Galactic Age Estimates from O-rich Stardust in Meteorites

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The $^{16}O/^{17}O$ and $^{16}O/^{18}O$ ratios of refractory oxide grains extracted from primitive meteorites suggest that they originated in low-mass red giant stars prior to the formation of the Solar System 4.6×10^9 years ago. Detailed comparison of the isotopic compositions of the grains with models of stellar evolution and galactic chemical evolution imply that the age of the Galaxy is 14.4 Gyr with a statistical error of ± 1.3 Gyr. Systematic uncertainties are of order several Gyr, however, and are primarily due to inadequacies in present theoretical modeling. [S0031-9007(96)02080-7]

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The first generation of stars in our galaxy consisted mostly of H and He from the big bang. Heavier elements were subsequently synthesized in stars by nuclear burning processes. We denote the time that has elapsed from the time of the formation of the first stars to the present as the age of the Galaxy, T_G. This age has previously been estimated by comparing Hertzprung-Russell diagrams of metal-poor globular clusters with theoretical isochrons [1]. Apart from its inherent interest, a knowledge of T_G provides a lower bound on the age of the Universe, T_U. This age in turn, in conjunction with the Hubble constant, H_o, yields an estimate of the mean mass density of the Universe. In this Letter we report a new way of estimating the age of the Galaxy, from studies of the O-isotopic compositions of stardust preserved in primitive meteorites.

Most of the gas and dust that made up the protosolar cloud from which the Sun and the planets condensed was thoroughly mixed and homogenized. Consequently, the isotopic ratios of the elements measured in material from widely varying sources, such as the earth, moon, solar wind, and even bulk samples of meteorites, are closely similar. In remarkable contrast are tiny grains with isotopic compositions different by orders of magnitude from the average composition of the Solar System, which have been extracted from primitive meteorites [2,3]. These grains of SiC, graphite, Si_3N_4, Al_2O_3, and $MgAl_2O_4$ are believed to be pristine presolar material which survived the formation of the solar system essentially unchanged. They formed in stellar outflows or in supernova ejecta and retain the isotopic compositions of their stellar sources. As a result, they provide new information on stellar evolution, nucleosynthesis, and mixing in stars, as well as the chemical (elemental abundance) evolution of the Galaxy.

Stardust is isolated from bulk meteorites by a complex series of chemical and physical treatments which result in residues highly enriched in chemically resistant phases [4]. Although most studies of presolar grains have focused on C-rich phases in these residues, we are concerned here with the compositions and sources of presolar oxide grains. These are considerably more difficult to identify than carbonaceous stardust due to the presence of large numbers of isotopically normal oxide grains which formed in the early (mostly oxidizing) Solar System. Nevertheless, we have located eighty-seven presolar oxide grains (out of ~30 000 measured grains), primarily corundum (Al_2O_3), in meteoritic separates [5–8]. Most of these were identified by means of a low-precision isotopic-ratio ion image mapping technique, developed for the Washington University ion microprobe [5]. The highly anomalous isotopic compositions of the grains were confirmed by high-precision O-isotopic measurements and clearly distinguish them from grains of solar system origin. Five additional presolar Al_2O_3 grains have been identified by other researchers [9–11]. Besides being highly anomalous in O, many of the 92 presolar oxide grains have large ^{26}Mg enrichments attributable to the radioactive decay of ^{26}Al ($t_{1/2} = 7.3 \times 10^5$ yr) present when the grains formed [5–7,9,10].

The $^{16}O/^{17}O$ and $^{16}O/^{18}O$ ratios for the 92 presolar oxide grains are plotted in Fig. 1 and divided into four groups following Nittler *et al.* [5,6]. Also shown are the isotopic ratios measured spectroscopically in several types of red giant stars [12–17]; the large error bars (typically ~50%) of these observations are left off for

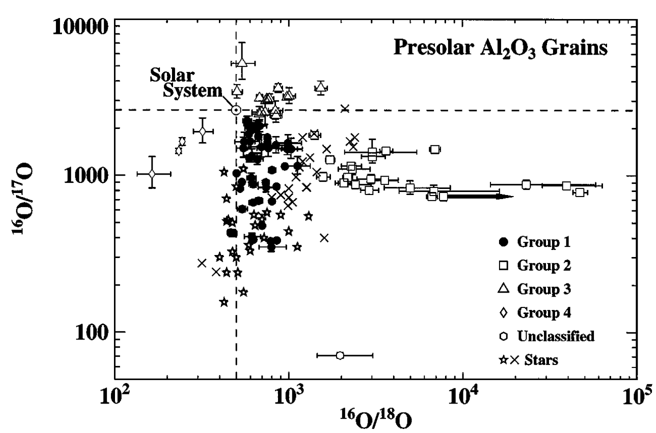

FIG. 1. O-isotopic ratios observed in 92 meteoritic Al_2O_3 grains [5–11] and the atmospheres of O-rich (☆) and C-rich (×) red giant stars [12–17]. Dashed lines indicate solar values in this and the subsequent figure.

clarity. As previously discussed [5], the similarity of the stellar observations to the group 1 oxide grains strongly suggests that these grains formed in red giant stars. The O-isotopic compositions and possible origins of grains from groups 2 and 4 are discussed elsewhere [6,18,19]. It is the group 3 grains that provide information about the age of the Galaxy, and although they do not have identified stellar counterparts, we show below that their O-isotopic ratios are consistent with an origin in low-mass red giants as well.

The surface O-isotopic compositions of red giants are believed to be established by the "first dredge-up," when deep convection following core H burning mixes the products of main-sequence nucleosynthesis with the outer layers of the star [20,21]. Partial H burning by the CNO cycles produces a layer highly enriched in ^{17}O and depleted in ^{18}O deep within the star. Consequently the first dredge-up is expected to significantly increase the surface ^{17}O abundance (lower $^{16}\mathrm{O}/^{17}\mathrm{O}$) and decrease slightly the ^{18}O abundance (higher $^{16}\mathrm{O}/^{18}\mathrm{O}$), as is observed in red giants (Fig. 1). Detailed calculations have shown that the resultant $^{16}\mathrm{O}/^{17}\mathrm{O}$ ratio following first dredge-up is a strong function of stellar mass [20–22]. For low-mass stars ($M \lesssim 2.5 M_{\odot}$), this dependence results primarily from the increased depth of dredge-up with stellar mass, mixing more ^{17}O to the surface. For higher-mass stars ($M \gtrsim 2.5 M_{\odot}$), the $^{16}\mathrm{O}/^{17}\mathrm{O}$ ratio is controlled by the destruction of ^{17}O in the nuclear reactions $^{17}\mathrm{O}(p,\alpha)^{14}\mathrm{N}$ and $^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$, which operate more efficiently at the higher temperatures obtained in these stars. The $^{16}\mathrm{O}/^{18}\mathrm{O}$ ratio, however, varies little with stellar mass, and variations in this ratio of greater than 20%–50% are most likely explained by variations in the initial compositions of the stars [21], resulting from the chemical evolution of the Galaxy. The isotope ^{16}O is produced by He-, C-, and Ne-burning reactions and can be synthesized in stars that initially consist only of H and He. The rarer O isotopes, ^{17}O and ^{18}O, are produced by proton captures on ^{16}O and α captures on ^{14}N, respectively, and thus can only be synthesized in stars which start out with some CNO nuclei. As a result, the abundances of ^{17}O and ^{18}O in the Galaxy are expected to increase with time, and stars of low metallicity should have high initial $^{16}\mathrm{O}/^{17}\mathrm{O}$ and $^{16}\mathrm{O}/^{18}\mathrm{O}$ ratios [23].

Displayed in Fig. 2 are the O-isotopic ratios of groups 1 and 3 Al_2O_3 grains, and superimposed are theoretical predictions for first dredge-up in low-mass red giants [22]. Each open circle represents a different star of a given mass [$M = (0.85–3)M_{\odot}$] and metallicity ($Z = 0.012–0.02$); solid curves connect the predictions for a given metallicity and dotted lines indicate intermediate values determined by bilinear interpolation. Clearly, most group 1 and group 3 grains have O-isotopic ratios consistent with an origin in red giants, provided they formed in several distinct stars with distinct masses and initial compositions. In particular, group 3 grains must have formed in very low-mass stars ($M < 1.4 M_{\odot}$) with

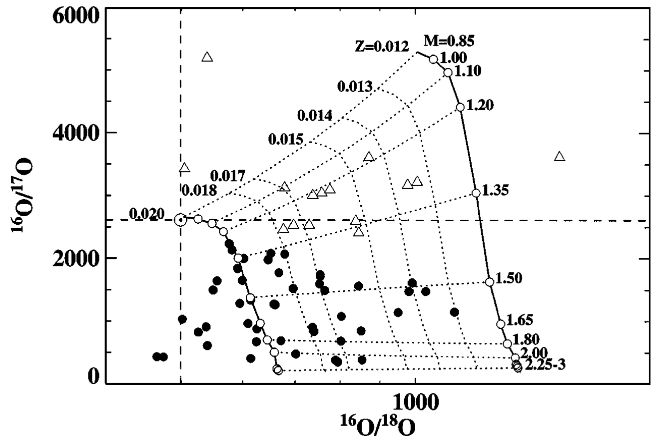

FIG. 2. Comparison of oxide grain data for groups 1 and 3 (see Fig. 1 for symbol definitions) with predictions of O-isotopic ratios following first dredge-up in red giant stars of initial mass $(0.85–3)M_{\odot}$ and metallicity $Z = 0.012–0.02$ [22]. For the sake of clarity, error bars on grain measurements are not shown. Each open circle corresponds to predictions for a distinct star. The dotted lines indicate interpolated values for masses and metallicities intermediate to those calculated. Oxide grains belonging to groups 1 and 3 have isotopic compositions consistent with these predictions, provided that they come from several different stars with distinct masses and initial compositions.

initial $^{16}\mathrm{O}/^{17}\mathrm{O}$ and $^{16}\mathrm{O}/^{18}\mathrm{O}$ ratios higher than the solar values. Because low-mass stars live longer than stars of higher mass, the high initial ratios of group 3 grains indicate that the parent stars of these grains formed at an early time in the Galaxy when the average ^{17}O and ^{18}O abundances were lower than those in the Sun.

Given that group 3 grains originated in low-mass red giants which ended their life before the formation of the Sun, we may use their compositions and predicted stellar lifetimes to determine the age of the Galaxy, T_{G}. The masses and metallicities inferred from first dredge-up models for the parent stars of group 3 grains are given in columns 4 and 5 of Table I; the stated errors are the ranges allowed by the 1σ uncertainties of the isotopic-ratio measurements. We do not include the two group 3 grains with solar $^{16}\mathrm{O}/^{18}\mathrm{O}$ ratios since these have large error bars and their O-isotopic compositions are not consistent with the first dredge-up calculations, indicating they might have a different origin. Column 6 shows the predicted lifetimes for the progenitor stars, T_*, taken from the metallicity- and mass-dependent stellar-lifetime expression of Mathews *et al.* [24]. We should now add the age of the solar system, 4.6 Gyr [25], to the ages of the red giants that are listed in column 6 to obtain lower bounds to the age of the Galaxy, T_{b}, as listed in column 7. To calculate T_{G}, we must estimate the mean time, T_{m}, that has to elapse from the birth of the Galaxy to build up the metallicity to the levels estimated for the progenitor stars. Observations of elemental abundances in field disk dwarf stars show that even though the average metallicity of the Galaxy has increased throughout the history of the disk, there is a very wide dispersion of the actual metallicities around the

TABLE I. Inferred masses, metallicities (Z), and lifetimes (T_*) for progenitor red giant stars of selected presolar oxide grains. O-isotopic ratios are given with ^{16}O in the denominator (in contrast to the figures) since in the reverse case the errors are asymmetric and nonlinear. See the text for the definitions of T_b and T_G.

Grain	^{18}O/^{16}O ($\times 10^4$)	^{17}O/^{16}O ($\times 10^4$)	Mass ($M_\odot$)	Z	T_* (Gyr)	T_b (Gyr)	T_G (Gyr)
Solar	20.05	3.83	1.00	0.02			
T67	6.54 ± 0.53	2.77 ± 0.28	1.32 ± 0.03	0.0100 ± 0.0004	$3.8^{+0.3}_{-0.3}$	8.4	12.3
T66	11.8 ± 0.9	4.15 ± 0.44	1.36 ± 0.03	0.0153 ± 0.0006	$4.0^{+0.4}_{-0.2}$	8.6	12.5
T62	11.9 ± 1.1	3.85 ± 0.52	1.32 ± 0.05	0.0152 ± 0.0007	$4.3^{+0.8}_{-0.4}$	8.9	12.8
T64	9.95 ± 0.80	3.10 ± 0.36	1.28 ± 0.04	0.0133 ± 0.0005	$4.7^{+0.6}_{-0.5}$	9.3	13.2
T5	10.2 ± 0.3	3.15 ± 0.10	1.28 ± 0.01	0.0136 ± 0.0002	$4.7^{+0.2}_{-0.2}$	9.3	13.2
T51	13.7 ± 2.5	3.95 ± 0.78	1.28 ± 0.09	0.0167 ± 0.0015	$5.0^{+2.0}_{-1.0}$	9.6	13.5
T80	14.3 ± 0.2	3.95 ± 0.10	1.27 ± 0.01	0.0173 ± 0.0001	$5.4^{+0.2}_{-0.2}$	10.0	13.9
T31	14.8 ± 1.5	4.06 ± 0.44	1.28 ± 0.05	0.0177 ± 0.0009	$5.4^{+1.0}_{-0.9}$	10.0	13.9
T15	12.9 ± 0.7	3.23 ± 0.23	1.21 ± 0.03	0.0157 ± 0.0004	$6.2^{+0.8}_{-0.5}$	10.8	14.7
T21	13.2 ± 0.6	3.28 ± 0.17	1.21 ± 0.03	0.0160 ± 0.0004	$6.3^{+0.7}_{-0.5}$	10.9	14.8
T74	13.6 ± 0.2	3.32 ± 0.08	1.21 ± 0.01	0.0163 ± 0.0001	$6.4^{+0.3}_{-0.2}$	11.0	14.9
T45	11.5 ± 0.6	2.77 ± 0.17	1.18 ± 0.04	0.0144 ± 0.0003	$6.6^{+1.1}_{-0.6}$	11.2	15.1
T23	14.7 ± 0.6	3.20 ± 0.15	1.10 ± 0.05	0.0169 ± 0.0003	$9.2^{+2.1}_{-1.2}$	13.8	17.7

average at any given time and at each galactocentric radius [26]. Because of this, we do not estimate a separate T_m for every grain, but instead use the average metallicity implied by the grains (0.0153; column 5) and use the galactic chemical evolution model of Timmes *et al.* [27] to estimate $T_m = 3.9$ Gyr. Adding this value of T_m to the values of T_b gives our estimates of T_G, listed in column 8. Finally, to reduce the effect of the various uncertainties we take a weighted average of the eight highest values of T_G, corresponding to the eight grains with ^{16}O/^{17}O ratios higher than the solar ratio, and obtain (in Gyr):

$$T_G = 14.4 \pm 1.3 \text{ (statistical)} \pm \text{(systematic errors)}. \quad (1)$$

This estimate agrees remarkably well with ages previously obtained from studies of globular clusters [1] and the age estimated from observed Th abundances in metal-poor stars [28]. The statistical error in Eq. (1) is the standard deviation of the eight estimates. Systematic errors are on the order of several Gyr and are discussed below.

(1) Uncertainties in the nucleosynthesis and first dredge-up models of red giants: Substantial variations exist between published predictions for the dependence of the first dredge-up ^{16}O/^{17}O ratio on stellar mass for low-mass ($\lesssim 2M_\odot$) stars [20], probably due primarily to differences in the treatment of convection. Small differences in the treatment of convection can lead to the same ^{16}O/^{17}O ratios in stars of significantly different mass and thus systematic differences in inferred stellar ages. Unfortunately, the dependence of ^{16}O/^{17}O on stellar mass is not well constrained by observations, due to large uncertainties in stellar mass and isotopic-ratio determinations. In any case, the uncertainty in the masses of the progenitor stars of group 3 oxide grains are probably more uncertain than suggested by the statistical errors reported in Table I. A systematic uncertainty of $0.1M_\odot$ would lead to an uncertainty of ~2 Gyr in our galactic age estimate.

Additional systematic uncertainties may arise from the intrinsic imcompleteness of stellar modeling. For example, discrepancies between observations and theoretical predictions of ^{12}C/^{13}C ratios in low-mass red giant stars have led several researchers to suggest that extra, nonconvective mixing occurs in these stars [19,29,30]. The effect of such extra mixing on O-isotopes would be to reduce the ^{16}O/^{17}O ratio and to increase the ^{16}O/^{18}O ratio, and this process has been proposed as the source of large ^{18}O depletions in group 2 presolar oxide grains [19]. If extra mixing occurring in the parent stars of the group 3 grains had, in fact, altered the surface O-isotopic ratios, the first-dredge-up compositions of these stars would have been further up and to the left in Fig. 2, i.e., toward lower masses and higher metallicities. This would increase our estimate of the age of the Galaxy.

(2) Uncertainties in the galactic evolution of the O isotopes: The first-dredge-up calculations used here assumed that the initial ^{17}O/^{16}O and ^{18}O/^{16}O ratios increase linearly with metallicity [22]. Radio observations of O isotopes in molecular clouds throughout the Galaxy suggest that ^{17}O and ^{18}O do indeed vary in step with one another [31], but the dependence of that variation on metallicity is poorly known. If ^{17}O/^{16}O and ^{18}O/^{16}O increase more slowly with Z than assumed here, the inferred metallicities of grain progenitors will be lower. Since stellar lifetimes decrease with decreasing metallicity, this would result in a systematically smaller estimate for the age of the Galaxy. A plausible lower limit on the metallicity of stars that contributed dust to the Solar System is given by the lowest value observed in disk stars with the same galactocentric radius as the Sun, $Z \approx 0.004$ [26]. Assuming that the grains originated in stars of the same masses as listed in Table I, but with $Z \approx 0.004$, reduces the inferred values of T_b by ~2 Gyr, and, since T_m is smaller for lower metallicity, would reduce our estimate of T_G by $\lesssim 6$ Gyr.

(3) Uncertainty in T_m, the time for the galactic metallicity to build up to the levels required by the grains:

This value is uncertain both because of uncertainties in the galactic chemical evolution models from which it is derived and because of the variations with respect to the mean of stellar metallicity at a given time and place in the Galaxy [26]. Based on the observed spread of galactic metallicity as a function of age, we estimate an uncertainty of $+2/-1$ Gyr in $T_{\rm m}$, but systematic errors due to uncertainties in the chemical evolution models may well be larger.

(4) Uncertainties in the stellar lifetime calculation: The stellar lifetimes used here were based on an analytical fit to full calculations of stellar evolution from the beginning of core H burning to the tip of the red giant branch (RGB) [24], i.e., following the first dredge-up but before core He burning. Very low-mass stars are expected to lose most of their mass on the upper RGB [22,32], so these time scales are plausible for the time between stellar formation and the ejection of grains. This is further supported by the calculations of Boothroyd and Sackmann [22] of the times at which most mass loss occurs in red giants; their results for stars of mass $(1.1-1.3)M_{\odot}$ are within 0.6 Gyr of the lifetimes used in our estimates of the age of the Galaxy.

(5) The assumed red giant origin of group 3 oxide grains: The galactic age estimates in this Letter rest on the assumption that group 3 grains formed in low-mass, low-metallicity red giants. Other potential sources of O-rich stardust—red supergiants, supernovae, Wolf-Rayet stars, and novae—are much less likely to have produced the group 3 grains. Of these possible sources, only grains condensing in O-rich shells of Type II supernovae should be rich in ^{16}O, compared to ^{17}O and ^{18}O, like group 3 grains. However, the predicted $^{16}\mathrm{O}/^{17}\mathrm{O}$ and $^{16}\mathrm{O}/^{18}\mathrm{O}$ ratios for these supernova shells are much higher than those observed in the grains [33]. Red supergiants, Wolf-Rayet stars, and novae are all expected to have ^{17}O and/or ^{18}O enrichments, relative to ^{16}O and the Sun [34–36], and are thus unlikely to have been sources of group 3 grains. We conclude that the most likely origin of these grains is indeed in low-mass red giant stars and their O-isotopic compositions can be used to constrain the age of the Galaxy.

It is our hope that the new method for estimating the age of the Galaxy presented in this Letter will lead to improved models of stellar nucleosynthesis, mixing, and galactic chemical evolution. Better theoretical calculations, as well as isotopic-ratio measurements on a much larger number of presolar oxide grains and improved isotopic-ratio measurements of stars would help in reducing the uncertainties in these age determinations.

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[1] D. A. Vandenberg, in *The Formation and Evolution of Star Clusters,* edited by K. Janes, Astronomical Society of Pacific Conference Series Vol. 13 (Astronomical Society of the Pacific, San Francisco, 1991), p. 183.
[2] E. Anders and E. Zinner, Meteoritics **28**, 490 (1993).
[3] U. Ott, Nature (London) **364**, 25 (1993).
[4] S. Amari, R. S. Lewis, and E. Anders, Geochim. Cosmochim. Acta **58**, 459 (1994).
[5] L. R. Nittler *et al.,* Nature (London) **370**, 443 (1994).
[6] L. R. Nittler *et al.,* in *Nuclei in the Cosmos III,* edited by M. Busso, R. Gallino, and C. M. Raiteri (AIP, New York, 1995), pp. 585–589.
[7] L. R. Nittler, Lunar Planet. Sci. **27**, 965 (1996).
[8] X. Gao *et al.,* Meteoritics Planet. Sci. **31**, A48 (1996).
[9] I. D. Hutcheon, G. R. Huss, A. J. Fahey, and G. J. Wasserburg, Astrophys. J. **425**, L97 (1994).
[10] G. R. Huss, A. J. Fahey, R. Gallino, and G. J. Wasserburg, Astrophys. J. **430**, L81 (1994).
[11] R. Strebel, P. Hoppe, and P. Eberhardt, Meteoritics Planet. Sci. **31**, A136 (1996).
[12] M. J. Harris and D. L. Lambert, Astrophys. J. **281**, 739 (1984).
[13] M. J. Harris and D. L. Lambert, Astrophys. J. **285**, 674 (1984).
[14] M. J. Harris *et al.,* Astrophys. J. **316**, 294 (1987).
[15] M. J. Harris, D. L. Lambert, and V. V. Smith, Astrophys. J. **325**, 768 (1988).
[16] V. V. Smith and D. L. Lambert, Astrophys. J. Suppl. **72**, 387 (1990).
[17] C. Kahane, J. Cernicharo, J. Gomez-Gonzalez, and M. Guélin, Astron. Astrophys. **256**, 235 (1992).
[18] A. I. Boothroyd, I.-J. Sackmann, and G. J. Wasserburg, Astrophys. J. **442**, L21 (1995).
[19] G. J. Wasserburg, A. I. Boothroyd, and I.-J. Sackmann, Astrophys. J. **447**, L37 (1995).
[20] M. El Eid, Astron. Astrophys. **285**, 915 (1994).
[21] A. I. Boothroyd, I.-J. Sackmann, and G. J. Wasserburg, Astrophys. J. **430**, L77 (1994).
[22] A. I. Boothroyd and I.-J. Sackmann (to be published).
[23] D. D. Clayton, Astrophys. J. **334**, 191 (1988).
[24] G. J. Mathews, G. Bazan, and J. J. Cowan, Astrophys. J. **391**, 719 (1992).
[25] J. H. Chen and G. J. Wasserburg, Earth Planet. Sci. Lett. **52**, 1 (1981).
[26] B. Edvardssen *et al.,* Astron. Astrophys. **275**, 101 (1993).
[27] F. X. Timmes, S. E. Woosley, and T. A. Weaver, Astrophys. J. **98**, 617 (1995).
[28] C. Sneden *et al.,* Astrophys. J. (to be published).
[29] K. K. Gilroy, Astrophys. J. **347**, 835 (1989).
[30] C. Charbonnel, Astron. Astrophys. **282**, 811 (1994).
[31] A. A. Penzias, Astrophys. J. **249**, 518 (1981).
[32] A. I. Boothroyd and I.-J. Sackmann, Astrophys. J. **328**, 653 (1988).
[33] B. S. Meyer, T. A. Weaver, and S. E. Woosley, Meteoritics **30**, 325 (1995).
[34] G. Schaller, D. Schaerer, G. Meynet, and A. Maeder, Astron. Astrophys. Suppl. **96**, 269 (1992).
[35] N. Prantzos and M. Cassé, Astrophys. J. **307**, 324 (1986).
[36] M. Politano *et al.,* Astrophys. J. **448**, 807 (1995).