Evidence from stable isotopes and $^{10}$Be for solar system formation triggered by a low-mass supernova

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About 4.6 billion years ago, some event disturbed a cloud of gas and dust, triggering the gravitational collapse that led to the formation of the solar system. A core-collapse supernova, whose shock wave is capable of compressing such a cloud, is an obvious candidate for the initiating event. This hypothesis can be tested because supernovae also produce telltale patterns of short-lived radionuclides, which would be preserved today as isotopic anomalies. Previous studies of the forensic evidence have been inconclusive, finding a pattern of isotopes differing from that produced in conventional supernova models. Here we argue that these difficulties either do not arise or are mitigated if the initiating supernova was a special type, low in mass and explosion energy. Key to our conclusion is the demonstration that short-lived $^{10}$Be can be readily synthesized in such supernovae by neutrino interactions, while anomalies in stable isotopes are suppressed.
N early four decades ago Cameron and Truran suggested that the formation of our solar system (SS) might have been due to a single core-collapse supernova (CCSN) whose shock wave triggered the collapse of a nearby interstellar cloud. They recognized that forensic evidence of such an event would be found in CCSN-associated short-lived (≤ 10 Myr) radionuclides (SLRs) that would decay, but leave a record of their existence in isotopic anomalies. Their suggestion was in fact stimulated by observed meteoritic excesses in 26Mg (ref. 2), the daughter of the extinct SLR 26Al with a lifetime of τ ~ 1 Myr. The inferred value of 26Al/27Al in the early SS, orders of magnitude higher than the Galactic background, requires a special source.

While simulations support the thesis that a CCSN shock wave can trigger SS formation and inject SLRs into the early SS4–6, detailed modelling of CCSN nucleosynthesis and an accumulation of data on extinct radionuclides have led to a confusing and conflicting picture7,8. CCSNe of ≥ 15 solar masses (M⊙) are a major source of stable isotopes such as 24Mg, 26Si, and 40Ca. The contributions from a single CCSN in this mass range combined with the dilution factor indicated by simulations4–6 would have caused large shifts in ratios of stable isotopes that are not observed3. A second problem concerns the relative production of key SLRs: such a CCSN source grossly overproduces 53Mn and 60Fe (ref. 3), while producing (relatively) far too little of 10Be.

Although the overproduction of 53Mn and 60Fe can plausibly be mitigated by the fallback of inner CCSN material, preventing the ejection of these two SLRs3,8, the required fallback must be extremely efficient in high-mass CCSNe.

Here we show that the above difficulties with the CCSN trigger hypothesis can be removed or mitigated, if the CCSN mass was ≤ 12M⊙. The structure of a low-mass CCSN progenitor differs drastically from that of higher-mass counterparts, being compact with much thinner processed shells. Given the CCSN trigger hypothesis, we argue that the stable isotopes alone demand such a progenitor. But in addition, this assumption addresses several other problems noted above. First, we show the yields of 53Mn and 60Fe are reduced by an order of magnitude or more in low-mass CCSNe, making the fallback required to bring the yields into agreement with the data much more plausible. Second, we show that the mechanism by which CCSNe produce 10Be, the neutrino spallation process 12C(n, n')11B, differs from other SLR production mechanisms in that the yield of 10Be remains high as the progenitor mass is decreased. Consequently we find that an 11.8M⊙ model can produce the bulk of the 10Be inventory in the early SS without overproducing other SLRs. We conclude that among possible CCSN triggers, a low-mass one is demanded by the data on both stable isotopes and SLRs.

It has been commonly thought that 10Be is not associated with stellar sources, originating instead only from spallation of carbon and oxygen in the interstellar medium (ISM) by cosmic rays (CRs)9 or irradiation of the early SS material by solar energetic particles (SEP)10,11 associated with activities of the proto-Sun. It was noted in Yoshida et al.12 that 10Be can be produced by neutrino interactions in CCSNe, but the result was presented for a single model and no connection to meteoritic data was made. Further, that work adopted an old rate for the destruction reaction 10Be(n, α)7Be that is orders of magnitude larger than currently recommended13, and therefore, greatly underestimated the 10Be yield.

10Be has been observed in the form of a 10B excess in a range of meteoritic samples. Significant variations across the samples suggest that multiple sources might have contributed to its inventory in the early SS14–19. Calcium-aluminum-rich inclusions (CAIs) with 26Al/27Al close to the canonical value were found to have significantly higher 10Be/7Be than CAIs with fractionation and unidentified nuclear isotope effects (FUN-CAIs), which also have 26Al/27Al much less than the canonical value18. As FUN-CAIs are thought to have formed earlier than canonical CAIs, it has been suggested15 that the protosolar cloud was seeded with 10Be/7Be ~ 3 × 10–4, the level observed in FUN-CAIs, by for example, trapping Galactic CRs, and that the significantly higher 10Be/7Be values in canonical CAIs were produced later by SEPs10,11.

A recent study20 showed that trapping Galactic CRs led to little 10Be enrichment of the protosolar cloud and long-term production by Galactic CRs could only provide 10Be/7Be ≤ 1.3 × 10–5. Instead, CRs from either a large number of CCSNe or a single special CCSN were proposed to account for 10Be/7Be ~ 3 × 10–4. While this pre-enrichment scenario is plausible, it depends on many details of CCSN remnant evolution and CR production and interaction. Similarly, further production of 10Be by SEPs must have occurred at some level, but the actual contributions are sensitive to the composition, spectra and irradiation history of SEPs as well as the composition of the irradiated gas and solids10,11,21, all of which are rather uncertain. In view of both the data and uncertainties in CR and SEP models, we consider it reasonable that a low-mass CCSN provided the bulk of the 10Be inventory in the early SS while still allowing significant contributions from CRs and SEPs. Specifically, we find that such a CCSN can account for 10Be/7Be = (7.5 ± 2.5) × 10–4 typical of the canonical CAIs22. Following the presentation of our detailed results, we will discuss an overall scenario to account for 10Be and other SLRs based on our proposed low-mass CCSN trigger and other sources.

Results

Explosion modelling. We have calculated CCSN nucleosynthesis for solar-composition progenitors in the mass range of 11.8–30M⊙. Each star was evolved to core collapse, using the most recent version of the 1D hydrodynamic code KEPLER23,24. The subsequent explosion was simulated by driving a piston from the base of the oxygen shell into the collapsing progenitor. Piston velocities were selected to produce explosion energies of 0.1, 0.3, 0.6 and 1.2 B (1 B = 1051 ergs) for the 11.8–12, 14, 16 and 18–30M⊙ models, respectively, to match results from recent CCSN simulations25,26. The material inside the initial radius of the piston was allowed to fall immediately onto the protoneutron star forming at the core. In our initial calculations, shown in Fig. 1 and labelled Case 1 in Table 1, we assume all material outside the piston is ejected. Neutrino emission was modelled by assuming Fermi-Dirac spectra with chemical potentials μ = 0, fixed temperatures Tν = 3 MeV and Tν ~ Tν ~ Tν ~ Tν ~ Tν ~ Tν ~ Tν ~ ~ 5 MeV, and luminosities decreasing exponentially from an initial value of 16.7 B ≈ 1 per species, governed by a time constant of ~ 3 s. This treatment is consistent with detailed neutrino transport calculations27 as well as supernova 1987A observations28. A full reaction network was used to track changes in composition during the evolution and explosion of each star, including neutrino rates taken from Heger et al.29.

Nucleosynthesis yields. Figure 1 shows the yields normalized to the 11.8M⊙ model as functions of the progenitor mass for stable isotopes 16O, 24Mg, 26Si, 40Ca and 60Fe as well as SLRs 10Be, 11B, 39K, 53Mn, 60Fe and 107Pd. It can be seen that except for 10Be, the yields of all other isotopes increase sharply for CCSNe of 14–30M⊙. Therefore, a high-mass CCSN trigger is problematic, generating unacceptably large shifts in ratios of stable isotopes and overproducing SLRs such as 53Mn and 60Fe (ref. 3). Fallback of ≥ 1M⊙ of inner material in such CCSNe was invoked in Takigawa et al.8 to account for the data on the SLRs 26Al, 41Ca, 53Mn and 60Fe. Using our models (Supplementary Table 1), we
find that similar fallback scenarios and dilution factors are required but the problem with stable isotopes persists (Supplementary Discussion). In contrast, even for Case 1 without fallback, the yields of the 11.8M⊙ model (Supplementary Tables 2 and 3) are consistent with meteoritic constraints for all major stable isotopes (Supplementary Discussion). We focus on the production of SLRs by this model below.

Figure 1 shows that in contrast to other isotopes, the 10Be yield from 12C via 12C(ν, νp)10Be is relatively insensitive to progenitor mass. This reflects the compensating effects of higher C-zone masses but lower neutrino fluxes (larger C-zone radii) in more massive stars (see Supplementary Discussion for more on SLR production). Our demonstration here that 10Be is a ubiquitous CCSN product of neutrino-induced nucleosynthesis consequently allows us to attribute this SLR to a low-mass CCSN, explaining its abundance level in canonical CAIs, while achieving overall consistency with the data on other SLRs coproduced by other mechanisms in the CCSN. More quantitatively, let R denote a given SLR, I its stable reference isotope, YR the total mass yield of R from the CCSN, and f the fraction of the yield that was incorporated into each M⊙ of the protosolar cloud (that is, the dilution factor). The number ratio of R to I in the early SS due to this CCSN is

\[
\left( \frac{N_R}{N_I} \right)_{\text{ess}} \sim \frac{Y_R/A_R}{X^\odot M_\odot/A_I} \exp\left( -\frac{\Delta}{\tau_R} \right),
\]

where A_R and A_I are the mass numbers of R and I, X^\odot is the solar mass fraction of I^\odot, Δ is the time between the CCSN explosion and incorporation of R into early SS solids, and τ_R is the lifetime of R.

Table 1 gives the mass yields of 10Be, 26Al, 36Cl, 41Ca, 53Mn, 60Fe, 107Pd, 135Cs, 182Hf and 205Pb for the 11.8M⊙ model. A comparison of equation (1) to the observed value, including uncertainties, yields a band of allowed f and Δ for each SLR. Simultaneous explanation of SLRs then requires the corresponding bands to overlap. Figure 2 shows a region of concordance for 10Be, 41Ca and 107Pd. This fixes f and Δ, allowing us to estimate the contributions from the 11.8M⊙ CCSN to other SLRs. The Case 1 contributions to 26Al, 36Cl, 33Mn, 60Fe, 135Cs, 182Hf and 205Pb in Table 1 correspond to f~5 × 10^-4 and Δ~1 Myr, the approximate best-fit point indicated by the filled circle in Fig. 2.

The slow-neutron-capture (s) process product 182Hf is of special interest, as the yield of this SLR is sensitive to the β-decay rate of 181Hf, which may be affected by thermally populated low-lying excited states under stellar conditions. We treat the excited-state contribution as an uncertainty, allowing the rate to vary between the laboratory value and the theoretical estimate of ref. 47 with excited states. (The latter is numerically close to

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**Table 1** | Yields of short-lived radionuclides from an 11.8-solar-mass core-collapse supernova.

| R/I        | τ_R (Myr) | Y_R (M⊙) | X/⊙ | (N_R/N_I)_{ess} | Data | Case 1 | Case 2 | Case 3 |
|------------|-----------|-----------|------|-----------------|------|--------|--------|--------|
| 10Be/9Be   | 2.00      | 3.26 (10) | 1.40 (10) | (7.5 ± 2.5)(-4) | 6.35 (-4) | 6.35 (-4) | 5.20 (-4) |
| 26Al/27Al  | 1.03      | 2.91 (-6) | 5.65 (-5) | (5.23 ± 0.13)(-5) | 1.02 (-5) | 9.90 (-6) | 5.77 (-6) |
| 36Cl/35Cl  | 0.434     | 1.44 (-7) | 3.50 (-6) | ~ (3-20)(-6) | 2.00 (-6) | 1.45 (-6) | 6.15 (-7) |
| 41Ca/40Ca  | 0.147     | 3.66 (-7) | 5.88 (-5) | (4.1±2.0)(-9) | 3.40 (-9) | 2.74 (-9) | 2.26 (-9) |
| 53Mn/52Mn  | 5.40      | 1.22 (-5) | 1.29 (-5) | (6.28±0.66)(-6) | 4.04 (-4) | 6.39 (-6) | 6.16 (-6) |
| 60Fe/56Fe  | 3.78      | 3.08 (-6) | 1.12 (-3) | ~ 1 (0,-8)(5-10)(-7) | 9.80 (-7) | 9.80 (-7) | 1.10 (-7) |
| 107Pd/106Pd| 9.38      | 1.37 (-10)| 9.92 (-10) | (5.9 ± 2.2)(-5) | 6.27 (-5) | 6.27 (-5) | 5.72 (-5) |
| 135Cs/133Cs| 3.32      | 2.56 (-10)| 1.24 (-9) | ~ 5 (4) | 7.5 (5) | 7.5 (5) | 3.18 (5) |
| 181Hf/180Hf| 12.84     | 4.04 (-11)| 2.52 (-10) | (9.72 ± 0.44)(-5) | 7.36 (-5) | 7.36 (-5) | 6.34 (-5) |
| 205Pb/204Pb| 24.96     | 8.84 (-12)| 3.47 (-10) | ~ 1 (0)(-4)(1)(-3) | 1.27 (-4) | 1.27 (-4) | 7.78 (5) |

Comparisons are made to the corresponding isotopic ratios deduced from meteoritic data. Case 1 estimates are calculated from equation (1) using the approximate best-fit f and Δ of Fig. 2, assuming no fallback. The higher and lower yields for 181Hf are obtained from the laboratory and estimated stellar decay rates, respectively. Case 2 (3) is a fallback scenario in which only 1.5% of the innermost 1.02 × 10^-2 solar mass (0.116 solar mass) of shocked material is ejected. With guidance from refs 22, 31, well-determined data are quoted with 2x errors, while data with large uncertainties are preceded by ~. Note that (~) denotes × 10^-2. Data references are: 10Be (refs 14, 16, 18, 19), 26Al (refs 3, 22), 36Cl (refs 33-35), 41Ca (refs 36, 37), 53Mn (ref. 38), 60Fe (refs 39, 40), 107Pd (ref. 41), 135Cs (ref. 42), 182Hf (ref. 43) and 205Pb (ref. 44, 45).
invoked for high-mass CCSNe in Takigawa et al.\textsuperscript{8} to account for 26Al, 41Ca, 53Mn and the higher observed value of 60Fe.

If, however, the higher 60Fe value\textsuperscript{40} is correct, then a plausible scenario like Case 2, where SS formation was triggered by a low-mass CCSN with modest fallback, would be in reasonable agreement with the data on 10Be, 41Ca, 53Mn, 60Fe and 107Pd. The nuclear forensics, notably the rapidly decaying 41Ca, determines the delay between the CCSN explosion and incorporation of SLRs into early SS solids, $\Delta \sim 1$ Myr. The deduced fraction of CCSN material injected into the protosolar cloud, $f \sim 5 \times 10^{-4}$, is consistent with estimates based on simulations of ejecta interacting with dense gas clouds\textsuperscript{4-6} (Supplementary Discussion). There is also an implicit connection to the CCSN explosion energy, which influences fallback in hydrodynamic models.

Discussion

In addition to neutrino-induced production, a low-mass CCSN can make 10Be through CRs associated with its remnant evolution\textsuperscript{20}. However, the yield of this second source is modest (Supplementary Discussion). The net yield in the ISM trapped within the remnant is limited by the amount of this ISM. Production within the general protosolar cloud during its initial contact with the remnant (that is, before thorough mixing of the injected material) would also be expected, and the yield could possibly account for $10Be/9Be \sim 3 \times 10^{-4}$ in FUN-CAIs\textsuperscript{20}. However, FUN-CAIs are rare, and their 10Be inventory may be more consistent with local production by the CCSN CRs. Taking the net CR contribution averaged over the protosolar cloud to be $10Be/9Be \sim 10^{-4}$, a value that we argue is more consistent with long-term production by Galactic CRs\textsuperscript{20}, we add the neutrino-produced $10Be/9Be \sim (5.2-6.4) \times 10^{-4}$ (Table 1) from the CCSN to obtain $10Be/9Be \sim (6.2-7.4) \times 10^{-4}$, which is in accord with $10Be/9Be = (7.5 \pm 2.5) \times 10^{-4}$ observed in canonical CAIs. In general, we consider that neutrino-induced production provided the baseline 10Be inventory in these samples and the observed variations\textsuperscript{14,16,18,19} can be largely attributed to local production by SEPs.

Our proposal that a low-mass CCSN trigger provided the bulk of the 10Be inventory in the early SS has several important features: (1) the relevant neutrino and CCSN physics is known reasonably well, and the uncertainty in the 10Be yield is estimated here to be within a factor of $\sim 2$; (2) the production of both 10Be and 41Ca is in agreement with observations\textsuperscript{36,37}, a result difficult to achieve by SEPs\textsuperscript{39}; and (3) the yield pattern of Li, Be and B isotopes (Supplementary Table 4) is distinctive, with predominant production of $^{7}$Li and $^{11}$B and differing greatly from patterns of production by CRs and SEPs, so that precise meteoritic data might provide distinguishing tests (Supplementary Discussion).

We emphasize that while 53Mn and 60Fe production is greatly reduced in a low-mass CCSN, some fallback is still required to explain the meteoritic data. The fallback solution works well for 53Mn (Table 1). When somewhat different meteoritic values of 53Mn/55Mn (refs 52,53) are used, only the ejected fractions of the innermost shocked material need to be adjusted accordingly. The case of 60Fe is more complicated. The meteoritic measurements are difficult, especially in view of a recent study showing the mobility of Fe and Ni in the relevant samples\textsuperscript{54}. Another recent study gave $5 \times 10^{-8} \leq 60Fe/56Fe \leq 2.6 \times 10^{-7}$ (ref. 55), which may be accounted for by Case 3 of our model (Table 1). However, $60Fe/56Fe \sim 10^{-8}$ (ref. 39), currently preferred by many workers, to be confirmed, we would have to conclude that either the present 60Fe yield of the low-mass CCSN is wrong or its contributions to SLRs must be reconsidered.
Several other issues with our proposed low-mass CCSN trigger merit discussion. Table 1 shows that such a CCSN underproduces \(^{26}\)Al, \(^{36}\)Cl and \(^{133}\)Cs to varying degrees. We consider that the ISM swept up by the CCSN shock wave before triggering the collapse of the protosolar cloud might have been enriched with \(^{26}\)Al by nearby massive stars. To avoid complications with \(^{53}\)Mn and \(^{60}\)Fe, we propose that these stars might have exploded only weakly or not at all\(^9\), but contributed \(^{26}\)Al through their winds. The total amount of swept-up \(^{26}\)Al needed to be \(\sim 10^{-3} M_\odot\) (see Table 1), which could have been provided by winds of stars of \(\gtrsim 35 M_\odot\) possibly in connection with an evolving giant molecular cloud\(^6\). Winds from massive stars may also have contributed to \(^{44}\)Ca and \(^{133}\)Cs (ref. 57). However, the wind contribution to \(^{44}\)Ca might be neglected given the rapid decay of this SLR over the interval of \(\sim 1\) Myr between the onset of collapse of the protosolar cloud and incorporation of SLRs into early SS solids (Supplementary Discussion). We agree with collapse of the protosolar cloud and incorporation of SLRs into a remnant and the resulting CR production and interaction, and progress depends on resolving discrepancies in \(^{60}\)Fe abundance\(^11\), this provides circumstantial support for the fallback model of the SLR129I. As emphasized above, a low-mass CCSN might have been enriched with \(^{26}\)Al by winds from massive stars in an molecular cloud interacting with a supernova remnant and the origin of short-lived radionuclides. We consider that the ISMShielding and light elements.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

P.B. and Y.-Q.Z. designed the work. P.B. ran the models with help from A.H. All the authors discussed the results and contributed to the writing of the manuscript.

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