Gamma-Ray Line Observations from Cosmic Nuclei

Roland Diehl
MPE Garching

• Gamma-Ray Line Astronomy: Tools, Objectives, Results
• Specific Astrophysical Studies
  • Diffuse Radioactivity ($^{26}$Al, $^{60}$Fe)
  • Supernovae ($^{44}$Ti)
• Prospects
**Gamma-Ray Astronomy: Lines of Interest**

**Radioactive Isotopes**

- Decay Time > Source Dilution Time
- Yields > Instrumental Sensitivities

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

- **Simple Detector (& Collimator)**
  (e.g. HEAO-C, SMM, CGRO-OSSE)
  Spatial Resolution (=Aperture) Defined Through Shield

- **Coded Mask Telescopes**
  (Shadowing Mask & Detector Array)
  (e.g. SIGMA, INTEGRAL)
  Spatial Resolution Defined by Mask & Detector Elements Sizes

- **Focussing Telescopes**
  (Laue Lens & Detector Array)
  (CLAIRE, MAX)
  Spatial Resolution Defined by Lens Diffraction & Distance

- **Compton Telescopes**
  (Coincidence-Setup of Position-Sensitive Detectors)
  (e.g. CGRO-COMPTEL, LXeGRiT, MEGA, ACS)
  Spatial Resolution Defined by Detectors’ Spatial Resolution

Achieved Sensitivity: $\sim 10^{-5}$ ph cm$^{-2}$ s$^{-1}$, Angular Resolution $\geq$ deg
**Gamma-Ray Astronomy: Measurements**

- **Satellite-Based Surveys and Balloon Experiments**
  - **Pioneering Space Missions**
    - Apollo Gamma-Ray Detector (1977)
  - **Balloon Experiments**
    - UCR, UNH and MPE Compton Telescopes (1978...1982)
    - SN1987A Balloon Programs (1987)
    - Xe and Solid-State Detector Compton Telescopes (1995-...)
    - Laue Telescopes (1998-...)

- **Experiments for other Prime Objectives**
  - Solar Observatories (SMM, HESSI) (1985-...)
  - “X-Ray” Missions (RXTE, BeppoSax, HETE-II)

- **Compton Gamma-Ray Observatory**
Gamma-Ray Astronomy: Results

Live Cosmic Nucleosynthesis Detected

- \( e^+ \) and \( ^{26}\text{Al} \) in ISM  
  (Haymes et al. 1976; Matteson et al. 1982)
- \( ^{56}\text{Ni} \) and \( ^{57}\text{Ni} \) in cc-SN  
  (Matz et al. 1988; Kurfess et al. 1992)
- \( ^{44}\text{Ti} \) from a cc-SN  
  (Iyudin et al. 1994)
- \( ^{56}\text{Co} \) Hints from a SN Ia  
  (Morris et al. 1995)

Cosmic Nucleosynthesis Environments Being Studied

- \( ^{26}\text{Al} \) throughout the Galaxy  
  (Diehl et al. 1995-2002)
- \( ^{26}\text{Al} \) Decay at \(~500\) km s\(^{-1}\)?  
  (Naya et al. 1996)
- \( e^+ \) Annihilation in Inner Galaxy  
  (Purcell et al. 1997; Milne et al. 2001)
- \( ^{44}\text{Ti} \) Source Limits & Constraints  
  (Schönfelder et al. 2000; Vink et al. 2000)
- \( ^{56}\text{Co} \) Limits for a SN Ia  
  (Georgii et al. 2002)
- \( ^{22}\text{Na} \) & \( ^{7}\text{Be} \) Limits for Novae  
  (Iyudin 1995-2002; Harris et al. 2001)
- \( ^{26}\text{Al} \) & Massive Stars in Cygnus  
  (Plüschke 2001, Cervino et al. 2002)
- \( ^{26}\text{Al} \) from Orion OB1  
  (Diehl et al. 2002)
The Sky at 1809 keV: $^{26}\text{Al}$

Complete CGRO Mission
(Plüschke et al. 2001)
The COMPTEL $^{26}$Al Image

- **Maximum-Entropy Method ("ME"):**
  - Global-Entropy-Damped & Misfit-Gradient Driven
  - Iterations Towards Maximum-Likelihood Fit

- **Multi-Resolution Expectation Maximization Method ("MREM"):**
  - Misfit-Gradient Driven and Scale-Hierarchically Noise-Damped
  - Iterations (RL) Towards Maximum-Likelihood Fit

- **Substantial Image 'Noise' (~4° FWHM!)**
- **Consolidated Galactic and Localized $^{26}$Al Sources**
$^{26}$Al Maps & Possible Source Tracers

Different Imaging Methods
(ME, MREM, MLik)

- CO map of molecular gas
- IR map at 240 µm, dust
- Radio map at 53 GHz, free electrons
- $\text{H}_\alpha$ Emission from Ionized Gas
\( ^{26}\text{Al}: \text{Plausible Sources & Open Issues} \)

- **Massive Stars are Dominating Sources**
  - (Diehl et al. 1995; Prantzos & Diehl 1996; Knödlseder 1999)
  - Ionization Correlated to \(^{26}\text{Al}\) (free electrons) (Chen et al. 1995)
  - Consistency Check on Massive-Star Outputs:
    - Line-of-sight integrated \( I_{1.8\text{MeV}} = I_{\text{free-free_emission}} \)
      - Plausible \( \sim 8 \times 10^{-5} M_\odot \) Average Yield of \(^{26}\text{Al}\) per "OV star"
      - Consistent total \(^{26}\text{Al}\) Mass of \( \sim 2.4 M_\odot \)
      - Plausible \( \sim 10000 \) WR Stars in Galaxy
      - But: \( \Rightarrow \) SN (II+Ib) rate \( \sim 1.8/100y \) (?)
  - Agreement of 1.8 MeV Emission Distribution with Source Tracers
    - Free-Electron Distribution (Pulsars: 53 GHz COBE), i.e., mainly from Ionization by Massive-Star UV Photons
    - Warm Dust Emission, i.e., from SN and Massive-Star Winds' Heating of IS Dust (>100 \( \mu \)m COBE)
    - Distribution of Known Massive Stars (i.e., Young Clusters, WR Stars, O Stars) (but: incomplete at d>3 kpc)
  - Irregular Patterns of Massive-Star Locations Observed in LMC, M31; Same as Overall Irregularity of 1.8 MeV Emission?
  - \(^{26}\text{Al}\) Disk Latitude Extent \( \Rightarrow \) Gas, But < Old Population
    - \( \Rightarrow \) "puffed up" by SN/Wind Ejection?

- **Contributions From WR Stars, cc-SNae, Novae, AGB Stars ?**
The COMPTEL $^{26}\text{Al}$ Image

Significances of Map Regions

- Image Quality Adequate for Galactic and Localized Analyses of Counterparts

Roland Diehl, Jan 2002

Complete CGRO Mission (Plüschke et al. 2001)
Fits of ME Map in ROI, relative to flattened ROI
Massive Star Clusters and $^{26}$Al Diagnostics: Cygnus

- Candidate $^{26}$Al sources in the Cygnus region: WR stars, SNR, OB Associations (top view of Galaxy)

- Cygnus region OB Associations and Foreground Molecular Clouds

- **Candidate Sources at <2.5 kpc, Relatively Well-Studied, No Bgd Sources**
- **Distance Uncertainties, Occultation (Massive-Star Census Incomplete)**
- **Bright Extended Diffuse $^{26}$Al Gamma-Ray Emission**
Modeling $^{26}$Al from Star Clusters

- **Stellar Content**
  - OB Association Richness, IMF

- **Stellar Evolution**
  - Lifetime
  - WR Phase

- $^{26}$Al Yields per Star

- 1.809 MeV “Light Curve” for a Massive-Star Cluster

- Other Observables
  - UV / Ionization (→ free-free Emission)
  - Kinetic Energy / X Brightness

→ Plüschke et al., 2001; Cerviño et al. 2002
Massive Star Clusters and $^{26}$Al Diagnostics: Cygnus

$^{26}$Al emission at 1809 keV (left), compared to a model map as derived from richness-corrected OB associations and individual known sources (right).

1809 keV Images of Source Models of the Cygnus Region: the “raw” model based on known sources and OB association knowledge (left); the model after correction of OB association richness with CO column density normalized on Cyg OB2 (middle); the model after OB association richness correction and accounting for ejecta diffusion (right).

The quality of the 1809 keV fit by different tracers (green) is approximately achieved with astrophysical source models after adjustment of their characteristics (blue).
Massive Star Clusters and $^{26}$Al Diagnostics: Orion

The COMPTEL 9-year Survey Detects Diffuse 1809 keV emission in the Orion/Eridanus Region at $\sim$7σ significance.

- **ME-deconvolved Image:** Extended Emission Southward of the Orion Clouds
- **Background-subtracted Count Spectra Clearly Show the 1809 keV Line, Following the Features in the Image**
Massive Star Clusters and $^{26}$Al Diagnostics: Orion

Dust Emission (IRAS) and HI Trace Neutral Gas Around the Eridanus Bubble, X-Ray Emission Traces Hot Gas Inside the Cavity

Massive Stars of the OB1 Association Located at the Edge of the Orion Molecular Clouds Appears to Eject $^{26}$Al Radioactivity into the Eridanus Cavity
Interesting Nearby Sources in front of Vela Molecular Ridge

- Vela SNR (d~250 pc)
- \( \gamma^2 \) Velorum (WR11) (d~258/400pc)
- RXJ0852 (200pc<d<1500pc)

Extended Diffuse \( ^{26}\text{Al} \) Emission

None of These Sources Clearly Seen in \( ^{26}\text{Al} \)
26Al from Supernovae: Help from 60Fe?

- Production in SNae (and Stars) through n Capture on 56,58Fe (s-Process; 13C/22Ne(α,n))

- Decay Time 2 Myr + SN Yields \( \rightarrow \) \( \Gamma_{60Fe} \sim 0.16 \) \( \Gamma_{26Al} \) for 26Al from SN only

- 60Fe from 26Al Sources?

- 60Fe in Oceanic Crust \( \Rightarrow \) Nearby SN \( \sim 3-5 \) My ago

- 26Al in Oceanic Crust?
\( ^{26}\text{Al} \): Lessons about Star Clusters & ISM?

- **GRIS Ge Detector Balloon Experiment**
  (Naya et al., 1996)
  - Line Width \( \sim 6.4 \pm 1.2 \text{ keV} \), > Instrumental
  - 5.4 keV Doppler Equiv. = \( \sim 540 \pm 140 \text{ km/s} \)

- **Interpretations:**
  (Chen et al. 1997; Sturner & Naya 1999)
  - Large Contribution from \(^{26}\text{Al}\) in Hot ISM (Loops/Worms/Superbubbles)
    - Fresh Nucleosynthetic \(^{26}\text{Al}\) from WR Winds
    - Re-Acceleration of ISM-\(^{26}\text{Al}\) from Grains at SN Shockfronts
  - Large Fraction of \(^{26}\text{Al}\) in Fast Grains
    - Reflected in 1.809 MeV Line Shape Are:
      - Hot Superbubble Interiors
      - Very Young Supernova Remnants
      - Cosmic-Ray Acceleration Scenarios
      - Cosmic Dust Formation Near WR Stars & SN
26Al Radioactivity: Summary

- Massive Stars Dominate
- Need Model for
  - Massive-Star Population
  - Nucleosynthesis
- Learn about:
  - Massive-Star / ISM Interaction
  - Pre-Supernova Evolution / Outer SN
- Individual Source not (yet) Isolated
Core-Collapse Supernovae: $^{44}$Ti from Cas A

- $^{44}$Ti Decay: $\tau \sim 89$y
- Difficult $\gamma$-Ray Region (78, 68, 1157 keV)
- $\rightarrow$ $^{44}$Ti Ejected Mass

$^{44}$Ti Decay Gamma-ray Fluxes from Cas A

- $\rightarrow$ Young SNR
- $\rightarrow$ Uncertain $I_\gamma$

$^{44}$Ti Ejected Mass $\sim 0.8$–$2.5 \times 10^{-4} \, M_\odot$
Cas A: A Well-Studied Young Nearby SNR

- ~330 year-old SNR at ~3.4 kpc
- Massive Progenitor (10-25 $M_\odot$)
- Filaments, Fast Ejecta (knots), Fe-rich Clumps, No Onion-Shell-Like Elemental Morphology, Jet: Asymmetric Explosion
- $^{44}$Ti (and $^{56}$Ni) Ejection
- Unseen SN $\rightarrow$ CSM Dust
- Central Object (NS/BH?)

$\Rightarrow$ (?)

- Core Collapse SN with Unusual Asymmetries / Hypernova?
44Ti Emission from cc-SNae: Open Issues

- **Consistency of Cas A cc-SN Model:**
  - 44Ti Yield in Models: \( \sim 2 - 4 \times 10^{-5} \ M_\odot \)
  - 44Ti Ejection Should Be Correlated to
    - High-Entropy Material \( \rightarrow \) \( \alpha \)-Rich Freeze-Out
    - Large Explosion Energy
  - Large Mass of Ejected \( 56\text{Ni} \) (Bright Supernova)

  \( \rightarrow \)

  - How Peculiar a cc-SN is Cas A?
  - 44Ti Only From Polar Regions of Accreting Collapse?

- **No 44Ti Sources in Inner Galaxy**
  - Small-Number Statistics? Observational Bias?
  - Metallicity Anticorrelation?

- **Can 44Ti Sources Reveal...**
  - Inner SN Velocity Profiles? Ionization-Inhibited Decay (EC)?
    - \( 44\text{Ti} \) Line Shape!
  - Asymmetric Core Collapses? Hypernovae?
Radioactivity Yields from Massive Stars

courtesy Nikos Prantzos 2002
Live Cosmic Nucleosynthesis Detected. More?

ISM: $e^+\ 26$Al; SNae: $^{56}$Ni, $^{57}$Ni, $^{44}$Ti $^{22}$Na?

Cosmic Nucleosynthesis Environments Being Studied

$^{26}$Al

$^{44}$Ti

$^{56}$Ni
Gamma-Ray Lines from Cosmic Nuclei: Prospects

**Astrophysics:**
- Origin of $^{26}\text{Al}$, e+, $^{60}\text{Fe} \rightarrow$ Massive Stars and SNae
- Core Collapse SNae: Inner Explosion, Asymmetries
- Thermonuclear SNae: Deflagration/Detonation Transition
- Novae: Progenitor Evolution, Mixing? Radioactive Ejecta?
- Cosmic-Ray Acceleration $\rightarrow$ Excitation Lines

**Observatories:**
- Gamma-Ray Line Shapes $\rightarrow$ INTEGRAL
- Surveys at Improved Sensitivity $\rightarrow$ MEGA, ACT
- Deep SN Measurements $\rightarrow$ Laue Tel.