THERMAL RADIATION FROM A NEUTRON STAR IN SN 1987A

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The supernova 1987A in the Large Magellanic Cloud has provided a new opportunity to study the evolution of a young neutron star right after its birth. A proto-neutron star first cools down by emitting neutrinos that diffuse out of the interior within a minutes. After the neutron star becomes transparent to neutrinos, the neutron star core with $> 10^{14}$ g cm^{-3} cools predominantly by Urca neutrino emission. However, the surface layers remain hot because it takes at least 100 years before the cooling waves from the central core reach the surface layers (Nomoto and Tsuruta 1981, 1986, 1987).

From the hot surface, thermal X-rays are emitted. The detection limit for X- rays from SN 1987A by the Ginga satellite is 3 $\times 10^{36}$ erg s^{-1} (Makino 1987; Tanaka 1987). If the thermal X-rays are to be observed by Ginga, the surface temperature should continue to be as high as $T_s > 8 \times 10^6$ $(R/10\mathrm{km})^{-1/2}$ K until the ejecta becomes transparent. The exact value of the initial surface temperature depends on various factors during the violent stages of explosion, cooling stages of the proto-neutron star through diffusive neutrinos, and possible re-infalling of the ejected material. Therefore, until the surface layers become thermally relaxed T_s may satisfy the above condition.

Figure 1 shows the cooling behavior of neutron stars during the first one year after the explosion. The total luminosity of the surface photon radiation L_{ph} (left) and the surface temperature T_s (right), both to be observed at infinity, are plotted as a function of time, for three nuclear models PS (stiff), FP (intermediate), and BPS (soft). The temperature scale refers to the FP model.

From Figure 1 it is clear that the surface radiation falls significantly below the Ginga detection limit within a few to $\sim$ 20 days for all the models considered. Such a decrease is caused by the plasmon neutrino emission from the outer layers of $\rho = 10^9$ - 10^{10} g cm^{-3}. The surface layers at the lower densities ($\rho < 10^{10}$ g cm^{-3}) are so thin that the time scale of thermal conduction is shorter than the time scale of the plasmon neutrino cooling. Consequently, the surface cooling quickly follows the plasmon neutrino cooling in the layers just beneath the surface. This mechanism of surface cooling by the plasmon neutrino process clearly wipes out the initial conditions. We note that during these early stages the surface temperature is independent of the complicated thermal behavior in the central core.

https://doi.org/10.1017/S0252921100094367 Published online by Cambridge University Press

Consequently, it is unlikely that Ginga would detect the thermal X-ray emission directly from the surface of a neutron star in SN 1987A even if the ejecta should become transparent right now.

Looking beyond Ginga, it should be important to search by other future X-ray satellites for a thermal soft X-ray point source in SN 1987A. This is because due to the finite time scale of thermal conduction, it will take at least another 100 years before the efficient cooling of the central core by the Urca process will be registered at the surface. Until then the observed surface temperature will remain at the level of at least two to four million degrees (see Figure 9 in Nomoto and Tsuruta 1987). These temperatures correspond to the observed luminosity of $> 10^{35}$ erg s^{-1}. Note that the expected detection limit for ROSAT is 10^{34} erg s^{-1} (Trumper 1981), while for AXAF it is less than 10^{32} erg s^{-1} (NASA 1980).

We conclude that future satellite observations of SN 1987A with high sensitivity soft X-ray detectors should be critical in order to test the evolution theories of young neutron stars. This goal may very well be realized within the next 10 years, by the programs such as ROSAT, SXO, GRANAT, SPECTRA, and AXAF.

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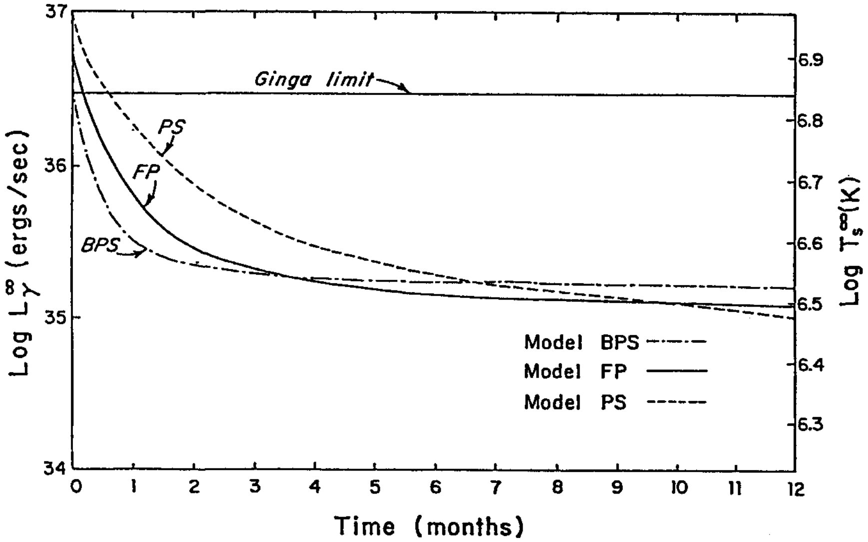

Figure 1: Observed photon luminosity vs. time during a year after the supernova explosion predicted from standard cooling theory of neutron stars. Shown are three representative nuclear models PS (dashed), FP (solid), and BPS (dot-dashed). The detection limit from Ginga is shown as a horizontal line.

https://doi.org/10.1017/S0252921100094367 Published online by Cambridge University Press