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Imprints of fast-rotating massive stars in the Galactic Bulge

Cristina Chiappini, Urs Frischknecht, Georges Meynet, Raphael Hirschi, Beatriz Barbuy, Marco Pignatari, Thibaut Decressin & André Maeder

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The first stars that formed after the Big Bang were probably massive[1], and they provided the Universe with the first elements heavier than helium ('metals'), which were incorporated into low-mass stars that have survived to the present[2,3]. Eight stars in the oldest globular cluster in the Galaxy, NGC 6522, were found to have surface abundances consistent with the gas from which they formed being enriched by massive stars[4] (that is, with higher α-element/Fe and Eu/Fe ratios than those of the Sun). However, the same stars have anomalously high abundances of Ba and La with respect to Fe[4], which usually arises through nucleosynthesis in low-mass stars[5] (via the slow-neutron-capture process, or s-process). Recent theory suggests that metal-poor fast-rotating massive stars are able to boost the s-process yields by up to four orders of magnitude[6], which might provide a solution to this contradiction. Here we report a reanalysis of the earlier spectra, which reveals that Y and Sr are also overabundant with respect to Fe, showing a large scatter similar to that observed in extremely metal-poor stars[7], whereas C abundances are not enhanced. This pattern is best explained as originating in metal-poor fast-rotating massive stars, which might point to a common property of the first stellar generations and even of the 'first stars'.

Subject terms: Astronomy

Main

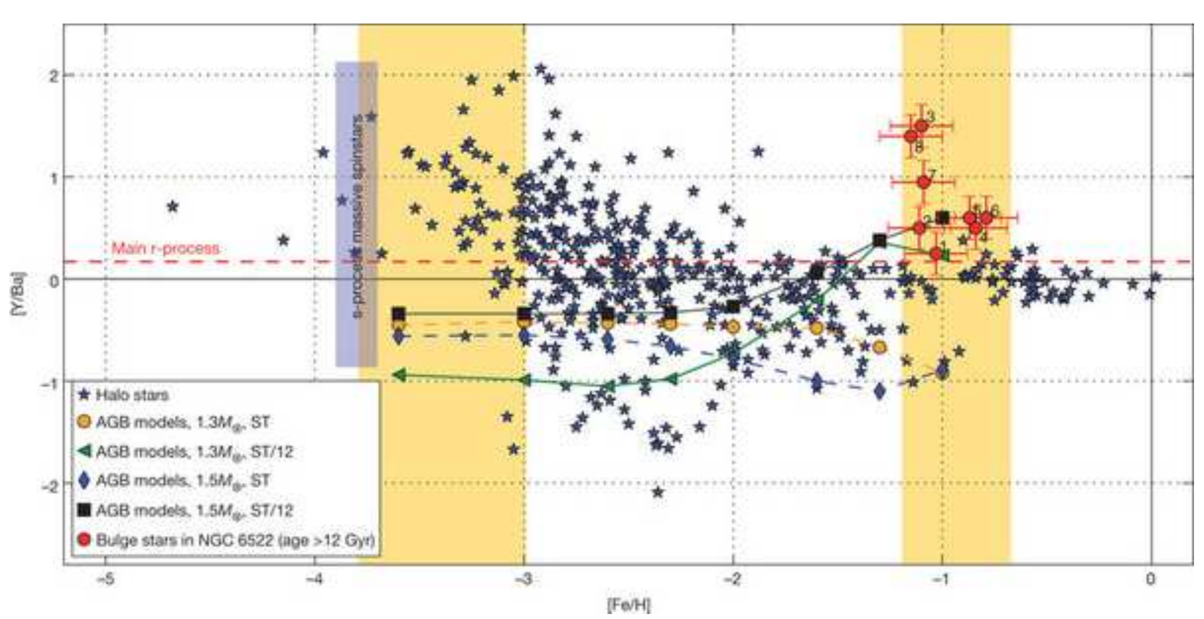
NGC 6522 has been confirmed to be older than any halo globular cluster, despite its metallicity being a tenth that of the Sun[4], and is therefore a witness of the early phases of the chemical enrichment of the Universe. Consistent with the age of this cluster, its stars show a chemical pattern typical of an interstellar medium enriched by core-collapse supernovae (in which thermonuclear supernovae of type Ia and low- and intermediate-mass stars did not have time to contribute to the chemical enrichment). However, the large [Ba/Eu] ratios found[4] in five of the eight stars of NGC 6522 studied (Table 1) shows that the excess in Ba cannot be attributed to the rapid-neutron-capture (r) process, and so the s-process must be invoked[4,5] (see Supplementary Information).

Table 1: Abundances of the eight stars in NGC 6522.

There are only two ways to explain the high Ba and La found in NGC 6522, namely: (1) the original gas from which the globular cluster formed had been pre-enriched in s-process elements by previous generations of massive stars, or (2) the original composition of the stars formed in the globular cluster was lately modified by mass-transfer episodes taking place in binary systems involving low-mass asymptotic giant branch (AGB) stars within NGC 6522.

From re-inspection of the spectra of NGC 6522 (ref. 4), we were able to obtain the Y abundances for eight giant stars, and estimate the Sr abundances for six of them (Table 1 and the Supplementary Information). We find large overabundances of Y (and Sr) with respect to Fe and Ba in the NGC 6522 stars, with a similar scatter to that observed in extremely metal-poor halo stars[7], but now also observed for bulge stars with [Fe/H] = −1, a result not seen previously (see Fig. 1). In addition, from the C_2 band-head (see Supplementary Information), we were able to estimate upper limits for the [C/Fe] ratio. We found that all studied stars have [C/Fe] ≲ 0.0, and hence are not enriched in C, as is the case in a significant fraction of very-metal-poor halo stars[8].

Figure 1: The [Y/Ba] scatter observed in the early Universe.

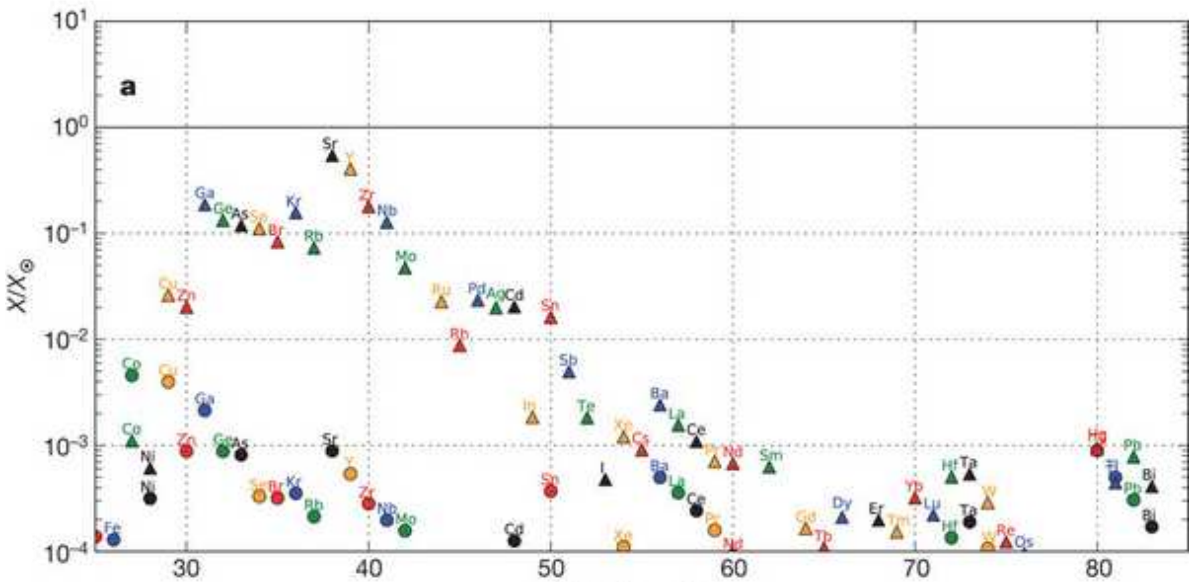


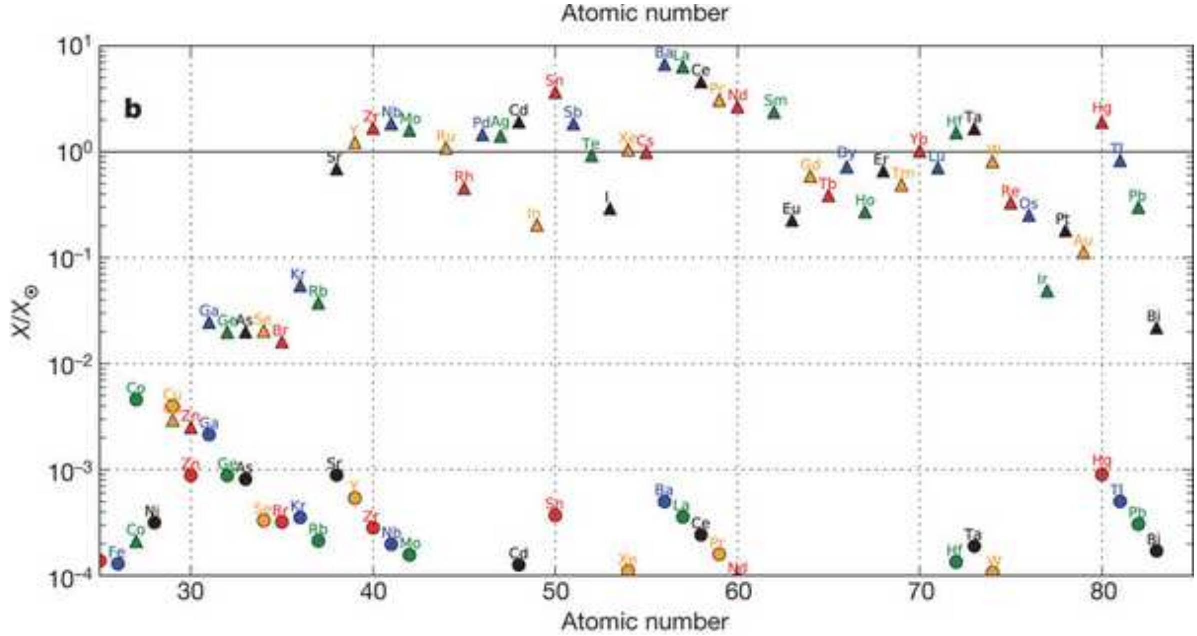
Observed [Y/Ba] scatter in the NGC 6522 stars, which have a metallicity of around [Fe/H] = −1 (ref. 4) (red circles with s.d. error bars) compared to that observed in extremely metal-poor halo stars[7] (with [Fe/H] < −3). The two yellow shaded areas mark the 'early Universe phase' sampled by halo and Bulge stars. We note the similar scatter in [Y/Ba] between the most metal-poor halo stars and our Bulge stars (compare the scatter inside the two yellow zones). Also shown is the [Y/Ba] scatter predicted for the very earliest phases of the chemical enrichment owing to 'spinstars' (indicated by the blue column). The dashed line indicates the [Y/Ba] ratio predicted from pure r-process[5]. Finally, the curves show the predictions for the [Y/Ba] ratio by recent AGB models[14], at different metallicities. The lowest ^{13}C-pocket efficiency model considered here[14] is 'ST/12' (where ST is for standard, and ST/12 means the efficiency of the standard case reduced by a factor of 12; the ^{13}C-pocket is a tiny radiative layer of material in the He-rich region just below the H shell, responsible for most of the s-process in AGB stars). We do not consider AGB models with lower efficiencies (showing higher [Y/Ba] ratios) because the corresponding [Ba/Fe] and [Y/Fe] ratios would be too low[14] (approximately solar) compared to the large enhancements observed in the NGC 6522 stars (Table 1). Finally, we note that whereas AGB mass-transfer and 'spinstar' models can explain stars with slightly sub-solar [Y/Ba] ratios (−1 < [Y/Ba] < 0), both scenarios have difficulties in explaining stars with [Y/Ba] ratios below −1. Gyr, billion year; $M_{\odot}$, solar mass.

Extremely metal-poor environments can produce noticeable effects on the properties of massive stars (more details can be found in the Supplementary Information). At very low metallicities, stars rotate faster[9]. Models of fast-rotating massive stars (hereafter 'spinstars') at very low metallicities[10, 11, 12] have shown that rotational mixing transports ^{12}C from He-burning core into H-rich layers where it is transformed to ^{14}N and ^{13}C. This primary ^{14}N is then transported back to the He-burning core where it is converted into ^{22}Ne, the main neutron source in massive stars for the s-process beyond Fe. Hence, the amount of ^{22}Ne and of s-process products in the He core is enhanced with respect to non-rotating models[6].

We have calculated extremely metal-poor 'spinstar' models[13] ([Fe/H] = −3.8) with a reaction network including 613 isotopes up to Bi (U.F. *et al.*, manuscript in preparation). Rotational mixing increases the s-process yields by about four orders of magnitude (Fig. 2a and b; see also Supplementary Information). The efficiency of this process depends on the rotation rate. A lower rotation rate leads to a more efficient production of the Sr peak compared to heavier species (for instance, in our models the upper limit of [Y/Ba] is about +2), whereas strong mixing driven by a high rotation rate boosts the peak of s-process products towards heavier elements, decreasing the [Y/Ba] ratio (we obtain a lower limit for [Y/Ba] of around −1), even producing non-negligible quantities of Pb. Hence, one of the main predictions of our 'spinstar' scenario is that the early Universe composition should exhibit not only a large scatter in several [s-process element/Fe] ratios, but also a large scatter in the abundance ratios of elements belonging to the different s-process peaks.

Figure 2: Impact of rotation on s-process element production in very-metal-poor massive stars.





The models show the production of s-process elements (where $X/X_{\odot}$ is the mass fraction of atoms normalized to solar) predicted in a $40M_{\odot}$ star with [Fe/H] = −3.8, which does not rotate (circles), and with an initial rotational velocity of 500 km s^{-1} (triangles). These models are shown at two different phases of He-burning: **a**, at the beginning of the s-process (about 127,000 years before He exhaustion); and **b**, at the end of the central He-burning phase. Rotation boosts production of the s-process elements by four orders of magnitude. $X_{\odot}$, solar abundance of given element.

Figure 1 compares the scatter in the [Y/Ba] ratio predicted by models of 'spinstars' in the very earliest phases of the chemical enrichment of the Universe with the scatter observed in extremely-metal poor halo field stars[7] (with [Fe/H] < −3) and in the stars of NGC 6522 (with [Fe/H] = −1; see Supplementary Information for a discussion on other abundance ratios). Two important conclusions can be drawn. First, the observed scatter in [Y/Ba] in the early Universe (both in the Bulge and in the very-metal-poor halo stars) is compatible with the expected scatter from 'spinstar' models, apart from very few objects with [Y/Ba] ratios below −1, in the case of the halo field stars. Second, whereas 'spinstars' can produce a large scatter in the [Y/Ba] ratios, covering a range of −1 < [Y/Ba] < +2, AGB models[14] at [Fe/H] = −1 (compatible with the observed high [Y/Fe] and [Y/Ba] ratios in Table 1) cover a smaller [Y/Ba] range (−1 < [Y/Ba] < 0.5), and cannot account for the large [Y/Ba] ratios of stars number 3, 7 and 8 in Fig. 1 (see Supplementary Information for more details). In addition, if we take into account the results shown in Fig. 1 together with the other element ratios presented in the Supplementary Information, a combination of the s-process component from 'spinstars' and the explosive r-process component may explain the heavy elements in all the stars observed in NGC 6522. Predictions from AGB models may explain the abundances in five out of eight stars (not reproducing those with the highest [Y/Ba]). However, the AGB mass-transfer scenario might have difficulty in explaining low [C/Fe] ratios. Hence it is of primary importance to obtain precise [C/Fe] ratios for the NGC 6522 stars, not just upper limits, in order to distinguish between 'spinstars' and AGB mass-transfer scenarios.

A possible observational test to confirm our scenario would be to look for the scatter in the [Pb/Fe] ratios in the early Universe. Low-metallicity AGB mass-transfer models[14, 15] have quite a robust prediction for the minimum expected [Pb/Eu] ratios, but 'spinstar' models predict a large scatter in the [Pb/Eu] ratios. Therefore, if Pb could also be measured for stars with known abundances of Sr, Y, Zr, Ba and La, it would be possible to distinguish between the two scenarios. Unfortunately, the useful Pb lines are in the ultraviolet part of the spectrum and thus are highly extinct for bulge stars.

Other processes besides fast rotation have been invoked in the literature to explain the large overabundances with respect to Fe of the light s-process elements (Y, Sr and Zr) in the very-metal-poor Universe[16, 17, 18], but it is unclear if they could also account for the abundances observed in NGC 6522. Here we propose that 'spinstars' offer another plausible explanation for this signature, both in the Bulge and in extremely metal-poor halo stars.

The impact of having had an early generation of 'spinstars' in the Universe is manifold. They may have contributed to the primary nitrogen production in the early Universe[19, 20]. The fast spins of the stars could have led to more mass loss than expected at these very low metallicities and thus could have prevented the first stars from dying as pair-instability supernovae[11], which would explain why halo stars do not bear the chemical signature of pair-instability supernovae. In addition, even if the more-massive 'spinstars' were to collapse into black holes without a supernova explosion, they would have been able to contribute to the chemical enrichment of the interstellar medium in the very early Universe via stellar mass-loss triggered by rotation. This also has implications for the fate of the stars, leading possibly to more gamma-ray bursts than previously thought, and more generally to magneto-hydrodynamic explosions[11]. Finally, 'spinstars' have longer lifetimes[11] and possibly higher surface temperatures and luminosities than non-rotating stars. It will therefore be worthwhile to study the impact of rotation on the ionizing power of the first stars. The fast rotation of the first stars is now also supported by the latest hydrodynamic simulations of the formation of the first stars[21].

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Download references

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Author information

Affiliations

Astrophysikalisches Institut Potsdam, An der Sternwarte 16, Potsdam, 14482, Germany
Cristina Chiappini

Geneva Observatory, University of Geneva, 51 Ch. des Maillettes, Sauverny, 1290, Switzerland
Cristina Chiappini, Georges Meynet, Thibaut Decressin & André Maeder

Istituto Nazionale di Astrofisica, Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, Trieste, 34143, Italy
Cristina Chiappini

Department of Physics, University of Basel, Klingelbergstrasse 82, Basel, 4056, Switzerland
Urs Frischknecht & Marco Pignatari

Astrophysics Group, Keele University, ST5 5BG, Keele, England
Urs Frischknecht & Raphael Hirschi

IPMU, University of Tokyo, Kashiwa, Chiba, 277-8582, Japan
Raphael Hirschi

University of São Paulo, IAG, Rua do Matão 1226, Cidade Universitaria, 05508-900, São Paulo, Brazil
Beatriz Barbuy

Contributions

C.C. led the analysis and the write-up of the paper. U.F., R.H., G.M. and A.M. computed the new stellar evolution models. B.B. measured the chemical abundances. T.D. and M. P. contributed to the analysis. All authors contributed to the analysis and text writing.

Competing financial interests

The authors declare no competing financial interests.

Corresponding author

Correspondence to: Cristina Chiappini

Supplementary information

PDF files

1. Supplementary Information (315K)
   This file contains Supplementary Text, additional references and Supplementary Figures 1-4 with legends.

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