A RUNAWAY WOLF–RAYET STAR AS THE ORIGIN OF $^{26}$Al IN THE EARLY SOLAR SYSTEM

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ABSTRACT

Establishing the origin of the short-lived radionuclide (SLR) $^{26}$Al, which was present in refractory inclusions in primitive meteorites, has profound implications for the astrophysical context of solar system formation. Recent observations that $^{26}$Al was homogeneously distributed in the inner solar system prove that this SLR has a stellar origin. In this Letter, we address the issue of the incorporation of hot $^{26}$Al-rich stellar ejecta into the cold protosolar nebula. We first show that the $^{26}$Al atoms produced by a population of massive stars in an OB association cannot be injected into protostellar cores with enough efficiency. We then show that this SLR likely originated in a Wolf–Rayet star that escaped from its parent cluster and interacted with a neighboring molecular cloud. The explosion of this runaway star as a supernova probably triggered the formation of the solar system. This scenario also accounts for the meteoritic abundance of $^{41}$Ca.

Key words: ISM: bubbles – nuclear reactions, nucleosynthesis, abundances – stars: formation – stars: Wolf–Rayet

1. INTRODUCTION

More than 30 years after Lee et al.’s discovery (1976) that calcium–aluminum-rich inclusions (CAIs) from the Allende meteorite contained $^{26}$Al (mean lifetime $\tau_{26} = 1.03 \times 10^5$ yr), the origin of this short-lived radionuclide (SLR) remains an open question. High precision Mg isotopic analyses of asteroids and bulk rocks from terrestrial planets (Thrane et al. 2006), as well as recent micrometer-scale data in chondrules (Villeneuve et al. 2009), showed that $^{26}$Al was homogenously distributed over at least the inner part of the solar system, i.e., over a reservoir of mass $> 2 M_\oplus$, and that no significant amount of freshly made $^{26}$Al was added to the protoplanetary disk after the CAI formation. The maximum amount of $^{26}$Al that could have been synthesized by in situ particle irradiation during the short duration of CAI formation ($\sim 10^5$ yr; Bizzarro et al. 2004) can account for the canonical $^{26}$Al/$^{27}$Al = $5 \times 10^{-3}$ over a rocky reservoir of only $\sim 0.1 M_\oplus$ (Duprat & Tatischeff 2007). Thus, the origin of this SLR cannot be related to the nonthermal activity of the young Sun and has to be searched for in a stellar nucleosynthetic event contemporary with the formation of the solar system.

An origin of SLRs in an asymptotic giant branch (AGB) star has been proposed (Wasserburg et al. 1994; Trigo-Rodríguez et al. 2009), but AGB stars are not associated with star-forming regions and the probability of a chance encounter between an AGB star and a star-forming molecular cloud is very low (Kastner & Myers 1994). It is more likely that the protosolar system was contaminated by material freshly ejected from a massive star, either a Type II SN (e.g., Cameron & Truran 1977) or a Wolf–Rayet (WR) star (e.g., Arnould et al. 1997). Massive stars have a profound influence on the surrounding molecular clouds and the process of star formation (e.g., Lee & Chen 2007). Cameron & Truran (1977) first suggested that a supernova (SN) responsible for injecting SLRs into the presolar nebula also may have been responsible for triggering the formation of the solar system. Detailed numerical simulations have shown that such simultaneous triggering and injection is possible, but the injection efficiency is lower than required (Boss et al. 2010). Alternatively, it has been suggested that a nearby SN ($\sim 0.3$ pc) may have injected SLRs into the already-formed protoplanetary disk of the solar system (see Ouellette et al. 2007, and references therein). In this scenario, it is assumed that the Sun was born in a large stellar cluster containing massive stars. But this model is questionable, because (1) protoplanetary disks in the vicinity of massive stars are exposed to a rapid photoevaporation and (2) the main-sequence lifetime of even the most massive stars is too long as compared to the mean lifetime of protoplanetary disks (Gounelle & Meibom 2008).

Gounelle et al. (2009) and Gaidos et al. (2009) recently suggested that the Sun is born in a stellar cluster of second generation, whose formation was triggered by the activity of a neighboring OB association. There are many observations of OB associations divided in spatially separated subgroups of different ages (e.g., Blaauw 1964), as well as observations of young stellar objects located on the border of H II regions (e.g., Karr et al. 2009) and superbubbles (e.g., Lee & Chen 2009). Adopting such an astrophysical context, in this Letter we study how hot stellar debris enriched in $^{26}$Al could be injected into a cold protostellar nebula. We show in Section 2 that $^{26}$Al produced by a population of massive stars in an OB association may not be delivered into molecular cores efficiently enough. In Section 3 we study a possibility already mentioned in the pioneering work of Arnold et al. (1997) and more recently by Gaidos et al. (2009) that the presolar nebula was contaminated by $^{26}$Al produced by a WR star that escaped from its parent cluster.

2. $^{26}$Al PRODUCTION BY AN OB ASSOCIATION IN A SUPERBUBBLE

Most massive stars are born in OB associations, where multiple stellar winds merge and expand to form large cavities of hot gas known as superbubbles (see, e.g., Parizot et al. 2004). The subsequent SNe generally explode inside the wind-generated superbubble. The radius of a superbubble can be
estimated from the standard wind bubble theory (Weaver et al. 1977):

\[ R_{SB} \approx (22\text{pc})^{3/5} n_{\text{Myr}}^{1/5} n_{H,100}^{1/5} \]  

(1)

where \( t_{\text{Myr}} \) is the time in units of Myr after the onset of massive star formation (assumed to be coeval for all stars), \( N_{e,30} = N_{e}/30 \) where \( N_{e} \) is the number of massive stars in the 8–120 \( M_{\odot} \) mass range, and \( n_{H,100} = n_{H}/(100 \text{ cm}^{-3}) \) where \( n_{H} \) is the mean \( H \) number density in the ambient interstellar medium. The superbubble radius is generally given as a function of the stellar wind mechanical power, \( L_{w} \), instead of the number of massive stars (e.g., Mac Low & McCray 1988). But Equation (1) uses the recent result of Voss et al. (2009) that the mean wind power per star from a coeval population of massive stars is nearly constant with time for \( \sim 5 \) Myr and amounts to \( \approx 1.5 \times 10^{36} \text{ erg s}^{-1} \). Similarly, the characteristic temperature and \( H \) number density in the interior of a superbubble can be written as (Weaver et al. 1977; Mac Low & McCray 1988)

\[ T_{SB} \approx (5.7 \times 10^{6} \text{ K}) n_{\text{Myr}}^{-6/35} N_{e,30}^{2/35} n_{H,100}^{2/35} \]  

(2)

\[ n_{SB} \approx (0.17 \text{ cm}^{-3}) n_{\text{Myr}}^{-22/35} N_{e,30}^{6/35} n_{H,100}^{19/35} \]  

(3)

WR wind and SN ejections of \( ^{26}\text{Al} \) occur at \( t_{\text{Myr}} \gtrsim 3 \) (Voss et al. 2009), when the superbubble blown by the winds from the main-sequence stars has already reached a radius of several tens of pc (Equation (1)). Noteworthy, SN blast waves within a superbubble will usually become subsonic in the hot gas before they reach the superbubble of swept-up interstellar material (Mac Low & McCray 1988; Parizot et al. 2004). This is true as well for winds of WR stars. Thus, most nuclei synthesized in massive stars first thermalize in the hot superbubble interior. Further incorporation of this material into molecular clouds and star-forming systems takes more than 10 Myr (Meyer & Clayton 2000), by which time the \( ^{26}\text{Al} \) will have decayed.

To solve this issue, Gaidos et al. (2009) proposed that \( ^{26}\text{Al} \) ejected in WR winds can be rapidly incorporated into high-speed (\( \sim 1000 \text{ km s}^{-1} \)) refractory dust grains of \( \sim 0.01–0.1 \mu \text{m} \) size that could dynamically decouple from the shocked wind gas and imbed themselves into the surrounding molecular material. But this proposal has two shortcomings. First, WR stars are thought to be a major contributor to the Galactic \( ^{26}\text{Al} \) detected through its gamma-ray decay line at \( E_{\gamma} = 1809 \text{ keV} \), and high-resolution spectroscopic observations of this emission with \( \text{RHESSI} \) and the \textit{International Gamma-Ray Astrophysics Laboratory (INTEGRAL)} gamma-ray satellites have shown that the line is narrow, \( \Delta E_{\gamma} = 1–2 \text{ keV FWHM} \), consistent with the instrumental resolution (see Diehl et al. 2006, and references therein). The non-detection of Doppler broadening in the Galactic 1809 keV line provides an upper limit on the mean velocity of the emitting \( ^{26}\text{Al} \) nuclei: \( v_{\text{max}} \sim 0.5c \Delta E_{\gamma}/E_{\gamma} \sim 150 \text{ km s}^{-1} \) (here, \( c \) is the speed of light). This maximum velocity is much lower than the speed that dust grains must acquire to survive sputtering as they pass the WR wind termination shock (Gaidos et al. 2009). Secondly, most grains formed in WR winds will slow down and stop in the superbubble interior before reaching the superbubble shell. According to the classical estimate of Spitzer (1978), the range of a grain of size \( a_{gr} \) and typical density \( \rho_{gr} \sim 2 \text{ g cm}^{-3} \) is \( X_{\text{gr}} = a_{gr}\rho_{gr} v_{\text{esc}} = (2 \times 10^{-6} \text{ g cm}^{-2})(a_{gr}/0.01 \mu \text{m}) \). In comparison, the radial path length in a superbubble is

\[ X_{SB} = 1.4 n_{H,100} \int_{0}^{R_{SB}} n(r) dr \]  

\[ \approx (4.6 \times 10^{-5} \text{ g cm}^{-2}) v_{\text{esc}}^{-1/35} n_{\text{Myr}}^{13/35} n_{H,100}^{12/35} \]  

(4)

where \( n_{H} \) is the \( H \) mass and \( n(r) = n_{SB}[1 - (r/R_{SB})]^{-2/5} \) (Weaver et al. 1977). Thus, grains with \( a_{gr} \lesssim 0.2 \mu \text{m} \) do not reach the supershell. In fact, even much larger grains should stop in the superbubble interior, because the Spitzer formula can largely overestimate the range of interstellar dust grains in hot plasmas (Ragot 2002).

Dense clumps of molecular gas can be engulfed by the growing superbubble, if they were not swept up by the expanding superbubble (e.g., Parizot et al. 2004). These clumps could potentially be enriched in \( ^{26}\text{Al} \) synthesized by WR stars and Type II SNe in the OB association. But recent two-dimensional hydrodynamic simulations (Boss et al. 2008, 2010) suggest that the amount of \( ^{26}\text{Al} \) that could be injected into such a molecular cloud core would be too low to explain the solar system’s canonical \( ^{26}\text{Al}/^{27}\text{Al} \) ratio. Boss et al. found that only \( 2–5 \times 10^{-5} M_{\odot} \) of hot SN shock front material could be incorporated into a cold molecular clump. But a \( 1 M_{\odot} \) presolar cloud would need to be contaminated by \( \sim 10^{-4} M_{\odot} \) of SN matter to explain the \( ^{26}\text{Al} \) meteoritic abundance (Takigawa et al. 2008). Although these two estimates are close, the main issue lies in the short lifetime of a small molecular cloud embedded in a hot plasma: the lifetime of a \( 1 M_{\odot} \) cloud against evaporation in the \( >10^{6} \text{ K} \) (Equation (2)) superbubble interior is only \( \sim 10^{5} \text{ yr} \) (McKee & Cowie 1977), much shorter than the duration of stellar main sequence. This scenario is therefore highly improbable.

3. \( ^{26}\text{Al} \) PRODUCTION BY A RUNAWAY WR STAR

If the vast majority, if not all O-type stars (the main-sequence progenitors of WR stars) form in clusters (e.g., Lada & Lada 2003), nearly half of them acquire velocities exceeding the escape velocity from the cluster’s potential well (Stone 1991). These runaway stars\(^5\) can be accelerated either by dynamical interactions with other stars in the dense cores of young clusters (Leonard & Duncan 1990) or by the SN explosion of a companion star in a massive binary system (Blaauw 1961). A star moving with a velocity \( V_{c} \gtrsim 15 \text{ km s}^{-1} \) relative to its parent cluster leaves the associated superbubble in less than 3 Myr (see Equation (1)). About 20% of the O-type stars have peculiar velocities exceeding 15 km s\(^{-1}\) (de Wit et al. 2005). These runaway short-living stars may have a significant probability of interacting with their parent molecular cloud complex. Outside the hot gas, the star’s motion is supersonic with respect to the ambient medium, which generates a bow shock (van Buren et al. 1990). There are many observations of bow shocks created by runaway OB stars in the vicinity of young clusters and associations (e.g., Gvaramadze & Bomans 2008).

The form of a bow shock is determined by the balance between the ram pressure of the stellar wind and the ram pressure of the ongoing circumstellar (CS) gas. The pressure equilibrium is reached in the star’s direction of motion at the so-called standoff distance from the star (van Buren et al. 1990; \( \ldots \))
of swept-up CS matter (\(M\)) due to both the Kelvin–Helmholtz and Rayleigh–Taylor instabilities (Brighenti & D’Ercole 1995), such that we expect an unstable contact surface between the shocked stellar wind and CS gas is seen Figure 1(b)), for \(\theta < 90^\circ\) is nevertheless significant: it amounts to 23 \(M\) for the 25 \(M\) star and is between 200 and 250 \(M\) for the three other stars.

Hydrodynamic simulations of stellar wind bow shocks have shown that the steady-state solution of Wilkin (1996) provides a good description of the time-averaged shape of the bow shock shell; although a bow shock is neither smooth nor steady (Raga et al. 1997; Blondin & Koerwer 1998). The shell is focused mechanism for large-scale gas stream, resulting in the buildup of dense cores. Thus, hydrodynamic simulations of the NTSI have shown that the density contrast in the shell can reach \(10^2\) to \(10^4\), depending on the gas cooling efficiency (e.g., Hueckstaedt 2003). The high-density seeds thus generated are likely sites of further star formation (Heitsch et al. 2008). However, the required gravitational collapse of these dense cores is probably not possible as long as the shell is exposed to the

\[
R_0 = (0.92 \, \text{pc})M_{W-5}^{1/2} V_{W,1500}^{1/2} V_{H,100}^{-1/2} V_{*,20}^{-1},
\]

where \(M_{W-5}\) is the stellar wind mass-loss rate in units of \(10^{-5} \, M_\odot \, \text{yr}^{-1}\), \(V_W = V_{W,1500} \times 1500 \, \text{km} \, \text{s}^{-1}\) is the wind’s terminal velocity, and \(V_{*,20} = V_\star / (20 \, \text{km} \, \text{s}^{-1})\). The interaction region between the stellar wind and the CS medium is a shell bounded by two shocks, in which the flows slow down from supersonic to subsonic velocities. One verifies that for \(V_W \gg V_\star\) the shell’s mass is due mainly to the shocked CS gas. The contact surface between the shocked stellar wind and CS gas is unstable due to both the Kelvin–Helmholtz and Rayleigh–Taylor instabilities (Brighenti & D’Ercole 1995), such that we expect an efficient mixing of the wind-ejected material with the swept-up CS gas. The \(26\text{Al}/27\text{Al}\) ratio in the bow shock shell of a runaway WR star just prior to the SN explosion can be estimated as a function of the polar angle \(\theta\) from the star’s direction of motion (see Figure 1(b)) by

\[
\frac{(26\text{Al})_{\text{s}}}{27\text{Al}} \sim \frac{N_{26} f_{26}}{4\pi x_{27} R_S^2(\theta) \Sigma_S(\theta)},
\]

where \(N_{26}\) is the total number of \(26\text{Al}\) nuclei ejected in the WR wind, \(f_{26} = (\tau_{26}/\Delta_{WR}) \times \left(1 - \exp(-\Delta_{WR}/\tau_{26})\right)\) is a factor that takes into account the decay of \(26\text{Al}\) during the duration \(\Delta_{WR}\) of the WR phase (\(\Delta_{WR} \approx 0.2 - 1.4 \, \text{Myr}\) depending on the star’s mass), \(x_{27} = 3.46 \times 10^{-6}\) is the \(27\text{Al}\) abundance by number in the CS medium assumed to be of solar composition (Lodders 2003), \(R_S(\theta)\) is the shell’s radius (Figure 1(b)), and \(\Sigma_S(\theta)\) is the shell’s H column density (\(\Sigma_S(0^\circ) \approx 0.75 R_0 n_H\); see Wilkin 1996). We took the \(26\text{Al}\) yields from the rotating stellar models of Palacios et al. (2005). \(R_S(\theta)\) and \(\Sigma_S(\theta)\) were calculated from the analytic solutions found by Wilkin (1996) in the thin-shell approximation. The WR star parameters \(M_W, V_W,\) and \(\Delta_{WR}\) were extracted from the grids of rotating stellar models of Meynet & Maeder (2003; see also Voss et al. 2009).

Calculated \(26\text{Al}/27\text{Al}\) ratios in bow shock shells of runaway WR stars are shown in Figure 2 for stars of initial masses 25, 60, and 85 \(M_\odot\) (the \(26\text{Al}\) yield for the 40 \(M_\odot\) star is not listed in Palacios et al. 2005). The \(26\text{Al}/27\text{Al}\) ratio is only weakly dependent on the star’s initial mass, because both \(N_{26}\) and the amount of swept-up CS matter (\(\propto R_S^2 \Sigma_S\)) increase with increasing stellar mass. We see that \((26\text{Al}/27\text{Al})_S\) reaches \(~1 - 2 \times 10^{-2}\) at \(0^\circ\). The isotopic ratio decreases with increasing

\[
\theta, \quad \text{because for the same solid angle as viewed from the star, the } 26\text{Al} \text{ atoms ejected at backward angles are mixed with a higher mass of shocked CS gas. The mass contained in the shell’s forward hemisphere (i.e., } \theta < 90^\circ\text{) is nevertheless significant: it amounts to 23 } M_\odot \text{ for the 25 } M_\odot \text{ star and is between 200 and 250 } M_\odot \text{ for the three other stars.}
\]

Hydrodynamic simulations of stellar wind bow shocks have shown that the steady-state solution of Wilkin (1996) provides a good description of the time-averaged shape of the bow shock shell; although a bow shock is neither smooth nor steady (Raga et al. 1997; Blondin & Koerwer 1998). The shell is subject to periodic oscillations in and out with respect to the equilibrium position, which has been interpreted as resulting from the nonlinear thin shell instability (NTSI; Vishniac 1994). This instability is also known to be an efficient dynamical focusing mechanism for large-scale gas stream, resulting in the buildup of dense cores. Thus, hydrodynamic simulations of the NTSI have shown that the density contrast in the shell can reach \(10^2\) to \(10^4\), depending on the gas cooling efficiency (e.g., Hueckstaedt 2003). The high-density seeds thus generated are likely sites of further star formation (Heitsch et al. 2008). However, the required gravitational collapse of these dense cores is probably not possible as long as the shell is exposed to the
The ratio is shown in Figure 3 as a function of $t_c$ to be constant. (see, e.g., Raga et al. 1997). Intense photoionizing radiation from the nearby massive star can produce $^{26}$Al, $^{36}$Cl, and $^{41}$Ca at levels compatible with the meteoritic measurements, provided that the delay before the incorporation of these SLRs into CAIs was ~1–3 x $10^9$ yr. But using the yields for a 60 $M_\odot$ star given by these authors, we obtain a $^{28}$Cl abundance well below the value reported in CAIs, as also found previously by Gaidos et al. (2009). On the other hand, the present work shows that both $^{26}$Al and $^{41}$Ca abundances in meteorites can result from the contamination of the presolar molecular core by material ejected from a runaway WR star, whose explosion as a SN triggered the formation of the solar system.

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