On the detection of the progenitor of the type Ia supernova 2007on

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ABSTRACT
We present new Chandra X-ray observations and detailed astrometry of the field of the type Ia supernova 2007on, for which the detection of a likely progenitor in archival Chandra data was recently reported.

No source is detected in the new Chandra images, taken six weeks after optical maximum. We calculate a 90–99 per cent probability that any X-ray source near the position of the supernova (SN) is fainter than in the pre-outburst images, depending on the choice of aperture, which supports the identification of the archival X-ray source with the SN.

Detailed astrometry of the X-ray and new optical images, however, gives an offset between the SN and the measured X-ray source position of 1.15 ± 0.27 arcsec. Extensive simulations show that the probability of finding an offset of this magnitude is ∼1 per cent, equal to the (trial-corrected) probability of a chance alignment with any X-ray source in the field. This casts doubt on the identification of the X-ray source with the progenitor, although the scenario in which at least some of the observed X-rays are connected to the SN may be the least unlikely based on all available data.

After a brief review of the auxiliary evidence, we conclude that only future X-ray observations can shed further light on the proposed connection between the X-ray source and the progenitor of SN 2007on, and thus whether an accreting white dwarf scenario is truly favoured for this SN Ia.

Key words: binaries: close – supernovae: general – white dwarfs – X-rays: binaries.

1 INTRODUCTION
Type Ia supernovae (SNe Ia) are thought to be the result of thermonuclear explosion of carbon–oxygen white dwarfs as they reach or exceed the Chandrasekhar mass limit (see e.g. Hillebrandt & Niemeyer 2000; Leibundgut 2000 for reviews). Broadly speaking, there are two main classes of models: the accreting models, in which the white dwarf more or less steadily accretes matter from a (hydrogen-rich) companion star (Whelan & Iben 1973; Nomoto 1982), and the merging models, in which two white dwarfs coalesce under the influence of angular momentum losses due to the emission of gravitational waves (Tutukov & Yungelson 1981; Iben & Tutukov 1984; Webbink 1984).

Deciding which of the scenarios contribute to the observed SN Ia rates is difficult from a purely theoretical point of view. One may, however, expect observable differences between the accreting and merging scenarios. In an effort to constrain the progenitor scenario for individual SNe Ia, Voss & Nelemans (2008) recently started a search for progenitor detections of newly reported, nearby SNe Ia in archival Chandra X-ray observatory images, arguing that the X-ray luminosities of progenitors in the accreting models are expected to be much higher than those of the progenitors in the merging models.

Their search was successful. The nearby SN Ia 2007on in NGC 1404 (Gal-Yam et al. 2007; Immler & Brown 2007; Morrell, Folatelli & Stritzinger 2007; Pollas & Klotz 2007) turned out to have an X-ray counterpart in a combined 75-ks Chandra/ACIS exposure, taken 4.5 yr before the explosion. The X-ray counterpart was detected at the 5σ level, and within 0.9 ± 1.3 arcsec of the optical SN. Based on the low chance alignment probability of ∼1 per cent, it was claimed to be the likely progenitor, favouring an accreting white dwarf scenario over a merger scenario for 2007on (Voss & Nelemans 2008).

Given the importance of the detection of the progenitor to an SN Ia, we obtained follow-up Chandra observations (section 2.1) and performed accurate astrometry of the field of 2007on using existing

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Figure 1. Pre-outburst (left-hand panel) and post-outburst (right-hand panel) Chandra/ACIS images of the region around 2007on. The grey-scale encoding of the squares indicates the integer number of counts in the corresponding pixels, white being zero and the darkest grey corresponding to three counts. The positions of the optical SN (×) and the X-ray source as reconstructed by wavdetect (+) are indicated. Note that the effective area times exposure time of the post-outburst image is approximately 65 per cent of that of the pre-outburst image (see also Fig. 2). The PSF in the post-outburst image should be slightly sharper since the source was aligned with the optical axis of Chandra. The pixel randomizations applied by the Chandra data processing pipeline were removed to produce these images.

and new imaging (Section 2.2). We briefly review the further evidence as to the nature of the X-ray source in Section 3, and conclude with a summary of our results in Section 4.

2 NEW RESULTS

2.1 Chandra DDT observations

Following the detection of the likely progenitor to 2007on by Voss & Nelemans (2008), we were granted 40 ks of Chandra/ACIS observations through the Director’s Discretionary Time (DDT) programme. Due to pointing restrictions, 2007on was observed for 18.5 ks on 2007 December 24, and 21.5 ks on 2007 December 27. We used the ACIS-S instrument with the source positioned at the aimpoint on CCD S3. Being one of the two back-illuminated CCDs, S3 has the best sensitivity to soft X-rays; the archival X-ray source close to 2007on had been observed to be quite soft. Fig. 1 shows the pre-outburst image together with the new DDT observations.

The source appears to have become fainter, with two photons in a 1.0-arcsec aperture that should contain ~90 per cent of the flux, centred on the position of the X-ray source in the archival images, and counting only photons in the 0.3–8.0 keV energy range (for rough comparison, there were 17 such photons in a 1.0-arcsec aperture in the progenitor image). Given the measured average background rate of 1.3 photons per 1.0-arcsec aperture, the observed two photons suggest that the source may have disappeared altogether. A larger, 2-arcsec aperture contains 10 counts (versus 22 in the pre-outburst image); this has a 4 per cent probability of happening by chance for a purely Poissonian background, or a measured 8 per cent probability of happening in a random aperture between 4 and 20 arcsec from the SN in the post-outburst image. There is thus no convincing evidence that there is still a source in the follow-up observations. As expected the wavdetect source-finding algorithm from the standard CIAO data reduction package (version 4.0) does not find a source when run with the standard false-alarm probabilities of 1 × 10⁻⁶ pixel⁻¹.

In order to be able to compare both epochs, we determined the relative effective collecting area times exposure time of the individual observations. Since part of the progenitor data were taken with one of the front-illuminated ACIS-I CCDs, which have different sensitivities especially in soft X-rays, and since furthermore the soft-X-ray sensitivity of ACIS has overall degraded significantly since 2003 Spring when the progenitor data were taken, the relative effective areas of the pre- and post-outburst data were expected to be a function of the assumed source spectrum. We thus worked out the relative effective areas times exposure times for the 2003 and 2007 epochs as a function of source temperature, which are shown in Fig. 2. As it turned out, the relative sensitivities were very much independent of the assumed source spectrum: the degradation in soft X-ray sensitivity of ACIS conspired with the lower soft X-ray sensitivity of the ACIS-I CCD used for part of the progenitor observations to produce an almost identical sensitivity versus energy curve for both epochs. This made comparison of both epochs considerably easier, since we did not have to worry about the source spectrum, or possible spectral changes between both epochs.

We performed a fully Poissonian Monte Carlo simulation to determine the probability of observing, by chance, the observed lower number of photons in the post-outburst image compared to the pre-outburst image, with the same (though unknown) underlying source luminosity. We did so for a range in apertures and, for completeness, also as a function of source spectral temperature, even though we had already concluded that the relative sensitivities of the observations in both epochs are quite insensitive to the assumed source temperature.
The results are also shown in Fig. 2. The confidence level for the X-ray source having dimmed increases with smaller aperture, to >99 per cent for apertures of radii ≤ 1.25 arcsec centred on the position of the pre-outburst X-ray source. SN 2007on fell a distance 2.5 and 1.7 arcmin away from the optical axis in the pre-outburst ACIS-I and ACIS-S observations, respectively, so that a 1.0-arcsec aperture should still contain approximately 80 per cent of the photons. However, if one allows the source to be slightly extended or blended, a larger aperture may be appropriate, with a correspondingly lower confidence level. The slightly smaller point spread function (PSF) of the on-axis, post-outburst observations will make us underestimate the confidence level of the source having dimmed or disappeared.

We should mention that these results change slightly if we do the data analysis with the standard photon position randomization applied during the data reduction. While there is no scientific justification for this randomization, it does shift several photons in the post-outburst image by 1 pixel, such that four instead of two 1.0-arcsec apertures, respectively, while the confidence levels for the larger apertures go up slightly compared to the non-randomized results.

Finally, to test for variability of the source in the pre-outburst observations, insofar as the limited number of photons allows, we performed a Kolmogorov–Smirnov test against a uniform distribution (more accurately a set of uniform distributions with Poisson-distributed average rate) for both the ACIS-S and ACIS-I observations. The photon arrival times, and also those of subsets of only the soft or hard X-rays, were found to be perfectly compatible with uniform distributions, within the 1σ confidence intervals. There is thus no evidence for variability in the pre-outburst images.

2.2 Astrometry

2.2.1 Method

Voss & Nelemans (2008) found an offset between the optical SN and the X-ray source of 0.9 ± 1.3 arcsec, entirely compatible with the X-ray source being the progenitor of the SN. In order to verify that there is no significant offset between the two, we tried to improve on their astrometry.

We retrieved archival observations of NGC 1404 obtained with the Wide Field Imager (WFI) at the ESO 2.2-m telescope, and of SN 2007on taken 2007 November 30 with the ESO Faint Object Spectrograph and Camera (EFOSC) at the 3.6-m telescope, both located at La Silla Observatory.

A 5-min R-band WFI image of NGC 1404 was used to astrometrically calibrate the EFOSC observation of the SN. A total of 76 stars from the Two Micron All Sky Survey (2MASS) coincided with the 8 × 16-arcmin² field of view of a single WFI chip; 38 of these were not saturated and appeared stellar. After iteratively removing outliers we obtained an astrometric solution using 31 2MASS stars, yielding rms residuals of 0.091 arcsec in both right ascension and declination.

A list of secondary astrometric standard stars was compiled by measuring the positions of stars on the WFI image. These calibrated positions were used to transfer the astrometry on to the 20-s R-band EFOSC image of the SN. The final astrometric calibration used 71 stars common to both the WFI and the EFOSC image, with rms residuals of 0.092 arcsec in right ascension and 0.077 arcsec in declination.

Based on this astrometric calibration, we determined the position of the SN in the EFOSC image to be \( \alpha_{\text{2000}} = 03^h 38^m 50.999^s \) and \( \delta_{\text{2000}} = -35^\circ 34' 31'' .12'\). The uncertainty of the position on the EFOSC image is about 0.006 arcsec in both coordinates, while the uncertainty on the absolute position is 0.13 arcsec in right ascension and 0.12 arcsec in declination (i.e. the quadratic sum of the uncertainties in the tie between the 2MASS catalogue and the WFI image, the tie between the WFI and the EFOSC images and the uncertainty of the SN position in the EFOSC image).

In order to compare the optical position of the SN with the X-ray position of the candidate counterpart in the pre-outburst Chandra ACIS-I (ObsID 4174) and ACIS-S (ObsID 2942) observations, we determined a boresight correction using X-ray sources (from WAVDET) which, by eye, had likely optical counterparts in the EFOSC images. Objects that appeared elongated or blended in either the optical or X-ray image were rejected, and one rejection iteration of optical sources outside the 95 per cent confidence circles as given by WAVDET was applied. For the ACIS-I observation we thus found seven suitable X-ray sources, which provided an offset to the raw X-ray positions of \(+0.031\pm 0.026\) arcsec in right ascension and \(-0.018\pm 0.025\) arcsec in declination. For the ACIS-S observation, we found 10 X-ray sources, providing an offset of \(-0.067\pm 0.049\) arcsec in right ascension and \(-0.059\pm 0.048\) arcsec in declination. The boresight corrections thus appear to be very small.

Applying these corrections to the pre-outburst X-ray observations gives \( \alpha_{\text{2000}} = 03^h 38^m 50.909^s \) and \( \delta_{\text{2000}} = -35^\circ 34' 30'' .70'\) for the absolute position of the X-ray source in the combined image, with uncertainties of 0.25 arcsec in right ascension and 0.20 arcsec in declination. For the relative positions of the optical SN and the X-ray source, the uncertainty in the referencing to the absolute ICRS frame is irrelevant, so the error in their relative positions

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1 See http://cxc.harvard.edu/ciao/threads/acispixrand/.
Figure 3. Spatial distribution of the sources used for the X-ray to optical referencing. Right ascension and declination are relative to SN 2007on, marked with ‘+’. The \texttt{WAVDETECT} standard errors in the source positions are indicated by circles, while arrows indicate the displacement between the X-ray sources and their likely optical counterparts in the boresight-corrected image. Circle radii and arrow lengths are exaggerated by a factor 120, so that a 0.5 arcmin arrow indicates a 0.25-arcsec displacement. Circles and arrows drawn with thick and thin strokes show the reference sources for the ACIS-I and ACIS-S observations, respectively.

is smaller. We find that the X-ray source is offset by 1.15 ± 0.27 arcsec from the optical SN, or 1.15 ± 0.08 arcsec excluding the error on the position of the X-ray source as given by \texttt{WAVDETECT} (i.e. only including the positional uncertainty of the optical SN relative to its reference stars, and the tie between the optical and X-ray reference stars), where we have conservatively added the errors on the boresight corrections in quadrature for want of a better method. The uncertainty in the position of the X-ray source, relative to its reference sources, is thus by far the dominant uncertainty, as expected.

2.2.2 Implications

To estimate the probability of such a misalignment happening by chance, i.e. with the X-ray source near 2007on still corresponding to the optical SN, we performed a detailed Monte Carlo simulation in which we added artificial sources to the combined progenitor image from the \textit{Chandra} archive. We began by running \texttt{WAVDETECT} on the image to detect the sources in the image. From the source and smoothed background images returned by \texttt{WAVDETECT}, we filtered all pixels that had an average background within 10 per cent of the value measured around the progenitor (6.9 counts per 2-arcsec aperture), and that had no detected source flux anywhere within five times this radius. We randomly picked coordinates from the qualifying pixels, took a random subpixel sampling, and added photons according to a bivariate normal distribution, until the number of photons in a 2-arcsec aperture equalled 21, the number found in the pre-outburst images (Voss & Nelemans 2008). Since the PSF width in \textit{Chandra} images varies quite a bit with energy, we probably gained little by modelling the PSF with a more complicated function. Instead we ran the simulation for three reasonable widths of the distribution, choosing 0.8, 1.0 and 1.2 arcsec radii of 86 per cent encircled energy, and doing 40,000 trials for each.

The resulting images were again analysed with \texttt{WAVDETECT}, and the positional offsets between the artificial sources and the reconstructed artificial sources were recorded. Fig. 4 shows the cumulative distribution of these offsets. The probability of finding a source a distance 1.15 arcsec or more away from the input source is low, close to 1 per cent for the 1.0-arcsec PSF, and slightly higher and lower for the larger and smaller PSFs, respectively.

An interesting feature of the probability distributions shown in Fig. 4 is the multiple components: a component that drops off quickly on roughly the pixel size scale, and a much slower component. Presumably, this slower component represents cases in which the new source combines with an undetected source or overdensity in the nearby background, pushing it above the detection threshold, and being detected as a source offset from the input source. To test this hypothesis we ran a further Monte Carlo simulation, this time with purely Poissonian backgrounds of the same average value (within 10 per cent of 6.9 counts per 2-arcsec aperture). The results are shown as the dotted lines in Fig. 4. Indeed, with the artificial backgrounds the slow component vanishes and the number of cases in which an offset of 1.15 arcsec or more is recorded drops, to about 0.3 per cent for a 1.0-arcsec PSF.

In order to test whether the \texttt{WAVDETECT} algorithm could be responsible for some of the positional scatter in the Monte Carlo simulation, we repeated the analysis with a simple centroid algorithm, which we again applied only to simulated sources that were first detected with \texttt{WAVDETECT} in order to ensure that they are still representative of sources that would have been found in the original search by Voss & Nelemans (2008). We measured centroids for the $N = 40,000$ set of simulated images with a 1.0-arcsec PSF. The amount of scatter in the centroid positions depends on the aperture chosen: for a 2-arcsec aperture it is slightly smaller, while for 1- and 3-arcsec apertures it is slightly larger than the \texttt{WAVDETECT} scatter. An

Figure 4. Probabilities of finding the detected source more than a certain distance from the optical source, shown by the solid lines, which from top to bottom represent the assumed 1.2-, 1.0- and 0.8-arcsec PSF widths in the progenitor X-ray images. Dotted lines are the same but for artificial, pure-Poissonian backgrounds. The dashed line shows the trial-corrected chance alignment probability, and the solid vertical line the observed offset between the optical and X-ray source.
adaptive aperture, starting from 3 arcsec and decreasing in 10 per cent steps to 1.5 arcsec after positional convergence in each step, gives the same scatter as a 2-arcsec aperture, suggesting that this is about the best one can do (in minimizing the positional scatter). For this ‘optimal’ aperture, the X-ray source centroid is offset from the optical SN by 1.09 arcsec, slightly less than the WAVDETECT offset of 1.15 arcsec. The net result is that the offset probability is very similar for centroid and WAVDETECT positions, at approximately 1 per cent.

The important question now is how these numbers compare to the probabilities of a chance alignment of the optical SN with an X-ray source in the field. For this we counted the number of X-ray sources in the progenitor image found by WAVDETECT. We filtered out the region around NGC 1404 where the background is within 50 per cent of the value measured around 2007on, which should be representative of both the position where a SN would typically be discovered, and of the probability of detecting an X-ray source there with WAVDETECT. In an area measuring 7.1 arcmin$^2$ WAVDETECT finds 17 sources, giving a probability of 0.28 per cent for a chance alignment within 1.15 arcsec of the optical position of 2007on. Note that this figure somewhat conservatively includes sources that are detected with a lower significance level than the possible progenitor of 2007on. Counting only equally or more significant detections gives 14 sources, or a 0.23 per cent chance alignment probability.

Given that SN 2007on was the fourth trial in their search for progenitor detections in archival Chandra data (Voss & Nelemans 2008), one has to conclude that the chance alignment probability for the detected source is $\sim0.9$ per cent, or $\sim1.1$ per cent for any detectable source.

3 DISCUSSION

Based on just the astrometry, the chances of the X-ray source being related to the SN are small but equal to the chances of a chance alignment. The fact that the X-ray source appears to have dimmed (or disappeared) in the Chandra DDT observations suggests that at least some of the X-ray photons in the progenitor images may have come from the progenitor, although alternatively, the X-ray source might be intrinsically variable (and unrelated). In this section we try to collect further evidence that may point to a relation (or not) between the X-ray source and the SN.

3.1 Soft versus hard X-ray photons

Voss & Nelemans (2008) mentioned the softness of the X-ray source close to 2007on as further suggestive evidence of a connection between the two. In the accreting models, the accretion of matter by a white dwarf at a high rate is expected to create a strong, soft X-ray source (e.g. van den Heuvel et al. 1992), which makes the hardness of the source a potentially useful property.

Fig. 5 shows the hardness ratios of all X-ray sources in the combined pre-outburst image that are detected with at least 15 photons. Photons are binned into S(oft), M(edium) and H(ard) energy bands, corresponding to 0.3–1.0 keV, 1.0–2.0 keV and 2.0–8.0 keV photon energies, respectively, and colours are constructed following the method of Prestwich et al. (2003). The source close to 2007on is the leftmost data point in both panels, shown in bold.

Figure 5. Hardness ratios of X-ray sources in the field of 2007on, measured in photons corrected for the background flux levels. The S, M and H energy bands correspond to 0.3–1.0, 1.0–2.0 and 2.0–8.0 keV, respectively. The source close to 2007on is the leftmost data point in both panels, shown in bold.

To further investigate the possibility of a two-component source, we show in Fig. 6 the pre-outburst X-ray image divided into soft (0.3–1.0 keV) and medium/hard (1.0–8.0 keV) photons, together with the position of the optical SN. The obvious problem is that the photon statistics of these images become even worse. Nevertheless the medium/hard photons are seen to line up with the position of the reconstructed X-ray source, while the soft photons appear more scattered. Although the photons closest to the optical SN are soft, there is no general trend by which the soft photons line up better with the optical position. The figure does therefore not provide convincing evidence for a connection between the optical SN and the soft X-rays in particular.

3.2 Hubble Space Telescope images

Given the indication that the progenitor X-ray source may (partly) have been an unrelated, nearby source, we reanalyse the archival Hubble Space Telescope (HST) images of the region around 2007on, while performing the same accurate astrometry. Fig. 7 shows a drizzled (Fruchter & Hook 2002) 1224-s image taken on 2006

pushed the source in the direction of the more ‘mundane’ region occupied by the majority of sources in the upper panel of Fig. 5, the source would still have shown an overabundance of soft X-rays, as is clear from the lower panel in this figure.

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Figure 6. Pre-outburst Chandra image split into soft (0.3–1.0 keV, left-hand panel) and medium/hard (1.0–8.0 keV, right-hand panel) photons. The positions of the optical SN (×) and the X-ray source as reconstructed by WAVDETECT for the combined image (+) are indicated.

Figure 7. Drizzled HST/ACS image of the region around 2007on, totalling 1224 s in the far-red F814W filter. A faint, extended object appears to be present near the X-ray source position from WAVDETECT (+), although it is close to the detection limit of $I \sim 26.5$. Nothing is visible at the position of the optical SN (×).

August 6 with the Advanced Camera for Surveys (ACS) using the F814W far-red filter. There is evidence for a faint, extended source close to the position of the X-ray source, although it is close to the detection limit of $I \sim 26.5$. Nothing is visible at the optical position of the SN.

If we compare the observed X-ray flux $f_X \sim 2 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ in the 0.3–8.0 keV band (see Nelemans et al. 2008, after a correction to the value given in Voss & Nelemans 2008) to the $I$-band flux $f_I$ of the object in the ACS image, and we compare this to results from the Chandra Deep Field-North and -South surveys (Alexander et al. 2001; Giacconi et al. 2002), we conclude that the observed flux ratio $f_X/f_I \gtrsim 10$ is at or beyond the upper ends of the distributions observed in those surveys. This makes it unlikely that all of the observed X-ray photons originate from this possible background source, although it is conceivable that a few of them do. Nevertheless we conclude that an origin within NGC 1404 for the X-ray source appears to be more likely.

4 CONCLUSION

We have presented accurate astrometry of the field of SN Ia 2007on, and conclude that there appears to be an offset of 1.15±0.27 arcsec between the optical SN and the X-ray source close to it in archival Chandra images. Based on just this information, and barring astrometric errors, the probability of the X-ray source being related to the SN is small: about 1 per cent. The probability for a chance alignment with an unrelated X-ray source is, unfortunately, equally small, which makes it difficult to decide between the two scenarios.

Several additional pieces of information suggest that at least part of the X-ray source may have been related to the SN, although none of them is decisive. First, there is the indication that the X-ray source has dimmed (or disappeared) in the post-outburst Chandra images taken about six weeks after optical maximum, at the 90–99 per cent confidence level depending on the choice of aperture size. Secondly, the source in the pre-outburst images shows an excess of soft X-ray photons relative to the other sources in the field, and SN Ia progenitors in the accreting models are expected to be prolific sources of soft X-rays. One could argue that the probability for a chance alignment between the optical SN and a soft X-ray source is much lower than the quoted 1 per cent probability of an alignment with any X-ray source, which would make a physical connection between the X-ray source and the optical SN less unlikely than a chance alignment. A possible extended
background object close to the X-ray source position (but away from the optical SN), as seen in archival HST/ACS data, could conceivably be responsible for some of the observed hard X-rays. Probably the only way out of the impasse will be future Chandra observations of 2007on, which can decide whether the X-ray source close to 2007on really has dimmed or disappeared. X-rays from the SN are not expected to be detectable with Chandra. Immler et al. (2006) consider Compton scattering of gamma-rays from radioactive decay which, although model dependent, is expected to fall short of the detection limit by three orders of magnitude, while the X-ray luminosity from interaction of the SN ejecta with the local interstellar medium is expected to fall off as 1/time and should thus have decreased by an order of magnitude since our DDT observations. A future detection would thus imply that the source is unrelated. Although the possibility of the X-ray source having been an unrelated transient source can never be ruled out completely, a future non-detection would further lower the probability of the source having been a chance alignment, since only a few per cent of all X-ray sources observed in a given extragalactic snapshot are transients (Voss & Gilfanov 2007).

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