Distances of Galactic Supernova Remnants Using Red Clump Stars

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Abstract

We carry out a project to independently measure the distances of supernova remnants (SNRs) in the first quadrant of the Galaxy. In this project, red clump (RC) stars are used as standard candles and extinction probes to build the optical extinction ($A_V$)–distance ($D$) relation in each direction of extinction-known SNRs. The distances of 15 SNRs are determined. Among them, the distances of G65.8–0.5, G66.0–0.0, and G67.6+0.9 are given for the first time. We also obtain $32$ upper/lower limits of distances, and the distances to G5.7–0.1, G15.1–1.6, G28.8+1.5, and G78.2+2.1 are constrained. Most of the distances measured by the RC method are consistent with previous results. The RC method provides independent access to the distances of SNRs.

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

Supporting material: figure sets

1. Introduction

Supernova remnants (SNRs) play key roles in the final evolution of stars, reshaping and heating the interstellar medium, and the birth of high-energy cosmic rays. Reliable distances to SNRs are essential to constrain physical parameters such as age, physical size, expansion velocity, and the explosion energy of the progenitor supernovae, which reveal the evolutionary process of SNRs. However, obtaining reliable distances of SNRs is a challenging job. About 20% of Galactic SNRs have distance measurements (Green 2014a).

There are several popular methods to measure the distances to Galactic SNRs. First, the kinematic method is based on the flat rotation curve of the Milky Way. By combining 21 cm H\text{I} absorption with CO emission, Tian et al. (2007) developed an improved way to measure the distances of extended radio sources by minimizing the possibility of a false absorption spectrum. Their methods have been applied to several SNRs, e.g., SNRs Kes 69 and 75, and Tycho’s SNR (Tian & Leahy 2008, 2011). Second, distance determinations to the shell-type SNRs can be inferred by the relation between the mean surface brightness ($\Sigma$) at a specific radio frequency and physical diameter ($D$) of an SNR, $\Sigma = a D^b$. Distance is the ratio of physical diameter and the angular diameter (e.g., Clark & Caswell 1976; Milne 1979; Case & Bhattacharya 1998). The $\Sigma$–$D$ relation is frequently used since $\Sigma$ is easy to observe in radio bands for most radio SNRs. Third, the distances can be accessible when SNRs are associated with objects with known distances like OB associations (e.g., Cha et al. 1999, Vela remnant) or pulsars (e.g., Cordes & Lazio 2002). Additionally, the proper motion and the shock velocity can be used to calculate the distance (e.g., Katsuda et al. 2008; Vink 2008, Kepler’s SNR). For shell-type SNRs in the adiabatic phase, distances can be calculated by the X-ray flux and thermal temperature of X-ray-emitting gas (Kassim et al. 1994). Finally, the extinction measurements can also indicate distances (e.g., Chen et al. 2017; Zhao et al. 2018), which this paper focuses on.

Red clump (RC) stars are characterized by an obvious concentration region in the color–magnitude diagram (CMD). They are usually low-mass stars in the early stage of core He-burning. Their helium cores almost have the same mass. Meanwhile their absolute magnitude weakly depends on metal abundance and ages in the $K$ band (Alves 2000). Hence, RC stars are good enough to be standard candles in the infrared band. Assuming that the intrinsic color of RC stars is homogeneous, then their CMD spread along the color is just caused by interstellar extinction. Therefore, RC stars can also be used as extinction probes (Gao et al. 2009; Girardi 2016).

RC stars are so abundant in our Galaxy that they are extensively used as an independent and reliable approach to trace distance. Lopez-Corredoira et al. (2002) used RC stars to directly measure the density distribution of stars in the line of sight. Durant & van Kerkwijk (2006) measured the running of reddening with distance in the direction of Galactic anomalous X-ray pulsars and obtained the distances of 5 pulsars. Güver et al. (2010) gave a distance estimate to the low-mass X-ray binaries 4U 1608-52 through the interstellar extinction traced by RC stars. Zhu et al. (2015) applied a similar measurement to determine the distance of SNR G332.5-5.6.

We closely follow the RC method and systematically measure the distances to 47 SNRs with known extinction in the first Galactic quadrant, with the aim of enlarging the reliable distance sample of SNRs. In Section 2, the method is described in detail. We summarize methods of measuring the optical extinction, the hydrogen column density, and the distances of SNRs compiled from the literature in Section 3. The uncertainties of this method are analyzed in Section 4. In Section 5, we discuss our results and make a comparison with distances measured by other methods. Finally, a brief summary is given in the final section.

2. Build $A_V$–$D$ Relation

To better illustrate this method, we start with G29.7–0.3 as an example. We extract the stars from the 2MASS All-sky Point Source Catalog in the $J$ and $K_S$ (hereafter $K$) bands.
(Skrutskie et al. 2006) centered on the SNR in 1° × 0°.5 (Δl × Δb) area. The reason why we choose the size of 0.5 deg² will be discussed later in this section. Their magnitudes in the J and K bands are used to construct the CMD (K versus J – K), since the RC stars are easy to identify on CMDs (e.g., Gao et al. 2009). In Figure 1, RC stars are concentrated in the middle of the CMD. The bulk of the stars in the left region of the CMD are main-sequence stars; those in the right are mainly dwarfs and red-giant-branch stars.

In principle, there is a maximal density of RC stars in each range of K apparent magnitude. We divide the stars into a number of horizontal strips in K through the CMD. The locations of the RC stars in different strips indicate different distances and reddening. The width of each strip is usually 0.3 mag and it will be extended to 0.5 mag or 0.7 mag when the counts of the RC’s peak density are less than 10. The length of each strip in J – K is fixed by the RC’s distribution in order to include most of the RC stars and minimize the contamination of stars of other types. For each strip, we apply an empirical function to fit the histogram of star counts (Durant & van Kerkwijk 2006):

\[
y = A_{\text{RCs}} \exp \left\{-\frac{(J - K) - (J - K)_{\text{peak}}}{2\sigma^2}\right\} + A_C(J - K)^n. \tag{1}
\]

Here, \( (J - K) \) represents the stellar color, and \( A_{\text{RCs}} \) and \( A_C \) stand for the normalizations of the RC stars and the contaminant stars, respectively. The first term is a Gaussian of \( (J - K)_{\text{peak}} \) and the width \( \sigma \) to fit the RC stars distribution; the second term is a power law to fit the contaminant stars. For instance, Figure 2 shows the best fit for the 11.1 < \( K < 11.4 \) strip: the stellar color \( (J - K) \) at the peak density of the RC stars \( (J - K)_{\text{peak}} \) is 1.56 mag and the \( \sigma \) is 0.19 mag. The \( (J - K)_{\text{peak}} \) value is applied to calculate the average extinction of this field as Equation (2). We assume that the intrinsic color \( (J - K)_0 \) is 0.63 mag and the mean absolute magnitude of RC stars in \( K \) band is −1.61 mag. We discuss this further in Section 4. Then, the extinction and the corresponding distance are derived from the following functions (Indebetouw et al. 2005):

\[
A_K = 0.67 \times [(J - K)_{\text{peak}} - (J - K)_0], \tag{2}
\]

\[
\frac{A_K}{A_V} = 0.1615 - \frac{0.1483}{R_V}, \tag{3}
\]

\[
D(\text{kpc}) = 10^{0.2(m_K - M_K + 5 - (0.1137 \pm 0.003) \times A_V)} / 1000, \tag{4}
\]

where \( A_V \) and \( A_K \) are extinction in the V and K bands, \( R_V = 3.1 \pm 0.18 \) (we discuss the value of \( R_V \) in Section 3.1). In Equation (3), the conversion from \( A_K \) to \( A_V \) follows the empirical relation of Cardelli et al. (1989), which contributes an uncertainty of ∼3% to the optical extinction.

This process is repeated for all strips until the 2MASS observational limit is reached. Since the extinction grows with increasing distance in a given line of sight, there is a one-to-one correspondence between the extinction and distance. Hence, the distance of G29.7–0.3 is obtained by overlapping its extinction value on the \( A_V - D \) relation in its direction.

We tempt to find an optimal bin size for each SNR. On the one hand, a larger bin size can help increase the accuracy of determining the extinction. This would enlarge the amount of RC stars, then decrease the uncertainty of RC’s color \( (J - K)_{\text{peak}} \). Meanwhile it would allow a narrow horizontal strip in \( m_K \) that is used to perform the fits of Equation (1), then yield a better sampling of the pairs of extinction and distance. On the other hand, a smaller bin size can decrease the dispersion of extinction in the line of sight.

We present two typical examples (one with high stellar density, the other one with low stellar density) to illustrate how to select the bin size. For an SNR with high stellar density in the sightlines, the \( A_V - D \) relations are constructed within bin sizes of 0.5 deg² (1°0 × 0°.5), 0.125 deg² (0°.5 × 0°.25), 0.0625 deg² (0°.25 × 0°.25), the smallest possible area around the target), respectively (See Figure 3(a)). It is found that the three \( A_V - D \) relations are fully consistent with each other. In this case, the effect of bin size can be neglected when deriving the distance of SNRs. For an SNR with low stellar density, the \( A_V - D \) relations are constructed within bin sizes of 1.5 deg² (Δl 1° × Δb 1°), 0.5 deg² (1°0 × 0°.5), 0.125 deg² (0°.5 × 0°.25), the smallest possible area around the target), respectively (See Figure 3(b)). The numbers of sampling points are 9, 7, 6, respectively. The
almost the same luminosity and electronic-degenerate core; while the SRCs whose luminosity are greatly changed contain non-degenerate He-cores (Girardi 1999). The largest sample of RC stars identified based on LAMOST survey DR3 (Wan et al. 2015, 2017) shows that the ratio of the main and secondary RC stars is about 3:1. To investigate the effects of SRCs for this method, we use a double Gaussian function to fit the distribution of RC stars of each strip. No apparent secondary Gaussian component can be found. Hence, the effects of the SRCs can be neglected in this method.

3. Compilation of \( A_V \), \( N_{HI} \), and \( D \)

Drawing from the catalogs of Green (2014b) and Ferrand & Saha (2012), we investigate 161 SNRs in the first Galactic quadrant. Among them, 47 SNRs have optical extinction or hydrogen column density data in the literature. We collect their parameters on optical extinction \( A_V \), hydrogen column density \( N_{HI} \), and distance \( D \), then discuss the methods for determining the three parameters. The three parameters and the corresponding methods are listed in Tables 1 and 2.

3.1. Optical Extinction \( A_V \)

The interstellar extinction is the absorption and scattering of electromagnetic radiation by dust and gas. The most common method to obtain optical extinction \( A_V \) is by measuring the reddening via the intensity ratios between the two emission lines and converting the reddening into the color excess \( E_{B-V} \). Then, we gain the extinction values \( A_V = R_V \times E_{B-V} \). The total selective extinction ratio \( R_V \) is \( \sim 3.1 \) for the diffuse interstellar medium in the Milky Way, which is widely used (e.g., Fitzpatrick 1999; Draine 2003; Schlaufy & Finkbeiner 2011). Schlaufy et al. (2016) measured the reddening of 37,000 stars in the Galactic disk based on APOGEE, PS1, 2MASS, and WISE data, then determined the uncertainty of the \( R_V \), \( \sim 0.18 \). Although \( R_V \) has significant variance in some regions, there is a wide wedge of intermediate \( R_V \) in the first quadrant (see the Figure 3 of the Schlaufy et al. 2017). Hence, it is robust to adopt \( R_V = 3.1 \pm 0.18 \). The uncertainties of \( A_V \) are approximately estimated as \( A_V \times \sqrt{\left( \frac{\sigma(R_V)}{R_V} \right)^2 + \left( \frac{\sigma(E_{B-V})}{E_{B-V}} \right)^2} \).

The frequently used line ratio we present in Table 1 is \( \mathrm{H}_\alpha(6563 \ \AA)/\mathrm{H}_\beta(4861 \ \AA) \) based on the Balmer decrements, which are strong enough to be resolved in the optical band. Other line ratios involve \( \mathrm{S}\ II(\sim 10320 \ \AA)/\mathrm{S}\ II(\sim 4068 \ \AA) \), \( \mathrm{Fe}\ II(\sim 1.6435 \ \mu m)/\mathrm{Fe}\ II(\sim 4068 \ \mu m) \). The group lines from the transition with the same upper level weakly depend on physical conditions such as the temperature and density of the gas. Hence, it is feasible to estimate the extinction to the extended sources (e.g., Oliva et al. 1989, SNRs and pulsar wind nebulae). And another approach is to measure the extinction of the individual stars with known distances that are associated with an SNR.

3.2. \( N_{HI} \)

Hydrogen column density \( N_{HI} \) is usually used to approximately denote X-ray extinction, which is caused by any element not fully ionized, especially abundant heavy elements when energy is above 0.25 keV. The dust grains of the same abundant heavy elements also contribute to the optical extinction \( A_V \) (Güver & Özel 2009). Both theoretical and observational studies have indicated for decades that there...
should be a reasonable correlation of \(A_V\) and \(N_H\). We adopt the latest value, \(N_H / A_V = (2.04 \pm 0.05) \times 10^{21} \text{H cm}^{-2} \text{mag}^{-1}\), for the first and fourth Galactic quadrants (Zhu et al. 2017). The conversion error is approximately estimated as \(\sigma_{N_H} / 2.04\) + \(\sigma_{A_V} / A_V\).

More than half of SNRs have been detected in the X-ray band (Ferrand & Safi-Harb 2012). About 30% of SNRs are associated with optical emission (Green 2014b). Therefore, we can obtain more \(A_V\) values transformed from the \(N_H\).

\(N_H\) is usually derived from the best fitting X-ray spectrum. Here, we only collect the \(N_H\) derived from solar abundances (Anders & Grevesse 1989) to keep interstellar abundances consistent for the whole transition. If the uncertainty of \(N_H\) has not been given in the literature, we use the average errors of the \(N_H\), 20%, which are derived from our sample with known uncertainties.

3.3. Distance

The distance measurements of SNRs mainly include the \(\Sigma–D\) relation, the kinematic method, proper motion measurements, extinction measurements, Sedov estimates, and associated objects with known distance. Due to different distance measurements with varying uncertainties, we select the distances of SNRs in the literature with the following priority:

4. Uncertainty Analysis

The uncertainties of the derived distances to SNRs are mainly attributed to the errors of the SNRs’ \(A_V\) and the RC’s distances. The errors of the SNRs’ \(A_V\) are calculated by a standard deviation formula. Here, we focus on the errors caused by RC stars. The errors of the RC’s distances mainly include the dispersion of absolute magnitude and extinction traced by RC stars.

The absolute magnitude \(M_K\) of RC stars is extensively studied from the perspective of observations, especially in the \(K\) band (e.g., Alves 2000; van Helsbech & Groenewegen 2007; Groenewegen 2008; Laney et al. 2012; Yaz Gökçe et al. 2013). In this work, we assume that the mean value of \(M_K\) is \(-1.61\) mag, which is consistent with \(M_K = -1.61 \pm 0.03\) mag derived by Grocholski & Sarajedini (2002) based on 14 open clusters, and also with the latest value \(M_K = -1.61 \pm 0.01\) mag determined by Hawkins et al. (2017) based on the 2MASS, \(Gaia\), and WISE data. However, van Helsbech & Groenewegen (2007) estimated a larger value of RC stars, \(M_K = -1.57 \pm 0.05\) mag derived by Groenewegen (2008). If the uncertainty of \(M_K\) has not been given in the literature, we use the average errors of the \(M_K\), 20%, which are derived from our sample with known uncertainties.
based on the revised Hipparcos parallaxes. Taking all of these studies into consideration, the variance of the absolute magnitude $M_K$ leads to a systematic uncertainty of 0.1 mag that contributes about 5% error in the mean distance calculated by Equation (3).

The uncertainties of extinction are caused by the dispersion of intrinsic color and random errors of the Gaussian fitting. The absolute magnitudes of RC stars are more sensitive to [Fe/H] and age in the $J$ band rather than $K$ band, which leads to variation of the intrinsic color ($J - K$)$_0$ (Güver et al. 2010). The values of intrinsic color ($J - K$)$_0$ for RC stars concentrate in the range from 0.5 to 0.75 mag (e.g., Grocholski & Sarajedini 2002; Yaz Gökçe et al. 2013). We adopt ($J - K$)$_0$ as 0.63 mag, and assume that its dispersion is 0.1 mag, which leads to about 5% uncertainty in the distance, according to Equations (2) and (3). Meanwhile, we estimate the uncertainty of mean color on the peak density location of RC stars: $\sigma_{J-K} = \sigma N_{RC}^{-1/2}$, where $N_{RC} = A_{RC} \sigma \sqrt{2\pi}$ is the sum of RC stars in each magnitude strip (Durant & van Kerkwijk 2006). It is a good estimate if the Gaussian fit is valid and the contamination is not significant. The typical error of the mean color is about 0.05 mag, which brings ~2% uncertainties in distance estimation.

In summary, the systematic uncertainties of the distances traced by the RC stars are about 10% in total.

5. Results and Discussion

We measure the run of reddening along distance using the RC method in each line of sight of 47 SNRs in the first Galactic quadrant. Among them, 32 SNRs’ extinctions are beyond the range of $A_V$ traced by the RC method, hence the upper/lower limits of distances are obtained. Fortunately, there are 15 SNR extinction bands overlapping with the extinction measured by the RC stars, which provides an opportunity to estimate the distance accurately and with precision. Figure 5 presents CMDs with the locations of the RC’s peak density for each of the 15 SNRs. Figure 6 shows corresponding $A_V$--$D$ relations and the probability distribution over distance to the SNRs.

5.1. Derive the Distances of SNR

To determine the distances of SNRs, we calculate the probability distribution of distance using the product of two probability distributions and marginalizing over the extinction (Güver et al. 2010):

$$P(D) = \int P_{SNR}(A_V) P_{RC}(D|A_V) dA_V,$$  \hspace{1cm} (5)

where $P_{SNR}(A_V)$ presents the probability distribution of an SNR’s extinction. We assume $P_{RC}(D|A_V) = P_{RC}(A_V|D)$.
Figure 5. CMDs within 0.5 deg$^2$ in each SNR direction; the gray colors denote stellar densities in the logarithmic scale. The red dot and lines show the fitted location of the RC peak density and its extent with 1σ. The CMD in the direction of G49.2–0.7 is built within 0.125 deg$^2$. 
$P_{\text{RC}}(A_V|D)$ presents the distribution of the extinction traced by the RC at each distance bin. Both distributions are denoted as Gaussian functions.

In Figure 6 (right column), the panels show the probability distributions over distance calculated by Equation (5). Then, we fit these distributions with a Gaussian function, yielding the distance with the highest probability. For the objects with good Gaussian fitting, the uncertainty of the 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 Figure 6). In this case, the uncertainty of the distance reflects the cutoff distance. The results are listed in Tables 1 and 2.

5.2. Summarize the Results

We obtain 15 new distances, 3 of which are given for the first time. G65.8–0.5, G66.0+0.0, and G67.6+0.9 are identified as SNRs by Sabin et al. (2013). We estimated their distances as 2.4 kpc, 2.3 kpc, and 2.0 kpc, respectively. Note that G66.0+0.0 is not detected in the most sensitive Galactic

Anderson et al. (2017) suggested that G65.8–0.5 is likely a H II region.
Plane surveys (Anderson et al. 2017). Maybe more observations are needed for its classification.

We have also given 20 lower distance limits and 12 upper distance limits. Among them, the distances of 4 SNRs have been further constrained by combining the lower or upper limits inferred by the RC method and the previous results.

The distance of G5.7–0.1 is ambiguous, at either 3.1 or 13.7 kpc, as inferred by the OH maser velocity (Hewitt & Yusef-Zadeh 2009). The RC method’s distance is about 2.9 kpc. Therefore, we predict its distance is around 3 kpc.

Boumis et al. (2008) suggested a lower limit distance of 2.2 kpc for G15.1–1.6. The RC method gives an upper limit distance of 2.1 kpc. Hence, we conclude that the distance of G15.1–1.6 is around 2.2 kpc.

The distance to G28.8+1.5 is estimated to be less than 3.9 kpc by Schwentker (1994). We obtain its lower limit as 2.8 kpc, so we suggest a distance of 28.8+1.5: 3.4 ± 0.6 kpc.

The distance to G78.2+2.1 is around 1.7–2.6 kpc by H1 absorption (Schwentker 1994). Our result is less than 2 kpc. Therefore, the distance of G78.2+2.1 is 1.9 ± 0.2 kpc.

5.3. Discussion

We have estimated distances for 15 SNRs and upper or lower limits for 32 SNRs using the RC method. (The limit distances are listed in Tables 3 and 4. Figures 8 and 9 show the CMDs and $A_V$–$D$ relations in the directions of 32 SNRs, respectively.)

To further understand the precision of the distances indicated using the RC method, we compare these results with the previous studies by two steps. First, we compare 8 new SNRs’ RC distances with their kinematic distances. The dashed line is fitted by black data points associated with uncertainties.

Figure 6. Left column: 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 column: probability distribution over distance to the SNRs and the best-fit Gaussian model with the cut-offs. The $A_V$–$D$ relations and probability distribution of 15 SNRs are available in the Figure Set.

(The complete figure set (15 images) is available.)

Figure 7. (a) Correlation between the RC distances and kinematic distances of SNRs. (b) Comparison of distances determined by the RC method with distances determined by other measurements. The red arrows present lower limits and the blue arrows represent upper limits. The dashed line is fitted by black data points associated with uncertainties.
kinematic method within the range of uncertainty. Second, we compare 44 distances constrained by the RC method with the corresponding distances measured by other methods. As Figure 7(b) shows, all distances estimated by the RC method are in the range of 1.5–8 kpc, which is consistent with our expectations. All 20 SNR distance lower limits coincide with the trend of the fitting lines, while 6 of the 12 upper limits are in agreement with other distance measurements. We conclude that most RC distances are in agreement with the previous measurements, and the lower limit distances are more reliable. Therefore, SNR distances can be independently constrained by the RC method.

We analyze the reasons why the RC method only can trace either upper or lower limits. For 20 relatively distant SNRs, we only draw their lower limits for two reasons. One restricted condition is the 2MASS Survey completeness limit as $J = 15.8$, $K_S = 14.3$ mag. The other is that the RC stars are likely mixed with the highly reddening main-sequence stars in CMDs when the apparent magnitudes begin to be fainter than 13 mag (see Figure 5). For 12 relatively closer SNRs, we only obtain their upper limits because the sample of RC stars is not enough for statistics when their apparent magnitudes are brighter than 9 mag in most cases. Hence, the RC method based on 2MASS data can be effective in the range from 1.5 kpc to 8 kpc and the specific range of distance it can trace depends on the RC star sample in a given direction.

We next check the seven discrepant measurements. First, the differences between old and new distances for G32.8–0.1, G39.7–2.0, and G73.9+0.9 are less than 30%, which may be caused by the uncertainties of the two different methods. Then, a key investigation is conducted for the other four SNRs. The optical extinction values toward SNRs G13.3–1.3, G85.9–0.6 are smaller than 1 mag. We expected that the extinction values would not be sensitive to the distance when extinction is extremely slight in the line of sight. For G32.1–0.9, the difference between the RC and kinematic distance is greater than 50%, likely due to the large error of $N_H$ that is up to 40%. Note that the distance of G67.7+1.8 listed in Table 1 is not reliable, since its probability distribution over distance is not well fitted by a Gaussian function. This might be a product of the broad range of the SNR’s $A_V$ and the slight extinction, which is much lower than the average magnitudes of extinction per kiloparsec ($c_V \sim 0.7$ mag kpc$^{-1}$) along the line of sight (Indebetouw et al. 2005). These discrepant results suggest that the slight extinction or large uncertainties of extinction might significantly affect the accuracy of the RC method.

6. Summary

We have taken advantage of the RC stars from 2MASS data to construct the $A_V$–$D$ relations along the directions of 47 SNRs in the first Galactic quadrant. In total, 15 distances and 32 upper or lower limit distances of SNRs have been obtained by overlapping their extinction values with $A_V$–$D$ relations. Among them, the distances of SNRs G65.8–0.5, G66.0–0.0, and G67.6+0.9 are estimated as 2.4 kpc, 2.3 kpc, and 2.0 kpc for the first time. The distances of SNRs G5.7–0.1, G15.1–1.6, G28.8+1.5, and G78.2+2.1 have been better constrained as about 3 kpc, 2.2 kpc, 3.4 kpc, and 1.9 kpc, respectively.

By comparison, distances estimated by the RC method are consistent with kinematic measurements within the range of the allowed errors. In addition, the RC method tends to give a reliable lower limit distance. In addition, we analyze the possible reasons why six upper limits are incompatible with the previous results. Finally, we note that the RC method can independently constrain the distances of SNRs in the range of 1.5–8 kpc and the distances can be determined by this method when the samples of RC stars are relatively abundant along the line of sight.

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Figure 8. The CMDs in the the directions of SNRs with upper/lower limit distances. All the CMDs are available in the Figure Set. (The complete figure set (32 images) is available.)

Table 3
Optical Extinction $A_V$ and Limits of Distances

| Source Name | $A_V$ (mag) | Method | $D_{\text{known}}$ (kpc) | Method | $D_{\text{bisquer}}$ (kpc) | References |
|-------------|-------------|--------|---------------------------|--------|---------------------------|------------|
| G6.4−0.1    | 3.3 ± 0.4   | H$_\alpha$/H$_β$ | 1.9 ± 0.3 | kinematic measurement | <2.3      | 1, 2        |
| G11.2−0.3   | 13.0 ± 1.9  | Fe II ratio  | 7.2, 5              | kinematic measurement, pulsar distance | >4.5      | 3, 4, 15    |
| G13.3−1.3   | 0.5 ± 0.1   | H$_\alpha$/H$_β$ | 2–4             | CO absorption | <1.5      | 6          |
| G15.1−1.6   | 3.1 ± 0.6   | H$_\alpha$/H$_β$ | >2.2            | Blast wave energy | <2.1      | 7          |
| G39.2−0.3   | 19 ± 2.3    | Fe II ratio  | 6.2               | kinematic measurement | >5.3      | 8, 9        |
| G39.7−2.0   | 2.3 ± 0.3   | H$_\alpha$/H$_β$ | 4.5 ± 0.2, 5.5–6.5 | proper motion, kinematic measurement | <3.5      | 10, 11, 12  |
| G53.6−2.2   | 3.4 ± 0.5   | S II ratio   | 3.8–6.3, 2.3 ± 0.8 | $\Sigma$−D, kinematic measurement | >5.3      | 13, 14      |
| G59.5−0.1   | 3.1 ± 0.7   | H$_\alpha$/H$_β$ | 11, 2.3          | $\Sigma$−D, kinematic measurement | <3.0      | 15, 16, 17  |
| G73.9−0.9   | 1.7 ± 0.4   | H$_\alpha$/H$_β$ | 4.4–4.5         | $\Sigma$−D, kinematic measurement | <3.0      | 18, 19      |
| G78.2+2.1   | 3.4 ± 0.6   | H$_\alpha$/H$_β$ | 1.7–2.6         | kinematic measurement | <2.0      | 1, 20       |
| G85.9−0.6   | 0.7 ± 0.1   | H$_\alpha$/H$_β$ | 4.8 ± 1.6       | kinematic measurement | <2.1      | 21, 22      |

Reference: (1) Zhu et al. (2017), (2) Velázquez et al. (2002), (3) Koo et al. (2007), (4) Kilpatrick et al. (2016), (5) Green et al. (1988), (6) Seward et al. (1995), (7) Bounis et al. (2008), (8) Lee et al. (2009), (9) Su et al. (2011), (10) Bounis et al. (2007), (11) Marshall et al. (2013), (12) Lockman et al. (2007) (13) Long et al. (1991), (14) Giacani et al. (1998), (15) Gök et al. (2008), (16) Xu & Wang (2012), (17) Guseinov et al. (2003), (18) Mavromatakis (2003), (19) Zdziarski et al. (2016), (20) Leahy et al. (2013), (21) Gök et al. (2009), (22) Jackson et al. (2008).
Figure 9. The $A_V$–$D$ relations along the directions of SNRs where the bands of SNR extinction are beyond the range of $A_V$ traced by the RC stars. All the figures are available in the Figure Set.

(The complete figure set (32 images) is available.)

Table 4
Hydrogen Column Density $N_H$ and Limits of Distances

| Source Name | $N_H$ (10$^{21}$ H cm$^{-2}$) | Model* | $D_{\text{proper}}$ kpc | Method | $D_{\text{proper}}$ kpc | References |
|-------------|-------------------------------|--------|-------------------------|--------|-------------------------|------------|
| G1.0–0.1    | 75.0 ± 15.0                   | TP     | 8.0                     | proper motion | >3.3                  | 1, 2       |
| G5.4–1.2    | 35.0±7.6                     | TP     | 5.2 ± 0.5               | pulsar distance | >3.3                 | 3, 4       |
| G8.7–0.1    | 12.0                         | TP     | 4.5, 4.4                | kinematic measurement, pulsar distance | ≥2.9 | 3, 5       |
| G12.8–0.0   | 100.0 ± 20.0                 | PL     | 8.5                     | kinematic measurement | >2.6 | 6, 7       |
| G15.9+0.2   | 39.0 ± 2.0                   | TP     | 4.5                     | kinematic measurement | >3.7 | 8, 7       |
| G20.0–0.2   | 41.0±24.0                    | PL     | 4.8                     | kinematic measurement | >3.0 | 9, 10      |
| G21.5–0.9   | 22.4 ± 0.3                   | PL     | 4.8                     | kinematic measurement | ≥2.9 | 11, 12     |
| G26.6–0.1   | 4.9 ± 1.7                    | TP     | 1.3                     | absorption column | ≥2.9 | 13         |
| G27.4+0.0   | 26.0±40.0                    | TT     | 8.7 ± 1.2               | kinematic measurement | ≥6.8 | 14, 15     |
| G28.6–0.1   | 37.0                         | TP     | 7.0                     | absorption column | ≥5.0 | 13         |
| G28.8+1.5   | 20.0                         | PL     | <3.9                    | Sedov estimates | ≥2.8 | 16, 17     |
| G29.7–0.3   | 29.0                         | TP     | 6.3 ± 1.2, 5.8±0.5,10.6 | kinematic measurement | ≥3.4 | 15, 18–20     |
| G32.1–0.9   | 2.3±1.8                      | TP     | 4.6                     | Sedov estimates | <2.0 | 21         |
| G32.4+0.1   | 52.0 ± 13.0                  | PL     | 17.0                    | absorption column | ≥5.3 | 22         |
| G32.8–0.1   | 8.1 ± 0.7                    | TP     | 4.8                     | kinematic measurement | <3.4 | 18, 23     |
| G41.1–0.3   | 31.0±2.0                     | TP     | 10.3                    | kinematic measurement | ≥5.4 | 24, 25     |
| G42.8+0.6   | 23.0 ± 10                    | PL+BB  | 7.7                     | PSR distance | ≥2.8 | 26, 27     |
| G43.3–0.2   | 51.8 ± 0.5                   | TP     | 10.0                    | kinematic measurement | ≥4.5 | 28–30      |
| G65.7+1.2   | 2.6±0.4                      | BB     | 1 ± 0.4                 | kinematic measurement | <3.6 | 31, 32     |
| G74.9+1.2   | 13.8 ± 1.7                   | PL     | 6.1 ± 0.9               | extinction measurement | ≥6.1 | 33, 34     |
| G76.9+1.0   | 17.0 ± 3.0                   | PL     | 8.0, 10.0               | pulsar distance | ≥3.6 | 35, 36     |

Notes.

* Model abbreviations: TP: thermal plasma; PL: power law; BB: blackbody; TT: a two-component thermal model.

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