Constraints on the luminosity of the stellar remnant in SNR1987A

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We obtain photometric constraints on the luminosity of the stellar remnant in SNR1987A using XMM-Newton and INTEGRAL data. The upper limit in the 2–10 keV band based on the XMM-Newton data is $L_X \lesssim 5 \times 10^{34}$ erg/s. We note, however, that the optical depth of the envelope is still high in the XMM-Newton band, therefore, this upper limit does not constrain the true unabsorbed luminosity of the central source. The optical depth is expected to be small in the hard X-ray band of the IBIS telescope aboard the INTEGRAL observatory, therefore it provides an unobscured look at the stellar remnant. We did not detect statistically significant emission from SN1987A in the 20-60 keV band with the upper limit of $L_X \lesssim 1 \times 10^{36}$ erg/s. We also obtained an upper limit on the mass of radioactive $^{44}$Ti $M(^{44}$Ti) $\lesssim 10^{-3}$ $M_\odot$.

Keywords: supernova remnants, pulsars

1. Introduction.

Owing to its proximity, Supernova SN1987A in the Large Magellanic Cloud provides a unique possibility to study the physics of a supernovae and supernova remnants.

Today it reveals itself as an extended object experiencing rapid evolution. The observed X-ray emission of the supernova is dominated by the interaction of the shock wave with the matter produced by the wind from a supergiant phase of its progenitor. As a result of this interaction the supernova was gradually increasing its luminosity during the past decade. This was followed by a strong brightening of the supernova on December 2002 when the shock wave encountered the so-called inner ring (see Park et al. (2004) and references therein).

Based on the Balmer lines in the optical spectrum, identification of a massive blue supergiant progenitor (Sonneborn et al., 1987) and the neutrino burst (Hirata et al., 1987) coincident with the SN event, SN1987A was classified as a Type II core-collapse supernova. The mass of the progenitor was estimated to be $\approx 15-20 M_\odot$ (Woosley et al., 1987). Sunyaev et al. (1987) detected strong very hard X-ray source after about 169 days from the explosion but this emission was connected with comptonisation of gamma-ray lines of Ce$^{56}$ decay in the optically thick envelope. The lines themselves became visible later (e.g. Teegarden et al., 1984).

The collapse of such a massive star should lead to the formation of a neutron star or a black hole. If a neutron star was born with strong magnetic field and was rapidly rotating, it should appear as a luminous Crab-like X-ray source or as an accreting pulsar, which usually also have very hard X-ray spectrum with maximal contribution to luminosity in the INTEGRAL band. Neutron star without strong magnetic field or a black hole might become a bright X-ray source due to the accretion of the matter of the dense envelope. Park et al. (2004) obtained from an imaging analysis of the Chandra data an upper limit $L_X(2-10\text{ keV}) < 1.5 \times 10^{34}$ erg/s on the luminosity of the central source. However the envelope continues to be optically thick and there is a possibility that its optical depth is still high in the standard X-ray band and does not permit us to observe the central source directly. It is important to check that it is not specially bright in the hard X-ray band, where the envelope is transparent both for the Thomson scattering and photoabsorption. In addition we decided to check the available data obtained by the XMM-Newton observatory, which has higher sensitivity for photons with energies $\gtrsim 5$ keV than Chandra.

Here we present results of analysis of INTEGRAL and XMM-Newton observations of SN1987A and constrain the luminosity of the stellar remnant embedded in the envelope based on its X-ray spectrum.

2. Data reduction and results

2.1. XMM-Newton

SNR1987A was observed by XMM-Newton in September and November 2000, April 2001 and May 2003. These
observations were processed with the Science Analysis System (SAS) v6.0.0. The data were screened for the soft proton flares by removing the time intervals where the count rate above 10 keV significantly exceeded the mean level. For the pointing in April 2001 because of numerous soft proton flares the background threshold was chosen higher than the quiescent background typical for time periods without flaring activity. To be sure that this does not influence our results, we repeated analysis with different thresholds on background level and a background subtraction from different regions on detector and found no significant variations in the obtained results.

The angular resolution of the XMM-Newton, unlike that of the Chandra, is insufficient to resolve the remnant, and it appears as a point-like source on the extracted images. However, XMM-Newton is more sensitive to the photons with energy $>5$ keV and therefore allows to reconstruct the sources spectra to higher energies. The EPIC spectra were extracted from a $30'' - 40''$ circle regions around the SNR. Corresponding background spectra were extracted from the nearby regions.

The spectra of the SN1987A remnant obtained with XMM-Newton on September 2000 and May 2003 together with NEI model fit (the plane-parallel shock model [Borkowski et al. 2001a] where the plasma has not reached the collisional ionization equilibrium) are shown in Fig. 1. As is evident from the figure, the luminosity of the remnant increased by a factor of $\sim 3$ during three years. This is expected from the interaction of the supernova shock with the matter left from the stellar wind of a supergiant progenitor. It seems that there is some excess of hard X-ray emission in comparison with NEI model for pointing on May 2003. Such a high energy tail could be associated with either a central source or a synchrotron radiation from the shell of the remnant (e.g. [Borkowski et al. 2001b]). We focus on the possible association of the high energy excess with the central source. Detailed analysis of the supernova remnant spectra is not a subject of this paper and could be found in e.g. [Park et al. 2004; Aschenbach 2002].

To obtain a conservative upper limit on the central source luminosity we shall assume that the total flux observed at the high energy part of the remnant’s spectrum is produced by the central source. For this analysis we used the data of the early pointings (2000 and 2001 years), as a contribution of the emission originating from the interaction of the shock with the medium would be smaller for them. Assuming the spectrum of the central source to be a powerlaw with a photon index $2.0$, we obtained the upper limit ($1\sigma$) for its 2-10 keV luminosity $L_X \lesssim 5 \times 10^{34}$ erg/s, assuming a distance to the source $d = 50$ kpc. The obtained value is in the same range, but somewhat higher than the upper limit obtained by Chandra from the imaging analysis [Park et al. 2004].

### 2.2. INTEGRAL

The international gamma-ray laboratory INTEGRAL [Winkler et al. 2003] observed the Large Magellanic Cloud several times on January 2003 with a total exposure about 1 Mln sec. In our analysis we used publicly available data obtained by the ISGRI detector of the IBIS telescope of the observatory. ISGRI is sensitive to the photons in the E> 20 keV energy band. The data of INTEGRAL/IBIS/ISGRI were processed with the method developed by Eugene Churazov and described in Revnivtsev et al. (2004). Detailed analysis of Crab nebula observations suggests that with the approach and software employed, the conservative estimation of the uncertainty in measurements of absolute fluxes from the sources is about 10%.

To investigate the hard X-ray emission from the SN1987A remnant we analyzed data obtained with INTEGRAL/IBIS/ISGRI in the 20-60 keV energy band, where the sensitivity of the ISGRI detector is maximal. We reconstructed the image of the central part of the Large Magellanic Cloud in this energy band (see Fig. 2 and did not find statistically significant emission from the remnant with the upper limit of $F_X \lesssim 3.7 \times 10^{-12}$ erg/s/cm$^2$ ($2\sigma$, assuming a Crab-like spectrum), that corresponds to the luminosity of $L_X \lesssim 1.1 \times 10^{36}$ erg/s.

### 2.3. Optical depth of the envelope

The envelope of the supernova at early times was optically thick both for photoabsorption and Thomson scattering. This, for example, follows from the observations of Renigen observatory on the KVANT module of MIR station (Sunyaev et al. 1987; see also Grebenev & Sunyaev 1987). As the envelope expands and its density decreases, its optical depth decreases with time as $\tau \propto t^{-2}$. Given the Fransson & Chevalier (1987) model for the photoabsorption optical depth of the envelope, and assuming $t^{-2}$ behaviour, we obtain $\tau_{photo} \sim 7$ for a 5 keV photons at the epoch of XMM-Newton observations. The photoabsorption optical depth reaches unity only on energies $\sim$11-15 keV. Thus, the optical depth is still high in the energy bands of Chandra and XMM-Newton. Therefore the upper limits provided by these observatories correspond to the small fraction of the central source emission which escaped the envelope, while the real central source luminosity could be much higher.

Similar estimate of the optical depth for 40 keV photons give value $\tau_{photo} \sim 0.02$, therefore the hard X-ray radiation escapes the envelope without absorption. For the
Thomson optical depth we obtained also very low values, \( \tau_T \sim 0.005 - 0.1 \) depending on the model of matter distribution in the envelope. Was the \( \tau_T \) close to unity or even a bit higher, it would not affect the flux in 20-60 keV energy band because of small energy change for one scattering, \( \Delta E/E \approx h\nu/m_e c^2 \sim 0.1 \) (Pozdniakov et al., 1983). Thus, the INTEGRAL observations offer us a direct look at the central source and its upper limit constraints the real luminosity of the stellar remnant.

Absorbed emission in the standard X-ray band is reemitted in the optical and infrared bands and an upper limit on the central source luminosity could be estimated based on a bolometric luminosity of the SNR in these energy bands. For example, Suntzeff (1997) estimated the bolometric luminosity of the remnant \( \log(L) \sim 36.1 - 36.4 \) after the 3600 days from the explosion. This value could be interpreted as an upper limit on the central source luminosity corrected for the absorption, what is close to a limit obtained from the INTEGRAL data. Obviously, the upcoming Spitzer data will provide an interesting estimates on the luminosity of the central source, absorbed and re-radiated in the infrared band by the optically thick for the standart X-rays envelope.

2.4. Limit on the nucleosynthesis of \(^{44}\text{Ti}\)

While the early (except for the first few weeks) bolometric luminosity of the supernova was powered by the \(^{56}\text{Co}\) decay \( (t_{1/2} \sim 77 \text{ days}) \), at later times elements with longer decay times, like \(^{44}\text{Ti}\) \( (t_{1/2} \sim 60 \text{ years}) \), give the main contribution. Decay of the \(^{44}\text{Ti}\) gives rise to two gamma photons with energies 67.9 keV and 78.4 keV. Simple estimations on the fluxes of these lines give value \( \sim 3 \times 10^{-13} \text{erg/s/cm}^2 \) (see e.g. Motizuki & Kumagai, 2004), assuming mass of titanium \( M(^{44}\text{Ti})= 10^{-4} M_\odot \). To estimate the mass of the synthesized \(^{44}\text{Ti}\), we calculated fluxes observed by INTEGRAL in the 61-73 keV and 73-88 keV energy bands, \( F_X(61-73 \text{ keV})=4.30 \pm 1.25 \times 10^{-12} \text{erg/s/cm}^2 \) and \( F_X(73-88 \text{ keV})=2.50 \pm 1.60 \times 10^{-12} \text{erg/s/cm}^2 \). In the first case the flux has a formal significance of 3.4\( \sigma \), however we consider it insufficient to claim a reliable detection of the line emission. Therefore to estimate the mass of \(^{44}\text{Ti}\), we assume both fluxes to be upper limits and obtain \( M(^{44}\text{Ti}) \leq 10^{-3} M_\odot \).

3. Conclusion

Based on the data of XMM-Newton and INTEGRAL, we provide broadband spectroscopic constraints on the luminosity of the central source in the SN1987A. Assuming that a hard energy tail of the XMM-Newton spectrum of the remnant is dominated by a central source, we obtained an upper limit \( L \leq 5 \times 10^{34} \text{erg/s} \) for 2-10 keV central source luminosity uncorrected for absorption, which is somewhat higher than the upper limit obtained by Chandra from imaging analysis. INTEGRAL did not detect any statistically significant emission from the remnant and provided an upper limit for 20-60 keV luminosity of \( L_X \leq 1.1 \times 10^{36} \text{erg/s} \), what corresponds to 2-10 keV luminosity \( L_X \leq (0.6 - 1.6) \times 10^{36} \text{erg/s} \) assuming Crab-pulsar like spectrum. The obtained upper limits on the possible central source luminosity in comparison with the typical
spectra of Crab-like pulsar, accreting X-ray pulsar and accreting black hole are shown on Fig. 3.

Based on the existing calculations of the photoabsorption optical depth of the envelope, we show that absorption in the standard X-ray band of the XMM-Newton and Chandra is still high and obtained upper limit corresponds to luminosity not corrected for absorption, which could be only a small fraction of a real luminosity. The optical depth in the INTEGRAL energy band is significantly less than unity and obtained upper limit constrain real luminosity of a stellar remnant.

We also obtained an upper limit on the mass of $^{44}$Ti $M(^{44}$Ti)$\lesssim 10^{-3}M_\odot$.

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**Fig. 2.** Map of the part of LMC around of the SN1987A position, obtained with INTEGRAL in the 20-60 keV energy band. Position of SN1987A is shown by the cross.

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Fig. 3. The typical spectra produced by accreting X-ray pulsar, accreting black hole (Gilfanov et al., 2000) and rotation-powered Crab-like pulsar. All spectra are normalised to the luminosity of $2.5 \times 10^{36}$ erg/s in the 1-12 keV energy band. This corresponds to the bolometric optical and infrared luminosity (Suntzeff, 1997), which could be interpreted as an upper limit on the central source luminosity absorbed by the envelope. Upper limits on the luminosity of central source in SNR1987A obtained by the XMM-Newton and INTEGRAL observatories are also shown.

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