Prospects with NuSTAR and \( \gamma \)-rays

- nuclear science with NuSTAR
- NCT and modern Compton telescopes
- Laue lenses
NuSTAR
Nuclear Spectroscopic Telescope Array

bringing the high energy universe into focus
NuSTAR will be the first focusing hard X-ray satellite:
- low backgrounds
- compact detector
→ ~200x more sensitive than previous hard X-ray missions

NuSTAR primary science:
- accreting supermassive black holes (e.g., quasars)
- the black hole at the center of the Milky Way Galaxy
- neutron stars, magnetars, white dwarfs in the Milky Way Galaxy
- historical supernova remnants
- the Sun
<table>
<thead>
<tr>
<th>Satellite (Instrument)</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTEGRAL (ISGRI)</td>
<td>~0.5 mCrab (20-100 keV) with &gt;Ms exposure</td>
</tr>
<tr>
<td>Swift (BAT)</td>
<td>~0.8 mCrab (15-150 keV) with &gt;Ms exposure</td>
</tr>
<tr>
<td>NuSTAR</td>
<td>~0.8 μCrab (10-40 keV) in 1 Ms exposure</td>
</tr>
</tbody>
</table>

**Energy Range:** 5-80 keV

**Angular Resolution:**
- ~50 arcsec (HPD)
- ~10 arcsec (FWHM)

**Field of View:**
- 12.5 x 12.5 arcmin
- two 4x(32x32) CdZnTe arrays

**Spectral Resolution:**
- 1.0 keV at 60 keV
- 400 eV at 6 keV

**Sensitivity (3σ, 1 Ms):**
- 2 x 10^{-15} erg/cm²/s (6-10 keV)
- 1 x 10^{-14} erg/cm²/s (10-30 keV)

**Timing Resolution:**
- 100 μsec relative
- 30 msec absolute

**ToO Response:**
- <24 hr req’t (6-8 hr typical)
- 85% sky accessible at all times

**Launch:** June 13, 2012

**Orbit:**
- 6 degree inclination
- 550 x 600 km (+40 km?)

**Mission Lifetime:**
- 2 years baseline
- >10 years orbit lifetime

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*current best estimates (CBEs), as of February 2012*
Sgr A* July 19

Joint campaign with Chandra and Keck
ULX with XMM

IC 342 – XMM

NuSTAR 10-70 keV
1 telescope, first visit
Vela X-1 Cyclotron Line

Fit to Vela X-1 alignment data – no cyclotron line in model
Historical & Nearby Supernovae

NuSTAR will map historic SNe

$^{44}$Ti lines at 68 and 78 keV
provides important, new diagnostics

<24 hr ToO capability to observe nearby (< 4 Mpc)
core collapse SNe and SNe Ia out to Virgo, should they
occur during the lifetime of the mission

Tycho

Kepler

SN 1987A

Cassiopeia A
**Cas A SNR**

Type Ib  
~1680 AD, 3.4 kpc  
$4.2 \times 10^{-5}$ ph/cm$^2$/s  
$M_{44} \Rightarrow 2.4 \times 10^{-4}$ M$_\odot$

**NuSTAR goals**
- precise $^{44}$Ti yield measurement
- mapping of $^{44}$Ti spatial & velocity distribution
- mapping of the hard X-ray continuum emission

(Vink 2005; Vink et al., 2001; Renaud et al., 2006)
Cassiopeia A

One telescope, Gaussian smoothed.

Red: NuSTAR Fe
Green: Chandra 4-6 keV
Blue: NuSTAR 10-25 keV
**SN 1987A in the LMC**

Blue supergiant (~20 $M_\odot$, 6 $M_\odot$ He core) (Arnett et al., 1989)

Spherical models predict $^{44}$Ti < 1000 km/s

$^{56}$Ni mixed out to ~3000 km/s (0.7 keV at 68 keV)

**Table 2**

<table>
<thead>
<tr>
<th>$^{44}$Ti Mass</th>
<th>68 keV Flux</th>
<th>78 keV Flux</th>
<th>511 keV Flux</th>
<th>1.16 MeV Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit</td>
<td>$2.3 \times 10^{-4}$</td>
<td>$5.0 \times 10^{-6}$</td>
<td>$5.2 \times 10^{-6}$</td>
<td>$1.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>Lower limit</td>
<td>$8.2 \times 10^{-5}$</td>
<td>$2.5 \times 10^{-6}$</td>
<td>$2.6 \times 10^{-6}$</td>
<td>$5.2 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

The $^{44}$Ti mass is given in the unit of $M_\odot$, and the fluxes are in photons cm$^{-2}$ s$^{-1}$. (Motizuki & Kumagai 2004)
The Youngest Galactic SNR: G1.9+0.3

~2'

<130 yrs, near GC
15,000 km/s expansion
SN Ia

Sc line @ 4.09 keV (EC from $^{44}$Ti decay)
$M_{44} = (1-7) \times 10^{-5} \, M_{\odot}$

Limits from INTEGRAL-SPI:
$M_{44} < 4 \times 10^{-5} \, M_{\odot}$
(Renaud et al., 2009)

(Borkowski et al., 2010, ApJ 724, L161)
**Tycho (1572 AD) SNR**

10.5’

- Type Ia
- 2.3 kpc (Smith et al. 1991)
- ~2000 km/s expansion
- up to $2 \times 10^{-6}$ ph/cm$^2$/s

(Warren et al., 2005)

**Kepler (1604 AD) SNR**

5’

- Type Ia (Reynolds et al. 2007)
- 4 kpc (Sankrit et al. 2005)
- ~2000 km/s expansion
- up to $2 \times 10^{-6}$ ph/cm$^2$/s

(Sanskrit & Blair, 2004)
Local Type Ia Supernovae (and Core Collapse)

*HXR flux & spectrum sensitive to overall nucleosynthesis & mixing.*

(Burrows & The, 1990)

NuSTAR sensitive to ~25 Mpc

Current detections ~1-2 per year within 20 Mpc

Requires coordination with nearby SNe surveys: KAIT, PTF, CHASE, amateurs, …. 

(Milne et al. 2004)
The Nuclear Compton Telescope

A balloon-borne $\gamma$-ray spectrometer, polarimeter & imager

The NCT Collaboration:
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H.-K. Chang, C.-L. Chiu (NTHU, Taiwan)
Y.-H. Chang (NCU, Taiwan)
C.-H. Lin (AS, Taiwan)  A. Huang (NUU, Taiwan)
P. Jean, P. von Ballmoos (IRAP, France)

Supported by grants from NASA
Compton Telescopes: Then & Now

**CGRO/COMPTEL**
- \( \sim 40 \text{ cm}^3 \) resolution
- \( \Delta E/E \sim 10\% \)
- 0.1\% efficiency

**NCT**
- 1 mm\(^3\) resolution
- \( \Delta E/E \sim 0.2\%-1\% \)
- 10-20\% efficiency
- background rejection
- polarization

30+ years development
SPI/INTEGRAL:
19 coaxial Ge detectors 
(Vedrenne et al., A&A 2003)

Ge has the highest spectral resolution of the gamma-ray detectors.

At the cost of cryogenic operation.

NCT: 12 cross-strip GeDs
- 37x37 strips/GeD
- 2-mm pitch
- 15-mm thickness
- 81000 mm$^3$ volume/GeD
- 1.6 mm$^3$ localization
- ~2.1-keV noise resolution
Comparable area to COMPTEL with 1% detector volume

... and wide field-of-view!

@511 keV

NCT First Light
NCT grasp in orbit:

- Fermi model – all sky survey
- bridge the MeV gap
- background rejection
- high spectral resolution
- polarization
Laue Lens: Focusing $\gamma$-rays

$T_0$

$d_{hkl}$

$\theta_B$

$E_1$

$E_2$

$\theta_B$

Gain = 140

30-m focal length

Effective area [cm$^2$]

Energy [keV]

(von Ballmoos et al., 2010, NIM A623, 431; Smither & Roa, 2001, SPIE 4322; Barrière et al., 2010, SPIE 7732)
Recent Reviews


Backup Slides
Nuclear Line Sensitivity

Sensitivities have only improved by factors of ~10 over the lifetime of this field.
NuSTAR: first focusing hard X-ray satellite

Three Key Technologies

- **hard X-ray optics**
  (HEFT balloon)

- **deployable mast**
  (SRTM: Shuttle Radar Topography Mission)

- **CdZnTe detector**
  (HEFT balloon)

(Harrison et al., 2010, SPIE 7732)
NCT 2.0
• New detector geometry, better FoV, low-energy response, polarimetry
• All new gondola, designed for superpressure, ULDB
• Solar power
• LN2 replaced by cryocooler
• replace BGO with CsI shields
2014/2015 Flight Campaign:
• Rebuilding of instrument has begun
• Designing for superpressure balloon
• Southern hemisphere launch, eventual ULDB Flight

Primary Science Goal:
• Use Compton Imaging to map the 511 keV positron annihilation line from the galactic center

Secondary Science Goals:
• SNe gamma-ray lines
  \((^{26}\text{Al} \text{ at } 1.809 \text{ MeV}, ^{60}\text{Fe} \text{ at } 1.173/1.333 \text{ MeV}, ^{44}\text{Ti} \text{ at } 1157 \text{ MeV})\)
• Compact Objects (AGN, black holes, neutron stars)
• Gamma-ray polarization

<table>
<thead>
<tr>
<th>Source</th>
<th>Decay</th>
<th>Energy</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNe Ia (?)</td>
<td>e$^+e^-$</td>
<td>0.511</td>
<td>$36\sigma$ map</td>
</tr>
<tr>
<td>SNe II/Ib</td>
<td>$^{26}\text{Al}$</td>
<td>1.809 MeV</td>
<td>$36\sigma$ map</td>
</tr>
<tr>
<td></td>
<td>$^{56}\text{Fe}$</td>
<td>1.173, 1.333</td>
<td>$5\sigma$ detect</td>
</tr>
<tr>
<td>SNe</td>
<td>$^{44}\text{Ti}$</td>
<td>1.157</td>
<td>resolved line</td>
</tr>
<tr>
<td>BHs</td>
<td>e$^+e^-$</td>
<td>$\leq 0.511$</td>
<td>discovery</td>
</tr>
</tbody>
</table>

Angular resolution – think spectrometer, with imaging!

Hybrid Compton/Mask?

- maintain diffuse sensitivity  
  ~ few degrees
- add point-source imaging  
  ~ few arminutes
- reduced sensitivity

(M. Galloway, A. Zoglauer, in progress.)