

**An Imaging and Spectroscopic Study of the Supernova
Remnant RCW 103 (G332.4–0.4) with the
CHANDRA X-ray Observatory**

by

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A thesis submitted to
The Faculty of Graduate Studies of
The University of Manitoba
in partial fulfillment of the requirements
of the degree of

MASTER OF SCIENCE

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Abstract

The explosion of a massive star results in an immense expulsion of energy and stellar debris (ejecta) that are heated to extremely high temperatures forming what is known as a supernova remnant (SNR). Presented is a CHANDRA 0.5–10 keV X-ray study of the SNR RCW 103, a bright SNR that contains the unusual compact object 1E 161348–5055. This study is the first dedicated and complete imaging and spatially resolved spectroscopic study of the SNR aimed at addressing the intrinsic properties of the SNR, including the explosion energy, ambient density, age, and distance. The SNR’s X-ray spectrum is dominated by thermal X-ray emission, requiring globally two components with temperatures at ~ 0.6 keV and ~ 0.27 keV and different ionization timescales and abundances. We identify clumpy regions of enhanced abundances suggesting the presence of ejecta. The SNR age is estimated at 1.0–3.7 kyr at a distance of 3.1 kpc.

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Acknowledgments

This research was supported by the National Science and Engineering Research Council of Canada (NSERC) through an NSERC Discovery Grant to my supervisor, Samar Safi-Harb, and through a Canada Graduate Scholarship (NSERC CGS-M).

Partial support was also provided by the University of Manitoba's GETS program.

This research had made use of data obtained from the *CHANDRA* Data Archive, software provided by the *CHANDRA* X-ray Center (CXC) in the software package CIAO, NASA's Astrophysics Data System (ADS), the *Aladin Sky Atlas* developed at *CDS, Strasbourg Observatory* (France), and *HEASARC* maintained at *NASA's* Goddard Space Flight Center.

List of Abbreviations

ACIS	Advanced CCD Imaging Spectroscopy
BI	Back Illuminated
CCD	Charged-Coupled Device
CCO	Central Compact Object
CIAO	Chandra Interactive Analysis of Observations
CIE	Collisional Ionization Equilibrium
CSM	Circumstellar Medium
DOF	Degrees of Freedom
EM	Emission Measure
FI	Front Illuminated
ISM	Interstellar Medium
NEI	Non-Equilibrium Ionization
ObsID	Observation ID
RGB	Red Green Blue
RRC	Radiative Recombination Continuum
SN(e)	Supernova(e)
SNR(s)	Supernova Remnant(s)
TPE	Two-Photon Emission
XSPEC	X-ray Spectral Fitting Package

Chapter 1

Introduction

The final phase of a massive star's life ends in a spectacular explosion known as a supernova (SN). This stellar explosion is so energetic that it can briefly outshine an entire galaxy while outputting more energy during its death than its entire lifetime as a star. Supernovae are of great importance in astrophysics. They are the mechanism for the nucleosynthesis of all the elements heavier than iron within the universe as well as the primary source of enrichment of the surrounding interstellar medium (ISM). Type Ia supernovae are believed to be "standard candles", objects with a well known luminosity, that allow astronomers to accurately measure distances. Finally, supernovae are one of the primary causes of high-energy cosmic rays, and a hot topic for astronomy today. Supernova events are short, rare events, about a rate of 1-2 per century in our galaxy, which reach a maximum brightness within a month before fading. However, what they leave behind after the explosion is known as a supernova remnant (SNR) that can last tens of thousands of years and acts as an excellent tool for astrophysicists to study the remnant itself as well as the explosion properties of the progenitor star.

The background material for this chapter was based primarily on the textbook “Exploring the X-ray Universe” by Seward & Charles (2010) and other references stated below.

1.1 Types of Supernovae

Historically, supernovae (SNe) have two basic types, type I and Type II. These types are defined by the light curve, a graph of luminosity versus time, and the chemical composition of their optical spectra. With more time, the classes were subdivided further by their explosion mechanisms, where Type Ia result from the disruption of white dwarfs in binary systems, and all other types like Ib, Ic, and II are considered core-collapse explosions such that the two basic types are now more generally regarded as Type Ia and core collapse. The type of supernova defines the explosion mechanism of the progenitor star and determines the type of remnant and the potential presence of a compact object.

Type Ia light curves are characterized by a quickly rising intensity to a maximum luminosity of more than $10^9 L_{\odot}$ followed by an initial rapid decay and then a long, slow decline in brightness (Seward & Charles, 2010). Due to the fairly uniform similarities of light curves between Type Ia supernovae, it is assumed they have a common progenitor star and explosion mechanism. Type II supernovae light curves rise more slowly to a maximum and are, in general, 2 orders of magnitude less luminous than the Type Ia. Type II light curves have broader maximum peaks followed by varying timescales of declining brightness, however, Type II SNe have a lot more individual characteristics that hint at varying ranges of progenitor stars and explosion mechanisms. This prompts further subdivisions of the Type II groups which will not be discussed.

The chemical composition between the two types can be primarily differentiated by the

presence of hydrogen lines (Balmer series) in their emission spectrum. Type I SNe have no hydrogen present in their spectra whereas the Type II SNe are dominated by broad hydrogen emission lines (Reynolds, 2008). Because of the presence of hydrogen in Type II SNe, it is suggested that the explosions occur in younger stars that contain hydrogen-rich envelopes. Type Ia SNe can be found in all galaxy types with no preference to spiral arms or halos, hinting at older progenitor stars that are not as massive (Weiler & Sramek, 1988). Alternatively, Type II SNe occur in the spiral arms of galaxies, regions that contain bright, young stars, and rarely occur in the elliptical galaxies that are comprised of an older stellar population. With such distinctions, this indicates that there must be differences between the types in both the progenitor star and the final stages leading up to the explosion.

As stated previously, the characteristics of Type Ia spectra are so similar to one another that it implies fairly uniform progenitors and explosion mechanisms. The progenitor to a Type Ia explosion is a white dwarf, an extremely hot and dense star with the approximate mass of the sun and the approximate size of the earth. The star is supported against the strong pull of gravity by degenerate electron pressure, electrons in the atoms acting to repel one another. Further evolution to an explosion of the star depends on the mass of this white dwarf. A star with mass less than $1.44 M_{\odot}$, the “Chandrasekhar limit”, will not evolve further (Seward & Charles, 2010). Specifically, the type Ia progenitor star is a white dwarf with a carbon/oxygen core and a mass at the Chandrasekhar limit that undergoes a thermonuclear explosion. The star is considered stable such that the addition of mass is necessary to trigger the explosion. Thus, the Type Ia SN must involve a white dwarf in a binary system, where the white dwarf is accreting mass from its companion star. Mass is added from the smaller companion until the gravitational force is enough to overcome the

electron degeneracy pressure. The resulting collapse raises the temperature of the core and initiates fusion at its center. This results in a deflagration, an explosion which propagates through heat transfer that completely destroys the star.

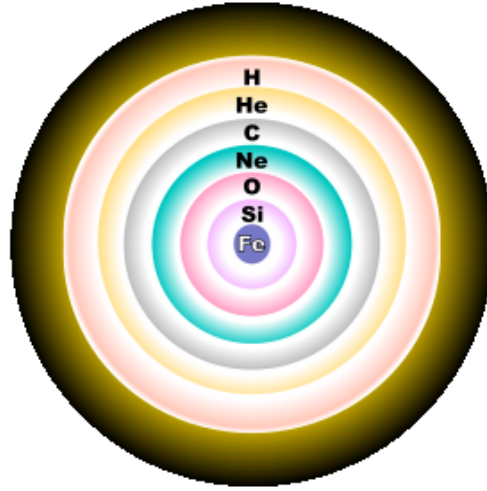


Figure 1.1 Composition of a massive star at the end of its life with the stratified layers due to different stages of core burning Hall (2007).

Type II SNe explosions occur via core-collapse where the explosion energy derives from the release of gravitational energy during the collapse of the stellar core. Core-collapse is the end result for massive main sequence stars with mass $M \geq 8 M_{\odot}$ (Woosley & Janka, 2005). At the beginning of a massive star's life, in its core, a star begins by fusing hydrogen into helium. When the hydrogen fuel in the core is mostly consumed into helium, the star will compress further until the gravitational energy is sufficient to begin fusing the helium core into carbon and oxygen and thereby halting further collapse. At the same time, there is a hydrogen layer surrounding the core, and with the increased pressure, ignites nuclear burning of hydrogen into a shell of helium surrounding the core. Continuing further, a star will go through these periods of fusion and contraction, burning increasingly heavier elements, until it starts to

develop a mostly iron core and a stratified composition similar to that of Figure 1.1. At this point, iron has a nuclear binding energy greater than any other element, which means any fusion of iron is an endothermic process and will actually require energy to continue fusion rather than releasing energy. With the thermonuclear burning halted, the star collapses further and requires another force to counteract gravity: the degenerate electron pressure. Gravity will continue to collapse the star to very high density, and the stability of the star is supported by the electrons in these atoms attempting to repel one another. Now, the iron core is only supported by electron degeneracy pressure, but as burning continues, the iron core increases and approaches the Chandrasekhar limit (Woosley & Janka, 2005). With an increasing core mass, so too does the temperature and density increase. This forces some of the iron to decompose into lighter nuclei, which absorbs energy, and allows the pressure to reduce and the core to shrink. As a result, neutrons and neutrinos are created from the free protons combining with the electrons. However, with the loss of electrons, the electron degeneracy pressure drops. The result is a run-away process where gravity simply overwhelms the electron pressure. Within milliseconds the core collapses to form a proto-neutron star (nuclear densities) which has the approximate mass of the Sun, but is compressed into a sphere with a radius of roughly 10 km. The energy from the in-falling matter creates a shockwave that propagates outward through the still in-falling outer layers of the star and ejects this material. The total energy released from the supernova is in excess of 10^{53} erg, which is largely carried off by neutrinos (99%), and with 10^{51} erg released in kinetic energy. What is left after the explosion is a remnant filled with stellar ejecta, shocked ISM/CSM (circumstellar medium), and possibly at the centre, a neutron star or black hole.

1.2 Supernova Remnants and Compact Objects

The supernova explosion event is so powerful that it expels most of the stellar material outward, creating a shock wave that expands into the surrounding interstellar medium (ISM). The shockwave sweeps up the ISM at large speeds of approximately 10,000 km/s in an expanding shell of stellar ejecta, gas and dust to form a shell known as a supernova remnant (SNR).

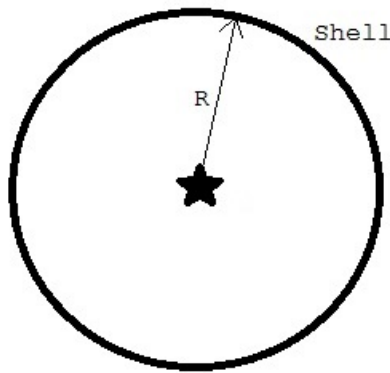


Figure 1.2 Cartoon supernova remnant structure with a shell of hot shocked plasma emitted outwards from the central progenitor star.

Supernova remnants have three types of classification: shell-like, filled-centre, and composite. Shell-like SNRs emit most of their radiation from a shell of shocked material and are strongly limb brightened in both X-ray and radio. A famous shell-like SNR is Cas A. Filled-centre SNRs are brightest in the central region in both X-ray and radio with limb brightening absent or very weak. A famous filled-centre SNR is the Crab Nebula. Composite SNRs have a mix of shell-like and filled-centre components, with a limb brightened shell plus some central component that further sub-divides the group into plerionic or thermal

composites (mixed morphology). Plerionic SNRs have a shell with a non-thermal, central pulsar wind nebula that powers the SNR. Thermal Composite SNRs have filled thermal centers in X-ray but limb brightened shells in radio. Further details can be found in *SNRcat*, a galactic supernova remnant catalogue¹ (Ferrand & Safi-Harb, 2012).

When a star explodes it can leave behind a “zoo” of neutron stars classes or, depending on how massive the progenitor star was, even a black hole (Safi-Harb, 2015). Neutron stars are among the densest and most magnetized objects known in existence and are comprised almost entirely of neutrons. Some called pulsars, referred to as rotation-powered pulsars, are powered by rotational energy loss (like the Crab pulsar). Others, dubbed as magnetars, are characterized by their super strong magnetic fields (Israel, 2015). Isolated neutron stars are powered by the latent heat of the neutron star matter, while binary/accretion-powered pulsars are powered by matter falling on to the neutron star from a companion star. Their emission spectra are also quite different where the majority will emit in radio, whereas other types, like the magnetars and the central compact objects (CCOs), are primarily X-ray emitting objects (De Luca, 2008). CCOs are X-ray sources located close to the center of SNRs. They differ from pulsars due to their lack of radio/IR/optical counterparts and differ from magnetars due to their low magnetic fields. The differences between the neutron star types are due mainly to their magnetic field properties; however there is still no clear picture of the evolutionary physics to unify the different neutron star types (De Luca, 2008).

¹<http://www.physics.umanitoba.ca/snr/SNRcat/>

1.3 Evolution of the Supernova Remnant

Following the core collapse of a massive star's explosion, the supernova remnant goes through three stages of evolution: the free expansion phase, the Sedov-Taylor phase, and the radiative phase. However, before investigating the underlying physics behind the separate phases, some shock physics must first be understood.

The following description and derivations have been based on primarily: 1) Dyson & Williams (1980) and 2) Seward & Charles (2010).

1.3.1 Shock Wave Physics

Shock wave properties are dependent on the flow variables on either side of the propagating shock which include P , gas pressure, velocity, u , relative to the shock (velocities characterized by ' u ' are given in the rest frame of the shock), and density, ρ . The subscripts 0 and 1 refer to before and after the shock, respectively (see Figure 1.3).

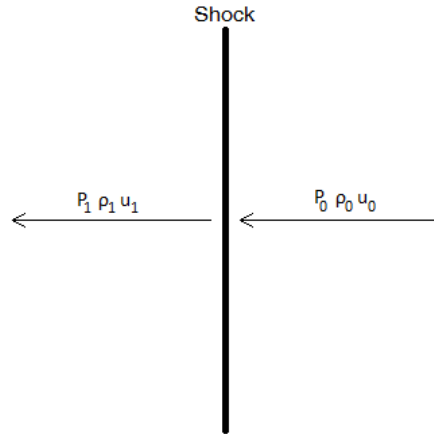


Figure 1.3 Schematic of the flow variables for both before and after the shock (adapted from Dyson & Williams (1980)).

The conserved quantities across the shock wave for an adiabatic shock are given below in terms of three constants ϕ , ζ , and ξ :

$$\begin{aligned}\phi &= \rho u \quad (\text{mass flux}), \\ \zeta &= P + \rho u^2 \quad (\text{pressure}), \\ \xi &= \frac{1}{2}u^2 + \frac{5}{2}\frac{P}{\rho} \quad (\text{energy}).\end{aligned}\tag{1.1}$$

The Rankine-Hugoniot conditions, known as the jump conditions, relate the upstream and downstream values of the flow variables across the shock and are simply derived from the conservation equations. The Rankine-Hugoniot conditions for a 1-D plane-parallel shock are given as:

$$\begin{aligned}\rho_0 u_0 &= \rho_1 u_1 \quad (\text{mass flux}), \\ \rho_0 u_0 u_1 - \rho_0 u_0^2 &= P_0 - P_1 \quad (\text{pressure}), \\ \frac{1}{2}u_0^2 + \frac{5}{2}\frac{P_0}{\rho_0} &= \frac{1}{2}u_1^2 + \frac{5}{2}\frac{P_1}{\rho_1} \quad (\text{energy}).\end{aligned}\tag{1.2}$$

Under the assumption of an adiabatic equation of state, a local sound speed, a , can be defined as $a^2 = \frac{5}{3}\frac{P}{\rho}$. Introducing a reference velocity, $\bar{u} = \zeta/\phi$, the momentum equation can be manipulated to express the specific total energy, ξ :

$$\xi = \frac{1}{2}u^2 + \frac{3}{2}a^2 = u\left(\frac{5}{2}\bar{u} - 2u\right)\tag{1.3}$$

and upon rearranging to form a quadratic equation:

$$u^2 - \frac{5}{4}u\bar{u} + \xi/2 = 0.\tag{1.4}$$

Then for given values of ξ and $\bar{u}$, the two roots of this equation represent the upstream velocity, u_0 , and the downstream velocity, u_1 , where the sum of the two roots becomes:

$$u_0 + u_1 = \frac{5}{4}\bar{u}. \quad (1.5)$$

Finally, with the introduction of the Mach number, $M = \frac{u}{a} = \sqrt{\frac{3}{5} \frac{u}{\bar{u}-u}}$, and its upstream, $M_0 = \frac{u_0}{a_0}$, and downstream, $M_1 = \frac{u_1}{a_1}$, counterparts, and under the assumption of strong shocks ($M_0 \gg 1$) we can derive from Equation 1.4 some of the fundamental properties of strong shocks:

$$\begin{aligned} \frac{u_1}{u_0} &= \frac{1}{4}, \\ \frac{\rho_1}{\rho_0} &= \frac{4}{1}, \end{aligned} \quad (1.6)$$

which relates the pre- and post-shock velocities and densities. One can also relate the temperature behind the shock, T_1 , to the pre-shock velocity using the conservation of energy in Equation 1.1 assuming an ideal gas equation of state $P = \frac{\rho k T}{\mu m}$:

$$T_1 = \frac{3}{16} \frac{\mu m}{k} u_0^2. \quad (1.7)$$

Next consider the fixed frame shock velocity, V_S , (velocities characterized by 'v' are given in the observation frame of the shock) with the upstream and downstream gas velocities v_0 and v_1 respectively written as $v_0 = u_0 + V_S$ and $v_1 = u_1 + V_S$. Under the strong shock regime of $V_S \gg v_0$ another strong shock property is derived:

$$v_1 = \frac{3}{4} V_S. \quad (1.8)$$

Knowing the relation of velocities across the shock from Equations 1.6 and 1.8, then the temperature behind the shock can be derived in terms of the shock velocity:

$$T_1 = \frac{3}{16} \frac{\mu m}{k} V_s^2. \quad (1.9)$$

Now from the momentum equation of the Rankine-Hugoniot conditions in Equation 1.2, recalling the strong shock velocity relations, and by neglecting P_0 then the post-shock pressure can be written as:

$$P_1 = \frac{3}{4} \rho_0 V_s^2. \quad (1.10)$$

Equations 1.8 to 1.10 can then be used to derive the specific internal, e_{I1} and kinetic, e_{k1} , energies (energy per unit mass) based on the shock velocity:

$$\begin{aligned} e_{I1} &= \frac{3}{2} \frac{P_1}{\rho_1} = \frac{9}{32} V_s^2, \\ e_{k1} &= \frac{1}{2} v_1^2 = \frac{9}{32} V_s^2. \end{aligned} \quad (1.11)$$

1.3.2 Free Expansion Phase

The free expansion phase is the first evolutionary phase of a supernova remnant. The model is very simplistic but can be a powerful tool in investigating the effects of the explosion on the surrounding interstellar material. The model assumes an instantaneous release of a large amount of energy, $E_* \sim 10^{51}$ erg, from a point source emitting equally in all directions into a uniform interstellar medium. The energy from the explosion heats the gas to very high temperatures and pressures, causing the shell of ejected material to expand at supersonic velocities. A shock wave immediately forms and sweeps up the surrounding gas, leaving a

low density region behind in the interior. The scenario is depicted in Figure 1.4, with an initial explosion energy of 10^{51} erg, creating a pressure driven shockwave, S , expanding a gas bubble with some radius, R , and velocity, $\dot{R}$, into the surrounding ISM of density n_0 .

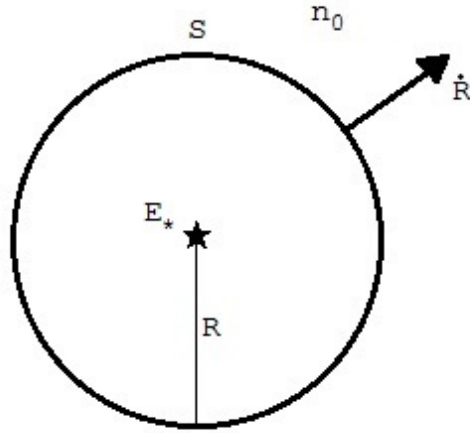


Figure 1.4 Schematic model of a supernova remnant expanding a shockwave, S , into the surrounding interstellar medium with density n_0 (adapted from Dyson & Williams (1980)).

In this phase, the mass of the ejecta, the ejected layers of the progenitor star, is much greater than the swept-up mass, the mass swept up by the SN blast wave. This allows for the shell to expand at a uniform velocity, and the simple equation of $R = \dot{R}t$ can be used to find the time, t , for an SNR of some radius, R , with typical velocities of $\dot{R} = 5000 - 15000 \text{ km s}^{-1}$. This phase ends when the swept-up mass becomes approximately equal to the mass of the ejecta.

1.3.3 Sedov-Taylor Phase

The second phase is termed the Sedov-Taylor phase, or the blast wave expansion phase. Some passage of time between the end of the first phase and the start of the second might be necessary in order for the shock to sweep up more mass. Once the mass of the swept-up material is large compared to the ejecta mass, then the SNR is considered in the Sedov-Taylor phase (Sedov, 1959). Now, because the energy radiated from the shell itself is small in comparison to the explosion energy, the expansion is considered adiabatic and the strong shock physics from Section 1.3.1 becomes relevant.

It was previously derived for strong, adiabatic shocks in Section 1.3.1, the specific thermal energy, e_t , and specific kinetic energy, e_k , from Equation 1.9 and is given as:

$$e_t = e_k = \frac{9}{32} \dot{R}^2, \quad (1.12)$$

where the velocity of the shock, v_s , is explicitly written as the time derivative of the radius, $\dot{R}$. The total energy, E_T , of the gas can be expressed in terms of the gas density in the bubble, ρ_0 , and can be rewritten as:

$$E_T = \frac{4}{3} \pi R^3 \rho_0 (e_t + e_k). \quad (1.13)$$

Substituting Equation 1.10 and recalling that the system is adiabatic and therefore $E_T = E_*$, then the result is:

$$R^3 \dot{R}^2 = \frac{4}{3\pi} \frac{E_*}{\rho_0}. \quad (1.14)$$

with the boundary conditions of radius zero at time zero (a shock developing from a point), the solution to Equation 1.11 is:

$$R = \left(\frac{25}{3\pi}\right)^{1/5} \left(\frac{E_*}{\rho_0}\right)^{1/5} t^{2/5}. \quad (1.15)$$

Therefore:

$$\dot{R} = \frac{2}{5} \left(\frac{25}{3\pi}\right)^{1/5} \left(\frac{E_*}{\rho_0}\right)^{1/5} t^{-3/5}, \quad (1.16)$$

and from looking at Equation 1.13 and 1.14, becomes:

$$\dot{R} = \frac{2}{5} \frac{R}{t}. \quad (1.17)$$

This is a simple yet powerful equation that can be used to determine the age of a remnant given the size and speed of the shock.

Now, if there was no material surrounding the SN, the shock would propagate outward completely unhindered. In reality, however, the surrounding interstellar medium forms a barrier that becomes increasingly more difficult for the expanding shell to sweep up.

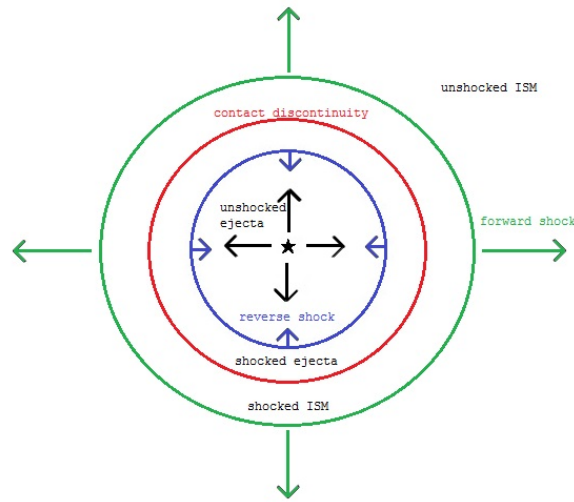


Figure 1.5 Cartoon of the Sedov-Taylor phase of an SNR including forward and reverse shock.

As a result, two shock waves form, the forward shock and the reverse shock (see Figure 1.5). The first shock, the forward shock, will propagate outward ahead of the ejecta and into the surrounding interstellar medium, the other, called the reverse shock, propagates backwards into the ejecta. The boundary between the shocked ISM and the ejecta is called the contact discontinuity. From an outside observer, both shocks travel initially outward until the swept-up mass exceeds the ejecta mass and then the reverse shock begins to travel inwards. It is only between the 2 shock waves where the material has been heated and compressed. The ejecta has, in turn, been slowed and compressed by the pressure of the ISM that it has been ploughing into, whereas in the central region the material is no longer hot and freely expands. Only the shocked material is hot enough to emit X-rays and this is the material that is detected when observing bright, young supernova remnants (Vink, 2012).

1.3.4 Radiative Phase

The final stage of a supernova remnant is the radiative phase or the momentum-conservation phase. As it expands, the remnant continues to sweep up cold interstellar gas, becoming cooler as its mass increases. Radiative cooling rates increase as temperature decreases, such that radiative cooling becomes increasingly important over time. This creates a thin shell of cool material immediately behind the shock. Although the inner hot gas does not cool as appreciably as the thin cool shell, by neglecting the pressure of this hot inner gas it allows for some simple analysis to be done on the shell. The thin shell is assumed to sweep material outward in such a way that the momentum of the shell is conserved. From momentum conservation for a thin shell of radius, R , and velocity, $\dot{R}$, the constant momentum, M_0 is:

$$\frac{4}{3}\pi R^3 \rho_0 \dot{R} = M_0(\text{constant}). \quad (1.18)$$

Now supposing that the thin shell was created at time zero, t_0 , when $R = R_0$ and $\dot{R} = \dot{R}_0$, such that:

$$M_0 = \frac{4}{3}\pi R_0^3 \rho_0 \dot{R}_0. \quad (1.19)$$

Then from integrating Equation 1.16 and substituting Equation 1.17:

$$R = R_0[1 + 4\frac{\dot{R}}{R_0}(t - t_0)]^{1/4} \quad (1.20)$$

$$\dot{R} = \dot{R}_0[1 + 4\frac{\dot{R}}{R_0}(t - t_0)]^{-3/4} \quad (1.21)$$

Now considering large times where $t \gg R_0 - \dot{R}_0$, then we get the relations $R \propto t^{1/4}$ and $\dot{R} \propto t^{-3/4}$ for the shell size and speed. Finally, substituting Equation 1.18 into 1.19 it can be shown that:

$$\dot{R} = \frac{2}{7} \frac{R}{t} \quad (1.22)$$

The SNR is in the final stage of its life. The remnant will radiate most of the internal energy away and the shell will continue expanding into the surrounding medium, cooling down and fading from view.

1.3.5 Summary

From the previous subsections it can be shown that the three phases each have equations relating the radius and expansion speed. These equations are useful to determine the age of

the remnant. For young remnants, they can be in a transitional period from free expansion to Sedov-Taylor, and so their equations are summarized in Table 1.1 and can be used to determine a minimum and maximum age range.

Table 1.1 SNR Phase Equation

Phase	Equation
free expansion	$\dot{R} \approx \frac{R}{t}$
Sedov-Taylor	$\dot{R} \approx \frac{2}{5} \frac{R}{t}$
radiative	$\dot{R} \approx \frac{2}{7} \frac{R}{t}$

1.4 Distance Calculations

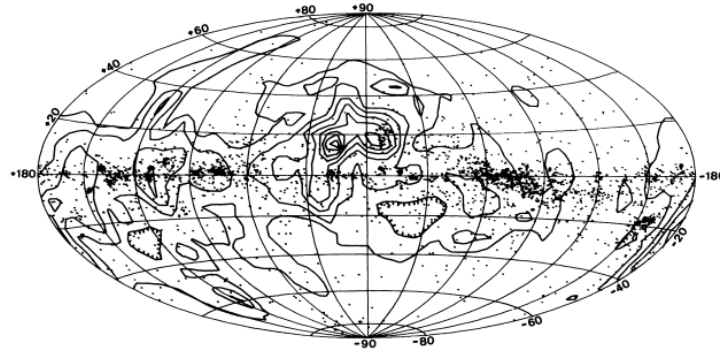


Figure 1.6 Mean color excesses per kiloparsec contours with intervals of 0.2 mag/kpc where the outermost contour is the lowest level. The Galactic center is at the center of the diagram with longitude increasing to the left and lines marked at 30° and latitude lines drawn every 20°. Image from Lucke (1978).

Calculating distances to objects is an important goal and is generally not a straightforward task in astrophysics. The approach used in this work relies on the fitted (from X-ray

spectra) column density, N_H , then using N_H and the Lucke (1978) diagram in Figure 1.6 to infer the distance. Lucke uses colour excesses, E_{B-V} , and photometric distances of 4000 O and B stars to construct contour plots to form the distribution of the mean colour excess per kiloparsec perpendicular to the Galactic plane.

From the figure, for a specific Galactic coordinate one can determine the mean colour excess per kiloparsec. The ratio of N_H to colour excess can be related as $\langle N_H/E_{B-V} \rangle = 5.55 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}$ as derived from X-ray dust scattering halos (Predehl & Schmitt, 1995). The X-ray halos were fit using dust models to determine the fractional halo intensity for 25 point sources and 4 SNRs. Predehl & Schmitt then looked at optical extinction from these halos to determine the equation above. The hydrogen column density of an SNR is determined through the model fits, where the model (TBABS) description can be found in Section 3.2.2 and parameters found in the Appendix.

1.5 Supernova Remnant Emission Spectra

There are several mechanisms by which supernova remnants produce X-rays, however the focus will be on thermal emission as RCW 103 is a purely thermal SNR. The shock wave produced from the collapse of the progenitor star creates the hot, shocked plasma of the remnant that emit in X-rays. This plasma has two important characteristics: it is to a very good approximation optically thin, and the ionization distribution of atoms is often out of equilibrium (Vink, 2012). As a result of optically thin plasmas, X-ray spectroscopy is a powerful tool for measuring abundances in SNRs. The thermal emission can be broken down into two dominant forms, thermal continuum emission due to thermal bremsstrahlung and line emissions from collisional excitation.

The following section has been based on primarily Vink (2012).

1.5.1 Thermal Continuum Emission

The thermal X-ray continuum of SNRs is due to mainly bremsstrahlung (free-free emission), but also recombination continuum (free-bound emission), and two-photon emission (TPE) which is explained in later. In general, the more dominant form of continuum emission is the bremsstrahlung emission.

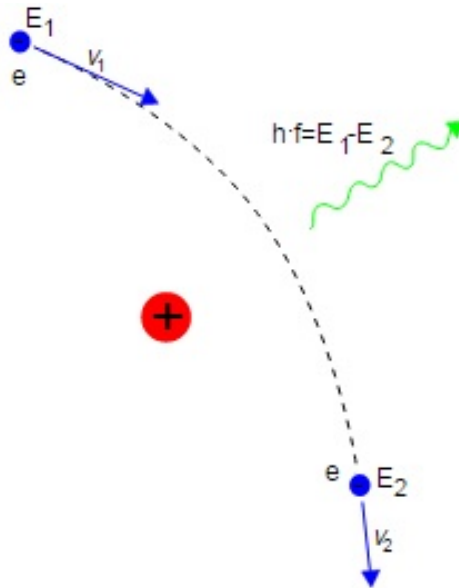


Figure 1.7 Bremsstrahlung emission for an electron deflected by the field of another charged particle. Created by Martin (2008).

Bremsstrahlung emission or “braking radiation” is electromagnetic radiation produced by the deceleration of a charged particle when deflected by the electric field of the nucleus of another charged particle, typically an electron by an atomic nucleus. The moving particle loses energy when it is deflected, and in order to conserve energy, a photon is emitted. The

higher the temperature, the faster the motion of the electrons and hence the higher the energy of the emitted photon. For temperatures above 1 million degrees, these photons are predominately X-rays (Seward & Charles, 2010). For a Maxwellian energy distribution of electrons, the emissivity, the measure of the efficiency in which a surface emits thermal radiation, is given as:

$$\epsilon_{ff} = \frac{2^5 \pi e^6}{3 m_e c^3} \left(\frac{2\pi}{3 k m_e} \right)^{1/2} g_{ff}(T_e) T_e^{-1/2} \exp\left(-\frac{h\nu}{kT_e}\right) \times n_e \sum_i n_i Z_i^2 \text{ ergs}^{-1} \text{ cm}^{-3} \text{ Hz}^{-1}, \quad (1.23)$$

where the gaunt-factor, $g_{ff} \approx 1$, and the subscript i denotes different ion species with charge eZ_i^2 (Vink, 2012). The emissivity is dependent on the last term $n_e \sum_i n_i Z_i^2$, and for SNR bremsstrahlung emission, it is dominated by electrons colliding with hydrogen and such that we only consider $n_i = n_H$ and $Z = 1$. Observations come from a volume of plasma, thus integrating the emissivity over the volume of the source is related to the flux. The important integral term is called the *emission measure* (EM), defined as a measure of the amount of plasma available to produce the observed flux and is used to give the temperature distribution of the emitting plasma:

$$EM = \int n_e n_H dV, \quad (1.24)$$

where n_e is the electron density, n_H is the hydrogen density. The EM is usually parametrized with the normalization factor as $K = \frac{10^{-14}}{4\pi D^2} \int n_e n_H dV$, where the denominator takes into account the distance, D , to the source (Arnaud et al., 2015).

Recombination emissions and TPE can be dominant in some metal-rich plasmas in young SNRs. Radiative recombination continuum (RRC) occurs when an ion is struck by an electron and recombines, emitting a photon in the process with energy $h\nu_n = E_e + \chi_n$, where E_e

is the energy of the free electron and χ_n is the ionization potential for an electron in level n . In hot, optically-thin plasma, recombination is very weak emission which can act as a small perturbation to the main bremsstrahlung emission (Foster et al., 2015). TPE is the result of electrons in meta-stable states. The most significant state is the 2s hydrogen-like atom where decay to the 1s level is forbidden. The atom will de-excite by emitting two photons of total energy related to the excited state. Both these emission processes can contribute to the main continuum bremsstrahlung emission.

1.5.2 Thermal Line Emission

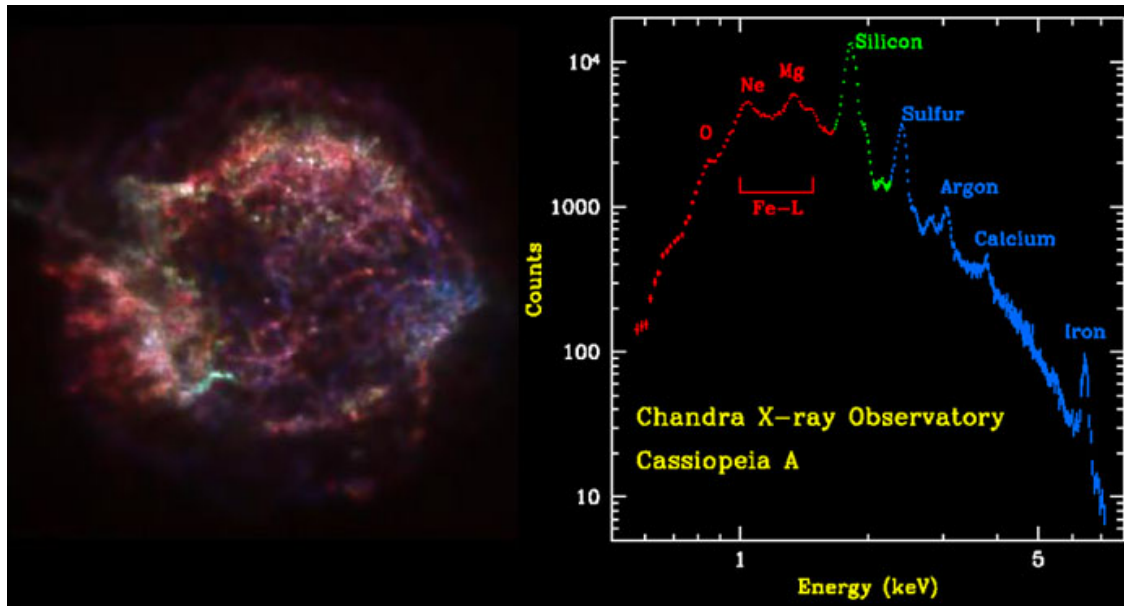


Figure 1.8 Common emission lines of supernova remnants with the famous Cas A as an example. Created by NASA/CXC/SAO (2014).

Line emission in SNRs is dominated by collisional excitation between electrons and ions. This can be either through a direct excitation or a recombination. When an electron strikes

an ion bound with electrons, it transfers energy to that ion, causing a transition to a higher energy level. The ion remains in an excited state only briefly and will decay back to its ground state by radiating a photon. This photon has a specific energy emission dependent on the excitation levels of the particular ion species and appears as spectral emission lines in the SNR spectrum. The density of the SNR plasma is very low, so most ions can be assumed to be in the ground state and furthermore, collisional de-excitation and further excitation can be neglected. For SNRs, the nucleosynthesis products have prominent emission lines in the 0.5–10 keV range and are referred to as the alpha-elements (O, Ne, Mg, Si, Ar, Ca) and the iron-group elements (mostly Fe and Ni). The most dominant lines from these elements occur in the helium-like transition state with those lines indicated in Table 1.2 (McCray & Wang, 2012). The Fe-L blend is a group of L-shell iron emission lines in the range as indicated in Table 1.2. These lines cannot be resolved by current generation telescopes and so appear as a broad peak rather than their individual lines. The presence of thermal line emission is heavily dependent on the ionization states of the ion species within the plasma, which can get difficult to determine due to most young SNRs being in non-equilibrium ionization. These lines are also much stronger than at equilibrium, which would lead to the conclusion that the abundance yields are much larger than is actually the case (McCray & Wang, 2012). See the Appendix for a visual representation of CIE vs NEI and the effects of the ionization timescale on the emission values.

1.5.3 Equilibrium and Non-Equilibrium Ionization

The shock waves found in supernova remnant shells are collisionless, which means that transition from pre-shock to post-shock states occurs on a length scale much smaller than

Table 1.2 Prominent X-ray Lines from Thermal Plasma Supernova Remnants

Phase	Transition Line Energy (keV)
O	0.570
Fe-L blend	0.68–1.15
Ne	0.916
Mg	1.34
Si	1.86
S	2.46
Ar	3.14
Ca	3.90
Fe	6.70

Note: CIE is assumed. (McCray & Wang, 2012).

a particle collisional mean free path. Just ahead of the outward moving shock, the kinetic energy of the infalling material resides in the positive ions that carry the bulk of the mass. The kinetic energy gets thermalised by the shock, and as the shock passes through the infalling material, the energy found in the rapid motion of the positive ions are in a state corresponding to a much lower temperature than their current motion would indicate. After a period of time, the free electrons create enough collisions with the positive ions to come into thermal equilibrium. With even more time, the fast moving electrons collide with and remove more electrons from the heavier positive ions eventually allowing for the ionization state to increase to the appropriate electron temperature.

For young SNRs, ionization is generally not in equilibrium because the plasma, being of such low density, has not had enough time since the shock to reach equilibrium. The two types of plasma ionization states are non-equilibrium ionization (NEI) and collisional ionization equilibrium (CIE). For the CIE type, it refers to an electron velocity distribution as described by the Maxwell-Boltzmann equation with an ion population for all atoms that is not time-dependent (the rate of ionization balances with the rate of recombination) (Foster et al.,

2015). An NEI plasma is defined as not being in CIE, however for SNRs specifically, this is mostly termed as “ionizing plasmas” which refers to a plasma undergoing more ionizations than recombinations. The main effects of NEI in young SNRs is that at a given temperature, the ionization states are lower than that in the CIE case (Foster et al., 2015). For an example of the effects of ionization timescale on the line emission, see the Appendix. For SNR modelling, the ionization timescale is given as $n_e t$ as a function of electron density, n_e , and for timescales $n_e t \leq 10^{12} \text{ cm}^{-3} \text{ s}$, the plasma is considered in NEI.

Chapter 2

RCW 103

Presented in the following chapter is an introduction to the supernova remnant RCW 103 as well as a brief history of previous published works and their results. RCW 103 has garnered much interest due to its peculiar CCO and many studies have been carried out on the central object. However, very little has been done in X-ray on the remnant itself.

RCW 103 is believed to be a young supernova remnant with Galactic coordinates G332.42–0.4 in the constellation Norma. It is a core-collapse supernova and a shell type remnant of roughly 10' across. Current distance calculations puts it approximately 3.1–3.3 kpc¹. At its center is a soft X-ray source labelled 1E 161348–5055.

¹<http://www.physics.umanitoba.ca/snr/SNRcat/>

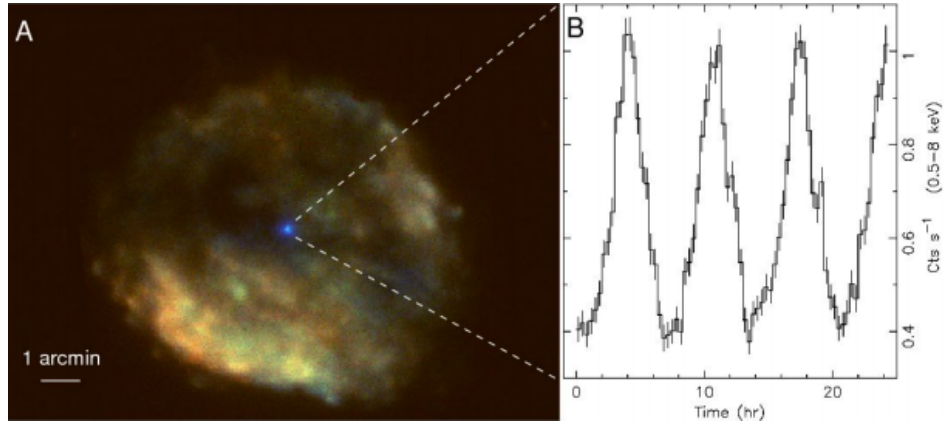
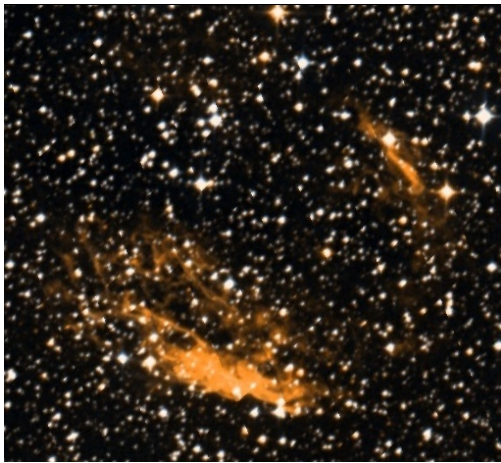


Figure 2.1 (Left) An XMM-Newton X-ray image from a CCO study by De Luca et al. (2006). Red corresponds to the energy range 0.5–0.9 keV, green to 0.9–1.7 keV and blue to 1.7–8 keV. North is up, East is left. (Right) Background-subtracted flux evolution of the CCO with a 6.67 hr periodicity (De Luca et al., 2006).



(a) DSS Optical Image



(b) 2MASS Infrared Image

Figure 2.2 (Left) An RGB image from the Digitized Sky Survey (DSS) with colours indicate optical wavelengths with red as $\sim 0.6 \mu\text{m}$, blue as $\sim 0.4 \mu\text{m}$, and green based on the mean of other components. (Right) An image from the Two Micron All Sky Survey (2MASS) created using a coloured image from the J-H-K infrared bands.

The remnant has had a few studies in multiple energy bands. The radio synchrotron emission data indicates a nearly circular, thick shell of a fairly young remnant with a radio index of 0.5 that has only recently transitioned from the double-shock phase of its evolution (Dickel et al., 1996). A study with the Australian Millimeter Radio telescope detected HCO^+ and ^{12}CO emissions at the southern shock front of the remnant that suggests interaction with a nearby molecular cloud (Paron et al., 2006). A maser SNR survey paper of the OH (1720.5 MHz) maser line provides further evidence of interaction with a molecular cloud in the south Frail et al. (1996). Oliva et al. (1999) performed an infrared study in the H_2 2.122 μm line and other infrared lines and found emission from both molecular and ionized gas in the southern shock front. *Spitzer* studies of $[OI]$, ionic lines, and molecular hydrogen from the Spitzer Multiband Photometer (MIPS) confirm these findings as well as some fainter emission in the northwest and number of HII regions and dark clouds (Reach et al. (2006); Andersen et al. (2011)). The remnant has very little detected in the optical range except for the bright southern and north-western regions similar to those found in X-ray (see Figure 2.2). From an optical expansion study it was determined that the shell expansion rate is 1100 km s^{-1} (Carter et al., 1997). A gamma ray study using the Fermi-LAT reveals a likely extended gamma ray source with a power law spectrum and photon index of 2.0 ± 0.1 (Xing et al., 2014). Finally, the Xing et al. (2014) group did an analysis of its 1-300 GeV spectrum and determined a luminosity of $8.3 \times 10^{33} \text{ erg s}^{-1}$ at a source distance of 3.3 kpc.

There has been very little study done on the remnant in the X-ray regime with current generation telescopes. Nugent et al. (1984) used the *Einstein* satellite to show that RCW 103 is consistent with the emission from shocked interstellar medium and has inferred approximately solar abundance values of the heavier elements. The group, however, could

not determine the plasma state. Lopez et al. (2011) did a *CHANDRA* morphology study of 24 SNRs, RCW 103 being one of them. The paper did not do a detailed report on the SNR's properties (temperature, abundances, ambient density, etc.) or the explosion properties, which will be the main focus of this Thesis. Another X-ray study was very recently published at the time of finalizing this thesis work using *CHANDRA* data by Frank et al. (2015). The Frank et al. study will be contrasted to this thesis work in greater detail in Chapter 6.

Finally, RCW 103 is well known for its peculiar compact object, 1E 161348–5055, first detected by Tuohy & Garmire (1980) and has been the focus of many recent studies (Reynoso et al. 2004; De Luca et al. 2006, 2007; Esposito et al. 2011). The particular interesting feature of the CCO was discovered with *XMM-Newton* data in 2006 that revealed the source was periodic at 6.67 ± 0.03 hours (De Luca et al., 2006). The CCO also had a period of brightness between October 1999 and January 2000 where it became 50 times brighter (De Luca et al., 2006). This period is much too large to fit its current age within the standard neutron star model and suggests two theories to explain this phenomena. One theory suggests the presence of a low-mass X-ray binary system. The companion star would orbit in an elongated orbit and when in closest approach to the neutron star, it would accrete mass to the neutron star and as a result, would produce the increased brightness that has been detected (De Luca et al., 2006). The companion star would also create a drag on the neutron star's magnetic field, causing the rotation of the neutron star to slow down. The second explanation would be a neutron star with a massive magnetic field. The strong field would break against the debris disk left behind by the supernova, slowing down the rotation, however this theory would not be able to explain the increase in brightness (De Luca et al., 2006). The nature of

this CCO is still up for debate with arguments for a binary system ((Pizzolato et al., 2008); (Bhadkamkar & Ghosh, 2009)) or for a massive magnetic field (Ikhsanov et al., 2015).

RCW 103 is the only SNR with a potential CCO in a binary system¹. With a lack of study on the SNR in X-ray and having such a unique CCO provides excellent motivation for an in-depth X-ray study of the SNR. An X-ray study provides insight on the explosion properties that led up to such a peculiar CCO as well as revealing the properties of the remnant that have not yet been investigated.

¹<http://www.physics.umanitoba.ca/snr/SNRcat/>

Chapter 3

Data Collection and Preparation

3.1 The *CHANDRA* X-ray Telescope

The *CHANDRA* X-ray Telescope is a space observatory launched by NASA in 1999 and provides a public archive of collected data. *CHANDRA* is highly sensitive to X-ray sources with the best angular resolution of the current generation of X-ray space telescopes. There are four main instruments on board the observatory: the advanced CCD spectrometer (ACIS), the low-energy transmission grating (LETG), the high-energy transmission grating (HETG), and the high resolution camera (HRC). For the study of SNRs, the ACIS detector is best suited for imaging and spectroscopy and will be the focus instrument for the data used in this thesis.

3.1.1 ACIS

ACIS consists of 2 separate arrays of CCD detectors labelled as ACIS-I and ACIS-S and arranged as seen in Figure 2.1. ACIS-I, used for imaging, is arranged in a 2x2 array whereas

ACIS-S, used for either imaging or grating spectrum read-out, is arranged as a 1x6 array. Each CCD spans 1024 pixels x 1024 pixels, which is equivalent to 2.5 cm x 2.5 cm or 8.3' x 8.3' in area coverage. From Figure 3.1 there are 2 back-illuminated (BI) CCDs, S1 and S3, while the rest are front-illuminated (FI). The BI chips are better in two areas than the FI: The response of the BI CCDs extends to energies below that accessible by the FI CCDs and the chip-average energy resolution of the BI CCDs is superior. ACIS detectors are sensitive to the 0.3 keV to 10 keV energy range, has an effective area of 600 cm², a field of view of 16' and a spectral resolution of 0.5''.

ACIS FLIGHT FOCAL PLANE

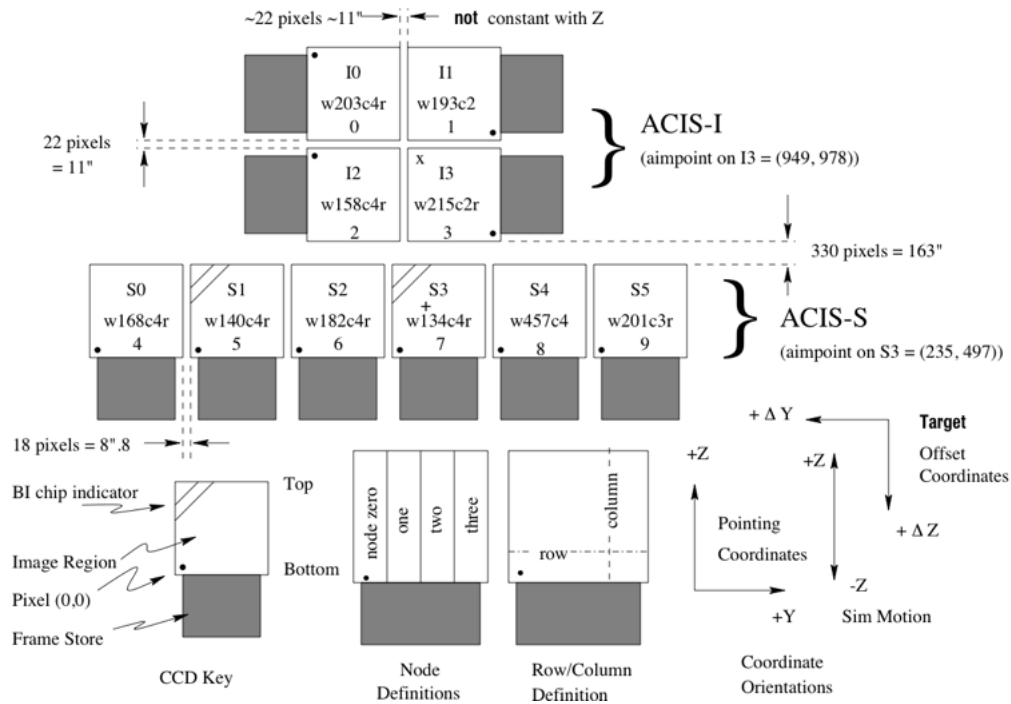


Figure 3.1 ACIS detector schematic with both ACIS-I and ACIS-S CCD arrays. Nominal aimpoints are represented by 'x' and '+'. ACIS instrument layout as provided by NASA/CXC (2014).

The ACIS detectors absorb X-rays through its individual pixels. When a photon is absorbed, the pixel accumulates a charge that is proportional to the energy deposited by the photon. Charge accumulates on the CCD in frames (known as frame time) of approximately 3.2 seconds and then transferred to storage, allowing the next exposure to begin. This data is processed onboard, followed by bias removal, and then identifies any “events” that require a local maximum in the charge distribution above the designated event threshold. In this way we get a position and amount of charge collected with the detector that can be used for imaging and spectroscopy. This data has to fall within good time intervals (GTIs), in which there is one GTI per CCD. GTIs are tables of sorted ‘START’ and ‘STOP’ times and “for pipeline-produced data, the GTIs give the time periods when the mission time line parameters [fall] within acceptable ranges” (NASA/CXC, 2014). An example for when to indicate a “STOP” for the GTIs table is when the temperature of portions of the telescope, which is closely monitored, falls outside acceptable operation temperatures. The GTI data is used later for data preparation during reprocessing which allows the user to remove the data that is deemed “unacceptable” in order to ensure the quality of the data. *CHANDRA* data is then stored on a public archive and labelled by their “Observation ID”, or ObsID.

ACIS has two data collection operating modes. The Timed exposure (TE) mode sets the CCDs to collect data for a preselected amount of frame time. Ideally this time is 3.2 seconds, however there is the option of choosing 0.2 s - 10 s increments. If the selected time is less than 3.2 s, then this can possibly introduce dead time (time in which no data is taken) into the duration of the measurement, and if greater, then pileup, when two or more photons are detected as a single event, becomes a possibility. Continuous clocking (CC) mode allows for 3 ms timing, but at the expense of a spatial dimension. Images are taken at 1 pixel x

1024 pixel with an integration time of 2.85 ms. Details to the spatial distribution are lost but this mode allows for timing studies.

ACIS also has a number of telemetry formats. The number of bits per event depends on the operating modes and the telemetry format. Bits per event indicates when the telemetry saturates and begins to limit the return of data. The two telemetry format of interest are the Faint and Very Faint (VFAINT) formats. For objects with weak or extended sources, a significant reduction of background at low and high energies can be done by using the VFAINT mode. However, there is a possibility of saturation with the VFAINT format so this mode should not be used for observing very bright sources.

The detector has received some damage and decline over its lifetime. The FI CCDs has shown some degradation to its energy resolution due to radiation damage. However, there has been no further damage to the FI CCDs and the energy resolution can be compensated by a correction algorithm in the software package tool, CIAO (see Section 3.2.1). The ACIS effective area below 2 keV has continuously declined since launch due to molecular build-up on the cold ACIS optical blocking filters. The contaminants are thought to be hydrocarbons from the spacecraft lubricant that are collecting on the filters, reducing the efficiency of the detectors at low X-ray energies so it may be necessary to restrict the low energy range data when performing spectroscopic analysis. The ACIS detectors are sensitive to optical light and hence optical blocking filters were necessary, however these are prone to molecular build-up and is most severe at lower temperatures. Every year a contamination model is updated in the CIAO package system to account for this build-up.

All information from this section is provided by the *CHANDRA* X-ray Observatory website¹ (NASA/CXC, 2014).

¹<http://chandra.harvard.edu/>

3.2 Software Packages

In this section is a description of the package software used for data preparation and analysis. The *CHANDRA* X-ray telescope provides the *CHANDRA* Interactive Analysis of Observations (CIAO)¹, a software package for processing and filtering *CHANDRA* data. This reprocessed data is analysed with SAOImage DS9, an astronomical imaging and data visualization application, and XSPEC, an X-ray spectral fitting package.

3.2.1 CIAO

CIAO provides data preparation and analysis guides for raw *CHANDRA* data. The *CHANDRA* data goes through a Standard Data Processing (SDP) where the most recent calibrations are applied. The amount of processing has several levels, Level 0 to 3. Level 0 (L0) takes raw *CHANDRA* spacecraft telemetry and splits it into convenient FITS files and then divides the telemetry along the observation boundaries. Level 1 (L1) takes L0 output and applies instrument-dependent corrections and have not had anything irreversible done to the data (for example, no photon rejection). Level 2 (L2) takes L1 outputs and applies standard corrections which include filtering the event file on the good times intervals GTIs, cosmic ray rejection, and position transformation to celestial coordinates (RA, Dec). This produces an event 2 file and is provided when acquiring the data from the *CHANDRA* database. Level 3 (L3) derives higher level information from the L2 outputs which includes more precise source detection and characterization (fluxes, morphology) and gets cross-correlated with other catalogues. Once an observation makes it through the SDP, the data is then passed to the Verification and Validation (V&V) team where the products are

¹<http://cxc.harvard.edu/ciao/>

checked by CXC scientists to ensure data quality including investigations for any causes of exposure loss. Observers then get access to the data once it passes verification along with a V&V report so that users are aware of any potential issues. Further data preparation can be done by the user with the provided L2 file.

All information from this section is provide by the CIAO website¹ (Fruscione et al., 2006).

3.2.2 XSPEC

XSPEC² is an interactive X-ray spectral fitting program that can be used with a variety of X-ray observatory data including *CHANDRA*. The software provides many useful models for analysing SNR physics, these include the multiplicative models TBABS and the additive models VPSHOCK, VNEI, and APEC used for SNRs. Specifically, the VPSHOCK and VNEI models are of great importance for they are time-dependent ionization plasma models that are especially important for describing emission from SNRs whose age is smaller than the time required to reach ionization equilibrium (Borkowski et al., 2001a).

The XSPEC package provides tools useful for statistical analysis. The fitting process used by XSPEC involves picking a suitable model based on the physics of the system with some allowed variable parameters that can describe the data and then matching, or fitting, the model to the spectral data. The parameters are varied about some starting values until they find the parameters that are referred to as the “best-fit parameters”, the parameters that give the best fit between the theoretical models and the observed data. The software program searches for these parameters using a modified Levenberg-Marquardt algorithm that yields the best statistical fit, which is based on the fit statistic, χ^2 , and its counterpart

¹<http://cxc.harvard.edu/ciao/>

²<https://heasarc.gsfc.nasa.gov/xanadu/xspec/>

termed the “reduced chi-squared”, χ^2_ν , based on the number of degrees of freedom (DOF), ν . Generally, a reduced chi-squared of close to 1 indicates a good fit, where values much larger than 1 indicates a increasingly poorer model fit, and values much smaller than 1 indicates the model is overestimating the error variance. A value of approximately 1 indicates the best fit between data and model. The parameters themselves have a confidence interval associated with them, where a range is given for the parameter by which one can be confident (to varying degrees of confidence) that the true value of the parameter lies. This thesis gives results to a 90% confidence interval (typical for astrophysical data). Finally, the last statistical tool provided by XSPEC is the FTEST, which calculates the f-statistic, a statistic that is used to determine whether adding an additional model component is statistically reasonable. If the FTEST probability is small, this indicates that it is statistically justified to add the secondary model component.

TBABS

TBABS is the Tuebingen-Boulder ISM absorption model. This model calculates the sum of the cross sections for X-ray absorption due to the gas-phase ISM, the grain-phase ISM, and the molecules in the ISM into a final cross section for X-ray absorption by the ISM (Arnaud et al., 2015). This model is used to determine the hydrogen column density in 10^{22} atoms cm^{-2} , where the column density is the number of units of matter observed along the line of sight. Further description of the parameters can be found in the Appendix.

VPSHOCK

VPSHOCK is a constant temperature, plane-parallel shock plasma model in non-ionization equilibrium that “comprises of a superposition of different ionization ages appropriate for

a plane-parallel shock” (Safi-Harb et al., 2000). It is characterized by a constant electron temperature, T_e in keV, and the shock ionization age, $\tau = n_e t$ in $\text{cm}^{-3} \text{ s}$ where n_e is the post-shock electron density and t is the time since the passage of the shock. The model allows for varying abundances of the elements C, N, O, Ne, Mg, Si, S, Ca, Ar, Fe, and Ni. Further description of the parameters can be found in the Appendix. Due to the superposition of different ionization ages, this is appropriate for fitting larger regions in non-equilibrium ionization. The next model, VNEI, is a similar model as VPSHOCK but only considers a single ionization age.

VNEI

VNEI is a non-equilibrium collisional plasma model characterized by a constant temperature and single ionization timescale. Similarly to VPSHOCK, it has a constant electron temperature, T_e in keV, and a shock ionization age, $\tau = n_e t$ in $\text{cm}^{-3} \text{ s}$. The model allows for varying abundances of the elements C, N, O, Ne, Mg, Si, S, Ca, Ar, Fe, and Ni. Further description of the parameters can be found in the Appendix.

VAPEC

VAPEC, the Astrophysical Plasma Emission Code, is an emission spectrum model of a hot, optically thin, collisionally-ionized plasma in ionization equilibrium (CIE). The model calculates line emission data from the atomic data database, ATOMDB (Foster et al., 2015). The model allows for varying abundances of the elements C, N, O, Ne, Mg, Al, Si, S, Ca, Ar, Fe, and Ni. Further description of the parameters can be found in the Appendix.

All information from this section is provided by the online XSPEC manual¹ (Arnaud et al., 2015). For a comparison and summary of the models and for an application to an ejecta-dominated SNR, see Safi-Harb et al. (2000) and Borkowski et al. (2001a).

3.3 Observations and Data Preparation

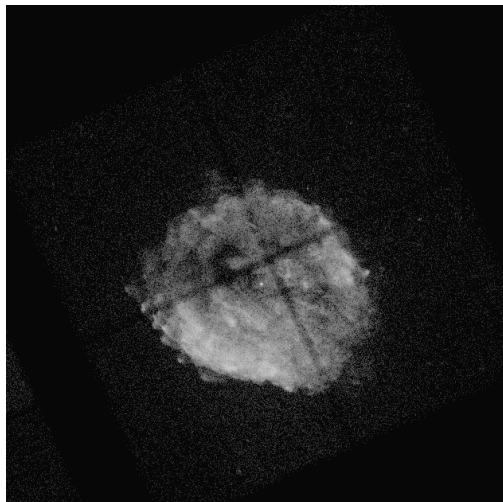
The supernova remnant RCW 103 was observed with the *CHANDRA* X-ray Telescope on four separate occasions as seen in Table 3.1. From the table, three of the four data sets used the 2x2 FI CCD grid detector, ACIS-I, whereas the data set 970 used a single BI CCD from ACIS-S. Figure 5.1 shows that the SNR was large enough to span the 4 CCDs of the ACIS-I detector, which left small gaps in the image between the gaps of the CCD chips. As well, the ACIS-S data had some of the outer edges of the SNR missing due to the SNR being larger than the chip size.

Table 3.1 *CHANDRA* Observation Data

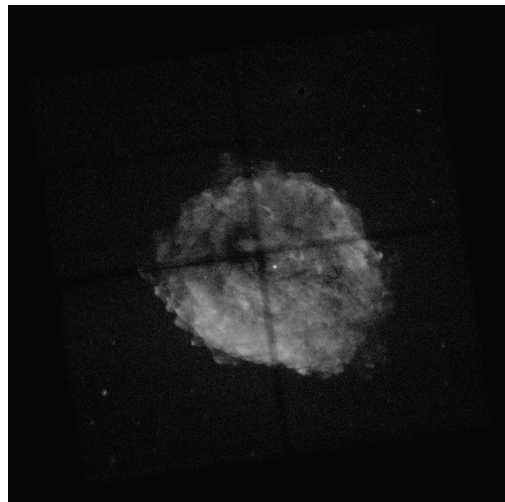
ObsID	Detector	Data Mode	Exposure Time (ks)	Effective Exp. Time (ks)	Observation Date (DD/MM/YY)
123	ACIS-I	VFAINT	19.60	13.36	26/06/99
970	ACIS-S	FAINT	22.32	17.46	08/08/00
11823	ACIS-I	FAINT	64.94	62.47	01/06/10
12224	ACIS-I	FAINT	20.01	17.82	27/06/10

Data reduction and analysis was done using the *CHANDRA* Interactive Analysis of Observations (CIAO) version 4.5 software package as described in Chapter 3.2. The data was reprocessed under the guidance of the CIAO data preparation thread to reprocess the level 2 X-ray data. Periods of high background rates were removed, giving the effective exposure

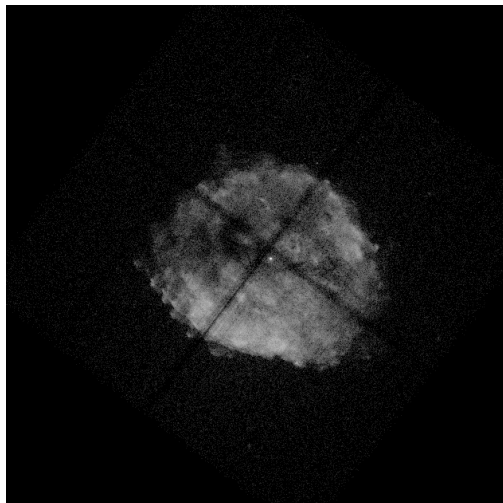
¹<https://heasarc.gsfc.nasa.gov/xanadu/xspec/>



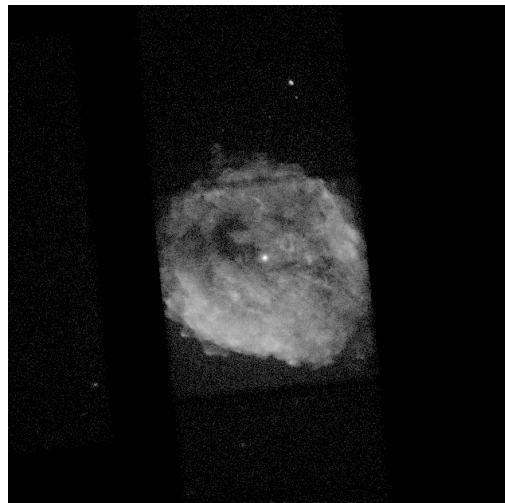
(a) ObsID 123



(b) ObsID 11823



(c) ObsID 12224



(d) ObsID 970

Figure 3.2 *CHANDRA* data sets that have been filtered to remove high background times, restricted to the energy ranges 0.3–10 keV and presented in a logarithmic scale. Images were produced using DS9. All data sets used the ACIS-I CCD arrays except for ObsID 970 which used the ACIS-S CCD array.

times as indicated in Table 3.1. Further filtering was done to restrict the data to the energy range 0.3–10 keV, the energy range the ACIS CCDs are calibrated over. Finally, the CIAO command *wavdetect* was used to detect external sources in the image and then removed using the *DS9* software. Data set 123 was used in creating the RGB image Figure 4.1 in Chapter 4, however, due to high temperature periods in the observation and no way to reprocess this data using the CIAO software, it was excluded from the spectroscopic study.

When performing the spectroscopic study in chapter 5, region selection was chosen to avoid chip gaps across the different data sets (see Figure 3.2). The background selection was chosen as the same region across all data sets with an exception for ObsID 970 where the background region was selected from a source-free region on the same CCD chip as the SNR is located. Background selection is very important for spectroscopic studies. Background data must be subtracted from the source data such that analysis is done solely on the source that is free from contamination by any background emission. Backgrounds were chosen to avoid chip gaps, to remain on the same chip as the region selected (to suppress any differences between the CCDs), and be source free. For the regions labelled as “bullets” (see Figure 5.1), region backgrounds were chosen as rings around the bullet. The full SNR background was also chosen as a ring background except for ObsID 970, which chose the biggest region possible on the same CCD chip as the SNR is located. Multiple background regions were looked at, yielding similar results within error, as expected. Spectral analysis for the spectroscopic study was performed using *XSPEC* version 12.7.0. The spectra were binned using a minimum of 20 counts per bin. The regions from each data set were modeled separately and then together. In total, there is 38 regions, 5 potential ejecta bullets, and the full SNR (see Figure 5.1).

Chapter 4

Imaging

This chapter presents a dedicated imaging study of RCW 103 using the *CHANDRA* X-ray data obsIDs 123, 11823, and 12224. The RGB image presented in Figure 4.1 is assigned a red colour to the soft band (0.5–1.2 keV), a green colour to the medium band (1.2–2.0 keV), and a blue colour to the hard band (2.0–7.0 keV). The second image presented is a *Molonglo Observatory Synthesis Telescope* radio contour overlay on top of a broadband (0.3–10.0 keV) image from the *CHANDRA* X-ray data. The individual data set images can be found in Figure 3.2.

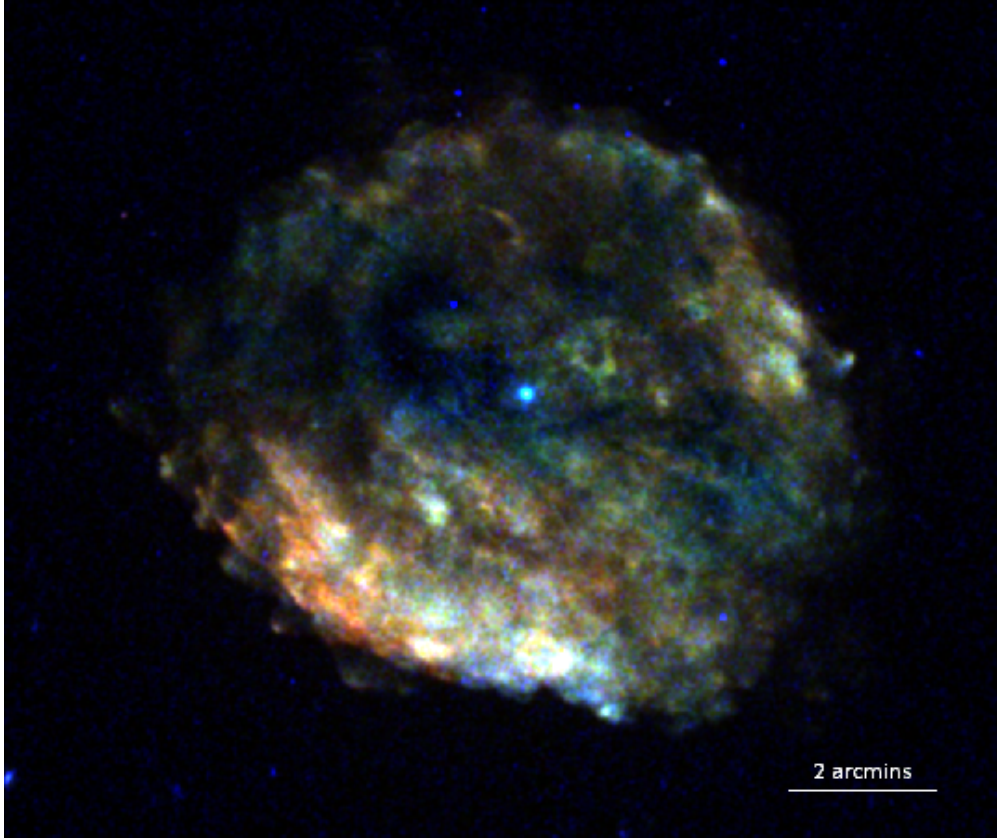


Figure 4.1 RGB *CHANDRA* image of RCW 103 using the ObsIDs 123, 11823, and 12224. The red, green and blue colours correspond respectively to the energy ranges 0.5–1.2 keV, 1.2–2.0 keV, and 2.0–7.0 keV. The image has been smoothed using a Gaussian kernel with a radius of 3 pixels. North is up and east is left.

The RGB image in Figure 4.1 reveals interesting structural details of the SNR. In X-rays, the remnant has a nearly circular morphology with a radius of approximately $10'$. The image clearly reveals two bright lobed regions, the larger one in the southern region, and a smaller one in the north. The southern lobe appears to have some soft (or low energy X-rays) sections in the east and some hard (or high energy X-rays) sections in the more southern portion with white multi-band knots throughout. The northern lobe has some multi-band

components across all energy ranges and appears harder overall than the southern lobe. The interior structure is inhomogeneous and reveals small-scale, clumpy structures throughout. There is also a peculiar "C-shaped" hole in the center as well as more diffuse emission regions in the north east. The more northern region reveals some soft, bright regions at the edge of the remnant that might indicate the edge of the shock wave. There also appears to be "ejecta bullets" coming from the southern lobe at the edge of the remnant, as well as one from the north west lobe. Finally, the CCO emits in hard X-rays at the center, as observed for a central compact object. These notable regions were selected for the spectroscopic study in Chapter 5 and can be seen in Figure 5.1.

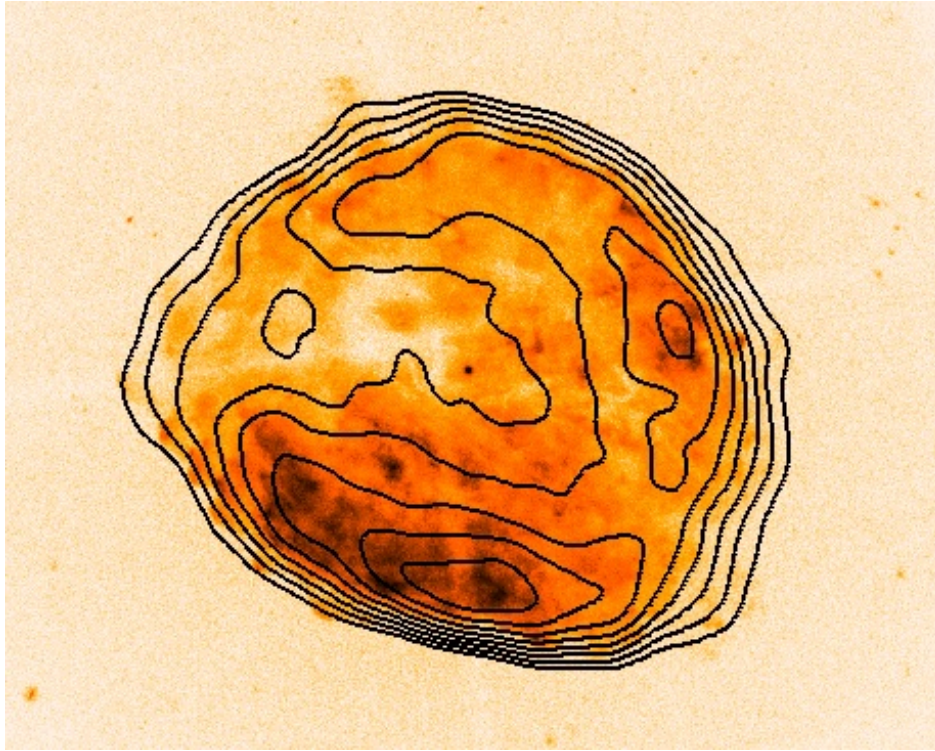


Figure 4.2 A *CHANDRA* X-ray broadband (0.3–10.0 keV) image using ObsID 123, 11823, and 12224 overlaid with a radio contour from the *MOST* telescope. 10 contours were presented as a logarithmic scale ranging in levels from 0.05 to 1.7.

In Figure 4.2 is a *Molonglo Observatory Synthesis Telescope* radio contours overlay at 843 MHz overlaid on top of a broadband (0.3–10 keV) X-ray *CHANDRA* combined image using ObsIDs 123, 11823, and 12224. The contours follow the same overall shape of the X-ray image, with large contours mimicking the bright lobed regions as discussed in the RGB image. The outermost radio shell also appears to extend slightly beyond the X-ray emission which likely indicates the location of the forward shock. Something to note is the contours seemingly ignore the “C-shaped” hole found in the X-ray data. The CCO is also completely absent in radio emission, as expected of central compact objects (see Section 1.2 for description of compact objects). Finally, a recent study of SNRs with “bilateral” symmetry in radio wavelengths was presented by West et al. (2016). The study examined all Galactic SNRs and compiled a sample that had a “bilateral” or “barrel”-shaped morphology, of which RCW 103 was one of them. The SNRs radio synchrotron emission was modelled and incorporated into current Galactic magnetic field models to simulate the emission from the SNRs as a function of their position in the Galaxy. The study strongly supports the effects of the Galactic magnetic field on the morphology of an SNR expanding into the Galaxy. For RCW 103, the study suggests that the Galactic magnetic field created the lobed morphology consistent with the brightened limbs in the south east and north west (see Figure 4.1).

Chapter 5

Spatially Resolved Spectroscopy

In this chapter, a spatially resolved spectroscopic study is presented as guided by the imaging study in the previous chapter, Chapter 4. The RGB image, Figure 4.1, was first used to pick out regions of interest for our spectroscopic study (see Chapter 4 and Figure 4.1), then regions were chosen to fully cover the whole SNR for the most complete study to date (see Figure 5.1). Such regions of interest are the bright, southern lobe for regions 1 to 4, where 1 to 2 are the softer (low X-rays) regions and 3 to 4 are harder (high X-rays). Regions 15 to 17 and 19 are the bright, northern lobe. Regions 15 to 17 and 13 to 14 were selected as candidates for the edge of the shock. Region 7 contains the “C-shaped” hole. Regions 26 to 28 were selected as they were the “bluest”, or hardest, regions. Regions 9, 14, and 17 are on the faint, outer edge of the shock which is the most likely location for emission due to shocked ISM/CSM. The bullets as indicated as Bullet 1 to 5 are selected as ejecta candidates. The rest of the image was filled in with regions large enough to do spatially resolved spectroscopy in order to address an overall study for the SNR while carefully avoiding chip boundaries.

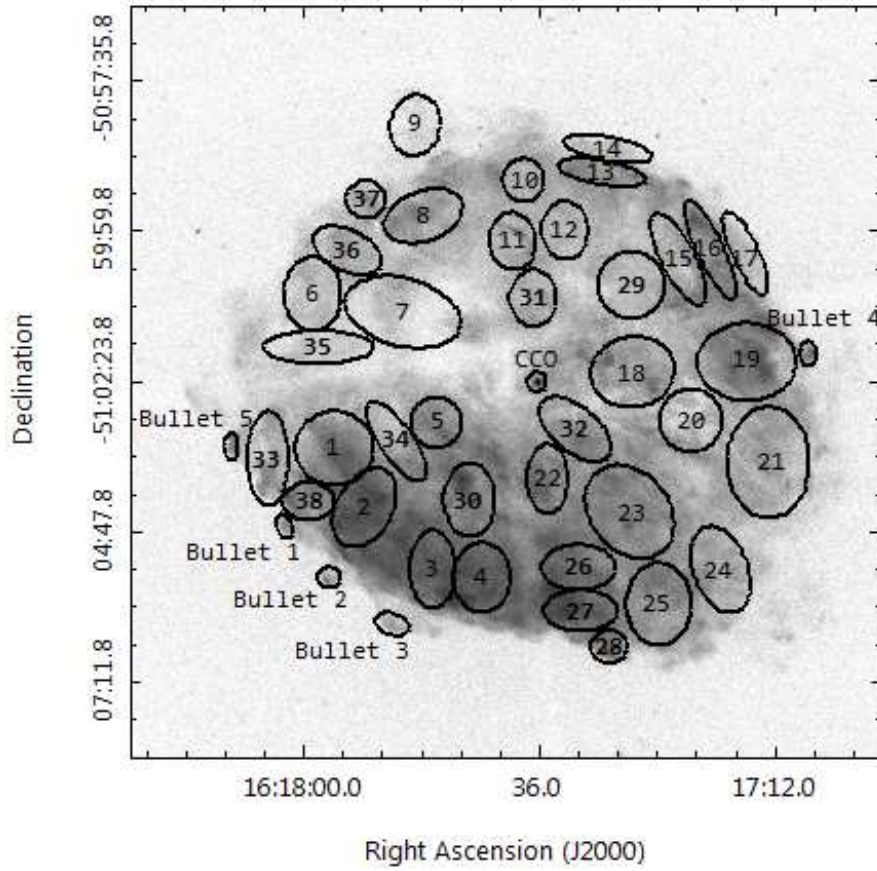


Figure 5.1 Region selection for the spectroscopic study. Fitted data for each region can be found in Table 5.3

The *CHANDRA* spectrum for RCW 103 is dominated by thermal emission with emission lines from the Fe L blend, Mg, Si, and S as seen in Figure 5.2. The spectral data was restricted to between 0.5–5.0 keV due to poor signal-to-noise ratio at energies higher than 5.0 keV; and for energies lower than 0.5 keV, molecular build up on the optical filters is the most severe at lower energies so the lower energy spectrum was omitted (see Section 3.1.1). Spectral data were extracted from the various regions as indicated in 5.1, where the larger regions or regions with higher count rates required additional model components. It should

be noted that due to the different type of CCD chip for ObsID 970 (see Chapter 3.2 for a description) a multiplicative constant was introduced to account for its higher sensitivity to lower energy emission as can be seen in Figure 5.2.

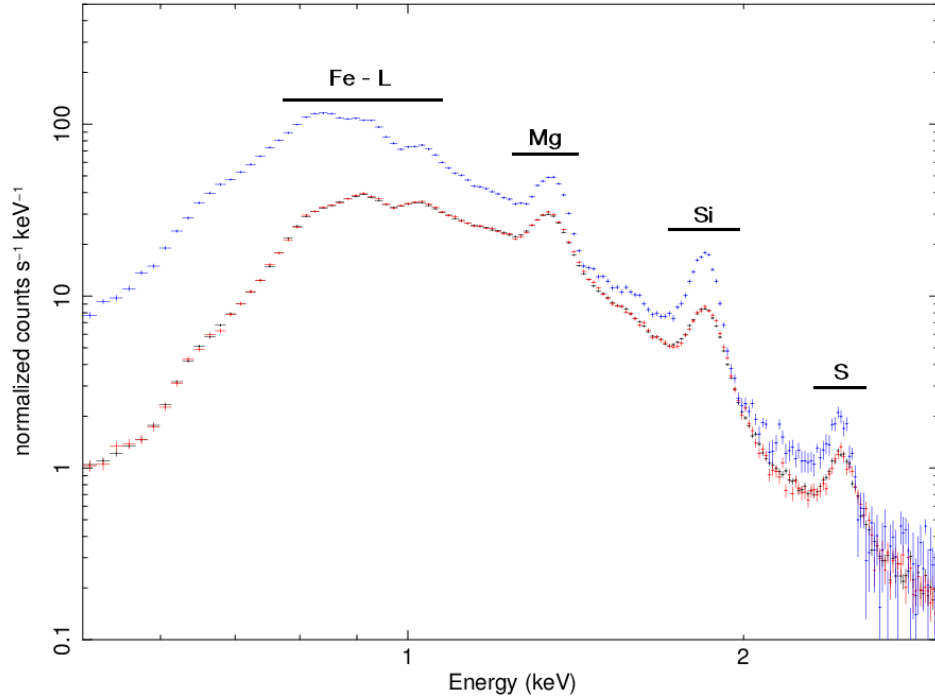


Figure 5.2 Prominent emission lines found in RCW 103's X-ray spectrum. ObsID 970 is in blue, ObsID 11823 is in black, and ObsID is in red.

5.1 One-Component Models

When fitting the various regions with models, the first step involves starting with a physically motivated model and binned data of 20 counts per bin. We considered a one-component non-equilibrium ionization (NEI) shock models typical for young SNRs multiplied by the TBABS model, a model to account for any X-ray absorption and characterized by

the molecular hydrogen column density, N_H . See Section 3.2.2 as well as the Appendix for further description of the models. The spectrum were originally fit with both a VNEI model and a VPSHOCK model to have a comparison between the two. The fitting process begins with all abundances frozen to solar and allowing only the temperature, N_H , and ionization timescale, $\tau = n_e t$, to vary. The fits improved by allowing the abundances to vary one at a time, starting with Mg, then, Si, S and Fe (tethering Ni to Fe). For some regions, the S peak had minimal data points such that a fit was unreliable so Ne was allowed to vary and S was frozen at solar. For small regions or data sets with low count rates, a single component model was adequate ($\chi^2_v < 2$; see Section 3.2.2 for an explanation on statistical analysis). However, a secondary component was also looked at and added if an acceptable FTEST threshold was met (probability < 0.00001). Both the VNEI and VPSHOCK models produced statistically good fits with similar χ^2_v values where VPSHOCK fits always had a value slightly closer to 1. For this reason, VPSHOCK models were used for the analysis.

The regions that only required a single component model are labelled: 7, 9, 10, 12, 14, 17, 37, and Bullets 1-5. The data can be found in Table 5.2. Notice that a single component model is distinguished by only having a single temperature component in the table, and the data has been organized by the temperature values depending on whether they fit into the hotter (harder) or cooler (softer) VPSHOCK component. The single-component models had N_H values ranging from $(0.43 - 1.2) \times 10^{22} \text{ cm}^{-2}$, temperatures ranging from 0.30 - 1.13 keV, and ionization timescales ranging from $(0.61 - 15) \times 10^{11} \text{ cm}^{-3} \text{ s}$. When separated into the hard and soft temperature components similar to the two-component models, then temperatures range from 0.30 - 0.39 keV for the soft component models and 0.57 - 1.13 keV for the hard component models. The hottest temperature across all regions comes from

Bullet 2 at 1.13 keV. As well, the ionization timescales for the soft component models range from $(1.4-15) \times 10^{11} \text{ cm}^{-3} \text{ s}$ and for the harder component models a range of $(0.61-5.1) \times 10^{11} \text{ cm}^{-3} \text{ s}$ which is consistent with the values given in the two-component models for the hard component but smaller for the soft (see Table 5.2 and Section 5.2). The abundance yields for the single component models had a majority at approximately solar values (≈ 1.0) or slightly subsolar values (< 1.0), with a few supersolar values (> 1.0) in region 7 (Mg), 37 (Mg, Fe), bullet 1 (Ne, Si), bullet 2 (Mg, Si, Fe), and bullet 3 (Mg, Si).

5.2 Two-Component Models

For most regions, a single component was not statistically successful ($\chi^2_v > 2$ prevents error estimates in the XSPEC software) and so a second VPSHOCK component was added to account for any mixing of shocked ejecta and circumstellar material. This was motivated by the failure of the one-component model fits in the previous section (5.1) and with the expectation of a high- and low-temperature plasma associated with the supernova blast wave and reverse-shocked ejecta as seen in many SNRs (e.g., Safi-Harb et al. 2005; Kumar et al. 2014). In Table 5.2 a summary of the VPSHOCK+VPSHOCK fits is shown, where the lower temperature (labelled soft) abundances were held at solar and the higher temperature abundances (labelled hard) were allowed to vary in the same way as explained in Section 5.1. The opposite arrangement was also completed, where the soft component abundances were varied and the hard component abundances were frozen at solar, however this consistently yielded statistically poorer results.

From Table 5.2, the N_H values range from $(0.66-1.1) \times 10^{22} \text{ cm}^{-2}$. The hard component has a temperature range 0.57 - 0.76 keV and an ionization timescale range of $(1.0-50) \times 10^{11}$

$\text{cm}^{-3} \text{ s}$. The soft component has a temperature range 0.25 - 0.30 keV and an ionization timescale range of $(0.46 - 12) \times 10^{12} \text{ cm}^{-3} \text{ s}$ with some reaching the upper limit for the VPSHOCK models (maximum allowed values up to $5.0 \times 10^{13} \text{ cm}^{-3} \text{ s}$) and replaced with the VAPEC model. From Table 5.2, in almost all cases, the soft ionization timescale had a consistently larger value of $\approx 10^{12} \text{ cm}^{-3} \text{ s}$ than its hard component's counterpart. The hard component ionization timescale is generally lower, $\approx 5.0 \times 10^{11} \text{ cm}^{-3}$.

5.3 Global SNR Model

The full SNR was fit with the following physical models: VNEI, VPSHOCK, and VSEDOV. The VSEDOV model is based on the Sedov-Taylor model, another non-equilibrium ionization model, based on the Sedov-Taylor dynamics as described in Chapter 1. This model is characterized by the ionization timescale and the mean and electron temperatures immediately behind the shock. Attempts were made to get an adequate fit by allowing the two temperatures to vary and then tethering them together, however, neither yielded a statistically acceptable fit ($\chi_v^2 > 20$). The two-component VPSHOCK+VPSHOCK model was more successful, however still not an acceptable fit with $\chi_v^2 = 5.62$. Abundances were allowed to vary in both the soft and hard components. The soft component, when allowed to vary, was in CIE so a VAPEC+VPSHOCK model replaced the soft component and had a fit with $\chi_v^2 = 5.55$. Both of these fits indicate that the SNR has a higher complexity and requires more multi-components to describe the small scale spatial variations as illustrated in the spatially resolved spectroscopic study section. See Table 5.1 for parameter details.

The VPSHOCK+VPSHOCK model has a hard and soft temperature of $0.599^{+0.007}_{-0.005} \text{ keV}$ and $0.268^{+0.007}_{-0.005} \text{ keV}$ respectively, with an N_H value of $0.789^{+0.006}_{-0.006} \times 10^{22} \text{ cm}^{-2}$ and a hard

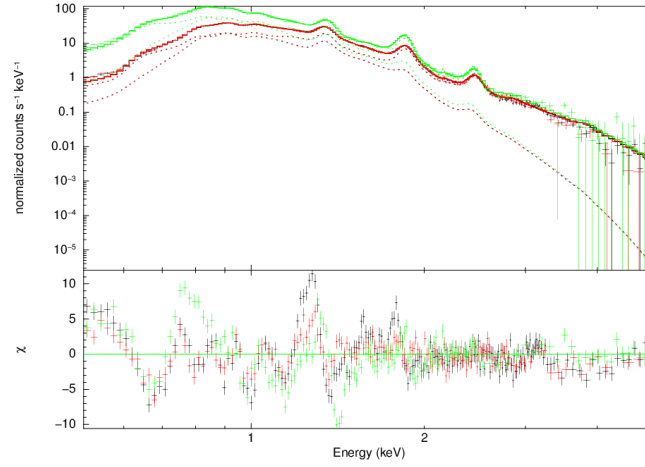
component and soft component ionization timescale of $1.00^{+0.11}_{-0.07} \times 10^{12} \text{ cm}^{-3} \text{ s}$ and $1.7^{+0.3}_{-0.3} \times 10^{12} \text{ cm}^{-3} \text{ s}$ respectively. The VAPEC+VPSHOCK model has a soft and hard temperature of $0.215^{+0.003}_{-0.004} \text{ keV}$ and $0.590^{+0.03}_{-0.007} \text{ keV}$ respectively, with an N_H value of $0.78^{+0.04}_{-0.02} \text{ cm}^{-2}$ and a hard ionization timescale of $6.6^{+1.0}_{-1.7} \times 10^{11} \text{ cm}^{-3} \text{ s}$. The full SNR in the energy range of 0.5 - 5 keV has an absorbed flux of $1.7 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$, an unabsorbed flux of $3.4 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ and a luminosity of $3.9 \times 10^{36} \text{ erg s}^{-1}$ at an assumed distance of 3.1 kpc.

From Figure 5.1, there appears to be little variation across the SNR regions in terms of the temperature from either component. The column density, N_H , is highest in the north east corner, where it reaches $> 1.0 \times 10^{22} \text{ cm}^{-2}$ and a slight increase in the south west corner. The many studies as discussed in Chapter 2 suggest the presence of a molecular cloud interacting with the SNR in the south. There is no similar evidence for the north east which would account for the higher absorption, although this region is much more diffuse than the rest of the SNR. The ionization timescale maps reveal the hard component has an overall smaller timescale than the soft component. The abundance maps show little global variation across the remnant due to the low yields. Most values are within their error ranges, so no clear pattern is present, although the bullet regions do show the more significant enhancements suggesting they are ejecta bullets, as described in Section 5.1 and found in Table 5.2.

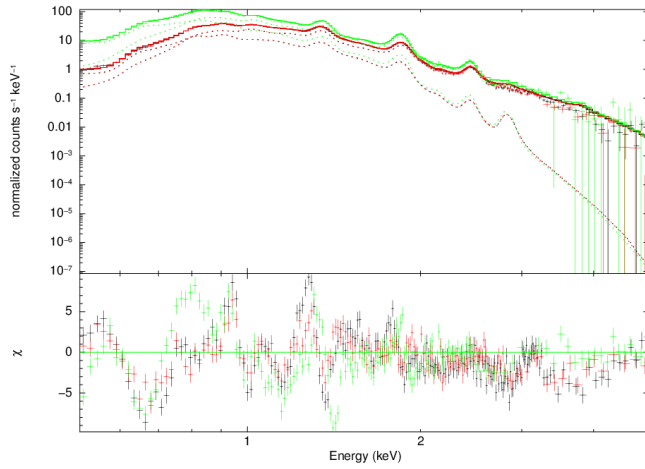
Table 5.1. Spectral Data for Full SNR

VPSHOCK+VPSHOCK		VAPEC+VPSHOCK	
$N_H(\times 10^{22} \text{ cm}^{-2})$	$0.789^{+0.006}_{-0.006}$	$N_H(\times 10^{22} \text{ cm}^{-2})$	$0.78^{+0.04}_{-0.02}$
Hard		Soft	
kT (keV)	$0.599^{+0.007}_{-0.005}$	kT (keV)	$0.215^{+0.003}_{-0.004}$
Mg	$1.34^{+0.04}_{-0.05}$	Mg	$1.3^{+0.2}_{-0.2}$
Si	$1.56^{+0.04}_{-0.07}$	Si	$3.24^{+0.8}_{-0.6}$
S	$1.38^{+0.11}_{-0.11}$	S	50^{+20}_{-20}
Fe = Ni	$1.42^{+0.04}_{-0.22}$	Fe = Ni	$1.1^{+0.2}_{-0.1}$
$\tau (\times 10^{12} \text{ cm}^{-3} \text{ s})$	$1.00^{+0.11}_{-0.07}$	...	...
Soft		Hard	
kT (keV)	$0.268^{+0.007}_{-0.005}$	kT (keV)	$0.590^{+0.03}_{-0.007}$
$\tau (\times 10^{12} \text{ cm}^{-3} \text{ s})$	$1.7^{+0.3}_{-0.3}$	$\tau (\times 10^{11} \text{ cm}^{-3} \text{ s})$	$6.6^{+1.0}_{-1.7}$
χ^2_ν (DOI)	5.62 (874)	χ^2_ν (DOI)	5.55 (875)

Note. — Global fits varying both the hard and soft abundances. The first is a two component VPSHOCK+VPSHOCK where the hard abundance variables were allowed to vary, whereas the second is a VP-SHOCK+VAPEC model where the abundances of the soft component were allowed to vary. Note that a VPSHOCK+VPSHOCK was fitted as well but the ionization timescale went to the maximum value of $5 \times 10^{-13} \text{ cm}^{-3} \text{ s}$ so the CIE VAPEC model was used instead. Abundances are given in solar units.



(a) VPSHOCK+VPSHOCK



(b) VAPEC+VPSHOCK

Figure 5.3 Two separate fits from the data in Table 5.1. (Top) A VPSHOCK+VPSHOCK fit with variable abundances in the hard component and solar abundances in the soft component. (Bottom) A VAPEC+VPSHOCK fit with variable abundances in the soft component and solar abundances in the hard component. The lower panel of each image shows the residual plots with χ vs energy. The individual additive model components are the dotted lines. Green data is from ObsID 970, black is ObsID 11823, and red is ObsID 12224.

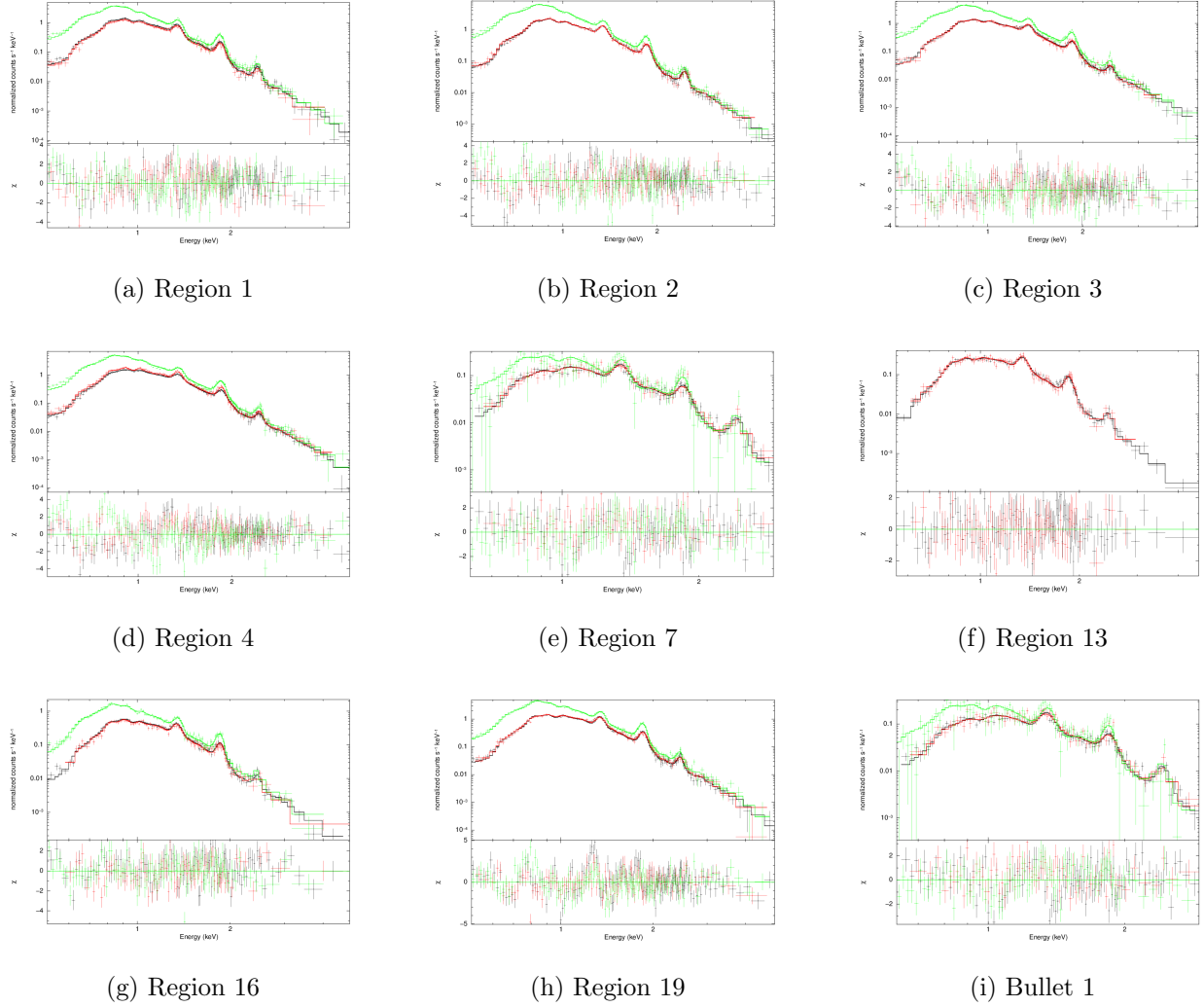


Figure 5.4 *CHANDRA* best-fit models for the given regions where the top plots are normalized counts vs energy and the bottom plots are the residual plots with χ vs energy. Regions 1, 2, 3, 4, 13, and 19 are VPSHOCK+VPSHOCK models, region 16 is a VPSHOCK+APEC model, and regions 7 and 9 are one-component VPSHOCK models. Region 1, 2, 3, and 4 are from the southern lobe, region 13, 16 and 19 are from the north-west lobe, region 7 covers the “C-shaped” hole, and Bullet 1 is from one of the southern bullets (see Figure 5.1). Green data is from ObsID 970, black is ObsID 11823, and red is ObsID 12224.

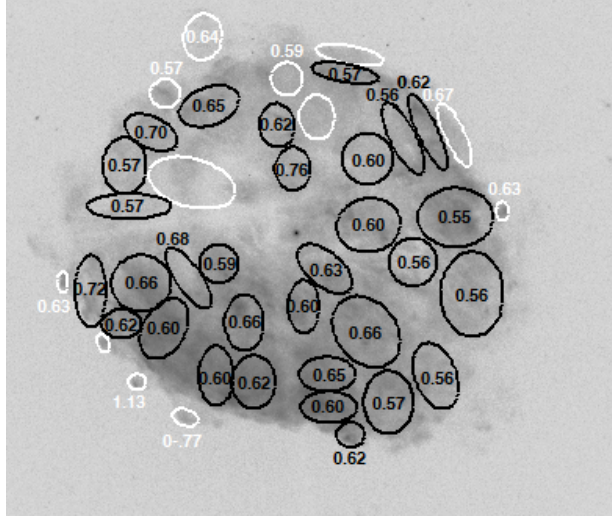
Table 5.2. Spectral Data for Selected Regions

Region	N_H $\times 10^{22} \text{ cm}^{-2}$	kT (Hard) keV	kT (Soft) keV	Ne	Mg	Si	S	Fe = Ni	τ_u (Hard) $\text{cm}^{-3} \text{ s}$	τ_u (Soft) $\text{cm}^{-3} \text{ s}$	χ^2_ν (DOI)
1	$0.69^{+0.04}_{-0.04}$	$0.66^{+0.09}_{-0.04}$	$0.30^{+0.02}_{-0.03}$	...	$1.8^{+1.0}_{-0.1}$	$1.5^{+0.2}_{-0.1}$	$1.8^{+0.6}_{-0.5}$	$2.0^{+0.2}_{-0.2}$	$3.3^{+2.2}_{-1.1} \times 10^{11}$	$1.4^{+2.9}_{-0.7} \times 10^{12}$	1.51 (372)
2	$0.66^{+0.03}_{-0.03}$	$0.60^{+0.02}_{-0.01}$	$0.27^{+0.02}_{-0.01}$	...	$1.4^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.1}$	$1.4^{+0.4}_{-0.3}$	$1.5^{+0.2}_{-0.1}$	$9.3^{+3.2}_{-2.0} \times 10^{11}$	$1.8^{+1.2}_{-0.7} \times 10^{12}$	1.90 (403)
3	$0.69^{+0.04}_{-0.01}$	$0.60^{+0.03}_{-0.01}$	$0.27^{+0.02}_{-0.01}$	...	$1.3^{+0.3}_{-0.2}$	$1.3^{+0.4}_{-0.2}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.5}_{-0.1}$	$1.5^{+2.7}_{-0.5} \times 10^{12}$	$3.8^{+23.2}_{-2.4} \times 10^{12}$	1.66 (384)
4	$0.74^{+0.03}_{-0.02}$	$0.62^{+0.02}_{-0.02}$	$0.28^{+0.03}_{-0.01}$	...	$1.1^{+0.5}_{-0.3}$	$1.2^{+0.5}_{-0.4}$	$1.0^{+0.8}_{-0.5}$	$1.3^{+0.6}_{-0.3}$	$1.4^{+1.1}_{-0.4} \times 10^{12}$	$3.4^{+8.7}_{-1.6} \times 10^{12}$	1.82 (418)
5	$0.74^{+0.06}_{-0.05}$	$0.59^{+0.03}_{-0.03}$	$0.26^{+0.06}_{-0.04}$	...	$1.6^{+0.3}_{-0.1}$	$1.6^{+0.4}_{-0.2}$	$1.6^{+0.9}_{-0.4}$	$1.4^{+0.6}_{-0.3}$	$1.4^{+2.7}_{-1.4} \times 10^{12}$	$3.4 (> 2.0) \times 10^{12}$	1.10 (313)
6	$1.1^{+0.1}_{-0.1}$	$0.57^{+0.06}_{-0.04}$	$0.25^{+0.01}_{-0.02}$	...	$1.7^{+0.5}_{-0.5}$	$2.3^{+0.7}_{-0.5}$	$1.7^{+0.1}_{-0.9}$	$2.1^{+9.2}_{-0.4}$	$3.0^{+4.5}_{-2.0} \times 10^{11}$	$9.2 (> 5.2) \times 10^{11}$	1.15 (257)
7*	$1.2^{+0.1}_{-0.1}$	...	$0.39^{+0.12}_{-0.09}$	...	$0.93^{+0.23}_{-0.14}$	$1.5^{+0.9}_{-0.6}$	$4.0^{+4.0}_{-2.4}$	$0.90^{+0.31}_{-0.23}$	...	$3.3^{+3.9}_{-1.9} \times 10^{11}$	1.46 (323)
8	$0.81^{+0.03}_{-0.16}$	$0.65^{+0.2}_{-0.04}$	$0.25^{+0.06}_{-0.03}$	...	$1.6^{+0.5}_{-0.5}$	$1.7^{+0.5}_{-12.7}$	$1.3^{+5.7}_{-0.8}$	$2.1^{+6.7}_{-0.5}$	$5.9^{+11.1}_{-4.5} \times 10^{11}$	$1.2 (> 0.6) \times 10^{13}$	1.52 (200)
9*	$0.69^{+0.26}_{-0.1}$	$0.64^{+0.31}_{-0.1}$	...	...	$0.91^{+0.34}_{-0.25}$	$0.75^{+0.32}_{-0.42}$	...	$0.96^{+0.27}_{-0.17}$	$1.8^{+7.2}_{-1.2} \times 10^{11}$	...	0.97 (122)
10*	$0.55^{+0.08}_{-0.08}$	$0.59^{+0.05}_{-0.04}$	...	$0.91^{+0.25}_{-0.22}$	$1.0^{+0.22}_{-0.16}$	$0.57^{+0.22}_{-0.20}$	...	$0.86^{+0.24}_{-0.21}$	$5.6^{+4.3}_{-2.4} \times 10^{11}$	...	1.11 (129)
11	$0.73^{+0.13}_{-0.08}$	$0.62^{+0.11}_{-0.05}$	$0.27^{+0.1}_{-0.02}$	...	$2.5 (> 1.9)$	$2.4 (> 1.2)$	$2.6^{+1.9}_{-1.6}$	$2.6^{+0.9}_{-0.4}$	$4.4^{+10.5}_{-3.1} \times 10^{11}$	$2.1 (> 0.7) \times 10^{12}$	1.06 (254)
12*	$0.97^{+0.06}_{-0.05}$	...	$0.31^{+0.04}_{-0.03}$	$1.2^{+0.2}_{-0.2}$	$0.75^{+0.18}_{-0.16}$	$1.1^{+0.6}_{-0.8}$	...	$0.91^{+0.21}_{-0.16}$	...	$4.3^{+4.0}_{-1.9} \times 10^{11}$	1.25 (232)
13	$0.97^{+0.07}_{-0.10}$	$0.57^{+0.15}_{-0.03}$	$0.26^{+0.06}_{-0.03}$	...	$2.0^{+2.4}_{-0.5}$	$2.7^{+3.7}_{-0.7}$	$2.1^{+5.7}_{-4.3}$	$2.2^{+3.1}_{-0.6}$	$7.2^{+17.8}_{-5.8} \times 10^{11}$	$2.3 (> 0.6) \times 10^{12}$	0.98 (186)
14*	$1.04^{+0.08}_{-0.08}$	...	$0.39^{+0.06}_{-0.05}$	$1.1^{+0.2}_{-0.2}$	$0.59^{+0.15}_{-0.13}$	$0.75^{+0.29}_{-0.13}$	...	$0.62^{+0.18}_{-0.14}$	...	$1.4^{+1.2}_{-0.6} \times 10^{11}$	1.20 (113)
15	$0.75^{+0.04}_{-0.03}$	$0.56^{+0.02}_{-0.03}$	$0.28^{+0.02}_{-0.02}$	...	$2.3^{+1.0}_{-0.5}$	$2.5^{+1.2}_{-0.7}$	$1.7^{+1.3}_{-0.8}$	$2.1^{+0.9}_{-0.5}$	$2.1^{+4.9}_{-0.8} \times 10^{12}$	$6.2 (> 2.4) \times 10^{12}$	1.40 (330)
16	$0.82^{+0.04}_{-0.03}$	$0.62^{+0.04}_{-0.02}$	$0.24^{+0.04}_{-0.02}$	...	$1.6^{+0.6}_{-0.4}$	$1.9^{+0.7}_{-0.6}$	$1.3^{+0.9}_{-0.5}$	$2.0^{+0.6}_{-0.4}$	$1.1^{+1.3}_{-0.5} \times 10^{12}$	...	1.38 (317)
17*	$0.62^{+0.16}_{-0.09}$	$0.67^{+0.07}_{-0.05}$	...	$0.89^{+0.36}_{-0.32}$	$0.89^{+0.15}_{-0.14}$	$0.85^{+0.20}_{-0.16}$	...	$0.87^{+0.16}_{-0.12}$	$2.0^{+1.6}_{-0.7} \times 10^{11}$	...	1.20 (199)
18	$0.86^{+0.04}_{-0.07}$	$0.60^{+0.03}_{-0.02}$	$0.29^{+0.04}_{-0.07}$	...	$2.0^{+0.4}_{-0.3}$	$1.7^{+0.3}_{-0.2}$	$1.4^{+0.5}_{-0.4}$	$1.9^{+0.5}_{-0.3}$	$6.7^{+2.7}_{-2.5} \times 10^{11}$	$8.9^{+11.1}_{-7.1} \times 10^{11}$	1.38 (353)
19	$0.78^{+0.04}_{-0.01}$	$0.55^{+0.03}_{-0.02}$	$0.26^{+0.03}_{-0.01}$	...	$1.7^{+0.4}_{-0.1}$	$2.0^{+0.7}_{-0.2}$	$1.6^{+0.8}_{-0.3}$	$1.7^{+0.6}_{-0.3}$	$2.0^{+2.4}_{-0.6} \times 10^{12}$	$4.6 (> 2.8) \times 10^{12}$	1.77 (407)
20	$1.00^{+0.05}_{-0.05}$	$0.56^{+0.04}_{-0.04}$	$0.29^{+0.03}_{-0.06}$	...	$1.8^{+0.8}_{-0.4}$	$2.6^{+2.2}_{-0.7}$	$2.3^{+1.8}_{-0.9}$	$1.9^{+1.1}_{-0.5}$	$8.6^{+7.2}_{-4.6} \times 10^{11}$	$1.7 (> 0.5) \times 10^{12}$	1.21 (288)
21	$0.98^{+0.04}_{-0.04}$	$0.56^{+0.02}_{-0.02}$	$0.26^{+0.02}_{-0.02}$	...	$1.8^{+0.4}_{-0.3}$	$2.3^{+0.5}_{-0.4}$	$2.0^{+0.6}_{-0.6}$	$1.7^{+0.3}_{-0.3}$	$1.2^{+0.7}_{-0.2} \times 10^{12}$	$1.8 (> 1.0) \times 10^{12}$	1.42 (376)
22	$0.71^{+0.05}_{-0.04}$	$0.60^{+0.03}_{-0.02}$	$0.28^{+0.04}_{-0.03}$	...	$1.7^{+0.7}_{-0.3}$	$1.5^{+0.7}_{-0.3}$	$1.7^{+1.1}_{-0.6}$	$1.7^{+0.9}_{-0.3}$	$1.0^{+0.8}_{-0.4} \times 10^{12}$	$3.3 (> 2.1) \times 10^{12}$	1.25 (329)
23	$0.75^{+0.03}_{-0.0}$	$0.66^{+0.03}_{-0.03}$	$0.30^{+0.01}_{-0.02}$	...	$2.0^{+0.4}_{-0.3}$	$2.2^{+0.5}_{-0.4}$	$1.8^{+0.5}_{-0.5}$	$2.0^{+0.5}_{-0.4}$	$5.2^{+68.0}_{-1.5} \times 10^{11}$	$3.6 (> 2.3) \times 10^{12}$	1.84 (407)
24	$0.77^{+0.04}_{-0.06}$	$0.56^{+0.04}_{-0.02}$	$0.27^{+0.05}_{-0.04}$	...	$1.4^{+0.2}_{-0.2}$	$1.8^{+0.4}_{-0.3}$	$1.5^{+0.8}_{-0.6}$	$1.4^{+0.4}_{-0.2}$	$7.8^{+4.8}_{-3.4} \times 10^{11}$	$1.1 (> 0.9) \times 10^{12}$	1.46 (313)
25	$0.77^{+0.03}_{-0.03}$	$0.57^{+0.02}_{-0.02}$	$0.26^{+0.02}_{-0.03}$	...	$1.4^{+0.2}_{-0.2}$	$1.7^{+0.3}_{-0.2}$	$1.4^{+0.5}_{-0.4}$	$1.5^{+0.3}_{-0.2}$	$1.3^{+1.5}_{-0.4} \times 10^{12}$	$3.5 (> 2.1) \times 10^{12}$	1.68 (365)
26	$0.88^{+0.03}_{-0.07}$	$0.65^{+0.04}_{-0.02}$	$0.27^{+0.03}_{-0.02}$	...	$1.2^{+0.4}_{-0.4}$	$1.7^{+0.6}_{-0.4}$	$1.3^{+0.8}_{-0.4}$	$2.4^{+0.9}_{-0.4}$	$7.7^{+10.5}_{-1.7} \times 10^{11}$	$4.5^{+17.5}_{-1.7} \times 10^{12}$	1.88 (241)
27	$0.86^{+0.04}_{-0.03}$	$0.60^{+0.03}_{-0.02}$	$0.27^{+0.02}_{-0.02}$	...	$1.0^{+0.2}_{-0.2}$	$1.4^{+0.3}_{-0.3}$	$1.5^{+0.6}_{-0.3}$	$1.4^{+0.4}_{-0.2}$	$5.0 (> 1.8) \times 10^{12}$	$1.4 (> 0.22) \times 10^{13}$	1.40 (277)
28	$0.82^{+0.05}_{-0.03}$	$0.62^{+0.03}_{-0.03}$	$0.27^{+0.03}_{-0.02}$	...	$1.2^{+0.3}_{-0.2}$	$1.6^{+0.6}_{-0.3}$	$1.5^{+0.5}_{-0.3}$	$1.2^{+0.3}_{-0.2}$	$2.0^{+3.4}_{-0.7} \times 10^{12}$	$2.9 (> 2.0) \times 10^{12}$	1.61 (392)

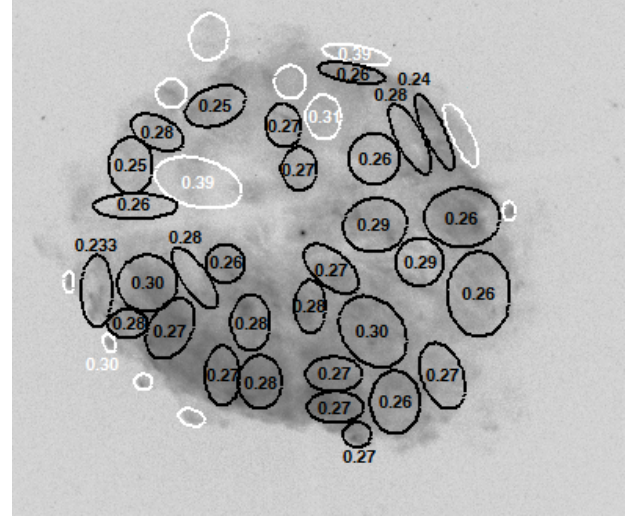
Table 5.2 (cont'd)

Region	N_H $\times 10^{22} \text{ cm}^{-2}$	kT (Hard) keV	kT (Soft) keV	Ne	Mg	Si	S	Fe = Ni	τ_u (Hard) $\text{cm}^{-3} \text{ s}$	τ_u (Soft) $\text{cm}^{-3} \text{ s}$	χ^2_ν (DOI)
29	$1.02^{+0.1}_{-0.07}$	$0.60^{+0.26}_{-0.05}$	$0.26^{+0.04}_{-0.03}$	...	$1.6^{+0.7}_{-0.5}$	$1.9^{+1.4}_{-0.5}$	$1.4^{+1.3}_{-0.8}$	$2.2^{+1.5}_{-0.7}$	$5.4^{+10.6}_{-2.0} \times 10^{11}$	$2.2 (> 0.6) \times 10^{12}$	1.21 (287)
30	$0.72^{+0.04}_{-0.04}$	$0.66^{+0.03}_{-0.03}$	$0.28^{+0.02}_{-0.02}$	...	$1.8^{+0.3}_{-0.2}$	$1.6^{+0.3}_{-0.2}$	$1.2^{+0.5}_{-0.3}$	$1.6^{+0.5}_{-0.3}$	$5.3^{+1.9}_{-1.5} \times 10^{11}$	$3.8 (> 1.2) \times 10^{12}$	1.55 (363)
31	$0.80^{+0.3}_{-0.09}$	$0.76^{+0.54}_{-0.15}$	$0.27^{+0.05}_{-0.04}$	$1.4^{+1.7}_{-1.0}$	$1.5^{+1.1}_{-0.3}$	$1.6^{+1.0}_{-0.3}$	...	$1.8^{+1.8}_{-0.4}$	$1.5^{+78.5}_{-0.9} \times 10^{11}$	$2.5 (> 0.5) \times 10^{12}$	1.26 (261)
32	$0.92^{+0.23}_{-0.05}$	$0.63^{+0.08}_{-0.03}$	$0.27^{+0.05}_{-0.04}$	...	$1.8^{+0.5}_{-0.3}$	$1.5^{+0.5}_{-0.3}$	$1.1^{+0.5}_{-0.4}$	$1.6^{+0.7}_{-0.3}$	$4.4^{+3.3}_{-2.2} \times 10^{11}$	$4.7 (> 1.0) \times 10^{12}$	1.35 (356)
33	$0.70^{+0.05}_{-0.06}$	$0.72^{+0.48}_{-0.12}$	$0.233^{+0.05}_{-0.006}$	...	$1.5^{+1.7}_{-0.5}$	$2.4^{+3.8}_{-0.9}$	$2.4^{+4.6}_{-1.0}$	$2.2^{+3.8}_{-1.2}$	$1.8^{+3.7}_{-0.8} \times 10^{11}$	...	1.15 (180)
34	$0.74^{+0.08}_{-0.06}$	$0.68^{+0.15}_{-0.06}$	$0.28^{+0.04}_{-0.04}$	...	$1.8^{+1.1}_{-0.5}$	$1.8^{+1.4}_{-0.6}$	$2.2^{+2.4}_{-1.0}$	$1.9^{+2.0}_{-0.5}$	$3.7^{+1.3}_{-2.1} \times 10^{11}$	$3.2 (> 0.8) \times 10^{12}$	1.22 (284)
35	$1.1^{+0.1}_{-0.1}$	$0.57^{+0.19}_{-0.10}$	$0.26^{+0.14}_{-0.08}$	...	$1.4^{+4.1}_{-0.8}$	$1.9^{+2.8}_{-0.8}$	$2.0^{+9.5}_{-1.4}$	$1.5^{+5.8}_{-0.8}$	$8.2^{+48.8}_{-7.9} \times 10^{11}$	$8.8 (> 2.3) \times 10^{11}$	1.19 (216)
36	$1.04^{+0.09}_{-0.09}$	$0.70^{+0.1}_{-0.08}$	$0.28^{+0.07}_{-0.02}$	...	$1.7^{+0.6}_{-0.5}$	$2.2^{+0.7}_{-0.5}$	$3.3^{+4.0}_{-1.3}$	$2.3^{+2.9}_{-0.5}$	$1.0^{+4.6}_{-0.9} \times 10^{11}$	$1.3 (> 0.5) \times 10^{12}$	1.37 (263)
37*	$0.72^{+0.06}_{-0.07}$	$0.57^{+0.06}_{-0.04}$	...	$0.32^{+0.32}_{-0.30}$	$1.3^{+0.4}_{-0.3}$	$1.1^{+0.5}_{-0.3}$	...	$1.4^{+0.8}_{-0.3}$	$3.8^{+4.4}_{-1.9} \times 10^{11}$	...	1.24 (172)
38	$0.58^{+0.06}_{-0.05}$	$0.62^{+0.21}_{-0.05}$	$0.28^{+0.05}_{-0.03}$	...	$1.6^{+0.6}_{-0.3}$	$1.7^{+0.9}_{-0.4}$	$1.1^{+1.1}_{-0.6}$	$1.6^{+0.8}_{-0.3}$	$4.3^{+2.9}_{-2.8} \times 10^{11}$	$2.6 (> 0.9) \times 10^{12}$	1.13 (270)
bullet 1*	$0.71^{+0.29}_{-0.17}$	...	$0.30^{+0.24}_{-0.08}$	$1.5^{+3.0}_{-0.7}$	$0.92^{+2.2}_{-0.68}$	$4.4^{+12.2}_{-3.6}$	...	$0.47^{+2.3}_{-0.37}$	...	$1.5 (> 1.0) \times 10^{12}$	0.82 (64)
bullet 2*	$0.45^{+0.14}_{-0.23}$	$1.13^{+1.8}_{-0.34}$	...	$1.0^{+2.4}_{-1.0}$	$1.2^{+5.2}_{-0.6}$	$1.2^{+6.0}_{-0.7}$	...	$1.5^{+3.4}_{-0.7}$	$6.1^{+8.4}_{-3.3} \times 10^{10}$	...	1.02 (54)
bullet 3*	$0.43^{+0.11}_{-0.15}$	$0.77^{+1.3}_{-0.12}$	...	$0.77^{+1.0}_{-0.77}$	$1.5^{+3.5}_{-0.7}$	$1.5^{+3.9}_{-0.7}$	...	$0.94^{+2.9}_{-0.64}$	$2.9^{+7.1}_{-0.8} \times 10^{11}$	...	1.02 (69)
bullet 4*	$0.80^{+0.13}_{-0.07}$	$0.63^{+0.03}_{-0.08}$	...	$0.29^{+0.81}_{-0.29}$	$0.88^{+1.6}_{-0.32}$	$0.90^{+0.80}_{-0.40}$	...	$1.1^{+1.2}_{-0.3}$	$5.1 (> 1.3) \times 10^{11}$	...	1.21 (82)
bullet 5*	$0.59^{+0.61}_{-0.04}$	$0.63^{+0.09}_{-0.16}$	...	$0.47^{+0.93}_{-0.47}$	$0.63^{+0.67}_{-0.25}$	$0.62^{+0.88}_{-0.42}$	...	$0.67^{+0.53}_{-0.27}$	$4.1^{+23.9}_{-3.2} \times 10^{11}$	...	1.35 (76)

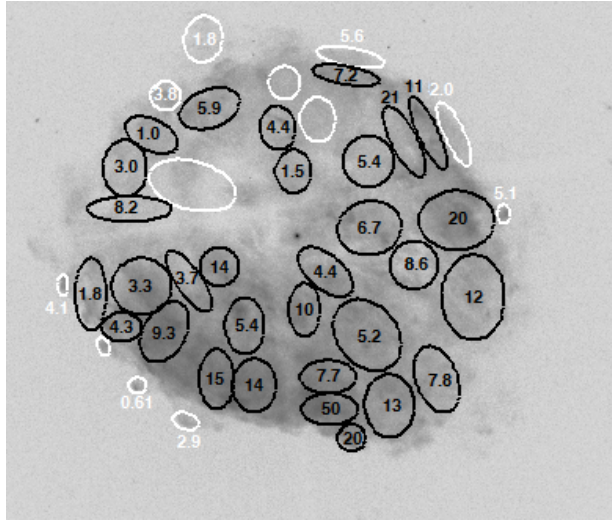
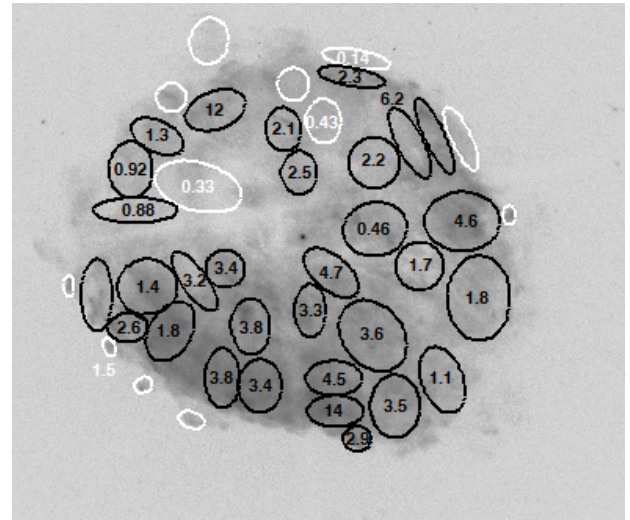
Note. — The one-component models regions are numbered: 7, 9, 10, 12, 14, 17, 37, and Bullets 1 to 5 and are arranged based on whether they are considered hard or soft and are denoted with a “*”. The rest are two-component VPSHOCK+VPSHOCK models with the exception of regions: 10, 16, and 33 which are VPSHOCK+APEC models and hence have no Tau (Soft) value. A few of the data sets only use the ObsID 11823 and 12224 due to chip gaps from 970 and are numbered: 8, 10, 13, 14, 33, Bullet 4 and Bullet 5 with the exception of Bullet 1 and 27, where region 27 had a poor fit ($\chi^2_\nu > 2$) and Bullet 1 had large error bars associated with obsID 970. The reported uncertainties on each fitted value are at a 90% confidence level. The abundances are given in solar units.

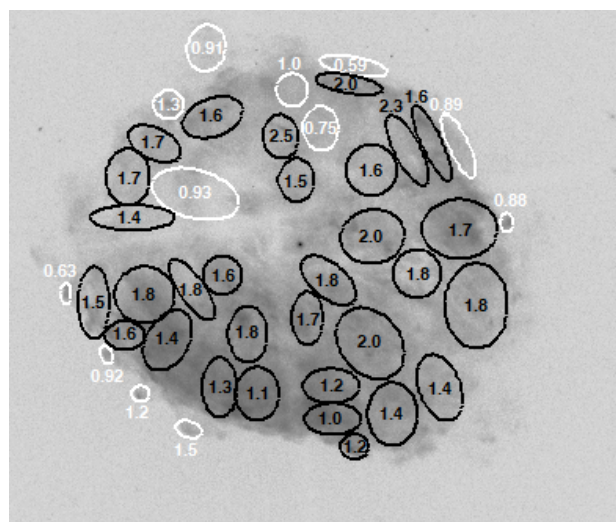


(a) Hard Component Temperature (keV)

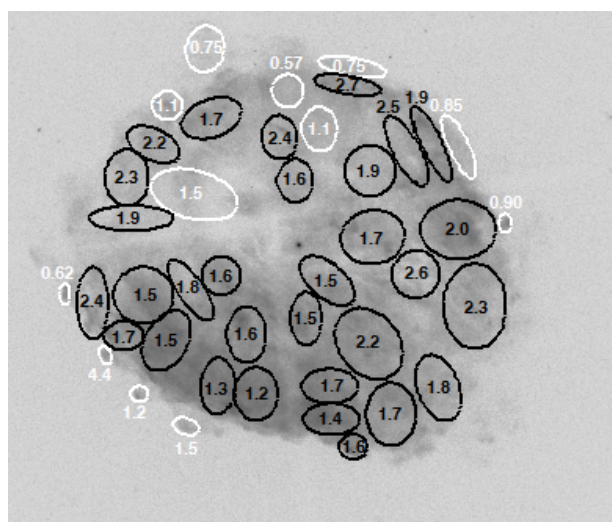


(b) Soft Component Temperature (keV)

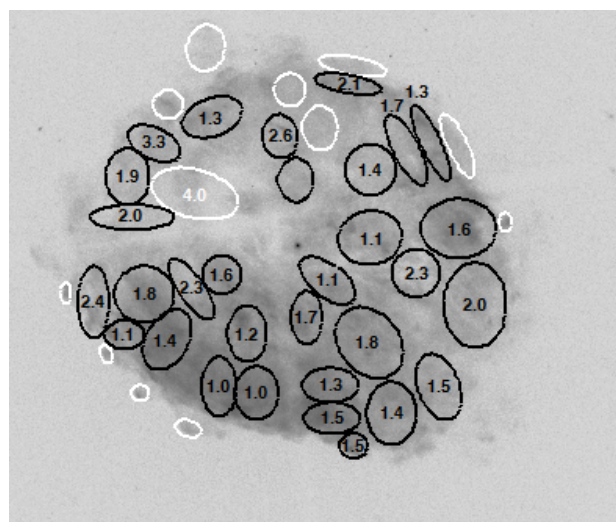
(c) Hard Component Ionization Timescale
($\times 10^{11} \text{ cm}^{-3} \text{ s}$)(d) Soft Component Ionization Timescale
($\times 10^{12} \text{ cm}^{-3} \text{ s}$)



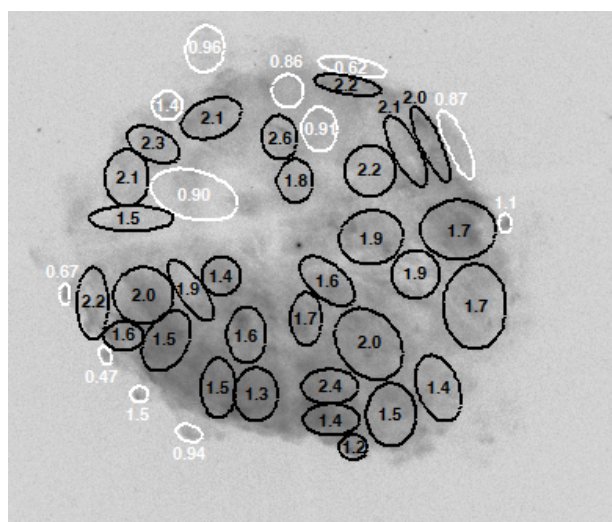
(a) Mg



(b) Si



(c) S



(d) Fe = Ni

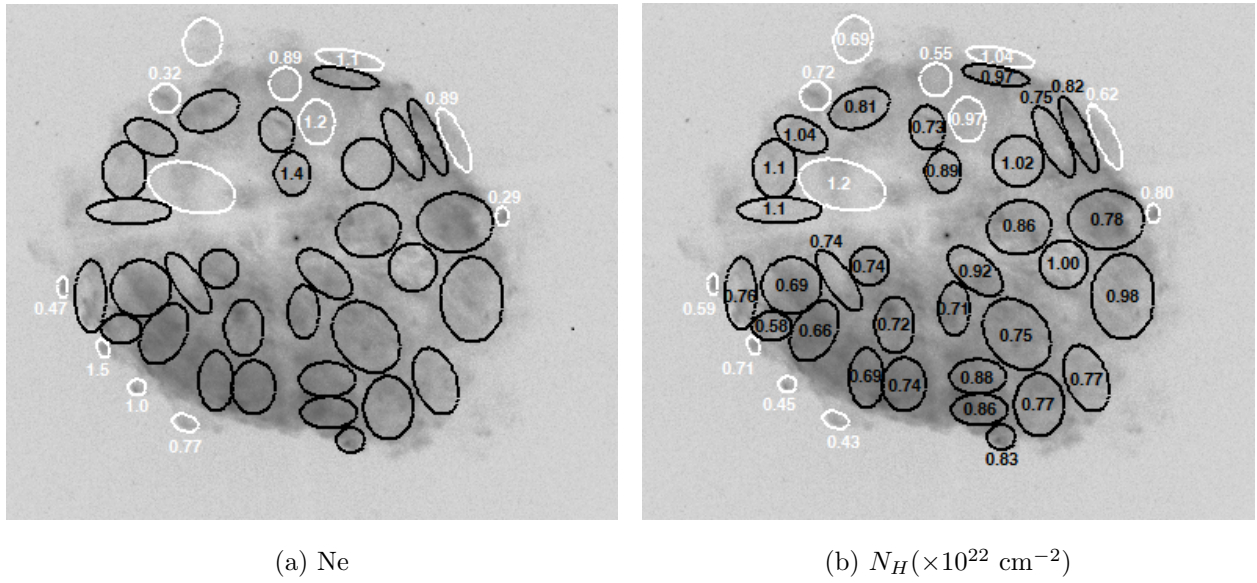


Figure 5.5 Fitted data results. One-component models are regions with white borders, whereas the rest are two-component models with black borders. If a region is left blank, the parameter was not free to vary in the fit or it was not a component of the model. Abundances are listed in units of solar. Refer to Table 5.2 for details.

Chapter 6

Discussion

In the previous chapter, a spatially resolved spectroscopic study of regions covering the entire SNR RCW 103 with 97.75 ks total effective exposure time of *CHANDRA* data was performed. Most of the emission from the region selection found in Figure 5.1 can be described by a two-component thermal+thermal (VPSHOCK+VPSHOCK) model with an exception for the smaller, more diffuse regions which only required a one-component thermal (VPSHOCK) model. In the following chapter, we present a discussion on these results based on the values tabulated in Table 5.2. Presented is the first detailed, dedicated study of the SNR aimed at addressing the SN explosion properties.

6.1 Blast Wave and Evidence of Ejecta

In the following, we discuss the origin of the hard and soft components derived from our spectral fits. The spatially resolved spectroscopic study of Chapter 5 confirms the necessity of a two-component thermal model to describe the X-ray emission of most selected regions.

As mentioned previously, the hard component, with plasma temperatures of $kT \approx 0.60$ keV, shows slightly enhanced abundances whereas the abundances of the soft component, with plasma temperatures of $kT \approx 0.27$ keV, was consistent with solar. Interestingly, these results seem to suggest that the hard component, with the enhanced abundances, arises primarily from the reverse shocked ejecta and the soft component, with abundances at solar, is dominated by the emission from the forward shock (the blast wave or shocked ISM/CSM). However, some of the single component VPSHOCK regions that are fitted with a hard component have solar/subsolar abundance yields (regions 9, 10, 17) and with their locations at the edge of the shock (see Figure 5.1), implies these are shocked ISM/CSM regions expanding into a lower density medium. This suggests a range of temperatures for the shocked ISM/CSM. A clear conclusion, then is that there exists mixing between the reverse shocked ejecta and the ISM/CSM and that there is a range of temperatures for the blast wave component expanding into varying ambient density regions.

The ionization timescales for the soft component for almost all regions has reached ionization equilibrium ($n_e \gtrsim 10^{12} \text{ cm}^{-3} \text{ s}$) whereas the ionization timescale for the hard component is almost always smaller and approaching ionization equilibrium with a range of $(1.0 - 50) \times 10^{11} \text{ cm}^{-3} \text{ s}$. The lower timescales attributed to the hard component implies it has been shocked more recently and with the low ejecta yields (≈ 2), could indicate that not all the ejecta has been shocked yet.

The hard component has slight enhanced abundance yields where the region maps from Figure 5.1 give values that are uniform across the remnant. The one-component regions are the only regions that contain any subsolar yields, which implies they are shocked ISM/CSM regardless of whether they are soft or hard, whereas the two-component regions are consis-

tently greater than solar. The bullet regions (except Bullet 1) are clearly hard, and have the most significant enhanced abundance values for Mg, Si, and Fe (=Ni) (see Figure 5.5) which suggests that they may be ejecta bullets.

6.2 Distance

The distance to the SNR can be estimated using our fitted column density to the remnant. The range for all regions found in Table 5.3 is given as $N_H = (0.43 - 1.2) \times 10^{22} \text{ cm}^{-2}$. The bullets regions have the smallest N_H values and due to their lower counts, it is more reliable to remove them from the given range of N_H values. Thus we take an average from the regions which gives $N_H = 0.84 \times 10^{22} \text{ cm}^{-2}$ from a range of $(0.66 - 1.2) \times 10^{22} \text{ cm}^{-2}$. The extinction per unit distance in the direction of the SNR is estimated from the contour diagrams given by (Lucke, 1978): $E_{B-V}/D \sim 0.4 \text{ mag kpc}^{-1}$ (see Section 1.4). Using the relation $N_H/E_{B-V} = 5.55 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}$ (Predehl & Schmitt, 1995), we derive a distance average of 3.8 kpc and a range of 3.0 - 5.4 kpc. This distance estimate is consistent with the distance derived from a systemic velocity study that determined a velocity of -43 km s^{-1} from H1 absorption in radio that corresponds to a distance of 3.1 kpc (Reynoso et al., 2004). Thus we subsequently scale our calculations to the parameter $D_{3.1} = D/3.1 \text{ kpc}$.

6.3 X-ray Properties of RCW 103

In the following is derived the X-ray properties of SNR RCW 103 shown in Table 6.1 using single and double VPSHOCK models as summarized in Table 5.2. In the calculations, take the radius to be 10' as estimated by the extent of the radio contours as seen in Figure

3, and the distance of 3.1 kpc which will be written in terms of the scaling factor introduced in Section 6.2 as $D_{3.1} = D/3.1$ kpc. The corresponding physical size is $R_s = 9.0 D_{3.1}$ pc $= 2.8 \times 10^{19} D_{3.1}$ cm.

The volume of the X-ray emitting regions, V , is estimated by assuming the plasma fills an ellipsoid with the semi-major and semi-minor axes equivalent to those of the extracted SNR regions and the depth along the line of sight equal to the radius of the remnant. The emission measure, as described in Section 1.5.1 in equation 1.24, is given as $EM = \int n_e n_H dV \sim f n_e n_H V$ where n_e is the post-shock electron density, n_H is the mean hydrogen density, and f is the volume filling factor of the gas. For the separate hard and soft components, two distinct filling factors must be used and are given as (f_h) and (f_s) respectively. For strong shock Rankine-Hugoniot jump conditions and cosmic abundance plasma, the ambient density, n_0 , can be estimated based on the electron density, n_e , such that $n_e = 4.8 n_0$, where here n_0 includes only hydrogen (Borkowski et al. 2001b; Safi-Harb et al. 2000). Recall from Section 1.5.1 the normalization factor, $K = \frac{10^{-14}}{4\pi D^2} \int n_e n_H dV$, which is obtained from the spectral fits and used to estimate the emission measure. Using the above equations, the post-shock electron density n_e , the ambient density n_0 , and the emission measure EM are summarized in Table 6.1.

To determine the age of the SNR, the phase of evolution becomes important. The remnant was previously mentioned to be entering the early stages of the Sedov-Taylor phase (or just Sedov phase) of evolution. To enter the Sedov phase, the swept-up mass (M_{sw}) must exceed the ejecta mass (M_{ej}). With the assumption of a uniform ambient medium, the swept-up mass from the full SNR fitted data is estimated as $M_{sw} = 1.4 m_p n_0 \times (4/3 \pi R_s^3 f) = 9_{-2}^{+3} f^{1/2} D_{3.1}^{5/2} M_\odot$ which is a small value consistent with an early Sedov evolutionary stage.

A lower estimate of the age can be inferred by assuming the SNR is still in the free expansion phase using the calculation $t = v_s/R_s$ where t is the age, v_s is the shock velocity, and R_s is the radius of the SNR (see Section 1.3.5). Using the typical initial free expansion velocity of 5000 km s^{-1} appropriate for a core-collapse SNR (Reynolds, 2008), we estimate a free expansion age of $880 D_{3.1} \text{ yr}$. If the SNR is just entering the Sedov phase, an upper limit for the age of the remnant is given by $t_{SNR} = 0.4R_s/v_s$, for a blast wave expansion in the Sedov phase as explained in Section 1.3.3. The shock velocity, v_s , was measured as 1100 km s^{-1} from the optical study of Carter et al. (1997) such that an estimated maximum age is determined to be $t_{SNR} = 1.6 D_{3.1} \text{ kyr}$. However, the shock velocity can also be derived as explained in Section 1.3.1 where Equation 1.9 can be rearranged to give the shock velocity from the shock temperature, T_s , such that $v_s = (16k_B T_s / 3\mu m_h)^{1/2}$, where $\mu = 0.604$ is the mean mass per free particle for a fully ionized plasma and $k_B = 1.38 \times 10^{-16} \text{ erg K}^{-1}$ is the Boltzmann's constant. Normally, the model component with abundances at solar values is considered the blast wave component, however in the case of RCW 103 this is not as clear cut a distinction. What is clear is that the temperature for the blast wave can vary from soft to hard, allowing for a range of temperatures that can be attributed to the blast wave. From Section 5.3 the full SNR was fit with a VPSHOCK+VPSHOCK model with variable abundances in the hard component and a VAPEC+VPSHOCK model with variable abundances in the soft component. The fitted data is tabulated in Table 5.1 and the derived X-ray properties from these 2 models, assuming ejecta in the hard component for the VPSHOCK+VPSHOCK fit and ejecta in the soft component for the VAPEC+VPSHOCK, is found in Table 6.2. For the VPSHOCK+VPSHOCK full SNR fit, the soft component had abundances at solar which indicates a blast wave temperature of

$kT_s = 0.268^{+0.007}_{-0.005}$ keV and infers a blast wave velocity estimated at 480^{+6}_{-4} km s⁻¹ and an upper age limit of $3.71^{+0.05}_{-0.04} D_{3.1}$ kyr. For the VAPEC+VPSHOCK full SNR fit, the hard component had abundances at solar which indicates a blast wave temperature of $kT_h = 0.590^{+0.03}_{-0.007}$ keV and infers a blast wave velocity estimated at 710^{+13}_{-10} km s⁻¹ and an upper age limit of $2.7^{+0.05}_{-}$ $D_{3.1}$ kyr. Now, these velocities are clearly smaller than the velocity of 1100 km s⁻¹ from Carter et al., which results in a larger age for the remnant. This discrepancy may be due to the incomplete equilibration at the shock which would lead to a higher shock velocity than is presented, yielding a younger age (See Section 1.5.3). SNR studies indicate that SN shocks at such high velocities are far from electron and ion temperature equilibration (Ghavamian et al., 2007), suggesting that RCW 103 is younger than the presented age. Regardless, previous age estimates from studies at other wavelengths give results between 2000 – 4000 yrs (McDonnell et al. 2008; Paron et al. 2006; Andersen et al. 2011; Oliva et al. 1999; Frail et al. 1996) which puts our upper limit estimates within this range.

Based on the Sedov blast wave model in which a supernova with an explosion energy, E_* , expands into the surrounding ISM of uniform density n_0 , we can estimate the SNR explosion energy as $E_* = (1/2.02)R_s^5 m_n n_0 t_{SNR}^{-2} = 3.7 \times 10^{49} f_s^{-1/2} D_{3.1}^{5/2}$ erg and $E_* = 4.3^{+0.2}_{-0.1} \times 10^{49} f_s^{-1/2} D_{3.1}^{5/2}$ erg from age calculations of the global SNR fits, VPSHOCK+VPSHOCK and VAPEC+VPSHOCK respectively, where $m_n = 1.4m_p$ is the mean mass of the nuclei and m_p is the mass of the proton (see Section 1.3.3 for derivation). These values are much lower than the canonical value of 10^{51} erg but are likely due to an under-estimated shock velocity. Recent studies indicate that in young SNRs where the plasma is in non-ionization equilibrium, the electron temperature, the temperature we measure from the model fits to X-ray spectra, can

be a lot smaller than the ion temperature (see e.g., Ghavamian et al. 2007), the temperature that should be used for the energetics of the system, leading to an under estimate of the shock velocity and thus explosion energy. Therefore, these explosion energies are low due to the age value being quite high and so using the age, $t_{SNR} = 1.6D_{3.1}$ kyr, as derived from the Carter et al. velocity of 1100 km s^{-1} the explosion energy is $E = 2.9 \times 10^{50} f_s^{-1/2} D_{3.1}^{5/2} \text{ erg}$ which is within the range of inferred values for SNRs (e.g., Kumar et al. 2014; Kumar et al. 2012).

6.4 Comparison to Other Studies

Another *CHANDRA* study on RCW 103 has been recently released on the arXiv, at the time of writing this thesis by Frank et al. (2015) using *CHANDRA* data. In the following we compare our studies. Firstly, the focus of the Frank et al. paper is on the progenitor which they determined had a mass of $18 - 20M_{\odot}$. This work, in contrast, is the first complete, detailed study of the *full* SNR aimed at determining the explosion and SNR properties namely the explosion energy, ambient density, age and distance as well as the variations of spectral properties across the entire SNR. There are 4 major points of interest differentiating the two works: 1) the focus of the individual studies as already expressed, 2) the region selection, 3) the background subtraction, and 4) the strong assumptions made by Frank et al. on the CSM abundances.

The Frank et al. paper looks at 27 small, specially selected regions based on their line emission study whereas in this study, a total of 43 regions were selected for a complete, detailed study of the entire SNR. As a consequence of smaller regions, Frank et al. only required single component VPSHOCK models for all their selected regions. This the-

sis work in contrast, had larger, higher count regions that required two-component (VP-SHOCK+VPSHOCK and VPSHOCK+VAPEC) models. They also restricted their energy band from 0.5–3.0 keV which would allow for an easier fit for a one-component model whereas this paper constrained spectra in a wider energy band of 0.5–5.0 keV. Furthermore, all but 1 of Frank et al.’s regions would fall within the hard component range of temperatures and ionization timescales as this thesis, and had almost no detection of the soft component as expressed in this work. They also had no detection of enhanced ejecta above solar values whereas this thesis found evidence of ejecta from the hard component of the VP-SHOCK+VPSHOCK models. Background subtraction is a crucial part of spectroscopy, especially as to minimize the contamination by the Galactic ridge emission as well as nearby source emission. Frank et al. used a single 6’ background region north of the SNR for all their spectral analysis whereas this study did a more careful background subtraction. This work chose different backgrounds depending on which CCD the region was located, chose a background region close to the region selected to reduce contamination by the Galactic emission, and chose a background region size in similar size to the selected region. This thesis work also tested different background regions for any variation in the results due to potential background contaminations. Finally, for a progenitor study, the presence of enhanced ejecta is essential for determining the mass of the progenitor. The Frank et al. group attempted to disentangle the CSM from the ejecta, a difficult task as also seen in this paper. Frank et al., with no two-component models, had argued that specific regions with the lowest abundance yields are representative of circumstellar regions at roughly 0.5 (setting this value to solar) and that anything greater than 0.5 was evidence of ejecta. This is a strong assumption for the progenitor mass estimates that relies on these specific regions acting as the baseline for

differentiating CSM from ejecta.

Comparing some of the Frank et al. results to this paper shows good agreement in variation of the column density, N_H , across the SNR with lowest in the southwest and highest in the north west with their values being slightly. Their temperature and ionization timescales match up well to the hard component values found in this paper, with average values of 0.60 keV and $(1-15) \times 10^{11} \text{ cm}^{-3} \text{ s}$ respectively. Frank et al. did report post-shock electron densities, that had their highest values in the southwest lobed region, similar to the results of this paper, with the other regions moderately lower. Finally, Frank et al. found their CSM values are in equilibrium, which matches the conclusion of our soft component in equilibrium. This could also strengthen the argument that the soft component of the VPSHOCK+VPSHOCK fits from this work primarily describes the blast wave and has reached ionization equilibrium.

Table 6.1. Derived X-ray Properties of SNR RCW 103

Region	EM_h $\times 10^{56} D_{3.1}^2 \text{ cm}^{-3}$	n_{eh} $f_h^{-1/2} D_{3.1}^{-1/2} \text{ cm}^{-3}$	EM_s $\times 10^{57} D_{3.1}^2 \text{ cm}^{-3}$	n_{es} $f_s^{-1/2} D_{3.1}^{-1/2} \text{ cm}^{-3}$	n_{0s} $f_s^{-1/2} D_{3.1}^{-1/2} \text{ cm}^{-3}$
1	$5.2^{+0.9}_{-1.3}$	$1.9^{+0.2}_{-0.2}$	$2.7^{+0.7}_{-0.4}$	$4.4^{+0.5}_{-0.3}$	$1.1^{+0.1}_{-0.08}$
2	$9.5^{+1.3}_{-2.3}$	$2.9^{+0.2}_{-0.3}$	$4.9^{+0.9}_{-0.6}$	$6.6^{+0.6}_{-0.4}$	$1.6^{+0.1}_{-0.1}$
3	$8.1^{+0.9}_{-2.1}$	$3.1^{+0.2}_{-0.4}$	$3.8^{+0.9}_{-0.5}$	$6.7^{+0.8}_{-0.5}$	$1.7^{+0.2}_{-0.1}$
4	$10.8^{+2.2}_{-10.0}$	$3.4^{+0.3}_{-1.5}$	$4.8^{+0.8}_{-0.8}$	$7.1^{+0.6}_{-0.6}$	$1.8^{+0.1}_{-0.1}$
5	$1.6^{+0.7}_{-0.8}$	$1.6^{+0.3}_{-0.4}$	$1.2^{+0.4}_{-0.3}$	$4.1^{+0.6}_{-0.6}$	$1.0^{+0.2}_{-0.1}$
6	$2.0^{+1.1}_{-1.0}$	$1.4^{+0.4}_{-0.4}$	$2.3^{+2.7}_{-1.2}$	$4.8^{+2.8}_{-1.2}$	$1.2^{+0.7}_{-0.3}$
7	...	...	$14^{+0.4}_{-0.7}$	$2.9^{+0.4}_{-0.7}$	$0.71^{+0.09}_{-0.3}$
8	$2.2^{+0.8}_{-0.4}$	$1.5^{+0.06}_{-0.1}$	$2.0^{+1.4}_{-3.5}$	$4.5^{+1.6}_{-0.4}$	$1.1^{+0.4}_{-0.1}$
9	$0.54^{+0.01}_{-0.02}$	$0.86^{+0.01}_{-0.02}$	...	...	...
10	$0.66^{+0.44}_{-0.24}$	$1.3^{+0.3}_{-0.2}$	...	...	...
11	$1.2^{+0.1}_{-0.1}$	$1.4^{+0.08}_{-0.1}$	...	...	...
12	...	...	...	...	...
13	$2.2^{+1.0}_{-1.5}$	$2.1^{+0.5}_{-0.7}$	$0.80^{+0.3}_{-0.2}$	$3.5^{+0.8}_{-0.4}$	$0.88^{+0.2}_{-0.1}$
14	...	...	$1.5^{+0.3}_{-0.2}$	$4.8^{+1.0}_{-0.7}$	$1.2^{+0.3}_{-0.2}$
15	$2.8^{+1.1}_{-1.6}$	$1.8^{+0.4}_{-0.3}$	$1.9^{+0.8}_{-0.6}$	$6.0^{+1.3}_{-1.0}$	$1.5^{+0.3}_{-0.2}$
16	$2.4^{+0.8}_{-0.7}$	$1.9^{+0.3}_{-0.7}$	$6.8^{+0.5}_{-0.3}$	$3.7^{+1.2}_{-0.7}$	$0.91^{+0.33}_{-0.24}$
17	$1.1^{+0.3}_{-0.1}$	$1.4^{+0.2}_{-0.09}$	$1.9^{+0.4}_{-0.4}$	$4.7^{+0.5}_{-0.5}$	$1.2^{+0.1}_{-0.3}$
18	$4.7^{+1.1}_{-1.2}$	$1.8^{+0.2}_{-0.2}$	$2.9^{+1.2}_{-1.1}$	$6.5^{+1.3}_{-1.2}$	$1.6^{+0.3}_{-0.3}$
19	$11^{+6.3}_{-3.6}$	$2.4^{+0.7}_{-0.4}$	...	...	...
20	$2.9^{+1.6}_{-1.4}$	$1.7^{+0.5}_{-0.4}$	$2.0^{+0.8}_{-0.4}$	$3.7^{+0.7}_{-0.5}$	$0.93^{+0.2}_{-0.1}$
21	$7.4^{+2.2}_{-1.7}$	$1.8^{+0.3}_{-0.4}$	$5.0^{+1.6}_{-0.6}$	$5.2^{+0.8}_{-0.3}$	$1.3^{+0.2}_{-0.08}$
22	$3.0^{+0.5}_{-0.6}$	$2.1^{+0.2}_{-0.2}$	$0.96^{+0.85}_{-0.44}$	$3.0^{+1.3}_{-0.7}$	$0.76^{+0.3}_{-0.2}$
23	$5.6^{+0.7}_{-0.5}$	$1.7^{+0.2}_{-0.08}$	$4.4^{+1.5}_{-1.0}$	$4.5^{+0.8}_{-0.5}$	$1.1^{+0.2}_{-0.1}$
24	$3.7^{+1.0}_{-1.0}$	$1.8^{+0.2}_{-0.3}$	$1.5^{+0.4}_{-0.3}$	$4.7^{+0.6}_{-0.4}$	$1.2^{+0.2}_{-0.1}$
25	$6.6^{+1.6}_{-1.7}$	$2.3^{+0.3}_{-0.3}$	$4.3^{+0.6}_{-0.5}$	$4.7^{+0.3}_{-0.3}$	$1.18^{+0.08}_{-0.07}$
26	$4.3^{+1.6}_{-1.6}$	$2.3^{+0.1}_{-0.08}$	$1.2^{+0.5}_{-0.4}$	$3.2^{+0.7}_{-0.5}$	$0.79^{+0.2}_{-0.1}$
27	$10.2^{+3.6}_{-2.6}$	$3.8^{+0.7}_{-0.5}$	$3.0^{+0.7}_{-0.6}$	$4.8^{+0.6}_{-0.5}$	$1.2^{+0.1}_{-0.1}$
28	$7.1^{+1.8}_{-1.8}$	$4.9^{+0.6}_{-0.7}$	$6.5^{+2.2}_{-2.2}$	$9.0^{+1.5}_{-1.5}$	$2.3^{+0.4}_{-0.4}$
29	$2.1^{+1.0}_{-0.9}$	$1.4^{+0.3}_{-0.3}$	$5.4^{+1.5}_{-1.7}$	$8.6^{+1.2}_{-1.7}$	$2.2^{+0.3}_{-0.4}$
			$3.2^{+0.9}_{-0.7}$	$10.3^{+1.5}_{-1.1}$	$2.6^{+0.4}_{-0.3}$
			$2.2^{+1.3}_{-0.7}$	$4.4^{+1.3}_{-0.8}$	$1.1^{+0.3}_{-0.2}$

Table 6.1 (cont'd)

Region	EM_h $\times 10^{56} D_{3.1}^2 \text{ cm}^{-3}$	$n_{e,h}$ $f_h^{-1/2} D_{3.1}^{-1/2} \text{ cm}^{-3}$	EM_s $\times 10^{57} D_{3.1}^2 \text{ cm}^{-3}$	$n_{e,s}$ $f_s^{-1/2} D_{3.1}^{-1/2} \text{ cm}^{-3}$	$n_{0,s}$ $f_s^{-1/2} D_{3.1}^{-1/2} \text{ cm}^{-3}$
30	$4.6^{+0.9}_{-0.9}$	$2.3^{+0.2}_{-0.2}$	$2.2^{+0.5}_{-0.5}$	$4.9^{+0.5}_{-0.5}$	$1.2^{+0.1}_{-0.1}$
31	1.8^{+10}_{-11}	$1.7 (< 6.6)$	$1.2^{+0.3}_{-0.3}$	$4.3^{+0.5}_{-0.6}$	$1.1^{+0.1}_{-0.2}$
32	$4.5^{+1.1}_{-11}$	$2.2^{+0.3}_{-0.4}$	$2.0^{+1.1}_{-0.5}$	$4.7^{+1.3}_{-0.6}$	$1.2^{+0.3}_{-0.1}$
33	$0.80^{+0.9}_{-0.3}$	$0.93^{+0.51}_{-0.37}$	$1.9^{+0.8}_{-0.6}$	$4.4^{+1.0}_{-0.7}$	$1.1^{+0.2}_{-0.2}$
34	$1.3^{+0.9}_{-0.7}$	$1.3^{+0.4}_{-0.4}$	$1.0^{+0.5}_{-0.4}$	$3.7^{+0.9}_{-0.6}$	$0.92^{+0.22}_{-0.16}$
35	$1.2^{+0.6}_{-0.6}$	$1.2^{+0.3}_{-0.3}$	$1.2^{+0.6}_{-0.5}$	$3.7^{+0.9}_{-0.7}$	$0.92^{+0.23}_{-0.19}$
36	$1.2^{+0.5}_{-0.6}$	$1.3^{+0.3}_{-0.3}$	$1.4^{+0.9}_{-0.4}$	$4.5^{+1.3}_{-0.6}$	$1.1^{+0.3}_{-0.2}$
37	$1.4^{+0.3}_{-0.3}$	$2.0^{+0.2}_{-0.2}$	...	...	...
38	$1.6^{+0.7}_{-0.9}$	$1.8^{+0.4}_{-0.5}$	$0.61^{+0.08}_{-0.3}$	$3.4^{+0.2}_{-0.7}$	$0.90^{+0.06}_{-0.17}$
Bullet 1	...	...	0.016^{+}_{-}	1.3^{+}_{-}	0.32^{+}_{-}
Bullet 2	$0.069^{+0.080}_{-0.054}$	$0.77^{+0.4}_{-0.3}$	...	...	...
Bullet 3	$0.15^{+0.02}_{-0.02}$	$0.90^{+0.05}_{-0.06}$	...	...	...
Bullet 4	$0.67^{+0.22}_{-0.20}$	$2.63^{+0.4}_{-0.4}$	...	...	...
Bullet 5	$0.47^{+0.16}_{-0.17}$	$2.22^{+0.4}_{-0.4}$	...	...	...

Note. — The subscripts "s" and "h" refer to the soft and hard components respectively. EM : Emission measure, n_e : electron density, t_{sh} : shock age, n_0 : ambient density, and f : filling factor.

Table 6.2. Derived X-ray Properties of SNR RCW 103 From the Full SNR

VPSHOCK+VPSHOCK	VAPEC+VPSHOCK
Hard	Soft
$EM_h (\times 10^{58} D_{3.1}^2 \text{ cm}^{-3})$	$EM_s (\times 10^{59} D_{3.1}^2 \text{ cm}^{-3})$
$n_{eh} (f_h^{-1/2} D_{3.1}^{-1/2} \text{ cm}^{-3})$	$n_{es} (f_s^{-1/2} D_{3.1}^{-1/2} \text{ cm}^{-3})$
Shock Age, $t_{shh} (f_h^{1/2} D_{3.1}^{1/2} \text{ kyr})$	Shock Age, $t_{shs} (f_h^{1/2} D_{3.1}^{1/2} \text{ kyr})$
Soft	Hard
$EM_s (\times 10^{59} D_{3.1}^2 \text{ cm}^{-3})$	$EM_h (\times 10^{58} D_{3.1}^2 \text{ cm}^{-3})$
$n_{es} (f_s^{-1/2} D_{3.1}^{-1/2} \text{ cm}^{-3})$	$n_{eh} (f_h^{-1/2} D_{3.1}^{-1/2} \text{ cm}^{-3})$
Shock Age, $t_{shs} (f_h^{1/2} D_{3.1}^{1/2} \text{ kyr})$	Shock Age, $t_{shh} (f_h^{1/2} D_{3.1}^{1/2} \text{ kyr})$
$n_{0s} (f_s^{-1/2} D_{3.1}^{-1/2} \text{ cm}^{-3})$	$n_{0h} (f_h^{-1/2} D_{3.1}^{-1/2} \text{ cm}^{-3})$
Shock Temperature, $kT_s (\text{keV})$	Shock Temperature, $kT_h (\text{keV})$
Shock Velocity, $v_S (\text{km s}^{-1})$	Shock Velocity, $v_S (\text{km s}^{-1})$
Age, $t (D_{3.1} \text{ kyr})$	Age, $t (D_{3.1} \text{ kyr})$
Explosion Energy, $E_* (\times 10^{49} f_s^{-1/2} D_{3.1}^{5/2} \text{ erg})$	Explosion Energy, $E_* (\times 10^{49} f_h^{-1/2} D_{3.1}^{5/2} \text{ erg})$

Note. — The subscripts "s" and "h" refer to the soft and hard components respectively. EM : Emission measure, n_e : electron density, t_{sh} : shock age, n_0 : ambient density, and f : filling factor.

Chapter 7

Conclusion

This work presents the first dedicated, detailed and complete study of the SNR through a full imaging and spatially resolved X-ray spectroscopic study of RCW 103 performed using 97.75 ks of *CHANDRA* data to determine the intrinsic properties of the supernova explosion and the physical properties of the remnant. The regions selected for spectroscopy are found in Figure 5.1 with the spectral fit data summarized in Table 5.2 and the derived X-ray property data in Table 6.1. Below is a summary of this study.

1. The high-resolution X-ray images confirm a spherical morphology of $\sim 10'$ size with bright, clumpy regions in the south and north. The southern bright region is mostly soft in the east and hard in the south west with some white multi-band regions, where white implies broad band emission in the soft, medium and hard X-ray bands. The bright northern regions are not as soft, and contain more medium band emission with some multi-band white regions. The SNR interior has small scale clumpy features, with the north east side being more diffuse than the rest of the SNR and a peculiar "C-shaped" hole to the north east of the CCO. The north east region has the highest

column density, N_H , which would indicate that this region's emission, including the hole, is absorbed by some foreground material. The CCO object is completely hard with no radio counterpart. The radio contours follow the same morphology as the bright X-ray lobes in the south east and north west. The outermost radio shell appears to extend slightly beyond the X-ray emission which likely indicates the location of the forward shock. A recent study by West et al. (2016) examined all Galactic SNRs and compiled a list of SNRs with “bilateral” morphology in radio wavelengths. The study concluded that the morphology of the majority of the “bilateral” SNRs is influenced by the Galactic magnetic field. RCW 103 is one of those SNRs with a “bilateral” morphology that mostly matches the bright lobes seen in X-rays in the south-east and north-west.

2. The X-ray emission from the SNR is dominated by thermal emission from a hot plasma, adequately described by a plane-parallel shock, non-equilibrium ionization model (VPSHOCK). The spectra for the smaller or low count regions were fit by a one-component VPSHOCK model, whereas the higher count, larger regions required a two-component VPSHOCK+VPSHOCK or VPSHOCK+VAPEC model. The two-component models were best fit with a harder component ($kT \approx 0.60$ keV) characterized by a smaller ionization timescale, $n_e t < 10^{12} \text{ cm}^{-3} \text{ s}$, and slight enhancements in Mg, Si, S and Fe (=Ni). The softer component, $kT \approx 0.27$ keV, has a larger ionization timescale, $n_e t \geq 10^{12} \text{ cm}^{-3} \text{ s}$, and abundances held constant with solar. These ionization timescales indicate that the hard component is not quite at ionization equilibrium whereas the soft component is either at equilibrium or approaching it. The north east region had the highest N_H values at $\geq 1.0 \times 10^{22} \text{ cm}^{-2}$ than the rest of the SNR, with

the lowest values being found in the bright, southeast lobed region at $\leq 0.72 \times 10^{22}$ cm^{-2} . The thermal fits indicate the presence of slightly enhanced abundances in the hard component from Ne, Mg, Si, S and Fe (= Ni), hinting at the presence of ejecta heated by the reverse shock. The soft component abundances were well fitted at solar values and suggests it is dominated by emission from the forward shock.

3. A distance calculation was done using the fitted column density of the SNR. From an average N_H value given as $0.84 \times 10^{22} \text{ cm}^{-2}$, an estimate of the distance to the SNR was done using the extinction per unit distances in the direction of the SNR from contour diagrams done by Lucke (1978) to give a distance of 3.8 kpc and a range of 3.0–5.4 kpc. The most recent distance range from Reynoso et al. (2004) from an HI absorption studies gives a distance of 3.1 kpc.
4. The global SNR was poorly fit by the VSEDOV model ($\chi_v^2 \approx 15$), with an improvement in fit for a two-component VPSHOCK+VPSHOCK model, however still statistically poor ($\chi_v^2 = 5.62$). This indicates the presence of multi-temperature components within the SNR. We have also determined a lower age limit of the SNR at $880 D_{3.1} \text{ yr}$ for the free expansion phase (assuming an expansion velocity of 5000 km s^{-1}) and an upper limit at $3.7 D_{3.1} \text{ kyr}$ assuming a Sedov phase of evolution. The Sedov phase yields a shock velocity of $480\text{--}710 \text{ km s}^{-1}$ which is smaller than the velocity given from an optical study by Carter et al. (1997) at 1100 km s^{-1} . Discrepancy in the velocity values can be attributed to the SNR youth since young SNRs tend to display an electron temperature that is much lower than the ion temperature. The latter velocity estimate of 1100 km s^{-1} yields an explosion energy of $E = 2.9 \times 10^{50} f_h^{-1/2} D_{3.1}^{5/2} \text{ erg}$, and a swept-up mass of $M_{sw} = 9.0 D_{3.1}^{5/2} M_\odot$ erg under the assumption of an explosion

in a uniform ambient density.

Future work on RCW 103 includes a thorough progenitor study with updated nucleosynthesis models, being discussed with Chris Fryer (Los Alamos National Laboratory) which will have better conclusive results than the current generation of progenitor models, including a nucleosynthesis model for a binary system as suspected for the progenitor of RCW 103's CCO. Another *CHANDRA* data set on RCW 103 is to be released in 2016 which can provide further analysis as well as a good comparison for discovering any small scale changes between the data sets over time and for a potential direct measurement of the shock velocity. Finally, some new X-ray telescopes are being launched/approved in the future: *ASTRO-H* (2016) and *Athena* (≈ 2028). *ASTRO-H* is to be launched in 2016 featuring an unprecedented high energy resolution with its microcalorimeter and a broadband of observations over the energy range 0.3 to 600 keV (Takahashi et al., 2014). The excellent spectral resolution will allow a much better measurement of the SNR age and for probing the SN progenitor (Hughes et al., 2014). *ATHENA* is still in the mission study phase but promises high resolution spectroscopy from 0.3–10 keV combined with good spectral imaging from 0.2–40 keV over a wide field of view (Nandra et al., 2013).

Appendix A

CIE vs NEI

A set of images detailing how the ionization timescales manipulate the emission lines using a TBABS*VPSHOCK model set at temperature 0.6 keV and solar abundances. In the case of CIE, the brightest emission lines are O at 0.570 keV, Fe-L blend at 0.68-1.15 keV, Ne at 0.916 keV, Mg at 1.34 keV, Si at 1.86 keV, and S at 2.46 keV (McCray & Wang, 2012). See Section 1.5.3 for a description of CIE and NEI plasmas.

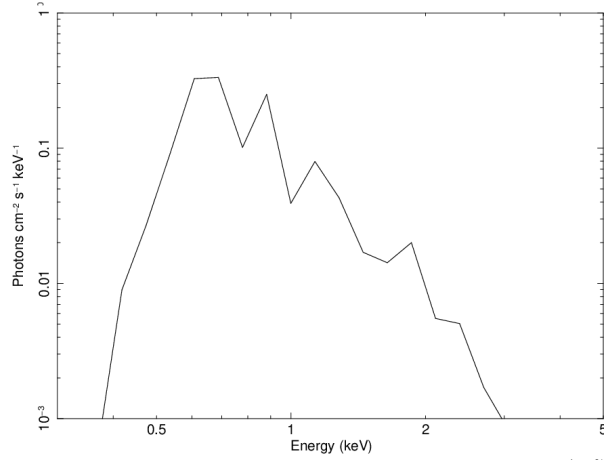
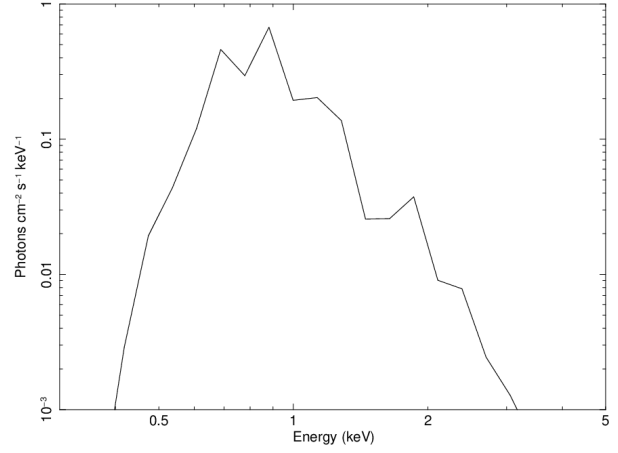
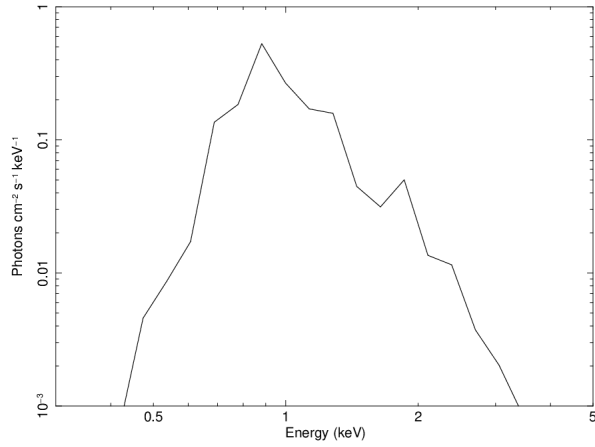
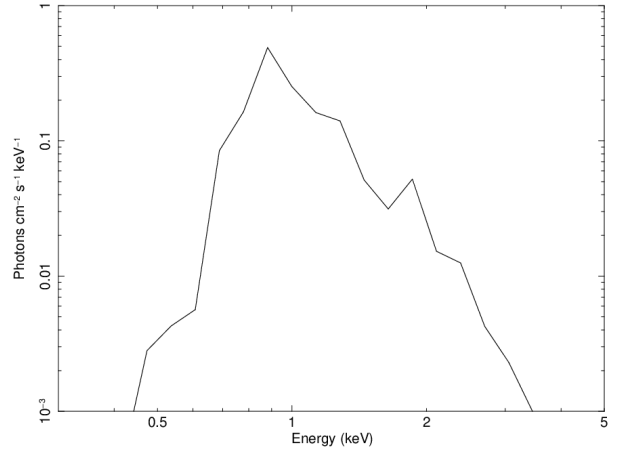
(a) $\tau = 1 \times 10^{10} \text{ cm}^{-3} \text{ s}$ (b) $\tau = 1 \times 10^{11} \text{ cm}^{-3} \text{ s}$ (c) $\tau = 1 \times 10^{12} \text{ cm}^{-3} \text{ s}$ (d) $\tau = 1 \times 10^{13} \text{ cm}^{-3} \text{ s}$

Figure A.1 TBABS*VPSHOCK models at 0.6 keV, N_H at $0.7 \times 10^{22} \text{ atoms cm}^{-2}$, and solar abundances with varying ionization timescales, τ . The other parameters did not change between images. A plasma is considered to be in CIE when $\tau > 1 \times 10^{12} \text{ cm}^{-3} \text{ s}$ (see Section 1.5.3).

Appendix B

XSPEC Models

A brief descriptions on each of the models can be found in Section 3.2.2.

Table B.1 TBABS Parameters

Parameter	units	Description
N_H	$\times 10^{22}$ atoms cm^{-2}	molecular hydrogen column density

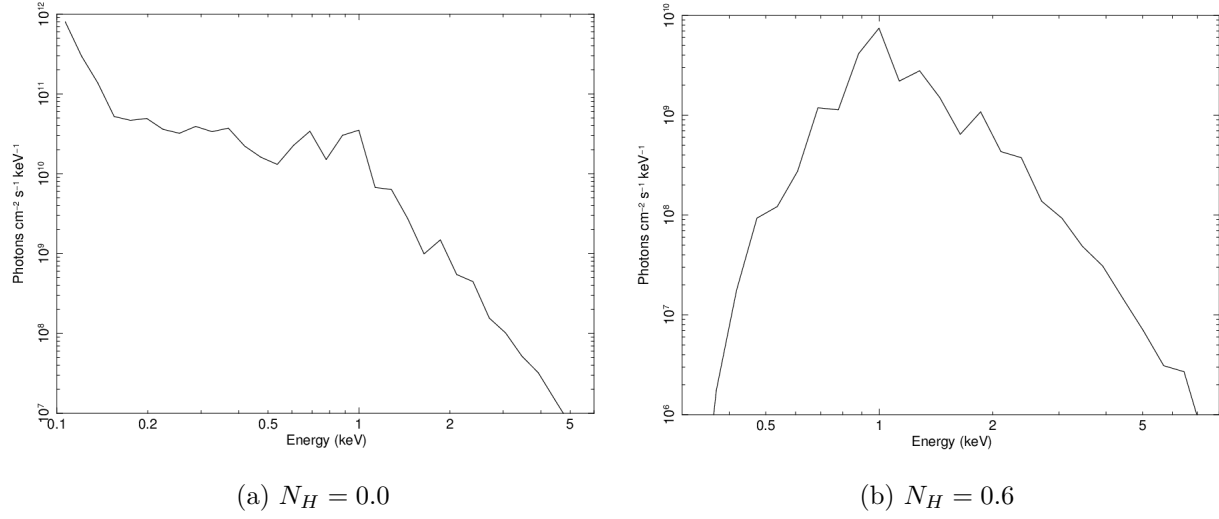


Figure B.1 TBABS*VPSHOCK models at 1.0 keV, solar abundances, and an ionization timescale, $\tau = 1 \times 10^{12} \text{ cm}^{-3} \text{ s}$ showing the change to the models depending on the N_H value. The other parameters did not change between images. (See Section 3.2.2).

Table B.2 VPSHOCK Parameters

Parameter	units	Description
kT	<i>keV</i>	constant electron temperature
C	-	carbon abundance ratio
N	-	nitrogen abundance ratio
O	-	oxygen abundance ratio
Ne	-	neon abundance ratio
Mg	-	magnesium abundance ratio
Si	-	silicon abundance ratio
S	-	sulphur abundance ratio
Ar	-	argon abundance ratio
Ca	-	calcium abundance ratio
Fe	-	iron abundance ratio
Ni	-	nickel abundance ratio
$\tau_l = n_e t$	$\text{cm}^{-3} \text{ s}$	lower limit ionization timescale
$\tau_u = n_e t$	$\text{cm}^{-3} \text{ s}$	upper limit ionization timescale
z	-	redshift
norm	-	$\frac{10^{-14}}{4\pi[D_A(1+z)]^2} \int n_e n_h dV$ ^(a)

^(a) where D_A is the angular diameter distance to the source in cm and n_e and n_H are the electron and hydrogen densities respectively in atoms per cm^3 . Note: The abundance ratios are relative to solar values, where solar is 1.

Table B.3 VNEI Parameters

Parameter	units	Description
kT	keV	constant electron temperature
C	-	carbon abundance ratio
N	-	nitrogen abundance ratio
O	-	oxygen abundance ratio
Ne	-	neon abundance ratio
Mg	-	magnesium abundance ratio
Si	-	silicon abundance ratio
S	-	sulphur abundance ratio
Ar	-	argon abundance ratio
Ca	-	calcium abundance ratio
Fe	-	iron abundance ratio
Ni	-	nickel abundance ratio
$\tau_l = n_e t$	$\text{cm}^{-3} \text{ s}$	lower limit ionization timescale
$\tau_u = n_e t$	$\text{cm}^{-3} \text{ s}$	upper limit ionization timescale
z	-	redshift
norm	-	$\frac{10^{-14}}{4\pi[D_A(1+z)]^2} \int n_e n_h dV$ ^(a)

^(a) where D_A is the angular diameter distance to the source in cm and n_e and n_H are the electron and hydrogen densities respectively in atoms per cm^3 . Note: The abundance ratios are relative to solar values, where solar is 1.

Table B.4 VAPEC/APEC Parameters

Parameter	units	Description
kT	keV	constant electron temperature
C	-	carbon abundance ratio
N	-	nitrogen abundance ratio
O	-	oxygen abundance ratio
Ne	-	neon abundance ratio
Mg	-	magnesium abundance ratio
Al	-	aluminum abundance ratio
Si	-	silicon abundance ratio
S	-	sulphur abundance ratio
Ar	-	argon abundance ratio
Ca	-	calcium abundance ratio
Fe	-	iron abundance ratio
Ni	-	nickel abundance ratio
z	-	redshift
norm	-	$\frac{10^{-14}}{4\pi[D_A(1+z)]^2} \int n_e n_h dV$ ^(a)

^(a) where D_A is the angular diameter distance to the source in cm and n_e and n_H are the electron and hydrogen densities respectively in atoms per cm³. Note: The abundance ratios are relative to solar values, where solar is 1. The parameters represented are for the VAPEC model, whereas the APEC model has a single abundance value instead of the listed C to Ni.

Table B.5 VSEDOV Parameters

Parameter	units	Description
kT_1	keV	mean shock temperature
kT_2	keV	electron temperature immediately behind the shock front
C	-	carbon abundance ratio
N	-	nitrogen abundance ratio
O	-	oxygen abundance ratio
Ne	-	neon abundance ratio
Mg	-	magnesium abundance ratio
Si	-	silicon abundance ratio
S	-	sulphur abundance ratio
Ar	-	argon abundance ratio
Ca	-	calcium abundance ratio
Fe	-	iron abundance ratio
Ni	-	nickel abundance ratio
$\tau_l = n_e t$	$s\ cm^{-3}$	ionization age of the remnant
z	-	redshift
norm	-	$\frac{10^{-14}}{4\pi[D_A(1+z)]^2} \int n_e n_h dV$ ^(a)

^(a) where D_A is the angular diameter distance to the source in cm and n_e and n_H are the electron and hydrogen densities respectively in atoms per cm^3 . Note: The abundance ratios are relative to solar values, where solar is 1.

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