Остаток Сверхновой 1987А и его наблюдения обсерваторией ИНТЕГРАЛ

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ИКИ РАН
Radioactive $^{56}$Co in the envelope

Next year we will celebrate 25 years of the Supernova 1987A explosion. It was the only local supernova for ~400 years and the first one from which radioactive emission has been really detected.

Optical light curves of SN1987A took an exponential shape (with a decay time of 111 days) in ~100 days after the explosion that indicates the formation of 0.07 $M_{\odot}$ of radioactive $^{56}$Co inside the envelope (~25000 Earth masses !)
Radioactive decay $^{56}\text{Ni} \to ^{56}\text{Co} \to ^{56}\text{Fe}$

$^{56}\text{Ni} \to ^{56}\text{Co}$ (8.8 days)

$^{56}\text{Co} \to ^{56}\text{Fe}$ (111.3 days)

$\langle N_\gamma \rangle \sim 2$ photons/decay

$\langle E_\gamma \rangle \sim 3.6$ MeV/decay

Photon transport in the envelope

Thomson depth $\tau_T = \int \sigma_T N_e(r) \, dr \sim 25 \, (t/\text{yr})^2$

Average number of scatterings $N_s \sim \tau_T^2 / 2$

Average change of photon energy $\frac{\Delta E_\gamma}{E_\gamma} \sim \left\{ \begin{align*}
-1/3, & \quad E_\gamma \sim m_e c^2 \\
-E_\gamma / m_e c^2, & \quad E_\gamma < m_e c^2
\end{align*} \right.$

Photoabsorption $\tau_a = \tau_T \left( \frac{Z}{Z_\odot} \right) \left( \frac{E_\gamma}{10 \text{ keV}} \right)^{-3}$

$Z$ - abundance of iron group elements
Monte-Carlo computations of multiple Compton scatterings of gamma-rays in the SN1987A envelope emitted due to the $^{56}$Co decay (Grebenev, Sunyaev, 87, based on the hydrodynamical model by Utrobin, Imshennik, 87) have shown that hard X-rays should appear at the detectable level already in half a year after the explosion. This conclusion stimulated earlier MIR-KVANT observations and led to the discovery of the continuum emission in August 1987.

Crosses - HEXE
Upper limits - TTM
Diamonds - PulsarX1

from Sunyaev et al. (Nature 1987)
Localization of the hard X-ray source

HEXE is a collimated instrument with the narrow field of view (< 1 deg). We pointed the observatory to slightly different directions to show that SN 1987A is indeed the source of the unusually hard X-ray emission discovered from the region.

Contours are given at 67, 99 and 99.9% confidence levels (dashed and solid lines - for 15-45 and 45-105 keV energy bands).

from Sunyaev et al. SvAL, 16, 171 (1990)
Hard X-rays from radioactive $^{56}$Co

Evolution of the hard X-ray spectrum of SN1987A as measured by MIR-KVANT and its explanation by radioactive decay of $^{56}$Co and Comptonization.

from Sunyaev et al. SvAL, 16, 171 (1990)
Hard X-rays from radioactive $^{56}\text{Co}$

Late evolution of the hard X-ray spectrum of SN1987A as measured by MIR-KVANT and its explanation by radioactive decay of $^{56}\text{Co}/^{57}\text{Co}$ and Comptonization.

Time scale for $^{57}\text{Co}$ decay is longer (391 days) and the emitted lines are softer (136, 122, 7.3 keV)

from Sunyaev et al. SvAL, 16, 171 (1990)
Gamma-ray lines from radioactive $^{56}$Co

Direct escape gamma-ray lines at 847 and 1238 keV from radioactive decay of $^{56}$Co in the envelope were detected by several balloon experiments and the SMM satellite.
Gamma-ray lines from radioactive $^{57}\text{Co}$

HEXE 3σ limit in the direct escape line at 122 keV corresponds to $^{57}\text{Co}/^{56}\text{Co}$ ratio 6 times exceeding the Earth's $^{57}\text{Fe}/^{56}\text{Fe}$ ratio.

OSSE measured the $^{57}\text{Co}/^{56}\text{Co}$ ratio to be $1.4 \pm 0.4$ the Earth's $^{57}\text{Fe}/^{56}\text{Fe}$ ratio (Kurfees et al. 1992).
The observed evolution of hard X-ray spectra measured with HEXE (and the evolution of flux in direct-escape gamma-ray lines) can be explained by strong mixing of radioactive $^{56}\text{Co}$ over the envelope (mushroom structure, asymmetry/jets).

For the case of spherically symmetric mixing the following distribution of $^{56}\text{Co}$ was obtained.

Sunyaev et al. (1990)

Kane, Arnett et al. (2000)
X-ray light curves as indicators of $^{56}$Co mixing

Evolution of X-ray flux from SN1987A as measured at different energies with HEXE and its sensitivity to $^{56}$Co mixing.

Solid - accepted model
Long-dashed - no mixing
Short-dashed - mixed over inner 6 $M_\odot$
Other energy sources in SN1987A (other isotopes, shock wave, and stellar remnant)?

The light curve began to deviate from the exponential law in one year when the envelope became more transparent and the energy taken by X- and gamma-rays became to be notable.
Long-term photometric light curve

After 3 years the contribution of an additional energy source (most likely $^{44}$Ti) led to another change in the slope of the light curve. According to Suntzeff (1997) the remnant’s luminosity was equal to $(1.3-2.5) \times 10^{36}$ erg/s and changes very slowly in 10 years after explosion.
Freeze-out phase

Effect of freeze-out may contribute strongly in the observed flattening of the bolometric light curve (Clayton et al. 1992; Fransson and Kozma 1993).

Assumed amount of $^{57}\text{Co}/^{56}\text{Co}$: 0, 1, 2 or 4 solar $^{57}\text{Fe}/^{56}\text{Fe} + 1.2 \times 10^{-4} M_\odot$ of $^{44}\text{Ti}$
GRANAT/ART-P observed SN1987A at 1309 day after the explosion. The figure on the left shows as Cyg X-1 hidden in the center of the envelope could be observed that time.
During last years Chandra observes a notable increase in the flux of soft thermal emission which is connected with interaction of the shock wave with the "inner equatorial ring" of SNR 1987A. The 0.3-8 keV ACIS images are shown (from Park et al. 2006).
The increase is different in the soft (0.5-2 keV) and hard (3-10 keV) bands. The hard flux correlates well with the radio flux. The luminosity of this emission increased 10 times during last 5 years and reached the value $1.6 \times 10^{36}$ ergs/s (Park et al. 2006).
X-ray emission from the shock wave

This evolution is accompanied by softening the spectrum (from $kT \sim 3$ keV at day 4600 to 2.2 keV at day 6200) and reducing the X-ray radial expansion rate (Park et al. 2006).
X-ray emission from the shock wave

Since 8000 days the light curve flattened at the level of $3.6 \times 10^{36}$ ergs/s (Park et al. 2011).
The Chandra/ACIS 90% confidence upper limit on the observed 2-10 keV luminosity of the point source (stellar remnant of SN1987A) was \(5.5 \times 10^{33}\) ergs/s (Park et al. 2004).

The XMM-Newton can not resolve the source and provides a higher limit \(5 \times 10^{34}\) ergs/s (2-10 keV, Shtykovskiy et al. 2005, Haberl et al. 2006).

Unfortunately photoabsorption is still very strong in this rather soft energy band. For the adopted \(^{56}\)Co distribution

\[ \tau_a \sim 6 \left( \frac{E_{\gamma}}{10 \text{ keV}} \right)^{-3} \left( \frac{t}{6000 \text{ days}} \right)^{-2} \]

at the epoch of obtaining the above limits. The corrected luminosity will exceed \(2 \times 10^{36}\) ergs/s in the case of Chandra.

XMM-Newton can not resolve the source and provides a higher limit $5 \times 10^{34}$ ergs/s (2-10 keV, Shtykovskiy et al. 2005, Haberl et al. 2006).
The limit for any continuum emitter in the broad optical band at the center of SNR 1987A was found to be $L_{\text{opt}} = 8 \times 10^{33}$ ergs/s (Graves et al. 2005).
Hubble R-band images

The observations on 1994-09-24, 2000-11-13 and 2009-04-29 (correspond to 2770, 5012 and 8101 days after the explosion). The red ellipse shows the expanding aperture used to extract the light curve.
Hubble light curves

They show the increasing contribution from illumination of the ejecta by X-rays from the shock wave (from Larsson 2011).
Международная Астрофизическая Лаборатория Гамма-Лучей ИНТЕГРАЛ
(International Gamma-Ray Astrophysics Laboratory - INTEGRAL)

Миссия ЕКА с участием России (Роскосмос, РАН), США (НАСА) и научных организаций Европы.

Предназначена для сверхтонкой гамма-спектроскопии (E/ΔE ~ 500), получения детальных изображений неба, локализации (с точностью до минут дуги) и исследования переменности космических источников в диапазоне энергий 15 кэВ - 10 МэВ с одновременным мониторингом в рентгеновском (4-35 кэВ) и оптическом (фильтр V, 550 нм) диапазонах.
Выведен на орбиту носителем ПРОТОН с космодрома Байконур 17 октября 2002 г.

Сейчас выполняет 1119 виток вокруг Земли
На борту находятся 4 научных прибора (SPI, IBIS, JEM-X и OMC). В обмен на запуск спутника ИНТЕГРАЛ на орбиту российские ученые получают ~25% долю наблюдательного времени всех приборов обсерватории. Приоритетное право на анализ данных и публикацию результатов дается сроком на 1 год. После этого данные поступают в общедоступный архив.
Восстановление изображений неба, полученных гамма-телескопами с кодированной апертурой

Crab

3C273
Гамма-спектрометр SPI  
(SPectrometer for INTEGRAL)

- Массив 19 Ge детекторов, охлажденных до 85 К
- Площадь 500 см², вес 1300 кг
- Диапазон энергий 20 кэВ - 8 МэВ
- Энергетическое разрешение 2.2 кэВ на 1.3 МэВ  
(ΔE/E=0.2%)
- Полностью кодированное поле зрения 16º (FCFOV)
- Угловое разрешение 2.5º
- PI институты: CESR Toulouse (F), MPE Garching (D)
Гамма-телескоп IBIS
(Imager on Board the INTEGRAL Satellite)

- Два слоя позиционно-чувствительных детекторов:
  - 16384 элементов CdTe 4х4х2 мм с общей площадью 2600 см²
  - 4096 CsI элементов 9х9х30 мм с общей площадью 2890 см²
- Вес 750 кг
- Диапазон энергий 15 кэВ -10 МэВ
- Энергетическое разрешение ΔE/E=7%
- Поле зрения 9°×9° (FCFOV)
- Угловое разрешение 12 мин. Дуги
- PI институты: IAS Roma (I), CEA Saclay (F), ITESRE Bologna (E)
INTEGRAL observations

The LMC field was observed by INTEGRAL in January, 2003, with a total exposure of about 1.2 Ms (it was one of the first targets of INTEGRAL).

The limit \(2\sigma\) for the 20-60 keV luminosity of SN1987A was equal to \(1.1 \times 10^{36}\) ergs/s. Being extrapolated to the soft X-ray band (2-10 keV) it gives the luminosity \((0.6-1.6) \times 10^{36}\) ergs/s (Shtykovsky et al. 2004).

ISGRI/IBIS (20-60 keV)
INTEGRAL observations

$^{44}\text{Ti} \rightarrow ^{44}\text{Sc} \rightarrow ^{44}\text{Ca}$ with the characteristic time $t_{44} = 86.6$ years

$$F_{44}(i) = \frac{M_{44} W_i}{4\pi d^2 44 \ m_p t_{44}} \ exp \ (-t/t_{44})$$

Two $^{44}\text{Ti}$ lines 67.9 and 78.4 keV with $W=88$ and 95% and
Two gamma-ray lines 511 and 1157 keV with $W=189$ and 99%

$M_{44} = 1.6 \times 10^{-4} \ M_{\odot}$ gives $F_{68} = 0.93 \ F_{79} = 0.88 \ F_{1157} = 4 \times 10^{-6}$ phot/cm$^2$/s.

Our estimates have shown that we can expect to measure the flux in two softer lines (at once) at 3.9-sigma level with an exposure of 4.5 Ms and at 5.3 sigma level with an exposure of ~9 Ms. Such exposures are not exotic for current INTEGRAL observations. We started to accumulate the data and now have ~6 Ms (1.1 Ms in AO-1, 0.4 in AO-2, 2.0 in AO-7, 1.5 in AO-8 + 1.0 Ms by Coe et al. in AO-7).
**JEM-X image of LMC**

Only known sources were detected

3-18 keV, ~1.2 Ms
IBIS/ISGRI image of LMC

Large population of sources

20-40 keV, ~4.8 Ms
A number of known sources were detected and many new ones.
IGR J05415-6900 was discovered and identified as Be-transient

20-40 keV, ~4.8 Ms

It is likely that there is another new source near PSR J0540-693.

No emission from SN1987A in this band
IBIS/ISGRI images of SN1987A

No emission from SN1987A in the 44-49 and 49-54 keV bands (in spite of huge exposure ~6 Ms). $S/N = 2.5, 3.0, 3.5, 4.0, ...$
Images of SN1987A

No emission in the 59-65, 82-89 and 89-100 keV bands
Images of SN1987A

But there is an obvious source in the 65-82 keV band where the Ti-44 lines are emitted (and in 2 more narrow bands).
Detection of $^{44}\text{Ti}$ lines from SNR 1987A with INTEGRAL

submitted to Nature by S. Grebenev, A. Lutovinov, S. Tsygankov, C. Winkler
Spectrum of SN1987A

The measured spectrum is consistent with two Ti-44 lines at 67.9 and 78.4 keV with the fluxes $\sim1.7\times10^{-5}$ phot/cm$^2$/s.

$S/N=4.1\sigma$ corresponds to chance probability $P=2\times10^{-5}$

In two bands 63-73 and 73-84 keV $S/N =3.0$ and 3.1 thus

$P=p_1 \times p_2 =1.3\times10^{-6}$ ($\sim4.7\sigma$)
Spectrum of SN1987A

The SPI spectrum in Ti-44 line at 1275 keV with the flux (for FWHM = 7.0 keV)

\( \sim (3.4+/-1.5) \times 10^{-5} \text{phot/cm}^2/\text{s}. \)
Amount of synthesized $^{44}$Ti in SN1987A

The measured fluxes in the lines correspond to the initial amount of $^{44}$Ti

$$M_{44} \sim (6.8+/-1.9) \times 10^{-4} \, M_{\odot} \text{ (3-4 times higher than was supposed)}$$

$^{44}$Ti can be produced due to

1). “alpha-rich freeze-out” (e.g. Woosley, Hoffman 91)

2). incomplete O-burning in the thin boundary shell

High amount of $^4$Ti $M_{44} > 4 \times 10^{-4} \, M_{\odot}$ was supposed earlier from the [OII] $\lambda \lambda 3726,3728$ observations with HST (Wang et al. 96, Chugai et al. 97) and from the observed flattening of the bolometric light-curve $M_{44} \sim 10^{-3} \, M_{\odot}$ (Suntzheff et al. 92, 97)
We are preparing now to detect radioactive emission from SN2011fe in M101. These figures were shown during 4 years ago.
Thank you!
Observations in the standard X-ray band

Nothing below 15 keV has been detected that confirms our conclusion on strong low energy cut-off in the X-ray spectrum of SN1987A (connected with photoabsorption).
Comparison with point source in other SNRs

<table>
<thead>
<tr>
<th>SNR</th>
<th>Source</th>
<th>$\log L_X$ (ergs s$^{-1}$)</th>
<th>$\log L_{opt}$ (ergs s$^{-1}$)</th>
<th>Age (yr)</th>
<th>Possible in SN 1987A?</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 1987A</td>
<td>Point source</td>
<td>$\leq 33.74$</td>
<td>$\leq 33.9$</td>
<td>16.75</td>
<td>...</td>
</tr>
<tr>
<td>Kes 75</td>
<td>PSR J1846−0258</td>
<td>$&gt;34.6$</td>
<td>...</td>
<td>1700</td>
<td>N</td>
</tr>
<tr>
<td>Crab</td>
<td>PSR B0531+21</td>
<td>$36.2$</td>
<td>$33.8$</td>
<td>950</td>
<td>N</td>
</tr>
<tr>
<td>N158A</td>
<td>PSR B0540−69</td>
<td>$36.4$</td>
<td>$33.9$</td>
<td>1660</td>
<td>N</td>
</tr>
<tr>
<td>N157B</td>
<td>PSR J0537−6910</td>
<td>$35.5$</td>
<td>$\leq 33.1$</td>
<td>5000</td>
<td>N</td>
</tr>
<tr>
<td>MSH 15−52</td>
<td>PSR B1509−58</td>
<td>$35.3$</td>
<td>...</td>
<td>1800</td>
<td>N</td>
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<tr>
<td>Vela</td>
<td>PSR B0833−45</td>
<td>$31.3$</td>
<td>$28.8$</td>
<td>$1.1 \times 10^4$</td>
<td>Y</td>
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<tr>
<td>Monogem Ring</td>
<td>PSR B0656+14</td>
<td>$30.2$</td>
<td>$28.2$</td>
<td>$1.1 \times 10^4$</td>
<td>Y</td>
</tr>
<tr>
<td>Geminga</td>
<td>PSR J0633+1746</td>
<td>$30.2$</td>
<td>$27.5$</td>
<td>$3.4 \times 10^4$</td>
<td>Y</td>
</tr>
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</table>

Nonpolaronic X-Ray Point Sources in SNRs

<table>
<thead>
<tr>
<th>SNR</th>
<th>Source</th>
<th>$L_X$ (ergs s$^{-1}$)</th>
<th>$L_{opt}$ (ergs s$^{-1}$)</th>
<th>Age (yr)</th>
<th>Possible in SN 1987A?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cas A</td>
<td>Point source</td>
<td>$33.8-34.6/33.3^c$</td>
<td>$\leq 29.1^{d}$</td>
<td>400</td>
<td>N/Y</td>
</tr>
<tr>
<td>Pup A</td>
<td>1E 0820−4247</td>
<td>$33.6^c$</td>
<td>$\leq 30.3^{d}$</td>
<td>3000</td>
<td>Y</td>
</tr>
<tr>
<td>RCW 103</td>
<td>1E 1614−5055</td>
<td>$33.9^c$</td>
<td>$\leq 30.8^{d}$</td>
<td>8000</td>
<td>N</td>
</tr>
<tr>
<td>PKS 1209−52</td>
<td>1E 1207−5209</td>
<td>$33.1^c$</td>
<td>$\leq 30.1^{d}$</td>
<td>7000</td>
<td>Y</td>
</tr>
</tbody>
</table>

Anomalous X-Ray Pulsars

<table>
<thead>
<tr>
<th>SNR</th>
<th>Source</th>
<th>$L_X$ (ergs s$^{-1}$)</th>
<th>$L_{opt}$ (ergs s$^{-1}$)</th>
<th>Age (yr)</th>
<th>Possible in SN 1987A?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kes 73</td>
<td>1E 1841−045</td>
<td>35.5</td>
<td>...</td>
<td>$\leq 2000$</td>
<td>N</td>
</tr>
<tr>
<td>G29.6+0.1</td>
<td>AX J1845−0258</td>
<td>$38.6/34.9^c$</td>
<td>...</td>
<td>$\leq 8000$</td>
<td>N</td>
</tr>
<tr>
<td>CTB 109</td>
<td>1E 2259+586</td>
<td>$36.9^d$</td>
<td>...</td>
<td>8800</td>
<td>N</td>
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</table>

Soft Gamma Repeaters

<table>
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<tr>
<th>SNR</th>
<th>Source</th>
<th>$L_X$ (ergs s$^{-1}$)</th>
<th>$L_{opt}$ (ergs s$^{-1}$)</th>
<th>Age (yr)</th>
<th>Possible in SN 1987A?</th>
</tr>
</thead>
<tbody>
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<td>SGR 1900+14</td>
<td>$34.6^{d}$</td>
<td>...</td>
<td>$10^{4}$</td>
<td>N</td>
</tr>
<tr>
<td>G337.0−0.1?</td>
<td>SGR 1627−41</td>
<td>$35.8$</td>
<td>...</td>
<td>5000</td>
<td>N</td>
</tr>
</tbody>
</table>

from Graves et al. (2005).
**SNII, 50 kpc, 1 Msec, 1,2,3 years**

*SPI will be able to detect SNII at ~1 Mpc!*
Spectrum of SN1987A

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The measured fluxes in the lines correspond to the initial amount of $^{44}$Ti

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$^{44}$Ti can be produced due to

1). “alpha-rich freeze-out” (e.g. Woosley, Hoffman 91)

2). incomplete O-burning in the thin boundary shell
Spectrum of SN1987A

The SPI spectrum in Ti-44 line at 1275 keV with the flux (for sigma= 2.1 keV)

~(3.2+/−1.4)x10^{-5} \text{ phot/cm}^2/\text{s}.