Gamma-Ray Telescope Design Principles & Abundance Targets

Vincenz Zimmer
Outline

I  Why $\gamma$-rays?

II $\gamma$-Telescope Design Principles

III Astrophysical Targets
Outline

I  Why γ-rays?

II  γ-Telescope Design Principles

III  Astrophysical Targets
Why are $\gamma$-rays of interest to astronomy?

Properties of cosmic rays:
- energies up to $10^{21}$ eV

How can we study such high energy physics? Cosmic rays?
- >99% charged particles
- $10^{-4}$ less $\gamma$-rays at same energy

Advantages of $\gamma$-rays:
- $\gamma$-rays are not deflected by magnetic fields like charged particles
  => contain information about sources
- $\gamma$-rays are highly penetrating
Which γ-rays are interesting for nuclear astrophysics?

γ-rays from radioactive isotopes:
- isotopes produced at sites of nucleosynthesis
- characteristic γ-ray lines
=> direct measurement of abundances
- stellar medium opaque for some time after an explosion
=> long enough lifetimes of the isotopes needed
Where to measure cosmic $\gamma$-rays?

- Earth’s atmosphere absorbs photons with different energies
- Also $\gamma$-rays of interest for nuclear physics are absorbed
  => need to measure above the atmosphere => in space
Outline

I. Why γ-rays?

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III. Astrophysical Targets
How do $\gamma$-rays interact with matter?

- photoelectric effect
- Compton effect
- pair production

$\Rightarrow$ information for the selection of the detector design and materials
Compton Telescopes - Principles

upper detector:  
- $\gamma$ is Compton-scattered  
- scattered electron deposits energy ($E_1$)

lower detector:  
- $\gamma$ is absorbed completely => energy ($E_2$)  
=> total $\gamma$-energy is sum of both

Where did the $\gamma$-ray come from?  
- deposited energies + positions of interactions + Compton scattering equation

$$\cos \theta = 1 - m_e c^2 \left( \frac{1}{E_2} - \frac{1}{E_1+E_2} \right)$$

=> Compton cone  
- many events  
=> $\gamma$-source on intersection of the Compton cones
COMPTEL on board the CGRO

energy range: 0.8-30MeV

assembly:
- upper detector: 7 modules with liquid scintillator
- lower detector: 14 NaI(Tl)-crystals
- anticoincidence shield: plastic scintillators surrounding the detectors

<table>
<thead>
<tr>
<th>characteristics</th>
<th>COMPTEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy resolution (FWHM)</td>
<td>5-8% (energy dependent)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>ca. 1%</td>
</tr>
<tr>
<td>Effective area for gamma-rays</td>
<td>20-50cm²</td>
</tr>
<tr>
<td>Field-of-view</td>
<td>1sr or 8% of the sky</td>
</tr>
<tr>
<td>Angular resolution (FWHM)</td>
<td>1.7-4.4°</td>
</tr>
<tr>
<td>Line sensitivity (3σ, 2-week observation)</td>
<td>$6 \times 10^{-5}$ cm$^{-2}$ s$^{-1}$ at 1 MeV</td>
</tr>
<tr>
<td></td>
<td>$1.5 \times 10^{-5}$ cm$^{-2}$ s$^{-1}$ at 7 MeV</td>
</tr>
<tr>
<td>Accuracy of Source Position Determination</td>
<td>5-30arcmin (source dependent)</td>
</tr>
</tbody>
</table>
Coded Mask Telescopes - Principle

assembly:
• mask with opaque and transparent elements
• detector with spatial resolution better than size of mask elements

principle:
• photons from a certain direction
  => cast a shadow of the mask onto the detector
• direction of the source
  => defined by the position of the shadow on the detector

But, there is not just one source!

=> different shadows at the same time
=> reconstruction of the image by complicated algorithms
SPI aboard INTEGRAL

mission start: 17 Oktober 2002

INTErnational Gamma-Ray Astrophysics Laboratory

© MPE Garching/Roland Diehl
SPI - SPeectrometer onboard INTEGRAL

energy range: 20keV-8MeV

assembly:
- distance mask-detector: 1.71m
- mask: 127 hexagonal elements (opaque ones: W)
- camera: 19 hexagonale Ge-detectors (cooled to 85K)
- anticoincidence system:
  - 91 BGO-scintillators around camera/„tower“ (ACS)
  - plastic scintillator beneath mask (PSAC)

<table>
<thead>
<tr>
<th>characteristics</th>
<th>SPI</th>
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<tbody>
<tr>
<td>Energy resolution (FWHM)</td>
<td>0,17% at 1,33MeV (each detector) 0,23% whole spectrometer</td>
</tr>
<tr>
<td>Line sensitivity (3σ, 10^6s)</td>
<td>3.3x10^{-5} ph cm^{-2}s^{-1} at 100keV 2.4x10^{-5} ph cm^{-2}s^{-1} at 1000keV</td>
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<tr>
<td>Mask dimensions</td>
<td>665 mm flat to flat, 30 mm thick Tungsten</td>
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<tr>
<td>Angular resolution</td>
<td>2,5° (point sources)</td>
</tr>
<tr>
<td>Point source positioning</td>
<td>&lt;1,3° (depending on point source intensity)</td>
</tr>
<tr>
<td>field-of-view</td>
<td>fully coded: 14°x16°, partially coded: 32°x35°</td>
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</tbody>
</table>
Outline

I. Why γ-rays?

II. γ-Telescope Design Principles

III. Astrophysical Targets
# Radioactive Isotopes of Interest

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Mean Lifetime</th>
<th>Decay Chain</th>
<th>$\gamma$-Ray Energy (keV)</th>
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<tbody>
<tr>
<td>$^7\text{Be}$</td>
<td>77 d</td>
<td>$^7\text{Be} \rightarrow ^7\text{Li}^*$</td>
<td>478</td>
</tr>
<tr>
<td>$^{56}\text{Ni}$</td>
<td>111 d</td>
<td>$^{56}\text{Ni} \rightarrow ^{56}\text{Co}^* \rightarrow ^{56}\text{Fe}^* + e^+$</td>
<td>158, 812; 847, 1238</td>
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<tr>
<td>$^{57}\text{Ni}$</td>
<td>390 d</td>
<td>$^{57}\text{Co} \rightarrow ^{57}\text{Fe}^*$</td>
<td>122</td>
</tr>
<tr>
<td>$^{22}\text{Na}$</td>
<td>3.8 y</td>
<td>$^{22}\text{Na} \rightarrow ^{22}\text{Ne}^* + e^+$</td>
<td>1275</td>
</tr>
<tr>
<td>$^{44}\text{Ti}$</td>
<td>89 y</td>
<td>$^{44}\text{Ti} \rightarrow ^{44}\text{Sc}^* \rightarrow ^{44}\text{Ca}^* + e^+$</td>
<td>78, 68; 1157</td>
</tr>
<tr>
<td>$^{26}\text{Al}$</td>
<td>$1.04 \times 10^6$ y</td>
<td>$^{26}\text{Al} \rightarrow ^{26}\text{Mg}^* + e^+$</td>
<td>1809</td>
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<tr>
<td>$^{60}\text{Fe}$</td>
<td>$2.0 \times 10^6$ y</td>
<td>$^{60}\text{Fe} \rightarrow ^{60}\text{Co}^* \rightarrow ^{60}\text{Ni}^*$</td>
<td>59, 1173, 1332</td>
</tr>
<tr>
<td>$e^*$</td>
<td>$\ldots \times 10^5$ y</td>
<td>$e^* + e^- \rightarrow \text{Ps} \rightarrow \gamma\gamma\ldots$</td>
<td>511, &lt;511</td>
</tr>
</tbody>
</table>

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**$^{44}$Ti - Puzzling Astrophysicists**

**Production:**
- only in ccSNe
- lifetime: ≈85yrs
- decays by EC to $^{44}$Sc
- $^{44}$Sc decays by $\beta^+$-decay or EC to $^{44}$Ca
- $\gamma$-energies: 68, 78 and 1157keV

**Observations:**
- seen in Cas A SN remnant (340yrs old)
- measured flux: $\approx 2,5 \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$
- no other SN seen in $^{44}$Ti $\gamma$-rays
- estimated ccSN rate: $\approx$ 2 per century
  => there should be other detectable SN

![SNR Cas A in X-rays](image-url)
$^{26}\text{Al}$ - COMPTEL Sky Map

- nucleosynthesis occurs in the present Galaxy
- patchy distribution argues for:
  $\Rightarrow$ massive stars main source of $^{26}\text{Al}$
$^{26}\text{Al} - \text{Galactic Rotation}$

- Ge-detectors of SPI => good energy resolution => spectroscopy possible
- results:
  - could see Doppler shifts
  - shows Galactic rotation
$^{26}\text{Al}$ - Doppler Broadening

- $^{26}\text{Al}$ is ejected with high velocities ($\geq 1000\text{km/s}$)
  => Doppler broadening expected
- former experiment measured 5.4 keV broadening
  => correspond to a mean velocity of $\approx 500\text{km/s}$
  => implausibly large
- also measured by SPI:
  => upper limit for mean velocity: 150 km/s
production:
• successive neutron captures on stable Fe isotopes
• in the hot interior of massive stars
=> only revealed by final SN
decay:
• $\beta^-$-decays via $^{60}$Co to $^{60}$Ni
• $\gamma$-rays at 1173 and 1332keV
• lifetime: ≈3.8Myrs
flux ratio:
• $^{26}$Al produced in same massive stars, but at different periods
=> comparison of $^{60}$Fe and $^{26}$Al fluxes good test on models

=> flux ratio $^{60}$Fe/$^{26}$Al: (14.8±6)%
$^{60}\text{Fe} - \text{Observations and Models}$

- Latest model: Woosley et al. 2007 (stellar evolution & nucleosynthesis & IMF)
- Latest FRANEC model: Limongi & Chieffi 2006 (stellar evolution & nucleosynthesis & IMF)
- Timmes et al. 1995
- Latest measurement (SPI): Wang et al. 2007

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TUM

13.05.2009
Gamma-Ray Telescope Design Principles & Abundance Targets – Vincenz Zimmer
e^+e^--Annihilation

observations: a bright and dominating emission from the bulge
=> was not expected
e\textsuperscript{+}e\textsuperscript{-}-Annihilation

- in addition to the bright bulge a hint of disk emission
- hint for an asymmetry of the disk
- at negative longitudes brighter than at positive longitudes
- might lead to candidate sources:
  - might correspond to hard LMXBs (low-mass x-ray binaries)
  - another explanation might be dark matter
• γ-rays from radioactive isotopes provide information about sites of nucleosynthesis in a quite direct way.

• The instruments targeting these isotopes have or had limited sensitivities (≈10^{-5} phcm^{-2}s^{-1}), but were able to obtain remarkable results.

• Several expected characteristic γ-ray lines could still not be seen, i.e. the lines from the short-lived isotopes (^7Be, ^22Na, ^56,^57Ni).

• Others, like ^26Al and the e^+e^--annihilation, help us to learn something about the interstellar medium around nucleosynthesis sites and about massive star interiors.

• They left us puzzling questions, e.g. the e^+e^--annihilation with it’s dominating bulge and asymmetric disk emission.
The End

Thank you for your attention!
References

- Wang, W., Harris, M.J., Diehl, R., SPI observations of the diffuse $^{60}\text{Fe}$ emission in the Galaxy, 2007
- C. Sánchez-Fernández, SPI Observer's Manual, INT/OAG/08-0295/Dc, 10.3.2008
- F. Wirner: Gammaastronomie (particle.astro.kun.nl/hs0607/Gamma.pdf)
  - http://integral.esac.esa.int/
  - http://heasarc.gsfc.nasa.gov/
  - http://www.mpe.mpg.de/~rod/rod.html
  - https://segue.atlas.uiuc.edu
  - http://www.wissenschaft-online.de/artikel/868484
Backup
### 44Ti – 57Co

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<th>Element</th>
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<th>Emission</th>
<th>Lifespan</th>
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<td>44V</td>
<td>111 MS</td>
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<td>45V</td>
<td>547 MS</td>
<td>ec</td>
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<td>46V</td>
<td>422.50 MS</td>
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<td>47V</td>
<td>32.6 M</td>
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<td>48V</td>
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<tr>
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<td>44Ti</td>
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<td>44Sc</td>
<td>2.97 H</td>
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<td>45Sc</td>
<td>STABLE 83.79 D</td>
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<td>46Sc</td>
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<td>41Ca</td>
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<td>22.3 H</td>
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<td>44K</td>
<td>22.13 M</td>
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<td>35.60 H</td>
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<td>58Ni</td>
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<td>59Ni</td>
<td>7.6E+4 Y</td>
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<tr>
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<td>77.233 D</td>
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<td>271.74 D</td>
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<td>58Co</td>
<td>70.86 D</td>
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<td>55Fe</td>
<td>2.737 Y</td>
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<td>56Fe</td>
<td>STABLE 91.754%</td>
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<td>STABLE 2.119%</td>
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<tr>
<td>57Mn</td>
<td>85.4 S</td>
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Coded Mask Telescopes - Assembly

coded mask (a):
• opaque and transparent elements
• arranged in a mathematical order
=> every source should cast a unique shadow

camera (b):
• detector:
  - spatial and
  - spectral resolution
• spatial resolution better than size of mask elements
Bilder

http://www.ikp.uni-koeln.de/students/fp/download/AnleitungVers4.pdf

planarer Ge Detektor

koaxialer Detektor

p+ Kontakt durch Bor-Implantation, ~50 μm dick;
n+ Kontakt durch Li-Diffusion, ~0.5 mm dick;

(b)

(c)
Satellitengestützte γ-Detektoren


\(^{26}\text{Al} - \text{Characteristics}\)

**production:**
- by p-capture on \(^{25}\text{Mg}\)
- in H-layers (core or shell) or Ne-O layers
- ejected by SNe or strong stellar winds
- sources: massive stars, novae, SNe

**decay:**
- \(\beta^+\)-decay or electron capture
- emitting a \(\gamma\) with 1809keV
- lifetime: \(\approx 1\)Myrs

**interpretation of the sky map:**
- irregular distribution
- concentrations at regions hosting young and massive stars (e.g. Cygnus)

\(=>\) massive stars main source of \(^{26}\text{Al}\)
\( ^{26}\text{Al} \)- Doppler Broadening and SFR

**Doppler broadening:**
- \( ^{26}\text{Al} \) is ejected with high velocities (\( \approx 1000\text{km/s} \))
  => Doppler broadening expected
- GRIS-experiment measured 5.4\text{keV} broadening
  => correspond to a mean velocity of \( \approx 500\text{km/s} \)
  => implausibly large
- also measured by SPI:
  => upper limit for mean velocity: 150\text{km/s}

**Star formation rate and core-collaps SN rate:**
- flux from inner Galaxy: \( (3,3+0,4) \times 10^{-4} \text{phcm}^{-2}\text{s}^{-1} \)
- with a model for the 3D spatial source distribution:
  => mass of \( ^{26}\text{Al} \) in the Galaxy: \( (2,8+0,8)\text{M}_{\odot} \)
- with this and more models:
  => star formation rate in the Galaxy: \( (3,8+2,2)\text{M}_{\odot} \)
  => ccSN rate in the Galaxy: 1,9+1,1 per century
**60Fe - Production Sites**

**production:**
- successive neutron captures on stable Fe isotopes
- competes with $\beta^-$-decays to Co

**production sites:**
- the hot interior of massive-stars
- neutrons sources: $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$, $^{13}\text{C}(\alpha,n)^{16}\text{O}$
- convective move $^{60}\text{Fe}$ away, before it is destroyed by another n-capture
- $^{60}\text{Fe}$ buried deep inside the stars

$\Rightarrow$ only revealed by final core-collapse SN

**decay:**
- $\beta^-$-decays via $^{60}\text{Co}$ to $^{60}\text{Ni}$
- $\gamma$-rays at 1173 and 1332keV
- lifetime: ≈3.8Myrs
e\textsuperscript{+}e\textsuperscript{-}-Annihilation - Pre-INTEGRAL Period

early experiments:
• balloone-borne instruments measured different fluxes of the 511keV line
  => interpretation: the „Great Annihilator“ (compact source at galactic center)
• following experiments measured constant fluxes over several years
  => disproved the „Great Annihilator“ theory
• obserations showed a diffuse distribution
  => interpretation: disk is responsible (here are most of the plausible sources)

OSSE/CGRO results:
• highest flux comes from the galactic center (bright bulge with a weak disk)
  => was not expected with many plausible sources located in the disk
• measured the positronium fraction
  => about 95% of the positrons form positronium befors the annihilation
e⁺e⁻-Annihilation - Spectrum

interpretations:
• annihilation takes place in a warm medium (several 1000K)