THE SIGNATURE OF ^{44}TI IN CASSIOPEIA A
REVEALED BY IBIS/ISGRI ON INTEGRAL

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ABSTRACT

We report the detection of both the 67.9 and 78.4 keV ^{44}Sc γ-ray lines in Cassiopeia A with the *INTEGRAL* IBIS/ISGRI instrument. Besides the robustness provided by spectro-imaging observations, the main improvements compared to previous measurements are a clear separation of the two ^{44}Sc lines together with an improved significance of the detection of the hard X-ray continuum up to 100 keV. These allow us to refine the determination of the ^{44}Ti yield and to constrain the nature of the nonthermal continuum emission. By combining COMPTEL, *BeppoSAX*/PDS and ISGRI measurements, we find a line flux of $(2.5 \pm 0.3) \times 10^{-5}$ cm^{-2} s^{-1} leading to a synthesized ^{44}Ti mass of $1.6^{+0.6}_{-0.3} \times 10^{-4}$ M$_\odot$. This high value suggests that Cas A is peculiar in comparison to other young supernova remnants, from which so far no line emission from ^{44}Ti decay has been unambiguously detected.

Subject headings: gamma rays: observations — ISM: individual (Cassiopeia A) — nuclear reactions, nucleosynthesis, abundances — supernova remnants

1. INTRODUCTION

Cassiopeia A (hereafter, Cas A) is the youngest known supernova remnant (SNR) in the Milky Way, located at a distance of $3.4^{+0.3}_{-0.1}$ kpc (Reed et al. 1995). The estimate of the supernova is A.D. 1671.3±0.9, based on the proper motion of several ejecta knots (Thorstensen et al. 2001). However, an event observed by Flamsteed (A.D. 1680) could be at the origin of the Cas A remnant (Ashworth 1980; Stephenson & Green 2002). The large collection of data from observations in the radio, infra-red, optical, X-ray (see *e.g.* Hwang et al. 2004) up to TeV γ-rays (Aharonian et al. 2001) allows us to study its morphology, composition, cosmic-ray acceleration efficiency and secular evolution in details. Young SNRs are thought to be efficient particle accelerators and represent the main galactic production sites of heavy nuclei, some of them being radioactives. Soft γ-ray observations, beyond the thermal X-ray emission (≥ 10 keV), can therefore provide invaluable information in both of these areas by studying the nonthermal continuum and the γ-ray line emission. Cas A then appears to be the best case for such investigations.

Few radioactive isotopes are accessible to γ-ray astronomy for probing cosmic nucleosynthesis (Diehl & Timmes 1998). Amongst them, ^{44}Ti is a key isotope for the investigation of the inner regions of core-collapse SNe and their young remnants. This nucleus is thought to be exclusively created in SNe but with a large variation of yields depending on their type. Recent accurate measurements by several independent groups give a weighted-average ^{44}Ti lifetime of 86.0 ± 0.5 years

(Ahmad et al. 1998; Görres et al. 1998; Norman et al. 1998; Wietfeldt et al. 1999; Hashimoto et al. 2001). The discovery of the 1157 keV ^{44}Ca γ-ray line emission from the decay chain of ^{44}Ti (^{44}Ti$\longrightarrow ^{44}$Sc$\longrightarrow ^{44}$Ca) with *CGRO*/COMPTEL (Iyudin et al. 1994) was the first direct proof that this short-lived isotope is indeed produced in SNe. This has been strengthened by the *BeppoSAX*/PDS detection of the two blended low energy ^{44}Sc lines at 67.9 keV and 78.4 keV (Vink et al. 2001). By combining both observations, Vink et al. (2001) deduced a ^{44}Ti yield of $(1.5 \pm 1.0) \times 10^{-4}$ M$_\odot$.

This high value compared to those predicted by "standard" models (*e.g.* Woosley & Weaver 1995b, WW95; Thielemann, Nomoto, & Hashimoto 1996, TNH96) as well as improved ones (Rauscher et al. 2002; Limongi & Chieffi 2003) could be due to several effects. First of all, the explosion of Cas A seems to have been intrinsically asymmetric since such asymmetries have recently been observed in the ejecta (Vink 2004; Hwang et al. 2004), and there are indications that its explosion energy was $\sim 2 \times 10^{51}$ erg (Laming & Hwang 2003), higher than the canonical value of 10^{51} erg. The sensitivity of the ^{44}Ti production to the explosion energy and asymmetries may explain the high ^{44}Ti yield compared to explosion models (Nagataki et al. 1998).

It is generally accepted that Cas A was formed by the explosion of a massive progenitor, from a 16 M$_\odot$ single star (Chevalier & Oishi 2003) to a Wolf-Rayet (WR) remnant of a very massive (< 60 M$_\odot$) precursor (Fesen & Becker 1991). Type Ib explosions, originating from progenitors which have experienced strong mass loss (see Vink 2004, Vink 2005), should on average produce more ^{44}Ti due to the lower fall back of material on the compact stellar remnant (Woosley et al. 1995a). However, there is some debate on the detailed stellar evolution scenario that may have accounted for the low mass of the star prior to the explosion. The amount of oxygen present (1-2 M$_\odot$, Vink et al. 1996) suggests a main sequence mass of 20 M$_\odot$. This may be too low to form a Type Ib progenitor by mass loss in a WR phase. Moreover, the high surrounding density is better explained if the shock wave is moving through the dense wind of a red supergiant

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rather than the more tenuous wind of a WR. Therefore, it has been recently suggested that the low mass of the progenitor is the result of a common envelope evolutionary phase in a binary system (Young et al. 2006). The authors demonstrated that such a scenario of a 15-25 $M_\odot$ progenitor which lost its hydrogen envelope due to a binary interaction can match the main observational constraints. In any case, the ^{44}Ti production is highly sensitive to details of the explosion as well as nuclear reaction rates. It is of interest to point out that the major ^{44}Ti production reaction ^{40}Ca$(\alpha,\gamma)^{44}$Ti has been revised (Nassar et al. 2006), implying an increase of the ^{44}Ti production by a factor of ~ 2.

In addition to the ^{44}Sc γ-ray lines, the hard X-ray spectrum is also of interest for its nonthermal continuum emission and because this underlying continuum is critical to properly measure the ^{44}Sc line flux. Nevertheless, its nature is still under debate. The nonthermal hard X-ray continuum could be due to either synchrotron radiation of TeV electrons (Allen et al. 1997) or nonthermal bremsstrahlung from supra-thermal electrons which have been accelerated by internal shocks (Laming 2001a,b; Vink & Laming 2003). Both cases predict a gradual steepening at high energies and then, reliable continuum flux measurements beyond the two low energy ^{44}Sc lines (> 80 keV) are necessary, as initiated with *CGRO*/OSSE (The et al. 1996). Soft γ-ray observations are therefore critical to better understand the nucleosynthesis and the particle acceleration processes in young SNRs such as Cas A. IBIS (Ubertini et al. 2003), one of the two main coded mask aperture instruments onboard the *INTEGRAL* satellite (Winkler et al. 2003), is best suited to study both the hard X-ray continuum and the line emission thanks to its low energy (15 keV – 1 MeV) camera ISGRI (Lebrun et al. 2003). IBIS/ISGRI provides spectro-imaging (13′ FWHM, 6 keV FWHM at 70 keV) over a large field of view (400 deg^2) in the energy range 15 keV-1 MeV with a milliCrab sensitivity at 70 keV (3 σ, $\Delta E/E = 2$, 10^6 s). The large field of view allows for long exposures devoted to the simultaneous observation of several sources. In this letter, we report the results of the spectro-imaging analysis of Cas A based on IBIS/ISGRI observations.

2. INTEGRAL/IBIS OBSERVATIONS AND DATA ANALYSIS

Since its launch, *INTEGRAL* has performed deep Open Time observations dedicated to the Cassiopeia region, mainly for measuring and constraining the ^{44}Ti production in the Cas A and Tycho SNRs. Preliminary results on these two young SNRs are reported in Vink et al. (2005) and Renaud et al. (2006), respectively. Moreover, den Hartog et al. (2006) have presented a comprehensive list of the sources detected by IBIS/ISGRI above 20 keV in this region. We have performed a detailed analysis of ~ 1800 pointings or science windows (hereafter, scws), each of them lasting typically between 1800 and 3500 s during which the telescopes are pointed at a fixed direction. We have selected pointings at less than 11° from Cas A and removed those for which the Veto and ISGRI (≥ 500 keV) counting rates were above 3.5×10^4 and 45 ct.s^{-1}, respectively. The total effective time is then ~ 3.2 Ms (over ~ 4.5 Ms of total exposure time).

For γ-ray line studies, the most critical part of the IBIS/ISGRI data analysis is the energy correction of detected events. The spectral performance of the ISGRI camera depends on the alignment of the pixel gains and offsets. Based on more than two years of observations, a fine in-flight calibration has been done by taking into account several param-
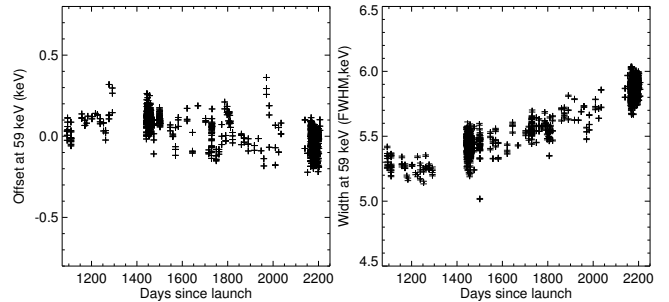

Fig. 1.— Position (left) and width (right) of the W K$_\alpha$ background line.

eters such as the temperature, the accumulated proton irradiation, and the time after the detector switch-on. Moreover, because of the charge loss in the Cadmium Telluride (CdTe) detectors and in their electronics, the ISGRI spectral response above ~ 60 keV depends on the pulse rise-time and a second software correction is needed (Lebrun et al. 2003).

To evaluate the efficiency of all these corrections, we measured the position and the width of the W K$_\alpha$ fluorescence background line at 59 keV for each scw. As shown in Figure 1, the dispersion of the 59 keV line position over the 3 years of observations is about 0.1 keV. The spectral degradation observed on the right panel of Figure 1 is due to the irradiation of the detector pixels but is still negligible after 3 years in terms of line sensitivity ($\sim 5\%$). The deconvolution of coded mask images (shadowgrams) removes completely the background only if it is flat. Background structures in the shadowgram produces large scale structures in the deconvolved image. To avoid them, a background map is first subtracted from the shadowgram. Such correcting background maps were produced by summing a large number of high latitude observations from all directions. In this way, the shadowgrams of the many weak sources are smeared out on the detector. With more than 2 Ms of exposure time, these ensure the best removal of structures in the detector images, mainly around the fluorescence lines located close to the two low energy ^{44}Sc astrophysical lines. We then used the Off-Line Scientific Analysis (OSA) software (Goldwurm et al. 2003) version 5.1 in order to obtain sky images and we have constructed mosaic images in 14 energy bands (see Figs. 2 and 3).

3. RESULTS

In order to estimate the source position of the hard X-ray continuum, we also analyzed the 18-25 keV energy band which has the best signal to noise ratio (hereafter, S/N) for a steep spectrum such as that of Cas A. We have fitted the source with a two-dimensional elliptical gaussian with the following parameters: the background level, the position and the value of the maximum, the widths on the two axes, and the rotation angle of the ellipse. We did not find any evidence of a source extent (the two widths are close to 14′ FWHM). The fitted position of Cas A is R.A. = 23^h 23^m 22.6^s, decl. = +58° 49′ 02.1″ (J2000) with a S/N of ~ 38. According to Gros et al. (2003), the corresponding point source location error (PSLE) radius at the 90% confidence level is $\sim 50″$. Therefore, the full error box is contained within the remnant.

Figure 2 shows IBIS/ISGRI images centered on Cas A in the six energy bands around the two ^{44}Sc lines that shows that the source brightens at the line energies. For building up the source spectrum, we first measured in each individual sky
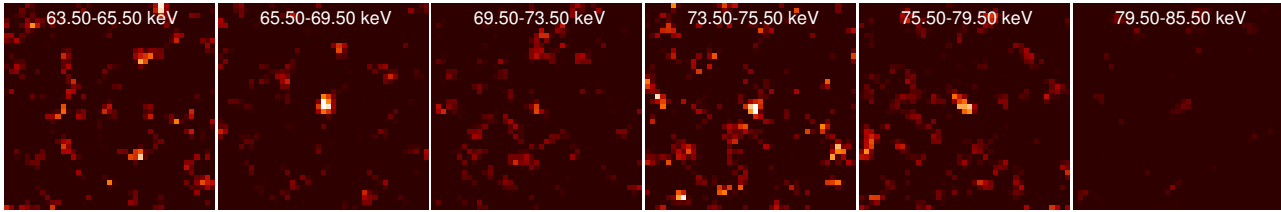
FIG. 2.— IBIS/ISGRI flux images centered on Cas A ($2.5° \times 2.5°$) in six energy bands. The linear scale is the same for all images, between 10^{-6} and 4.7×10^{-6} cm^{-2} s^{-1} keV^{-1}. Note that the noise in the images depends on the energy band widths.
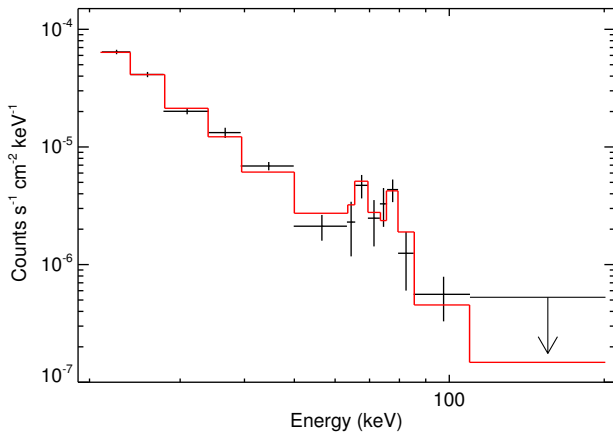

FIG. 3.— IBIS/ISGRI spectrum of Cas A and the best-fit model as described in the text (solid red line) with the following boundaries: 21, 24, 28, 34, 39.5, 50, 63.5, 65.5, 69.5, 73.5, 75.5, 79.5, 85.5, 109.5 and 201 keV. The count rates and the model have been divided by the effective ISGRI area at the center of each channel, in order to obtain approximate flux density units. The upper limit above 110 keV is given at the 3 σ confidence level.
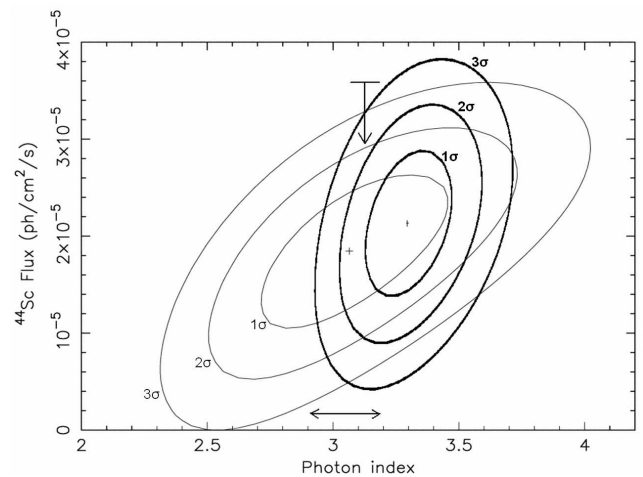

FIG. 4.— Confidence ellipses for the combination of the ^{44}Sc line flux and the power-law photon index in the 21-120 keV band with IBIS/ISGRI (thick lines), and in the 30-100 keV band with *BeppoSAX*/PDS (thin lines, Vink et al. 2001). The vertical arrow corresponds to the *RXTE* upper limit at 90 % confidence level on the ^{44}Sc line flux (Rothschild & Lingenfelter 2003) and the horizontal arrow presents the first *RXTE* and OSSE measurements of the photon index (Allen et al. 1997).

image the flux and its associated variance at the pixel corresponding to the fitted position in the 18-25 keV energy range. Note that this variance takes into account all uncertainties, in particular those resulting from the background subtraction. We then calculated the weighted mean count rate and corresponding error for each of the 14 energy bands. This spectrum is presented in Figure 3, showing the clear detection of the two low energy ^{44}Sc lines. We tested two different models for the continuum emission: the pegged power-law pegpwrlw in the 21-120 keV band and the srcut (Reynolds & Keohane 1999) model in XSPEC v.11.3. This latter is an approximation of the X-ray synchrotron radiation from young SNRs. The ^{44}Sc lines were fitted with two gaussians of equal intensity at fixed positions and with no line broadening.

The obtained best-fit parameters together with their 1 σ confidence levels are given in Table 1. The best-fit model is found with a pure power-law continuum spectrum and a ^{44}Sc line flux of $(2.2 \pm 0.5) \times 10^{-5}$ cm^{-2} s^{-1} in each line (χ^2 = 9.5 for 10 dof) consistent with previous COMPTEL and *BeppoSAX*/PDS measurements. Taken together the ^{44}Sc lines are detected at the 4.5 σ confidence level ($\Delta\chi^2 = 20$) and each is individually detected at 3 σ above the continuum emission. Relaxing the constraints on the line positions and width results in fitted line flux ($2.3 \pm 0.5 \times 10^{-5}$ cm^{-2} s^{-1}), positions (67.8 ± 1.6 and 77.4 ± 1.4 keV) and width (< 1.6 keV) consistent with the expected values and does not improve the fit (χ^2 = 9.5 for 7 dof). The 3 σ upper limit on the line broadening translates to a non-constraining upper limit of $\sim$ 14,000 km s^{-1} for the expansion velocity. For the srcut model, the

flux density at 1 GHz and the radio spectral index were fixed to 2720 Jy and 0.77 (Green 2005). We find a χ^2 of 18.5 for 11 dof. According to the F-test, a power-law is favored over the srcut model at 2.5 σ (98.8 %). It would be also the case of any other model that predicts a substantial steepening of the continuum emission above 50 keV. From Table 1 it is clear that the estimate of the ^{44}Sc line flux is sensitive to this continuum modeling and we then explored the correlation between the ^{44}Sc line flux and the power-law photon index. Figure 4 presents such a correlation diagram. A detailed analysis of the nature of the hard X-ray continuum, its effect on the ^{44}Sc line flux estimate, and the results obtained with the *INTEGRAL*/SPI data will be presented in a forthcoming paper (Vink et al. 2006, in preparation).

4. DISCUSSION

The IBIS/ISGRI observations confirm the presence of the two low energy ^{44}Sc γ-ray lines in Cas A. By performing a weighted average of the three independent measurements of COMPTEL, *BeppoSAX*/PDS (Vink et al. 2001) and ISGRI , we find a line flux of $(2.5 \pm 0.3) \times 10^{-5}$ cm^{-2} s^{-1}. Taking into account uncertainties on its age (Thorstensen et al. 2001), distance (Reed et al. 1995) and ^{44}Ti lifetime (Vink 2005), this is translated into an initial synthesized ^{44}Ti mass of $(1.6^{+0.6}_{-0.3}) \times 10^{-4}$ M$_\odot$. This mass of ejected ^{44}Ti is generally thought to be unusually large (or for few specific cases, marginally consistent) in comparison with spherical explosion models of

TABLE 1. SPECTRAL MODEL FITS

Model	^{44}Sc Flux (10^{-5} ph cm^{-2} s^{-1})	Power-Law Index	Total flux in the 21-120 keV range (10^{-12} erg cm^{-2} s^{-1})	Flux density at 1 GHz (Jy)	Radio Index	Roll-off Energy (keV)	χ^2/ν
Power-Law	2.2 ± 0.5	3.3 ± 0.1	37.5 ± 1.5	—	—	—	9.5/10
SRCUT	2.9 ± 0.5	—	—	2720 (fixed)	0.77 (fixed)	0.97 ± 0.02	18.5/11

WW95 and TNH96 (Timmes et al. 1996). Moreover, in the standard frame where ^{44}Ti and ^{56}Ni are co-produced during the first stages of the explosion, Cas A should have been a very bright, ^{56}Ni-rich SN, in contrast with its non detection or with the Flamsteed's historical record. However, the large ^{44}Ti/^{56}Ni ratio could be explained by the high degree of asymmetries (Nagataki et al. 1998).The high ^{44}Ti yield thus supports the idea that Cas A is the result of an asymmetric and/or a relatively more energetic explosion, consistent with other observational evidence (Vink 2004; Hwang et al. 2004).

Anyway, the ^{44}Ti production in core-collapse SNe is highly sensitive to the network used to compute nuclear reactions. With the recent revised ^{40}Ca$(\alpha,\gamma)^{44}$Ti reaction rate (Nassar et al. 2006), theoretical models become more compatible with the ^{44}Ti yield deduced from IBIS/ISGRI and previous observations. However, this would make the lack of other Galactic ^{44}Ti sources an even more serious problem: several γ-ray line surveys (Dupraz et al. 1997; Renaud et al. 2004; The et al. 2006) have highlighted the problem of the "young, missing, and hidden" Galactic SNe, those that should have occurred since Cas A and are still not detected through the line emission from ^{44}Ti decay. This would strengthen the idea that Cas A is peculiar (Young et al. 2006). On the other hand, the high ^{44}Ti yield of both Cas A and SN 1987A (Fransson & Kozma 2001) is more in accordance with the solar ^{44}Ca/^{56}Fe ratio, whereas this ratio is underpredicted by current spherically symmetric explosive nucleosynthesis models (Prantzos 2004; Young et al. 2006).

Besides the robustness provided by these IBIS/ISGRI spectro-imaging observations, the main improvements compared to previous observations (Vink et al. 2001; Rothschild & Lingenfelter 2003) are the improved spectral resolution and the improved significance of the detection of the hard X-ray nonthermal continuum up to 100 keV well fitted by a single power-law. The latter gives more stringent constraints on both the line intensities and the underlying continuum. Therefore, the scenario of a synchrotron radiation by TeV electrons (Allen et al. 1997) as modeled by Reynolds & Keohane (1999) seems not appropriate in the case of Cas A. On the other hand, the model developed by Laming (2001a,b) implying a nonthermal bremsstrahlung emission of supra-thermal electrons could be an alternative scenario. Based on this firm detection of the ^{44}Sc lines with IBIS/ISGRI, the expected results with SPI, thanks to its fine spectral resolution ($\Delta E \sim 2$ keV FWHM at 1 MeV), should help us for the first time to constrain the kinematics of the innermost layers of the explosion (Vink et al. 2006, in preparation).

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