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COMPTTEL

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COMPTTEL PREPRINT No. 16

COMPTTEL Papers
presented at the

COSPAR Gamma-Ray Astronomy Symposium

HAMBURG

July 1994

THE COMPTTEL COLLABORATION

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²⁶Al IMAGING DETAILS FROM COMPTEL

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ABSTRACT

The COMPTEL map of 1.809 MeV emission from Galactic ²⁶Al is now based on 2 1/2 years of data. Different imaging analysis approaches are discussed: Likelihood maps from point source scans are utilized for searches of emission regions; astrophysical source models are fitted to the measurement with the maximum likelihood method; deconvolved images are produced with the maximum entropy algorithm. Simulations and statistical analysis with the bootstrap method demonstrate that the intensity irregularity and asymmetry along the Galactic plane is significant, although weaker individual features are insignificant by themselves. The comparison of classical ²⁶Al source tracer distributions shows that none of these models represents the COMPTEL data well. The measured 1.809 MeV feature from the Vela region, positionally consistent with the Vela supernova remnant, shows an indication for extended emission.

INTRODUCTION

The COMPTEL gamma-ray telescope aboard the NASA Compton Observatory measured the distribution of 1.809 MeV emission from radioactive ²⁶Al along the plane of the Galaxy /1,2/. COMPTEL data from the sky survey and subsequent observations have confirmed the expectation /3,4/ of recent Galactic nucleosynthesis being traced by this isotope with its radioactive decay time of $1.04 \cdot 10^6$ years. Earlier observations of the sky in this gamma-ray line /5/ had reported prominent emission from the Galactic Centre region — the imaging capabilities of most instruments were insufficient to map the intensity distribution, however. From these observations, it was commonly concluded that $\sim 2\text{-}3 M_{\odot}$ of ²⁶Al exist within the Galaxy. The COMPTEL capability /6/ to image the observed 1.809 MeV flux down to intensities at the 10^{-5} ph cm⁻² s⁻¹ level provides a new quality of these 1.809 MeV measurements. The line position and width agree with the 1.809 MeV line and instrumental width (59 keV), respectively. The observed distribution (see Figure 1), however, shows remarkable deviations from the expected smooth distributions attributed to the candidate ²⁶Al sources, such as novae, supernovae, and massive stars /4/.

In this paper, we present a discussion of the imaging aspects of COMPTEL data, as they affect the significances of image structures. Also, the previous results on 1.809 MeV imaging of the Galactic plane,

Fig. 1: Image of galactic 1.8 MeV emission as derived from COMPTEL observations 1-301 through Maximum-Entropy deconvolution. Significant irregularities along the plane of the Galaxy are confirmed on model fits, and on specific investigations of the Vela region, are updated based on more observations.

COMPTEL 1.8 MeV RESULT DETAILS

Imaging analysis was made with coarse software collimation methods /2/, but also in the 3-dimensional imaging data space of COMPTEL /7/ spanned by the primary photon scatter angle and the secondary photon's scatter direction angles. The latter utilizes the full imaging capability of the COMPTEL telescope, preserving the primary measured directional parameters measured for each detected event. For the ^{26}Al study, the data space consists of a 200 keV wide window in energy enclosing 48% of all measured events from a celestial 1.809 MeV source /8/, essentially the photopeak part of the response; the angular ranges spanned by the data space in the directional parameters χ, ψ (the direction of the scattered photon as it travels from upper to lower detector plane of the instrument) and the Compton scatter angle ϕ cover the full

Fig. 2a: Longitude projection of the COMPTEL 1.8 MeV image, within a latitude range of $\pm 5^\circ$

Fig 2b: Latitude projection of the COMPTEL 1.8 MeV image along the entire plane of the Galaxy. Variations of different source region locations around the plane cause a broadening of the intrinsically narrow latitude extent of typical source regions.

ranges of measured values ($< 50^\circ$) with a resolution of 1° in χ, ψ and 2° in ϕ .

Three approaches have been employed to derive imaging results /1,2/:

(1) The point source response of the telescope in the 3-D data space yields a likelihood value for any specific position of such hypothetical source, which can be compared to representing the data with a model for instrumental background only /9/. From scans of point-source positions over the sky likelihood ratio maps have been obtained, in 3 energy bands 200 keV wide, centered at 1.8 MeV

and adjacent bands below and above. These likelihood maps revealed prominent 1.8 MeV band emission along the plane of the Galaxy, above a continuum contribution which is estimated to be $\sim 25\%$ of the total 1.809 MeV intensity. The background in this analysis was estimated from special filtering of the measured data, which eliminates the signal from celestial sources /10/. A celestial 1.809 MeV source in the direction of the inner Galaxy improves the data fit by $4-5 \sigma$, derived from a likelihood ratio ≥ 15 . The assumption of a single point source representing the measured celestial 1.809 MeV signal is not expected to be adequate. Therefore this detection significance value represents a conservative estimate for the total Galactic ^{26}Al measurement, yet representing the significance of signal from localized regions along the inner Galaxy.

(2) More realistic 2-dimensional distributions for candidate ^{26}Al sources were compared to the measured data, deriving the fit improvement above background and between models with the maximum likelihood method /11/. Again the 1.809 MeV emission is detected with all models, at significances well above 10σ for all models: an exponential disk representing novae, a CO distribution /12/ modelling supernova activity through the distribution of molecular gas, and two distributions derived from the CO map by introduction

Model	Significance	Likelihood
Exponential Disk	12.4	153
CO Model	12.0	145
SN Model	11.9	141
WR Model	11.5	131
Segmented Plane	13.6	184
MEM Map	> 22	

Table 1: Comparison of different source models to represent the COMPTEL measurement.

of metallicity-dependent ^{26}Al yields for core collapse supernovae, and Wolf Rayet stars, respectively /13/. The differences among models are negligible, compared to the improved data fits obtained from empirical models such as a set of 20° wide longitude segments representing the Galactic plane, or Maximum Entropy models. Table I lists the likelihood values (and associated significances) for the (canonical) models that have been used up to now, and the 'empirical' models which are not based on candidate

source distributions. From this, we conclude /2/ that all the Galaxy-wide models tested by us are still inadequate representations of our data. We interpret this as supporting evidence for a non-steady-state situation of recent nucleosynthesis in our Galaxy, as suggested by the irregularity of our image: Localized regions of recently enhanced, or more alternatively more nearby, element formation activity could be superimposed on the smooth classical candidate source distributions discussed above. This would reduce the total mass of ^{26}Al assigned to the smooth Galaxy-wide components to $\sim 1 M_\odot$, below the $2\text{--}3 M_\odot$ that result from interpretation of the total 1.809 MeV signal being due to such smooth Galaxy-wide distribution of sources.

(3) An unbiased image of celestial 1.809 MeV emission was derived with the Maximum Entropy method from our measurements (see Figure 1). Refined background modelling from energy bands adjacent to the 1.8 MeV band /8/ effectively suppresses continuum contributions to the ^{26}Al gamma-ray line emission. In this method, an initially flat image is iterated to improve the fit of the convolved trial image to the measured data in the 3-D data space. Criteria for iterative modification of the image are the overall image entropy and the quality of the fit in data space. With higher iterations, the entropy constraint is reduced, successively resulting in more structured images until in high iterations a maximum-likelihood image shows overinterpreted structures much sharper than instrumental resolution. We have simulated the impact of this method on the imaging of extended emission, and on derived fluxes /8/. As a result for our measurements we find that the fifth iteration of the maximum-entropy algorithm produces an image that reflects all observed celestial structures without super-resolution, and provides a conservative image suppressing insignificant structures through the entropy constraint. For determination of flux values, we choose a high iteration (~ 30) and integrate flux values over regions larger than the instrumental angular resolution (determined from prelaunch calibrations as 1.6° ($1\text{-}\sigma$ width of the angular response at 1.8 MeV /6/. Our image is updated with data from Phases I, II, and III of the Compton mission (observations 1-301, Figure 1 /8/). The Galactic plane emission clearly stands out, but also the generally irregular structure along the plane, with pronounced localized emission regions and a remarkable asymmetry with respect to the Galactic Centre. Figure 2 shows projections of this image: Figure 2a represents a profiles along Galactic longitude, obtained from a high-iteration flux image, integrated over a $\pm 5^\circ$ latitude region in 1° steps; Figure 2b shows the corresponding profile in latitude, now integrated over the full Galactic plane ($\pm 180^\circ$ in longitude; note that the scatter of individual emission features around the Galactic plane results in broadening of the latitude profile compared to the locally narrow latitude extent of the emission, see Fig. 1).

A bootstrap sampling method /14,8/ was employed to estimate the sensitivity of the imaging results to statistics of the measurement. In this method, the N measured events form the basis of artificial event sets. Such an artificial 'bootstrap dataset' is obtained by drawing at random N single events, each one out of the full measured set. Thirty such bootstrap datasets were evaluated then with identical analysis tools and procedure as for the actual measurements, to derive a set of 30 images. These yield a range of result values ('error bars') per pixel, which can be used to estimate result variances without *a priori* assumptions about distributions and distortions within the instrument and analysis procedure. Figure 3 shows the longitude profile together with these bootstrap-based 'error bars'. The significance of individual structures in the profile may be estimated from the possibility to smooth out such a feature when making use of the amplitude bandwidth given by the error bars. With this criterion, the inner $\pm 40^\circ$ of the Galaxy show at least 3, possibly 5, distinct emission features. Also, the Carina, Vela, and Cygnus region signal is well above the statistical noise regime. In the bootstrap sampling procedure some information on the original measurement is lost (or, equivalently, with a signal-to-background ratio of 4% it is more likely to re-sample the data with

Fig. 3: Estimate of the variability of the 1.8 MeV longitude profile due to statistical fluctuations, derived from bootstrap sample analysis (see text for description of the method)

increased background contribution on the average). Therefore, on the average, deconvolved images from bootstrap-re-sampled data yield a lower signal amplitude than the image from the real data for the features well above the noise.

An estimate of the extent of individual emission features in our image can be obtained from a comparison of the concentrations of deconvolved intensity for different pronounced features. Growth curves of integrated intensity as a function of integration radius for circles around some features were derived. In a region with extended diffuse emission such as the Galactic Centre vicinity, the integrated flux is proportional to the integration region, and it is difficult to determine a flux for an individual hot spot. Our quoted flux for the hot spot close to the Galactic Centre region at $l=2.0^\circ/b=-1.5^\circ$ of $3.6 \cdot 10^{-5} \text{ ph cm}^{-2} \text{ s}^{-1}$ is derived through integration over a radius of 3.5° , a 'beam width' enclosing the full instrument angular response. For the regions of Cygnus, Carina, and Vela, the different growth curves of flux versus integration region indicate different extents of the emission region: The Cygnus region emission is diffuse over $\sim 15^\circ$, while the Carina feature is compatible with the instrumental angular resolution. The Vela feature is an intermediate case. The exceptionally nearby most prominent candidate ^{26}Al sources of this region, the Vela supernova remnant and the Wolf-Rayet star WR11 within the binary system ' γ velorum' motivate a more detailed study of this feature /15/. Fits of extended sources with different radii also suggest a somewhat ($\sim 4^\circ$) extended source /16/.

The detailed imaging studies with COMPTEL 1.809 MeV data consolidate our resulting image, with prominent emission from the Galactic plane, and outstanding features in the Galactic Centre region, and the Vela, Carina, and Cygnus regions. The existence of those prominent emission regions is consistent with our finding that classical smooth Galaxy-wide source models are inadequate to explain the data.

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