ABSTRACT

E0102 was observed with the HETG on Chandra at two epochs and these data are analysed here in the context of cross-calibration activities of the IACHEC. The HETG data are described and images and spectra are presented. E0102’s emission lines observed with the HETG are consistent with their rest wavelengths (< 200 km s\(^{-1}\) shift) and have real spectral widths of order FWHM = 2.35 \times 900 km s\(^{-1}\) due to Doppler motions.

Comparison of the HETG data with the RGS-derived model – “v1.9” – shows good general agreement of the brightest lines present and a broadband flux (7.85–23Å) agreement within 5% for each of the four MEG spectra (2 epoch \times two orders.) To quantify the discrepancy between the model and the HETG-observed data in a way similar to the comparisons of CCD instruments (Plucinsky et al. 2008), sets of lines were tied together and adjusted with common norm factors, specifically the O\text{VII}, O\text{VIII}, Ne\text{IX}, and Ne\text{X} line sets. The best-fit to the MEG data is attained with less than 5% adjustment to the nominal model norms.

Initial consideration of background events in the data show that they are especially important for the HEG spectra. Including background corrections brings the HEG–MEG difference down to of order 6%.

Subject headings: radiation mechanisms: thermal — supernova remnants — ISM: individual(E0102) — Techniques: Spectroscopic — X-rays: ISM

1. Introduction

The SNR 1E0102.2-7219, hereafter E0102, is a bright, compact source with X-ray emission dominated by lines of H– and He–like oxygen and neon (Rasmussen et al. 2001; Flanagan et al. 2004). Lines from other elements are visible (e.g., C, N, Mg, Si, S) over the 0.3 to 10 keV range covered by present X-ray observatories. If Fe-L line emission is present (as seems likely) it is at a lower level as compared with O, Ne, and Mg lines.
2. HETG Observations and Data Processing

E0102 was observed at two epochs with the HETG: Sept.-Oct. 1999 and Dec. 2002, summarized in Table 1. These data sets differ in roll angle by \( \approx 78 \) degrees.

Analysis of the archive-retrieved data was carried out with TGCat ISIS scripts\(^1\) that called current CIAO tools. Of note in the analyses\(^2\): the origin was set at the bright inner spot of the Q-stroke feature; zeroth-order radius was 60 pixels; events were extracted from widths of \( \pm 60 \) pixels (\( \pm 0.0096 \) in \text{tg}\_d); and order sorting values of 0.25 and 0.20 were used for the first and second epochs, respectively. Note that the first epoch is at a focal plane temperature of \(-110^\circ\) C.

The nominal spectral extraction produces a type-II PHA file consisting of the projections of the dispersed data onto the wavelength axis, Figure 1. Even with the much reduced effective spectral resolution due to the extended nature of E0102, discrete lines are resolved in the 12 Å to 22 Å range which corresponds to the \( \approx 1 \) keV to 0.55 keV energy range. Looking ahead, more information is retained if the data are viewed as 2D spectral images (Figure 3); here the emission from many discrete lines are clearly visible as rings in the images.

\(^{1}\text{http://space.mit.edu/cxc/analysis/tgcat}\)

\(^{2}\)The data extraction was carried out in /nfs/spectra/d1/Science/E0102/Data as documented in the file \text{wid\_e0102.txt}.

<table>
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Note. — The data from obsids 120 and 968 were taken at a focal plane temperature of \(-110^\circ\) C and are combined for analyses. All HETG E0102 observations were taken as part of the HETG GTO program.

\(^{a}\)Number of zeroth-order events within 29.52” (60 sky pixels) radius and in the ENERGY range 0.4–8.0 keV.
Fig. 1.— PHA spectra from obsid 3828. The effect of the extended nature of E0102 is clear in the broad flat-topped “line profile” of spectral lines. Color code: MEG+1 (red), MEG-1 (blue), HEG+1 (orange), and HEG-1 (green).

3. Continuum in the E0102 Spectrum

An attempt at estimating the underlying continuum of the E0102 spectrum is given in Appendix A. Because there are few “continuum” regions in the HETG dispersed data, we can only make very rough estimates of the underlying continuum and, in particular, cannot separate out any pseudo-continuum from Fe line emission. Even so, simple continuum fitting suggests components at $\approx 0.3$ keV and $\gtrsim 2.0$ keV. The SMC-$N_H$ value is likewise difficult to constrain because of the lack of counts below the O VII region.

4. Lines in the E0102 Spectrum

The model lines and continuum of the IACHEC SNR group,”v1.9” (Plucinsky et al. 2008)$^3$, is used for comparison with the HETG data. For reference the v1.9 model components are plotted in Figure 2 along with an indication of the non-Fe and Fe emission expected from a simple 2-shock model described in Appendix B.

The model line energies are set to their nominal values because analysis of HETG data (Flanagan et al. 2004) concluded that the observed line centroids are seen at wavelengths within 200 km s$^{-1}$ of the “laboratory” rest values.

$^3$http://cxc.harvard.edu/twiki/bin/view.cgi/SnrE0102/FinalModel. See also the script e0102_line_set.sl
As for the width of the emission lines, the analyses done by Rasmussen et al. (2001) produced a lower limit to line-of-sight velocity broadening given by a “square velocity profile of an expanding shell” of ±1350 km s$^{-1}$ for all of the lines. This can be approximated by a Gaussian broadening with a sigma of ≈800 km s$^{-1}$. HETG results (Flanagan et al. 2004) gave a Ne X line-of-sight broadening with a Gaussian sigma of ≈1100 km s$^{-1}$. These are consistent and suggest that the real X-ray emission model should include finite line widths at the level of a Gaussian sigma of 800–1200 km s$^{-1}$ (aka a FWHM of 1900–2800 km s$^{-1}$). In round values it’s reasonable to set $\sigma_E = 0.003 E$ for all lines (900 km s$^{-1}$); with larger values possible in the case of line-blends, e.g., for some lines in the v1.9 model.

5. Comparing Data and Model

5.1. 2D Images and Residuals

Figure 3 compares the HETG composite data images with simulations based on the model spectrum$^4$. As the color-coded residual images imply, the data-model residuals are dominated by small-scale differences between the data and model images. These are the result of inaccuracies of the line-images used in the model as well as spatial–Doppler-velocity

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$^4$These and other post-PHA analyses were carried out in /nfs/spectra/d1/Science/E0102/e2d_080504 using Event-2D software, http://space.mit.edu/hydra/E2D_demo/e2d_demo.html, and many custom scripts, generally mentioned or called from the top-level script: analysis_lines.txt. Notable among these are e0102_data.sl and e0102_cal_model.sl which load the data sets and setup the model definition.
5.2. 1D Comparisons

The 2D data and model can be binned and compared in 1D along the wavelength axis using coarse binning, e.g. upper plots in Figure 4. Another option for 1D comparison is a K-S test, lower panel in Figure 4, which avoids the need to set a binning scale. Both of these comparisons suggest that the model is slightly over-predicting the NeIX line region; this is also suggested by the large amount of green residual at the center of the MEG residual image of Figure 3.
Fig. 4.— Comparing MEG $-1$ order 1D data (obsid 3828) and model (v1.9). The upper panels show coarsely binned 1D distributions and residuals. The lower panel shows a K-S test comparison plot between the data and model events. Both comparisons suggest a small excess of model counts (blue) at $13.5\,\text{Å}$, Ne IX.
5.3. Flux Ratios in Regions

For purposes of comparing the data-model flux, however, it is useful to compare counts in broad dispersed-wavelength regions. Because of the small PSF of the HETG spectral images there is very little cross-contamination in wavelength bands especially if the regions are chosen with boundaries in low-count spectral regions.

Very similar to the comparison to the v1.9 model made for CCD instruments, the wavelength range is broken into six regions: O\textsuperscript{VII}, O\textsuperscript{VIII}, O-Ly\beta+Fe-L, Ne\textsuperscript{IX}, Ne\textsuperscript{X}, and Ne-Ly\beta+Mg. These regions are indicated in Figure 5 along with the counts ratios between data and the un-adjusted (“frozen”) v1.9 model\(^5\). This shows that the MEG calibration generally agrees within 5% of the v1.9 model. It is these MEG measurements at epoch 2003.0 (lower panel) that were used to determine the HETG-MEG values listed in Plucinsky et al. (2008).

The discrepancy between the HEG and MEG values in Figure 5 is bothersome. One possible source of the difference is background counts which will be more important for the HEG spectra because they have higher dispersion (more readout area per Angstrom) and lower effective area. As a first look into this, a background extraction of obsid 3828 was made with the center of the extraction offset by 150 pixels in the +CHIPY direction\(^6\). The background counts in the coarse regions were subtracted from the data counts to get corrected D/M values. The MEG–1 order has background fractions in the 1–4% range whereas the HEG±1 orders have values of 5–11% and higher. As the bottom panel of Figure 6 shows, the HEG-MEG discrepancy is reduced to an average of \(\approx 6\%\) by including the background correction.

The background-corrected MEG values have been used to create an updated version of the “Table 5” fit values and associated plot that are given in Plucinsky et al. (2008). The new value of the Constant is 0.990 (was 1.012) and the 90% CL norm ranges (unscaled) are, respectively: [1.27,1.37], [4.56,4.68], [1.31,1.36], [1.37,1.41]. Figure 7 gives an updated plot using these values, differing very little from the Plucinsky et al. (2008) plot. In particular, the difference in error “pattern” between HETG-MEG and ACIS-S3 remains, showing an \(\approx 10\%\) difference at O\textsuperscript{VII}.

Lastly, if one takes the two epochs of data in Figure 6 at face value (making the large

\(^5\)Most of this region analysis is carried out by the scripts: fill\_regions.sl, write\_regions.sl, plot\_regions.sl, load\_\*\_regions.sl and region\_stats.sl. Warning: this is very ad hoc and messy!

\(^6\)The +CHIPY direction in Sky coordinates is given by: \((\Delta X, \Delta Y) = (-\sin(\rho), -\cos(\rho))\) where \(\rho\) is the ROLL\_NOM angle.
Fig. 5.— Ratios of D/M in six broad energy regions for epoch 1999.8 (top) and 2003.0 (bottom). The model counts are from the baseline v1.9 model with no adjusted parameters. No background correction has been applied to either dataset.
Fig. 6.— Ratios of D/M for epoch 1999.8 (top) and the background corrected 2003.0 (bottom). The 5 nominal model parameters (Const., O VII, O VIII, Ne IX and Ne X) have been adjusted for a best fit to the background corrected MEG ±1 2003.0 data (bottom panel). Note that comparing the lower panels here and in Figure 5 the HEG-MEG discrepancy has decreased due to the background subtraction.
assumption of calibration stability between them), it appears that E0102 has increased in flux overall by 2–3\% over the \( \approx 3 \) year time span. The Ne\( X \) line shows a larger increase, by perhaps an additional 5\% above this amount – this might be expected for a still-ionizing plasma.

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Facilities: CXO (HETG).

REFERENCES


A. Fitting a 2-NoLine Continuum

Although there are not very many line-free regions in the HETG spectra of E0102, e.g., those highlighted in blue in Figure 8, one can at least make an attempt to fit the nominal calibration continuum model to the continuum-like regions of the data.

The nominal continuum model\textsuperscript{7} is of the form \texttt{tbabs*tbvarabs(apec+apec)}. The first \texttt{tbabs} represents Galactic absorption with fixed $N_H = 0.0536$ and all abundances at 1.0\texttt{[wilms]}. The \texttt{tbvarabs} term is the SMC absorption with abundances set according to PPP's absorption model and its $N_H$ parameter is to be determined. We have the comment by Blair that 'the [optical] extinction to E0102 is about half Galactic and half from the SMC'. Since the extinction is due to dust scattering this suggests that SMC-$N_H$ could be $\approx 0.05$ (assuming the SMC has the same dust-to-H ratio as Galactic) to perhaps as large as 0.21 (assuming that the SMC dust-to-H is $\approx 0.25$ Galactic like the metal abundances).

For the continuum emission components, the two \texttt{apec} models are “NoLine” models from Randall Smith\textsuperscript{8}. Besides normalizations (to be fit) and redshifts (0), the NoLine models also include a temperature (keV) and an overall metal Abundance. For the simple fitting to HETG data here\textsuperscript{9} I fix the high-T component to 2.0 keV and use the agreed-upon high-T component abundance of 1.0\texttt{[wilms]}

Thus, in fitting the HETG continuum-like regions there are 5 free parameters in the model: the 2 norms, the SMC-$N_H$, the $kT$ of the low-T NoLine component, and the Abundance of the low-T NoLine component. As examples, fits made by fixing the SMC-$N_H$ at values of 0.05, 0.21, and 0.50 are overplotted in Figure 8 with the values of other interesting parameters given in the caption. To explore the parameter space a bit, contours of $\Delta \chi^2$ are shown in $N_H$–Abundance space in Figure 9. Note that the best-fit Abundance value changes from a high value (which I’ve clipped at 9.5) at low SMC-$N_H$ to a low value (ditto to 0.5) at higher SMC-$N_H$ values but the main dependance is on the SMC-$N_H$ value with a minimum near 0.5 ($\times10^{22}/$cm$^2$ of course.) From the simple model fits of Appendix B we might expect the low-T abundance value to be of order 4, following the models’ oxygen abundance values.

Looking at a different slice of parameter space, the variation of $\Delta \chi^2$ as a function of SMC-$N_H$ and $kT$-low is shown in Figure 10; here the Abundance value has been set using the

\textsuperscript{7}http://cxc.harvard.edu/twiki/bin/view.cgi/SnrE0102/AbsorptionModel

\textsuperscript{8}http://cxc.harvard.edu/twiki/bin/view.cgi/SnrE0102/NoLine

\textsuperscript{9}See the file \texttt{analysis_phacon.sl} for the messy specifics.
Fig. 8.— The four HETG spectra from obsid 3828 with continuum-ish regions indicated in blue. The best-fit continuum model for three values of SMC-$N_H$ are over plotted: SMC-$N_H=0.05$ (green, with $kT$-low = 0.274 keV, Abund-low = 15.0, $\chi^2 = 514.$), SMC-$N_H=0.21$ (red, 0.272 keV, 1.56, 439.), and SMC-$N_H=0.50$ (orange, 0.235 keV, 0.5, 388.).
gray-curve (optimum) values\textsuperscript{10}. There is a general correlation of the $kT$-low with SMC-$N_H$, though $kT$-low only varies over a small range.

Note that in these contour plots I’ve indicated data-model agreement $\Delta \chi^2$ levels. These are different from the usual parameter estimation levels of $\Delta \chi^2$ which are a constant, e.g., 2.71 for 90%. The data-model agreement levels reflect how large a variation in $\chi^2$ is expected from one observation to another and therefore the confidence with which one can reject the null hypothesis that the data come from the model distribution. This $\chi^2$ variation depends on the number of degrees of freedom and can be approximated by: $\Delta \chi^2 \approx s \sqrt{2 \frac{N_{dof}}{s}}$, where $s$ is the number of sigma that corresponds to the desired confidence level for a Gaussian\textsuperscript{11}, i.e., for 68%, 90% and 99% we have $s = 1.0$, 1.39, and $\approx 2.0$.

Finally, it’s worth commenting that this is a lot of “fancy machinery” that is being applied to rather scruffy data. This approach of fitting just the continuum regions might be better applied to the XMM-Newton RGS data where line-free regions might be more plentiful and better identified.

\textsuperscript{10}This is equivalent to just fitting the Abundance as well, however, because of the clipping of the values to 0.5 to 9.5 the fitting tends to find false minima and the contour gets messed up. So I’ve explicitly set Abundance(SMC-$N_H$) based on individual fits where I can verify that the minimum was found.

\textsuperscript{11}This equation follows from Fisher’s approximation that $\sqrt{2 \chi^2}$ is normally distributed with mean $\sqrt{2 \frac{N_{dof}}{s}} - 1$ and variance 1.0, given at \url{http://en.wikipedia.org/wiki/Chi-square_distribution}. 
Fig. 9.— Contours of chi-squared in $kT$-low-Abundance vs SMC-$N_H$ space. At each point, the two norms and the temperature of the $kT$-low NoLine component were fit; the location of the curves of Figure 8 are marked with “x”s. The “+” marks the best-fit and the contours are at $\Delta \chi^2$ values corresponding to data-model agreement (see text) with confidence levels 68%(red), 90%, 99%(aka 2-sigma), 3-sigma, and 5-sigma. The gray curve traces the best Abundance value for a given SMC-$N_H$ value.

Fig. 10.— Contours of chi-squared in $kT$-low vs SMC-$N_H$ space. At each point, the two norms were fit with the Abundance of the $kT$-low component set at optimum value by the gray curve of Figure 9. The “+” marks the best-fit and the inner set of contours (red, green, blue) are spaced at the usual $\Delta \chi^2$ levels for parameter estimation confidence of 68%, 90% and 99%. The larger contours are at $\Delta \chi^2$ values corresponding to data-model agreement (see text) with confidence levels 68%(red), 90%, 99%(aka 2-sigma), 3-sigma, and 5-sigma.
B. Two \texttt{vpshock} Approximate Model

In order to get some idea of what the actual line emission from E0102 might look like at high-resolution, it is useful to fit the data to a simple model consisting of some nominal \texttt{tbabs*tbvarabs} absorption times the sum of two \texttt{vpshock} components. This was done with the HETG zeroth-order data from obsid 3828 and Figure 11 shows the data and model for an example fit. The two shock temperatures were fixed at 0.272 and 2.0 keV and the SMC-$N_H$ fixed at 0.21 (this was before the nominal $N_H$ values were set.) The fit parameters were the abundances (tied between components) and Tau$_u$’s. A reasonable fit (i.e., D/M within 10–20\%) is achieved and gives abundances of O, Ne, Mg, Si and Fe of order 4.0, 7.7, 3.2, 1.2, and 2.0 [wilms] respectively.

The lower panel of Figure 11 shows the contributions of the two components (red, blue) as well as their values if Fe is set to 0 (orange, light blue. The orange curve is hidden under the light blue in the 0.7–0.9 keV range.) At CCD resolution the Fe in the model clearly contributes flux but without producing the signature of a clear line, though perhaps the Fe enhances a slight bump at $\approx 0.8$ keV.

Another 2-shock fit was done using the composite Suzaku dataset of Miller. In this case an SMC-$N_H$ value of 0.05 was used and other parameters are low and high $kT$ [$\tau$] values of 0.30 keV [9.6e11] and 2.0 keV [1.3e11], and abundances for O, Ne, Mg, Si, and Fe of: 3.4, 8.1, 4.4, 1.3, and 1.4 [wilms], respectively. Note that these abundances are similar to the HETG zeroth-order values above inspite of the different SMC-$N_H$’s and instruments used.

A final example of a 2-shock model fit to the data is the one shown for reference at high-resolution in the plot of Figure 2. This model was fit to the HETG zeroth-order data and used the nominal “v1.9” absorption (\texttt{tbabs $\times$ tbvarabs}) along with a very low low-T shock temperature of 0.2 keV and the nominal “v1.9” high-T value of 1.736 keV. In this case the fit abundances of O, Ne, Mg, Si and Fe are 8.0, 8.3, 5.1, 2.2, and 5.8 [wilms]. The Ne:Mg:Si ratios are similar to the other fits above but the O and Fe are relatively elevated, likely due to the very low low-T value used.

These fitting examples\textsuperscript{12} show that i) a 2-shock model can reasonably (10 \%) reproduce the observed E0102 spectrum in the 0.4 to 3.0 keV range, and ii) Fe-L emission is needed in the model. As mentioned in Plucinsky et al. (2008), a future project is to investigate self-consistent Fe-L emission scenarios that can give rise to the Fe as-observed in the “v1.9” model.

\textsuperscript{12}See the files: \texttt{e0102_zomodel.sl} and \texttt{e0102_suzaku.sl}.
Fig. 11.— The HETG zeroth-order data and a 2-shock model. The upper panel shows the data (black) and model (red) for one of the 2-vpshock models mentioned in the text. The lower panel shows the data (gray) and the low-T (red) and high-T (blue) shock model components. Also plotted are the same components but with the Fe abundance set to zero (orange, light blue. The orange curve is hidden by the light blue in the 0.7–0.9 keV range.)
Fig. 12.— Line-images used in simulating the HETG dispersed events. *Top row, l-to-r:* O VII, O VIII, Ne IX and Ne X. Middle row: C&N, Fe-L, Mg+Si+S, and All-energies. The purple circles are for reference. The larger image shows a colored combination of these individual images; note that the color coding is not by energy per se.

C. Ion-based line images of E0102

The modeling of the expected dispersed line-images from E0102, Figure 3, requires not only the instrument ARF and the emission spectrum (the “v1.9” model spectrum), but also template image(s) of the source being observed. For the modeling done here a set of ion-based line images were extracted from the zeroth-order data\textsuperscript{13} and used in the model. These images are shown in Figure 12 along with some fiducial reference rings. This approach does a reasonable job at a coarse level but residuals still remain between the model and data images. Of course, this means that there is more information in the dispersed data to be extracted. ;-)

\textsuperscript{13} By e0102_line_image.sl.