THE DETECTION OF THE ^{44}Sc NUCLEAR DE-EXCITATION LINES AND HARD X-RAY EMISSION FROM CAS A

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We discuss the detection of ^{44}Sc (product of ^{44}Ti) in the supernova remnant Cas A with the *BeppoSAX*-PDS instrument, and elaborate on the nature of the hard X-ray continuum, which is not only important for correctly estimating the ^{44}Sc flux, but is interesting in its own right. We apply the lower hybrid wave electron acceleration model to the hard X-ray data and use upper limits on the cosmic ray injection spectrum to infer that $B > 2$ mG. We conclude with the prospects of observing nuclear decay lines and electron-positron annihilation in Cas A with *INTEGRAL*.

1 Introduction

Cas A is the brightest radio source, and one of the best studied supernova remnants. With its likely explosion date of AD 1680, it is also the youngest known galactic remnant.[1] Optical and X-ray spectroscopy strongly suggest that its progenitor was a massive star, probably a Wolf-Rayet star, which had lost most of its mass by the time it exploded.[2,3] The explosion was not recorded as a bright event, suggesting an underluminous supernova. Its radio brightness identifies Cas A as a source of cosmic rays, and its youth makes it one of the best remnants to study the explosive nucleosynthesis of massive stars.

In this paper we will relate to both topics, as the deep observation of Cas A with *BeppoSAX* discussed here resulted in the first detection of ^{44}Sc nuclear de-excitation emission, confirming the synthesis of a substantial amount ^{44}Ti by the explosion.[4] In addition the deep observation constrains the properties of the hard X-ray continuum emission.

2 The detection of ^{44}Sc

The composition of the inner most layers of supernova ejecta is to a large extent determined by nuclear statistical equilibrium, ^{56}Ni being the most abundant element. However, as the layer expands the density decreases and the triple-α reaction stops, resulting in an excess of α-particles; a process referred to as alpha-rich freeze out.[5] This condition favors the production of ^{44}Ti. Although ^{44}Ti is much less abundant than radio-active ^{56}Ni, the longer decay time of 85.4 ± 0.9 yr[6,7,8] makes ^{44}Ti the main energy source for the expanding ejecta of some supernovae $\gtrsim$ 2000 days after the explosion, as is the case for SN 1987A.[9,10] The observation of ^{44}Ti in young

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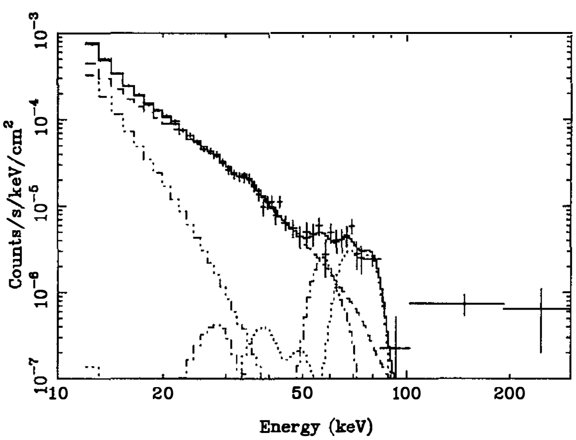

Figure 1: *BeppoSAX*-PDS spectrum of Cas A with the best fit ^{44}Sc/non-thermal bremsstrahlung model (solid line). The individual emission components are: ^{44}Sc line emission (dotted line), non-thermal continuum (dashed line), thermal continuum (3 dots-dashed line) and possible line contamination from collimator material (Tantalum, dashed-dotted line). The observed count rate in each channel has been divided by the effective area in order to yield approximate flux densities.

supernova remnants provides information about the explosion that formed them, as the amount synthesized depends sensitively on explosion energy, explosion asymmetries, pre-supernova mass loss[b], and the mass cut.[c]

The decay chain is ^{44}Ti$\rightarrow$ ^{44}Sc $\rightarrow$ ^{44}Ca, and is in more than 99% of the decays accompanied by the emission of three photons at 68 keV, 78 keV (from excited ^{44}Sc) and 1157 keV (from excited ^{44}Ca). Although Cas A is the best candidate for observing ^{44}Sc and ^{44}Ca emission, the detection of ^{44}Ca emission with *CGRO-COMPTEL*[11] was a surprise, as the implied synthesized ^{44}Ti mass was large compared to model predictions. Moreover, hard X-ray observations failed to detect ^{44}Sc line emission.[12,13,14]

To address this issue Cas A was observed in May and June 2001 for 500 ks with the *BeppoSAX*, its hard X-ray experiment, PDS [15], being best suited for detecting ^{44}Sc line emission, in part due to the low particle background of the *BeppoSAX* orbit. With an additional 100 ks of archival data the resulting spectrum is of high quality with an energy resolution 9 keV (FWHM) around 75 keV.

Fitting the data with a simple power law continuum model, shows a significant excess at the energies of the ^{44}Sc emission. The excess can be fitted with gaussian lines at the ^{44}Sc line energies, with a flux for each line of $(2.0 \pm 0.4) \times 10^{-4}$ ph^{-1}cm^{-2}s^{-1} and a combined detection significance of more than 5σ.[4] For a distance of 3.4 kpc and an age of 320 yr this implies an initial ^{44}Ti mass of 10^{-4}M$_\odot$. The measured power law slope is $\Gamma = 3.30 \pm 0.04$. The ^{44}Sc line flux is lower, but consistent with the latest *CGRO-COMPTEL* measurements of the ^{44}Ca line flux of $(3.4 \pm 0.4) \times 10^{-4}$ ph^{-1}cm^{-2}s^{-1}.[16] However, the measured ^{44}Sc line flux depends on the assumed shape of the continuum, whose nature is not yet established.

3 The nature of the hard X-ray emission

The hard X-ray emission of Cas A is interesting in its own right, and its existence is connected with the physics of electron heating and acceleration. The hard X-ray component is likely to extend to lower photon energies, where it interferes with the accurate measurement of the thermal bremsstrahlung component, which is important for inferring elemental abundances and temperatures.

[b]A strong mass loss reduces late time fall back on the stellar remnant.

[c]The mass cut defines the mass of the stellar remnant. A massive stellar remnant will have accreted most of the ^{44}Ti (and ^{56}Ni) produced.

The hard X-ray emission may be the result of synchrotron emission from extremely energetic cosmic ray electrons ($E \gtrsim 10$ TeV), similar to what is now established to be the dominant X-ray continuum emission for SN 1006.[17,18] Alternatively, it can be the result of bremsstrahlung from subrelativistic or mildly relativistic electrons, in which case the electrons may constitute the cosmic ray injection spectrum, but not necessarily so.[19,20]

Here we highlight the application of a particular bremsstrahlung model, which involves electrons accelerated by lower hybrid waves (LHW), which have frequencies intermediate to the electron and ion gyrofrequencies.[21,22] LHW are excited in plasma in which the magnetized electrons are in the presence of free streaming ions reflected by primary or secondary shocks. They can explain the observation of energetic electrons at the earth bow shocks, and X-ray emission from comets, and have in fact been observed in situ for Halley's comet.[23] LHW are promising for explaining the hard X-ray emission from Cas A, as the magnetic field is relatively high (~1 mG, see next section). The fact that Cas A is oxygen-rich is important, because it means that for a given shock velocity the average ion is more energetic than for solar abundances.

The emission model consists of a thermal bremsstrahlung component of $kT_e = 3.5$ keV and a bremsstrahlung component from accelerated electrons. The maximum electron energy obtained by the process, E_{max}, is a free parameter. The model fits the *BeppoSAX*-PDS data remarkable well up to 100 keV (Fig. 1). The data indicate $E_{max} \sim 95$ keV and the emission measure of the non-thermal component is 1/11th of that of the thermal component. The model predicts a steepening of the spectrum near E_{max}. For this model the measured ^{44}Sc line flux is $(3.2 \pm 0.3) \times 10^{-5}$ ph^{-1}cm^{-2}s^{-1} , implying an initial ^{44}Ti mass of 1.5×10^{-4} M$_\odot$, higher than for the assumption of a power law continuum. Note that synchrotron models also predict a spectral steeping, resulting in a similar ^{44}Sc flux estimate.[4]

4 New constraints on the average magnetic field in Cas A

The relativistic electrons responsible for the radio synchrotron emission from Cas A also give rise to gamma-ray bremsstrahlung and inverse Compton emission. The synchrotron emission for an electron energy power law distribution with index q, normalization K, and magnetic field B scales as $KB^{(q+1)/2}\nu^{-(q-1)/2}$.[24] Bremsstrahlung on the other hands scales with $K\Sigma_i n_i Z_i^2$, with n_i, Z_i the density and charge of ion i. Inverse Compton emission scales with the photon energy density and has a spectral slope that is equal to that of synchrotron emission. For Cas A the radio flux density for the epoch 2000.0 is 2522 Jy at 1 GHz with a spectral index of $\alpha = -0.78$, which is based on a compilation of radio measurements.

From the above it is clear that measuring bremsstrahlung or inverse Compton emission will constrain the average magnetic field strength.[d] This method has been used to derive lower limits on B from upper limits on gamma-ray emission, the latest estimate being $B > 0.35$ mG.[25,26] Here we apply this method to the hard X-ray emission, using the *BeppoSAX* data in combination with archival *CGRO-OSSE* data (viewing periods 34 to 815). The *CGRO-OSSE* data are useful for setting limits on the emission above 100 keV.[12]

It turns out that limits on the inverse Compton emission does not constrain the magnetic field significantly. Taking into account the cosmic microwave background, synchrotron self Compton emission and Cas A's infrared emission, we estimate $B > 2 \times 10^{-5}$ G.

Bremsstrahlung from the cosmic ray electrons is, however, much more constraining, but for the hard X-ray emission there is the caveat that the emitting electrons are only mildly relativistic and cannot be simultaneously observed at radio frequencies, unlike electrons with $E \gtrsim 100$ MeV. Even in the simplest model we have to take into account that the shock acceleration process produces a power law spectrum in momentum, producing a steepening in the energy spectrum

[d] More precisely, with bremsstrahlung we can determine $< KB^{(q+1)/2} > / < K\Sigma_i n_i Z_i^2 >$.

from $E^{-\frac{1}{2}(q+1)}$ for $\gamma \lesssim 2$ to E^{-q} for $\gamma \gg 1$.[19] More realistic models, incorporating the injection of electrons from the thermal plasma, predict a flattening of the energy spectrum from $E \sim kT_e$ to $E \sim m_e c^2$.[20] In fact, it is possible that the hard X-ray emission is the result of this injection spectrum. Note, however, that we can still use the simpler model for obtaining upper limits. The reason is that a hard X-ray spectrum steeper than assumed here results in a lower electron cosmic ray normalization, K, for $\gamma \gg 1$, resulting in a higher magnetic field.

The electron energy distribution scaling with $E^{-\frac{1}{2}(q+1)}$ produces a spectrum with a spectral index of 2.2. The best fit normalization for such a component is $(4.0\pm1.5)\times10^{-7}$ ph s^{-1}keV^{-1}cm^{-2} with a 2σ upper limit of 6.2×10^{-7} ph s^{-1}keV^{-1}cm^{-2}. Fitting a complete bremsstrahlung model gives $K\Sigma_i n_i Z_i^2 V/4\pi d^2 < 65$, with d the distance to Cas A and V the emitting volume. Soft X-ray observations imply $\Sigma_i n_i Z_i^2 \simeq 20$.[3] Combining this with the expression for radio synchrotron emission[24] gives $B > 2$ mG. This is comparable to, or even larger than estimates based on magnetic field equipartition. Such a high magnetic field is necessary for the LHW model to work, given the observed electron temperature.[22] Note that the upper limits on the bremsstrahlung component predict a continuum flux density an order of magnitude below the recent marginal continuum detection around 2 MeV by *CGRO-COMPTEL*.[27]

5 Future observations with *INTEGRAL*

INTEGRAL, ESA's next major gamma-ray mission, will cover the energy range of 15 keV to 10 MeV and is planned for launch in October 2002.[28] Observations of nuclear line emission are one of its goals. Cas A will be observed for 1.5 Ms by *INTEGRAL* in order to observe ^{44}Sc and ^{44}Ca line emission with its two main instruments SPI and IBIS. Other young supernova remnants that will be observed are Tycho's supernova, SN 1987A and RX J0852.0-4622 ("Vela jr").[29]

For Cas A the presence of ^{44}Ti is now well established, but *INTEGRAL* will be able to obtain new science with SPI's ability to detect Doppler shifts of the ^{44}Ca line with an accuracy of ~ 300 km/s, from which important explosion properties can be inferred. ^{44}Ti is expected to be at the base of the ejecta, implying a relatively low velocity. However, in the case of SN1987A it was discovered that ^{56}Ni, which also originates from deep inside the ejecta, was partially mixed with the outer layers. Moreover, in Cas A iron rich knots have been found outside the ejecta shell, implying that some core material was ejected with surprisingly high velocities.[30]

IBIS is the most sensitive instrument for the ^{44}Sc lines and the hard X-ray continuum. Although it will not dramatically improve the continuum spectrum observed by *BeppoSAX*-PDS, the fact that the ^{44}Sc line contribution will be better known allows for a better measurement of continuum spectrum around 80 keV, where, a spectral steepening is expected. The coded mask design will ensure a better discrimination of possible background sources.

One of the other goals of *INTEGRAL* is the observation of the electron-positron annihilation radiation, which has been observed in the inner galaxy for a long time, most recently by *CGRO-OSSE*.[31] The principle origin for the positrons is thought to be the decay of ^{44}Sc and ^{56}Co, the daughter of ^{56}Ni. One might wonder whether it is possible to observe the annihilation radiation directly in Cas A and other young supernova remnants. Assuming for the annihilation time scale $\tau >> 300$ yr, the expected 511 keV line flux, F_{511}, can be expressed as: [32]

$$F_{511} = (2 - 1.5f)\frac{N_{\beta+}}{4\pi d^2\tau} = (2 - 1.5f)(0.19e\frac{M_{56}}{56\text{amu}} + 0.94\frac{M_{44}}{44\text{amu}})\frac{1}{4\pi d^2\tau}, \quad (1)$$

where f is the annihilation fraction due to the formation of positronium, which is probably small for the hot plasma in Cas A, M_{44} and M_{56} are the explosion yields of ^{44}Ti and ^{56}Ni respectively, e is the escape fraction of ^{56}Co generated positrons and d is the distance toward Cas A. τ depends on the electron density and is expected to be 5×10^4 to 5×10^5 for electrons densities typical for Cas, $10 - 100$ cm^{-3}. We assume $M_{44} = 10^{-4}$M$_\odot$ and $M_{56} = 0.07$ M$_\odot$. It

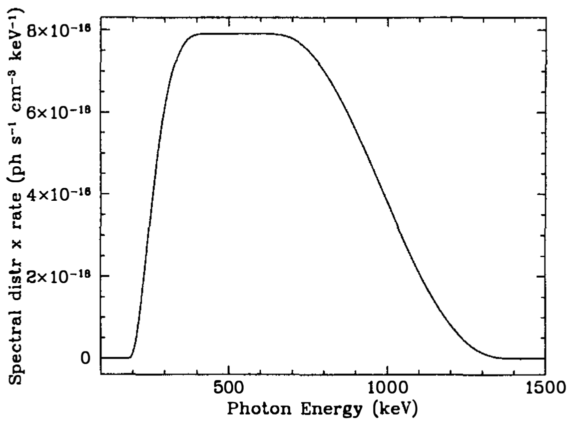

Figure 2: Expected positron annihilation spectrum resulting from ^{44}Sc and possibly ^{56}Co decay positrons, in the case of negligible positron energy losses. The input positron spectrum was taken from ref. [32].

turns out that the detectability of the 511 keV emission from Cas A depends critically on the escape fraction e.

Note that for $e = 0$, i.e. only ^{44}Sc contributes, we obtain $F_{511} = 3\times10^{-6}$ at best. The average positron emitted by ^{44}Sc has an energy of ~600 keV, so the line may actually be significantly broadened to a continuum. To our knowledge the emission spectrum of those hot positrons have never been published before, we therefore show it in Fig. 2.

If the 511 keV line is observed at all it must due to a large escape fraction of ^{56}Co positrons. Calculations show typical escape fractions of 1% with possible fractions as high as 10%.[32] In the latter case, assuming $\tau = 4 \times 10^4$ yr, and if the positrons have slowed down considerably, a flux as high as $3 \times 10^{-5}\mathrm{ph}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ might be expected, which is observable by *INTEGRAL*. Although the prospects for such a high flux seems dim, it is certainly worth looking for in Cas A and other supernova remnants.

The observation of annihilation radiation will further improve our understanding of the explosion. The positron escape fraction depends sensitively on the explosion energy and asymmetries. The reason is that early annihilation of positrons is slowed down if the density in the expanding ejecta drops fast. The annihilation in the ejecta depends on the positron energy losses, mainly caused by ionizations.[32] For that reason also the composition matters, e.g. ionization losses are smaller for He-rich ejecta. Interestingly, most of the conditions that ensure a large escape fraction are similar to the conditions for a high ^{44}Ti yield. Note that high positron and gamma-ray escape fractions make a dim supernova remnant. This is consistent with the lack of a bright supernova event accompanying the explosion.

6 Discussion

We have discussed the recent detection of ^{44}Sc line emission, which supports the finding by *CGRO-COMPTEL* of ^{44}Ca emission and firmly establishes the presence of ^{44}Ti in Cas A. Although there are some uncertainties in the flux values, caused by uncertainties about the nature of the hard X-ray continuum, it nevertheless suggests that the ^{44}Ti production was relatively high. This could be caused by a combination of factors such as a highly asymmetric explosion or a very energetic explosion. However, there are also some uncertainties in the modeling of supernovae preventing a definitive conclusion on basis of ^{44}Ti alone. The amount of ^{44}Ti synthesized indicates that at least 0.05 $M_\odot$of ^{56}Ni should have been synthesized, but this does not necessarily lead to a bright explosion as SN1987A, in which similar amounts of ^{44}Ti and ^{56}Ni were synthesized, was underluminous. If Cas A was indeed an energetic explosion, and

0.07 $M_\odot$was synthesized, it may be possible to detect 511 keV electron-positron annihilation emission. However, this is only possible under favorable circumstances, i.e. high annihilation rates now, and slow annihilation rates during the first few hundred days.

Future work, e.g. with *INTEGRAL*, will focus on the kinematics of ^{44}Ti and further investigation of the nature of the hard X-ray continuum, which may be either synchrotron emission or bremsstrahlung.

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