The hard X-ray emission properties of young supernova remnants observed by INTEGRAL

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Main Contents

• Science goals:
  supernova remnants (SNRs) connected to galactic cosmic rays;
  constraints on the progenitors of historic SN events.

• Main results:
  (1) Discovering the hard X-ray tails to 220 keV in Cas A, no cutoff;
  (2) $^{44}$Ti line detections in Cas A and Tycho, constraints on their progenitors

• Summary and future work
Motivations

• Connections between SNRs and high energy CRs

SNRs are thought to be the main contributor to Galactic CRs, specially around knee energy ranges ($3 \times 10^{15}$ eV). But we still be lack of direct evidence in observations.

One way – detect TeV photons Gound Cherenkov Telescopes (HESS, MAGIC, VERITAS) detected TeV gamma-rays in some SNRs, show evidence for accelerating particles to $10^{14}$ eV in SNRs. In future, evidence would come from detecting 100 TeV photons.
The other way to probe the accelerating ability in SNRs: non-thermal hard X-ray emissions

Hard X-ray synchrotron radiation photons up to 20 keV by ASCA in shells of SN 1006 implied accelerated electron energy to 100 TeV (Koyama et al. 1995).

RXTE detected hard X-ray tails in Cas A up to 60 keV, suggested Cas A can accelerate electrons to at least 40 TeV (Allen et al. 1997). This hard X-ray tails were confirmed by COMPTON/OSSE, which can extend to 100 keV (The et al. 1996).

Hard X-rays attributed to synchrotron radiation of accelerated electrons in SNRs can reflect the acceleration ability of high energy particles. Observing hard X-ray photons (specially above 100 keV) could help to searching for evidence of accelerating cosmic rays to the knee region (PeV) in SNRs.
$^{44}$Ti emission lines (by-product in hard X-ray observations) – probe the progenitors of supernovae

- $^{44}$Ti radioactive isotope (lifetime 86 yr) only comes from supernova (SN) explosions, emitting three lines at 68, 78, 1157 keV.
- $^{44}$Ti yield varies in different types of SNe.
- Generally type II/Ib/Ic SNe are thought to be main origin of $^{44}$Ti in the Galaxy. The standard spherical explosion models predict the $^{44}$Ti yield of $10^{-5}$-$10^{-4}$M⊙.
- Standard type Ia SN models (explosions of 1.4M⊙ WD) cannot produce enough $^{44}$Ti (3D simulations, <10^{-5} M⊙); But Ia SNe could be produced by double WD mergers, but unclear in $^{44}$Ti yield; some people proposed sub-chandra sekhar mass WD as progenitor of type Ia SNe which can produce high $^{44}$Ti yield, larger than $10^{-4}$M⊙.
- Thus detecting $^{44}$Ti lines at 68 and 78 keV can directly probe the progenitors of SNe.
Main Contents

• Studying hard X-ray emission properties of Galactic young SNRs with INTEGRAL/IBIS:

  (1) spectral properties of hard X-rays - accelerating ability of these SNRs - origin of high energy cosmic rays

  (2) searching for $^{44}$Ti line features – progenitors of SNe

• IBIS aboard INTEGRAL: good detector in the bands of 18 – 500 keV, could search for > 100 keV hard X-rays in SNRs;

• JEM-X aboard INTEGRAL can provide a lower energy band data (3-30 keV), constraint on the continuum properties.

• INTEGRAL have performed hard X-ray surveys over ten years, 2003 – 2012.

• With the deep survey data, we reported the new results on two SNRs: Cas A, Tycho
New results for Cas A

famous young SNR, bright in all electromagnetic bands
Age: 330 yr; distance: 3.4 kpc

Gamma-ray band observations:
HEGRA, MAGIC, VERITAS detected its TeV photons (Aharonian et al. 2001; Albert et al. 2007; Humensky 2008);
Fermi/LAT reported the GeV spectrum (Abdo et al. 2010);

Early hard X-ray observations:
RXTE detected Cas A up to 60 keV, above 15 keV, $\Gamma \sim 3.04$ (Allen et al. 1997)
COMPTON/OSSE reported the detection to 100 keV, $\Gamma \sim 3.0$ (The et al. 1996)
BeppoSAX also detected it, $\Gamma \sim 2.9$; a bump in the bands 60–90 keV which is attributed to the $^{44}$Ti lines (Vink & Laming 2003)
Suzaku detected it from 12–40 keV, $\Gamma \sim 3.06$ (Maeda et al. 2010)
Early INTEGRAL/IBIS data reported the spectrum from 20–100 keV, $\Gamma \sim 3.0$, and detected the $^{44}$Ti lines at 68, 78 keV (Renaud et al. 2006)。
Images by INTEGRAL/IBIS

Collecting the data from 2003 - 2012:

- 3 – 10 keV
- 20 – 60 keV
- 60 – 90 keV
- 90 – 200 keV

Cas A

3 keV: 58.2σ  
20 keV: 54.8σ  
60 keV: 14.9σ  
90 keV: 7.3σ
Hard X-ray spectrum from 3–500 keV: JEM-X and IBIS

Continuum spectrum models: Bremss + Power-Law

$\kT \sim 0.81 \pm 0.08$ keV; $\Gamma \sim 3.13 \pm 0.03$

Fe K$\alpha$ line $6.61 \pm 0.14$ keV

>200 keV 非热辐射光子
Non-thermal emission photons up to 220 keV in Cas A

• Non-thermal spectrum of Cas A from 10 – 500 keV, single power-law $\Gamma \sim 3.1$, without cutoff at least to 220 keV.
• Hard X-ray emissions come from synchrotron radiation of accelerated electrons in shock waves; the spectrum shows an exponential cutoff around several keV.
• Thus the power-law emission from 10 - $>220$ keV in Cas A challenges the particle accelerating models in shock waves!
• Some possibilities:
  higher magnetic field emitting regions
  special electron spectrum in high energy band ($>100$ TeV)
  contributions by secondary electron emission from P-P interactions
New INTEGRAL/IBIS derived the mean flux at 68, 78 keV: $(2.3 \pm 0.5) \times 10^{-5} \text{ ph cm}^{-2} \text{ s}^{-1}$, the $^{44}\text{Ti}$ yield is $(1-2) \times 10^{-4} \text{ M}_\odot$. The standard spherical explosion models predict the $^{44}\text{Ti}$ yield of $<10^{-4} \text{ M}_\odot$ - there exists a large difference; the case of Cas A is challenge to the supernova explosion models.

$^{44}\text{Ti}$ production depends on the symmetries and energies (Nagataki et al.1998); The explosion of Cas A could be intrinsically asymmetric; - supported by some observational evidence in the X-ray emitting ejecta of Cas A (Vink 2004; Hwang et al. 2004, 2012).
Tycho SNR

Famous historic SNR occurring in 1572; thought to be type Ia/Ib SN, recently indentified as Ia (Krause et al. 2008).

Gamma-ray observations:
GeV by Fermi/LAT, $\Gamma \sim 2.3 \pm 0.3$ (Giordano et al. 2012);
TeV by VERITAS and MAGIC, $\Gamma \sim 1.95 \pm 0.81$ (Acciari et al. 2011).

Early hard X-ray observations:
HEAO 1 (Pravdo et al. 1979) detected non-thermal emission from 5 - 25 keV with $\Gamma \sim 2.72$.
RXTE detected it up to 20 keV, $\Gamma \sim 3$ (Petre et al. 1999).
Suzaku reported non-thermal emission from 13 - 28 keV, $\Gamma \sim 2.8 \pm 0$, implying Tycho can accelerate electrons to at least 10 TeV (Tamagawa et al. 2009).
INTEGRAL observations on Tycho

- Hard X-ray flux of Tycho is about 15% of Cas A, difficult to be observed
- Our data of JEM-X and IBIS with nearly 10 tens years: first detecting hard X-ray photons to 100 keV in Tycho

3 – 10 keV  9.8σ  
20 – 60 keV  11.6σ  
60 – 90 keV  5σ
Tycho spectrum: 3–200 keV

Single power-law: $\Gamma \sim 3.18 \pm 0.09$; to 100 keV
A bump feature in 60 – 90 keV, attributed to $^{44}$Ti line signals!
**$^{44}$Ti yield in Tycho**

The observed mean flux at 68 and 78 keV: $(1.3 \pm 0.5) \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$

Distance of Tycho SNR: 1.7 – 5 kpc

$^{44}$Ti yield as function of the distance: compared with theoretical predictions:

1. Standard models (1.4 M$_\odot$ WD);
2. Double WD merger: uncertain, can produce enough $^{44}$Ti if one WD is He WD;
3. Sub-Chandrasekhar WD model (0.8 - 1.2 M$_\odot$).

The detected $^{44}$Ti lines do not support Tycho progenitor is not a Chandra-mass WD explosion.
Summary and future work

- Hard X-ray observations need more: now INTEGRAL, NuStar, in future HXMT;
- Detecting 44Ti lines in young SNRs (Cas A, Tycho) provides strong constraint on progenitors of SNe.
- Hard X-ray emissions of Cas A and Tycho show power-law components, $\Gamma \sim 3.1$, no cutoff; Detecting 220 keV photons in Cas A.
- Hard X-ray tails in SNRs challenge the present models of accelerating particles in shock waves: high magnetic field regions; particles to PeV energy bands by SNRs.
- In a relatively old SNR **RX J1713.7–3946** is also detected by IBIS, more analysis will be done.
In future, multi-wavelength data will be studied and fitted with different models: lepton and hadron models.
Hard X-ray data combined with GeV – TeV data will help to discriminate the lepton and hadron models for different SNRs.
Thank you for attention!

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