Spectral Analysis of Bullet Fragments in RCW 103

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Abstract

We conduct spectral analysis on what appear to be explosion fragments outside of the forward shock boundary of SNR RCW 103. We compare the metal abundances of these fragments to the metal abundances of regions of shocked ISM material near the edge of the remnant, in order to determine whether the fragments are supernova ejecta, or heated clouds of shocked ISM. We detect overabundances of Silicon in all three fragments, which suggests that the fragments are ejecta.

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1. Introduction

Big Bang nucleosynthesis produced elements no heavier than Beryllium, and inside of stars, only elements up to iron are produced. The 64 remaining naturally occurring elements are fused in supernova explosions, and seeded throughout the galaxy via the interactions of the explosion's remnant with the interstellar medium (ISM). From a biological perspective, supernova remnants (SNRs) are important because life as we know it is dependent on elements originally found only inside these remnants. By acting as light-year-wide mixing grounds, supernova remnants make the galaxy a chemically diverse place, and one in which life can flourish.

Several other important galactic phenomena are the direct result of SNRs. Galactic cosmic rays, for example, are widely believed to originate in the shock fronts of supernova remnants. They themselves are of great scientific value because their incredibly high energies are orders of magnitude above those achieved by the most powerful man-made particle accelerators. In fact, due to the increasing challenges of producing ever more powerful accelerators, it is likely that over the next several decades, the field of particle physics may turn to cosmic rays as a way to probe ever smaller scales. Additionally, cosmic rays originating from supernova remnants ionize molecular clouds, affecting their chemical, thermal, and dynamical evolution[1], and thus both the local, and overall galactic environment. For example, the radiation and pressure imbalances introduced by a remnant in a star forming region, may accelerate or reduce star formation rates in the region by either contributing to the collapse of the gas, or dispersing it away. In either case, the chemical composition of the gas in the area will have been enriched by the SNR, and any resulting stars will exhibit different dynamics during their lifetimes because of it. The type of planetary system that forms, whether dominated by rocky planets, or super Jupiter, will likely also depend hugely on the abundances of elements in the cloud that collapses into the planetary disk.

Supernova remnants can also tell us about their progenitor stars, as each particular type of remnant is tied to a specific type supernova explosion, which themselves are bound to a certain type of star and stellar environment. For example, shell-like remnants lacking a central neutron star are the result of Type Ia supernova explosions, which always involve a white dwarf progenitor driven over the Chandrasekhar limit of 1.4 $M_\odot$ via the accretion of matter from a nearby partner or its merging with a fellow neutron star.

The study of supernova remnants offers glimpses into both the past and the future of the regions of space in which they are found; beginning only a decade ago, a generation of powerful X-ray space telescopes such as XMN-Newton and the Chandra X-Ray Observatory allowed for closer scrutiny of these marvelous objects. Many new interesting features have since been detected in SNRs, revealing their complexity, and raising up more questions than answers. One such feature is the presence of bullet like ejecta beyond the forward shockwave of certain supernova remnants. In this study, we believe to have identified at least three such fragments in supernova remnant RCW 103. In this paper, we offer a concise overview of the classification and dynamics behind supernova remnants, followed by a brief discussion of the history of the discovery of bullet-like ejecta. We conclude with the presentation of our findings, and a discussion of the mechanisms that may give rise to this phenomenon.

1.1 Classification of Supernova Remnants

Supernova remnants are roughly classified into four categories based on their morphologies: *Shell type SNRs*, *plerions*, *composite SNRs*, and *mixed morphology SNRs*.[2] [1]

Shell type SNRs are structurally the simplest of all supernova remnants. They are characterized by a limb brightened shell of shock heated plasma created as the blast wave produced by the explosion travels through the ISM. Limb brightening is a perceived increased in the intensity of the radiation coming from the edges of the remnant due to there being more material along the line of sight near the edges of the remnant, with respect to the center. This causes the remnant to take on a ring like appearance.

Plerions, also know as *pulsar wind nebulae* have the bulk of their emission radiating from near the center of the remnant, where a rapidly spinning neutron star is found. They are characterized by a highly energetic wind of relativistic electrons and positrons driven by the neutron star's rotation. This wind terminates in a shock where it meets the ISM, there the particles are accelerated to ultra-relativistic energies. By diffusing away from the shock, the particles create a nebula of electrons/positrons, which emits via synchrotron radiation (from radio to soft γ bands) and inverse Compton scattering (soft γ to TeV).

Composite SNRs are remnants which exhibit a combination of the previous two morphologies, having both a well-defined shell, and pulsar wind nebulae emission. These are mostly young (~20, 000 yr), energetic SNRs containing a *pulsar wind nebula* that is yet to blow away its shell. Both the shell and the inner pulsar wind nebula are well defined in the radio an X-ray bands.

Mixed morphology SNRs, also know as *thermal-composite SNRs* are remnants which display a shell in the radio band, but which exhibit thermal radiation from hot plasma (rather than being powered by a pulsar) near the center of the remnant in the X-ray band.

With developments in X-ray spectroscopy allowing for ever more detailed examinations of SNRs, new classifications based on properties such as enhanced abundances, or remnant origins, have begun to be adopted. Examples are *Oxygen-rich SNRs* and *Type Ia SNRs*. These may be more useful than morphological classifications of SNRs in certain niche studies.

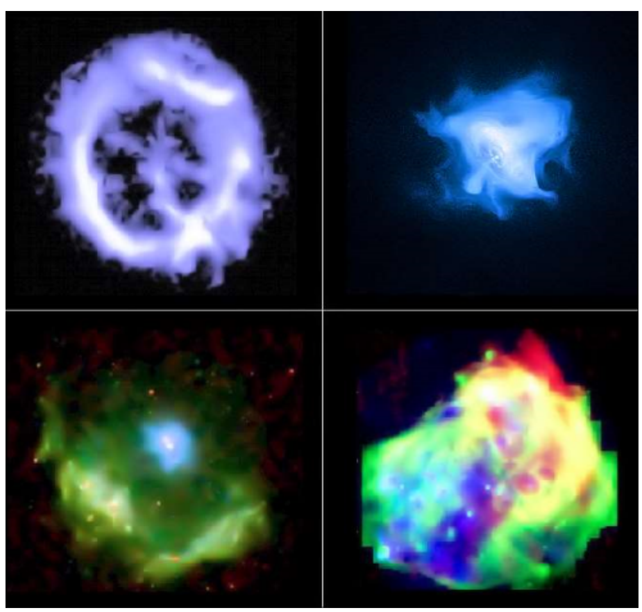

Fig. 1 Examples of SNR morphological types. From top left to bottom right: (**a**) (SNR) E0102 - 72, a shell-type supernova remnant in the Small Magellanic Cloud. (Image Credit: NASA/CXC/SAO). (**b**) The Crab Supernova Remnant, the most famous pulsar wind nebula. Notice the centralized emis-

sion, shocks fronts, and lack of a shell. (Image Credit: NASA/CXC/Penn State/G.Garmire et al). (**c**) (SNR) Kes 75, notice hard X-ray emission from both a shell, and a pulsar near the center of the remnant. (Image Credit: NASA/CXC/GSFC/F.P.Gavriil et al). (**d**) Thermal composite (SNR) 3C 391. This image is a composite of X-ray emission (blue), radio emission (red), and IR emission (green). (Image Credit: Su et al 2008).

1.2 Dynamics of Supernova Remnants

Over its lifetime, the dynamics dictating a supernova remnant's expansion, temperature, and radiation will change. Depending on the specific mechanism dominating the remnant's evolution, it can be said to be in one of the following three phases.[3] It should be noted that the transition from one phase to the next occurs over hundreds, even thousands of years. There is no well-defined cutoff point between one phase and the next.[2]

Free expansion phase: During this phase, ejecta from the explosion sweeps through the ISM, creating a shockwave of superheated plasma. This phase is characterized by nearly constant temperature and expansion velocity of the shock boundary. The phase comes to an end once the shockwave has swept up enough mass from the ISM to equal the mass of expanding ejecta. This phase can last up to the first two hundred years after the explosion, but its duration is highly dependent on the density of the ISM surrounding the progenitor star.

Sedov/Adiabatic phase: The material swept up by the shockwave begins to slow down its expansion. Deceleration of the shockwave happens as $\frac{1}{r^{3/2}}$, and cooling of swept up material and ejecta as $\frac{1}{r^3}$, where r is the radius away from the center of the remnant. Rayleigh-Taylor instabilities develop in the shock boundary, which causes the shocked ISM to mix with the ejecta. The mixing of material enhances the magnetic field inside the SNR shell. This phase usually lasts from 10, 000 to 20, 000 years.

Radiative phase: This phase is characterized by further cooling of the remnant's shell. Once the remnant has cooled to $\sim 10^6$K, recombination of electrons and heavier atoms occurs. Recombination cools the remnant, in a run away loop that increases the rate of subsequent recombinations, thus the remnant begins to cool exponentially. Eventually the remnant has cooled so much that the bulk of its emission radiates in the optical. All the while, the expansion velocity of the shockwave decreases as $\frac{1}{r^3}$, the shockwaves becomes less and less defined as time goes one. This phase can last for millions of years, as the remnant mixes with the ISM and eventually becomes unrecognizable.

1.3 Discovery of Bullet Ejecta Fragments

The discovery of bullet ejecta fragments was made public by Bernd Ashenbach in 1995.[4] They were detected in the Vela supernova remnant, which is ~11, 000 years old and lies 500pc away, in the Vela constellation. Ashenbach proposed that the X-ray signatures he saw were the result of the passage through the ISM of fragments formed by instabilities during the collapse and explosion of the progenitor star. An alternate hypothesis was that they could be clouds of ISM accelerated by the Vela SNR blast wave, but how clouds of such mass could have survived this encounter without dissipating sheds doubt on this idea. Subsequent spectral analysis confirmed the ejecta hypothesis by detecting significant overabundances of heavy elements in the fragments. Interestingly each fragment was found to contain very different ejecta overabundances (i.e. fragment A was Si-dominated, while fragments D and B were Ne, Mg, and O-dominated).[5]

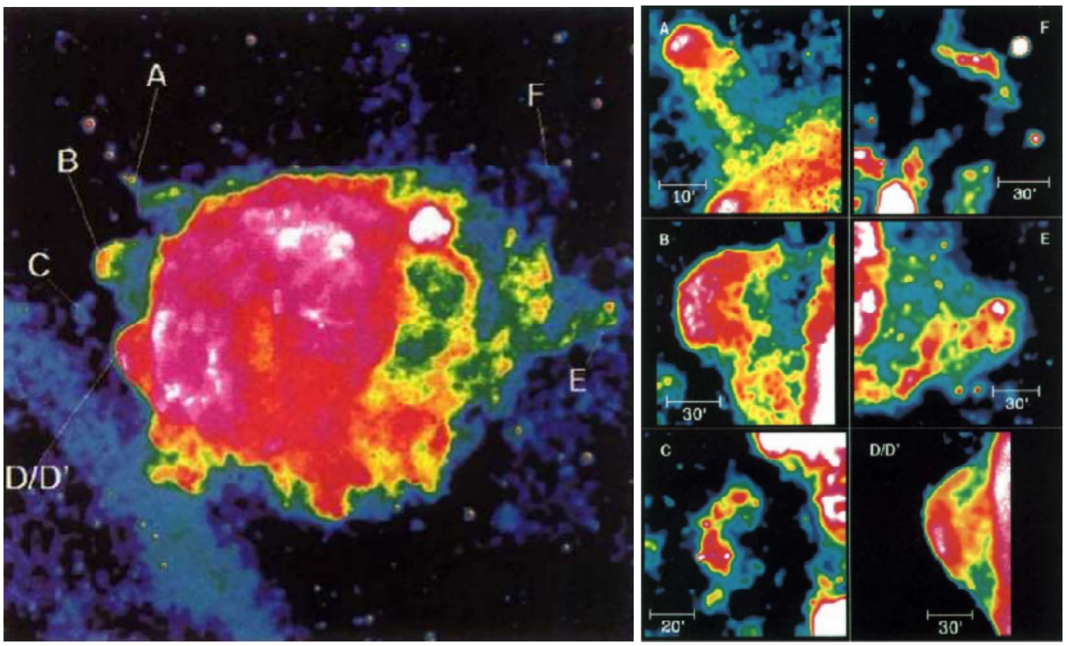

Fig. 2 The Vela supernova remnant, and its ejecta fragments.

Following the discovery and confirmation of the Vela findings, astronomers were on the look out for similar phenomena in other supernova remnants. Structures with similar morphology to fragment D in Vela were spotted in (SNR) N63A, and were initially thought to be the result of shock heating of the ISM by clumps of ejecta.[6] It was later found that the features were not dominated by ejecta, signaling that either they were the result of something other than the high-speed ejecta clump scenario, or that perhaps this remnant showed the final stages of such a scenario. The destruction of the fragments could have led to significant mixing between the ejecta and the ISM, making the detection of overabundances impossible. At any length, confirmation of the features as ejecta fragments could not be given.

We believe to have spotted such fragments in (SNR) RCW 103. They lie just beyond the shockwave boundary, to the south-west of the remnant, in what appears to be a high density region of the ISM. There are various other suspicious features elsewhere in the remnant, which might reveal themselves to also be ejecta bullets upon spectral analysis. For this study, we chose to focus on the three best well-defined features.

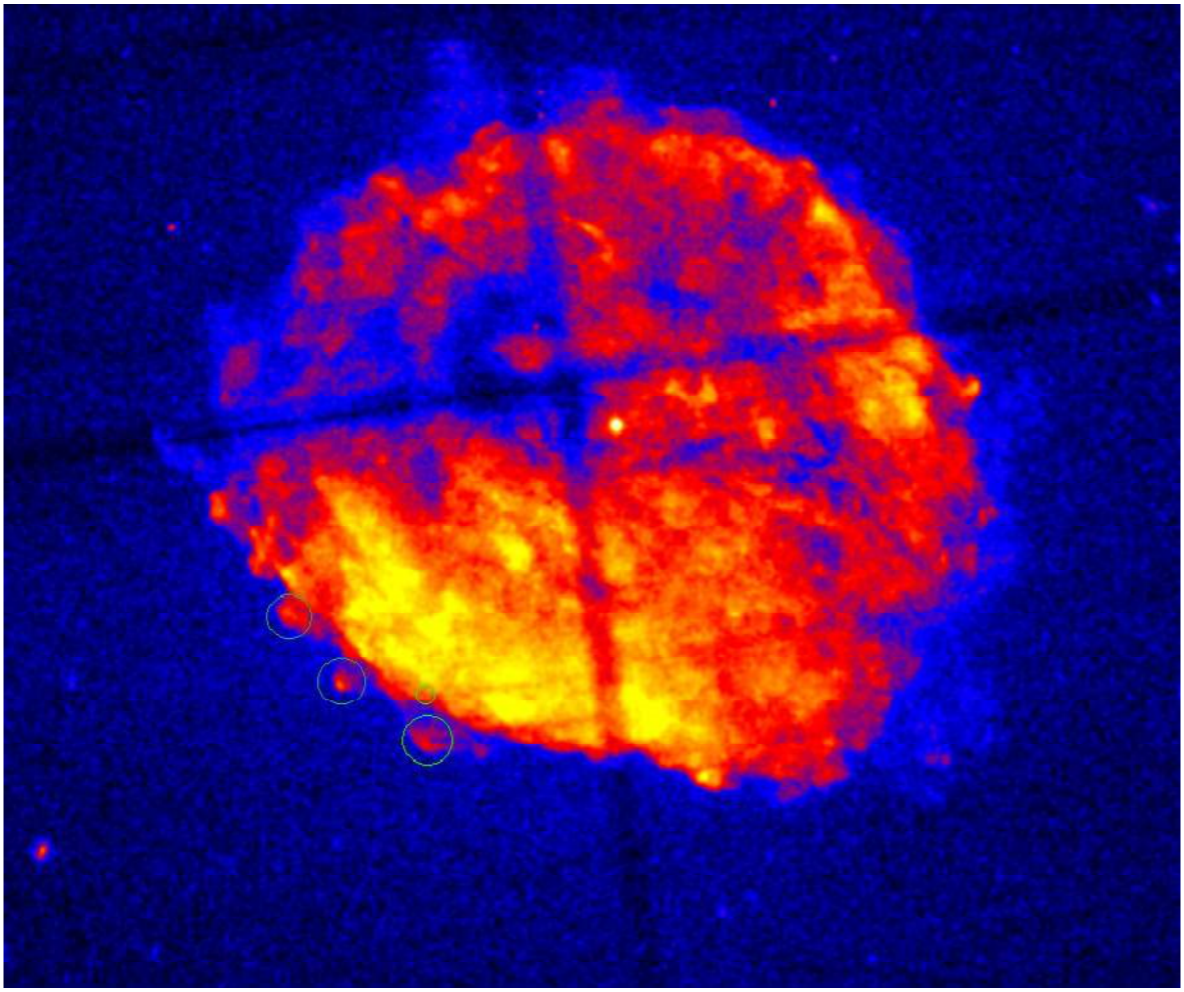

Fig. 3 X-ray image of RCW 103 displayed in ds9. The three large circles enclose the fragments we believe to be ejecta (lowermost circle, fragment 1, middle circle, fragment 2, uppermost circle, fragment 3), the smaller circle just above the lowest fragment, encloses a region of shocked ISM.

Confirmation of the presence of ejecta fragments beyond the shock boundary of RCW 103 will enhance our understanding of the remnant as a whole, as well a provide further insight into the phenomenon of ejecta bullets itself, which is currently not very well understood. Our data can be used as constraints in recent efforts to model this behavior using hydrodynamic models for supernova explosions. All current data relevant to ejecta shrapnel comes from observations of the fragments in the Vela SNR, due to their rarity, new sources such as ours are extremely valuable and necessary for further progress in the field.

2. Observations

(SNR) RCW 103 lies ~3100 pc away, in the Norma Constellation (RA 16h 17m 36.30s, Dec -51° 02' 24.40"). Morphologically, it is a *shell type remnant*. Near its center, it contains a compact X-ray source believed to be a neutron star left over from the collapse and subsequent explosion of the progenitor star. The remnant is young, approximately 2000 years old.[7]

The X-ray source at the center of the remnant exhibits unusually large and still unexplained variations in its emission over a period of years. Even more strange, X-ray radiation pulses from the source have a period of 6.67 hrs, extremely slow for a neutron star its age (average emission periods for young neutron stars range from 1.4 ms to 30s). This has led some to hypothesize that it may be a Thorne-Zytkow Object descendant.[8] Alternatively, others have suggested that magnetic interactions between the neutron star and an undetected low mass partner may be the cause of the anomaly. Gas from the low-mass star would in this case be accreting into the central neutron star, powering its X-ray emission. No connection has yet been drawn between the behavior of the compact X-ray source, and the focus of our study, the shrapnel like ejecta fragments in the lower left section of the remnant.

For our analysis, we used archival data from the Chandra Data Archive. Our event file is a 62.47 ks exposure of RCW 103, with observation id 11823, taken by the Chandra X-ray observatory on June 1st, 2010. The instrument used by Chandra was ACIS-I.

3. Data Analysis

To prepare and extract data from our event file, we used software packages CIAO and Sherpa. We selected four sources in the remnant, the three ejecta bullets, and a region of shocked ISM near the shockwave boundary in order to compare their chemical compositions via spectral analysis. We used ds9, an imaging and data visualization application, to manually select in the remnant the sources of interest plus a background region to correct for noise. After producing background subtracted spectra for each of the sources, we binned the counts in each spectrum in order to reduce the uncertainty of the value of number of counts per keV. For the fragments, the binning was done at 25 counts/bin. The shocked ISM source region contained significantly more counts than the fragments, so when calculating its individual spectrum, the binning used was 45 counts/bin. To apply a fit to the spectra, we drew from a pool of XSpec models. We found those models which assumed non-equilibrium ionization for the material to be the most successful fits. XSpec models nei, and pshock were the single two best models, and produced nearly identical results. In this study, we report our results using pshock.

When fitting, we assumed identical hydrogen column density (nH) values for each source, given their proximity to each other. We also began assuming identical temperatures and element abundances (frozen at solar). We then varied these values manually in order to obtain the best possible fit.

4. Results

Despite picking the longest usable observation in the Chandra archives, and binning our counts, the error bars obtained in our spectral plots, particularly around values of 1 keV, were large enough that some of finer elements of the spectra might have escaped detection. On average, our data was accurate up to two standard deviations, plus or minus one standard deviation. Future studies should be done using longer exposure times, or combining spectral data from several different observations in order to decrease uncertainty. No data could be obtained for energy values bellow .5 keV, due to column density absorption by the ISM between the remnant and the Earth.

We found that there was a significant over abundance of silicon in all three fragment regions as compared to the shocked ISM. Confirming that the fragments are in fact, ejecta. We detected practically zero silicon emission coming from the shocked ISM region analyzed, suggesting that mixing of ejecta and the ISM has yet to happen in this particular region. In both the shocked ISM and the ejecta fragment spectra, there were well defined Magnesium and Neon lines. In the ejecta fragments, emission was on average .02 Counts/sec/keV higher than in the shocked ISM, indicating a higher temperature in the fragments than in the shocked ISM.

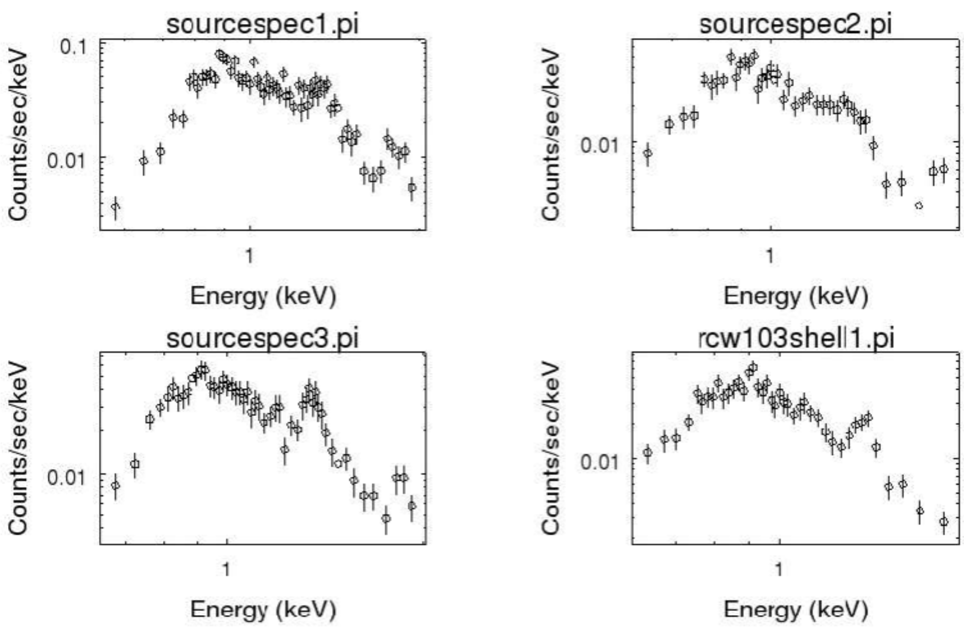

Fig. 4 From top left to bottom right: the spectra of fragments 1, 2, 3, and a region of shocked ISM. Notice the bump near the end of each of the first three spectra, at around 2 KeV, which is not present in the last plot. The bump corresponds to Silicon emission lines. Silicon is fused in the layer just outside the iron cores of super-massive stars, over abundances of this element in a region of a supernova remnant, confirms that region as ejecta.

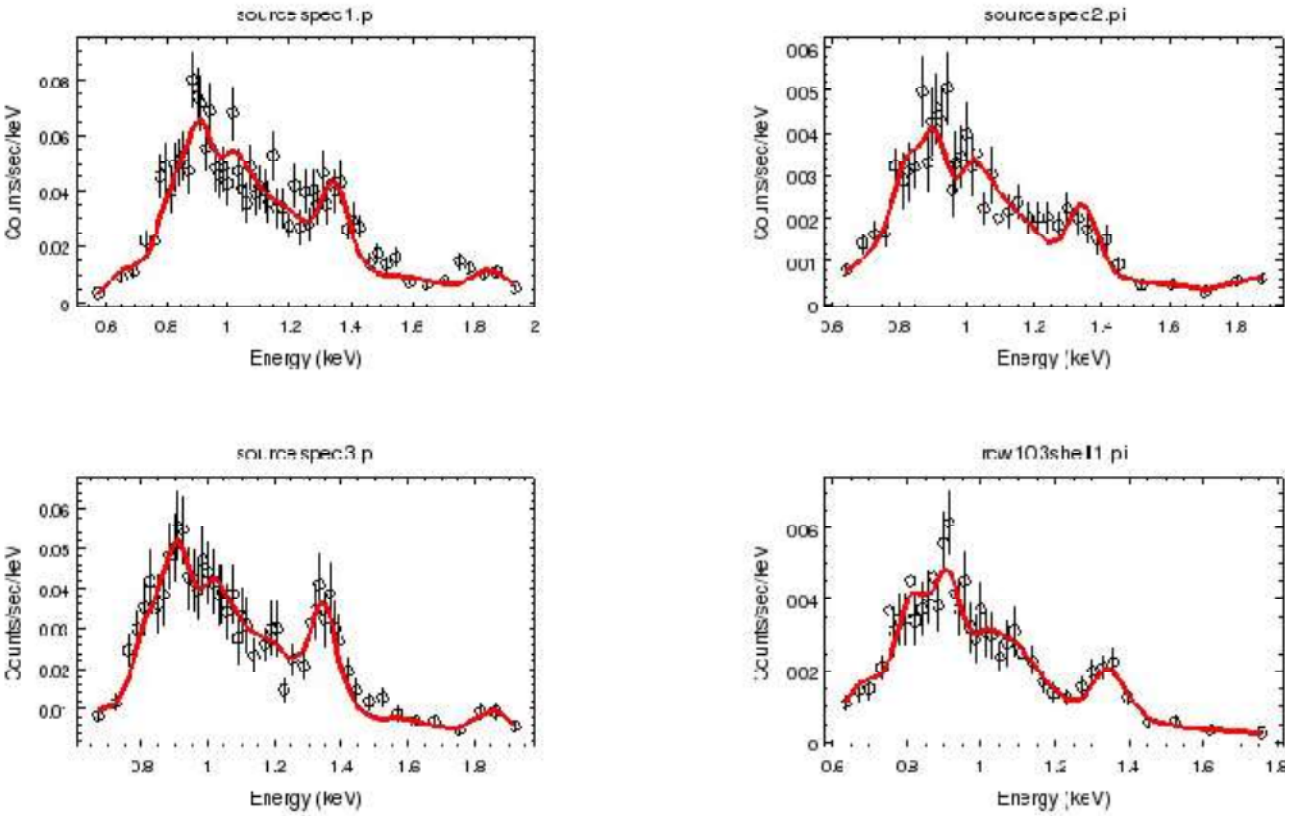

Fig. 5 Charts of the best fit lines produced by our models for each fragment, and the region of shocked ISM.

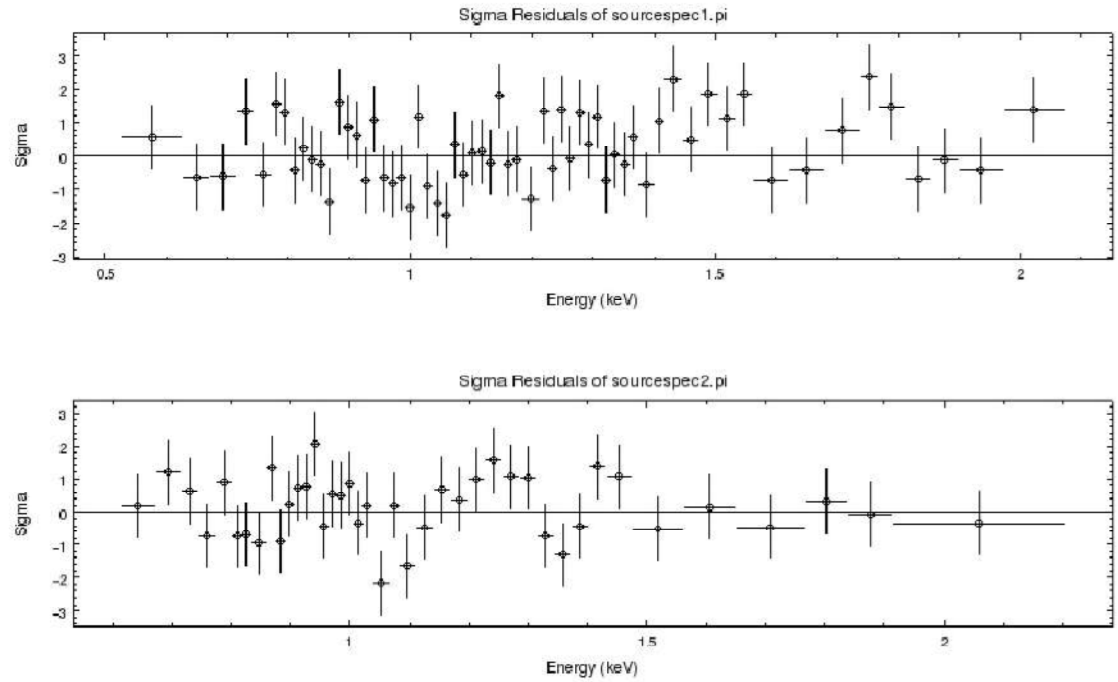

Fig 6. Sigma residuals for model fits. First plot corresponds to fragment 1, second plot, to fragment 2.

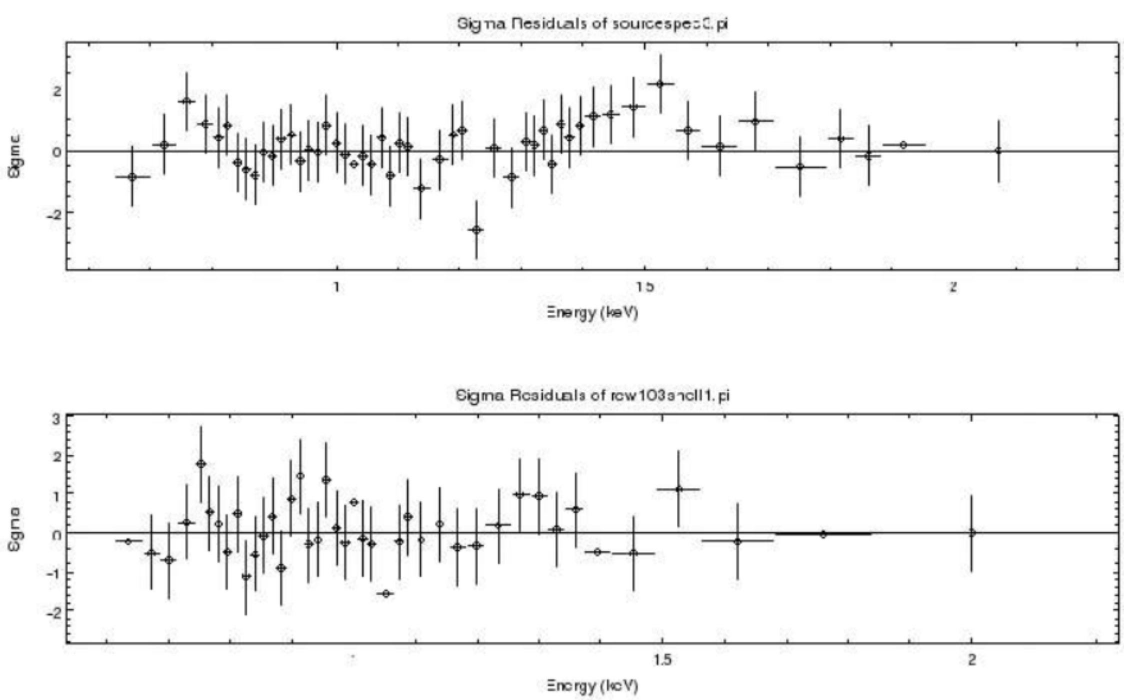

Fig 7. Sigma residuals for model fits. First plot corresponds to fragment 3, second plot, to shocked ISM.

Table 1. Modeled Properties of Observed Sources

Model Parameter	*Ejecta Fragment 1*	*Ejecta Fragment 2*	*Ejecta Fragment 3*	*Shocked ISM Region*
Temperature (kT)	.701	.526	.870	.443
Si Abundance $(S_\odot)$	1.170	1.413	1.000	.661
nH	.600	.600	.600	.600
Upper Ionization Timescale Limit (s cm^{-3})	1.495e+11	2.004e+11	8.448e+10	$9.762\, e + 10$
Probability [Q − value]	.0148	.574	.956	.988
Reduced Statistic	1.194	.940	.681	.548

Notice that model fits for the last two fits are significantly more accurate than the first two, this is because there were significantly more counts per energy level in the last two plots, than in the first two.

5. Discussion

Although rudimentary in nature, our study has managed to identify a valuable source of information. For over a decade, the Vela supernova remnant has been the only object to exhibit confirmed ejecta bullets. This has now changed. Future studies of the ejecta fragments in RCW 103 are sure to shed more light on this apparently rare phenomenon. Although longer-exposure observations will be required in order to gain a more in-depth understanding of how ejecta bullets are made and their evolution, we can still infer useful information from this study. First, the presence of Silicon in the fragments suggests that any instabilities that led to the formation of the bullets should have occurred near the center of the star. Future models for supernova explosions that produce ejecta bullets should account for this finding. Second, a recent hydrodynamic model (Miceli et al, 2013)[9] trying to account for the formation of ejecta bullets in Vela predicted that the shrapnel ejecta should reach the reverse shock approximately 2500 to 3000 years after the explosion. Given that we know RCW 103 to be approximately 2000 years old, and the ejecta here seems to have just moved past the forward shock wave, we can say that perhaps this model is early by a few hundred years. Nevertheless, the difference may be accounted for by the different conditions surrounding each supernova explosion. The area in RCW 103 where the fragments seem to have broken through appears to be a high density region in the ISM, as the forward shockwave appears to be held back compared to other areas of the remnant. There seems to be no such effect in Vela. Perhaps the ejecta fragments were able to move past the forward shock earlier in RCW 103 because the shock was not able to travel as far in the same amount of time as in Vela, due to it encountering this higher density region. Future comparisons of models for ejecta formation for Vela and RCW 103 will provide excellent opportunities to explore this phenomenon further.

We hope to pave the way into further studies of ejecta fragments in RCW 103 by conducting spectral analysis of several other regions of interest in the remnant. A protruding feature to the upper left of the remnant, diametrically opposed to where the confirmed ejecta fragments lie, may be an ejecta bullet itself. There may be other hidden bullets in this region, which are just now beginning to encounter the reverse shock, as predicted by Miceli et al. The ISM bounding the shockwave to the upper left, appears to be significantly less dense than that which bounds the lower right, where we found our bullets. Perhaps the shock has been able to expand more freely there, meaning any possible ejecta bullets are still trailing behind. The ejecta fragments in Vela seem to follow a reverse symmetry, with bullets flying out of the shockwave near the same locations on opposite side of the remnant. Perhaps the detection of such diametrically opposed fragments in RCW 103 may suggest that the instabilities that lead to the formation of ejecta shrapnel follow some kind of mirror symmetry. The discovery of ejecta fragments in RCW 103 is sure to lead to new developments in this new and exciting division of supernova research.

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References

[1] Most of the information for this section came from Jacco Vink's *Supernova remnants: the X-ray perspective,* section 2.

[2] The information for most of this section came from: http://imagine.gsfc.nasa.gov/docs/science/-know_l2/supernova_remnants.html/ (cited bellow)

1. Padovani, Marco and Galli, Daniele and Glassgold, Alfred E., *Cosmic-ray ionization of molecular clouds*. $JOURNAL$, 2009.
2. Vink, Jacco, *Supernova remnants: the X-ray perspective*. Astron.Astrophys.Rev., 2012.
3. The Imagine Team, Goddard Space Flight Center @http://imagine.gsfc.nasa.gov/docs/science/know_l2/supernova_remnants.html/, *Supernova Remnants*. $JOURNAL$, 2011.
4. Bernd, Aschenbach, *Discovery of explosion fragments outside the Vela supernova remnant*. Nature, 1995.
5. T.J Gaetz, *X-ray Observations of the Vela SNR Ejecta Fragments @http://lbb.gsfc.nasa.gov/*. $JOURNAL$, 2008.
6. Warren, Jessica S. and Hughes, John P. and Slane, Patrick O., *Revealing new physical structures in the supernova remnant N63A through Chandra imaging spectroscopy*. Astrophys.J., 2003.
7. $AUTHOR$, *RCW 103: A Star with a Mystery Partner? @http://chandra.harvard.edu/*. $JOURNAL$, 2012.
8. Liu, X.W. and Xu, R.X. and Qiao, G.J. and Han, J.L. and Han, Z.W. and others, *The extremely long period X-ray source in a young supernova remnant: a Thorne-Zytkow Object descendant?*. $JOURNAL$, 2012.
9. Miceli, M. and Orlando, S. and Reale, F. and Bocchino, F. and Peres, G., *Hydrodynamic modelling of ejecta shrapnel in the Vela supernova remnant*. $JOURNAL$, 2013.