X and γ-ray studies of Cas A: Exposing Core Collapse to the Core

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Abstract

In this review of X-ray and gamma-ray observations of Cas A, evidence is discussed that Cas A was a Type Ib supernova of a Wolf-Rayet star with a main sequence mass between 22–25 $M_{\odot}$, that exploded after stellar wind loss had reduced its mass to $\sim$ 6 $M_{\odot}$. The observed kinematics and the high ^{44}Ti yield indicate that the supernova explosion was probably assymetric, with a kinetic energy of $\sim 2 \times 10^{51}$ erg.

Key words: Supernova remnants, Supernovae, Nucleosynthesis
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1 Introduction

Cas A is the youngest known, and one of the brightest supernova remnants (SNRs). It is therefore, arguably, the best galactic SNR to study the fresh products of explosive nucleosynthesis.

The aim of this review is to discuss the observed properties in order to put the detection of ^{44}Ti emission from Cas A into the more general context of observed nucleosynthesis products, inferred explosion energy and progenitor type. This means I will neglect the equally fascinating topic of cosmic ray acceleration by Cas A's blastwave (e.g. Vink, 2003).

Cas A, being the brightest radio source in the sky, was first discovered in the radio (Ryle & Smith, 1948). Its distance, based on combining Doppler shifts and proper motions, is $3.4^{+0.3}_{-0.1}$ kpc (Reed et al., 1995), at which distance the outer radius of

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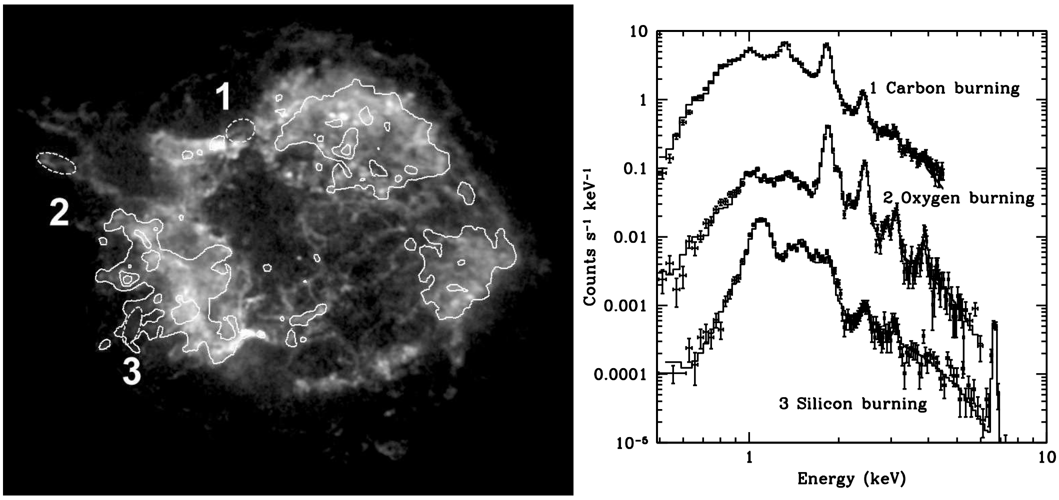

Fig. 1. Left: *Chandra*(ACIS-S3) Si-K image with Fe-K contours overlayed. The ellipses and labels correspond to the extraction regions for the spectra in the right hand figure. The spectra are labeled according to their dominant nucleosynthesis products. Note that spectrum no. 3 shows both dominant Fe-L ($\sim$1 keV) and Fe-K (6.7 keV) emission.

2.55′ corresponds to 2.55 pc. The proper motion of optical knots indicate an explosion date around AD 1671 (Thorstensen et al., 2001). This is very close to a putative observation of the supernova by Flamsteed (Ashworth, 1980). However, Stephenson & Green (2002) argue that the spurious star in Flamsteed's catalog, which he observed in AD 1680 and is about 10′ away from the position of Cas A, is not the supernova, but is best explained by assuming that he mixed up the relative positions of two different stars.

The optical emission consists of fast moving knots, characterized by velocities ranging from $\sim 4000\,\mathrm{km\,s^{-1}}$ up to $\sim 15000\,\mathrm{km\,s^{-1}}$ and nitrogen-rich, slow moving knots with typical velocities of $\sim$ 150 $\mathrm{km\,s^{-1}}$ (Kamper & van den Bergh, 1976). The fast moving knots are hydrogen deficient, and dominated by forbidden O and S emission (e.g. Fesen et al., 2001). The lack of hydrogen-rich ejecta [3] suggests that Cas A was a Type Ib SN; the result of the core-collapse of a Wolf-Rayet (WR) star (see e.g. Woosley et al., 1993).

2 Spatial abundance variations

X-ray studies of SNRs have the advantage that most of the shocked ejecta emit X-rays, whereas the optical emitting knots constitute only a small fraction of the ejecta. Moreover, the 0.5-7 keV band covers line emission from all alpha elements between O and Fe, mostly from H-like and He-like ions. This makes it relatively easy to compare the yields of the most abundant nucleosynthesis products. This is

[3] There are some exceptions, consisting of knots with traces of hydrogen and nitrogen, see Fesen & Becker (1991).

much harder to do in the optical, where the line emission is very different from one element to another, and where some elements (e.g. an abundant element like Si) are not observable at all. Due to the large absorption toward Cas A ($\sim 10^{22}$ cm^{-2}), C and N emission cannot be observed.

The SNR mass can be estimated from modeling the X-ray spectrum with a non-equilibrium ionization model. For Cas A good results are obtained with a two component model, for which the cooler plasma component is thought to arise from the shocked ejecta. The emission measure, together with the assumed or measured abundances, and an estimate for the volume, can be directly related to the mass of the plasma components (Vink et al., 1996). The lack of hydrogen in the fast moving optical knots suggests that the X-ray emitting ejecta are hydrogen deficient as well. This has an important implication for the ejecta mass, as ionized O, the most abundant element, is an efficient bremsstrahlung emitter, resulting in a relatively low ejecta mass estimate, despite the X-ray luminosity of $\sim 2 \times 10^{36}$ erg/s (Vink et al., 1996). Taking this into account, current ejecta mass estimates range from 2-4$M_\odot$ and an O mass of 1–3 $M_\odot$ (Vink et al., 1996; Willingale et al., 2002), with some uncertainty due to the uncertain volume filling fraction and temperature structure of the ejecta.

The recent advances in X-ray imaging spectroscopy have enabled a detailed study of spatial abundance variations (Fig. 1). *Chandra* and *XMM-Newton* show that the bright X-ray shell is very rich in oxygen burning products (Si, S, Ar, and Ca), with a tight correlation between the abundances of those elements (Willingale et al., 2002).

Remarkably, although Cas A is an oxygen-rich remnant, there is a lack of the carbon-burning products Ne and Mg (Table 1). The Ne/O and Mg/O ratio are almost an order of magnitude lower than the models of Woosley & Weaver (1995) (WW95), although a few regions show enhanced Ne and Mg emission (Fig. 1). This is in contrast to other O-rich SNRs like 1E0102.2-72192 and G292-1.8 (e.g. Rasmussen et al., 2001; Park et al., 2002) that show prominent Ne and Mg line emission. The lack of Ne is also apparent from optical observations (Fesen, 1990). The reason for this deficiency is not clear; it seems unlikely that most Ne and Mg is still unshocked, as the ubiquitous Si is formed closer to the core of the SN, but, as indicated below, the radial ejecta structure may be more complicated than usually assumed.

Even more remarkable is the fact that in the southeast Fe-rich material exists outside the Si-rich shell. The high Fe abundance clearly indicates that the knots are ejecta (Fig. 1 Hughes et al., 2000; Hwang & Laming, 2003), consisting of material from the explosive Si-burning shell, where it was synthesized as radio-active ^{56}Ni close to the collapsing SN core. The Fe knots must have penetrated the outer SN layers. In fact, most Fe-K emission is located outside a radius of 1.45′, ranging almost out to the blast wave at 2.55′, corresponding to average velocities of 4500 - 7800 km s^{-1}. Interestingly the Fe rich knots have an ionization parameter higher than the Si-rich ejecta ($n_{\rm e}t \sim 5 \times 10^{11}$ cm^{-3}s, Willingale et al., 2003; Hwang &

Table 1
Elemental mass ratios as determined by Vink et al. (1996, VKB96) and Willingale et al. (2002, W02), with comparisons to models by WW95 and WLW93 by Woosley et al. (1993).

	VKB96	W02	S12A	S22A	S30A	S30B	WLW93
Ne/O	0.022	0.026	0.140	0.046	0.119	0.100	0.109
Mg/O	0.009	0.006	0.053	0.026	0.074	0.071	0.025
Si/O	0.039	0.043	0.441	0.161	0.039	0.079	0.123
S/O	0.026	0.026	0.378	0.080	0.004	0.022	0.071
Ar/O	0.008	0.007	0.127	0.015	0.001	0.004	0.014
Ca/O	0.009	0.005	0.071	0.007	0.004	0.003	0.010
Fe/O	0.014	0.022	0.071	0.017	0.008	0.009	0.174

Laming, 2003) indicating that the Fe knots were among the first to be shocked. [4] Recently Hwang & Laming (2003) reported the discovery of a Fe-rich knot that seems almost devoid of Si. This suggests that at least this knot is a product of α-rich freeze out, which results in a lower Si to Fe ratio than explosive Si-burning (Arnett, 1996). This process is also the main source of radio-active ^{44}Ti. Interestingly, recent 2D simulations of core-collapse supernovae show that high velocity ^{56}Ni-rich clumps are formed, which are not slowed down in Type Ib explosions (Kifonidis et al., 2003).

3 The detection of ^{44}Ti

Alpha-rich freeze out occurs when, in the expanding Si-burning plasma, the density drops below the threshold for the triple-α reaction, and an excess of α-particles results in a relatively large build up of ^{44}Ti. Although, its yield is low compared to the ^{56}Ni, ^{44}Ti is an excellent explosion diagnostic, as it depends sensitively on the explosion energy and asymmetry, and the mass cut (Diehl & Timmes, 1998).

^{44}Ti decays into ^{44}Sc by electron capture with a decay time of 86 yr, which decays in 5.7 hr by beta decay into ^{44}Ca (Hashimoto et al., 2001, for the latest measurements). The decay is therefore long enough to hope to detect the associated γ-ray line emission from young SNRs at 68 keV and 78 keV (from excited ^{44}Sc) and 1157 keV (^{44}Ca). The detection of 1157 keV from Cas A (Iyudin et al., 1994) came nevertheless as a surprise, as the flux observed by *CGRO-COMPTEL*, $(7 \pm 1.7) \times 10^{-5}$ ph cm^{-2}s^{-1}, implied a much higher yield than predicted (WW95). However, additional observations, and finally a detection of the ^{44}Sc lines by *BeppoSAX*, indicate a lower flux of $(3 \pm 0.6) \times 10^{-5}$ ph cm^{-2}s^{-1}, implying a yield of $1.8 \times 10^{-4}\ M_{\odot}$ (Vink et al., 2001; Vink & Laming, 2003). This is still on the high side of the predicted yields, and is more consistent with models for supernovae with

[4] A plasma is in collisional ionization equilibrium when $n_{\rm e}t >\ 10^{12}$ cm^{-3}s. For most of the plasma in Cas A $n_{\rm e}t \sim 1 \times 10^{11}$ cm^{-3} (Willingale et al., 2002).

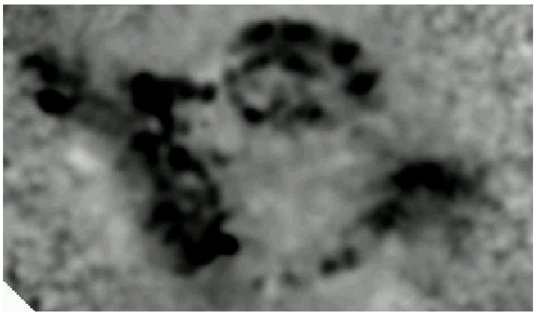

Fig. 2. Ratio map of *Chandra* Si-K and Mg-K images, suggesting the presence of a counter jet.

high explosion energies or asymmetries (Nagataki et al., 1998, WW95,). The ^{44}Ti yield for Cas A may also have been lower, if, in the course of its lifetime, a substantial fraction of ^{44}Ti was ionized beyond the Li-like state (Mochizuki et al., 1999). However, this effect depends sensitively on the ionization history and, even if substantial, is still more in agreement with a higher than expected yield (Mochizuki, 2001; Laming, 2001).

4 Cas A's dynamics

Asymmetric SN Type Ibc explosions have recently received a lot of attention, as they may be related to the highly collimated explosions of gamma-ray bursts. Cas A's high ^{44}Ti yield may be the result of either an asymmetric or a more energetic explosion. Observations support both possibilities. The optical morphology and Doppler shifts clearly show an asymmetric expansion (Reed et al., 1995; Lawrence et al., 1995), but the optically knots are dynamically not very significant, as they comprise only a small fraction of the total mass ($< 0.1\ M_\odot$ Willingale et al., 2003). Most of the shocked plasma is hot enough to be visible in X-rays. The X-ray emitting material is, therefore, from a dynamical point of view more important.

The first hints for an asymmetrical expansion of the hot plasma came from *Einstein* FPCS observations of Si and S lines (Markert et al., 1983), showing that the southeast has an overall redshift, whereas the northern part is blueshifted. The most comprehensive X-ray Doppler study is based on *XMM-Newton* data, showing that the north/southeast asymmetry is even more apparent for Fe-K emission, with Doppler velocities up to 2500 km s^{-1} in the North (Willingale et al., 2002). So, interestingly, Fe rich material is ahead of the Si rich material in "Doppler space" in the North, whereas in projection Fe is ahead of Si-rich material in the Southeast. This also indicates that there is no obvious symmetry to the Fe kinematics; there is no evidence for a Fe-rich jet, nor a well defined Fe-rich equatorial structure. The jet-like structure in the East is Si-rich (Fig. 1). There is no clear evidence for a counter jet, but mapping the ratio of Si-K and Mg-K emission does reveal a structure that hints at the presence of counter jet (Fig. 2). In fact the *Chandra* images show Si-rich knots outside the main shell that seem to have pierced through the denser material in the

West.

The rim of continuum emission surrounding Cas A is likely due to synchrotron emission associated with the blastwave (Gotthelf et al., 2001; Vink & Laming, 2003). Apart from near the jet region and the West, this rim is remarkably circular, much more so than the Si-emitting material. This is a clear hint that the observed asymmetries are predominantly due to an asymmetric explosion, as opposed to pre-existing structures in the circumstellar medium (CSM).

Note that the Doppler shifts are based on centroid fitting and are possibly affected by line of sight effects, so that actual velocities may be higher. Based on X-ray proper motions using *Einstein* and *ROSAT* Vink et al. (1998) inferred a blastwave velocity for Cas A of 5200 $\mathrm{km\,s^{-1}}$, a value that has recently been confirmed with *Chandra* (Delaney & Rudnick, 2003). Based on the Doppler velocities Willingale et al. (2003) estimated the explosion energy of Cas A to be 10^{51} erg. However, they ignored the high blastwave velocity. If that is taken into account, an explosion energy of 2×10^{51} erg can be inferred. Hydrodynamic modeling of the blast wave velocity and the blastwave and reverse shock radii also suggests 2×10^{51} erg (Laming & Hwang, 2003).

5 The progenitor's stellar wind

The presence of N-rich ejecta suggests that Cas A is sweeping up CSM from the wind of its progenitor. The swept-up mass is estimated to be 8 $M_\odot$ (Vink et al., 1996; Willingale et al., 2003). Such a high mass is supported by hydrodynamical calculations (Laming & Hwang, 2003; Chevalier & Oishi, 2003), and by the high ionization parameter ($n_{\rm e}t$) close to the shock front (Vink & Laming, 2003), which suggests an electron density of 30 $\mathrm{cm^{-3}}$, which translate into a pre-shock H density of 7.5 $\mathrm{cm^{-3}}$ or, if the medium is dominated by He, a He density of 3 $\mathrm{cm^{-3}}$. For a uniform wind profile, the density, ρ, relates to the mass loss rate, $\dot{M}$, radius, r, and wind velocity, v_w, as $\rho = \dot{M}/4\pi r^2 v_w$. Integration to $r = 2.55$ pc gives a swept up mass of $M = 2.5(\dot{M}/10^{-3} M_\odot yr^{-1})(v_w/1000\,\mathrm{km\,s^{-1}})^{-1}\,M_\odot$. This means that for a WR wind of typically 2000 $\mathrm{km\,s^{-1}}$, a mass loss rate of 6.4×10^{-3} $M_\odot$/yr is required, which is in conflict with the observed WR mass loss rates. It is, however, more consistent with the slower ($\sim 10 - 300$ $\mathrm{km\,s^{-1}}$) wind of a red super giant (RSG) or LBV star. This indicates that not too long for the explosion (at maximum 10^4 yr, the expansion time scale of the optical knots) the progenitor was still in an RSG/LBV phase, placing strong constraints on the main sequence mass of Cas A's progenitor (Garcia-Segura et al., 1996).

6 Possibility of enhanced positron escape

One of the important goals of the *INTEGRAL* mission is the galactic e^+e^- annihilation radiation (see Jean et al., 2003, for some first results). A dominant source for this emission is probably positrons that have escaped supernovae (e.g. Milne et al., 2001), where they are produced by the beta decay of ^{44}Sc and ^{56}Co. The escape fraction is of importance for the bolometric light curve of supernovae (Ruiz-Lapuente & Spruit, 1998).

Cas A will be observed by *INTEGRAL*, and apart from ^{44}Ti, it is interesting to look for e^+e^- annihilation radiation. The typical annihilation time scale is 10^5 yr. The estimated escape fraction for positrons produced by ^{56}Co decay is ~1% (Chan & Lingenfelter, 1993). Given the ^{44}Ti yield, this would mean a current annihilation line flux of $\sim 10^{-6}$ ph cm^{-2}s^{-1}, below the *INTEGRAL* sensitivity limits.

However, the conditions that have led to a high ^{44}Ti yield may also have favored a high positron escape fraction. Annihilation during the explosion involves the slowing down of the positrons, mainly through ionization losses (Chan & Lingenfelter, 1993). Alpha-rich freeze occurs if the plasma is expanding rapidly, but the rapid drop in density also decreases the positron loss and annihilation rate. Moreover, the ionization losses in the presence of He-rich plasma are decreased, due to the small He ionization cross-sections. Preliminary calculations show that these effects may increase the escape fraction to 10%, if most of the $\sim 0.07\ M_\odot$ of ^{56}Ni had initial velocities in excess of 5000 km s^{-1}. This would increase the expected line flux to $\sim 10^{-5}$ ph cm^{-2}s^{-1}. Unfortunately, the circumstances that lead to a large escape fraction, will result in a population of energetic positrons. The annihilation line may therefore be too much affected by line broadening to detect with *INTEGRAL*. Nevertheless, this mechanism may be important, as it potentially contributes to the galactic positron production (Milne et al., 2002).

7 Conclusion

Observational evidence suggests that Cas A was a Type Ib SN. The estimated O mass of 1-3 $M_\odot$ corresponds to a main sequence mass of 18-25$M_\odot$ (WW95). An additional mass constraint is that the progenitor was probably a WR star, which puts a lower limit on the main sequence mass of $22M_\odot$ (Massey et al., 2000). One should be careful with using the O mass, as WW95 also predict a higher than observed Ne and Mg yield. However, a relatively low mass WR star is supported by a large amount of swept up mass and the high density behind the blastwave, which suggests that the progenitor was only briefly in the WR phase.

The mass of the progenitor at the time of explosion is difficult to reconcile with current knowledge of WR stars. X-ray studies suggest an ejecta mass of less than $4M_\odot$, adding to that the mass of the compact object, for which the *Chandra* point source is an excellent candidate (Tananbaum, 1999), suggests a progenitor mass of

$\sim 6M_\odot$. The fact that we see nucleosynthesis products from near the core, indicates that most of the ejecta mass must have been shocked. This is at odds with current evolutionary models for massive stars with rotation, which suggest that WR star end their lives with about $12M_\odot$ left (Meynet & Maeder, 2003). Note that Type Ib SN ejecta estimates seem to agree with that of Cas A: 2–4.4$M_\odot$ (Hamuy, 2003).

An alternative scenario, which could explain the low ejecta mass, is binary mass transfer, but there is no evidence yet (e.g. in the form of a runaway star) that the progenitor was part of a binary system. However, the modeling of supernova explosions is an active field of research, which received a boost from the new found connection between Type Ibc supernovae and gamma-ray bursts. For some recent developments and discussions see for example Heger et al. (2003) and Kifonidis et al. (2003).

Cas A's high ^{44}Ti yield suggests a relatively explosive or an asymmetric SN event. The X-ray emission supports both possibilities, with an estimated explosion energy of 2×10^{51} erg and evidence for a Si-rich jets and fast moving "plumes" of Fe-rich plasma. A more compact progenitor can also cause a higher ^{44}Ti yield, as a lower ejecta mass results in less fall back on the stellar remnant.

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