Using Red Clump Stars to Determine Supernova Remnant Distances: A Postprint

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Abstract

Supernova remnants (SNRs) are important sources of interstellar medium and serve as crucial carriers for understanding supernova explosion mechanisms, the acceleration of Galactic cosmic rays, and chemical element abundances in the interstellar medium. Accurate distance measurements of SNRs can provide better constraints on other physical parameters of these remnants. Among the currently confirmed SNRs and newly discovered SNR candidates, approximately one-third have relatively reliable distance measurement information. There are typically three main methods for measuring SNR distances: the kinematic method, the Σ-D relation method, and the extinction-distance method. In recent years, based on the principle of extinction-distance measurement, the method of using red clump stars as probes to measure SNR distances has developed rapidly and been widely applied. Red clump stars are a class of low-mass stars in the helium core-burning stage, characterized by small dispersions in absolute luminosity and intrinsic color, which makes them easily identifiable; therefore, they are often used as standard candles to measure distances to celestial objects. This paper presents the current progress in SNR distance measurement and summarizes the advances in using red clump stars to measure SNR distances.

Full Text

Preamble

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Measuring Distances of Supernova Remnants Using Red Clump Stars

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Abstract

Supernova remnants (SNRs) are important sources of interstellar medium and serve as crucial probes for understanding supernova explosion mechanisms, the acceleration of Galactic cosmic rays, and chemical element abundances in the interstellar medium. Accurate distance measurements to SNRs enable better constraints on their other physical parameters. Among currently confirmed SNRs and newly discovered SNR candidates, approximately one-third have relatively reliable distance measurements. Three primary methods are commonly used to measure SNR distances: the kinematic method, the Σ-D relation, and the extinction-distance method. In recent years, based on the extinction-distance principle, the method of using red clump stars as probes to measure SNR distances has developed rapidly and been widely applied. Red clump stars are low-mass stars in the helium core-burning phase with small dispersions in absolute luminosity and intrinsic color, making them easily identifiable and frequently used as standard candles for distance measurements. This paper introduces current progress in SNR distance measurements and summarizes achievements using the red clump star method.

Keywords: supernova remnants; extinction-distance; red clump stars

1. Background

During the late stages of stellar evolution, catastrophic explosions occur. The star rapidly ejects large amounts of material, which expands and interacts with surrounding interstellar medium to form filamentary gas clouds that remain in space, creating supernova remnants (SNRs). SNR ejecta contain heavy elements formed through thermonuclear reactions and explosive nucleosynthesis, representing an important source of heavy elements in galaxies. Currently, the number of SNRs and candidates in the Milky Way is approximately 300–400. SNR radiation spans the entire electromagnetic spectrum from radio to γ-rays. In the SNR catalogs of Ferrand and Safi-Harb and Green, about 93% of SNRs have radio observations, approximately 42% have X-ray observations, about 31% have optical observations, and approximately 50 SNRs are associated with γ-ray sources.

SNRs are associated with various highly energetic astrophysical phenomena, including anomalous X-ray pulsars, soft γ-ray repeaters, pulsar wind nebulae, non-thermal X-rays, and very high-energy γ-rays. Their morphology is dominated by two processes: (1) shell structures formed by shock waves interacting with surrounding medium, and (2) nebulae driven by pulsar winds. Spatially independent evolution of these processes produces "shell-type"and "filled-center" SNRs, respectively. When a pulsar wind nebula resides within an SNR shell, it is called a "composite" type. For a few SNRs without pulsars where central X-ray emission originates from hot plasma, they are termed "thermal composite" types. In Green' s SNR catalog, approximately 80% are shell-type, about 13% are composite, and approximately 3% are filled-center.

If supernova explosions were isotropic, SNRs would have symmetric morphologies; however, they are irregular. Factors influencing SNR morphology include: (1) circumstellar medium—when shaped by powerful stellar winds into complex cavity networks, SNRs exhibit multi-shell structures (e.g., IC 443); (2) interstellar medium—observationally, SNR shells appear brighter toward the Galactic plane, and simulations show that higher interstellar medium density produces brighter shells; (3) progenitor stars—progenitor motion and stellar winds can explain double-arc shell structures; and (4) associated pulsars—with average birth velocities of approximately 100 km s^{-1}, pulsar wind nebulae are typically not at the geometric centers of shells.

SNR distances are crucial parameters for studying the remnants themselves and their environments. Distance measurements are essential for determining other fundamental parameters such as age, size, luminosity, and evolutionary stage. Accurate distances also enable studies of associated objects like pulsars, pulsar wind nebulae, H II regions, and molecular clouds. For many SNRs with existing distance measurements, both reliability and accuracy require improvement. SNR distance measurement has long been a key focus for astronomers, with methods continuously being refined. This paper summarizes current progress in SNR distance measurements: Section 2 overviews common methods and achievements, Section 3 introduces progress using red clump stars as probes, and Section 4 provides a summary.

2. Common SNR Distance Measurement Methods

Currently, three primary methods are used to measure SNR distances: the kinematic method, the Σ-D relation, and the extinction-distance method. These rely on SNR environments, associated objects, and evolutionary stages. Neutral hydrogen (HI) widely distributed throughout the Milky Way enables kinematic distance measurements. Statistical analysis of shell-type SNRs with known distances yields Σ-D relations for distance estimation. The extinction-distance method uses extinction jumps caused by dust clouds. Since some Milky Way SNRs are associated with molecular clouds, this method has been developed and applied. Among 294 SNRs in Green' s catalog, approximately one-third have relatively reliable distance measurements. Methods continue to be improved to increase both the number and accuracy of distance measurements.

2.1 Kinematic Method

HI is widely distributed in the interstellar medium, with cold HI clouds separated by average distances less than 0.2 kpc. When HI clouds exist near SNRs in the Galactic plane, distances to foreground and background HI clouds can be calculated to constrain SNR distances along the line of sight. As shown in Figure 1 [Figure 1: see original paper], panel (a) illustrates HI clouds behind a continuum source (SNR) producing 21 cm emission lines; panel (b) shows HI clouds in front producing absorption lines; and panel (c) depicts the realistic situation with both foreground and background HI clouds, where analyzing both absorption and emission yields distance constraints. This method is reliable for radio-bright SNRs, while absorption lines from fainter SNRs are affected by background emission, making the method more direct.

The kinematic method derives HI absorption lines from radiative transfer equations. Under local thermodynamic equilibrium, the source function equals the Planck function ($S_\nu = B_\nu(T) = 2k_{BT}/\lambda^2$). Using $I_\nu = 2k_{BT}B(v)/\lambda^2$, radiative transfer is expressed as the HI brightness temperature T_B at velocity v:

$$T_B(v) = \Sigma_m B_m e^{(-\tau_m(v))} + \Sigma_n \int (\tau_n)(v) T_{B,n}(v) e^{(\tau_n(v))}$$

where indices m sum over emission regions and n over emitting/absorbing HI clouds. $\tau_m(v)$ and $\tau_n(v)$ represent total optical depths from each continuum or HI region to the observer, while $\tau^{(n)}(v)$ is the optical depth of individual HI clouds along the line of sight. Subtracting an off-source spectrum $T_{off}(v)$ from an on-source spectrum $T_{on}(v)$ yields the HI 21 cm absorption:

$$e^{(-\tau_v)} - 1 = (T_{B,on}(v) - T_{B,off}(v))/T_c$$

where τ_v is HI optical depth and $e^{(-\tau_v)}$ is plotted as the absorption spectrum. This method was first applied to Cassiopeia A (Cas A). Traditional approaches suffer from false absorption features due to non-uniform HI cloud distributions across source and background regions.

Kinematic distances depend on Galactic rotation curve models. Assuming flat rotation outside the bulge, line-of-sight velocities from solar neighborhood observations directly yield cloud distances. Doppler shifts produce radial velocities that ideal rotation curves relate to Galactocentric radii. For given Galactic longitude and radial velocity, a unique orbital radius exists:

$$r = R_0 sin(l) V(r)/(V_r + V_0 sin(l))$$

where R_0 is the Sun-Galactic center distance, V_0 is solar orbital velocity, $V(r)$ is the rotation curve, V_r is cloud radial velocity, and l is Galactic longitude. As shown in Figure 2 [Figure 2: see original paper], inside the solar orbit ($r < R_0$), one radial velocity corresponds to two distances:

$$d = R_0cos(l) \pm \sqrt{}(r^2 - R_0^2sin^2(l))$$

At the tangent point, these distances (near: $d = R_0cos(l)$; far: $d = R_0sin(l)$) are equal where cloud orbital velocity parallels the line of sight. Outside the solar orbit ($r > R_0$), one radial velocity corresponds to a single distance.

Recent improvements in resolution and sensitivity led Leahy and Tian and Tian et al. to enhance the method by incorporating CO emission line observations. CO clouds behind SNRs don’ t produce HI absorption features, so combined analysis of HI absorption and CO emission better constrains distances. For SNR W44 (G34.7-0.4) shown in Figure 3 [Figure 3: see original paper], HI absorption shows maximum velocity 50 km s^{-1}, far below the tangent velocity along this line of sight. Since CO emission lines all have corresponding HI absorption, HI clouds lie in front of W44, establishing a lower distance limit of 3.3 kpc. HI emission lines beyond 50 km s^{-1} show no associated absorption, yielding a distance of 3.3 kpc.

Approximately 90 SNRs with distance measurements have been determined or revised using kinematic methods. While 21 cm HI lines have been used for decades, non-uniform HI distributions create uncertainties. Tian et al. and Leahy and Tian improved accuracy by combining HI absorption with CO emission features, measuring and revising distances for 43 SNRs. Lee et al. systematically analyzed H_2 emission from Milky Way SNRs using UWISH2, revising distances for 16 SNRs. Frail et al. measured OH (1720.5 MHz) maser lines in 20 SNRs, determining distances for five. CO emission line velocities can also directly estimate distances, as Chen et al. calculated six SNR distances.

Typical kinematic method errors are 10%-25%. Limitations include: (1) Galactic rotation curve uncertainties, causing errors up to several kpc in regions with significant velocity field deviations; (2) near/far distance ambiguity inside the solar orbit; and (3) difficulties constructing reliable absorption spectra, particularly for faint, diffuse SNRs with weak background HI emission.

2.2 Σ-D Relation

The radio surface brightness-to-diameter relation (Σ-D) is a statistical distance estimation method. For a given radio frequency ν, the relation is:

$$\Sigma_\nu(D) = AD^{-\beta}$$

where Σ_ν is surface brightness (distance-independent and calculable from radio data), D is diameter, and A and β are parameters determined from observational or theoretical models. Σ-D calibration relies on SNR samples with known distances. SNR Cas A is typically excluded due to its extreme brightness. Surface brightness Σ is usually evaluated at 1 GHz, where flux density measurements are available. $\Sigma_1 GHz$ is derived from observed radio spectra following $S_\nu \propto \nu^{-\alpha}$. As shown in Figure 4 [Figure 4: see original paper], Pavlovic et al. constructed the relation using 65 SNRs:

$$\Sigma_1 GHz = 6.9^{+4.6}_{-2.1} \times 10^{-14} D^{-5.2\pm1.3}$$

where $\Sigma_1 GHz$ units are W m^{-2} Hz^{-1} sr^{-1}. Two fitting methods were used: (1) orthogonal regression yielding $\beta \approx 5.2$, and (2) least squares yielding $\beta \approx 2.1$, with differences up to a factor of two.

Over decades, Σ-D relations have been repeatedly updated as distance measurements increased (see Table 1). Case and Bhattacharya used 37 shell-type SNRs, yielding 40% errors for individual distances. Guseinov et al. used 31 reliable shell-type and composite SNRs to predict distances for all observed SNRs. Pavlovic et al. used 60 shell-type SNRs to estimate distances for two new SNRs with 50% errors, later updating with 65 SNRs to measure five faint SNRs with 35%-40% uncertainties. Vukotic et al. used 110 SNRs to measure five new SNRs and 27 candidates.

Σ-D relation uncertainties are large. Defining error as $|d_{obs} - d_{sd}|/d_{sd}$ (where d_{obs} is measured and d_{sd} is Σ-D estimated distance), average individual SNR errors are 40%, while collective errors are lower at 20%-30%. Large errors arise from: (1) uncertainties in measured SNR distances; (2) calibration sample selection affecting β by >40%, with fitting algorithm differences up to a factor of two; (3) observational effects like telescope sensitivity, resolution, and sky coverage; (4) assumptions that all shell-type SNRs have identical radio flux, requiring similar explosion mechanisms, energies, and environments; and (5) MHD simulations showing radio flux depends on viewing angle relative to magnetic fields in massive progenitors.

2.3 Extinction-Distance Method

In the Milky Way, interstellar dust and gas absorb and scatter light, causing extinction that makes observed objects appear dimmer. Though dust comprises only 1% of interstellar medium mass, it absorbs 30% of starlight and re-radiates in the infrared. Large stellar samples with accurate photometry, spectroscopy, and distances enable precise SNR distances via extinction-distance methods. Two approaches exist: (1) measuring molecular cloud distances via extinction-distance relations, then using SNR-associated clouds to determine SNR distances (Method 1); and (2) using known SNR extinction and line-of-sight extinction-distance relations to estimate distances (Method 2). This section focuses on Method 1.

Method 1 depends on SNR environments. Approximately 70 SNRs are associated with molecular clouds (MCs). Three-dimensional dust distribution maps can provide distance information. The method divides samples into pixel sets of specified size, parameterizing each pixel’ s extinction as:

$$A_r(\mu) = \Sigma \Delta A_i$$

where μ is the distance modulus and ΔA_i represents extinction in the i-th distance bin. MCMC procedures determine optimal ΔA_i values via maximum likelihood:

$$L = \Pi(1/\sqrt{}(2\pi\sigma_n^2))exp[-(A_n^{obs} - A_n^{mod}(\mu))^2/(2\sigma_n^2)]$$

where n indexes pixels, A_n^{obs} is derived extinction, A_n^{mod} is modeled extinction from the equation, and σ_n is total extinction and distance error. The resulting ΔA_i values yield composite extinction versus distance, with SNR distances measured where extinction increases sharply.

Figure 5 [Figure 5: see original paper] shows the extinction-distance distribution for molecular cloud S147. Pixels 22–30 represent foreground clouds, while pixels 1–22 show extinction from S147. Fitting the extinction curve for pixels 1–22 (Figure 6 [Figure 6: see original paper]) reveals an extinction increase of 0.24 mag, cloud width of 81 pc, and peak distance of 1.223 kpc, yielding S147’ s distance as 1.22 kpc. This method requires detailed discussion of whether extinction-traced clouds are truly associated with the SNR.

Stellar photometry, spectroscopy, and astrometry along SNR lines of sight also constrain distances. Using stars as extinction tracers with color excess ratios ($A_{Ks} = E(J - Ks)$) builds extinction curves. Extinction versus distance positions and amplitudes estimate MC distances, constraining SNR distances. KS-band extinction $A_{Ks} = c_e \times E(J - Ks)$ is needed for stellar distances, where coefficient c_e derives from near-infrared extinction laws: $A_\lambda \propto \lambda^{-\alpha}$.

This method is independent of SNR extinction values. For SNR-MC associations, distance errors depend on single-star distance measurement errors. Using photometric distances, Chen et al. achieved 17% error for S147. Zhao et al. improved precision using spectroscopic distances instead of photometry, constructing extinction curves for 33 SNRs and measuring 23 distances, with 16 having high reliability. Wang et al. used red clump stars to trace distances for 63 SNRs, with 34 having high accuracy. Red clump stars’ stable colors and luminosities enable higher individual remnant distance accuracy. Yu et al. constructed three-dimensional dust maps for 12 SNRs in the outer Galactic disk ($150° < l < 210°$), identifying interacting MCs and measuring four SNR distances using Gaia parallaxes. For nearby SNRs, extremely precise individual stellar distances yield some SNR distance errors as low as 5%.

2.4 Other Distance Measurement Methods

Specific conditions enable additional methods: (1) Measuring distances to associated point sources like OB stars and pulsars (e.g., Vela SNR’ s distance from OB star parallax). Pulsar distances can be calculated from dispersion measures. (2) For nearby SNRs, shock proper motion and velocity estimate distances (e.g., Kepler’ s SNR). (3) For shell-type SNRs, adiabatic expansion models and X-ray gas temperatures provide distance estimates.

3. Measuring SNR Distances Using Red Clump Stars

Red clump (RC) stars are important horizontal branch stars in helium core-burning phases. As shown in Figure 7 [Figure 7: see original paper], RCs cluster in a specific region of color-magnitude diagrams (CMDs), making them easily identifiable. Compact RCs are younger and more metal-rich than diffuse horizontal branch stars. RCs serve as “standard candles” because: (1) they are in stable helium core-burning phases with constant colors and luminosities over long timescales; (2) small helium core mass dispersion produces small luminosity dispersion; and (3) they are abundant, comprising 1/3 of red giants in star-forming galaxies. Applications include measuring stellar density distributions, anomalous X-ray pulsar distances, and constraining neutron star equations of state for low-mass X-ray binaries like 4U 1608-52.

Section 2.3 introduced extinction-distance Method 1, which Wang et al. used with RC tracers to measure 63 SNR distances with high precision. Method 2 uses RCs to measure remnant extinction and line-of-sight extinction-distance relations. This section focuses on Method 2’ s application and progress.

3.1 Calculating SNR Extinction

Extinction refers to interstellar dust and gas absorption/scattering of electromagnetic radiation. Extinction A_V depends on parameter R_V, determined by measuring emission line ratios to estimate reddening $E(B-V)$, then calculating $A_V = R_V \times E(B-V)$. For diffuse Galactic interstellar medium, the average total-to-selective extinction ratio is $R_V = 3.1$, though individual values vary. Schlafly et al. measured reddening for 37,000 disk stars using APOGEE, PS1, 2MASS, and WISE data, finding R_V errors of 18%. A_V errors can be estimated via error propagation.

Reddening is commonly measured using Balmer line ratios Hα (6563 Å) and Hβ (4861 Å) due to their strength and observability. Other useful ratios include [S II] (10320 Å)/[S II] (4068 Å) and [Fe II] (1.6435 m)/[Fe II] (1.2567 m). These line pairs originate from similar upper levels with weak dependence on physical conditions like temperature and density, making them suitable for extended sources like SNRs, H II regions, and planetary nebulae. Alternatively, extinction toward associated stars can approximate SNR extinction.

3.2 Building Line-of-Sight Extinction-Distance Relations

RCs typically cluster in CMDs within given magnitude ranges. Skrutskie et al. selected stellar samples within 0.5 square degrees of SNRs from the 2MASS point source catalog, constructing CMDs using J and Ks bands. Using SNR G29.7-0.3 as an example (Figure 8 [Figure 8: see original paper]), RCs concentrate at the red point indicated. The $A_V - D$ relation construction involves horizontally slicing CMDs into strip subsamples of width 0.3 mag in Ks, expanding to 0.5-0.7 mag for small RC densities. Subsample lengths depend on local RC distributions to maximize RC inclusion while minimizing contamination.

As shown in Figure 9 [Figure 9: see original paper], each strip' s histogram is fitted with a Gaussian for RCs at $(J{-}Ks)_{peak}$ plus a power law for contaminants:

$$y = A_{RCs}exp[-((J-Ks)-(J-Ks)_{peak})^2/(2\sigma^2)] + A_C(J-Ks)^\gamma$$

where $J - Ks$ is stellar color. RC intrinsic color $(J - Ks)_0 = 0.63$ mag, and Hawkins et al. derived average absolute magnitude $M_{Ks} \approx -1.61$ mag using 2MASS, Gaia, and WISE data. Fitted $(J - Ks)_{peak}$ values yield extinction A_V and distance D, building one-to-one distance-extinction relations. Known SNR extinction values then determine distances via the line-of-sight $A_V - D$ relation.

3.3 Progress in Using Red Clump Stars for SNR Distance Measurement

RC applications have enabled first-time measurements and improved accuracy for many SNRs. Using Method 1, Wang et al. employed RC tracers with 2MASS, UKIDSS, and VVV near-infrared photometry (quality < 0.05 mag) to measure distances for 63 Milky Way SNRs, including seven first-time high-accuracy measurements: G5.4-1.2, G308.8-0.1, G318.2+0.1, G318.9+0.4, G327.1-1.1, G329.7+0.4, and G341.2+0.9.

Using Method 2, Shan et al. constructed $A_V - D$ relations for 48 SNRs with known extinction in the first Galactic quadrant. Sixteen SNRs had extinction within the RC-traced range, enabling distance measurements for three first-time SNRs (G65.8-0.5, G66.0-0.0, G67.6+0.9). The remaining 32 SNRs yielded only upper or lower limits. Shan et al. subsequently measured nine SNRs in the fourth quadrant, though second and third quadrant attempts were hindered by slowly increasing extinction producing flat $A_V - D$ curves. Systematic RC-induced distance errors are 10%, with individual SNR errors reaching 30% due to uncertain intrinsic extinction values.

4. Summary and Outlook

Reliable SNR distance measurements are essential for understanding remnant physics and the three-dimensional distribution of supernovae in the Galaxy. Table 2 summarizes current status.

Table 2. Summary of SNR Distance Measurement Methods

Method	Number of SNRs Measured	Reliability Overview
Kinematic method	120	Reliable for radio-bright SNRs; faint SNRs suffer from background HI absorption; typical errors 10%-25%
Σ-D relation	200	Individual SNR errors 40%; collective errors lower at 20%-30%
Extinction-distance (Method 1)	70	Precision depends on single-star distance errors; high-precision nearby stars yield errors as low as 5%
Red clump stars	100	Method 1 provides high individual SNR precision; Method 2 has 10% systematic RC errors, with some SNRs reaching 30%

Section 2 introduced kinematic, Σ-D, and extinction-distance (Method 1) principles and progress. Kinematic methods, applied to 60% of measured SNRs, have been refined through improved resolution and sensitivity, measuring or revising 40 SNR distances with typical 10%-25% errors. The Σ-D relation is most common, with individual uncertainties of 40% and collective uncertainties of 20%-30%. Method 1' s precision depends on single-star distance errors, achieving 5% for some nearby SNRs with high-precision stellar distances. Section 3 focused on Method 2 using RC standard candles. Shan et al. systematically measured distances for over 100 SNRs with extinction information, with systematic RC errors of 10% and individual SNR errors up to 30% due to uncertain intrinsic extinction.

RC-based SNR distance measurements are limited by sample size and purity. With upgraded telescopes (LAMOST, Gaia, LSST, WFIRST, and asteroseismic surveys), millions of RCs are being or will be precisely characterized, enabling reliable distance measurements for numerous SNRs and X-ray binaries. Future work will focus on: (1) studying physical properties and environments of SNR-TeV associations using existing samples, and (2) utilizing LHAASO survey data to identify new TeV sources and constrain Galactic cosmic ray origins.

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