# $^{11}$B and Constraints on Neutrino Oscillations and Spectra from Neutrino Nucleosynthesis

Sam M. Austin, Alexander Heger, and Clarisse Tur

Phys. Rev. Lett. **106**, 152501 — Published 11 April 2011

DOI: 10.1103/PhysRevLett.106.152501

LY12770

# $^{11}$B and Constraints on Neutrino Oscillations and Spectra from Neutrino Nucleosynthesis

Sam M. Austin,[1, 2, *] Alexander Heger,[3] and Clarisse Tur[1]

[1] *National Superconducting Cyclotron Laboratory, 1 Cyclotron, Michigan State University, East Lansing, MI 48824-1321 Joint Institute for Nuclear Astrophysics*

[2] *Department of Physics and Astronomy, Michigan State University, East Lansing Michigan 48824*

[3] *School of Physics and Astronomy, University of Minnesota, Twin Cities, Minneapolis, MN 55455-0149 Joint Institute for Nuclear Astrophysics*[†]

(Dated: March 9, 2011)

We have studied the sensitivity to variations in the triple alpha and $^{12}C(\alpha,\gamma)^{16}O$ reaction rates, of the yield of the neutrino process isotopes $^{7}$Li, $^{11}$B, $^{19}$F, $^{138}$La, and $^{180}$Ta in core collapse supernovae. Compared to solar abundances, less than 15% of $^{7}$Li, about 25-80% of $^{19}$F, and about half of $^{138}$La is produced in these stars. Over a range of $\pm 2\sigma$ for each helium-burning rate, $^{11}$B is overproduced and the yield varies by an amount larger than the variation caused by the effects of neutrino oscillations. The total $^{11}$B yield, however, may eventually provide constraints on supernova neutrino spectra.

PACS numbers: 26.30.Jk, 26.50.+x, 14.60.Pq



About $10^{58}$ neutrinos are emitted during a typical core collapse supernova explosion. For some time it has been known (see [1] for a detailed history) that interactions of these neutrinos with the stellar envelope can produce certain rare nuclei in abundances close to those observed in nature. These nuclei, called here the neutrino nuclei, include $^{7}$Li, $^{11}$B, $^{19}$F, $^{138}$La, and $^{180}$Ta [1, 2].

It was pointed out [2] that the production of some of the $^{180}$Ta and most of the $^{138}$La by the neutrino process was sensitive to the electron neutrino temperatures, and might serve to probe the value of the neutrino oscillation parameter $\sin^2 2\theta_{13}$. Recently, [3–5] showed that the yields of $^{7}$Li and $^{11}$B in supernova explosions are also sensitive to $\sin^2 2\theta_{13}$ and to whether the neutrino mass hierarchy is normal or inverted. In both cases, this sensitivity arises because neutrino oscillations can change the neutrino spectra produced during core collapse supernovae, increasing the average energies of the $\nu_e$ and $\bar{\nu}_e$ and affecting the synthesis of the neutrino nuclei. Since two of the main goals of neutrino physics [6] are to determine better the value of $\sin^2 2\theta_{13}$ and the nature of the mass hierarchy, the possibility that the observed abundances of the neutrino nuclei might constrain these quantities is of great interest.

Their use for this purpose depends, however, on the robustness of the stellar yield predictions. Studies of the dependence of nucleosynthesis on the helium burning reaction rates have shown [7, 8] that both the yields of the more abundant nuclides and stellar structure are significantly affected. Since the neutrino nuclei result from neutrino induced spallation of abundant progenitor nuclei, their production depends on the abundances of these nuclei and on their location within the star, and thereby on the rates of the helium burning reactions.

In this paper, we examine the changes in the production of $^{7}$Li, $^{11}$B, $^{19}$F, $^{138}$La, and $^{180}$Ta caused by changes in the astrophysical helium burning rates within their uncertainty limits, and compare the yield changes of $^{7}$Li, and $^{11}$B, with the predicted [3–5] effects of oscillations.

We then discuss how, and whether, the neutrino process nuclei can be used to constrain the neutrino spectra from supernovae. We find that the constraints provided by neutrino process nucleosynthesis are interesting but not yet definitive. Because of the great interest in these issues it appears that a major effort to sharpen these constraints is warranted; a discussion of important measurements and calculations is given below.

We used the KEPLER code [9–12] to model the evolution of 15, 20, and 25 solar mass stars from central hydrogen burning up to core-collapse; a piston placed at the base of the oxygen shell was then used to simulate the explosion. Following [2] we assumed a total energy of $5\times10^{52}$ ergs per neutrino species, i.e. a total of $3\times10^{53}$ ergs energy release in the supernova explosion. Mass loss processes were included. The neutrino spectra were approximated by Fermi-Dirac distributions with a zero degeneracy parameter, a luminosity exponentially decaying after onset of core collapse with a time-scale of 3 s and a constant neutrino temperature: $T = 4$ MeV for $\nu_e$ and $\bar{\nu}_e$; $T = 6$ MeV for $\nu_\mu,\ \bar{\nu}_\mu,\ \nu_\tau, and\ \bar{\nu}_\tau$. For further details, see [2, 7, 8, 13]. These choices are consistent with estimates of neutrino emission intensity and time dependence from supernovae [14].

Initial stellar abundances were taken from both Anders & Grevesse [15] and from Lodders [16], hereafter AG89 and L03. The L03 abundances for C, N, O, Ne are roughly 15%-25% lower than those of AG89, whereas the abundances of heavier elements are roughly 15% higher. For calculations of neutrino process cross sections we used the results from [2]. Briefly, in that paper the charged and neutral current cross sections were first used to calculate the excitation

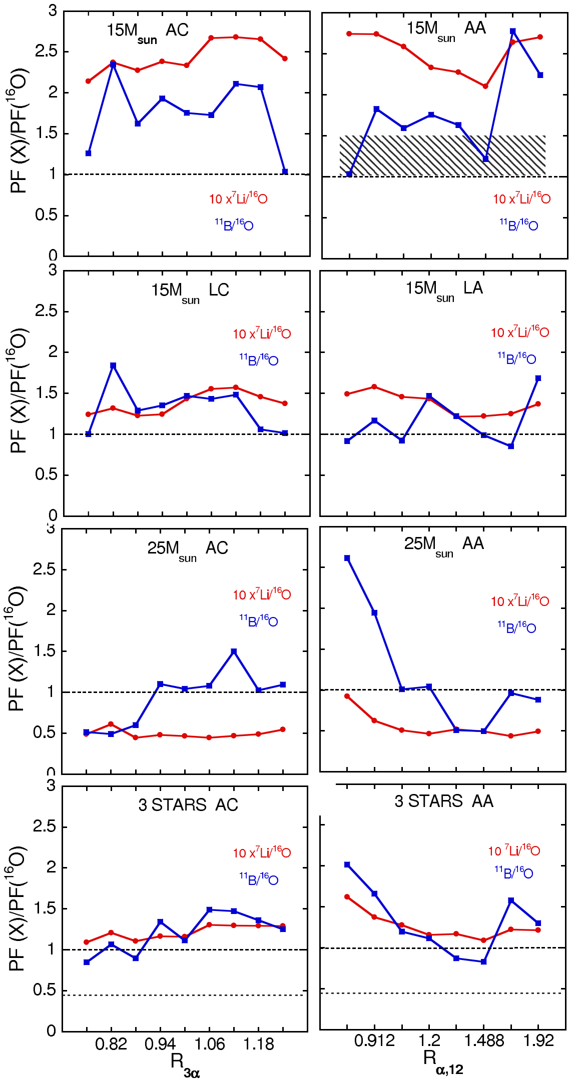


FIG. 1: Production factors of $^7$Li and $^{11}$B compared to those of $^{16}$O for various reaction rates. The left hand column shows the results when the triple-alpha reaction rate $R_{3\alpha}$ is varied about the central value of 1.0, the rate of ref. [17]. The right-hand column shows the results when $R_{\alpha,12}$ is varied about the central value of 1.2. The value for $^7$Li has been multiplied by a factor of 10. An example of the range of variation in $^{11}$B yield predicted in [3] is shown as a band in the upper right-hand panel. The dotted line at 0.4 is the production factor ratio that would give the solar abundance of $^{11}$B not made in the galactic cosmic rays. For more information see the text.

spectra of the product nuclei; experimental data and $0\hbar\omega$ shell-model estimates were used to determine the Gamow-Teller response for $^{12}$C and $^{20}$Ne (leading to $^{11}$B and $^{19}$F) and RPA estimates for the $J \leq 4$ multipoles for all other transitions. The SMOKER statistical model code [11], was then used there to follow the ensuing decays. The $\gamma$ process contributions to the yields are also included in our calculations, but are important only for $^{180}$Ta.

Isotope yields were stored at nine key points of stellar evolution [8, 13]. As anticipated, $^7$Li and $^{11}$B were produced essentially only during the supernova stage; their yields are shown in Fig. 1. Here an initial "A" (or "L") label means that the calculations were done for the AG89 (or L03) abundances, and a final "A" (or "C") means that the $^{12}$C$(\alpha,\gamma)^{16}$O (or triple-alpha) rates were varied by $\pm 2\sigma$ from their central values. These central values were, resp., 1.2 times the rate recommended by Buchmann [18] with $\sigma = 25\%$ and that recommended by Caughlan and Fowler [17] with $\sigma = 12\%$. For the $^{12}$C$(\alpha,\gamma)^{16}$O rate, the central value is that commonly used in calculations with the KEPLER code [7, 19]; it is consistent with recent measurements [20]. The 25% uncertainty is based primarily on our evaluation of the uncertainties of these measurements and secondarily on the results of [7], Fig. 3(c). The energy dependence obtained by Buchmann was used for all calculations. The labels also give the stellar mass, or 3 STARS, the average for the 15, 20, and 25 M$_\odot$ stars using a Scalo [21] Initial Mass Function (IMF) with a slope of $\gamma = -2.65$. For

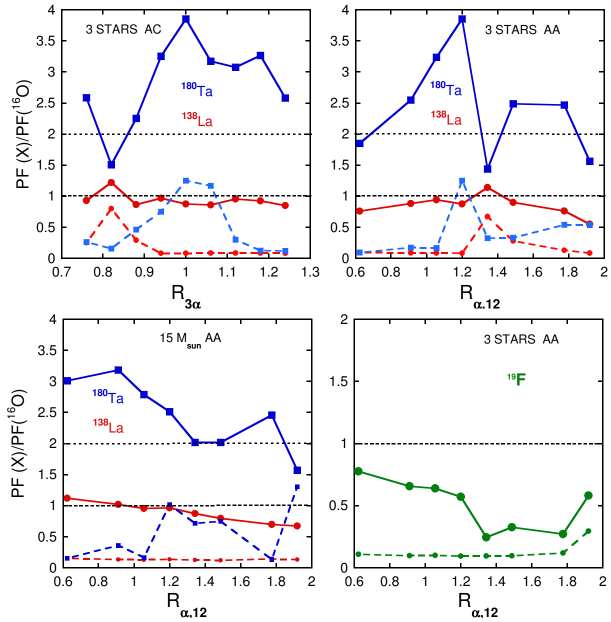


FIG. 2: (Top left): Production factors (three star averages) for $^{138}$La and $^{180}$Ta using Anders and Grevesse abundances and varying the triple alpha rate. (Top right): Same but varying $R_{\alpha,12}$. (Lower left): Same for 15 $M_{\odot}$ star, varying $R_{\alpha,12}$. (Lower right): Production factors (3 star average) for$^{19}$F. The solid curves are for the final abundances and the dashed curves are for the pre-SN stage. All production factors are ratios to that of $^{16}$O.

normalization purposes we compare to the production factor for oxygen. Since $^{16}$O is made mainly in massive stars, a production factor ratio near one is consistent with all (or most) of an isotope being made in a primary neutrino process (as are $^{7}$Li, $^{11}$B, and $^{19}$F).

Examining first the results for average production in the three-star sample, and assuming that this is a reasonable approximation of the total production process, we see that only 10%-15% of $^{7}$Li is made in the neutrino process. This is not surprising, since there are many processes, including the Big Bang, that make or destroy $^{7}$Li and that are not fully understood. On the other hand, for most values of the reaction rates $^{11}$B is overproduced, even if one ignores production by cosmic rays.

Fig. 2 shows the results for $^{138}$La and $^{180}$Ta. Here we show also results for the pre-SN stage, the time when the contraction speed in the iron core reaches 1000 km sec$^{-1}$, since production during that stage is not negligible, especially for $^{180}$Ta. A detailed examination, however, shows that most of the $^{138}$La and $^{180}$Ta that is ejected was newly synthesized during the explosion [2, 11].

Since these two isotopes are secondary products (produced from pre-existing spallation targets) a production ratio of about two for $^{138}$La and $^{180}$Ta (see the dotted line on Fig. 2) would be necessary to reproduce the solar abundance. An additional complication is that our models do not distinguish production in the short lived ground state from that in the long-lived isomeric $9^-$ state in $^{180}$Ta; a better, but still approximate, treatment [22] gives an isomer production of about 40% of the total production. It then appears that the production of $^{180}$Ta is roughly consistent with the solar abundance, given the uncertainties in the production calculations, and that the production of $^{138}$La corresponds to about half the solar abundance. $^{19}$F is a primary product, and it appears that 25%-75% of solar $^{19}$F could be made by the neutrino process. This complicates the determination of the importance of other sources such as AGB stars and Wolf-Rayet winds.

We now consider whether a comparison of the observed abundances of $^{7}$Li and $^{11}$B to SN model predictions can place constraints on the neutrino oscillation process, as was suggested in Refs. [3–5]. These investigations were for a 16.2 $M_{\odot}$ star, using parameters almost identical to those we have used, except that the explosion energy, $T_{\nu_e}$, and $T_{\bar{\nu}_e}$ were 1.0 Bethe, 3.2 MeV, and 5.0 MeV instead of 1.2 Bethe, 4.0 MeV and 4.0 MeV. The near equality of the average neutrino energies should yield similar production for the two models in the absence of neutrino oscillations.

In [3–5] neutrino oscillations produce significant increases in $^{7}$Li production, up to 75%, as $\sin^2 2\theta_{13}$ increases from $10^{-6}$ to $10^{-2}$ for the normal neutrino hierarchy–the changes are much smaller, around 15% for an inverted hierarchy. The changes for $^{11}$B are small for either hierarchy, around 20%. The number ratio $N(^{7}\mathrm{Li})/N(^{11}\mathrm{B})$ is assumed to be less susceptible then the absolute yields, to systematic uncertainties in the calculations and has approximately 50% changes for the normal hierarchy, and less than 10% for the inverted hierarchy. This provides, in principle, some hope that observation of an enhanced ratio could place a lower limit on the value of $\sin^2 2\theta_{13}$ and eliminate the option of an inverted hierarchy.

The variations with the helium burning reaction rates, of the production of $^7$Li by the neutrino process are relatively small, about 20%, but it will be difficult to untangle the relatively small amount of neutrino-produced $^7$Li from other sources of $^7$Li. One might hope that observations of $^7$Li in pre-solar grains would make it possible to isolate the effects of individual supernovae. Unfortunately, few, if any, relevant observations have been made to date. Lithium isotopic ratios have been measured in very large SiC grains by Gyngard, et al. [23], but Li is very volatile and is not expected to condense into SN SiC grains [24]. Thus, while its production does not depend strongly on the helium burning rates, other considerations limit its usefulness.

The situation for $^{11}$B is also unclear. Hoppe et al. [25] measured B in supernova SiC grains. Their measured isotopic ratio, $^{11}\mathrm{B}/^{10}\mathrm{B} = 3.46 \pm 1.36$, is, however, consistent with laboratory contamination by solar system B ($^{11}\mathrm{B}/^{10}\mathrm{B}= 4.045$). They conclude that at most 30% of the measured B is attributable to the neutrino process. Their Fig. 5 [25] shows a corrected value reduced by a corresponding factor of three. After this correction, the abundance of B is lower than expected, by over an order of magnitude. They consider some possible explanations, but it appears that the grain formation process is not well understood.

Moreover, as we see in the top four panels of Fig. 1, variations in $^{11}$B yields with reaction rate are large, a factor of two or more, making the uncertainties in its predicted ratio to $^7$Li and in its absolute value much larger than the effects predicted by [3–5]. We conclude that this approach to constraining neutrino oscillations will not be productive until there are significant improvements in the helium burning rates discussed here, as well as in grain observations and their interpretation.

Before considering whether the gross production rates might eventually provide a constraint on neutrino spectra, we need to examine the total production of $^{11}$B. Both $^{11}$B and $^{10}$B are made in the galactic cosmic rays (GCR) with the ratio $^{11}\mathrm{B}/^{10}\mathrm{B}$ lying between 2.2 and 2.5 [26, 27]. The $\pm 0.15$ uncertainties in the ratio reflect, mainly, uncertainties in the cosmic ray sources and the propagation model. (For reviews see [28, 29]). We take as the observed meteoritic ratio 4.045 [16]; the other recent abundance summaries [15, 30] quote results within 0.5% of this value. Since we find that the neutrino process makes little $^{10}$B ($^{11}\mathrm{B}/^{10}\mathrm{B} \approx 50$), about $42 \pm 4$% of the $^{11}$B must be made in the neutrino process. A possible contribution of (so far unobserved) low energy cosmic rays would increase the $^{11}\mathrm{B}/^{10}\mathrm{B}$ ratio in cosmic ray production [26] but it has been found [31] that this process is energy inefficient and unlikely to produce a significant amount of $^{11}$B. The neutrino process $^{11}$B should then be compared to about $0.4\times$(solar $^{11}$B)–see Fig. 1.

Summarizing, except for $^7$Li and $^{19}$F, which have other known production sites, it appears that production by the neutrino process (and partially, for $^{180}$Ta by the gamma process), as shown in the 3-Star panels of Figs. 1 and 2, is within a factor of three of the observed abundances except for extreme values of the rates.

It has been shown previously that neutrino process yields increase strongly for larger neutrino energies. For example, increasing the temperature of $\nu_e$ and $\bar{\nu}_e$ neutrinos from 4 to 6 MeV increases the yields of the neutrino nuclei by factors from 1.5 to 2 [2]. Similar changes were obtained for $\nu_\mu$. This strong dependence raises the possibility of constraining the ranges of allowable neutrino temperatures, spectral shapes and neutrino intensity. Such constraints depend on the robustness of the model predictions, and thereby on the nuclear rates, on the neutrino interaction cross sections, on the form of the neutrino spectra, and on the astrophysical modeling uncertainties of the underlying stellar models. It is probable that the best limits will be obtained for $^{11}$B. The neutrino interaction cross sections for $^{12}$C can be more reliably calculated than those for the heavier nuclei, because the strong Gamow-Teller cross sections are mainly experimentally based, and shell model estimates can replace RPA calculations for the $L > 0$ cross sections [32–34]. The constraint imposed by the meteoritic and GCR $^{11}\mathrm{B}/^{10}\mathrm{B}$ ratios is also useful in determining the appropriate SN $^{11}$B yield.

Taken at face value, it seems that significantly harder neutrino spectra than we have used are improbable–the yield is already overestimated. But improvements in the neutrino process calculations are necessary to make this constraint credible. It appears likely [35] that the uncertainty in the triple alpha rate will be halved in the near future and there are major efforts to improve the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ rate. Better estimates of neutrino spectra can also be employed; it is now known [36, 37] that the mean energies of the various neutrino species are more similar than had been thought, and that the high energy tail is suppressed by inclusion of inelastic scattering processes. The mean energies and second energy moments of these new spectra are, however, similar to those of the Fermi-Dirac distributions we have used, differing by less than 12 % in all cases-the second moments are related to the neutrino process cross sections. The astrophysical model uncertainties could be reduced using techniques informed by 3-D calculations.

To summarize, we explored changes in the core-collapse supernova yields of $^7$Li, $^{11}$B, $^{19}$F, $^{138}$La, and $^{180}$Ta that arise from changes in the triple alpha and $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rates within our adopted $\pm 2\sigma$ uncertainties. We found that the rate changes result in factor of two changes in the production of $^{11}$B in a 15 $M_\odot$ star. This, for the present at least, rules out the techniques proposed [3–5] to constrain the neutrino oscillation parameter $\sin^2 2\theta_{13}$. For the assumed neutrino spectra there is significant overproduction of $^{11}$B for all values of the rates we have used ($\pm 2\sigma$). It seems reasonable to expect that a factor of two improvement in the precision of neutrino-process nucleosynthesis can be achieved, especially for $^{11}$B. This may provide a constraint on the neutrino energy spectrum. If one assumes that model calculations can accurately fix the spectral shape, neutrino process nucleosynthesis could provide an estimate of the neutrino flux from supernovae and a check on supernova models that does not depend on occurrence of (infrequent) supernova explosions.

We thank Robert Hoffman and Stan Woosley for assistance with reaction rates and for helpful discussions. Research support from: US NSF: grants PHY06-06007, PHY02-16783(JINA)); US DOE: contract DE-AC52-06NA25396, grants DE-FC02-01ER41176, FC02-09ER41618 (SciDAC), DE-FG02-87ER40328.

* Electronic address: austin@nscl.msu.edu; URL: www.nscl.msu.edu/~austin
† Electronic address: alex@physics.umn.edu

[1] S. E. Woosley, *et al.*, **356**, 272 (1990).
[2] A. Heger, *et al.*, Phys. Lett. B, **606**, 258 (2005).
[3] T. Yoshida, *et al.*, Phys. Rev. Lett. **96**, 091101 (2006).
[4] T. Yoshida, *et al.*, Astrophys. J. **649**, 319 (2006).
[5] T. Kajino, *et al.*, Mod. Phys. Lett. A, **23**, 1409 (2008).
[6] Report of the Particle Physics Project Prioritization Panel, p. 34-5(2008) .
[7] C. Tur, A. Heger, and S. M. Austin, Astrophys. J. **671**, 821 (2007).
[8] C. Tur, A. Heger, and S. M. Austin, Astrophys. J. **702**, 1068 (2009).
[9] T. A. Weaver, G. B. Zimmerman, and S. E. Woosley, Astrophys. J. **225**, 1021 (1978).
[10] S. E. Woosley and T. A. Weaver, Astrophys. J. Suppl. **101**, 181 (1995) .
[11] T. Rauscher, *et al.*, Astrophys. J. **576**, 323 (2002).
[12] S. E. Woosley, A. Heger, and T. A. Weaver, Rev. Mod. Phys. **74**, 1015 (2002).
[13] C. Tur, A. Heger, and S. M. Austin, Astrophys. J. **718**, 357 (2010).
[14] D. Arnett, *et al.*, Ann. Rev. Astron. Astrophys. **27**, 629 (1989).
[15] E. Anders and N. Grevasse, Geochim. Cosomochim. Acta **53**, 197 (1989).
[16] K. Lodders, Astrophys. J, **591**, 1220 (2003).
[17] G. R. Caughlan and W. A. Fowler, At. Data Nucl. Data Tables, **40**, 283 (1988).
[18] L. R. Buchmann, Astrophys. J. **468**, L127 (1996); erratum: **479**, L153 (1997).
[19] S. E. Woosley and A. Heger, **442**, 269 (2007).
[20] X. D. Tang, *et al.*, Phys. Rev. C **81**, 045809 (2010).
[21] J. M. Scalo, Fund. Cosmic Phys. **11**, 1 (1986).
[22] T. Hayakawa, *et al.*, Phys. Rev. C **81**, 052801 (2010).
[23] F. Gyngard, *et al.*, Astrophys. J. **694**, 359 (2009).
[24] L. Nittler, Priv Comm.
[25] P. Hoppe, *et al.*, Astrophys. J. **551**, 478 (2001).
[26] M. Meneguzzi, J. Audouze, and H. Reeves, Astron. Astrophys. **15**, 337 (1971).
[27] N. Prantzos, Priv. Comm..
[28] N. Prantzos, Space Sci. Rev. **130**, 27 (2007).
[29] N. Prantzos, ArXiv:1003.2317.
[30] K. Lodders, p. 379, in Astrophys. Space Sci. Proc., Springer-Verlag, Heidelberg, 2010.
[31] R. Ramaty, *et al.*, Astrophys. J. **488**, 730 (1997).
[32] N. Auerbach and B. A. Brown, Phys. Rev. C **65**, 024322 (2002).
[33] C. Volpe, *et al.*, Phys. Rev. C **62**, 015501 (2000).
[34] A. C. Hayes, and I. S. Towner, Phys. Rev. C **61**, 044603 (2000).
[35] C. Tur, A. Heger, and S. M. Austin, POS (NIC XI).
[36] H.-Th. Janka, *et al.*, Phys. Reports **442**, 38 (2007).
[37] K. Langanke, *et al.*, Phys. Rev. Lett. **100**, 011101 (2008).