Estimating the Oxygen Ejecta Mass in E0102-72


Abstract

The Chandra HETGS observation of SNR E0102-72 in the SMC provided flux measurements of individual emission lines of oxygen, neon, magnesium and silicon. Ratios of these line fluxes provide diagnostic information of the emitting plasma (insofar as integrated measurements are appropriate). Using this technique, a best-fit plasma model for oxygen was obtained. Assuming a pure metal plasma consisting of O, Ne, Si and Mg, we estimate the electron density and calculate the mass of oxygen which gives rise to the measured line flux. The results from the best-fit oxygen plasma model yield an ejecta mass of \( \sim 6 M_\odot \), consistent with a massive progenitor of \( \sim 30 M_\odot \). We briefly discuss the importance of several assumptions which go into this estimate of ejecta mass.

Introduction

1E0102.2-7219 is a young (\( \sim 1000 \) years) supernova remnant (SNR) in the Small Magellanic Cloud. It was discovered in X-rays with the Einstein Observatory (Seward and Mitchell, 1981), and shortly afterwards optical filaments of oxygen were found (Dopita et al., 1981) and measured to have velocities of thousands of km/s (Tuohy and Dopita, 1983), pegging it as one of a small number of identified oxygen-rich SNRs. As a class, these SNRs are believed to come from massive progenitors.

Chandra HETGS observations have allowed us to constrain the plasma characteristics of the X-ray emitting material in the SNR (Fredericks et al. 2001, 2002, 2003). In this poster, we build on this analysis, estimating the oxygen ejecta mass and examining the implications for the mass of the progenitor.

Prior Analysis - Determining the Plasma Properties

Individual emission lines of O VII, O VIII, Ne IX, Ne X, Mg XI, Mg XII, and Si XIII were resolved in the spectrum. In determining line flux, each emission line had four potential distinct measurements for each observation in 1st order: Medium Energy Grating (MEG) \( \pm 1 \) orders and High Energy Grating (HEG) \( \pm 1 \) orders (Figure 2), for a potential total of eight measurements for each line. Techniques for determining line flux and associated errors on this extended source were presented in Fredericks, et al. 2001.

In order to characterize the X-ray emitting plasma, we took ratios of measured (global) line fluxes and compared them against ratios predicted by plasma models. (By taking ratios, the impact of unknown quantities such as abundance and distance is minimized.) We used a plane-parallel shock model, vnpshock (Borkowski et al. 2001), in which the electron and ion temperatures were assumed equal and the ionization parameter, \( \tau \), assumed a range of values from zero to an upper limit, \( \tau_{upper} \). Details were given in Fredericks et al. 2002. Figure 1 shows contours of constant line ratio in the grid of interesting model parameters, \( T_e \) (electron temperature) and \( \tau_{upper} \). These contours delimit the range of model parameters consistent with the ratios and errors measured for the oxygen lines. The yellow region in the figure is the “allowed” region of the parameter space, and the black cross denotes our best-fit model. Note that global flux measurements (i.e., the integrated measurement from the entire SNR) may not be appropriate as the plasma properties may vary.
within the SNR (see Fredericks et al. 2003.)

**Determining the Ejecta Mass**

The flux\(^1\) of a line observed at earth with no redshift or column density, is given by

\[ F = \frac{\epsilon(T_e)}{4\pi R^2} \int n_en_HdV, \quad (1) \]

where \( F \) is the flux in ph cm\(^{-2}\) s\(^{-1}\), \( \epsilon(T_e) \) is the emissivity in ph cm\(^3\) s\(^{-1}\), \( R \) is the distance to the source in cm and \( n_e \) and \( n_H \) are electron and hydrogen number densities in the source, respectively. \( \int n_en_HdV \) is the emission measure in cm\(^{-3}\).

Assuming \( n_e \) and \( n_H \) constant, and substituting the abundance relation, we obtain

\[ n_en_Z = F\frac{4\pi R^210^{4-12}}{\epsilon(T_e)V}, \quad (2) \]

where \( A \) is the relative abundance (by number) with respect to hydrogen and \( n_Z \) is the number density of element \( Z \).

The parameters on the right-hand side of this equation are obtained straightforwardly. For \( \epsilon(T_e) \), we assume a specific plasma model for the element in question. The vnpshock model which we use generates emissivities normalized to cosmic abundances, thus defining the value of \( A \) (Grevesse and Anders, 1991). We have assumed values for the distance, \( R \), and the volume, \( V \), of 59 kpc and \( 6.6 \times 10^{57} \) cm\(^3\), respectively. We have measured the flux, \( F \), and assumed a column density of \( N_H = 8 \times 10^{20} \) cm\(^{-2}\) with cosmic abundances to obtain the unabsorbed flux. Our volume estimate assumes a simple geometric ring-type model as illustrated in Figure 6: a portion (±30 degrees) of a shell of inner radius 3.9 pc and outer radius 5.5 pc. We have assumed a filling factor of 1.

**Selecting a plasma model**

For the case of oxygen, ratios of measured emission lines indicate the allowed region (in yellow) shown in Figure 1. The best-fit model is indicated by the cross. A similar diagnostic plot was used to select a model for the neon plasma (see Figure 2.) Since the neon emission line fluxes did not have the underlying continuum removed, these plasma diagnostic ratios are less reliable. For the case of magnesium, silicon and iron, we selected plasma models based on Hayashi, et al. (1994). The models we assumed are shown in Table 1.

**Determining electron density, \( n_e \)**

To determine the electron density, we have made the important assumption that this is a pure metal plasma consisting of O, Ne, Mg, Si and Fe. (Based on the dominance of the oxygen and neon lines and the relative weakness of the iron lines and continuum in the spectrum, we take the remnant to be ejecta-dominated and make the simplifying assumption that the electrons are contributed predominantly by these metals.) We assumed the oxygen, neon and magnesium were in helium-like, hydrogen-like, or fully stripped configurations (i.e., each oxygen atom contributes 7 ±1 electrons.) We assumed the silicon is helium-like, and the iron is neon-like. Thus,

\(^1\)See http://cxc.harvard.edu/atomdb/physics/physics_units/physics_units.html
\[ n_e = (7 \pm 1)n_O + (9 \pm 1)n_{Ne} + (11 \pm 1)n_{Mg} + 12n_{Si} + 16n_{Fe}. \] (3)

Multiplying by \( n_e \), and substituting Equation 2 into each term on the right-hand side (using measured fluxes of the brightest hydrogen-like and helium-like lines for each of the elements), we obtain an estimate of \( n_e^2 \).

With the plasma conditions of Table 1 and the assumed volume, distance and column density, we obtain \( n_e \sim 0.9 \text{ cm}^{-3} \). We find that oxygen contributes about 69% of the electron density, neon about 12%, and Fe, Mg, and Si contribute the remainder.

**Deriving Oxygen Ejecta Mass**

Having determined an estimate for \( n_e \), we substitute it into Equation 2 with the measured flux of the brightest oxygen lines and the emissivity from our best-fit plasma model to obtain the density of oxygen ions, \( n_O \). We multiply by the mass of an oxygen ion and the assumed volume to obtain the mass of the oxygen ejecta. The result, \( \sim 5.7 \text{ M}_\odot \), is listed in Table 1. Similar analysis yields \( \sim 2.2 \text{ M}_\odot \) for the neon ejecta, but the plasma model relies on emission line measurements from which we could not remove the continuum component.

**Assumed Plasma Parameters**

<table>
<thead>
<tr>
<th>Element</th>
<th>( T_e )</th>
<th>( \tau )</th>
<th>plasma model basis</th>
<th>Ejecta Mass (M(_\odot))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>0.34</td>
<td>11.9</td>
<td>HETG plasma diagnostics</td>
<td>5.7</td>
</tr>
<tr>
<td>Neon</td>
<td>0.58</td>
<td>11.9</td>
<td>HETG plasma diagnostics</td>
<td>2.2</td>
</tr>
<tr>
<td>Magnesium</td>
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<td>12.0</td>
<td>Hayashi et al. (1994)</td>
<td></td>
</tr>
<tr>
<td>Silicon</td>
<td>0.6</td>
<td>11.80</td>
<td>Hayashi et al. (1994)</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>3.25</td>
<td>10.45</td>
<td>Hayashi et al. (1994)</td>
<td></td>
</tr>
</tbody>
</table>

**Results and Discussion**

We used the nucleosynthesis models of Nomoto, et al. (1997) to relate our estimate of oxygen ejecta mass to the progenitor mass. Oxygen provides a particularly sensitive indicator of progenitor mass, as shown in Figure 3. Assuming a linear interpolation between models is appropriate, **our estimate of 5.7 M\(_\odot\) of oxygen ejecta suggests a massive progenitor of \( \sim 32 \text{ M}_\odot \).**

Hughes (1994) has analyzed ROSAT HRI observations of E0102-72. He found evidence for a ring component and a shell component, much as suggested by the HETG observation. Hughes finds much higher densities for the ring component, \( (n \sim 6.0 \text{ cm}^{-3}) \), implying \( n_e \) even higher) and obtains a mass estimate of up to 75 M\(_\odot\) for the x-ray emitting gas of the SNR (assuming a filling factor of 1.) He concludes that, even for a small filling factor of \( \sim 0.1 \), the progenitor was a massive star.

Blair et al. (2000) examined optical and UV spectra and compared derived ejecta abundances to the models of Nomoto et al. (1997). Their abundance ratios appear to be consistent with the 25 M\(_\odot\) model. Because they find no significant Fe or Si, they suggest that the progenitor was a W/O star that exploded as a type Ib supernova.
The HETG results are consistent with Blair et al (2000) and support the conclusion of a massive progenitor. Several assumptions have significant impact on our calculations. The most important issues are:

- the assumption of a “pure metal” plasma (which may yield an underestimate to $n_e$),
- the volume estimate (i.e., Hughes 1988 model suggests a factor of $\sim2$ larger volume) and volume filling factor, and
- the assumed plasma model (the “allowed region” for the oxygen plasma permits the oxygen emissivity to range within a factor of 2.5 and the neon emissivity to vary within a factor of 1.5).

The impact of uncertainties in $n_e$ and volume are illustrated in Figures 4 and 5.

**Acknowledgements**

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Figure 1: HETG integrated line flux ratios constrain the oxygen plasma conditions to the yellow region. The cross marks the best-fit model.

Figure 2: HETG integrated line flux ratios constrain the neon plasma conditions to the yellow region. The cross marks the plasma model used in estimating ejecta masses. Note that the neon ratios are slightly compromised because the continuum component could not be removed.
Figure 3: Nucleosynthesis models of Nomoto et al. 1997 predict specific amounts of oxygen as a function of progenitor mass. The estimated ejecta mass of $5.7 \, M_\odot$ (marked by a cross on the plot) indicates a massive progenitor of $\sim 32 \, M_\odot$.

Figure 4: Uncertainties in electron density have an impact on the derived oxygen and neon mass. Within the context of our assumptions, a 15% uncertainty in our value of $n_e \sim 0.9 \, \text{cm}^{-3}$ is reasonable. However, we have neglected hydrogen and assumed a “pure metal plasma” of O, Ne, Mg, Si and Fe. If this assumption is inappropriate, $n_e$ would be underestimated.
Figure 5: Uncertainties in volume have an impact on the derived oxygen and neon mass. The volume we have used is $6.6 \times 10^{57}$ cm$^3$. Hughes (1988), however, considers a volume almost twice as large.

Figure 6: Model of SNR Volume.