SEARCH FOR THE ^{44}TI LINES IN CASSIOPEIA A WITH INTEGRAL/SPI

Pierrick Martin[(1)], Jürgen Knödlseder[(2)], Jacco Vink[(3)]

[(1)] CESR - 9, avenue du Colonel Roche – BP4346 – 31028 Toulouse Cedex 4 – France – martin@cesr.fr
[(2)] CESR - 9, avenue du Colonel Roche – BP4346 – 31028 Toulouse Cedex 4 – France – knodlseder@cesr.fr
[(3)] Astronomical Institute Utrecht – P.O. Box 80000 – 3508TA Utrecht – The Netherlands – j.vink@astro.uu.nl

ABSTRACT

We report on the search for the ^{44}Ti decay lines in Cassiopeia A with the spectrometer SPI aboard INTEGRAL, after about 4.8 Ms of effective observation. The low-energy lines, at 67.9 and 78.4 keV, are detected, though only marginally for the former, and the flux derived, $(3.3\pm1.2)\times10^{-5}$ ph/cm^2/s, is consistent with previous estimates. The source spectrum suggests little line broadening and/or asymmetry, but the result is still too weak for these awaited conclusions to be drawn. At high energy, the non-detection of the 1157.0 keV line implies a velocity broadening of at least 400 km/s, assuming that ^{44}Ti is located in a shell type structure.

1. INTRODUCTION

Despite three decades of numerical and theoretical research, the detailed mechanism of core-collapse supernova explosion remains unclear. In the current model, the explosion is powered by the intense neutrino emission from the cooling proto-neutron star, but alternative scenarios of jet-induced explosions, strengthened by the recent GRB-supernova connection, are also considered (see [1] and [2]). There is consequently a great need for observational constraints on the inner workings of supernova explosions. Invaluable information is carried by neutrinos and gravitational waves, but these are currently inaccessible. Nuclear gamma-rays then offer what may be the best prospect for obtaining insight into supernovae explosions. ^{44}Ti is one of the few radio-isotopes accessible to gamma-ray astronomy and is expected to bring an important contribution to the understanding of supernovae. ^{44}Ti results mostly from explosive nucleosynthesis in the innermost layers of core-collapse supernovae, and its yield per event is very sensitive to the dynamics of the explosion. After a mean lifetime of 85.6±0.5 yr, ^{44}Ti decays to ^{44}Sc and then to ^{44}Ca by emitting three photons at 67.9, 78.4 and 1157.0 keV. The features of this characteristic emission, line flux, shift and/or broadening, could therefore tell us about the intimate details of the explosion. Cassiopeia A is the remnant of the most recent galactic supernova known so far (about 320 yr) and is therefore the ideal place to search for the ^{44}Ti lines.

There have been previous detections of ^{44}Ti in CasA through the high energy line with CGRO/COMPTEL (first by [3] then revisited by [4]) and through the hard X-ray lines by BeppoSAX/PDS [5] and more recently by INTEGRAL/IBIS [6]. All three observations converge towards a value of $(2.5\pm0.3)\times10^{-5}$ ph/cm^2/s for the flux in each line. The spectrometer SPI aboard the INTEGRAL observatory, with its unprecedented energy resolution, is expected to add spectral information to this result and thus reveal the kinematics of the ejecta.

2. ANALYSIS

Activation and excitation of nuclei by the solar and cosmic-ray particles constantly pelting the satellite result in background noise that overwhelms the signal by a factor of 100. If this background were constant, any detection of even a weak astrophysical signal would only be a matter of patience. Yet, the background shows strong time, spectral, and even spatial variations. That is, in every dimension of the data-space in which it could vary, it does. The key to successful data analysis then resides in the modelling of this background, so that proper subtraction can be achieved and the true astrophysical signal can be unearthed.

2.1 Data

The data set used in this work consists of all pointings lying within 20° around Cassiopeia A and achieved between revolution 7 and revolution 394. These observations comprise series of dedicated observations of the Cas A remnant plus a number of pointings from the periodic Galactic Plan Survey.

This initial selection is cleared of all abnormal data such as pointing with anomalously high counting rate due to radiation belt crossing or enhanced solar activity. The data set eventually comprises 2409 pointings to the Cas A region, amounting to about 4.8 Ms of effective observation time.

Proc. 6th INTEGRAL Workshop 'The Obscured Universe', Moscow, 3-7 July 2006 (ESA SP-622)

Only single events have been considered, that is the counts where the gamma photon energy was deposited in a single detector (as opposed to multiple events that affect several detectors through Compton scattering or pair creation).

2.2 Methods

Most methods implemented in the SPI data analysis make use of activity tracers that it is hoped reflect the time variability of the background. These can be the number of saturated events in the Germanium detectors, the number of saturated or non-saturated events in the anti-coincidence shield, the IREM counting rate or the counting rate in certain background lines. A background model often consists of a combination of several tracers, either used directly or after processing (smoothed, or convolved with an exponential decay law), scaled to the level of the data. This multi-component background model is then fitted simultaneously with the sky model (here a point-source at the position of Cas A) to the data using a Maximum Likelihood criterion for Poissonian statistics. The fit can be performed independently for each energy bin to produce a source spectrum. The parameter set for the background models depends on the ability of the background model to reproduce long-term evolutions. A compromise is then necessary between the reduction of systematic errors and obtaining the highest sensitivity. The results are then checked for statistical consistency in the three dimensions of the data-space (pointings, energies, detectors). For a detailed description of such methods, see [7].

In the case of the ^{44}Ti lines, this method proved not entirely satisfactory, as shown by statistical tests of the residuals. The more data that were added, the greater were the systematics in the final spectrum. We therefore adopted a different technique, which is somewhat akin to a detector background map. The 19 Germanium detectors are divided into 9 overlapping subgroups of 3 adjacent detectors. Inside each detector subgroup, the relative counting rate of each detector is determined for each energy bin from a set of high-latitude pointings (OFF pointings) that are assumed to contain only background counts. This yields, for a given detector i (i=1-3) belonging to group j (j=1-9) a coefficient k_{ij}. Then, for a given ON pointing p and energy bin e, we expect the number of background counts to verify the following relations for each detector subgroup j :

$$x_{ij} = k_{ij} \sum_{i=1}^{3} x_{ij} \qquad (1)$$

$$\sum_{i=1}^{3} x_{ij} = n_j \qquad (2)$$

where x_{ij} is the (unknown) number of background counts in the detector i of group j and n_j is the number of observed counts in group j. Since the 9 detector subgroups are overlapping (ie some of the 19 Germanium detectors appear in more than one subgroup), we thus have 36 equations for only 19 unknowns (the numbers of background counts in the 19 Germanium detectors for pointing p and energy bin e). The whole system is then solved using Singular Value Decomposition, which finds a least-square solution. For each detector subgroup, Eq. 2 is weighed by a factor $1/\sqrt{n_j}$ to account for the statistical uncertainty in the observed counts n_j. The method is then equivalent to a Maximum Likelihood for Gaussian statistics with a constraint on the topology over the detector array. Compared to a simple background map (where the count rate for each detector is relative to the entire array), subdividing in subgroups brings in some "flexibility" to the map and allows to account for any spatial variability of the background. The main drawback of this method lies in the fact that the background time variability comes from the data themselves. The time residuals summed over the entire detector array are therefore too good with a reduced chi-square around 0.2. Individually (ie by detector), however, the residuals are rather satisfying (between 0.8 and 1.0). Since the background model is determined for each pointing from a mix of background and source counts, it is important to fit this model (together with the sky model) to the data using a parameter per pointing or at least per orbit. It should be noted, however, that the employed parameter set has no significant impact on the resulting source spectrum.

3. RESULTS

The source spectrum obtained for the low-energy lines is shown in Fig. 1. Also presented is a raw SPI spectrum in the same energy range, so that any bias from the initial shape of the data can be assessed. As can be seen, the 67.9 keV line is shrouded in an intense background line complex and is therefore hardly accessible. We fit the source spectrum assuming no underlying continuum, a line width equal to the instrumental resolution (as no broadening seems apparent at first glance) and a spacing between the two lines fixed at the theoretical value. The flux obtained, $(3.3\pm1.2)\times10^{-5}$ ph/cm^2/s, is consistent with previous measurements within the statistical uncertainties. The lines do not seem to be shifted or broadened, but the uncertainties are too large for these assertions to be firm and for any conclusion about the ejecta to be drawn.

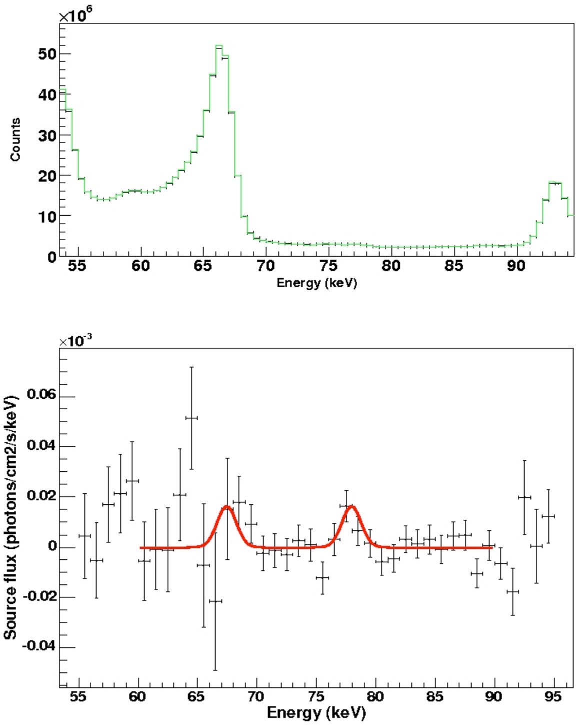

Fig. 1
Top : raw SPI spectrum
Bottom : source spectrum for the low-energy lines

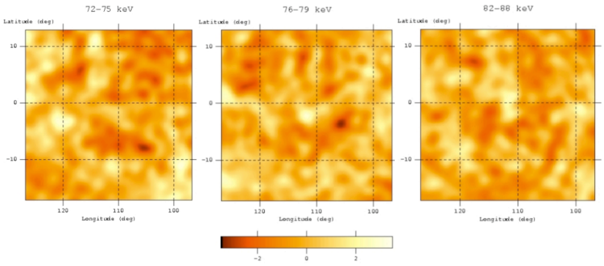

Fig. 2
SPIROS significance maps in the
72-75,76-79,82-88 keV bands
(from left to right respectively)

The detection is confirmed by the fact that changing the sky model, ie the position of the source, yields a nearly flat spectrum and that the SPIROS imaging program ([8]) shows a 3σ source at the position of CasA in the 76-79 keV band (white spot at the center of the middle image), while images in adjacent energy bands do not show such a level of significance at this position (Fig. 2).

At high energy, the spectrum (Fig. 3) appears rather flat, hence indicating that the expected line is broadened. The corresponding counts are therefore spread over many energy bins and drowned in the Poisson fluctuations of the background noise. Assuming that all ^{44}Ti lies in a thin spherical shell in uniform expansion and assuming a line flux of $2.5.10^{-5}$ ph/cm^2/s, this non detection implies an expansion velocity above 400 km/s for the ejecta (2σ limit). This lower limit translates into a line broadening of about 0.1 keV at 78.4 keV which is about twenty times smaller than the SPI spectral resolution at these energies.

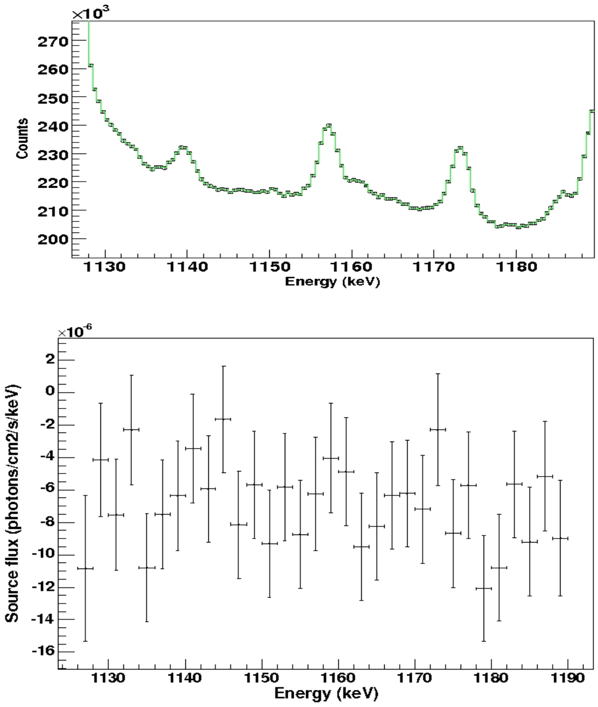

Fig. 3
Top : raw SPI spectrum
Bottom : source spectrum for the high-energy line

The negative flux offset in the high-energy spectrum probably comes from the method used for background modelling. As exposed in §2, the inversion of Eqs. 1-2 by SVD is equivalent to a Maximum Likelihood for Gaussian statistics. At 1 MeV, the number of counts is so low that this assumption is not correct anymore and as a consequence probably leads to the observed offset. A program is currently under development to implement Poissonian statistics in our method.

4. CONCLUSION

The low energy lines of the ^{44}Ti decay, especially the 78.4 keV one, are detected by SPI in Cassiopeia A. The line width is compatible with the instrumental resolution of about 1.9 keV at these energies. Due to the weakness of the signal in the present dataset, we are unable to derive firm constraints on the ^{44}Ti kinematics from our measurements. The flux derived is consistent with the previous estimates by COMPTEL, BeppoSAX and IBIS. At high energy, the non-detection of the 1157.0 keV line indicates an expansion velocity above 400 km/s for an assumed ^{44}Ti shell, which is consistent with the apparent non-broadening of the low-energy lines.

The result obtained for the low-energy lines is close to the 3σ sensitivity limit of SPI considering the 4.8 Ms of observing time of our dataset and the actual background level. Increasing the significance of the result would require reducing the number of fitting parameters, but none of the background models tested so far succeeded in reproducing the true evolution of the background. Further work will include the extension of the analysis to the double events, which account for about one quarter of the counts around 1 MeV, to confirm the present result, and of course renewed efforts to understand and model the instrumental background. However, to constrain the expansion velocity seriously, substantial additional observing time will be needed.

5. REFERENCES

1. Wheeler J.C. et al., *ApJ*, Vol. 568, 807-819, 2002
2. Burrows A. et al ., *ASPC*, Vol. 342, 184, 2005
3. Iyudin A.F.et al., *A&A*, Vol. 284, L1-L4, 1994.
4. Iyudin A.F. et al., *ApL&C*, Vol. 38, 383,2000.
5. Vink J. et al., *ApJ*, Vol. 560, L79-L82, 2001.
6. Renaud M. et al., *ApJ*, Vol. 647, L41-L44, 2006.
7. Knödlseder et al., *A&A*, Vol. 441, 513-532, 2005.
8. Skinner G. and Connell P., *A&A*, Vol. 411, L123-L126, 2003.