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EVIDENCE FOR NEARBY SUPERNOVA EXPLOSIONS

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Supernova explosions are one of the most energetic—and potentially lethal—phenomena in the Universe. Scientists have speculated for decades about the possible consequences for life on Earth of a nearby supernova, but plausible candidates for such an event were lacking. Here we show that the Scorpius-Centaurus OB association, a group of young stars currently located at ~ 130 parsecs from the Sun, has generated 20 SN explosions during the last 11 Myr, some of them probably as close as 40 pc to our planet. We find that the deposition on Earth of ^{60}Fe atoms produced by these explosions can explain the recent measurements of an excess of this isotope in deep ocean crust samples. We propose that ~ 2 Myr ago, one of the SNe exploded close enough to Earth to seriously damage the ozone layer, provoking or contributing to the Pliocene-Pleistocene boundary marine extinction.

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It has been proposed that the Local Bubble, a 150 pc hot ($T \approx 10^6$K), low-density gas cavity which surrounds the solar system, was formed by several SN explosions during the last ≈ 10 Myr [1]. The paucity of SNe in the Galaxy makes very unlikely that several isolated SN explosions would happen in short succession within such a small region, but about 20% of all SNe originate in OB star associations, and are therefore strongly clustered in time and space. By tracing back in time the positions of all nearby OB associations, it is possible to show that the Sco-Cen association was the only one able to produce SNe in the right numbers and places to generate the Local Bubble [2].

This association can be divided into three subgroups [3]: Lower Centaurus Crux (LCC), Upper Centaurus Lupus (UCL) and Upper Scorpius (US). Using detailed age [4] and membership information [3], it is possible to compare the current numbers of early/late OB stars in each subgroup with the predictions of synthetic star formation models. The agreement with these models is good and based on them it can be estimated that each subgroup started producing SNe at 3-5 Myr after their formation, i.e. $7-8$, $10-11$ and $2-3$ Myr ago respectively, with an expected constant rate of ~ 1 SN Myr^{-1} (see Ref. [2] for details).

The current distances to the Sco-Cen subgroups can be reliably calculated using trigonometric parallaxes [5], and then traced back in time taking into account the motion of both the Sco-Cen association and the Sun with respect to the local standard of rest which rotates with the Galaxy, as described in Ref. [2]. Fig 1. shows how the distance from Earth of each subgroup has evolved during the epoch in which they were actively producing SNe. At its closest, about $2-3$ Myr ago, the center of LCC was at ~ 100 pc from the Solar System; the spatial extent of these groups can be approximated by a Gaussian with $\sigma = 25-30$ pc, what means that SNe from LCC could have exploded as close as ~ 40 pc from Earth (2σ lower limit).

The explosion of a nearby SN can be detected by isotope anomalies in the geological record caused by the deposition of SN debris [6]. Recently, Knie et al. [7] measured a significant excess of ^{60}Fe atoms in two layers of deep ocean crust corresponding to the intervals $0-2.8$, $3.7-5.9$ Myr (see Table 1). They concluded that these ^{60}Fe atoms could only be produced by a SN explosion, which they proposed took place about ~ 5 Myr ago at $D \sim 30$ pc, causing the excess of ^{60}Fe in the second layer. The youngest layer results were tentatively explained as due to a background of radioactive iron in the solar neighborhood. A reanalysis of these data came to similar conclusions[8], but attributed the presence of ^{60}Fe in the younger layer to biomixing. Here we propose that the origin of the ^{60}Fe atoms are the Sco-Cen SNe. As we show below, both the amplitude and timing of their expected deposition rate are in the right range to explain the observed excess.

Gas ejecta from a SN explosion cannot easily reach the Earth unless the pressure from the SN blast front is larger than the ram pressure of the solar wind at the Earth orbit. For an isolated SN, whose front reaches the Solar System driven by momentum conservation[9], this

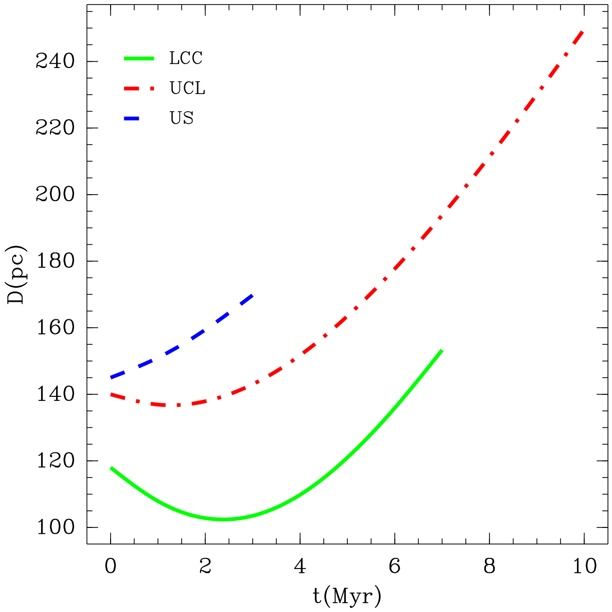

FIG. 1: Evolution of the total distance between the Sun and Sco-Cen subgroups during the last 11 Myr. For each subgroup, only the epoch during which SNe were being formed is shown (see also Fig. 1 of Ref. [2] which shows the projection onto the Galactic Plane of the positions of the Earth and the Sco-Cen association)

roughly defines a cut-off distance of $15-100$ pc (depending on the geometrical configuration of the SN, the Sun and the Earth)[6]. This is also true in the case of multiple SN, though in that case the second and subsequent SNe explode in a very low density medium, making their expansion follow the Sedov regime[1, 10, 11] up to distances comparable with Local Bubble size ~ 200 pc. Although this would make it difficult for *gaseous* debris from all but the closest Sco-Cen SNe to penetrate the heliosphere up to the Earth's radius, observations show that most of the iron in the Local Bubble is condensed forming dust [1, 12]. The interaction of interstellar dust with the solar wind and magnetic field is a complex problem, which strongly depends on the size of the dust particles[13], but interstellar dust containing iron has been found at the Earth's orbit [14], and it seems reasonable to assume that most, or at least a large fraction of the iron reaching the heliosphere traveling in a SN blast front would have reached the Earth's orbit.[13].

Table 1 presents the typical distance and expected number of Sco-Cen SNe in each of the corresponding time intervals. The expected surface density of ^{60}Fe (corrected for in situ decay) deposited in a layer $N(\Delta l)$ can be estimated [8] as:

$$N(\Delta l) = 4.1 \times 10^7 N_{\rm SN} f \left(\frac{M_{^{60}{\rm Fe}}}{10^{-5}{\rm M}_\odot}\right)\left(\frac{100\,{\rm pc}}{D}\right)^2 {\rm cm}^{-2}\ ,$$

where $N_{\rm SN}$ is the number of SNe, which are assumed to happen at a typical distance $\sim D(\Delta l)$ during the time interval covered by each of the sediment layers, f is the uptake factor that [7] estimate as 1/100, and $M_{^{60}{\rm Fe}}$ is the expected ^{60}Fe yield by a SN. To compare with the results of Ref. [7], we divide $N(\Delta l)$ by the Δt covered by each layer, which yields the flux $\phi_{\rm SN}$ (cm^{-2} Myr $^{-1}$)presented in Table 1.

TABLE I: PREDICTIONS AND MEASUREMENTS OF ^{60}FE EXCESS IN DEEP OCEANIC CRUST SAMPLES (CORRECTED FOR IN SITU DECAY)

	Layer 1	Layer 2	Layer 3
age(Myr)	0-2.8	3.7-5.9	5.9-13
$N_{\rm SN}$	8	4	6
D$_{\rm SN}$ (pc)	130	140	205
$\phi_{\rm SN}$ (10^6cm^{-2} Myr^{-1})	$0.7^{+6.30}_{-0.06}$	$0.4^{+3.6}_{-0.04}$	$0.08^{+0.8}_{-0.01}$
$\phi_{\rm b}$(10^6 cm^{-2} Myr^{-1})	0.11	1.5	5
$\phi_{\rm SN}+\phi_{\rm b}$ (10^6cm^{-2} Myr^{-1})	$0.81^{+6.30}_{-0.06}$	$1.9^{+3.6}_{-0.04}$	$5.08^{+0.8}_{-0.01}$
$\phi_{\rm obs}$ (10^6 cm^{-2} Myr^{-1})	$1.0^{+0.5}_{-0.3}$	8^{+11}_{-5}	$10^{+22}_{-8.5}$

This estimation has several sources of uncertainty. The ^{60}Fe yield can vary from 10^{-4} M$_\odot$ to 10^{-6} M$_\odot$ depending on the SN mass (type II SN, [15, 16, 17, 18, 19, 20]). Also, the uptake factor f, which represents the fraction of ^{60}Fe atoms present in the ocean which is deposited in the crust, has large and difficult to estimate uncertainties [8]. To compound these two error sources, the positions and time of the explosions can have a considerable scatter, and even the total number of SNe has a Poisson uncertainty of 24%. Therefore, we consider the values of $\phi_{\rm SN}$ in Table 1 to be, at best, order-of-magnitude estimates, and that is reflected in the error bars assigned to our predictions in Fig 2. Table 1 also presents the inferred average fluxes $\phi_{\rm obs}$ measured by Ref. [7], and the expected background level $\phi_{\rm b}$ based on a measurement of a 13 Myr old core. Note that in Fig 2, we have added the ^{60}Fe background rate [7] $\phi_{\rm b}$ to the contribution from the Sco-Cen SNe $\phi_{\rm SN}$, and that the error bars correspond only to the uncertainty in $\phi_{\rm SN}$, since the above reference does not provide an error estimate for the background.

The agreement is excellent for the first and youngest layer, which has the highest signal-to-noise. The flux measured in the second layer is a factor 4 higher than our prediction, but there is an ample overlap between the error bars of both quantities, and thus the results can be considered consistent. Regarding the third, oldest layer, it is not clear whether there is any signal above the background, so our prediction of a very small flux is also compatible with the observation . It should also be noted that no signal of SN origin was detected in the same layers for another isotope ^{53}Mn [7, 8], which is again consistent with our scenario since the predicted ^{53}Mn deposition rates are much lower than the background of cosmogenic origin. We therefore conclude that the Sco-Cen SNe are enough to explain the excess of ^{60}Fe in the deep

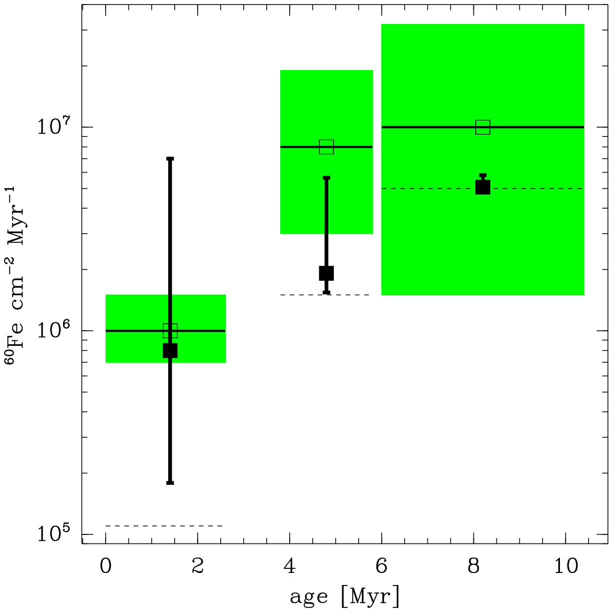

FIG. 2: Comparison between the ^{60}Fe deposition rate predicted from the Sco-Cen SNe and the measurements of deep ocean crust samples. The horizontal continuous lines/empty squares and the shadowed boxes represent respectively the data and errors of Ref. [7], while our predictions and associated error estimates are represented by the filled squares and error bars. The dashed lines correspond to the background estimates of Ref. [7]

ocean crust. It will be very interesting to obtain crust data with better "temporal" resolution to identify individual SN explosions; including in the search other SN-created radioisotopes with low backgrounds and proper decay rates would allow to pin down the mass range of the progenitors and the distance at which the SNe exploded.

Several authors [21, 22, 23, 24] have proposed that the explosion of a nearby SN could have caused one or more of the massive extinction events in the fossil record. At distances larger than a few pc, the only component of the SN emission capable of performing serious damage to the biosphere is the charged cosmic ray radiation [25] (for instance, hard UV radiation from the SN shock breakout would produce flux levels above the atmosphere of $F_{UV} \sim 10^7 (50\mathrm{pc/D})^2$ ergs cm−2 during 1 day [26], a level smaller than the amount of similar radiation received from the Sun [27]). A strong increase in the flux of cosmic rays reaching the upper levels of the atmosphere speeds up the production of NO, which catalytically destroys large amounts of ozone molecules [24]. Assuming that the energy released by the SN in cosmic rays is 10^{50} ergs, the time integrated flux or fluence reaching Earth will be [25]:

$$\phi_{CR} \Delta t \approx 2.2 \times 10^9 \left(\frac{10\,\mathrm{pc}}{D} \right)^2 \mathrm{ergs\,cm^{-2}}$$

It has usually been considered in the literature [24, 25, 28] that the cosmic rays would travel by diffusion in a random Galactic magnetic field with a scale-length of 1 pc and that, therefore, the above flux would be spread over a period of $\Delta t \approx 3(D/1\ \mathrm{pc})^2$ yr. However, the assumption of randomness is not valid in this case: the magnetic field in the outer 'shell' of the Local Bubble is probably coherent on large scales and very weak or inexistent in its interior [29], being pushed out by the effects of the SN explosions. Therefore, the amount of cosmic rays reaching the Earth in the event of a nearby SN explosion would strongly depend on the relative position of the SN with respect to Earth and the Local Bubble shell. If both the SN and the Sun are within the cavity, the cosmic rays will probably travel unhindered and hit the Earth spread over a $\Delta t \sim \tau$, where τ corresponds to their emission period, estimated to be in the range $\tau \sim 10 - 10^5$yr [25, 30]. If the SN were in the outside, the Bubble shell would serve as a "conductor" for the cosmic rays if the Sun were also outside the Bubble, or as an "insulating" shield, if the Sun were inside.

This means that the value of the time interval Δt is highly uncertain, and the best we can do is estimate the *maximal* CR flux produced by one of the Sco-Cen SNe by taking the fluence above and a Δt similar to the lower limit of the typical cosmic ray acceleration time $\tau \sim 10$ yr. Using the minimal distance for the Sco-Cen SNe $D \geq$ 40pc we find that $\phi_{CR} \leq 1.4 \times 10^7 \mathrm{ergs\ cm^{-2} yr^{-1}}$, within a factor 2 of the flux estimated by [25] for a 10 pc event using the random magnetic field assumption. It has been estimated [31] that such an event would lead to a ozone depletion of 60% at high latitudes and about 20% at the equator.

Therefore, the subsequent increase in the UV-B flux from the Sun reaching the Earth surface due to one or more of the Sco-Cen SNe could have caused at most a minor extinction [32, 33], but would not be enough to provoke a major mass extinction like e.g. the Cretaceous-Tertiary event (see also [26], where the mutagenic effects of excess UV radiation are discussed in detail). This extinction would particularly affect marine ecosystems, as first proposed by Ref. [25]; an increase on the UV-B flux over the ambient level can provoke a significant reduction in phytoplankton abundance and biomass, propagating to at least one species of zooplankton as a secondary effect [34]. Despite the uneven distribution of the ozone depletion, tropical species would be more affected due to the higher solar angle at which they receive their UV dose [33]. Therefore, the biological signature of a SN explosion provoking a "clean" UV-B catastrophe would be a decline of ocean surface phytoplankton productivity not associated with other causes as volcanic activity, climate changes or impact events. A decline in plankton productivity would be very difficult to detect in the fossil record, but it could be inferred from secondary effects, in particular an extinction of mollusks [35].

Such an extinction affecting marine tropical, subtropical and temperate American bivalves characterized the Pliocene-Pleistocene boundary, ~ 2 Myr ago [32, 36, 37, 38] (see also Ref. [39]). Two hypotheses have been advanced to explain this phenomenon: the emergence of the Panama isthmus [40, 41] and cooling due to the onset of Northern Hemisphere glaciations [42, 43, 44]. However, this extinction episode was too rapid to be due to the Panama isthmus closure [43, 44] and a detailed analysis of the extinction patterns seems to rule out cooling as the cause [35, 40]. A simultaneous, although slower, episode of extinction affected corals [44], which are known to be highly susceptible to UV-B radiation [33]. This leaves a SN-provoked UV-B catastrophe as a possible candidate for the Pleistocene–Pliocene extinction; it should be noted that this epoch roughly coincides with the time of closest approach of LCC (see Fig. 1), during which the probability of nearby SN explosions would have been highest. In addition, Ref. [45] proposed that a SN blast wave ionized the local interstellar medium between 2 and 3.6 Myr ago.

To test this hypothesis, the time and distance at which individual SN explosions took place should be determined more precisely, using geological information as suggested above. A coincidence in time between the SN expected to have strongest effects on the biosphere and the Pleistocene-Pliocene extinction, would strongly support the existence of a link between both events.

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