A giant X-ray dust scattering ring around the black hole transient MAXIJ1348–630 discovered with SRG/eROSITA *

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ABSTRACT

We report the discovery of a giant dust scattering ring around the Black Hole transient MAXI J1348−630 with SRG/eROSITA during its first X-ray all-sky survey. During the discovery observation in February 2020 the ring had an outer diameter of 1.3 deg, growing to 1.6 deg by the time of the second all sky survey scan in August 2020. This makes the new dust ring the by far largest X-ray scattering ring observed so far. Dust scattering halos, in particular the rings found around transient sources, offer the possibility of precise distance measurements towards the original X-ray sources. We combine data from SRG/eROSITA, XMM-Newton, MAXI, and Gaia to measure the geometrical distance of MAXI J1348−630. The Gaia data place the scattering dust at a distance of 2050 pc, from the measured time lags and the geometry of the ring, we find MAXI J1348−630 at a distance of 3390 pc with a statistical uncertainty of only 1.1% and a systematic uncertainty of 10% caused mainly by the parallax offset of Gaia. This result makes MAXI J1348−630 one of the black hole transients with the best determined distances. The new distance leads to a revised mass estimate for the black hole of 11 ± 2 M☉, the transition to the soft state during the outburst occurred when the bolometric luminosity of MAXI J1348−630 had reached 1.7% of its Eddington luminosity.

Key words. Scattering – X-rays: surveys – X-rays: individual (MAXI J1348−630)

1. Introduction

Similar to optical light, X-rays of cosmic sources are affected by the interstellar medium in our Galaxy. These effects consist on the one hand of photo-electric absorption and on the other hand of dust extinction (Corrales et al. 2016), which is caused by photo absorption and by scattering from dust grains, where in contrast to visible light the scattering of X-rays takes place at small angles. The scattered radiation forms a halo around the point source, such that both components of the extinction can often be determined in a single observation. Such observations allow us to draw conclusions about the physical and chemical properties of the interstellar dust (Mathis & Gorenstein 1986, Mathis & Lee 1991, Predehl & Schmitt 1995, Draine 2003, Xi-ang et al. 2011, Corrales et al. 2017 and references therein).

Since the scattered light has to travel a longer distance than the direct light, brightness variations of the central source appear with a delay in the “echo” of the dust scattering halo. This was proposed as early as 1973 as a method to determine the geometrical distance of X-ray sources (Trümper & Schönfelder 1973), but was only realised 27 years later through a Chandra observation of Cyg X-3 (Predehl et al. 2000). As a rule of thumb, the delay of the echo for a source at a distance of 5 kpc and dust in the middle between source and observer for sake of simplicity is a few hours at 1°, some weeks at 10°, and one year at half a degree.

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Since in practice most X-ray sources show variability on all timescales, the variability of the halo is very complex as it is the convolution of the impulse response of the halo with the source variability. This makes distance measurements with dust scattering halos challenging. The best sources for distance measurements with scattering halos are, therefore, transient X-ray sources, such as X-ray binaries (XRB), soft gamma repeaters (SGRs), or gamma-ray bursts (GRBs) as for these well-defined light echos in the form of distinct rings of X-rays will occur that grow with time. In the case of sources whose distance is known (or very large), such an observation allows a tomography of the dust distribution. Utilising an XMM-Newton observation of expanding rings around GRB031203, Vaughan et al. (2004) were the first to succeed with the determination of the distance of two dust clouds at 880 pc and 1.3 kpc. Clark (2004), with a Chandra observation of the X-ray pulsar 4U1538−52, was able to determine both its distance (4.5 kpc) and that of three layers of dust in between (1.3 kpc, 2.56 kpc, and 4.05 pc). Heinz et al. (2015) managed to identify a total of four rings (“Lord of the Rings”) around Cir X-1. A general consideration of the possibilities of such observations can be found in Corrales et al. (2019). For dust scattering rings where either the distance of the source or of the scattering dust is known from other measurements the second distance can be calculated geometrically using the ring radius and the time lag of the scattered X-rays. In other cases both distances have been constrained by modelling the temporal intensity evolution of the expanding rings (e.g. Tiengo et al. 2010). However, this method requires the knowledge of the dust scattering cross section and the results therefore depend on the...
2. X-ray observations

2.1. eROSITA observations

Launched on 2019 July 13 into an orbit around the \( L_2 \) point of the Earth-Sun system, the eROSITA instrument on board the Spectrum-X-Gamma spacecraft (SRG, Sunyaev et al. 2021, in prep.) consists of seven X-ray camera assemblies behind seven identical and co-aligned Wolter telescopes. See Merloni et al. (2012) and Predehl et al. (2020) for a description of the instrument and its science goals.Sensitive in the 0.2–8 keV band and with a peak on-axis effective area of over 2000 cm\(^2\), since the end of its performance verification phase on 2019 December 13, until the end of 2023 eROSITA will perform the deepest X-ray all sky survey to date. The eROSITA survey is a slew survey. The telescopes scan along great circles that are approximately perpendicular to the ecliptic, with a rotational axis pointing towards the Earth. This way the whole sky is scanned within 6 months. The rotational period of 4 h together with the 1\( \degree \) field of view means that any patch of sky is seen every 4 h for several eROSITA slwes (depending on the ecliptical latitude of the object), and then again half a year later.

2.1.1. eRASS1

The area around MAXI J1348–630 was scanned 31 times with SRG/eROSITA between MJID 58897.825 and MJID 58903.344. We assume a mid-point of the observations of MJID 58900.583 (2020-02-21 14:00:00 UTC), 391.3 d after the MAXI discovery of the burst. The dust scattering ring, which is rather inconspicuous in unsmoothed event images, was first discovered in smoothed sky maps produced from these data. The vignette exposure, i.e., the equivalent exposure time of an on-axis observation with all 7 telescopes, varies between 150 s and 300 s over the area of the scattering ring. We have created images in the energy bands 0.2–0.6 keV, 0.6–1.0 keV and 1.0–2.3 keV. For the purpose of visualisation the 3 energy band images were exposure corrected and adaptively smoothed using the eSASS (Brunner et al. 2021, in prep.) task erbackmap and combined into a pseudo RGB image (Fig. [1]).

From the unsmoothed, exposure corrected image in the 1.0–2.3 keV band we derived a radial profile of the surface brightness centered at the position of MAXI J1348–630 (Fig. [2]). The scattered radiation is detected in an annulus with inner and outer radii of 34’ and 40’, respectively.

2.1.2. eRASS2

The sky area of the scattering ring was covered again during the second eROSITA all-sky survey (eRASS2) with 31 single scans between MJID 59078.597 and MJID 59083.772, the mid-point is MJID 59081.201 (2020-08-20 04:50:00 UTC), or 571.9 days after the MAXI burst detection. The vignette exposure of the relevant sky region varies only slightly between 203 s and 210 s.

The data were processed in the same way as the eRASS1 data. The dust echo is still visible at the now expected radius, about 1.2 larger than during the eRASS1 observation but with significantly lower surface brightness (Figs. [1] and [2]).

2.2. XMM-Newton

MAXI J1348–630 was observed on 2020 March 10 and 11 by XMM-Newton in Directors Discretionary Time in mosaic mode (observation identifier 0870590101). EPIC/pn, MOS1, and
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Fig. 1. False-colour images of the eRASS1 (18-24 Feb 2020, left) and eRASS2 (17-22 Aug 2020, right) observations in the energy bands 0.2–0.6 keV (red), 0.6–1.0 keV (green), 1.0–2.3 keV (blue), adaptively smoothed. The size of the images is 3° × 3°. North is at the top and East to the left.

Fig. 2. Radial profile of the eRASS1 (black) and eRASS2 (blue) images in the energy band 1.0–2.3 keV with a resolution of 20 arcsec. The scattered emission is detected at radii ∼ (34 – 40) arcmin in eRASS1 and between ∼ (40 – 47) arcmin in eRASS2.

MOS2 were operated in full-frame mode using the medium filter. Eleven EPIC pointings with a total exposure time of 75 ks covered MAXIJ1348–630 and almost 60% of the dust ring. The first pointing was exposed for 5.0 ks in MOS and 2.5 ks in pn, the last pointing for 6.2 ks in MOS and 5.9 ks in pn, and the other pointings for 6.6 ks in all instruments. Figure 3 shows the contours of the EPIC/pn and MOS detectors for each sub-pointing. The mosaic-mode data were reduced using the XMM-Newton Science Analysis System (SAS, Gabriel et al. 2004) and split into the sub-pointings by the task esplinemap.

To create mosaic images and to perform source detection, they were projected onto common coordinates centered at the mean attitude of all pointings by the task edetect_stack (Traulsen et al. 2019). Stacked source detection by edetect_stack was used to mask sources in the event lists, from which the radial profile and the spectra were derived. Since images with spatially very inhomogeneous background are prone to misinterpretation of background features as extended sources, the task parameters were optimised for point sources. esplinemap in smoothing mode was run with the parameters given by Traulsen et al. (2019), and the source-detection task emldetect was run without extent fitting. In addition to MAXIJ1348–630, 280 sources were found. Circular regions with brightness-dependent radius were cut out, a mask including the good source-free regions generated, and source-excised event lists created for each pointing and instrument.

Images of all pointings and instruments were created in common coordinates using the task edetect_stack in the five standard XMM-Newton energy bands (1) 0.2–0.5 keV, (2) 0.5–1.0 keV, (3) 1.0–2.0 keV, (4) 2.0–4.5 keV, (5) 4.5–12.0 keV, and in three energy bands optimised for the flux maximum of the dust ring, derived from the spectra (Sect. 3.4): 0.2–0.8 keV, 0.8–2.2 keV, and 2.2–7.0 keV. The individual images were corrected for background emission and different exposure times and combined into mosaics as follows.

The background of the dust-ring observations is composed of the instrumental background, the local particle background in the orbit, the cosmic X-ray background, and the Galactic components along the line of sight. We model this complex mixture based on source- and ring-free regions in the sub-pointings by the task esplinemap in smoothing mode. For each energy band and instrument, the smoothed background maps of ten sub-pointings were averaged, scaled to the exposure of each sub-pointing and subtracted from the original images. Pointing 7 was excluded from the averaging because of its high background emission. For EPIC/pn, the out-of-time events were modelled within esplinemap and also subtracted. The background-subtracted images were exposure-corrected with a combination of the mean attitude of all pointings and the exposures of individual pointings.
Fig. 3. False-colour image of the XMM-Newton mosaic-mode observations in the energy bands 0.2–0.8 keV (red), 0.8–2.2 keV (green), 2.2–7.0 keV (blue), adaptively smoothed with a 2-pixel tophat. The right panel illustrates the eleven sub-pointings with the contours of the three detectors EPIC/pn, MOS1, and MOS2. The position of MAXI J1348–630 is marked near the centre of sub-pointing 04.

Spectra were generated from the data taken during individual pointings in their genuine coordinates by the task especget, using the source-excised event lists. The pn and MOS spectra of MAXI J1348–630 were taken from a circular extraction region with a radius of 20'' and the background from a nearby half annulus, both centered at the source position. They were grouped to include at least one count in each bin. For the ring spectra, an annular region with an inner radius of 34.5'' and an outer radius of 41.0'' was chosen from the radial profile (Fig. 8). Background spectra were generated from large circular source-free regions outside the ring structure and applied to all sub-pointings for which a similar background level can be expected. The background spectra generated from pointing 1 were used for the ring spectra of pointing 2 and the background of pointing 6 for 6, 8, and 9. In the pointings 7, 10, and 11, the background spectra could be used directly. The EPIC/MOS1 and MOS2 spectra of each pointing and their responses were merged by the task epicspeccombine. All spectra were binned to a minimum signal-to-noise ratio of 1.0 and analysed jointly using Xspec version v12.11.1 (heasoft-6.28).

2.3. MAXI

X-ray flux at energies 2–50 keV from MAXI J1348–630 was detected by MAXI for most of the period within 175 days after the initial discovery on 2019 January 26 (Tominaga et al. 2020). The first outburst peaked 14 days after discovery and...
after a roughly exponential decay the source disappeared after 104 days. A second, spectrally harder outburst was recorded between days 126 and 175 after discovery. Another re-brightening of MAXI J1348–630 in 2020 February was reported by Shimomukai et al. (2020). The flux levels of this re-brightening were more than two orders of magnitude lower than the primary outburst and therefore this re-brightening is not relevant for the observation of dust scattering.

The dust scattering ring is detected by SRG/eROSITA and XMM-Newton at photon energies 0.8–2 keV, an energy band not covered by MAXI. In order to obtain a light curve in a band which matches the photon energies relevant for the scattering as closely as possible, we downloaded the 2019 MAXI data from the HEASARC mirror. We then used the HEASOFT task mxproduct with standard settings to extract a light curve for MAXI J1348–630 in the energy band 2–3 keV. We removed bad stretches of data during which the line of sight to MAXI J1348–630 was blocked by the Crew Dragon space craft docked to the ISS. The remaining data were binned to a resolution of 0.1 days and stretches of missing data were filled by means of interpolation. This light curve (inset in Fig. 2) was used as reference for the analysis of time lags between the direct X-rays from MAXI J1348–630 and the scattered X-rays detected by SRG/eROSITA and XMM-Newton.

### 3. Analysis and results

#### 3.1. Scattering geometry

The scattering geometry is illustrated in Fig. 5. It is determined by the distance D to the source, the distance to the scattering layer xD, the opening angle of the scattering ring, θ, and the time delay Δt between the arrival times of the original signal and the light echo at the observer. The scattered signal will arrive with a time delay of

\[ \Delta t = \frac{\Delta D}{c} = \frac{xD\theta^2}{2c(1-x)} \]  

where the small-angle approximation was used and where ΔD is the additional distance the X-rays take due to scattering.

Solving Eq. [1] for the angular offset from the source position, θ, results in

\[ \theta = \sqrt{\frac{2c(1-x)}{xD\Delta t}} \]  

For well defined values of Δt and xD, i.e., a sufficiently short burst of radiation and a single layer of dust at distance xD, a scattering ring can be observed.

Observationally, one needs to determine θ and Δt to fix the relative geometry. If either xD or D can be determined independently, the absolute size of the triangle can be derived. Fortunately this is possible for the light echo around MAXI J1348–630.

#### 3.2. Location of scattering dust

Following Fig. 5 and Eq. [1] the distance D towards the source can be determined from the time lag, Δt, if the distance towards the scattering material xD is known. In the real world, however, this measurement is complicated by the structure of the interstellar medium along the line of sight. The intensity distribution of the halo is therefore given by a convolution of time lags introduced by the dust distribution along the line of sight with the variability of the source.

The circumstances leading to the giant scattering ring around MAXI J1348–630 make this event an ideal opportunity to measure the distance of MAXI J1348–630. The well-defined annular shape of the dust echo is due to the basically single-peaked burst and also implies the presence of a single, well defined layer of scattering material. We can confirm this conjecture with a more detailed study of the dust distribution using new Gaia data. Since the Gaia data release DR2 (Arenou et al. 2017) several 3-dimensional maps of the interstellar dust extinction in our Milky Way have been published (e.g., Lallement et al. 2019, Chen et al. 2019a). The 3D dust extinction cube published by Lallement et al. (2019) covers a volume of 6 × 6 × 0.8 kpc in the solar neighbourhood with 5 pc spatial binning and was derived by combining photometric and astrometric data from Gaia and 2MASS for 27 million stars with Gaia parallax uncertainties < 20%. We have analysed the data cube at the celestial position of MAXI J1348–630 where it extends to a maximum distance of ~3.9 kpc. The most significant regions of extinction are found at distances from the Sun between 1800 and 2200 pc with an integrated AV = 0.9 mag (Fig. 6).

The accuracy of the distances in the extinction cube is, however, limited by the fact that the stellar distances were derived by simple inversion of parallaxes, introducing significant bias to the absolute distance scale. In order to eliminate this bias, ancillary data sets with Bayesian estimates of the distances and other
stellar parameters have been created. The currently most comprehensive distance set is the Gaia DR2 StarHorse data set (Anders et al. 2019). This catalogue contains 265 million stars with distance, extinction, and other parameters estimated by the StarHorse Bayesian code (Queiroz et al. 2018) using data from Gaia, Pan-STARRS1, 2MASS, and AllWISE. The catalogue is available at gaia.aip.de.

In order to determine the dust distribution, we utilise the subset of the catalogue for the region within 0.9 of the position of MAXI J1348–630, covering the whole extent of the scattering ring in eRASS1 and eRASS2. We then selected the objects in the area of “red clump” giant stars in the dereddened $M_v$–(B – R) plane for our analysis, since these stars are luminous enough to cover the relevant distances and their stellar parameters have accurate estimates. We again consider only stars with relative uncertainties in distance < 20%. When plotting extinction versus distance for the resulting sample, a steep increase in $A_V$ is visible at 2000 pc. It is this region where the scattering ring is formed.

In order to determine the distance of the dust causing this extinction, we fits a model for the $A_V$ of a simple, homogeneous layer of dust to the data in the distance interval 1500–3000 pc (Fig. 7). The free parameters of the fit are $A_{V,0}$ (on the near side of the layer), $A_{V,1}$ (behind the dust) and $d_0$ (distance). The geometrical depth of the dust sheet is well constrained by the X-ray images of the scattering ring and is fixed at 190 pc (see Sect. 3.3 and Table 1). The best fitting mid-point distance of the dust sheet is at 2047 ± 22 pc, the best fit extinction values are $A_{V,0} = 0.78$ mag, $A_{V,1} = 1.90$ mag (see Fig. 7). The resulting distance remains very stable even if the depth of the layer is left free to vary.

3.3. Distance towards MAXI J1348–630

With the distance $xD$ well constrained by the StarHorse data, the distance $D$ to MAXI J1348–630 can be determined using the geometry shown in Fig. 5. However, as discussed above, both the distribution of time lags resulting from the burst light curve (Fig. 4) and the distribution of dust along the line of sight contribute to the width and the radial profile of the ring. For an accurate determination of $D$ we therefore modelled the radial profile with the following steps:

1. As for the fit in Fig. 7 we assume a homogeneous dust layer of a certain thickness $d_{dust}$ at a distance $xD$. The layer was divided into slices of 1 pc depth. For each slice and angle $\theta$ we calculated the X-ray flux $F_X(\theta)$ from the 2-3 keV MAXI lightcurve (Fig. 4) using the matching time delay $\Delta t$ at the time of the observation according to Eq. 2.

2. Following Mathis & Lee (1991) and Xiang et al. (2011) the observed brightness distribution as a function of $\theta$ from each dust slice at relative distance $x$ is given by

$$I(\theta, E) = F_X(\theta, E)N_H(1 - x)^{-2} \frac{d\sigma(E, \theta_{sca})}{d\Omega}$$

(3)

where $F_X(E, \theta)$ is the source X-ray flux relevant at angle $\theta$ as determined in step 1, $N_H$ is the hydrogen column density in the distance slice, and $\theta_{sca} \sim \theta/(1 - x)$. The scattering cross section $d\sigma/d\Omega$ depends on the composition and size distribution of the dust. Draine (2003) gives easy-to-use analytical approximations to the cross sections for the dust model by Weingartner & Draine (2001) which we adopt here:

$$\frac{d\sigma}{d\Omega} = \frac{1}{\pi \theta_{sca}^2 (1 + (\theta_{sca}/\theta_{sca,0})^2)^2}$$

(4)

We evaluated Eq. 4 at $E = 1.5$ keV where the characteristic scattering angle is $\theta_{sca} = 4^\prime$. We made no attempt to model the absolute flux of the scattering ring, hence in Eqs. 3 and 4 only the dependencies on $\theta$ are important here. Since at a given epoch the scattering ring covers a relatively small range of angles $\theta$, the exact function of $d\sigma(\theta_{sca})/d\Omega$ only marginally changes the model profile $I(\theta)$. Hence the choice of the model on dust composition and grain size distribution has only negligible influence on our results.

3. The ring profiles from each distance slice were added and the total flux normalised to the observed flux. The result is a model profile for the parameter pair $d_{dust}$ (depth of the dust layer) and $D$ (source distance). To find the best fitting values for the parameters $D$ and $d_{dust}$, we calculated the profiles for a grid of $D$ and $d_{dust}$ values and then determined the $\chi^2$-values for each resulting profile with respect to the measured profiles from eRASS1 and XMM-Newton. Since the X-ray images constrain the depth of the dust layer better than the Gaia data, we re-iterated fitting $xD$ to the StarHorse data with the $d_{dust}$ values derived from X-rays. The parameter space covered in the final run was 140 pc < $d_{dust}$ < 220 pc, 3280 pc < $d_{dust}$ < 3480 pc for the eRASS1 profile and 175 pc < $d_{dust}$ < 205 pc, 3350 pc < $d_{dust}$ < 3440 pc for the XMM-Newton profile.

The fit results for both the eRASS1 and XMM-Newton observations are presented in Table 1 and Fig. 5. It should be noted that using the dust distribution given by the extinction cube by Lallement et al. (2019) (Fig. 6) in the model results in a ring profile which is much broader and more structured than the observed profile, hence we conclude that our model assumption of a simple homogeneous layer is a better approximation to the actual distance distribution.

The distance ratio $x$ between the scattering dust and MAXI J1348–630 can be measured with remarkable precision: 0.25% for the XMM-Newton observation and 0.7% for eRASS1. For the XMM-Newton data the total statistical uncertainties (1.1%) are dominated by the errors in the distance towards the dust layer.

The absolute accuracy of the distance essentially depends on the systematic parallax uncertainties in the Gaia DR2 catalogue, which are still under investigation. Analysis of QSO parallaxes revealed a global negative parallax zero-point but also...
Table 1. Results of distance measurements.

| Data set     | $d_{\text{dust}}$ | $x D$  | $x$   | $D$   |
|--------------|-----------------|--------|------|-------|
| eRASS1       | 180$^{+22}_{-23}$ | 2046$^{+23}_{-25}$ ± 205 | 0.6035$^{+0.0046}_{-0.0036}$ | 3390$^{+46}_{-43}$ ± 339 |
| XMM EPIC     | 190$^{+10}_{-8}$  | 2047$^{+22}_{-25}$ ± 205 | 0.6029$^{+0.0008}_{-0.0012}$ | 3395$^{+38}_{-37}$ ± 340 |

Notes. (1) For the parameters $x D$ (distance to the dust layer) and $D$ (distance to MAXI J1348–630), the statistical uncertainty and the 10% systematic error due to Gaia parallax uncertainties are listed. The error bars in $D$ are calculated by quadratically adding the statistical uncertainties for $x D$ and $x$.

Table 2. Parameters of the fits to XMM-Newton EPIC ring spectra with absorbed power-law models*, all performed with $\chi^2$ fit statistics

| Parameter | Units | Model 1 | Model 2 | Model 3 |
|-----------|-------|---------|---------|---------|
| $N_H$     | $10^{21}$ cm$^{-2}$ | 8.0$^{+1.2}_{-1.1}$ | 7.5$^{+0.4}_{-0.4}$ | 7.5$^{+0.4}_{-0.4}$ |
| $N_{H,\text{North}}$ | $10^{21}$ cm$^{-2}$ | 8.7$^{+0.7}_{-0.7}$ | 8.7$^{+0.7}_{-0.7}$ | 8.7$^{+0.7}_{-0.7}$ |
| $N_{H,\text{South}}$ | $10^{21}$ cm$^{-2}$ | 6.8$^{+0.5}_{-0.5}$ | 6.8$^{+0.5}_{-0.5}$ | 6.8$^{+0.5}_{-0.5}$ |
| $\Gamma$  |                     | 4.2$^{+0.4}_{-0.4}$ | 4.0 | 4.0 |
| norm      |                     | 1.7$^{+0.5}_{-0.5}$ | 1.5$^{+0.2}_{-0.2}$ | 1.4$^{+0.2}_{-0.2}$ |
| $(10^{-5}$ ph keV$^{-1}$ cm$^{-2}$ arcmin$^{-2}$) | | | | |
| $\chi_{\text{red}}(dof)$ | 0.9 (1258) | 0.9 (1259) | 0.9 (1257) |

Notes. (1) Model const$t$babs(powerlaw), abundance=wilm in Xspec. Model 1: $N_H$ and power-law parameters allowed to vary. Model 2: power-law index fixed to 4.0. Model 3: Separate absorption terms for the Northern, the Southern, and three Southern parts. All parameter errors correspond to 90% confidence limits for 1 parameter.

3.4. X-ray spectral analysis of the dust scattering ring

The XMM-Newton EPIC spectra of the dust ring were binned to reach signal-to-noise ratios of at least 1.0 per bin in the energy range between 0.7 keV and 2.2 keV in the individual pointings. We fitted them jointly with an absorbed power-law, using the absorption model and abundances of Wilms et al. (2000). A multiplicative factor accounted for the different extraction regions and a flux of the spectra (Xspec model const$t$babs(powerlaw)). The best fit ($\chi_{\text{red}}^2 = 0.9$ for 1258 degrees of freedom) resulted in $N_H = 8.0^{+1.2}_{-1.1} \times 10^{21}$ cm$^{-2}$ and a power-law index of $\Gamma = 4.2 \pm 0.4$. This $N_H$ is consistent with the values obtained for MAXI J1348–630 from other missions. Tominaga et al. (2020) modelled the MAXI spectrum during the high/soft state with a disk black body model and upscattering at higher energies (tfabs $^*$simpl $^*$ diskb). The resulting disk temperatures at the innermost radius $kT_{\text{Rin}}$ are in the range 0.6–0.75 keV. In the energy range contributing to the dust scattering ring such a disk black body can be approximated by a power-law with $\Gamma \sim 2$. When taking into account the modification of the incident spectrum by the energy dependence of the scattering cross section which is approximately $E^{-2}$, an absorbed power law with $\Gamma \sim 4$ can be expected for the ring spectrum. Fixing the power-law index at $\Gamma = 4.0$, the absorption is better constrained to 7.5 $\pm$ 0.4 $\times 10^{21}$ cm$^{-2}$. To investigate the spatial dependence of the absorption terms, we employ two independent values for the Northern and for the Southern part of the dust ring, coupling pointings 2, 10, 11 in the North and 6, 7, 8 in the South. For the fixed power-law index of 4.0, we measure $N_{H,North} = 8.7 \pm 0.7 \times 10^{21}$ cm$^{-2}$ in the Northern part of the ring and $N_{H,South} = 6.8 \pm 0.5 \times 10^{21}$ cm$^{-2}$ in the Southern part. Figure 9 shows example spectra of a Northern and a Southern pointing and Table 2 the full list of model parameters.

For both the eRASS1 and eRASS2 observations, event files from the latest eSASS pipeline version (c946) were used to extract spectra of the ring area using the srctool task. For the eRASS1 data an annulus around the position of MAXI J1348–630 with radii $R_1 = 34.4$ arcmin, $R_2 = 40.6$ arcmin was used to extract the source events. For eRASS2 events in the annulus between $R_1 = 41.8$ arcmin, $R_2 = 49.3$ arcmin were extracted. In both cases the background was extracted from annuli larger than the source annuli, intervening sources were excised from the source and background regions. Given the limited SNR in the eRASS2 spectrum, we do not expect to measure a spectral index or $N_H$ significantly different from eRASS1. Therefore we only fit this spectrum together with the eRASS1 spectrum and tie the $\Gamma$ and $N_H$ parameters, leaving only the normalisations free to vary independently. The resulting model parameters are compiled in Table 2. The spectral indices and absorbing columns densities are in line with the XMM-Newton measurements. When fixing $N_H$ at the value measured for MAXI J1348–630 (Tomina et al. 2020), 8.6 $\times 10^{21}$ cm$^{-2}$, the best fit photon index is $\Gamma = 4.0$, as expected for an incident spectrum with $\Gamma \sim 2$. When fitting both the eRASS1 and eRASS2 spectra with fixed $N_H = 8.6 \times 10^{21}$ cm$^{-2}$ and $\Gamma = 4.0$, the resulting 0.5–2.0 keV fluxes are 5.32 $\pm$ 0.27 $\times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (eRASS1) and 1.57 $\pm$ 0.27 $\times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. With 3.4 $\pm$ 0.61(1$\sigma$) the eRASS1 / eRASS2 flux ratio is somewhat higher than the factor (1.2)$^4 = 2.1$ expected due to the increasing scattering angles and the $\theta^{-4}$ function of the Draine (2003) cross sections. This might be an indication for a decrease of the scattering cross sections deeper than $\sim \theta^{-4}$. On the other hand one has to consider the large linear size of the ring with a diameter of $\sim 50$ pc during the time of the eRASS2 observations. Given the azimuthal brightness variations visible in Fig. 3 variations in the dust distribution may also contribute to the observed flux ratio.
3.5. X-ray spectral analysis of MAXI J1348–630 in the post-outburst phase

3.5.1. eRASS1 & eRASS2

In the eRASS1 image MAXI J1348–630 was clearly detected, in a circular area with 0.5 arcmin radius we extracted 95 net counts (0.18 cts/s). The spectrum was fitted in Xspec with an absorbed power-law model. The data have been binned to a signal-to-noise ratio of at least 2 for clarity. The residuals (data–model)/error are shown separately in the lower panels.

![XMM-Newton ring spectra](image)

Fig. 9. XMM-Newton ring spectra taken by EPIC/ pn and MOS in the Northern pointing 2 (blue crosses) and the Southern pointing 6 (red diamonds) with an absorbed power-law model. The data have been fitted with an absorbed power law (tbabs*powerlaw), abundance=wilm in Xspec. Model 1: $N_H$ and power-law parameters allowed to vary. Model 2: $N_H$ fixed to $8.6 \times 10^{21}$ cm$^{-2}$. Model 3: power-law index fixed to 4.0.

![Background subtracted XMM EPIC ring profile](image)

Fig. 8. (left) Background subtracted eRASS1 ring profile (1.0–2.3 keV) with best fit model (red line, $D = 3390$ pc, $d_{\text{dust}} = 180$ pc). (right) Background subtracted XMM EPIC ring profile (1.0–2.0 keV) with best fit model (red line, $D = 3395$ pc, $d_{\text{dust}} = 190$ pc).

![Normalized counts vs. Energy](image)

Table 3. Parameters of the spectral fits to the dust scattering rings in eRASS1 and eRASS2.

| Param. | Units | Model1 | Model2 | Model3 |
|--------|-------|--------|--------|--------|
| $N_H$  | 10$^{21}$ cm$^{-2}$ | $11.1^{+3.5}_{-2.8}$ | 8.6 | $8.4^{+0.9}_{-0.8}$ |
| $\Gamma$ | | 5.04$^{+1.25}_{-1.02}$ | 4.17$^{+0.30}_{-0.31}$ | 4.0 |
| norm1  | 10$^{-3}$ ph keV$^{-1}$ cm$^{-2}$ | $23.0^{+21.6}_{-9.7}$ | $14.2^{+1.3}_{-1.4}$ | $13.3^{+2.0}_{-1.8}$ |
| $\chi^2_{\text{red}} (dof)$ | | 1.0 (284) | 1.0 (285) | 1.0 (285) |

| Param. | Units | Model1 | Model2 | Model3 |
|--------|-------|--------|--------|--------|
| $N_H$  | 10$^{21}$ cm$^{-2}$ | $12.6^{+4.0}_{-3.0}$ | 8.6 | $8.7^{+0.9}_{-0.8}$ |
| $\Gamma$ | | 5.42$^{+1.32}_{-1.10}$ | 4.09$^{+0.29}_{-0.29}$ | 4.0 |
| norm1  | 10$^{-3}$ ph keV$^{-1}$ cm$^{-2}$ | $29.0^{+31.0}_{-13.1}$ | $14.0^{+1.3}_{-1.4}$ | $14.0^{+2.0}_{-1.8}$ |
| norm2  | 10$^{-3}$ ph keV$^{-1}$ cm$^{-2}$ | $9.1^{+10.3}_{-4.5}$ | $4.1^{+1.2}_{-1.2}$ | $4.1^{+1.4}_{-1.4}$ |
| $\chi^2_{\text{red}} (dof)$ | | 1.0 (570) | 1.0 (571) | 1.0 (571) |

Notes. (*) Model const*tbabs(powerlaw), abundance=wilm in Xspec. Model 1: $N_H$ and power-law parameters allowed to vary. Model 2: $N_H$ fixed to $8.6 \times 10^{21}$ cm$^{-2}$. Model 3: power-law index fixed to 4.0. For the eRASS1 + eRASS2 fits both spectra were fitted simultaneously with $N_H$ and $\Gamma$ tied between the spectra and norm1 and norm2 left to vary independently. All parameter errors correspond to 90% confidence limits for 1 parameter.

3.5.2. XMM-Newton

MAXI J1348–630 was faint at the time of the XMM-Newton observation with a mean count rate of about 0.005 cts s$^{-1}$. The EPIC spectra were fitted with an absorbed power law and W statistic (cstat in Xspec), resulting in a poorly constrained $N_H = 7.7^{+7.8}_{-4.9} \times 10^{21}$ cm$^{-2}$ and a power-law index of $\Gamma = 1.9^{+0.8}_{-0.7}$. From the fit to the EPIC/pn spectrum, we derive an absorbed 0.5–2.0 keV flux of $1.1^{+0.1}_{-0.1} \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, roughly a factor 10 lower than during eRASS1 just three weeks before the XMM-Newton data were obtained. Fixing column density and power-law index at the eRASS1-derived values, we obtain a flux of $9.2^{+1.3}_{-1.6} \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ in the same band.
4. Discussion and Conclusion

Since the first idea about dust scattering halos was formulated and after the first successful attempt of its realisation almost three decades later, X-ray scattering on interstellar dust has become an established method of determining distances. The method works particularly well when the X-ray source shows bursts, because then instead of a uniform halo, expanding rings can usually be observed. The ambiguity between the distance of the source and the position of the dust can be resolved if one of the two quantities is known. If it can be assumed to be infinite, as in the case of GRBs, the distance between the interstellar dust layers can be determined.

MAXI J1348–630 presents an ideal case for such studies, since the only layer of dust in between is already precisely known based on Gaia measurements, so that we were able to measure the distance of the X-ray source itself. The distance of 3390 pc has very low statistical uncertainty (1.1%) with respect to the Gaia distance frame, the absolute accuracy is limited by systematics of the Gaia parallaxes which amount to an uncertainty of 10%. This makes the distance to MAXI J1348–630 one of the best known distances to a black hole binary, which were typically measured with Very Long Baseline Interferometry with typical statistical uncertainties on the order of 5–10%. Examples include Cyg X-1, with 1.86$^{+0.15}_{-0.11}$ kpc (Reid et al. 2011), the systematic uncertainty of this position is large, given its Gaia DR distance of 2.39$^{+0.11}_{-0.12}$ kpc (Gandhi et al. 2019), which makes it consistent with newer VLBI data (Miller-Jones et al., 2020, submitted). A distance to Cyg X-1 has also been estimated by the analysis of its dust scattering halo by Xiang et al. (2011), who arrive at a distance in the interval 1.72 – 1.90 kpc.

Our distance improves the earlier distance estimates for MAXI J1348–630, which were based on not well-calibrated distance indicators such as the transition luminosity between the hard and the soft state. Assuming that this luminosity is significantly lower than the integrated 21 cm interstellar column density, Tominaga et al. (2020) estimate the distance of 3–8 kpc (Russell et al. 2019a). Using the same ansatz, Tominaga et al. (2020) estimate the distance to MAXI J1348–630 to 4.8 kpc. Noting that with $N_H \sim 8.6 \times 10^{21}$ cm$^{-2}$ the measured X-ray absorption column is significantly lower than the integrated 21 cm interstellar column density ($N_H \sim (1.45 \cdots 1.53) \times 10^{21}$ cm$^{-2}$) (HI4PI Collaboration et al. 2016), however, Tominaga et al. argue that MAXI J1348–630 must be in front of the Scutum-Centaurus arm (consistent with our result), and then argue for a most likely distance of 3.8 kpc.

Using the MAXI monitoring, Tominaga et al. (2020) utilised the measured evolution of the inner radius of the accretion disk during the soft state to estimate the mass of the black hole (e.g., Steiner et al. 2010, and references therein). With our improved distance, we can revise their inner disk radius measurements to $R_{in} = 97 \pm 13$ km (including a systematic error of 10%), leading to a revised estimate of the black hole mass of

$$M_{BH} = \frac{c^2 R_{in}}{6G} \sim (11 \pm 2) \left(\frac{D}{3.39 \text{kpc}}\right) (\cos^{-1}\frac{1}{2} M_\odot)$$

compared to the earlier estimate of 13 $\pm$ 2 $M_\odot$ (Tominaga et al., 2020). The transition to the soft state, which MAXI measured at a bolometric flux of $\sim 1.7 \times 10^{-8}$ erg s$^{-1}$ cm$^{-2}$ therefore occurred at a luminosity of 1.7% of the Eddington luminosity. With our revised distance and mass the peak flux of $1.0 \times 10^{-7}$ erg s$^{-1}$ cm$^{-2}$ given by Tominaga et al. (2020) corresponds to 10% of the Eddington luminosity.

The distance measurement places MAXI J1348–630 at a position between the Sagittarius and Scutum-Centaurus spiral arms of the Milky Way. Figure 10 shows that MAXI J1348–630 is located in an area of relatively low stellar density. With our distance modulus $\mu = 12, A_V = 2.4$ and the quiescence brightness $r' = 20.69$ (Baglio et al., 2020) we derive an absolute magnitude $M_r = 6.24$, consistent with a main sequence K-type donor star. Both the late type secondary and the location of the object suggest a relatively old age of the system.

The discovery of this giant scattering ring demonstrates the power of the SRG/eROSITA surveys for this type of science, with their unlimited field of view and 6-monthly observing cadence. With the incidence of new black hole transients about once per year and the outburst activity of other powerful X-ray sources in our galaxy, we expect further discoveries of dust scattering halos and rings during the 4 years of the survey and significant insights into the physics of both the transient sources and the interstellar medium.

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