Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 2 (OG part 1), pages 27–30

30TH INTERNATIONAL COSMIC RAY CONFERENCE

Can ^{59}Ni Synthesized in OB Associations Decay to ^{59}Co Before Being Accelerated to Cosmic-ray Energies?

W.R. BINNS [1], A.C. CUMMINGS [2], G.A. DE NOLFO [3], M.H. ISRAEL [1], R.A. LESKE [2], R.A. MEWALDT [2], T.T. VON ROSENVINGE [4], E.C. STONE [2], M.E. WIEDENBECK [5]

[1] *Washington University, St. Louis, MO 63130 USA*
[2] *California Institute of Technology, Pasadena, CA 91125 USA*
[3] *CRESST and Astroparticle Physics Laboratory NASA/GSFC, Greenbelt, MD 20771, USA*
[4] *NASA/Goddard Space Flight Center, Greenbelt, MD 20771 USA*
[5] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA*
wrb@wuphys.wustl.edu

Abstract: Observations from the Cosmic Ray Isotope Spectrometer (CRIS) aboard NASA's Advanced Composition Explorer (ACE) have shown that all relevant galactic cosmic-ray isotopic ratios measured are consistent with an OB-association origin of galactic cosmic rays (GCRs). Additionally CRIS measurements of the isotopic abundances of ^{59}Ni and ^{59}Co have shown that the ^{59}Ni has completely decayed into ^{59}Co, indicating a delay of $>10^5$ years between nucleosynthesis and acceleration. However, it has been suggested that shocks generated from high-velocity Wolf-Rayet winds in the OB-association environment must accelerate nuclei synthesized in nearby core-collapse supernovae on a time scale short compared to the ^{59}Ni half-life of 7.6×10^4 years. If this were the case, it would imply that OB associations could not be the source of most galactic cosmic rays. In this paper, we describe the OB-association history and environment and show that the time scales for acceleration are such that most ^{59}Ni should be expected to decay naturally in that setting, strengthening the argument that OB associations are the likely source of a substantial fraction of galactic cosmic rays.

Introduction

Cassé et al. [1] first suggested that ejecta from Wolf-Rayet stars, mixed with material of solar energetic particle composition, which was taken to be similar to solar system composition, could explain the large ^{22}Ne/^{20}Ne ratio measured in the galactic cosmic rays (GCRs) by several experiments referenced in [2]. Subsequently, Higdon et al. [3] have shown that the ^{22}Ne/^{20}Ne ratio measured by the Cosmic Ray Isotope Spectrometer (CRIS) aboard NASA's Advanced Composition Explorer (ACE) is consistent with a superbubble origin of GCRs. In their model ejecta from Wolf-Rayet (WR) stars and supernovae (SNe) from massive precursor stars (Types Ibc, II) in superbubbles are mixed with interstellar medium material (ISM) of solar wind (SW) composition. They find that a mixture of 18±5% of WR plus SN ejecta with the remainder being ISM material can account for the ^{22}Ne/^{20}Ne ratio measured by ACE-CRIS. They conclude that the large neon ratio is a "natural consequence of the superbubble origin of GCRs".

Binns et al. [2] compared a number of other isotopic ratios, in addition to ^{22}Ne/^{20}Ne, with results from a two-component model in which WR ejecta are mixed with ISM material (see [4,5,6] for model details). They find good agreement for all relevant isotopes with the models if ~20% of WR material is mixed with ISM, consistent with the fraction obtained by Higdon et al. [3]. (Note that the fraction of WR material in both [3] and [2] refers to the total amount of mass ejected from the star from birth until the end of the WR phase.) Binns et al. [2] concluded that that OB associations within superbubbles are the likely source of at least a substantial fraction of GCRs.

Another important constraint for the origin of cosmic rays, also obtained from ACE-CRIS measurements, is the requirement that nuclei synthesized and accelerated by SNe must be accelerated at least 10^5 yr after synthesis. Wiedenbeck, et al. [7] showed that ^{59}Ni, which decays only by electron-capture, has completely decayed, within the measurement uncertainties, to ^{59}Co. The ^{59}Ni can decay if, prior to its acceleration as cosmic rays, it resides for $>10^5$ years in dust grains or in a plasma environment. In the superbubble environment, the mean time between SNe is ~$3\text{-}35\times10^5$ years, depending upon the number of stars in the OB association [8]. If SN shocks are the accelerators of the superbubble material, then this gives sufficient time for ^{59}Ni, synthesized in previous SNe, to decay.

However, it has been suggested that the high-velocity WR winds, which contain a similar kinetic energy to that contained in SNRs, should accelerate ^{59}Ni on time scales shorter than its half-life, thus not allowing the ^{59}Ni to decay [9]. If this were the case, it would be a strong argument against the OB-association origin of GCRs.

In the above scenario, is there a mechanism that allows the ^{59}Ni to decay? Binns et al. [10, 11] note that, although the kinetic energy in WR winds and SNe are similar, the power in WR winds is approximately one-tenth that in SNe. In addition, ^{59}Ni can still decay if it is accelerated to energies <150 MeV/nuc since the nucleus will not always be fully stripped of orbital electrons [12]. Adiabatic deceleration may also be significant within the superbubble. However, there is another mechanism that should allow most ^{59}Ni synthesized in superbubbles to decay.

OB Association Timeline

OB associations are stellar clusters containing massive stars with initial mass $>8M_\odot$. The most massive stars have short lifetimes before core-collapse (a few million years) while an 8 $M_\odot$ star (the lightest star that can undergo core-collapse [5, 6]), has a life time of ~40 MY. In Fig. 1 we show a schematic OB-association timeline for an association in which the stars are coeval. The OB-association lifetime begins with the condensation of molecular cloud material into massive stars at T=0 and ends when the least massive star that can undergo core-collapse (~8 $M_\odot$) ends its life as a supernova, ~40 MY later. Shortly after the stars are formed, the most massive stars evolve into the Wolf-Rayet phase as shown in Fig. 1. Their high-velocity winds (~2,000-3,000 km/s) produce large low-density bubbles in the molecular cloud. Expanding shocks from subsequent SN explosions then coalesce, producing a superbubble.

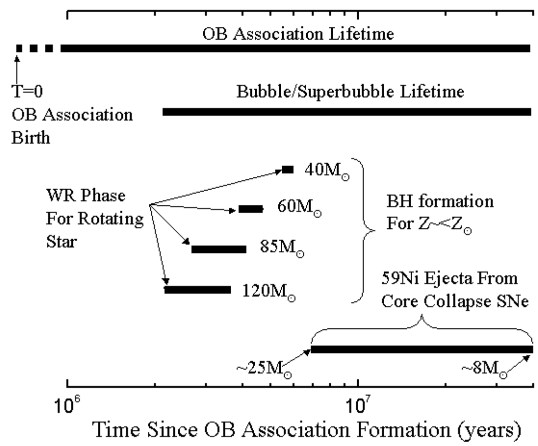

Figure 1: Schematic OB-association timeline

Fig. 1 shows the time interval that the most massive stars spend in the WR phase, and the epoch for which that occurs in the OB association, for rotating stars with initial masses ranging from 40 to 120 $M_\odot$. The most massive star modeled enters the WR phase ~2 MY after association birth, and the least massive star that can evolve into a WR star exits that phase roughly 4 MY later. The low-initial-mass cutoff for entering the WR phase is model dependent and is believed to be between 25 $M_\odot$ and 40 $M_\odot$ [4, 5, 6]. The end of the WR phase is followed by core collapse. So there is, at most, an approximate 4 MY period in the life of a coeval OB association for which acceleration of superbubble material by WR winds could occur. The most massive stars are very rare, so except for very large associations, this period will be significantly less than 4 MY. The initial mass function for OB associations is often taken to go approximately as $dN/dM \propto M^{-2.35}$ [13, 14].

Let us suppose, as is argued by Heger et al. [15], that most stars with initial mass $\geq$ 40 $M_\odot$ and metallicity roughly solar or less do not undergo a SN explosion after core collapse, but instead "directly" collapse to form a black hole. Stars with initial mass 25-40 $M_\odot$ and metallicity roughly solar or less undergo core-collapse to form a black hole by “fallback”, resulting in a very weak SN shock with little ejecta.

Daflon et al. [16] have measured the metallicity of young OB stars in associations as a function of galacto-centric radius. Their observations show that for OB associations within 1kpc of the Sun, most have metallicity that is solar or less. (Note that the metallicity of the stars, which condense out of old giant-molecular-cloud material, is distinct from that of the superbubble medium, which has a high metallicity resulting from fresh ejecta from recent SNe in the association). In the Heger et al. picture [15], stars with metallicity higher than ~solar result in SNe of type SNIb,c. These SNe are believed to result from WR stars. Additionally, there are massive stars that core-collapse into “hypernova”, which are poorly understood, and estimated to occur in ~1-10% of the massive core-collapse events [17]. If this picture is correct we see that a substantial fraction of core-collapse events during the WR epoch will not eject large amounts of newly synthesized material, including ^{59}Ni, into the superbubble. So the predominant material available for acceleration by the WR winds appears to be wind material ejected from the association stars since their birth, plus any normal ISM that is in the vicinity.

Fig. 1 also shows that stars with mass low enough so that they do not enter the WR phase (~8 $M_\odot \leq M \leq 25\ M_\odot$) undergo core-collapse as SNe in which ^{59}Ni is synthesized and injected into the superbubble. The most massive stars will undergo SN explosions first with later SNe accelerating previously injected material in the superbubble.

In this simple picture it appears that the injection of the ^{22}Ne-rich wind material from WR stars and the injection of ^{59}Ni from the SNe of stars with initial mass 8 $M_\odot \leq M \leq 25\ M_\odot$ into the superbubble are largely separated in time. Thus the appropriate time scale for acceleration of most SN ejecta, including the ^{59}Ni, would be the time between SN shocks after the WR epoch in superbubbles, not the shorter time scales associated with WR shocks in the WR epoch. Since the time between SNe is typically ~3 $\times$ 10^5 years for a large association [9], and the ^{59}Ni half-life for decay is 7.6 x 10^4 years, in this picture, there is sufficient time for it to decay to ^{59}Co.

However, many OB associations are composed of “subgroups” with different ages [18]. For these associations, this simple picture needs to be modified since the WR winds from younger subgroups occur during the time when substantial ^{59}Ni is being ejected by SNe in older subgroups. To quantitatively estimate the fraction of OB-association lifetime for which WR winds are active, we have performed a Monte Carlo calculation. In this calculation, we randomly generated ~6$\times$$10^4$ stars with mass >8$M_\odot$ using the initial-mass distribution $dN/dM \propto M^{-2.35}$. The stars were then grouped into subgroups containing, e.g., 10 stars each (top panel in Fig. 2), and four subgroups were grouped to form associations. Thus, about 1,500 associations with four subgroups of 10 stars each were generated. The time that each star in an association was in the WR phase was then obtained from [5, 6] and the sum of the time with one or more stars in the WR phase was calculated (times appropriate for rotating stars were used). It was assumed that there is a 4 MY

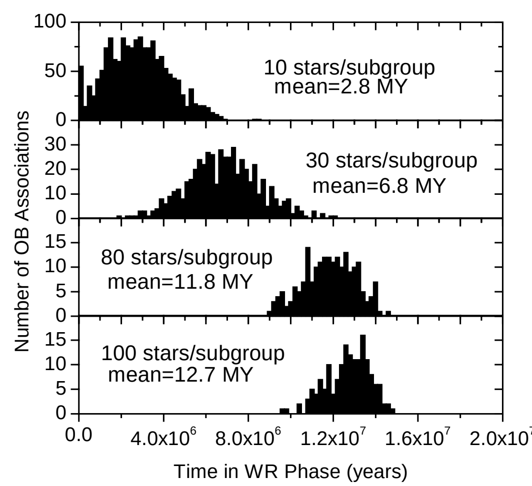

Figure 2: Monte Carlo calculation of the total time that at least one star in an OB association is in the WR phase.

time interval between subgroup formation time [18]. Fig. 2 shows the results of this calculation for subgroup sizes of 10, 30, 80, and 100 stars. Note that for four subgroups spaced in time intervals of 4MY, the association lifetime is ~52 MY. In Fig. 3 we show a plot of these results as a function of subgroup size for both rotating and non-rotating WR stars [5, 6]. We see that for associations with four subgroups, with each subgroup having ~20 OB stars, the time with one or more stars in the WR phase is ~5 MY, or ~10% of the

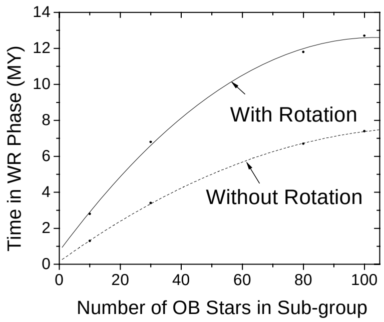

Figure 3: Plot of Monte Carlo results—Total time in WR phase vs. number of OB stars/subgroup.

association lifetime, for rotating star models, and is about half that for non-rotating stars. For large subgroups WR winds are blowing for as much as ~25% of the time for rotating star models.

In Fig. 4, we show a plot of the radial distance from the Sun of OB associations in the solar neighborhood. The vertical and horizontal bar lengths represent the number of OB stars and the age respectively (see figure legend), for those associations for which that information is available. SCO-OB2 subgroups 2, 3, and 4, are large, with ~100 stars/subgroup while the Orion-OB1 subgroups have 15-20 stars each.

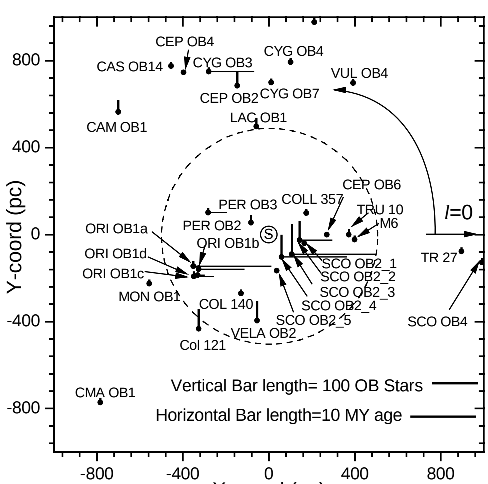

Figure 4: Plot of OB associations near the Sun

Summary

Thus we see that even if WR winds do accelerate particles to cosmic ray energies, the WR epoch is confined in time and could result in the acceleration of only a relatively small fraction of ^{59}Ni synthesized in OB associations. For this reason and for the other reasons cited in the introduction, it appears that the observation by Wiedenbeck et al. [7] that all or most of the ^{59}Ni in GCRs has decayed to ^{59}Co is likely consistent with the OB-association origin of galactic cosmic rays. Furthermore, the nearby associations shown in Fig. 4 are the likely sources of GCRs observed at Earth.

Acknowledgements

This research was supported by NASA at Caltech, WU, the JPL, and GSFC (under Grants NAG5-6912 and NAG5-12929).

References

[1] M. Cassé, et al., ApJ, 258, 860, 1982.
[2] W.R. Binns, et al., ApJ, 634, 351, 2005.
[3] J.C. Higdon, et al., ApJ, 590, 822, 2003.
[4] M. Arnould, et al., A&A, 453, 653, 2006.
[5] G. Meynet, et al. A&A, 404, 975, 2003.
[6] G. Meynet, et al., A&A, 429, 518, 2005.
[7] M.E. Wiedenbeck, et al., ApJ, 523,L61, 1999.
[8] J.C. Higdon, et al., ApJ, 509, L33, 1998.
[9] N. Prantzos, 2005, Private communication.
[10] W.R. Binns, et al., New Astron. Revs, 50, No. 7-8, 516, 2006.
[11] W.R. Binns, et al., Accepted for publication in Space Sci. Revs., Vol 27, 2007.
[12] M.E. Wiedenbeck et al., AIP Conference Proc,. 528, 363, 2000.
[13] E.E. Salpeter, ApJ, 121, 161, 1955.
[14] J.C. Higdon, et al., ApJ, 628, 738, 2005.
[15] A. Heger, et al., ApJ, 591, 288, 2003.
[16] S. Daflon, et al., ApJ, 617, 1115, 2004.
[17] C.L. Fryer, et al., ApJ, 650, 1028, 2006.
[18] A.I. Sargent, ApJ, 233, 163, 197.