News on Gamma-Ray Line Studies with SPI/INTEGRAL
- Observations and their Interpretations -

Massive Stars and $^{26}\text{Al}$
Supernovae and $^{60}\text{Fe}$

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The Sky at 1809 keV: $^{26}\text{Al}$
The Sky at 1809 keV: $^{26}$Al

The Complete CGRO Mission
(Plüschke et al. 2001)
Ejection and Slowing-Down of $^{26}$Al from Sources

- $^{26}$Al Ejected into Hot Cavities (WR Winds, ...)
  -> ISM Turbulence <-> Line Width
- $^{26}$Al Condensed on Dust, Re-accelerated -> High-Velocity Tail?
  $^\text{‡}$ Chen et al. 1997; Sturmer & Naya 1999

Galactic Rotation

- $^{26}$Al Sources
  in Spiral Arms, Along Line-of-Sight
  -> $^{26}$Al Source Location Along LoS
  $^\text{‡}$ Gehrels et al. 1996; Kretschmer et al. 2003

<CARINA Meeting, Aiguablava (E), Jun 8-10, 2005>
26Al Line Width: Velocity of 26Al in ISM

☆ Broad Line was Difficult to Understand
★ 26Al on Dust?
★ Huge ISM Cavities?
★ Chen et al. 1997

☆ Issue Dissappeared?
$^{26}\text{Al}$ in the Cygnus Region

- Well-Confined Candidate Sources
  - 9 OB Associations
  - Special: Cyg OB2

- Test Laboratory for Age Discrimination of Sources

- Plüschke et al., 2001; Cerviño et al. 2002

Flux : $(7.2 \pm 1.8) \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$
Position : $1808.4 \pm 0.3$ keV $\Rightarrow v_{\text{rad}} = -41 \pm 50$ km s$^{-1}$
Width : $3.3 \pm 1.3$ keV $\Rightarrow \Delta v = 550 \pm 210$ km s$^{-1}$
SPI's Inner Galaxy Survey

INTEGRAL Core Program: “GCDE”

Inner-Galaxy Observing Times:

- GCDE1: ~1 Msec
- GCDE1+2: ~3.6 Msec
- Rev15-259 ~14 Msec

Line Shape now Constrained to ~Instrumental, Intrinsic ~x keV

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Roland Diehl
High-Resolution Spectroscopy with SPI

- Cosmic-Ray Damage of Charge Collection
  - Annealings
- Time-Variable Response

K. Kretschmer et al.
Spectra for Diffuse Emission

Coded-Mask Shadowing ~ Fuzzy
Spectra from Sky Model Fitting

- Line Shape Model:
  - Cumulative (degraded/distorted) Instrumental
  - Celestial (broadened?)

Data:
- Orbits 15-259 (1.5y)
- 16 Ms
- 4Ms at GC

\[ E = 1808.77 \pm 0.20 \]
\[ FWHM = 1.16 \pm 0.77 \]
\[ I = 3.29 \pm 0.38 \]
The $^{26}$Al Line is “Narrow” (~instrumental width)

- SPI: 0.2...1.2 keV
- <2.8 keV
- ISM velocities 25...150 km s$^{-1}$
Galactic Rotation and the $^{26}$Al Line

- **Galactic Rotation Affects the Line Centroid ~as Expected**
  - Consolidation: These sources are NOT Localized
  - Basis for GALACTIC $^{26}$Al Amount Determination using geometrical / tracer models

- **Observed (small) Line Broadening from Inner Galaxy Consistent with an Intrinsically-Narrow Line**
26Al in the Galaxy

- Line Broadening is not “unusual”
  - Determine line width for Regions of Different Cluster Ages
- 26Al Emission from inner Galaxy
  - Study Galactic Star-Formation/Massive-Star Population

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$^{60}$Fe Detections
with RHESSI & SPI/INTEGRAL

**RHESSI**

- $2.6\sigma$ Detection
- $I = 0.91 \pm 0.31 \times 10^{-4}$ ph cm$^{-2}$ s$^{-1}$
  
  *Smith 2004*

**SPI**

- $3\sigma$ Detection
- $I = 0.4 \pm 0.2 \times 10^{-4}$ ph cm$^{-2}$ s$^{-1}$
  
  *Harris et al. 2005*
Two Radioactivities from Massive Stars:  
$^{26}\text{Al}$ and $^{60}\text{Fe}$

**Production Sites**
- Hydrostatic Core & Shell Burning
- Explosive Burning

**Ejection**
- (Late) Wind Phases ($\frac{dM}{dt} \sim 10^{10} \times \text{solar}$)
- SN Explosion

**Main Processes**
- $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$ H burning
- $^{58}\text{Fe}(n,\gamma)^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}$ n capture

**Net Yields?**
- 0.7 ($25M_\odot$) ... 1.8 ($80M_\odot$) (e.g. Chieffi & Limongi 2005)

**ISM Yield Ratios?**
- 0.14 (GCE Model) (e.g. Timmes et al. 1995)

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Updated Massive-Star Synthesis ($^{26}\text{Al}$, $^{60}\text{Fe}$)

- Follow Stellar Evolution Consistently
  - Hydrodynamic Structure Evolution
  - Nuclear Energy Generation
  - Mass Loss Phases
  - Supernova Progenitor and Explosion
- Calculate a Complete Set of Stars (Mass Range)
  - Find Structural Discontinuities (Shell Burning; NS/BH; WR)
  - Cover IMF Range Well

Woosley et al. 2005
The $^{60}$Fe Puzzle

\begin{itemize}
  \item No Source Would Bring the $^{60}$Fe/$^{26}$Al Gamma-Ray Intensity Ratio Close to Measurement Constraints! (\textasciitilde{}Factor 3...5!)
  \item Model Sample Statistics (LC)?
  \item SN not a Significant $^{26}$Al Source?
  \item Nuclear Physics?
\end{itemize}

Uncertainties:
- $n$ Capture Cross Sections for Fe Isotopes $^{59}$Fe, $^{60}$Fe
- $\beta$ Decay Rate for $^{59}$Fe
- Development of Hot-Base He Shell, C Shell
- $n$ Source Activation

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Core-Collapse Supernovae: $^{44}\text{Ti}$ from Cas A

$^{44}\text{Ti}$ Decay: $\tau \approx 89\text{y}$

Difficult $\gamma$-Ray Region (78, 68, 1157 keV)

$\rightarrow$ $^{44}\text{Ti}$ Ejected Mass

$\rightarrow$ Young SNR

$\rightarrow$ Uncertain $I_\gamma \approx 2.5 \times 10^{-5}$

$\sim 1-2 \times 10^{-4} M_\odot$

Detections:
- Iyudin et al. 1994: COMPTEL 1.157 MeV
- Vink et al. 2001, 2005:
  - SAX & IBIS 68/78 keV
  - Comparable Upper Limits by RXTE, OSSE
  - Hints for Broad Line from SPI (Vink 2005)

$^{44}\text{Ti}$ from Cas A

Ti from Cas A

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Summary: Gamma-Ray Line News from SPI

- $^{26}$Al line is moderately broadened by
  - Galactic rotation
  - interstellar turbulence

- $^{60}$Fe supernova model yields are too low

- $^{44}$Ti from Cas A: Broad Line?

- Positron annihilation occurs in
  - a symmetric bulge-like region around the Galactic Center
  - a warm, partly-ionized medium