On the X-ray Spectrum of the Putative Central Compact Object in 1E 0102.2-7219

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Abstract

We have analyzed the archival Chandra X-ray Observatory observations of the compact feature in the Small Magellanic Cloud supernova remnant (SNR) 1E 0102.2-7219 which has recently been suggested to be the Central Compact Object remaining after the supernova explosion. In our analysis, we have used appropriate, time-dependent responses for each of the archival observations and we have modeled the background instead of subtracting the background. We fit unbinned spectra and use different statistics to evaluate the quality of the fit. We find that the blackbody model is rejected at the 90% confidence level. The spectrum is described adequately by a non-equilibrium ionization model similar to other regions in the SNR which are dominated by ejecta heated by the reverse shock. Based on an MCMC analysis, the abundances of O and Ne are significantly enhanced compared to typical SMC abundances, but the the abundances of Mg, Si, S, are not constrained well enough to determine an enhancement. The spatial distribution of the counts is not consistent with that of a point source from SAOTrace and MARX simulations.

Spectral Analysis

We fit spectra for the 25 observations simultaneously with appropriate time dependent responses applied to each observation. For each observation, we have 3 spectra, one from the source region and two from two different background regions. One of the background spectra is extracted near the source region to model the emission from the region around the source, called near background. The other background is extracted off the remnant, in order to model the sky and detector background. The salmon ellipse in Figure 1 is the source region, the white regions are the near background regions.

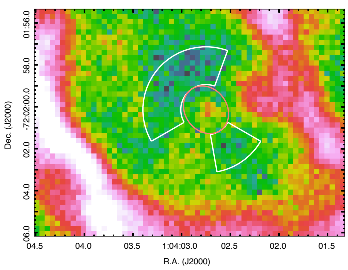

Figure 1. The source and near background region. The image pixel size is half a sky pixel (0.246") and the energy range is 0.35-4.0 keV.

An empirical near background spectrum

The near background spectrum was fitted with a two *vnei* component model in XSPEC. In this model, *wilm* abundances and the *vern* photoelectric constants are used, the abundances of O, Ne, Mg, Si, S in the two *vnei* component are linked, and the other elements are set to SMC abundances (0.2). The temperature, ionization time scale and normalization are free. The fitted temperature and ionization timescale produce values that are difficult to reconcile with the shocked ejecta scenario. However, an empirical background model is acceptable for the purposes of our analysis as long as it reproduces the background spectrum well. The Pearson χ^2 is 12701 for 12437 degrees of freedom. The goodness of fit is 0.67 which is an acceptable value.

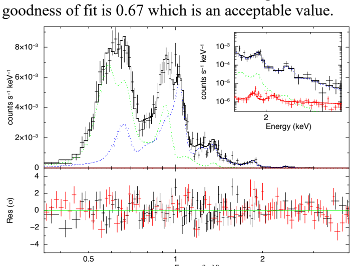

Figure 2. Near background spectrum fit with two *vnei* model. The green and blue dotted lines are the two components, respectively. The red points and line are the sky and detector background.

Vogt, F. P. A., Bartlett, E. S., Seitenzahl, I. R., et al. 2018, Nature Astronomy, 2, 465
Hebbar, P. R., Heinke, C. O., & Ho, W. C. G. 2019, MNRAS, 2213
Pavlov, G. G., & Luna, G. J. M. 2009, ApJ, 703, 910
Kaastra, J. S. 2017, A&A, 605, A51

Source Spectrum fit with Near Background Model

We fit the source spectrum with the near background spectrum model, allowing only a global normalization to vary. We are testing the hypothesis that the source and near background spectrum have the same intrinsic shape but differ only in intensity. The result is shown in Figure 3. The near background model can not fit the source spectrum at O, Mg, and above 2 keV. The source spectrum has a different shape than that of the near background spectrum.

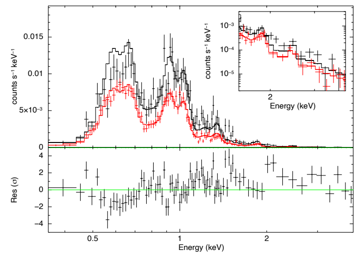

Figure 3. Source spectrum fit with the near background model. The red points and line are the near background data and model respectively. The black points are the source data and the black line is the fitted near background model with only the normalization free.

Blackbody model Can be rejected

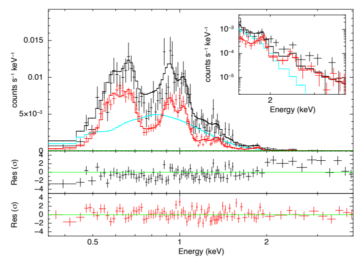

Figure 4. Source spectrum fit with a blackbody and the near background model. The parameters of the blackbody model are fixed to the values reported in Vogt et al. (2018). The black data points and line are the source spectrum and model. The red is near background. The cyan line is the blackbody component in source model

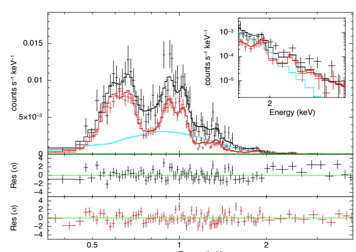

Figure 5. Source spectrum with the blackbody temperature and normalization free in the fit.

The Anderson-Darling (AD) test statistic is sensitive to the tails of the cumulative distribution. We use a goodness based on the AD statistic to rule out the blackbody model at more than a 90% confidence level.

Table 1. Source spectrum fit with a blackbody model and our near background model. The temperature and normalization of blackbody component are set to the Vogt values in one fit and allowed to vary in the other fits. C_{90} is the 90% confidence level for the distribution of the *C-statistic* (Kaastra 2017).

model	fixed T and norm	free T and norm
temperature (keV)	0.19	$0.22^{+0.01}_{-0.01}$
normalization (10^{-7})	3.399	$2.034^{+0.15}_{-0.14}$
near background scale	$0.975^{+0.014}_{-0.014}$	$1.012^{+0.015}_{-0.015}$
C-statistic (dof)	9749 (18672)	9684 (18670)
C_{90}	9721	9752
log(CvM) (goodness)	-8.32 (1.00)	-10.78 (0.89)
log(AD) (goodness)	-6.71 (1.00)	-8.72 (0.98)

NEI model is adequate

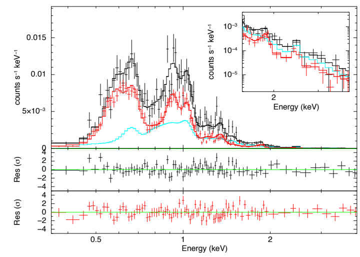

Figure 6. Source spectrum fit with a *vnei* and the near background model. The black data points and line are the source spectrum and model. The red are the near background. The cyan line is the *vnei* component in the source model.

Table 2. Source spectrum fit with *vnei* model. The uncertainties are 1σ error from MCMC analysis with 50,000 steps.

Parameters	vnei
$kT_e\ (keV)$	$0.86^{+0.02}_{-0.11}$
$n_e\,t_1, (10^{11}\ \mathrm{cm^{-3}s})$	$4.23^{+0.00}_{-0.00}$
$Norm, (10^{-5})$	$1.29^{+0.12}_{-0.11}$
Oxygen	$3.31^{+3.35}_{-1.04}$
Neon	$1.20^{+1.47}_{-0.44}$
Magnesium	$0.31^{+0.44}_{-0.25}$
Silicon	$0.01^{+0.38}$
Sulfur	$0.84^{+2.25}_{-0.43}$
C-statistic (dof)	9659(18664)
C_{90}	9881
log(CvM) (goodness)	-11.6 (0.57)
log(AD) (goodness)	-9.27 (0.77)

Image Analysis

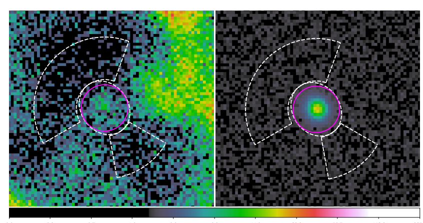

Figure 7. Left: Image of merged 10 registered observations. Right: Image created from a simulation of a point source, averaging from 100 simulation to reduce the Poisson noise.

We test if the counts distribution of the CCO region is consistent with the counts distribution of a point source in a uniform background in our simulations. The white dashed regions are used for determining the scale factor of the spectral flux in simulation. The counts in the dashed regions are equal for the observation and the simulation. The radial distribution of the counts from the regions described by the magenta circles around the putative CCO position are calculated. The radius of the magenta circles are 2 sky pixels (0.984").

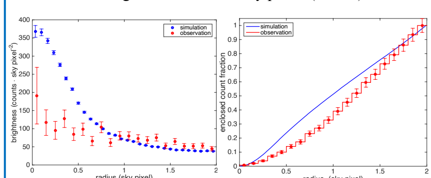

Figure 8. Left: The radial profile for the simulation and the observation in the magenta circle in Figure 7. Right: The cumulative distribution for the simulation and the observation in the magenta circle in Figure 7.

Comparing the cumulative distribution, the Kolmogorov-Smirnov D statistic (maximum absolute difference of the cumulative distributions) is 0.189. The sample size is 87417 for the simulation, and 838 for the observation. According to J. V. Wall and C. R. Jenkins (2003), the D value for the 0.001 significance level is 0.068. The hypothesis that the counts distribution is consistent with that of a point source can be rejected at the 99.9% confidence level.