 1).

At least one well studied outburst follows the typical hysteresis pattern described in Tomsick & Kaaret (2000). However, most other outbursts have shown very different behavior (Abe et al. 2005; Tomsick et al. 2005). In the 2010 outburst decay, using Neil Gehrels Swift Observatory (hereafter Swift) XRT, a very low-luminosity soft state has been discovered, at $L / L_{\text{Edd}} = 0.03 M_{10}^{-1}\%$ (with bolometric correction, distance taken as 10 kpc) where $M_{10}^{-1}$ is the mass of the black hole in units of $10^9 M_\odot$ (Tomsick et al. 2014, hereafter T14). Apart from the erratic outburst behavior, another peculiarity is the apparent baryonic content of the jet. The baryonic jet interpretation is based on modeling the iron line features observed simultaneously with radio originated from a local jet (Díaz Trigo et al. 2013). We must note that models without the presence of baryonic jets can explain the data as well (Wang & Méndez 2016), and an even a simpler explanation could be that the radio emission is unrelated to iron line features, because it is caused by the interaction of a previously launched jet with a thick interstellar medium (ISM) (Neilsen et al. 2014).

Why does 4U 1630–47 behave differently than other sources? First of all, this source is behind a high and varying hydrogen column density (Augusteijn et al. 2001; T14). Second, the source is surrounded by a dust-scattering halo (DSH) as evidenced by archival Chandra and Swift observations (see Section 3). Our hypothesis is that some of the peculiarities of 4U 1630–47 can be explained with the presence of a local dust cloud, and to test this hypothesis we analyzed archival Chandra data together with recently obtained data taken at the end of the 2016 outburst utilizing our Chandra observing program and Swift TOO observations. While it is well known that dust scattering affects the X-ray spectra of X-ray binaries (Smith et al. 2016, and references therein), to the best of our...
knowledge, the effects of a DSH on spectral properties at very low luminosity levels have not been studied extensively.

1.2. Dust-scattering Halos

Studies with DSHs (Overbeck 1965; Mathis & Lee 1991; Predehl & Schmitt 1995), especially in high-mass X-ray binaries (HMXBs), have been used to understand spectral variations during eclipses (Audley et al. 2006), the physical properties of the dust grains and their distribution along the line of sight (Xiang et al. 2011; Corrales et al. 2015), X-ray extinction (Predehl & Schmitt 1995; Corrales et al. 2016), and to calculate the distance to the source by relating changes in DSH profile to flares or long-term X-ray evolution of the sources (Trümper & Schönfelder 1973; Thompson & Rothschild 2009; Xiang et al. 2011).

If a source exhibits outbursts followed by a long period of quiescence, the dust-scattered emission takes the form of discrete rings. The main reason for this is that most of the dust along the line of sight to a source would be in molecular clouds, and each ring is due to a single cloud producing delayed scattered emission as X-rays traverse a longer path than the X-rays directly observed by the telescope (Heinz et al. 2016, and references therein). A cartoon image of the dust-scattering geometry for singly scattered emission is given in Figure 2.

As the behavior of 4U 1630–47 and the nature of Swift and Chandra observations are similar to those of V404 Cyg in its 2015 outburst, we followed a similar methodology to analyze our data as Heinz et al. (2016). The relevant formulation is derived from simple geometrical arguments.

The delay in the arrival time of scattered photons (Δt) from a source at distance D and from a dust cloud at xD is given by

$$\Delta t = \frac{xD \theta^2}{2c(1-x)}$$  \hspace{1cm} (1)

where c is the speed of light. The observed intensity of a ring due to single scattering from a cloud (with thickness CT much less than D and outburst timescale shorter than or comparable to Δt) is

$$I_{c,r} = N_{H,r} \frac{d\sigma_{\text{sc,E}}}{d\Omega} F_r(t = t_{\text{obs}} - \Delta t) \exp\left[-\frac{\sigma_{\text{ph,E}}}{1-x} \sum_{i=1}^{r} N_{H,r}\right]$$  \hspace{1cm} (2)

where $\frac{d\sigma_{\text{sc,E}}}{d\Omega}$ is the differential dust-scattering cross section per hydrogen atom, $F_r(t)$ is the flux of the outburst at time t, $\sigma_{\text{ph,E}}$ is the total photoelectric cross section at energy E, $N_{H,r}$ is the hydrogen column density corresponding to the dust cloud, and the sum is taken over all clouds (including a uniform continuum for the dust distribution) in between the cloud in question and the observer. The scattering cross section is a strong function of both the scattering angle and energy, and it depends on the dust distribution along the line of sight. In this work we used a simplified functional form of the cross section:

$$\frac{d\sigma_{\text{sc,E}}}{d\Omega} \sim C \left(\frac{\theta_{\infty}}{1000^\circ}\right)^{-\alpha} \left(\frac{E}{1\text{ keV}}\right)^{-\beta}$$  \hspace{1cm} (3)

where C is a normalization (scattering cross section per hydrogen atom at 1000° and 1 keV), $\alpha \sim 3-4$ and $\beta \sim 3-4$ (Draine 2003), and the physical scattering angle is simply

$$\theta_{\infty} = \frac{\theta}{1-x}$$  \hspace{1cm} (4)

as can be deduced from Figure 2.

2. Observations and Analysis

We have utilized several pointed observations with Chandra and Swift as summarized in Table 1. Apart from pointed observations, we have also used MAXI GSC (Matsuoka et al. 2009) and Swift BAT to understand the spectral evolution of 4U 1630–47 during the 2016 outburst. The MAXI and BAT light curves, the hardness ratios, and the dates of Swift and Chandra observations can be seen in Figure 4. The pointed observations took place when the source flux was already too low to be detected over the background by the all-sky monitors.

2.1. Swift Observations and Point-source Analysis

During the 2016 outburst decay of 4U 1630–47, we obtained several TOO observations with Swift. The first observation on MJD 57769.8 was in the windowed timing (WT) mode and the rest of the observations (from MJD 57771.8 to 57789.0) were in photon counting (PC) mode.

After detection of the DSH in the Swift observations we have extended the analysis to all Swift PC mode observations in the archive.

For all observations for which 4U 1630–47 was detected, we determined the point-source flux and spectral parameters using High Energy Astrophysics Software (HEASOFT) v6.20. We first produced photon event lists and exposure maps using xrtpipeline. We extracted the photons from a circle with a radius of 20 pixels (47″) centered on 4U 1630–47 for the source spectrum, and used a source-free and DSH-free region for the background spectrum.

We created the exposure-map-corrected ancillary response matrix
using xrtmkarf, and selected the appropriate response matrix from the calibration database (CALDB).

2.2. Chandra Observations and Point-source Analysis

We have investigated all Chandra archival observations to search for extended emission around 4U 1630–47. We eliminated observations in continuous clocking mode because they did not produce an image of the DSH. While the DSH is apparent in four Chandra observations (obsids 13714 through 13717), due to high count rates the observations were taken in a sub-chip and graded as well, which made it difficult to analyze the extended emission. Similarly, obsid 15511 uses a sub-chip, and is extremely piled up, making it difficult to use. Obsid 15524 taken on MJD 56439.8 is mildly piled up and shows the extent of the DSH at 2% Eddington luminosity. The DSH profile of this observation will be analyzed in a separate work. Here, we only utilized the archival observation of the Norma Arm (obsid 12530) taken on MJD 55728.5 to assess the possibility of extended background emission from other sources when 4U 1630–47 was in quiescence.

As the outburst decayed at the end of 2016 we triggered our Chandra observation and conducted a single observation on MJD 57789.4. Since the Swift flux evolution indicated very low count rates, we asked to remove the gratings and obtained the image only in the ACIS-S chip.

We used Chandra Interactive Analysis of Observations (CIAO) v4.9 tools for the analysis of the Advanced CCD Imaging Spectrometer (ACIS, Garmire et al. 2003). We created event and aspect solution files using chandra_repro. Using standard procedures we cleaned the event list from flares (which resulted in removing less than 1% of events). For obsid 19004, the source spectrum was extracted from within a radius of 8″ and the background was extracted within an annulus of 12″–50″ chosen to be inside the DSH ring. The spectrum is created using the specextract tool of CIAO.

2.3. Analysis Methods Related to the DSH

To calculate the surface brightness profile (SBP) using the Chandra data we followed these steps.

1. Determine the energy range in which the DSH is present over a background, and find three energy bands with approximately equal counts in the SBP.
2. Compute fluxed images in these three energy bands (a composite image is given in Figure 3).
3. Find point sources in the image using wavdetect (Freeman et al. 2002), and remove flux in circular areas around the source positions that would correspond to 99% of full energy deposition in the point-spread function (PSF).
4. Divide the fluxed images into circular regions of equal angular thickness, and find the total flux and area of each region that is observable in ACIS-S. Apply an exposure-map cutoff of 15% to calculate flux and areas.
5. Apply a background correction.
6. Divide corrected fluxes in each ring by the angular area of each ring to obtain the final SBP in each band. The area of each ring is corrected for detected point sources and chip boundaries.

For the background correction, we first created fluxed images for each CCD using the standard blank-sky fields as described in the CIAO thread and Hickox & Markevitch (2006). The normalization of the background fields is calculated by matching hard counts above 10 keV in each CCD separately with the corresponding blank-sky background files. Using these images, we obtained background SBP profiles in each energy band for each CCD. The random errors in each bin are calculated by finding total counts in each ring and assuming Poisson statistics. Several factors affect the systematic errors in the process of obtaining SBPs, such as image and spectral uniformity. There are additional errors arising from blanksky background subtraction as well. We added 3% systematic errors to the entire SBP to take those effects into account.

For the Swift profiles, the procedure was slightly different. We first made an energy cut in the event file (1.5–5 keV), and divided the resultant image by the exposure map. We then divided the image into circular regions of equal angular thickness from the source to the edge of the chip. For each ring we calculated the average energy of events and the average off-axis angle of the ring, and used the parameterization in CALDB file swxvign20001010v001.fits to obtain a vignetting correction in each ring. The vignetting correction amounts to <5% inside 250″ and becomes as large as 25% at 600″ (Moretti et al. 2009). To obtain fluxed images in units of photons cm^{-2} s^{-1} we divided each count by the effective area corresponding to the

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Table 1: Observations Used in the Analysis

| Date (MJD) | Obsid | Exposure (ks) | State | Notes |
|------------|-------|---------------|-------|-------|
| 55728.5    | 12530 | 19.3          | …     | Norma Arm for background, no DSH, no point source |
| 57789.4    | 19004 | 39.2          | Hard  | Faint mode, ring DSH |

| Swift XRT Observations |
|------------------------|
| Date (MJD) | Obsid | Exposure (ks) | State | Notes |
|------------|-------|---------------|-------|-------|
| 55392.5    | 00031224006 | 4.6          | an. soft | PC mode, DSH, T14 |
| 57769.8    | 00031224046 | 2.3          | Hard   | WT mode |
| 57771.8    | 00031224047 | 2.6          | Hard   | PC mode, ring DSH |
| 57773.2    | 00031224048 | 2.2          | Hard   | PC mode, ring DSH |
| 57777.9    | 00031224050 | 2.0          | Hard   | PC mode, ring DSH |
| 57781.9    | 00031224052 | 1.9          | Hard   | PC mode, ring DSH |
| 57783.8    | 00031224053 | 1.7          | Hard   | PC mode, ring DSH, no point source |
| 57787.0    | 00031224055 | 2.3          | Hard   | PC mode, ring DSH, no point source |
| 57789.0    | 00031224056 | 2.9          | Hard   | PC mode, ring DSH, no point source |

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4 http://space.mit.edu/CSC/docs/expmap_intro.pdf
energy of the photon. Finally we divided the flux in each ring by the angular area of the rings to obtain the SBP. The background is determined from the SBP at radii >600″. Vignetting and background correction are the main sources of systematic error in Swift SBPs. We also added 3% systematic errors to the Swift SBPs.

To calculate PSF profiles, we used Chart simulations for Chandra, and the King function discussed in Moretti et al. (2005) for Swift XRT.

3. Results

3.1. Evolution of the Outburst

The evolution of soft and hard X-ray counts, and the hardness ratio are given in Figure 4. The outburst starts on ∼MJD 57620 and quickly rises, reaching a plateau of 0.8 counts s⁻¹ in the MAXI 2–20 keV rate in 10 days. Like some of the previous outbursts, the initial hard state is not clearly observed. In fact, the BAT/MAXI ratio, and the MAXI evolution in different energy bands indicate that the hardness did not vary significantly throughout the outburst until around MJD 57730. After this date, an increase in the BAT count rate indicates a hardening, and the Swift observations after MJD 57750 are all consistent with being in the hard state.

3.2. Chandra Point-source Spectrum

The Chandra point-source spectrum within a source region of 8″ and a background region of 12″–25″ is shown in Figure 5. The spectrum is fitted with a model tbabs × power-law with abundances of Wilms et al. (2000) and cross sections of Verner et al. (1996). Cash statistics are used for the fit (Cash 1979). This gives a 2–10 keV unabsorbed flux of 2.6 × 10⁻¹³ erg cm⁻² s⁻¹, a photon index Γ of 1.85 ± 0.50, and an N_H of 1.3 × 10²³ cm⁻². Using a fiducial mass of 10 M☉ and a distance of ∼11.5 kpc as discussed in this work, the observed Eddington-scaled luminosity in the 1–200 keV band is ∼1.3 × 10⁻⁵.

Figure 3. Chandra ACIS-S smoothed RGB fluxed image of obsid 19004. Red: 1.5–2.15 keV, green: 2.15–3.25 keV, blue: 3.25–5.00 keV. The flux scale is given on the right. The image is oriented such that north is to the left. The annulus with 100″ inner and 200″ outer radius roughly encloses the main halo feature.

Figure 4. Top: MAXI count rates in 2–20 keV range for the 2016 outburst of 4U 1630–47. Red arrows indicate times of pointed Swift observations, and the thick blue arrow shows the time of the Chandra observation. Middle: Swift BAT 15–50 keV count rate. Bottom: Ratio of the 15–50 keV BAT rate to the 2–4 keV MAXI rate to indicate hardness.

The photon index is critically dependent on N_H at these count rates. To determine how Γ and N_H are correlated we calculated ΔC-statistics contours of 90%, 95%, and 99% confidence levels using steppar in XSPEC. The results, shown in Figure 5, indicate that for a typical hard-state spectrum N_H
should be greater than \(7 \times 10^{22} \text{ cm}^{-2}\), consistent with previous reports of the hydrogen column density \((T14)\). For the photon indices commonly observed at these luminosity levels \((\text{Plotkin et al. 2013})\), \(N_H > 10^{23} \text{ cm}^{-2}\).

### 3.3. Chandra DSH Profile Results

Figure 3 shows the RGB composite fluxed image of the region around 4U 1630−47 obtained by the Chandra ACIS-S. The energy ranges that we used are 1.5–2.25 keV, 2.25–3.15 keV, and 3.15–5 keV. The energy ranges are chosen to have approximately equal numbers of counts in each band. A DSH ring and a point source can be clearly observed.

After going through the procedure discussed in Section 2.3, we obtained the SBP for the three energy bands used in the composite image, as well as the SBP for the full 1.5–5 keV range as shown in Figure 6.

### 3.4. Swift DSH Profile Results

Swift SBP profiles for all pointing observations have been determined in the 1.5–4.5 keV band as described in Section 2.3. In Figure 7, we show the SBP profiles and modeling results of obsid 00031224047, which is the first PC mode observation during the 2016 decay, and obsid 00031224052, which shows the fully formed ring. The ring formation is evident even for obsid 00031224047. Obsid 00031224006, the XRT observation that shows the anomalous soft state in T14, is discussed in detail in Section 4.6. The SBP models are discussed in Section 4.2.

### 4. Discussion

The Chandra observation clearly shows a DSH ring with a profile such that there is a bright region between 80″ and 250″ with excess emission extending up to 600″ (see Figures 3 and 6). This ring profile is consistent with the overall evolution of the source in X-rays, which shows a sharp rise in flux between MJD 57620 and MJD 57630, and slower decay in the hard state after MJD 57740. Therefore, the most important result of this study is that there should be a massive dust cloud relatively close to the source because we see a single bright ring structure consistent with the outburst profile only days after the outburst ended. As discussed in Section 1.2, the SBP together with the flux history of the source can be used to determine the distance to the source if the distance to the cloud is known.

#### 4.1. Distance of 4U 1630−47

4U 1630−47 is in a region of the Galaxy covered by a rich cluster of H II emitting clouds (Mezger et al. 1970). In Figure 8, we show the integrated \(^{12}\text{CO} (J = 1−0)\) velocity map from the data release of the Planck Collaboration et al. (2014), which shows the distribution of molecular clouds in the line of sight (similar to Figure 2 in Corbel et al. 1999, showing both SGR 1627−41 and 4U 1630−47). The same figure shows the spectrum toward 4U 1630−47 obtained using data from the CO survey of Bronfman et al. (1989). We fitted each feature in the spectrum with a Gaussian. We obtained near and far...
kinematic distances of all CO-emitting clouds using the estimation based on the method described in Reid et al. (2009) with the Galactic parameters from model A5 in Reid et al. (2014).

By comparing the optical extinction of 4U 1630−47 (derived from X-ray spectral fitting of $N_H$ values) to the total optical extinction toward MC −71 as given in Corbel et al. (1999), Augusteijn et al. (2001) argued that the source must be in front of the molecular cloud MC −71, which is located at 11 kpc. However, a close inspection of the position of 4U 1630−47 in the CO map (Figure 8, left) shows that at the position of 4U 1630−47, the integrated CO emission is much less than that of SGR 1627−41. Moreover, along the line of sight to 4U 1630−47, the dominant emitter is not MC −71 but another cloud with velocity peaking at $-79 \text{ km s}^{-1}$. The complex of MC −117 and MC −122 is also not present in the line of sight to 4U 1630−47.

Since the DSH ring indicates one dominant scattering cloud we placed the source behind MC −71. Then, we obtained the distance to 4U 1630−47 using the SBP modeling, and double-checked this result by recalculating the total extinction. To be able to do both of these calculations we need to resolve the ambiguity in kinematic distances of all clouds in the line of sight to 4U 1630−47, especially the distance to MC −79.

Recent work by Miville-Deschênes et al. (2017) identified 8107 molecular clouds in the entire survey of CO clouds of Dame et al. (2001) between $b = -5^{\circ}$ and $5^{\circ}$ utilizing Gaussian decomposition of the spectra. From this survey we identified clouds encompassing the position of 4U 1630−47 with central velocities within $4 \text{ km s}^{-1}$ of the cloud velocities we show in Table 2. An example map of clouds at central velocity close to $-79 \text{ km s}^{-1}$ is given in Figure 9. To remove the ambiguity between the far and near distances, Miville-Deschênes et al. (2017) compare the apparent radius of the cloud $R_{\text{app}}$ with the radius $R$ obtained using the correlation between line width $\sigma$ and $\Sigma R$, where $\Sigma$ is the surface density. A more common method is to resolve distance ambiguity using the canonical $\sigma$–$R$ correlation (Solomon et al. 1987). In this work we adapted the $\sigma$–$R$ correlation method. The results are given in Table 2.

For those cases where no cloud encompasses the source position (indicated by footnote e in Table 2), we assumed that these clouds are small and have not passed the pixel threshold in Miville-Deschênes et al. (2017). An inspection of the CO spectra within $0.5$ of 4U 1630−47 from the survey data of Bronfman et al. (1989) supports this conclusion because the Gaussian components corresponding to MC −105, MC −99, and MC −47 are only present in a few pixels ($7/5 \times 7/5$ resolution) around the source. Therefore we concluded that the apparent radii $R$ of these clouds (if they are real, and not a result of velocity crowding) are small. Using a comparison of $R$ with size from the $\sigma$–$R$ correlation from the spectra shown in Figure 8, we estimated that they are more likely to be at the near distance. The Gaussian component corresponding to MC −33 might be at the edge of a cloud detected by Miville-Deschênes et al. (2017) at $-33.5 \text{ km s}^{-1}$, which is estimated to be at the far distance. $\sigma$ of MC −111 is high and therefore we

![Figure 7](image-url)
could not resolve the ambiguity for the distance to this cloud. It is tentatively placed at the far distance.

Here, the most critical cloud is MC \(-79\), and the ambiguity has not been resolved completely. The \(\sigma-\Sigma R\) relation indicates near distance, whereas the \(\sigma-R\) relation indicates far distance. We favor the far distance from the SBP modeling, but for completeness we have analyzed the near-distance case as well.

4.2. Distance to the Source by Modeling the Dust Distribution

Standard geometrical analysis of scattering from a single dust cloud provides a relation between the time delay \(\Delta t\), distance between the observer and the source \(D\), distance to the dust layer \(xD\), and the scattering angle \(\theta\) (see Figure 2 and Equation (1)). Together with Equation (2), we can model the SBP, which is a result of scattering of the source flux by dust present in different clouds. To be able to utilize Equation (2) we need the entire flux evolution, which we have thanks to \textit{MAXI} and \textit{Swift} monitoring. In the top panel of Figure 10 the 2–4 keV \textit{MAXI} GSC light curve is shown. Beyond MJD 57750 the background measurement becomes unreliable. This is clearly shown by the evolution of \textit{Swift} XRT fluxes in the 2–4 keV band. Since the decay beyond MJD 57760 is well represented by an exponential decay, the entire flux history can be reconstructed. We also smoothed out sudden dips and peaks most probably caused by poor background subtraction in \textit{MAXI}.

To complete the analysis, we need the distances, \(N_{\text{H}},\) content, and thickness of all clouds between the source and the observer. For those clouds encompassing 4U 1630–47 in the survey of Miville-Deschênes et al. (2017), we estimated the thickness based on the entire cloud size obtained using \(R_{\text{app}}\) and the estimated distance as well as position of 4U 1630–47 within the cloud. For the rest, we again used the assumption that \(R_{\text{app}}\) must be small not to be detected in Miville-Deschênes et al. (2017) and used generic 20 pc for near and 30 pc for far sources.

To find the distance to the source we primarily match the rising part of the SBP in the 2.25–3.15 keV band between 100\(^{\circ}\) and 120\(^{\circ}\) by adjusting the distance \(D\) while keeping the main scatterer distance \(xD\) at 10.86 kpc. The free parameters of our model are: a general normalization parameter (which adjusts for differences in flux level in different energy bands as well as the constant \(C\) in Equation (3)), the thickness of the cloud \(MC-79\) in the line of sight, the distance \(D\), and the ratio of total \(N_{\text{H}}\) to the total \(N_{\text{H}}\) in clouds. The \(N_{\text{H}}\) not in clouds is assumed to be distributed uniformly along the line of sight. We refer to this uniform component of the ISM as the “continuum” hereafter. The total \(N_{\text{H}}\) in the \textit{Chandra} observation was determined to be \(1.32 \times 10^{23} \text{ cm}^{-2}\). We also fitted the \textit{MAXI} spectrum in the peak of the outburst with a model of \(tbabs \times diskbb\) and obtained a similar value of \(1.30 \times 10^{23} \text{ cm}^{-2}\). \(N_{\text{H}}\) in each dust cloud is found by taking the ratio of integrated velocities in CO spectra to that of \(MC-79\) and normalizing such that the total is equal to the total \(N_{\text{H}}\) in the clouds. We fixed \(\alpha\) and \(\beta\) to 3. Despite these simplifications, we were able to match the given SBP with this model by placing the source at 11.5 kpc. The individual contributions of dust clouds before absorption, and the overall fit are shown in Figure 10 in the panel labeled “Far distance, minimum free parameters.”

As a way of checking our calculations, we have applied the same modeling without changing a single cloud parameter to earlier \textit{Swift} observations. Only \(\Delta t\) changes in Equation (2), and the agreement of the model with the data confirms our methodology (Figure 7).

4.3. Validity of the Approach and the Distance Error

While the overall modeling represents the SBP in the most interesting region, there have been many simplifications applied, and therefore it is important to understand the impact of these simplifications on the overall distance measurement.

4.3.1. Ambiguity and Error in Estimation of Cloud Distance

Resolving the ambiguity of cloud distances in the line of sight is not straightforward, and different approaches result in different distances. In our case, the distance of \(MC-79\) is the critical measurement, and the near-distance case will be discussed in Section 4.4. As seen in Table 2, there are other cases in which the distances are ambiguous, but the impact will be much lower for those because their \(W(CO)\) indicates lower dust content, and hence their amplitudes are often low.

\(MC-67\) is the other important component with a strong impact on our conclusions. First of all, if \(MC-67\) is at the near distance our modeling will not be able to fit below 100\(^{\circ}\) (but see Section 4.3.3) when \(MC-79\) is at the far distance.

At the far-distance estimate of \(MC-67\) favored by both \(\sigma-R\) and \(\sigma R-R\) relations, the cloud is extremely close to the source; in fact, given the error in cloud distances, it is plausible that 4U 1630–47 is inside this cloud! With a small adjustment to its distance (well within the errors) and \(N_{\text{H},r}\) content, one can...
obtain a much better representation of the data. Similarly, we had difficulty resolving the ambiguity of distance for MC$–111$, but placing it at the far distance and making a small adjustment to $N_{\text{H}_2}$ of this cloud leads to a better representation of the data in our modeling.

### 4.3.2. Resolution of the Submillimeter Spectrum

We have used the low-resolution data of Bronfman et al. (1989) for the CO spectrum, yet the ISM is fractal (S. Corbel 2018, private communication) and the integrated velocities in the line of sight to 4U 1630$–$47 can be significantly different. An example is the case of integrated velocity toward SGR 1627$–$41 obtained with 45$^\circ$ resolution (Corbel et al. 1999), which is significantly larger than that obtained from the survey of Bronfman et al. (1989) with a resolution of 7.5$^\circ$. Using low-resolution data does not change the fact that the source should be behind MC$–79$; however, the $N_{\text{H}_2}$ values in each cloud will change. Also, the central velocity may be different along the line of sight to 4U 1630$–$47, introducing problems in determining the correct dust cloud.

#### Table 2

| Name   | $V_{lsr}$a (km s$^{-1}$) | $\Delta V$(FWHM) (km s$^{-1}$) | Near Dist. (kpc) | Far Dist. (kpc) | $D_1 (\sigma$–$R)$b (kpc) | $D_2 (\sigma$–$\Sigma R)$c (kpc) | $W(\text{CO})$d (K km s$^{-1}$) | $N(\text{H}_2)$e (10$^{21}$ cm$^{-2}$) |
|--------|--------------------------|-------------------------------|------------------|-----------------|--------------------------|-------------------------------|-------------------------------|-----------------------------------|
| MC$–111$ | $–111.0$ | $9.0$ | $5.75$ | $9.70$ | $9.70^e$ | $–$ | $6.3 \pm 0.5$ | $1.2 \pm 0.4$ |
| MC$–105$ | $–104.9$ | $3.6$ | $5.32$ | $9.92$ | $5.33^e$ | $–$ | $5.1 \pm 0.8$ | $1.0 \pm 0.3$ |
| MC$–99$ | $–98.6$ | $4.7$ | $9.6$ | $10.15$ | $5.32^e$ | $–$ | $6.5 \pm 0.8$ | $1.2 \pm 0.4$ |
| MC$–79$ | $–79.4$ | $9.6$ | $4.63$ | $10.86$ | $4.63$ | $–$ | $46.2 \pm 1.7$ | $8.8 \pm 2.6$ |
| MC$–72$ | $–72.3$ | $4.1$ | $4.37$ | $11.14$ | $11.14$ | $–$ | $6.0 \pm 2.0$ | $1.1 \pm 0.3$ |
| MC$–67$ | $–66.6$ | $10.1$ | $4.14$ | $11.38$ | $11.38$ | $–$ | $13.0 \pm 3.0$ | $2.5 \pm 0.8$ |
| MC$–56$ | $–56.1$ | $3.9$ | $3.71$ | $11.84$ | $11.84$ | $–$ | $3.3 \pm 0.7$ | $0.6 \pm 0.2$ |
| MC$–47$ | $–47.0$ | $4.0$ | $3.30$ | $12.27$ | $3.30^e$ | $–$ | $3.4 \pm 0.3$ | $0.6 \pm 0.2$ |
| MC$–39$ | $–39.3$ | $6.4$ | $2.92$ | $12.67$ | $2.92$ | $–$ | $11.5 \pm 1.3$ | $2.2 \pm 0.7$ |
| MC$–33$ | $–33.5$ | $3.2$ | $2.62$ | $13.01^e$ | $13.01^e$ | $–$ | $3.5 \pm 0.8$ | $0.7 \pm 0.2$ |
| MC$–19$ | $–19.1$ | $2.8$ | $1.76$ | $13.94$ | $1.76$ | $–$ | $4.0 \pm 0.5$ | $0.8 \pm 0.2$ |

Notes.

a. Velocity of the local standard of rest.

b. Distance ambiguity resolved based on the $\sigma$–$R$ relation.

c. Distance ambiguity resolved based on the $\sigma$–$\Sigma R$ relation.

d. Integrated $^{12}\text{CO}$ emission ($J = 1$–$0$).

e. See text for the choice of distance.

Figure 9. Clouds with central velocity within 4 km s$^{-1}$ of that of MC$–79$ from the catalog of Miville-Deschênes et al. (2017). The velocity of each cloud (in km s$^{-1}$) is given inside it. The second number is the distance (in parsecs) determined by Miville-Deschênes et al. (2017). The diamond is the position of 4U 1630$–$47, the cross is the position of SGR 1627$–$41, and the square is the resolution element of the survey of Bronfman et al. (1989).

Figure 10. Top panel: flux evolution of the outburst in the 2–4 keV band. MAXI data are shown by diamonds, and Swift XRT data are shown with filled circles. The solid line is an extrapolated light curve using the MAXI and Swift data. Bottom two panels: SBP in the 2.25–3.15 keV band and the model components. The dashed line is the overall model with absorption taken into account, the dotted lines are the contribution from each cloud before absorption, and the dot-dashed line is the contribution from uniformly distributed dust in the continuum. See the text for the distinction in cases of far and near distance. Clouds are labeled according to their velocities (in km s$^{-1}$).
In Figure 10, in the near-distance case we adjusted the \( N_{\text{H}_2} \) values of three clouds and obtained a better representation of the entire SBP. With high-resolution submillimeter observations we would have stronger constraints on the integrated velocity and therefore could fix \( N_{\text{H}_2} \) values, and fitting the data then would require adjusting their thicknesses and dust properties.

4.3.3. Modeling of the Chandra Background SBP

One of the arguments for MC \(-79\) being at the far distance is that it places the source very close to MC \(-66\), and therefore we could model the SBP below 100". If we underestimated the background SBP in the Chandra data, and the excess between 20" and 100" is absent, then the distance ambiguity will be harder to resolve (see Section 4.4). Apart from this, a possible incorrect estimation of the background SBP will also impact the ratio of \( N_{\text{H}_2} \) in dust clouds and the continuum significantly because the profile beyond 300" is almost entirely due to dust in the continuum in our model. Its effect on the distance estimate will be small if the background SBP is constant in the region of interest.

On the other hand, since the same model fits the Swift XRT SBP as well, if we are underestimating Chandra background in the SBP, we should also be underestimating Swift XRT background in the SBP.

4.3.4. The X-Ray Flux Evolution

The flux evolution has been determined using MAXI and Swift. Yet the period between MJD 57750 and MJD 57770 bears some uncertainty because this is the region where MAXI background is unreliable and no Swift observations were possible because of the constraint of the Sun angle. This region corresponds to 80"–120" in the SBP. The approximation of exponential decay works well in terms of representing multiple Swift observations.

We also have not made a correction to MAXI fluxes due to the DSH. We can justify this as follows. On MJD 57772 the flux in the PSF of Swift XRT is comparable to the flux in the DSH. We stop using MAXI data on MJD 57761, and the overall MAXI flux is a factor of 70 larger than the flux on MJD 57772, whereas the SBP modeling indicates only a factor of 3 more flux in the DSH. Therefore for the data range in which we use the MAXI data, the DSH contribution to MAXI is negligible.

4.3.5. Other Parameters

The other notable parameters that can impact the overall model are variations of scattering cross section per hydrogen atom, \( \alpha \), and \( \beta \) parameters in the clouds. These will result in minute differences in the overall shape of the model. The \( \alpha \) parameter will also affect the ratio between \( N_{\text{H}_2} \) in the clouds and continuum because clouds at lower scattering angles will be affected more strongly by \( \alpha \).

The quality of the SBP data is not high enough to distinguish these minute differences from the more important effects. One can envision several ways to improve the distance measurement with this method, as well as to constrain cloud distances and dust properties by even fitting fine features in the SBP:

1. Better quality Chandra data taken at a higher luminosity. The observation must be taken at a level in outburst decay such that the ring has formed and the SBP of the cloud and the PSF are not intersecting.
2. High-resolution submillimeter data to obtain the cloud velocities and distances more accurately. This will not only help in resolving ambiguity but will also provide more accurate \( N_{\text{H}_2} \) values that can be fixed, allowing other parameters to be varied.
3. Swift XRT (or any other low-energy imaging instrument) monitoring at times when MAXI has problems with background.
4. Detailed spectral modeling of the DSH and comparison of dust properties obtained from spectral modeling with expected parameters.

4.4. The Alternative Distance Estimate

As discussed earlier, MC \(-79\) could also be at a distance of 4.63 \( \pm \) 0.25 kpc. We have adjusted the model parameters to model the SBP for the case in which MC \(-79\) is at the near distance (see Figure 10, labeled "Near distance, Adjusted parameters"). To be able to get a meaningful fit we needed to place all clouds in the near-distance estimate. In this case we get the best fit at a distance of 4.7 kpc. In the near-distance case, we cannot explain the continuum SBP below 100" unless our background estimate is wrong, or else MC \(-79\) is not a single cloud but consists of a couple of clouds (a larger cloud with a central velocity of \( \sim \) 79 km s\(^{-1}\) and a smaller cloud at \( \sim \) 81 km s\(^{-1}\)). This scenario is not ruled out completely, because the modeling in Miville-Deschênes et al. (2017) indicates that two clouds with velocities of \(-78.7\) and \(-79.3\) km s\(^{-1}\) encompass the position of 4U 1630–47, and another cloud with a central velocity of \(-80.5\) km s\(^{-1}\) extends to the edge of the resolution element that includes 4U 1630–47, and all these clouds are at the near distance according to the distance estimate from \( \sigma-\Sigma R \) correlation (see Figure 9).

Moreover, with the near-distance estimate, it is difficult to model the SBP beyond 200" as well. To be able to get a fit we placed MC \(-67\) and MC \(-72\) at the near distance, but for both clouds, both methods of resolving distance ambiguity point to the far-distance estimate. Removing contributions from these clouds (see Figure 10) results in a big gap between 200" and 400" that cannot be filled with a simple adjustment of the continuum parameters.

4.5. Extinction toward 4U 1630–47

Now we can check whether the \( N_{\text{H}} \) values we use in our modeling and those found in general in the literature are consistent with the extinction estimated from CO maps toward the line of sight to 4U 1630–47. The integrated spectrum for all clouds in front of 4U 1630–47 for MC \(-79\) at the far distance is \( \text{W} \text{CO} = 102 \text{ K km s}^{-1} \). Using the conversion factor \( X_{\text{CO}} = N(\text{H}_2)/W(\text{CO}) \) of \((2 \pm 0.6) \times 10^{25} \text{ molecules cm}^{-2} (\text{K km s}^{-1})^{-1} \) (Bolatto et al. 2013), we found a column density of molecular hydrogen \( N(\text{H}_2) \) of \((20.4 \pm 6.1) \times 10^{21} \text{ cm}^{-2} \). The total hydrogen column density is \( N(\text{H}) = N(\text{H}_2) + 2N(\text{H}_2) \). Using \( \text{H}_2 \) surveys, Augusteijn et al. (2001) cite a contribution of \( 2 \times 10^{22} \text{ cm}^{-2} \) to the total \( N(\text{H}) \).

Since this could be an underestimation, the lower limit to total \( N(\text{H}) \) is then estimated to be \( 6.1 \times 10^{22} \text{ cm}^{-2} \) toward the line of sight to 4U 1630–47. The X-ray derived \( N(\text{H}) \) values are often much larger than \( 6 \times 10^{22} \text{ cm}^{-2} \) (this work; T14; Wang & Méndez 2016). Therefore, the extinction determined from the radio maps when the source is behind MC \(-79\) is consistent with extinction derived
using X-ray spectral fitting. In our modeling, we took the total $N_H$ to be $13 \times 10^{22} \text{ cm}^{-2}$, and the best representation of the data is obtained when the distribution of dust in the molecular clouds and in the continuum is 52%–48%, which is consistent with the $N_H$ in clouds derived from the integrated velocity from the survey of Bronfman et al. (1989).

Finally, using the conversion factor of $N_H = (2.87 \pm 0.12) \times 10^{21} A_V \text{ cm}^{-2}$ (Foight et al. 2016), which uses the ISM abundances of Wilms et al. (2000) and the XSPEC $tbabs$ absorption model as used in this work, we obtain an optical extinction of 45.

### 4.6. Anomalous Soft State Revisited

One of the motivations for this work was to assess whether the observation of an anomalously low-luminosity soft state during the 2010 decay of 4U 1630–47 has been an artifact of a DSH softening the point-source spectrum. In fact, a DSH is present in the XRT image of obsid 0003124006 (see Figure 11), and the 47″ source region used in T14 could include softer emission from the halo. In this section we try to assess how much of the emission is from the DSH within the 47″, and whether the actual spectrum of the point source is hard when this contribution is taken into account.

Based on the Chandra SBP modeling, we already obtained a possible distribution of dust clouds and thicknesses along the line of sight. To verify the methodology and for a consistency check we applied exactly the same model without changing any parameter to the SBPs of Swift observations on MJD 57771.8 and MJD 57781.9, and we obtained the results shown in Figure 7. The model represents the data well. Then we took the same dust distribution and same form of the cross section, and applied the model for obsid 0003124006, again without tweaking any parameters (even though now it is a different outburst where the spectral evolution is slightly different than the 2016 outburst). Despite the simplicity of our approach, the modeled SBP represents the data well, as shown in Figure 12. The SBP model shown indicates that the DSH is not affecting the 47″ spectral region used in T14, and indeed that this observation is anomalously soft. We note that, if the source is at the near-distance estimate, the observation of the anomalous soft state would have been at an Eddington luminosity fraction a factor of four lower than the value given in T14.

### 4.7. Nature of 4U 1630–47

While many of the X-ray spectral and timing properties of this source are similar to those of other low-mass X-ray binaries (LMXBs), there also are arguments in favor of this system being an HMXB. Augusteijn et al. (2001) point out that the donor star should be intrinsically luminous, because the amplitude of the variation in the infrared from quiescence to outburst was small. It might also help explain why the rise time of the outburst is short, and it might explain the high duty cycle of the outbursts, and why they are fairly erratic (as seen in Figure 1).

For the far-distance scenario, the SBP between 20″ and 80″ can be modeled by a dust cloud (MC –66) very close (<100 pc) to 4U 1630–47. For the near-distance scenario, the modeling indicates that 4U 1630–47 should only be 70 pc from MC –79. If we assume that the X-ray binary was produced in the nearby cloud, and that it was born with a low natal kick (e.g., 30 km s$^{-1}$, at the low end of kick velocities discussed in Miller-Jones 2014), it would take approximately 3 Myr to get to 100 pc distance. A potential problem with this timescale is whether the source would have time to evolve into Roche lobe overflow, and whether the system would be circular enough that we would not see an obvious signature of the orbital period. This would not be a problem if the source is an HMXB.

The Be X-ray binary scenario provides a reasonable way to make the system so close to a molecular cloud without it being a coincidence. This allows the system to show strong mass transfer without having to recircularize and get it back into Roche lobe overflow in ~2 Myr. It also provides a way for the outbursts to rise rapidly. It might also explain the “double” outbursts that are sometimes observed if there are two passages through the decretion disk near the periastron for those outbursts, and both transfer a significant amount of mass. This
system shows a mixture of normal outbursts that are nearly periodic and then much stronger outbursts as seen in Figure 1. This could be explained as Type I and Type II outbursts for a Be X-ray binary (Reig 2011; Martin et al. 2014).

However, the outbursts are not exactly periodic and are complex (Kuulkers et al. 1997) and may not be related to the orbital period as expected from Be binary systems. Alternatively, if the system is an LMXB, it may have an evolved donor star in order to explain the low amplitude of variability in the infrared. In such a case, the variations in the brightness and durations of the outbursts may be the result of the tidal–thermal instability producing “super-outbursts” (Osaki 1996). The two scenarios can be distinguished in future work by making high-cadence measurements of infrared variability. In the Be X-ray binary scenario, the normal outbursts proceed with a periodicity that is the orbital period. In the super-outburst scenario, the orbital period will be considerably shorter than the time between outbursts, and there should be modulations due to superhumps that will be at a period within a few percent of the orbital period (e.g., Haswell et al. 2001).

5. Summary and Future Work

We have analyzed the DSH of 4U 1630–47 observed with Chandra and Swift during the decay of its 2016 outburst. The ring structure of the SBP indicates that the source is behind a massive molecular cloud, which is determined to be McG 79 from CO maps. While the kinematic distance estimate of McG 79 is ambiguous, we favor the far-distance estimate because it allows us to model the SBP less than 100" better.

The ambiguity in the source distance can be resolved with a more detailed spectral analysis of the halo, which we plan to conduct in a future work. Also, Chandra observations at a higher luminosity and a submillimeter mapping with higher resolution toward the line of sight would also provide additional information to break the degeneracy.

Given the large number of clouds along the line of sight, the probability of a source lying quite close to a cloud is relatively high. There are uncertainties due to the near–far degeneracy, but it is likely that more than 10% of the line of sight is within 500 pc of a molecular cloud. Still, an association with a molecular cloud could potentially help explain several of the peculiarities of this source. First, a cloud might provide a “working surface” for the jet to interact with that would not be present for most soft X-ray transients. This could, in turn, explain the baryonic content of the jets found from observations using gratings. Second, Augusteijn et al. (2001) found that the ratio of the amplitude of the infrared variability to the X-ray variability was anomalously low for an LMXB. This could be explained by having a high-mass donor star, in association with the star formation in the cloud.

Normally, HMXBs are not transients unless the donor star is a Be star. A Be donor might explain a few additional elements of the phenomenology of the outbursts of this system. The outbursts are nearly (although not strictly) periodic, except for some very strong outbursts. These may be indicative of Type I/II outbursts from Be transients.

A clear observational test exists for determining whether the HMXB scenario is a reasonable one. If the system was formed in a particular molecular cloud and stayed there, it should have a space velocity very close to the space velocity of the cloud. The radial velocity can be determined from infrared emission lines in outburst. The proper motion can be determined, eventually, by radio measurements using very long baseline interferometry taken during the outburst.

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