THE GALACTIC $^{26}$Al PROBLEM AND THE CLOSE BINARY TYPE Ib/c SUPERNOVA SOLUTION?

J. C. Higdon
W. M. Keck Science Center, Claremont Colleges, 925 North Mills Avenue, Claremont, CA 91711-5916; jimh@lobach.jsd.claremont.edu

and

R. E. Lingenfelter and R. E. Rothschild
Center for Astrophysics and Space Sciences, University of California at San Diego, Code 0424, 9500 Gilman Drive, La Jolla, CA 92093; rlingenfelter@ucsd.edu, rothschild@ucsd.edu

Received 2004 February 25; accepted 2004 June 23; published 2004 July 12

ABSTRACT

The origin of the long-lived (1.07 Myr mean life) radioactive $^{26}$Al, which has been observed in the Galactic interstellar medium from its 1.809 MeV decay gamma-ray line emission, has been a persistent problem for over 20 years. Wolf-Rayet (W-R) winds were thought to be the most promising source, but their calculated $^{26}$Al yields are not consistent with recent analyses of the 1.809 MeV emission from the nearest W-R star and nearby OB associations. The expected $^{26}$Al yield from the W-R star exceeds, by much as a factor of 3, that set by the 2 $\sigma$ upper limit on the 1.809 MeV emission, while the W-R yields in the OB associations are only about $\frac{1}{4}$ of that required by the 1.809 MeV emission. We suggest that a solution to these problems may lie in $^{26}$Al from a previously ignored source: explosive nucleosynthesis in the core-collapse Type Ib/c supernovae (SNe Ib/c) of W-R stars that have lost most of their mass to close binary companions. Recent nucleosynthetic calculations of SNe Ib/c suggest that their $^{26}$Al yields depend very strongly on the final pre-SN mass of the W-R star and that those with final masses around 6–8 $M_\odot$ are expected to produce as much as $10^{-2} M_\odot$ of $^{26}$Al per SN. Such binary SNe Ib/c make up only a small fraction of the current SNe Ib/c and only about 1% of all Galactic core-collapse SNe. But they appear to be such prolific sources that the bulk of the present $^{26}$Al in the Galaxy may come from just a few hundred close binary SNe Ib/c, and the intense 1.809 MeV emission from nearby OB associations may come from just one or two such SNe. More extensive SN Ib/c calculations of the $^{26}$Al yields versus pre-SN mass are clearly needed to test this possibility.

Subject headings: Galaxy: abundances — nuclear reactions, nucleosynthesis, abundances — stars: Wolf-Rayet — supernovae: general

1. INTRODUCTION

Observable diffuse Galactic 1.809 MeV line emission from the decay of long-lived (1.07 Myr mean life) radioactive $^{26}$Al was predicted (Arnett 1977; Ramaty & Lingenfelter 1977) from early estimates (Schramm 1971) of the nucleosynthetic yields in explosive carbon burning in core-collapse supernovae (SNe) of about $10^{-3} M_\odot$ per SN of $^{26}$Al. Assuming a Galactic SN rate of 1 SN every 30 yr, this yield suggested an average steady state radioactive mass of 0.3 $M_\odot$ of $^{26}$Al in the Galaxy. The 1.809 MeV line emission was subsequently discovered by Mahoney et al. (1982, 1984) with the high-resolution gamma-ray spectrometer on HEAO 3 at an intensity of $\sim 5 \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$ sr from the inner Galaxy. This flux, confirmed by later observations, is nearly an order of magnitude higher than that predicted and implies a steady state Galactic mass of $3.1 \pm 0.9 M_\odot$ of $^{26}$Al (e.g., Knödlseder 1999).

This much higher $^{26}$Al mass, together with a lack of information about its spatial distribution and the uncertainties in model predictions of $^{26}$Al yields, led to suggestions of a variety of additional possible sources for $^{26}$Al, including the winds of Wolf-Rayet (W-R) stars, asymptotic giant branch (AGB) stars, novae, and other transient sources. For a time, however, the yield calculations of neon burning and neutrino interactions in Type II SN (SN II) core collapse of the massive ($>25 M_\odot$) stars without wind losses appeared (e.g., Timmes et al. 1995) to be adequate to account for the observed $^{26}$Al. But calculations (e.g., Schaller et al. 1992) of the evolution of these stars showed that the SN II models with hydrogen-rich envelopes were not appropriate in this mass range, because their winds blow off their hydrogen envelopes leaving much smaller W-R stars, which are expected to end in SNe Ib/c instead. The SN II yields (Timmes et al. 1995; Thielemann et al. 1996) of less massive ($<25 M_\odot$) stars could account for no more than about $\frac{1}{4}$ of the observed $^{26}$Al, and calculations (Woosley et al. 1995) of the yields of the SNe Ib/c of the small final mass stars that resulted from the expected large W-R wind losses in single stars suggested that these stars were also minor contributors. Thus, the deep dredging of the W-R winds themselves were explored as a possible major source. Early calculations (Langer et al. 1995; Meynet et al. 1997), assuming W-R wind mass-loss rates that were much larger than observations now suggest, gave yields that could account for about $\frac{1}{3}$ of the observed $^{26}$Al, and very recent calculations (Vuissiez et al. 2004) using current wind loss estimates, but including the effects of stellar rotation, now give even higher $^{26}$Al yields.

Studies of the spatial distribution of the Galactic $^{26}$Al from COMPTEL, by Knödlseder et al. (1999a, 1999b), have also shown that the diffuse 1.809 MeV line emission most closely correlates with the distributions of young massive stars. This clearly implies that such stars are the source of the bulk of the Galactic $^{26}$Al and rules out novae, AGB stars, and other older population sources. This would also seem to support W-R winds as the source, but other recent observations argue against that.

2. PROBLEMS WITH A W-R WIND SOURCE OF $^{26}$Al

First, the 1.809 MeV flux and $^{26}$Al yields that would be expected from W-R winds in the most recent calculations (Vuissiez et al. 2004) exceed by as much as a factor of 3 the upper limits on the 1.809 MeV line from COMPTEL for the closest W-R star, $\gamma$ Velorum, assuming (Oberlack et al. 2000; Pozzo...
et al. 2000) a distance of 258–410 pc. This star has an estimated (Schaerer et al. 1997) initial mass of 57 ± 15 $M_\odot$, and for a 60 $M_\odot$ W-R star Vuissoz et al. (2004) calculate a $^{26}$Al wind yield of $2.24 \times 10^{-4} M_\odot$, with a maximum capture of $\frac{1}{3}$ of that mass by its companion (e.g., Vanbeveren et al. 1998b), whereas the 2 $\sigma$ upper limit of $1.1 \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ on the 1.809 MeV line flux from this star (Oberlack et al. 2000) places a 2 $\sigma$ upper limit of $(0.6–1.5) \times 10^{-4} M_\odot$, depending on the distance.

Second, recent analyses of the intense 1.809 MeV line fluxes observed from the direction of the massive star formation regions, Vela OB1, Cygnus OB2, and Orion OB1a, seem to further compound the problem. Analyses of Vela OB1 by Lavraud et al. (2001) show that using the $^{26}$Al yields (Meynet et al. 1997) for large W-R wind losses, the expected 1.809 MeV emission from both the W-R winds and SNe II was only about $\frac{1}{3}$ of that observed. The recent yields of Vuissoz et al. (2004) are only about 60% higher for the expected W-R stars in this association, so the W-R wind yields are still only about $\frac{1}{3}$ of that required. Similarly, analyses of Cygnus OB2, using the Meynet et al. (1997) yields, can account for only $\frac{1}{3}$ of the observed emission (Knödlseder et al. 2002; Pluschke et al. 2002), even after making a factor of 3 increase over the number of observed O stars as a correction for obscuration. Although the recently calculated yields could further close that gap, they already appear to be too high. As we show below, the recent W-R wind yields also fail to account for the 1.809 MeV emission observed from Orion OB1a. Lastly, the general problem is further complicated by the fact that no 1.809 MeV emission, comparable to that from Vela OB1, Cygnus OB2, or Orion OB1a, has been observed (Knödlseder et al. 1999c) from the half-dozen other equally large nearby OB associations (Brown et al. 1996).

3. THE SOLUTION: CLOSE BINARY SN Ib/c?

We suggest that the solution to all of these $^{26}$Al problems may lie in the new nucleosynthetic calculations of SNe Ib/c by Nakamura et al. (2001) for larger final-mass W-R stars, which are expected (Van Bever & Vanbeveren 2003) to result from mass transfer to close binary companions. Nakamura et al. (2001) calculate for He cores without late mass loss that in final pre-SN W-R masses of 6–8 $M_\odot$, the $^{26}$Al yields reach $6.7 \times 10^{-3}$ to $1.2 \times 10^{-2} M_\odot$, while at high masses of 10–16 $M_\odot$ the yields drop precipitously. Although the 6–8 $M_\odot$ yields might seem surprisingly large, such yields do seem to be quite consistent with the very steep dependence of the $^{26}$Al yield on final mass that Woosley et al. (1995) found for SNe Ib/c of much smaller final masses expected from the earlier large wind losses. They calculated SN Ib/c yields of $4.9 \times 10^{-6}$ to $8.4 \times 10^{-3} M_\odot$ of $^{26}$Al for final masses ranging from 2.3 to 3.5 $M_\odot$, respectively, which can be approximated by a power law in final mass to roughly the 6.5 power. Such a power-law dependence would give a yield of $7.6 \times 10^{-3} M_\odot$ of $^{26}$Al at 7 $M_\odot$, which is quite comparable to the SN Ib/c values calculated by Nakamura et al. (2001), as can be seen in Figure 1.

The relationship between the initial and final pre-SN masses of W-R stars is still uncertain. Perhaps the best determined final masses are those for W-R stars in close binaries, where the mutual gravitational forces, Roche lobe overflow, and common envelope evolution are dominant (e.g., Paczynski 1971; Vanbeveren et al. 1998b; Taam & Sandquist 2000), and the distribution of final masses depends most strongly on the range of orbital parameters and stellar mass ratios, which have been extensively measured (e.g., Popova et al. 1982; Duquennoy & Mayor 1991). The final masses of single W-R stars, however, depend (e.g., Vanbeveren et al. 1998b; Maeder & Meynet 2000) solely on the radiation-driven wind loss rates, which vary strongly with the changing stellar luminosity, mass, rotation, and metallicity.

Currently the principal source of W-R stars with final masses in the peak $^{26}$Al producing range from 6 to 8 $M_\odot$ appears to be those produced by mass transfer from massive stars in close binary systems with orbital periods of 1 day to 10 yr calculated by Van Bever & Vanbeveren (2003). Their calculated final masses, averaged over the measured ranges of orbital period, angular momentum, and stellar mass ratios, are shown as a function of initial mass in Figure 2b. Such binary systems appear to make up about 30% of all binaries (e.g., Duquennoy...
of such stars are expected to have low \(^{26}\)Al yields that would make them minor contributors. Other recent calculations by Vanbeveren et al. (1998a), however, suggest that a significant fraction of these stars may also have lower final masses. Clearly, further work is needed to resolve this question, and its age is estimated to be 1–5 Myr (Comeron et al. 1998; Lavraud 1997). 1.809 MeV line emission of (5.8 ± 0.6) \(\times 10^{-7}\) photons cm\(^{-2}\) s\(^{-1}\) was observed (Oberlack 1997) from that region with COMPTEL. As can be seen (Fig. 4a), we find from Monte Carlo simulations that such a flux would be expected from the \(^{26}\)Al in one or two SNe Ib/c from close binary W-R stars in that association about 40% of the time for ages between 5 and 6 Myr.

Cygnus OB2 is the largest of the OB associations in the Cygnus region, and the 1.809 MeV line emission of (5.8 ± 1.5) \(\times 10^{-7}\) photons cm\(^{-2}\) s\(^{-1}\) observed from that direction by COMPTEL. (Plussche et al. 2002; Knödlseder et al. 2002) is centered on it. Cygnus OB2 is at a distance of 1.7 ± 0.4 kpc, and its age is estimated to be 1–5 Myr (Comeron et al. 1998; Herrero et al. 1999; Plussche et al. 2002; Knödlseder et al. 2002). We would expect at least 120 initial SN progenitors, based on optical observations of 40 O stars (Massey et al. 2002).
1.809 MeV line intensity from $^{26}$Al decay in the OB associations, (a) Vela OB1, ages 4–7 Myr, (b) Cygnus OB2, ages 4–5 Myr, and (c) Orion OB1, ages 9.5–12.5 Myr, for different assumed ages, showing a roughly $\frac{1}{3}$ probability that just one or two close binary SNe Ib/c can account for the observed flux from the directions of those associations. Such a probability is also consistent with the fact that 1.809 MeV emission has only been seen from $\frac{1}{3}$ of the comparable OB associations.

1995). But since the region lies along a spiral arm, it is highly obscured, and the actual number may be significantly larger (e.g., Knödlseder 2000). Nonetheless, from Monte Carlo simulations of just the minimum number of progenitors (Fig. 4b), we would expect 1.809 MeV line fluxes in the observed range from the $^{26}$Al in one or two close binary SNe Ib/c in that association about 20% of the time if the age is in fact about 5 Myr, and that probability would rise to about 50% if even an additional $\frac{1}{2}$ of the O stars are unseen because of obscuration.

Orion OB1a is an older and smaller but much closer association at a distance of about 0.34 kpc and an age of 11.4 ± 1.9 Myr, with an estimated initial 25 SN progenitors, based on the identification (Brown et al. 1994) of 53 stars between 4 and 15 $M_\odot$. The 1.809 MeV flux observed (Diehl 2002; R. Diehl 2004, private communication) by COMPTEL from this region was about $(1-4) \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$. From Monte Carlo simulations (Fig. 4c) of this older association, we would expect contributions primarily from the $^{26}$Al produced in SNe II for ages greater than 10 Myr that cannot account for the observed flux, but for ages of 9.5–10 Myr we would expect a residual contribution from an earlier close binary SN Ib/c about 30% of the time, which could account for the observed flux.

Last, we note that the stochastic nature of the emission also seems to be supported by the fact that 1.809 MeV emission so far has been found (Knödlseder et al. 1999c) from only $\frac{1}{3}$ of the nine (seen from Vel OB1, Cyg OB2, and Ori OB1a but not from Cep OB2, Gem OB1, Mon OB2, Cen OB1, Ara OB1, and Sco OB1) largest nearby (<2 kpc) OB associations (Brown et al. 1996) in which $^{26}$Al from even a single high-yield close binary SN Ib/c could be seen. Such a fraction, however, is consistent with the expectations of our Monte Carlo simulations. Clearly, more extensive calculations of the $^{26}$Al yields of SNe Ib/c as a function of pre-SN mass are needed to test such a source.

This work was supported by NASA’s International Gamma-Ray Astrophysics Laboratory Science Program.

REFERENCES

Arnett, W. D. 1977, in Ann. NY Acad. Sci., 302, Eighth Texas Symposium on Relativistic Astrophysics, ed. M. D. Papagiannis, 90
Brown, A., Blauw, A., Hoogerwerf, R., de Bruijne, J., & de Zeeuw, P. 1996, in The Origin of Stars and Planetary Systems, ed. C. Lada & N. Kylafis (Dordrecht: Kluwer), 411
Brown, A., de Geus, E., & de Zeeuw, P. 1994, A&A, 289, 101
Comeron, F., Torra, J., & Gomez, A. 1998, A&A, 330, 975
Diehl, R. 2002, NewA Rev., 46, 547
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Herrero, A., Corral, L. J., Villamariz, M. R., & Martín, E. L. 1999, A&A, 348, 542
Knödlseder, J. 1999, ApJ, 510, 915
Knödlseder, J., et al. 1999a, A&A, 344, 68
Knödlseder, J., et al. 1999b, Astrophys. Lett. Commun., 38, 363
Knödlseder, J., et al. 1999c, A&A, 345, 813
———. 2002, A&A, 390, 945
Langer, N., Braun, H., & Fliegener, J. 1995, Ap&SS, 224, 275
Lavraud, B., Knödlseder, J., Cerviño, M., von Ballmoos, P., & Schaefer, D. 2001, in Exploring the Gamma-Ray Universe, ed. B. Battrick (ESA SP-459; Noordwijk: ESA), 79
Maeder, A., & Meynet, G. 2000, ARA&A, 38, 143
Mahoney, W. A., Ling, J. C., Jacobsen, A. S., & Lingenfelter, R. E. 1982, ApJ, 262, 742
Mahoney, W. A., Ling, J. C., Wheaton, W. A., & Jacobsen, A. S. 1984, ApJ, 286, 578
Massey, P., et al. 1995, ApJ, 454, 151
Meynet, G., Arnould, M., Prantzos, N., & Paulus, G. 1997, A&A, 320, 460
Meynet, G., & Maeder, A. 2003, A&A, 404, 975
Nakamura, T., et al. 2001, ApJ, 555, 809
Oberlack, U. 1997, Ph.D. thesis, Tech. Univ. München
Oberlack, U., et al. 2000, A&A, 353, 715
Paczynski, B. 1971, ARA&A, 9, 183
Plutschke, S., et al. 2002, NewA Rev., 46, 535
Popova, E. I., Tutukov, A. V., & Yungelson, L. R. 1982, Ap&SS, 88, 55
Pozzo, M., et al. 2000, MNRAS, 313, L23
Ramaty, R., & Lingenfelter, R. E. 1997, ApJ, 213, L5
Rauscher, T., Heger, A., Hoffman, R. D., & Woosley, S. E. 2002, ApJ, 576, 323
Salpeter, E. E. 1955, ApJ, 121, 161
Schaefer, D., Schmutz, W., & Grenon, M. 1997, ApJ, 484, L153
Schaller, G., Schaefer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Schramm, D. N. 1971, Ap&SS, 13, 249
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Thielemann, F.-K., Nomoto, K., & Hashimoto, M.-A. 1996, ApJ, 460, 408
Timmes, F. X., et al. 1995, ApJ, 449, 204
Van Bever, J., & Vanbeveren, D. 2003, A&A, 404, 63
Vanbeveren, D., De Donder, E., Van Bever, J., Van Rensbergen, W., & De Loore, C. 1998a, NewA, 3, 443
Vanbeveren, D., De Loore, C., & Van Rensbergen, W. 1998b, A&A Rev., 9, 63
Vuissoz, C., et al. 2004, NewA Rev., 48, 7
Woosley, S. E., Langer, N., & Weaver, T. A. 1995, ApJ, 448, 315

This work was supported by NASA’s International Gamma-Ray Astrophysics Laboratory Science Program.