The distance measurements of supernova remnants in the fourth Galactic quadrant

Su-Su Shan\textsuperscript{1,2}, Hui Zhu\textsuperscript{1,3}, Wen-Wu Tian\textsuperscript{1,2}, Hai-Yan Zhang\textsuperscript{1}, Ai-Yuan Yang\textsuperscript{4} and Meng-Fei Zhang\textsuperscript{1,2}

\textsuperscript{1} Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China; shansusu@nao.cas.cn, zhuhui@nao.cas.cn
\textsuperscript{2} School of Astronomy, University of Chinese Academy of Sciences, Beijing 100049, China
\textsuperscript{3} Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
\textsuperscript{4} Max-Planck-Institut für Radioastronomie, Aufdem Hügel 60, D-53121, Bonn, Germany

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Abstract We take advantage of red clump stars to build the relation of the optical extinction ($A_V$) and distance in each direction of supernova remnants (SNRs) with known extinction in the fourth Galactic quadrant. The distances of nine SNRs are determined well by this method. Their uncertainties range from 10\% to 30\%, which are significantly improved for eight SNRs, G279.0+1.1, G284.3–1.8, G296.1–0.5, G299.2–2.9, G308.4–1.4, G309.2–0.6, G309.8–2.6 and G332.4–0.4. In addition, SNR G284.3–1.8 with the new distance of 5.5 kpc is not likely associated with the PSR J1016–5857 at 3 kpc.

Key words: ISM: supernova remnants — ISM: dust, extinction — stars: distances

1 INTRODUCTION

Distance is a basic and important parameter for a supernova remnant (SNR) to constrain its size, age, expansion velocity and explosion energy of the progenitor supernova (e.g., Tian & Leahy 2008; Zhou et al. 2018). However, it is challenging to obtain reliable distances of SNRs. About 30\% of SNR distances are available in the Galactic SNR catalog of Green (2014) and \~{}50\% of SNRs have distances in the catalog of Ferrand & Safi-Harb (2012). Uncertainty estimates are not given for most of these distances.

There are several methods to measure the distance of SNRs. Firstly, the kinematic distances of SNRs are likely to be measured based on their HI absorptions or molecular line emissions from the clouds interacting with them (e.g., Leahy & Tian 2010; Su et al. 2011; Ranasinghe & Leahy 2018). Secondly, for shell-type radio SNRs, distances can be estimated by the $\Sigma - D$ relation (e.g., Case & Bhattacharya 1998). Thirdly, the distances of SNRs are usually equivalent to the distances of their possible associations, for example, OB associations (e.g. Cha et al. 1999, Vela remnant) and pulsars (e.g. Cordes & Lazio 2002). For some rare SNRs, distances can also be obtained by proper motion (e.g. Vink 2008; Katsuda et al. 2008, Kepler’s SNR), Sedov estimates (Bocchino et al. 2000), blast wave method (McKee & Cowie 1975) or extinction measurement (Chen et al. 2017; Zhao et al. 2018).

Red clump (RC) stars are characterized by their concentration in an obvious region of the color-magnitude diagram (CMD) (Gao et al. 2009). They are usually low mass stars in the early stage of core-He burning and are widely used to trace distances, and probe extinction towards Galactic objects since the dispersions of their absolute magnitude and intrinsic color are small (Girardi 2016). The relation of extinction and distance has been used to estimate the distances of these objects in cases with known extinction, such as pulsars (Durant & van Kerkwijk 2006) and low-mass X-ray binaries (Güver et al. 2010). Zhu et al. (2015) first applied the RC method to determine the distance of SNR G332.5–5.6. Shan et al. (2018) applied a similar method to systematically analyze the extinction distances towards SNRs in the first Galactic quadrant and independently obtained new extinction distances of 15 SNRs. Their results have demonstrated that the distances traced by RC stars are reliable and consistent with kinematic distances. This paper presents our new results aiming at the SNRs in the other Galactic quadrants.
2 METHOD

We follow the RC method of Shan et al. (2018). Here we briefly describe this method. To select RC stars, we build the $K_s$ (hereafter $K$) vs. $J - K$ CMD in the direction of each SNR with the 2MASS All-Sky Point Source Catalog (Skrutskie et al. 2006). The area around the SNR is $1^\circ \times 0.5^\circ$ ($\Delta l \times \Delta b$). Figure 1(a) displays an example for SNR 308.2–1.4.

We bin the star sample into a number of horizontal strips according to $K$ magnitude. The sample for each bin is constructed as the star count histogram. Then we use the function below to fit the histogram (Durant & van Kerkwijk 2006)

$$N = A_{RCs} \exp \left\{ -\left[ (J - K) - (J - K)_{peak} \right]^2 / 2\sigma^2 \right\} + A_C (J - K)^\alpha .$$

(1)

Here $(J - K)$ represents the stellar color, and $A_{RCs}$ and $A_C$ stand for the normalizations of RC stars and contaminant stars, respectively. The first term is a Gaussian function to fit the RC star distribution; the second term is a power law to fit the contaminant stars (see Fig. 1(b)). The best fit yields the stellar color of RC stars at peak density $(J - K)_{peak}$ for each strip. The extinction and distance are calculated from

$$A_K = 0.67 \times [(J - K)_{peak} - (J - K)_0],$$

(2)

$$\frac{A_K}{A_V} = 0.1615 - \frac{0.1483}{R_V} ,$$

(3)

$$D(\text{kpc}) = 10^{[0.2(m_K - M_K + 5 - 0.1137A_V)]}/1000 .$$

(4)

Here $A_V$ and $A_K$ are extinction in the $V$ and $K$ bands respectively. We adopt the total to selective extinction ratio $R_V = 3.1 \pm 0.18$ (Schlafly et al. 2016), the intrinsic color of RC stars $(J - K)_0 = 0.63 \pm 0.1$ mag (e.g., Yaz Gökçe et al. 2013; Grocholski & Sarajedini 2002) and the absolute magnitude of RC stars $M_K = -1.61 \pm 0.1$ mag (e.g., Alves 2000; Grocholski & Sarajedini 2002; Hawkins et al. 2017). The uncertainties of $R_V$, $(J - K)_0$ and $M_K$ are transferred to $A_V$ and $D$ via an error propagation formula (see Shan et al. 2018 and references therein).

In Figure 1(c), the relation between the optical extinction $A_V$ and distance $D$ (hereafter, $A_V - D$) is built along the direction of G308.4–1.4. Combining the $A_V$ value of G308.4–1.4, its distance is estimated by the Bayesian method (Güver et al. 2010). Figure 1(d) shows the probability distribution over distance calculated by

$$P(D) = \int P_{SNR}(A_K)P_{RC}(D|A_V)dA_V .$$

(5)

Here $P_{SNR}(A_V)$ represents the probability distribution for an SNR’s extinction. We assume $P_{RC}(D|A_V) = P_{RC}(A_V|D)$. $P_{RC}(A_V|D)$ signifies the distribution of the extinction traced by the RC at each distance bin. Both distributions are assumed to be Gaussian functions. Then we fit these distributions by a Gaussian function, yielding the distance with the highest probability. For the objects with good Gaussian fitting, the uncertainty in distance is equal to the standard deviation of the Gaussian. However, for some objects, there are apparent and sudden decreases in the distance probability. The red lines mark such decreases (see Fig. 3). In this case, the uncertainty in distance reflects the cut-off distance.

3 RESULTS AND BRIEF DISCUSSION

New distances for nine SNRs are obtained. The results are summarized in Tables 1 and 2. We also note that this method does not work for SNRs in the second and third quadrants after tens of trials. This might be caused by the fact that the extinction towards our targets in the two quadrants grows slowly with increasing distance, which makes the $A_V - D$ relation too flat to give a reliable distance. Hence, we just discuss the results from the fourth quadrant. Figure 2 presents the CMDs with the locations of the RC’s peak density for each SNR and the best-fit Gaussian model. We discuss them in detail below.

G279.0+1.1

The distance of G279.0+1.1 is estimated at 3 kpc by the blast wave method and $\Sigma - D$ relation (McKee & Cowie 1975; Stupar & Parker 2009). However, Stupar & Parker (2009) warned that this distance should be treated with caution since McKee & Cowie (1975)’s estimate depends on the initial explosion energy of the progenitor star and the $\Sigma - D$ relation might have an error up to 40%. Our RC method estimates its distance as $2.7 \pm 0.3$ kpc which coincides with the previous measurements.

G284.3–1.8

G284.3–1.8 was suggested to be associated with the pulsar PSR J1016–5857 (3 kpc, Kargaltsev et al. 2013) or the $\gamma$-ray binary 1FGL J1018.6–5856 (5.6$^{+4.6}_{-2.1}$ kpc (Napoli et al. 2011)). We estimate its distance at 5.5$^{+0.7}_{-0.7}$ kpc. The new distance indicates that G284.3–1.8 is not likely to be associated with PSR J1016–5857 at 3 kpc.

G296.1–0.5

G296.1–0.5 is a middle-aged SNR with complex structures. Longmore et al. (1977) estimated its distance between 3 and 5 kpc from two independent ways of red-
Fig. 1 (a) The CMD in the direction of G308.4–1.4 within 0.5 deg$^2$. The red dots and red lines mark the fitted locations of the RC peak density and its extent with 1σ. (b) Histogram of the $J - K$ values for the selected stars in 10.6 < $K$ < 11.1. The black curve is the best fit to this histogram. The red dotted curves are the Gaussian and power-law components. (c) The $A_V - D$ relation in the direction of G308.4–1.4. The dashed line is the $A_V$ value of this SNR. The dotted lines are the uncertainties of $A_V$. (d) Probability distribution over distance to the SNRs and the best-fit Gaussian model (Color version of Figs. 1–4 is online).

Table 1 Optical Extinction $A_V$ and Distance

| Source name   | $A_V$ (mag) | Distance (kpc) | Previous measurement | Method          | Reference |
|---------------|-------------|----------------|----------------------|-----------------|-----------|
| G279.0+1.1    | 1.6±0.1     | 2.7±0.3        | 3                    | Blast wave and $\Sigma - D$ | [1]       |
| G284.3–1.8    | 4.4$^1$     | 5.5±0.7        | 3, 5.6$^1$–$^1.6$    | Distance of association | [2], [3], [4] |
| G206.1–0.5    | 1.9±0.3     | 4.3±0.8        | 3±1.0                | Reddening measurement | [5], [6] |
|               |             | 3.8±1.9        |                      | Kinematic measurement | [5], [6] |
|               |             | 7.7, 6.6, 4.9  |                      | $\Sigma - D$      | [7], [8], [9] |
| G315.4–2.3    | 1.7±0.2     | ≤ 2.0          | 2.8±0.4, 2.3±0.2     | Kinematic measurement | [10], [11], [12] |
|               |             | 1.2 ± 0.2      |                      | Sedov estimate    | [13]      |
| G332.4–0.4    | 4.7±0.7     | 3.0±0.3        | 3.3, 3.1–4.6         | Kinematic measurement | [14], [10], [15] |
|               |             | 6.5            |                      | Extinction measurement | [16]      |

Notes: $^1$ We assume the error of $A_V$ as 10% when determining the distance of G284.3–1.8. References: [1] Stupar & Parker (2009); [2] H. E. S. S. Collaboration et al. (2012); [3] Kargaltsev et al. (2013); (4) Napoli et al. (2011); [5] Castro et al. (2011); [6] Longmore et al. (1977); [7] Caswell & Barnes (1983); [8] Case & Bhattacharya (1998); [9] Clark et al. (1973); [10] Zhu et al. (2017); [11] Rosado et al. (1996); [12] Sollerman et al. (2003); [13] Bocchino et al. (2000); [14] Caswell et al. (1975); [15] Reynoso et al. (2004); [16] Ruiz (1983).

G315.4–2.3 (RCW 86)

Rosado et al. (1996) fitted the radial velocity of $\mathrm{H_\alpha}$ with respect to the local standard of rest and converted it to...
Fig. 2 The CMDs within 0.5 deg$^2$ in the directions of eight SNRs. The grey colors denote stellar densities in the logarithmic scale. The red dots and lines mark the fitted location of the RC peak density and its extent with 1$\sigma$ respectively.
Fig. 3 Left: The $A_V - D$ relation traced by RC stars along the direction of each SNR. The dashed line is the $A_V$ value of each SNR. The dotted lines are the uncertainties of $A_V$. Right: Probability distribution over distance to the SNRs and the best-fit Gaussian model with the cutoffs. The red line in the right panel for G315.4–2.3 is the upper limit of distance.
Fig. 3 — Continued.
located at 3.0 kpc. The extinction traced by RC stars infers that this SNR is about 6.5 kpc by extinction measurement. However, Reynoso et al. (2004) estimated its distance to be around 2.3 kpc by the RC method. The extinction estimate of G315.4–2.3 is in the range of 0.7 kpc; (3) the Sedov-analysis-based distance is 2.8 kpc or 12.5 ± 0.7 kpc. The RC distance of this SNR is 3.1 ± 0.3 kpc, which is consistent with the lower limits of extinction distance and kinematic distance.

**G299.2–2.9**

We derive an RC distance of G299.2–2.9 at 2.8 ± 0.8 kpc for the first time. A low interstellar column density in the line of sight hinted at a very nearby distance (∼0.5 kpc) based on the *ROSAT* Position Sensitive Proportional Counter observation (Slane et al. 1996). However, spatially resolved spectroscopy with the *Chandra X-Ray Observatory* indicated a higher hydrogen column density ($N_H \sim 3.5 \times 10^{21}$ cm$^{-2}$), which suggested a distance of 2–11 kpc (Park et al. 2007). The RC distance is the best so far.

**G308.4–1.4**

Prinz & Becker (2012) published a detailed analysis of the distance to G308.4–1.4: (1) the distance indicated by extinction is 5.9 ± 2.0 pc; (2) a kinematic distance is 2.0 ± 0.6 kpc or 12.5 ± 0.7 kpc; (3) the Sedov-analysis-based distance is 9.8 ± 0.7 kpc. The RC distance of this SNR is 3.1 ± 0.3 kpc, which is consistent with the lower limits of extinction distance and kinematic distance.

**G309.2–0.6**

HI absorption against G309.2–0.6 yielded a kinematic distance from 5.4 ± 1.6 to 14.1 ± 0.7 kpc (Gaensler et al. 1998). Rakowski et al. (2001) estimated the distance of 6.5 ± 1.0 kpc.

**G309.8–2.6**

A $A_V$ limit for smaller distance of 2.3 kpc was determined with Sedov estimate (Bocchino et al. 2000). There is a cutoff in the probability distribution of distance because only the upper limits for $A_V$ of G315.4–2.3 is in the range of $A_V$ traced by the RC stars. Therefore, the red line in the right panel for G315.4–2.3 is the upper limit of distance, estimated to be 2.0 kpc by the RC method.

### Table 2 $A_V$ Converted from Hydrogen Column Density $N_H$ and Distance

| Source Name | $N_H$ (10$^{21}$ cm$^{-2}$) | $A_V$ (mag) | Distance (kpc) | Previous measurement (kpc) | Method | Reference |
|-------------|-----------------------------|-------------|----------------|-----------------------------|--------|-----------|
| G299.2–2.9  | 3.5±1.5                     | 1.7±0.7     | 2.8±0.8        | 0.5, 2–11                   | Hydrogen column density [1], [2] |
| G308.4–1.4  | 10.2±1.4                    | 5±0.7       | 3.1±0.3        | 5.9±2.0                     | Extinction estimate [3] |
|             |                             |             |                | 2.0 ± 0.6, 12.5±0.7         | Kinematic measurement [3] |
|             |                             |             |                | 9.8±0.9, 9.7 ±0.7           | Sedov estimate [3] |
| G309.2–0.6  | 6.5±3.0                     | 3.2±1.5     | 2.8±0.8        | 4 ± 2                       | Hydrogen column density [4] |
|             |                             |             |                | 5.4±1.6 to 14.1±0.7         | Kinematic measurement [5] |
| G309.8–2.6  | 3.9±0.4                     | 1.9±0.2     | 2.3±0.2        | 2.5                         | Pulsar distance [6], [7] |

Notes: $1^A_V = N_H / (2.04±0.05) \times 10^{21}$ cm$^{-2}$ mag$^{-1}$ (Zhu et al. 2017). References: [1] Park et al. (2007); [2] Slane et al. (1996); [3] Prinz & Becker (2012); [4] Rakowski et al. (2001); [5] Gaensler et al. (1998); [6] Lemoine-Goumard et al. (2011); [7] Camilo et al. (2004).
this SNR to be $4 \pm 2$ kpc from the foreground hydrogen column density. The distance measured by the RC method is $2.8 \pm 0.8$ kpc, which is consistent with the lower limits of previous measurements.

**G309.8–2.6**

We estimate the distance of G309.8–2.6 at $2.3 \pm 0.2$ kpc for the first time. The RC distance further supports that G309.8–2.6 is associated with the very young pulsar PSR J1357–6429 located at 2.5 kpc (Camilo et al. 2004).

We compare the nine RC distances of SNRs with the distances from other methods in Figure 4. Note that there might be several distance measurements for one SNR and a few of them do not have uncertainty estimates. The RC distances are generally consistent with the previous measurements within error bars. The distance uncertainties from the RC method range from 10% to 30% and the accuracies of distances are significantly improved for eight SNRs.

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