LINEAR RELATION FOR WIND-BLOWN BUBBLE SIZES OF MAIN-SEQUENCE OB STARS IN A MOLECULAR ENVIRONMENT AND IMPLICATION FOR SUPERNOVA PROGENITORS

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ABSTRACT

We find a linear relationship between the size of a massive star’s main-sequence bubble in a molecular environment and the star’s initial mass: \( R_b \approx 1.22 M/M_\odot - 9.16 \) pc, assuming a constant interclump pressure. Since stars in the mass range of 8 to 25–30 \( M_\odot \) will end their evolution in the red supergiant phase without launching a Wolf–Rayet wind, the main-sequence wind-blow bubbles are mainly responsible for the extent of molecular gas cavities, while the effect of the photoionization is comparatively small. This linear relation can thus be used to infer the masses of the massive star progenitors of supernova remnants (SNRs) that are discovered to evolve in molecular cavities, while few other means are available for inferring the properties of SNR progenitors. We have used this method to estimate the initial masses of the progenitors of eight SNRs: Kes 69, Kes 75, Kes 78, 3C 396, 3C 397, HC 40, Vela, and RX J1713–3946.

Key words: ISM: bubbles – ISM: clouds – ISM: molecules – ISM: supernova remnants – stars: early-type – supernovae: general

1. INTRODUCTION

An isolated massive star modifies its surroundings with various stellar winds throughout its evolution. During the main-sequence stage, the fast stellar wind sweeps up the ambient interstellar medium to form an interstellar bubble. During the red supergiant (RSG) or luminous blue variable (LBV) phase, the copious slow wind builds up a circumstellar nebula, which is subsequently swept into a circumstellar bubble by the fast wind if the Wolf–Rayet (WR) phase follows (e.g., Garcia-Segura et al. 1996a, 1996b). As a massive star ends its life in an explosion and forms a supernova remnant (SNR), the SNR shocks rapidly pass through the circumstellar material and impact the massive shell of the interstellar bubble with drastic deceleration (Chen et al. 2003), and such SNRs reflect mostly the interstellar bubble sizes.

Massive stars are born in molecular clouds, and the clouds are mostly clumpy. In a giant molecular cloud, the mean pressure is \( p/k \sim 10^7 \text{ cm}^{-3} \text{ K} \) (e.g., Krumholz et al. 2009), and this number is indeed needed to define the dense clumps and to support the cloud against gravitational collapse (Blitz 1993; Chevalier 1999). In such an environment, a supernova (SN) will explode in an interclump medium rather than in a dense clump, as the SN progenitor has blown a bubble or carved a cavity via its energetic stellar winds. The final size of the stellar wind bubble created in a molecular environment during the main-sequence stage depends on the stellar mass loss, wind velocity, and environmental pressure. By expressing these parameters as functions of stellar mass, we find a nearly linear relationship between the bubble size and the initial mass of the star. This relationship provides a powerful way to assess the initial masses of the progenitors for SNRs associated with molecular clouds.

2. LINEAR RELATION FOR THE WIND-BLOWN BUBBLE SIZE OF MAIN-SEQUENCE OB STARS

2.1. Linear Relation Expected from Theoretical Model

According to a theoretical study of SNRs in molecular clouds by Chevalier (1999), the maximum size of a bubble blown by a main-sequence star, when the bubble is in pressure equilibrium with the ambient medium, is expressed as

\[
R_b = 15.8 \left( \frac{M}{10^{-7} M_\odot \text{ yr}^{-1}} \right)^{1/3} \left( \frac{\dot{M}}{10^{-8} M_\odot \text{ yr}^{-1}} \right)^{1/3} \left( \frac{v_w}{10^3 \text{ km s}^{-1}} \right)^{2/3} \times \left( \frac{p/k}{10^5 \text{ cm}^{-3} \text{ K}} \right)^{-1/3} \text{ pc},
\]

where \( \dot{M} \) and \( v_w \) are the mass-loss rate and terminal velocity of the stellar wind, respectively, \( \tau_{\text{ms}} \) is the main-sequence age, and \( p \) is the pressure of the surrounding interclump medium. The stellar parameters can be estimated from theoretical or empirical studies, and are ultimately functions of stellar mass mainly, as shown below.

The mass-loss rate is dependent on the stellar luminosity, \( L \), and effective temperature, \( T_{\text{eff}} \) (de Jager et al. 1988). For main-sequence massive stars, both \( L \) and \( T_{\text{eff}} \) are functions of stellar mass, \( M \); thus, \( M \) can be expressed as a function of only \( L \):

\[
M \propto L^{\zeta_1},
\]

where the index \( \zeta_1 \) has been estimated to be 1.6–1.7 by empirical or theoretical studies. For example, Garmany & Conti (1984) examined a sample of 50 OB stars and found \( \zeta_1 = 1.62 \pm 0.19 \); Howarth & Prinja (1989) used a sample of \( \sim 200 \) O stars and
obtained $\zeta_1 = 1.69$; and Maeder (2009) suggested $\zeta_1 = 1.6$ for OV stars.

The stellar luminosity is largely a function of the stellar mass, and the mass–luminosity relation can be expressed as

$$ L \propto M^{\xi_2}. $$

The index $\xi_2$ has been empirically determined by Vitrichenko et al. (2007) to be $2.76$ for a stellar mass range of $10–50 M_\odot$. This $\xi_2$ value is consistent with the index, $2.26–2.98$, given by Maeder (2009) for stellar masses of $9–60 M_\odot$.

The main-sequence lifetime, $\tau_{ms}$, is proportional to the available fuel and inversely proportional to the burning rate, which is proportional to $M$ and $L$, respectively. Thus,

$$ \tau_{ms} \propto \frac{M}{L} \propto M^{1-\xi_2}. $$

The terminal velocity of stellar wind is proportional to the escape velocity, and thus $v_w \propto \sqrt{M(1-\Gamma)/R_s}$, where $M(1-\Gamma)$ is the reduced stellar mass and $\Gamma$ is the ratio of the stellar to the Eddington luminosity. Maeder (2009) derived that the reduced stellar mass is a function of stellar luminosity

$$ M(1-\Gamma) \propto L^{\xi_3}, $$

with $\xi_3 = 0.327$ for $10–120 M_\odot$, and that the stellar radius of a main-sequence star is a function of stellar mass

$$ R_s \propto M^{\xi_4}, $$

with $\xi_4 = 0.56$ for $15–120 M_\odot$.

Using Equations (2)–(6) to express $M$, $\tau_{ms}$, and $v_w$ as functions of $M$ and substituting them into Equation (1), we obtain

$$ p^{1/3} R_b \propto M^\eta, $$

where $\eta = [\xi_2(\zeta_1 + \xi_3 - 1) - \zeta_4 + 1]/3$. Adopting $\zeta_1 = 1.6–1.7$, $\xi_2 = 2.7\pm0.3$, $\xi_3 = 0.327$, and $\xi_4 = 0.56$, we find $\eta = 1.0\pm0.1$. This result indicates that for a given interstellar pressure, the $R_b$–$M$ relationship is very close to linear.

### Table 1

Parameters for Wind Bubbles of Early-type Stars

| No. | type | $r_s$ (pc) | Exemplified Star | $M$ ($M_\odot$) | $M$ ($M_\odot$ yr$^{-1}$) | $v_w$ ($10^3$ km s$^{-1}$) | $\tau_{ms}$ (10$^6$ yr) | References | $p^{1/3} R_b$ (pc) |
|-----|------|------------|------------------|----------------|--------------------------|--------------------------|-------------------------|------------|-------------------|
| 1   | B3V  | 0.4        |                  | 8              | $1 \times 10^{-11}$     | 0.7                      | 31.6                    | r1, r6     | 0.9               |
| 2   | B2V  | 0.8        |                  | 10             | $5 \times 10^{-10}$     | 0.7                      | 22.5                    | r1, r6     | 2.8               |
| 3   | B1V  | 1.4        |                  | 12             | $6 \times 10^{-9}$      | 0.7                      | 16.0                    | r1, r6     | 5.7               |
| 4   | B0.5Vp| 2.9        | HD 93030         | 14             | $1.3 \times 10^{-8}$    | 0.9                      | 12.6                    | r2, r5, r6 | 8.4               |
| 5   | B0V  | 7.0        | HD 149438        | 18             | $3.5 \times 10^{-8}$    | 1.2                      | 9.3                     | r2, r5, r6 | 12.4              |
| 6   | O9.5V| 9.8        | HD 38666         | 21             | $4.2 \times 10^{-8}$    | 1.1                      | 7.7                     | r2, r4, r5, r6 | 11.8           |
| 7   | O9V  | 11.7       | HD 216800        | 24             | $1.3 \times 10^{-7}$    | 1.4                      | 6.7                     | r3, r4, r5, r6 | 19.1           |
| 8   | O8.5V| 13.1       | HD 46149         | 27             | $1.9 \times 10^{-7}$    | 1.8                      | 6.0                     | r3, r4, r5, r6 | 24.5           |
| 9   | O8V  | 14.5       | HD 101413        | 28             | $1.3 \times 10^{-7}$    | 3.0                      | 5.7                     | r3, r4, r5, r6 | 29.8           |
| 10  | O7V  | 17.9       | HD 47839         | 33             | $3.1 \times 10^{-7}$    | 2.6                      | 5.0                     | r3, r4, r5, r6 | 34.2           |
| 11  | O7V  | 17.9       | HD 53619         | 40             | $5.6 \times 10^{-7}$    | 2.5                      | 4.3                     | r3, r4, r5, r6 | 38.9           |
| 12  | O6V  | 24.1       | HD 101190        | 49             | $5.9 \times 10^{-7}$    | 3.2                      | 3.8                     | r3, r4, r5, r6 | 44.9           |
| 13  | O4V  | 40.6       | HD 46223         | 54             | $1.7 \times 10^{-6}$    | 3.1                      | 3.6                     | r3, r4, r5, r6 | 62.3           |
| 14  | O4V  | 40.6       | HD 242908        | 54             | $8.9 \times 10^{-7}$    | 3.2                      | 3.6                     | r3, r4, r5, r6 | 50.7           |
| 15  | O4V  | 40.6       | HD 164794        | 72             | $3.5 \times 10^{-6}$    | 3.4                      | 3.1                     | r3, r4, r5, r6 | 80.2           |

**Notes.** The parameters of B3–B1 stars (rows 1–3), except main-sequence age $\tau_{ms}$, are from r1 (in which the $v_w$ values are assumed). The $M$ values of the exemplified stars of spectral types B0.5–O9.5 (rows 4–6) and O9–O4 (rows 7–15) are adopted from r2 and r3, respectively, and the $v_w$ values of the exemplified stars of spectral types B0.5–B0 (rows 4–5) and O9.5–O4 (rows 6–15) are from r2 and r4, respectively. The $M$ values of the exemplified B0.5–O4 stars are obtained from r5. All of the $\tau_{ms}$ values are estimated from the evolutionary tracks of r6.

**References.** (r1) Chevalier 1999; (r2) Snow & Morton 1976; (r3) Bernabei 1992; (r4) Bernabei et al. 1989; (r5) de Jager et al. 1988; (r6) Schaller et al. 1992.

### 2.2. Another Derivation of the Linear Relationship

The almost linear relationship between $p^{1/3} R_b$ and $M$ can be derived semi-empirically using observationally determined $M$ and $v_w$ and model-estimated $\tau_{ms}$. In Table 1, we have compiled 15 main-sequence stars with spectral types ranging from B3 to O4. For all spectral types, the $\tau_{ms}$ values are estimated from the evolutionary tracks of Schaller et al. (1992). For B3–B1-type stars, the other parameters are adopted from Chevalier (1999), in which the $v_w$ values are reasonably assumed. For the exemplified B0.5–O4 stars, the $M$ values are adopted from Snow & Morton (1976) and Bernabei (1992), the $v_w$ values are from Snow & Morton (1976) and Bernabei et al. (1989), and the $M$ values are empirically given by de Jager et al. (1988). Using these $M$, $\tau_{ms}$, and $v_w$ values in Equation (1) and defining $p_b \equiv (p/k)/(10^5 \text{cm}^3 \text{K})$, we have computed $p_b^{1/3} R_b$ for the 15 stars in Table 1 and plotted them against $M$ in Figure 1. It is clear that $p_b^{1/3} R_b$ does correlate linearly with $M$ for the interstellar wind-blow bubbles of main-sequence OB stars; furthermore, a good linear regression for the $p_b^{1/3} R_b$–$M$ relation can be obtained as

$$ p_b^{1/3} R_b = \alpha \left( \frac{M}{M_\odot} \right)^\beta \text{pc}, $$

where $\alpha = 1.22 \pm 0.05$ and $\beta = 9.16 \pm 1.77$. If the interclump pressure $p/k$ is constant and $\approx 10^5 \text{cm}^{-3} \text{K}$ (i.e., $p_b \approx 1$) as suggested, e.g., by Chevalier’s (1999), then $R_b$ is linearly correlated with $M$.

### 2.3. Post-main-sequence Evolution

Whether a wind-blow bubble may survive the post-main-sequence evolution without much change until the SN explosion depends on the initial mass of the central massive star. In a recent review, Smartt (2009) concludes that RSGs with an initial mass in the range 8 to 25–30 $M_\odot$ can be progenitors for SNe II-P and those with an initial mass above 17 $M_\odot$ could end as...
SNe II-L, IIn, and Ib/c. In the He-core burning stage, the RSG wind expands in the low-density interior of the main-sequence bubble with the outer edge of the RSG wind bounded by the pressure of the surrounding gas. For RSGs terminating their lives in SNe II-P, their winds reach an outer radius of \( \lesssim 1 \) pc, and for RSGs ending in SNe II-L their winds’ outer boundaries approach \( \sim 5 \) pc (Chevalier 2005). These radii are much smaller than the expected \( R_b \); thus their RSG winds do not interact with the shell of the main-sequence bubble at all.

For an initial mass greater than 25–30 \( M_\odot \), however, the star will evolve through an RSG phase or an LBV phase before turning into a WR star (e.g., Maeder 2009; Smartt 2009). The fast, strong WR wind will interact with the circumstellar material shed by the star during the RSG or LBV phase and form a circumstellar bubble. Observations have shown that the radii of circumstellar bubbles are small, usually \( \lesssim 1 \) pc for LBV bubbles and a few pc for WR bubbles (Chu 2003), much smaller than their corresponding main-sequence interstellar bubbles; furthermore, infrared (IR) observations of WR bubbles have detected larger shell structures that correspond to the main-sequence interstellar bubbles (e.g., Nichols-Bohlin & Fesen 1993; Marston 1996). Nevertheless, it is possible that a WR star’s circumstellar bubble has merged with its main-sequence progenitor’s interstellar bubble, in which case no strong abundance anomaly is seen and the bubble expansion velocity is only \( \sim 20 \) km s\(^{-1}\), such as NGC 2359 and NGC 3199 (Esteban et al. 1992). These merged bubbles may be further accelerated by the WR winds. At the time of SN explosion, the bubble size may or may not have grown significantly from the stalled main-sequence interstellar bubble.

3. APPLICATION TO SN PROGENITORS

Among the core-collapse SNe, more than \( \sim 75\% \) are of Type II and the greatest majority of these are of Type II-P (Smartt 2009), for which the SN explosions occur during the RSG phase and the initial masses of the progenitors fall in the range of 8 to 25–30 \( M_\odot \). For this mass range, if a progenitor star was in a molecular environment with \( p_5^{1/3} \approx 1 \), its SN will explode within a bubble that follows the linear \( R_b - M \) relation described in Section 2. Therefore, the size of such an SNR may reflect the size of the main-sequence interstellar bubble and the \( R_b - M \) relation can be used to estimate the initial mass of the SN progenitor.

SNe Ib/c have been suggested to originate from WR progenitors that had shed most or all of their H envelopes (Gaskell et al. 1986) or moderate-mass interacting binaries in which the exploding star’s envelope had been stripped through Roche lobe overflow or common-envelope evolution (Podsiadlowski et al. 1992; Nomoto et al. 1995). According to population analysis, it is concluded that WR stars cannot be responsible for all SNe Ib/c and that binary production of SNe Ib/c has to be significant (Smartt 2009). Based on theoretical modeling, it is suggested that massive WR stars may collapse into black holes without SN explosions (e.g., Fryer 1999; Heger et al. 2003). In view of these factors, the sizes of SN Ib/c remnants cannot be used to estimate the stellar progenitors’ masses, as it is uncertain whether and how the binary progenitors form interstellar bubbles and it is also uncertain to what extent the WR winds affect the evolution of the main-sequence bubbles.

Multiwavelength observations of Galactic SNRs have shown that at least a few tens of them are evolving in a molecular cloud environment (Jiang et al. 2010). Some of these SNRs appear to be located within molecular gas cavities or in contact with molecular shells, which are likely the relics of wind-blown bubbles created by the stellar progenitors. The photoionized regions are significantly smaller than the wind-blown bubbles in size for massive stars. A comparison in size between the wind-blown bubbles and photoionized regions can also be seen in Table 1, where the “Strömgren radii” (see Spitzer 1978) \( R_s \) are calculated for an interclump density \( 5 \) H atoms cm\(^{-3}\) (Chevalier 1999) and the ionizing flux for each spectral type is adopted from Panagia (1973). Assuming that these cavities or shells are indeed interstellar bubbles blown by the progenitors during the main-sequence stage and the bubbles had been stalled in pressure equilibrium with the ambient interclump medium at \( p_5 \approx 1 \), we may use the bubble sizes and Equation (8) to estimate the masses of their SN progenitors. Below, we discuss eight SNRs and carry out the mass estimates individually. The results are summarized in Table 2.

G21.8–0.6 (a.k.a. Kes 69). In this SNR, a partial molecular arc at a systemic velocity of \( v_{\text{LSR}} \sim 85 \) km s\(^{-1}\) is detected in the southwest with morphological correspondence to the brightened partial SNR shell seen in the radio, IR, and X-ray wavelengths; it is suggested to be a part of the cooled material swept up by the progenitor’s stellar wind (Zhou et al. 2009). Assuming that the molecular arc is associated with the main-sequence bubble, its 13 pc radius implies that the SN progenitor star had an initial mass of \( \sim 18 \pm 2 \) \( M_\odot \), of spectral type around B0.

G29.7–0.3 (a.k.a. Kes 75). This SNR is in a cavity surrounded by a molecular shell unveiled in the broadened blue wing of the \(^{12}\)CO line at \( v_{\text{LSR}} \sim 54 \) km s\(^{-1}\), and the southern part of the molecular shell is likely the cooled, clumpy shell of the progenitor’s main-sequence bubble (Su et al. 2009). Thus, the progenitor of Kes 75 may have an initial mass \( \sim 12 \pm 2 \) \( M_\odot \), corresponding to a B0.5–B2 star, which is expected to end its life in a Type II-P SN explosion (Heger et al. 2003; Smartt 2009). The pulsar PSR J1846–0258 at the center of Kes 75 has been suggested to be a magnetar (Gavriil et al. 2008; Kumar & Safi-Harb 2008). Although a few magnetars are inferred to have progenitors with mass \( \geq 30 \) \( M_\odot \), smaller mass is also suggested (e.g., \( 17 \) \( M_\odot \) for SGR 1900+14), and the mass of the magnetar’s progenitor may span a wide range (see Safi-Harb & Kumar 2013 and references therein).
Galactic SNRs with Molecular Shells/in Molecular Cavities

| SNR          | Attribute | Radius of Bubble (pc) | Distance (kpc) | Reference | Progenitor Mass (M⊙) |
|--------------|-----------|-----------------------|----------------|-----------|----------------------|
| G21.8–0.6 (Kes 69) | S         | 13                    | 6.2            | r1        | 18 ± 2               |
| G29.7–0.3 (Kes 75)  | S         | 6                     | 10.6           | r2        | 12 ± 2               |
| G32.8–0.1 (Kes 78)  | S         | 7                     | 4.8            | r3        | 21 ± 2               |
| G39.2–0.3 (3C396)   | C         | 7                     | 6.2            | r4        | 13 ± 2               |
| G41.1–0.3 (3C397)   | C         | 4.5–7                 | 10.3           | r5        | 12 ± 2               |
| G54.4–0.3 (HC 40)   | S         | 18/43                 | 3/7            | r6        | 22 ± 2/3             |
| G263.9–3.3 (Vela)   | S         | 14–19                 | 0.29           | r7, r8    | 21 ± 3               |
| G347.3–0.5 (RXJ1713–3946) | C | 9                     | 1.1            | r9, r10   | 15 ± 2               |

Notes.

a C: SNR is discovered to be in a molecular cavity; S: SNR has a coincident molecular shell-like structure.

b References. (r1) Zhou et al. 2009; (r2) Su et al. 2009; (r3) Zhou & Chen 2011; (r4) Su et al. 2011; (r5) Jiang et al. 2010; (r6) Junkes et al. 1992; (r7) Moriguchi et al. 2001; (r8) Dodson et al. 2003; (r9) Fukui et al. 2003; (r10) Moriguchi et al. 2005.

G32.8–0.1 (a.k.a. Kes 78). Kes 78 is found to be interacting with a clumpy molecular cloud, which is at a systemic velocity of vLSR ∼ 81 km s⁻¹ and shows a clumpy arc in the west bearing kinematic signatures of shock perturbations (Zhou & Chen 2011). The entire SNR appears to be in a cavity surrounded by molecular material. If the molecular cavity of Kes 78, 17 pc in radius, was created by the progenitor’s main-sequence wind, our linear relation implies a progenitor mass of ∼21 ± 2 M⊙, corresponding to a spectral type around O9.5.

G39.2–0.3 (a.k.a. 3C 396). 3C 396 is coincident with a molecular cavity at vLSR ∼ 85–87 km s⁻¹, and the western boundary of the SNR perfectly follows the eastern face of a molecular wall (Su et al. 2011). Lee et al. (2009) attribute the near-IR [Fe II] emission to the SN shock overtaking the RSG wind of the SN progenitor, and suggest a progenitor mass of 25–35 M⊙. Such a mass is higher than the mass limit, ≤25 M⊙, for neutron stars’ progenitors with solar metallicity (Heger et al. 2003). Assuming that the abundances of the X-ray-emitting gas in 3C 396 are enriched by the SN ejecta, Su et al. (2011) derived a progenitor mass of 13–15 M⊙, suggesting a spectral type of B1–B2. If we regard the cavity as the extent of the progenitor’s main-sequence bubble, then the progenitor’s mass estimated from our linear relation is ∼13 ± 2 M⊙, consistent with that estimated from the ejecta abundances.

G41.1–0.3 (a.k.a. 3C 397). 3C 397 is a radio- and X-ray-bright Galactic SNR with a peculiar rectangular morphology (Chen et al. 1999; Safi-Harb et al. 2005) and its Fe-rich ejecta essentially aligning along a diagonal of the rectangle (Jiang & Chen 2010). The SNR is confined in a molecular cavity with an extent 9 × 14 pc² at vLSR ∼ 32 km s⁻¹, and the cavity was likely sculpted chiefly by the progenitor star and the cavity walls hampered the expansion of the ejecta, sending a reflected shock back to the ejecta (Jiang et al. 2010). Thus, using the size of this molecular cavity we estimate the progenitor mass to be ∼12 ± 2 M⊙, which corresponds to a spectral type B0.5–B2. A recent XMM-Newton X-ray study of this remnant has analyzed the metal abundances of the SN ejecta and thus given an independent assessment of the progenitor’s mass, 11–15 M⊙ (S. Safi-Harb et al., in preparation), in good agreement with our estimate.

G54.4–0.3 (a.k.a. HC 40). SNR HC 40 exhibits a perfect CO shell at vLSR ∼ 36–44 km s⁻¹ aligning with the SNR’s radio continuum shell (Junkes et al. 1992). This radial velocity corresponds to two kinematic distances, 3 and 7 kpc, but the shorter distance is favored because it agrees with an independent distance estimate for nearby H II regions and OB association. Using the 3 kpc distance and assuming that the CO shell corresponds to the main-sequence bubble, we estimate an initial mass of ∼22 ± 2 M⊙ for the progenitor, which is in the range for Type II SN explosion of an RSG (Heger et al. 2003; Smartt 2009). If the 7 kpc distance is adopted, the CO shell radius will be larger than 30 pc and the progenitor mass would be so high (>30 M⊙) that it may be expected to collapse into a black hole without an energetic SN explosion. Thus, we suggest that HC 40 is at a distance of ∼3 kpc and that its progenitor was a B0–O9 star.

G263.9–3.3 (a.k.a. Vela). The Vela SNR has been shown to coincide with a molecular void of angular diameter 5.4–7.4, delineated by molecular clumps in a velocity range of vLSR = −5 to 85 km s⁻¹, with a total mass of the order of 10¹⁴ M⊙. It is further suggested that the molecular clumps are pre-existent, rather than having been swept up by the SNR shock, and that the SNR may have been expanding in a low-density (of the order of 10⁻² cm⁻³) medium (Moriguchi et al. 2001). Thus, it is reasonable to assume that the low-density region is a wind-blown cavity enclosed by the observed molecular clumps. A pre-existent wind-driven shell, currently impacted by the SN ejecta/shock, has been previously proposed to explain the filamentary structures seen in radio, optical, and X-ray bands (Gvaramadze 1999). The very long baseline interferometry parallax measurements suggest a distance of 290 pc (Dodson et al. 2003). For this distance, the cavity has a radius of 14–19 pc, which then leads to an inference of a B0–O9 progenitor star, with an initial mass of 21 ± 3 M⊙, if it was a single star. This estimate is similar to a previous suggestion of a 15–20 M⊙ progenitor for a Type II-P SN explosion based on the moderate size of the wind-blown bubble (Gvaramadze 1999).

G347.3–0.5 (a.k.a. RX J1713.7–3946). This SNR is a TeV γ-ray and non-thermal X-ray source, and it appears to be confined in a molecular gas cavity at vLSR ∼ −11 to −3 km s⁻¹ (Fukui et al. 2003; Moriguchi et al. 2005). It is suggested that this SNR is still in the free expansion phase and the non-decelerated blast wave is colliding with the dense molecular gas after it traveled in a low-density cavity that perhaps was produced by the stellar wind or pre-existing SNe (Fukui et al. 2003). If we assume that the cavity was created by the wind of a single progenitor star, then the star might have an initial mass of ∼15 ± 2 M⊙, with a spectral type B0–B1.
It would be safe, however, to regard the above mass estimates as lower limits (e.g., in the case of Kes 69). Actually, in some cases, a bubble’s blowout from the side of a molecular cloud can be possible, and thus the progenitors’ masses may be underestimated. But because $R_b \propto p^{-1/3}$ and the dependence on $p$ is insensitive, the underestimate would be small, if most of the volume of the bubble is in the cloud.

4. SUMMARY

For OB stars in a molecular gas environment with a postulated constant interclump pressure $p/k \sim 10^5 \text{cm}^{-3} \text{K}$, we find a linear relation between the sizes of the main-sequence wind-blown bubbles and the stellar masses: $R_b \approx 1.22 M/M_\odot - 9.16 \text{pc}$. Since stars in the mass range 8 to 25–30 $M_\odot$ will end their lives in the RSG phase and will not launch a further WR wind, the extent of molecular gas cavities is largely determined by the main-sequence wind bubbles. The linear $R_b - M$ relation can thus be used to assess the initial masses of SN progenitors for SNRs evolving in molecular cavities. We have applied this method to estimate the masses of the stellar progenitors of eight SNRs: Kes 69, Kes 75, Kes 78, 3C 396, 3C 397, HC 40, Vela, and RX J1713−3946. The progenitor masses of these eight SNRs are in the range of 10–24 $M_\odot$.

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