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Type I Supernovae and Iron Nucleosynthesis in the Universe

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Abstract. It is argued that the iron nucleosynthesis rate in the universe due to SNI outbursts is dependent on the mass function of star formation. Since the mass function depends on the chemical composition and since the masses of SNI precursors have upper limits, the iron nucleosynthesis rate was low at an earlier evolutionary epoch of the universe when mainly massive stars were formed. The iron nucleosynthesis rate should reach a maximum near $z \sim 0.5$. At such or similar value of z the well-known 'step' in the cosmic γ-ray background spectrum may be explained by the presence of γ-gray quanta accompanying the radioactive $^{56}Co \rightarrow {}^{56}Fe$ decay. An argument is presented against the identification of the hidden mass of the universe with black-hole remnants of 'type III' stars.

Key words: pregalactic stars—Supernovae—nucleosynthesis—cosmic γ-ray background

The idea that each outburst of a type I supernova (SNI produces about $1M_\odot$ of radioactive ^{56}Ni in the decay of which, with a half-life of 6.1d, radioactive ^{56}Co is generated transforming (half-life 77 d) in its turn into a stable isotope of iron ^{56}Fe, has a fairly long history (*cf.* Colgate & McKee 1969). The analysis of the spectra of SNI 1972e at a late stage of its evolution has yielded convincing arguments in favour of this idea (Kirshner & Oke 1975). These spectra have most reliably shown that beyond 50 d after the maximum, the SNI radiation in the visual band is determined by the blending of allowed and forbidden lines of Fe I and Fe II . According to Kirshner & Oke, the mass of ionized iron in the shell of this SN is about 10^{-2} $M_\odot$. Meyerott (1980), and independently Shklovskiĭ (1981) have shown that in such a shell, iron should mainly be present as Fe III with the total mass of about $1M_\odot$.

Until recently, the hypothesis of 'radio-active nickel' faced a serious difficulty: X-ray spectroscopy methods failed to reveal an anomalously high iron abundance in the remnants of historic SNI (Tycno 1572, Kepler 1604, and 1006), though many attempts have been made. However, the IUE satellite observations of the fairly faint blue star SM onto which the central part of the SNR 1006 remnant is projected, helped to identify in its spectrum wide ($\Delta v \sim 5 \times 10^3$ km s^{-1}) and intense (apparently saturated) absorption lines of multiplets I, II, III of ionized iron. The total amount of iron in the ejected shell may reach 1 $M_\odot$ (Wu *et al.* 1983).

These observations show most convincingly that each SNI outburst does generate about $1M_\odot$ of iron. Meanwhile, observations in the optical and X-ray spectral regions do not imply any excess iron in the shells and remnants of larger-mass type II

Supernovae (SNII). Apparently SN of this type are responsible for the nucleosynthesis of such abundant nuclei as C, O, N and Si. We may thus postulate that iron nucleosynthesis in the universe owes its origin only to SNI outbursts. Though it is impossible at present to prove this postulate, it seems fairly well established empirically.

The postulate that only SNI are responsible for Fe nucleosynthesis enables several important cosmological conclusions. We begin by noting that the masses of stars exploding as SNI are comparatively small, or at least have an upper limit. It is a simple and well-known fact that SNI outbursts are not connected with the spiral structure of galaxies (Maza & van den Bergh 1976), that allows the conclusion that masses of SNI precursors are $< 7M_{\odot}$. We have argued recently that SNI represent the final evolutionary stage of stars whose core masses differ only slightly from the Chandrasekhar limit M_{Ch} (Shklovskiĭ 1983b)*. According to Paczynski (1970), such stars have initial masses from 3 to $7M_{\odot}$. Stars with masses over $7M_{\odot}$ form, during their evolution, cores whose masses exceed M_{Ch}. The evolution of these stars ends in an SNII explosion. Finally, stars of comparatively small mass—with a core mass smaller than M_{Ch}—end their evolution as white dwarfs prior to which their outer shell is detached producing a planetary nebula. Thus, iron nucleosynthesis occurs during the final stage of evolution of stars with initial masses within a comparatively narrow range of $3–7M_{\odot}$†. The question is when these stars might form.

The mass function $\psi(M)$ of stars newly formed from the diffuse medium depends on the chemical composition of the latter, or, on the percentage of heavy elements (by mass) Z, to be more exact. If $\psi(M) = AM^{-\alpha}$, then, as Terlevich & Melnik (1983) showed recently for galactic and metagalactic objects, the following empirical relation is valid:

$$\alpha = \log Z + 5.05. \qquad (1)$$

This relation implies, *inter alia*, that if the diffuse medium from which stars form could be very poor in heavy elements (*e.g.* $Z \sim 10^{-5}$), mainly massive stars would form in it. Thus there would be no stars capable of exploding as SNI at the end of their evolution. Therefore, no iron nucleosynthesis would occur.

Recently a new interest has been shown in hypothetical stars of ‘population III’ (‘zero’ generation) which apparently preceded the formation of contemporary stars and galaxies (see *e.g.* Bond, Carr & Arnett 1983). As stars of this type should form from the primordial hydrogen-helium medium with negligible amounts of other elements, Z is very small, and therefore the mass function exponent α should be negative. This means that only stars of large (perhaps very large) mass could form at that epoch and no SNI outbursts or related iron nucleosynthesis would occur.

Stars with the masses corresponding to the precursors of SNI could form only after the interstellar diffuse medium became sufficiently enriched with heavy elements. It might possibly occur, for example, when zero-generation stars evolved and most of them exploded as SNII. According to Bond, Carr & Arnett (1983), the evolution of stars of very large mass should be accompanied by the formation of a considerable number of heavy elements (up to 10 per cent by mass). However, if zero-generation stars really did exist, they could hardly enrich the diffuse medium to an appreciable degree. The fact

* Recent estimates show that among the three bright nuclei of planetary nebulae in the Magellanic Clouds (the distance to which is well known and prevents possible mistakes) one nucleus has a mass of $1.2M_{\odot}$, which is sufficiently close to M_{Ch} (Stecher *et al.* 1982).

† SNI outbursts may also occur in old binary systems due to gas accretion onto a degenerate component after the mass of the latter reaches M_{Ch}.

that among oldest galactic populations (globular clusters, halo stars) there are stars extremely poor in metals ($Z < 10^{-4}$) should imply that the diffuse medium from which they formed had a similar low Z. But, in line with the assumption, the medium should have been enriched with heavy elements, by the end products of zero-generation stars. Hence it follows that only an insignificant part of the primordial diffuse medium (~ 10^{-1} to 10^{-2}) might have condensed into stars of 'zero' generation. For during the evolution of such stars most of their material should have been reworked into heavy elements and swept away into the interstellar space. But if the total mass of 'zero'-generation stars were essentially smaller than the mass of the interstellar medium, the 'hidden' mass of the universe cannot be explained by black-hole remnants of such stars. An impression sets in that stars of zero generation (population III) do not yet provide a clear possibility of the evolution of matter in the universe*. There is no need to introduce into cosmology those hypothetical objects to explain nucleosynthesis. We should then consider a continuous enrichment of iron in the universe, and the enrichment rate should be related to the variation of the mass function of star formation, which, in turn, depends on the continuous increase of Z.

The following circumstance should be emphasized. In the 'old' objects with a reduced abundance of heavy elements, the abundance ratio Fe/O is much lower than that of the Sun's. For example, according to Peimbert (1973) the abundance ratio Fe/O in the planetary nebula K 648 that belongs to the globular cluster M 15, is lower by about a factor of 10 compared to the solar value. Sneden, Lambert & Whitaker (1979) have showed that this ratio is lower than the solar value by a factor of 3 in stars of low metallicity. The extended X-ray halo of M 87 has a similar deficiency of Fe/O (Canizares *et al.* 1982), though the stellar halo has the same O/H as the Sun. We have recently interpreted these observations on the assumption that the SNI precursors have a low mass of 1.5–2$M_\odot$ (Shklovskiĭ 1983a). However, reliable observational and theoretical data indicates a much larger precursor mass of about 3–7$M_\odot$ (Clayton & Silk 1969). Hence the explanation we have given earlier for the smallness of abundance of old objects seems to be wrong.

Much more natural, in our opinion, is the assumption of a gradually changing mass function of newly generated stars, the change being the result of a continuous increase of heavy-element abundance in the interstellar medium. At the epoch when the process of star formation was just beginning, Z was very small and so was accordingly the index α in Equation (1). At this epoch almost no stars formed in the range of 3–7 $M_\odot$, and the iron enrichment of the interstellar medium was slow. However, the rate of production of comparatively massive stars having been high, the interstellar medium was being enriched with lighter elements (C, O, N and Si) at a high speed, inducing a change in the mass function and a growing number of stars in the mass range corresponding to the precursors of SNI. The Fe nucleosynthesis rate first became equal to and then larger than, that of lighter 'metals'.

Since Z increases continuously, the Fe nucleosynthesis rate should decrease after reaching the maximum at a certain redshift, say, z_1. It is of interest to estimate the epoch $T_1 = T_0 (1 + z_1)^{-3/2}$ (T_0 being the age of the universe), when the rate reached the maximum. The rigorous mathematical consideration of this problem requires the knowledge of parameters such as the absolute value of the rate of star formation in

* In our view, the recent discovery of an infrared background radiation announced by Matsumoto, Akiba & Murakami (1983) and interpreted by them as the total radiation from zero-generation stars red-shifted by $z \sim 10$, is questionable and needs verification.

galaxies of various types, of the frequency and intensity of flashes of star-formation, *etc.* Values of these parameters are not even known to a first approximation. A method could, however, be suggested which—at least in principle—may help solve this problem. It is well known that γ-ray lines with the energy of ~ 1 MeV are emitted due to the radio-active decay in an SNI shell. Since even before half of ^{56}Co has decayed, the SNI shells become semi-transparent to radioactive γ-radiation, a considerable part of that radiation first enters the interstellar, and next the inter-galactic medium where the probability of their absorption is negligible. Thus it may be expected that the γ-ray lines, accompanying iron nucleosynthesis in SNI outbursts, will be present in the background cosmic hard-photon radiation.

According to Meyerott (1980), the surface density of an SNI shell is several g cm^{-2} after $t_{1/2}$ = 77 d (^{56}Co half-life). At this epoch, the absorption coefficient—the main contribution to which is from the Compton effect—equals 0.25 cm^2 g^{-1}, and hence the optical depth of the shell for γ-ray quanta generated within is τ_γ (t = $t_{1/2}$) ~ 1· Taking into account the attenuated power of radioactive γ-radiation, an assumption can be made that 0.3 of the quanta produced in the radioactive decay of ^{56}Co diffuse into the interstellar space, and then into the metagalaxy.

Thus a certain spectral feature should be expected in the background of the metagalactic isotropic γ-radiation. This idea was first suggested by Clayton & Silk as early as in 1969. However, accurate measurements of the γ-ray background had not yet been made at the time, and the nature of SNI phenomenon was much farther from understanding than it is now. Besides, Clayton & Silk believed that the rate of enrichment in the universe is either constant or increases inversely proportional to that of the universe. On the other hand, according to the above considerations, it reaches a fairly smooth maximum at $z = z_1$. This implies that there is a fairly wide spectral feature in the hard background radiation spectrum, that is, a radiation band. What are the chances of observing it?

Assume that the 'smeared' density of matter in the universe is ρ_0. The local density of γ-quanta produced when iron nuclei form via the ^{56}Co → ^{56}Fe radioactive decay will then be

$$n_\gamma = \frac{\rho_0}{m_{\text{Fe}}} \delta\xi \tag{2}$$

where m_{Fe} is the mass of the iron nucleus, $\delta \simeq 10^{-3}$ is the present average cosmic Fe abundance, ξ is the fraction 0.3 of γ-ray quanta freely leaving the SN I shell. The intensity of this radiation calculated per unit energy interval is

$$I = \frac{n_\gamma c}{4\pi} \frac{E}{\Delta E} \text{keV cm}^{-2} \text{sr}^{-1} \text{keV}^{-1} \tag{3}$$

where E is the energy of the quanta and ΔE the width of the spectral region. We assume that $\Delta E \sim E$ and $\rho_0 = 10^{-30}$ g cm^{-3}. Then

$$I \sim 10^{-2} \text{keV cm}^{-2} \text{sr}^{-1} \text{keV}^{-1} \tag{4}$$

Observations have long ago shown a 'step' (bending) in the spectrum of the background cosmic γ radiation for E = 1 to 2 MeV (*cf.* Ramaty & Lingenfelter 1982b). The background intensity in the considered range is just equal to the value needed. The energies of γ-ray quanta of lines that occur in ^{56}Co radioactive decay are 0.845 (1), 1.26

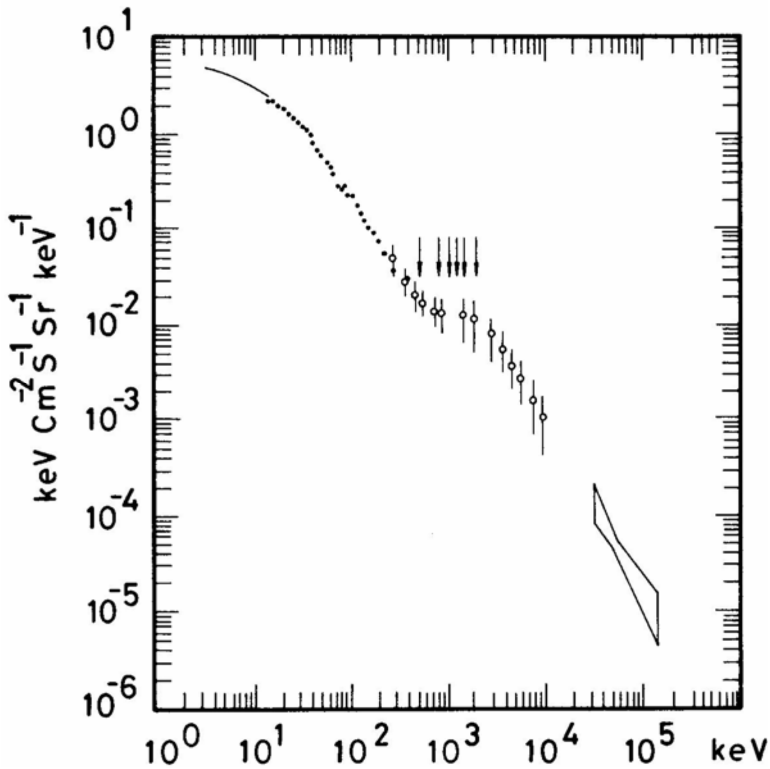

Figure 1. The diffuse X-ray and gamma-ray back ground spectrum. Nuclear lines of ^{56}Fe, 0.85, 1.26, 1.74, 2.01, 2.55 and 3.25 MeV which are radiated during the decay of ^{56}Co (Ramaty & Lingenfelter 1982a) are shown (arrows) corresponding to a cosmological redshift $z = 0.5$.

(0.5), 1.74 (0.2), 2.01 (0.1), 2.55 (0.2) and 3.25 (0.2) MeV. (The numbers in parentheses are the relative intensities of the respective lines.) If these lines are assumed to be responsible for the step in the spectrum of the background soft cosmic γ-radiation, they need to be redshifted by $z_1 \sim 0.5$. It should be kept in mind that the step is observed in the portion of the spectrum showing steep rise towards lower energies. Thus less intense though harder quanta make the largest contribution. The epoch of maximum Fe-production rate $T_1 \simeq T_0/(1 + z_1)^{3/2} = 0.5T_0$ corresponding to $z_1 \sim 0.5$; here T_0 is the present age of the universe. It is evident that the estimate of the intensity of γ-ray quanta accompanying iron nucleosynthesis is very crude. New high-quality observations of the cosmic background should be carried out in the range 0.8–3 MeV.

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