The Distance to and the Near-infrared Extinction of the Monoceros Supernova Remnant

He Zhao, Biwei Jiang, Shuang Gao, Jun Li, and Mingxu Sun
Beijing Normal University, Beijing, People’s Republic of China

bjiang@bnu.edu.cn, hezhao@mail.bnu.edu.cn, sgao@bnu.edu.cn, lijun@mail.bnu.edu.cn, mxsun@mail.bnu.edu.cn

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Abstract

Supernova remnants (SNRs) contain information on the influence of supernova explosions on dust properties. Based on the color indices from the Two Micron All Sky Survey and the stellar parameters from the SDSS–DR12/Apache Point Observatory Galactic Evolution Experiment and LAMOST–DR2/LAMOST Experiment for Galactic Understanding and Exploration spectroscopic surveys, the near-infrared extinction law of and the distance to the Monoceros SNR are derived together with those of two nebulae close to it, the Rosette Nebula and NGC 2264. The distance is found at the position of the sharp increase of the interstellar extinction with distance, and the nebular extinction is calculated by subtracting the foreground interstellar extinction. The distance to the Monoceros SNR is determined to be 1.98 kpc, larger than previous values. Meanwhile, the distance to the Rosette Nebula is 1.55 kpc, which is generally consistent with previous work. The distance between these two nebulae suggests no interaction between them. The distance to NGC 2264, 1.20 kpc, exceeds previous values. The color excess ratio, $E_{\text{HI}}/E_{\text{Ks}}$, is 0.657 for the Monoceros SNR, consistent with the average value of 0.652 for the Milky Way. This consistence results from the fact that the SNR material is dominated by interstellar dust rather than by supernova ejecta. $E_{\text{HI}}/E_{\text{Ks}}$ is equal to 0.658 for the Rosette Nebula, further proving the universality of the near-infrared extinction law.

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

1. Introduction

A leading school of thought on the origin of interstellar dust (ISD) is that they arise from the envelopes of low-mass stars during their asymptotic giant branch stage. But with the discovery of large amounts of dust in galaxies at high redshifts ( Maiolino et al. 2004; Watson et al. 2015) and in Galactic ( Gomez et al. 2012; Owen & Barlow 2015; Biscaro & Cherchneff 2016; De Looze et al. 2017) and extragalactic supernova remnants (SNRs) such as SN 1987A ( Matsuura et al. 2011; Indebetouw et al. 2014; Wesson et al. 2015; Bevan & Barlow 2016) and others ( Bocchio et al. 2016; Bevan et al. 2017; Temim et al. 2017), supernovae (SNe) are now thought to be more important than before in alleviating the dust budgetary problem ( e.g., Matsuura et al. 2009; Dunne et al. 2011). Dust formed in the explosive ejecta of SNe disperses into the interstellar medium (ISM) during the SNR phase. Theoretical computations demonstrate that small grains may be completely destroyed by reverse shock, but very large grains can survive and be dispersed into the ISM without significantly decreasing their sizes ( Nozawa et al. 2007). The amount of dust formed by SNe is a topic of much debate. Considering all estimates in the literature, the dust mass of the Cassiopeia A (Cas A) SNR has an uncertainty of two orders of magnitude, from $\sim 10^{-3} M_\odot$ ( Hines et al. 2004) to $\sim 0.5 M_\odot$ ( De Looze et al. 2017). Recently, Barlow et al. (2010) derived a cool ($\sim 35 K$) dust component with a mass of 0.0075 $M_\odot$ and a size of $\lesssim 0.1 M_\odot$ cold dust in the unshocked ejecta. De Looze et al. (2017) also identified a concentration of cold dust in the unshocked region and derived a mass of 0.3–0.5 $M_\odot$ for the silicate grains, with a lower limit of $\geq 0.1 M_\odot$. Although these values are in better agreement because of more sophisticated techniques and better data, estimating dust mass is still a difficult job. Because the majority of dust in SNRs is cold and thus radiating weakly in the far-infrared (FIR), its radiation can hardly be detected. It is therefore hard to estimate the mass of dust produced by SNe when only warm dust is being detected, which makes up just a small fraction of the total dust (the fraction of warm dust is usually two orders lower than that of the cold component; Gomez et al. 2012; De Looze et al. 2017). Bevan & Barlow (2016) present an alternative method. They study the late-time optical and near-infrared (NIR) line profiles of SNRs, which exhibit a red–blue asymmetry as a result of greater extinction due to the internal dust. Bevan et al. (2017) applied this approach to estimate the dust mass for three SNRs, and gave an estimate of $\sim 1.1 M_\odot$ for Cas A. The technique we adopt in this paper also exploits the extinction effects of dust rather than its infrared emission in order to trace all of the dust (both warm and cold components). Our approach is based on the fundamental principle that absolute extinction is proportional to dust mass.

The Monoceros Nebula (G205.5+0.5) is an old ($1.5 \times 10^5$ yr; Graham et al. 1982) nebulous object that was first verified to be an SNR through its fine filamentary structure observed in the Palomar Sky Atlas red plates and the nonthermal radio emission at 237 and 1415 MHz (Davies 1963). It lies between the Rosette Nebula (southeast) and NGC 2264 (north). It has the largest angular diameter, 220′, among the Galactic SNRs (Green 2014). Table 1 presents its position, lying almost in the midplane of the Milky Way, together with that of the Rosette Nebula and NGC 2264, which are both slightly above the Galactic plane.

The Monoceros SNR has been observed in almost all wavebands, from gamma-ray to radio. With the observation of Fermi/LAT, Katagiri et al. (2016) suggest that the gamma-ray
Table 1

Geometrical Information of the Three Targets

| Object       | R.A. (h.m) | Decl. (d.m) | GLON (deg) | GLAT (deg) | Angular Diameter (arcmin) |
|--------------|------------|-------------|------------|------------|--------------------------|
| Monoceros    | 6 39       | 6 30        | 205.73     | 0.21       | 220                      |
| Rosette      | 6 34       | 5 00        | 206.47     | -1.65      | 78                       |
| NGC 2264     | 6 41       | 9 53        | 202.95     | 2.20       | 20                       |

emission from the Monoceros SNR is dominated by the decay of $\pi^0$ produced by the interaction of shock-accelerated protons with ambient matter. Leahy et al. (1986) find that the X-ray-bright regions correlate well with the bright optical filaments, but none of his six point sources seems to be a neutron star. Based on its optics, the Monoceros SNR appears to have two distinct parts: one part is diffuse in the center, and the other is a filamentary structure along the edge of the remnant (Davies et al. 1978). Based on the observations at 60 $\mu$m, and 6, 11, and 21 cm, a new southern shell branch and a strong western regular magnetic field were found in the region of Monoceros (Xiao & Zhu 2012).

Near the Monoceros SNR, the Rosette Nebula is a large H II region located near a giant molecular cloud, associated with the open cluster NGC 2244. It appears that the Rosette Nebula overlaps with the filamentary structure of Monoceros in the southeast (Davies 1963). North of the Monoceros SNR, NGC 2264 contains two astronomical objects: the Cone Nebula, an HII region located in the southern part, and the Christmas Tree Cluster, located in the northern part. The Cone Nebula’s shape comes from a dark absorption nebula consisting of cold molecular hydrogen and dust. The region occupied by the Cone Nebula and the cluster is very small (about 20′ in diameter), but there seems to be a much larger dust cloud surrounding them. The rim of the cloud extends southward to the edge of Monoceros. This is supported by Davies et al. (1978) and the observation of the Infrared Astronomical Satellite (IRAS; Neugebauer et al. 1984; Wheelock et al. 1994) at 60 $\mu$m (Figure 1).

The distances to the three nebulae are not definitively determined. By making use of the empirical surface brightness —diameter relation (the $\Sigma$—D relation; Mills 1974), Davies et al. (1978) estimate the distance to Monoceros to be 1.6 ± 0.3 kpc. Other studies give 1.5 kpc (Leahy et al. 1986) and 1.6 kpc (Graham et al. 1982; with the same $\Sigma$—D relation, but different values of parameters). For the two neighboring nebulae, the average distance to NGC 2264 is around 0.8 kpc, with values of 0.715 kpc (Becker & Fenkart 1963), 0.8 kpc (Walker 1956), and 0.95 kpc (Morgan et al. 1965). For the Rosette Nebula, the results are highly diverse, 1.66 kpc (Johnson 1962), 1.7 kpc (Morgan et al. 1965), and 2.2 kpc (Becker & Fenkart 1963). From the measurement of Hα, Davies et al. (1978) present a systematic change of heliocentric radial velocities ($V_{HEL}$) from north to south, which gives some clues concerning their relative distances and suggests that there may be an interaction between Monoceros and Rosette, while NGC 2264 is in front of them. Xiao & Zhu (2012) also suggest that Monoceros has probably triggered some of the star formation in the Rosette Nebula.

In this work, we try to determine simultaneously both the extinction of and the distance to the Monoceros SNR by measuring the corresponding parameters of a number of stars in its sightline. At the same time, the extinctions and distances are determined for two neighboring nebulae, the Rosette Nebula and NGC 2264. Stellar extinction will increase sharply when meeting the nebula, due to its dust density being higher than that of the diffuse medium; therefore, the distance to the nebula can be found at the position where the extinction increases sharply. The main steps are as follows:

1. We determine the relation between the intrinsic color index in the NIR and the stellar effective temperature, and use it to calculate the NIR extinction and color excess for each star.
2. The absolute magnitudes of and distances to individual stars are calculated based on stellar parameters and photometry by using the PAdova and TRieste Stellar Evolution Code (PARSEC) model.
3. The distance to the Monoceros SNR, as well as to the Rosette Nebula and NGC 2264, is derived from the position of sharply increased extinction along the lines of sight.
4. The extinction produced by the SNR and the two other nebulae is derived by subtracting the foreground extinction. The color excess ratio, $E_{\text{H}\alpha}/E_{\text{JK}\text{s}}$, is used to describe the NIR extinction law.
5. A rough estimate of the dust mass in the SNR is derived from its extinction.

In Section 2, the data sets and quality controls are described. We determine the extinction of and distance to the individual stars in Section 3. We use these results to estimate the distances to the three nebulae in Section 4. The NIR extinction law is derived in Section 5. We estimate the dust mass in the region of the Monoceros SNR according to its extinction in Section 6. Finally, we summarize the results and implications of this study in Section 7.

2. Data and Quality Control

In order to complete the task, the NIR photometric data are taken from the Two Micron All Sky Survey (2MASS), and the stellar parameters are taken from spectroscopic surveys—the SDSS–DR12/Apache Point Observatory Galactic Evolution Experiment (APOGEE) and LAMOST–DR2/LAMOST Experiment for Galactic Understanding and Exploration (LEGUE).

2.1. Data

2.1.1. 2MASS

2MASS is an all-sky photometric survey in the NIR bands $JHK_S$ (Cohen et al. 2003). There are over 470 million stars in the 2MASS All-Sky Point Source Catalog (Cutri et al. 2003).

2.1.2. APOGEE

As one of the four experiments in the Sloan Digital Sky Survey III (SDSS-III), APOGEE is a high-resolution ($R \approx 22,500$), NIR ($H$-band, 1.51–1.70 $\mu$m) spectroscopic survey with high signal-to-noise ratio (about 85% stars with S/N > 100) of more than 100,000 Galactic red giant stars. APOGEE measures stellar parameters, including effective temperature $T_{\text{eff}}$, surface gravity $\log g$, and metallicity $[\text{M}/\text{H}]$. The most recently released APOGEE catalog we use contains 163,278 stars (Eisenstein et al. 2011; Alam et al. 2015).

2.1.3. LEGUE

The Large Sky Area Multi-Object fiber Spectroscopic Telescope (LAMOST) is a Chinese national scientific research
Section 2.3

20 regions of the Rosette Nebula and NGC 2264 are both over 50 MJy/sr, with the maximum reaching about 250 MJy/sr. The blue and red dots are the tracers (see Section 2.3)—dwarfs and giants in the selected regions, respectively. The yellow lines are the borders of eight diffuse regions. Additionally, the black dotted-dashed lines, surrounding DF5 and DF6, enclose the reference region mentioned in Section 4.1.

2.2. Data Quality Control

In order to determine both the extinction of and the distance to the Monoceros SNR, as well as those of NGC 2264 and the Rosette Nebula, dwarfs and giants are chosen as extinction tracers and distance indicators, mainly because their intrinsic colors are well-determined by Jian et al. (2017) and Xue et al. (2016). The preliminary operation combines NIR photometry with stellar parameters. The data are collated by matching the 2MASS photometry since the APOGEE survey was based on 2MASS. The data quality is controlled for a precise result. The stars are chosen only if they have complete information of the photometry in all JHK$_S$ bands and of the stellar parameters $T_{\text{eff}},$ log $g$ and [Fe/H]. Although APOGEE measures [M/H] instead of [Fe/H], Mészáros et al. (2013) point out that [M/H] is generally close to [Fe/H]. Therefore, we assume that [M/H] is equivalent to [Fe/H]. The measurements are required to fulfill the following criteria.

1. The photometric error of the JHK$_S$ bands is $\sigma_{\text{JHK}_S} < 0.05$ mag.
2. The errors of the stellar parameters from LEGUE are $\sigma_{\text{Teff}} < 300$ K, $\sigma_{\log g} < 0.5$ dex, and $S/N > 30$ (signal-to-noise ratio in the g-band).
3. The errors of the stellar parameters from APOGEE are $\sigma_{\text{Teff}} < 300$ K, $\sigma_{\log g} < 0.2$ dex, and $S/N > 100$. In addition, the velocity scattering of the multi-epoch measurements is VSCATTER $< 0.3 \text{ km s}^{-1}$ to exclude binary stars.

The different criterion in log $g$ for LEGUE and APOGEE is caused by the much higher accuracy of APOGEE than LEGUE, because of its much higher spectral resolution.

Furthermore, the dwarf and giant stars are chosen according to the following criteria:

1. $4000 \text{ K} < T_{\text{eff}} < 7000$ K for dwarfs, because of the relatively uncertain parameters at both lower and higher effective temperatures for the LAMOST/DR2 catalog. $4000 \text{ K} < T_{\text{eff}} < 5200$ K for G- and K-type red giants for which the intrinsic NIR colors are well-determined by Xue et al. (2016). Although G- and K-type giants have a $T_{\text{eff}}$ range extending to 3600 K, most giants with $3500 \text{ K} < T_{\text{eff}} < 4000$ K have log $g < 1,$ i.e., they are red supergiants.
2. log $g > 4$ for dwarfs, and $1 < \log g < 3$ for giants. Worley et al. (2016) set the value of $\log g = 3.5$ as the boundary of giant and dwarf. Taking the typical value of $\Delta \log g$ of LEGUE ($-0.5$ dex) into account, Jian et al. (2017) shifted the boundary, and stars with $3 < \log g < 4$ are dropped to avoid ambiguity, which has little effect on the result thanks to the numerous stars in the database.

3. $-0.5 < [\text{Fe/H}] < 0.5$ for both dwarfs and giants. Both metal-poor and metal-rich stars are removed to reduce the influence of metallicity on intrinsic colors in the NIR bands. Moreover, this metallicity range is very precisely determined.

Under these criteria, 374,052 dwarfs and 90,741 giants (45,444 from LEGUE and 45,297 from APOGEE) were selected to constitute the star sample for our study of the relation between stellar intrinsic colors and effective temperatures.

Based on our criteria, stars fainter than $K_S = 14.4$ mag will be excluded, as most of them are far away or highly obscured by dust. But our star sample can still reach as far as 8 kpc, with most within 6 kpc, covering the three targets (around 2 kpc). Additionally, it is enough to trace the extinction of the faint SNR. Meanwhile, such depth may be unable to trace the dense regions of the three nebulae.

### 2.3. Selecting the Area of the Monoceros SNR

SNRs radiate in both radio and infrared. Since we are interested in the extinction and dust of SNRs, the dust emission map would be the appropriate indicator of the region of the SNR. As dust dominates the infrared emission between 5 and 600 $\mu$m (Draine 2011), we make use of the observation by IRAS at 60 $\mu$m to trace the warm dust toward the line of sight of a $7^\circ \times 7^\circ$ field centered at (Gal: $205^\circ.5, +0^\circ.5$), which is almost the very center of the Monoceros SNR (Figure 1). The whole field contains 2725 stars all picked from our star sample described above, which form a subsample to study the extinction of and distance to the stars and nebulae. We will use it to analyze the uncertainties of the derived distance in Section 3.5.

Using the contour map of the target regions (Figure 1), we determine the bounds of the faint SNR using the 25 MJy/sr contour (the magenta line), while we use the 50 MJy/sr contour for the compact region of the Rosette Nebula (the cyan line). For NGC 2264, the bound is also defined by the 25 MJy/sr contour (the white line) in order to include as many stars as possible to trace its extinction. After defining the borders of the nebulae, the “tracing stars” are extracted from the subsample in an irregular polygonal field for Monoceros, which basically follows the bound defined by the infrared flux, and the same is done for the other two nebulae. In order to study the foreground extinction, we additionally select eight rectangular diffuse fields (DFs) around the three nebulae, where no obvious dust emission is visible. The number of selected stars in each field is displayed in Table 2.

### 3. Calculation of Stellar Extinction and Distance

#### 3.1. Intrinsic Color Indexes

We determine stellar intrinsic color indices between band $\lambda_1$ and $\lambda_2$, $C_{\lambda_1\lambda_2}^0$, from their $T_{\text{eff}}$ measured by APOGEE or LEGUE. Ducati et al. (2001) suggest that the stars around the blue edge in the $T_{\text{eff}}$–$C_{\lambda_1\lambda_2}$ diagram have the smallest extinction. For large sky survey projects, such as LEGUE and APOGEE, extinction-free stars are included and appear as the bluest ones in the $T_{\text{eff}}$–$C_{\lambda_1\lambda_2}$ diagram. That is, the observed colors of these stars are indeed their intrinsic colors. By fitting the $C_{\lambda_1\lambda_2}$ of the chosen extinction-free stars in some temperature intervals, an analytical relation of $C_{\lambda_1\lambda_2}^0$ with $T_{\text{eff}}$ can be derived. This method has recently been applied to determine stellar intrinsic colors in the infrared (Wang & Jiang 2014; Xue et al. 2016; Jian et al. 2017). Here, we adopt the analytical function determined by Xue et al. (2016) to calculate the intrinsic colors, $C_{\lambda_1\lambda_2}^0$, and $C_{\lambda_1\lambda_2}^0$, for giants:

$$C_{\lambda_1\lambda_2}^0 = a_0 + a_1 \times \left( \frac{T_{\text{eff}}}{1000 \text{ K}} \right) + a_2 \times \left( \frac{T_{\text{eff}}}{1000 \text{ K}} \right)^2. \quad (3)$$

The result is shown in Figure 2, and the coefficients for $C_{\lambda_1\lambda_2}^0$ and $C_{\lambda_1\lambda_2}^0$ are listed in Table 3. High consistency is found with the very recent determination of intrinsic colors for dwarfs by Jian et al. (2017). The difference is no larger than 0.05 for $C_{\lambda_1\lambda_2}^0$ and 0.005 for $C_{\lambda_1\lambda_2}^0$.

As discussed by Jian et al. (2017), the uncertainty of the intrinsic color index comes from a few contributors and can be expressed as

$$\sigma_{\text{C}_{\lambda_1\lambda_2}} = \sqrt{\sigma_{\text{para}}^2 + \sigma_{[\text{Fe/H}]}^2 + \sigma_{\text{ratio}}^2}, \quad (4)$$

where $\sigma_{\text{para}}$ represents the error from the uncertainties of the photometry and stellar parameters, and we finally obtain 0.002 for dwarfs and 0.003 for giants using a Monte Carlo simulation (MCS). The specific technique of the simulation is presented in detail in Section 3.1.1. $\sigma_{[\text{Fe/H}]}$ refers to the influence of [Fe/H];
we suggest an error of 0.02 for dwarfs and 0.04 for giants, based on the discussion in Section 3.1.2. σ_ratio refers to the error induced by the bluest fraction we adopt to choose extinction-free stars. Jian et al. (2017) discussed different fractions and their effect on the intrinsic colors, and set the error to 0.02.

### 3.1.1. The MCS

MCS is a simple way to estimate the statistical uncertainty caused by the stellar parameter measurement and photometry. First, we assume a Gaussian error distribution on each observed data point in the $T_{\text{eff}} - C_{\lambda, \lambda'}$ plane and on the estimated errors in $JHK_s$ magnitude and $T_{\text{eff}}$. The peak value of the distribution is the observed value of each parameter, like the colors and $T_{\text{eff}}$, and the Gaussian has a width equal to the estimated error. Then, a random data point is sampled for each observed point from two independent Gaussian functions because the colors and $T_{\text{eff}}$ are determined independently, $f(x; A, \mu, \sigma) = A \exp \left[ -\frac{(x - \mu)^2}{2\sigma^2} \right]$, (5)

where $x$ is the color or $T_{\text{eff}}$, and $\mu$ and $\sigma$ are correspondingly the observed values and estimated errors, respectively. We subsequently redid the fitting described in Section 3.1 with these randomly sampled points to get new coefficients. LAMOST/LEGUE dwarfs make up the sample set to determine the intrinsic colors for dwarfs. Meanwhile, for giants, we still follow the functional form of and use the same data set as Xue et al. (2016).

This process is carried out 20,000 times to yield an overall distribution of coefficients, and the standard deviation of the distribution is the uncertainty of the coefficients, which are listed in Tables 3 and 4. Furthermore, the standard deviations of the intrinsic colors can also be calculated by these sets of coefficients. As the coefficients correlate with each other, we take some typical temperatures and calculate the intrinsic colors using the MCS result. The errors are derived from the resultant distribution and presented in Figure 3. We find that the errors are no larger than 0.002 for dwarfs, and no larger than 0.003 for giants. Although $\sigma_{T_{\text{eff}}}$ is on the order of one hundred Kelvin, and photometric errors are at hundredth magnitudes, the statistical method based on the large sample makes these measured and observed uncertainties have very weak influence on the intrinsic colors.

### 3.1.2. The Influence of $[\text{Fe/H}]$

Jian et al. (2017) analyzed the influence of $[\text{Fe/H}]$ on the infrared intrinsic colors. They found that the difference between the metal-normal and metal-poor groups (with a border at $[\text{Fe/H}] = -0.5$) is a few percent magnitude, no larger
The universality of the NIR AEs as = = = presents the result derived using all of the solid line. For higher accuracy, dwarfs are further divided into than 0.06. For higher accuracy, dwarfs are further divided into eight groups from [Fe/H] = −0.5 to [Fe/H] = 0.5 with a step of 0.125 dex, and giants are divided into six groups from [Fe/H] = −1 to [Fe/H] = 0.5 with a step of 0.25 dex. In each [Fe/H] bin, C_0^{fi} is determined by the method described in Section 3.1. Figure 4 shows the fitting results and the influence of [Fe/H] on the intrinsic color.

Metal-rich stars account for a pretty small proportion of both dwarfs and giants, which leads to the removal of the last group of dwarfs and the abnormal behaviors of the fitting curves (the dashed blue line in the solid red line in Figure 4 (left)). The differences for dwarfs are mainly within [−0.02, 0.02], so we take 0.02 as the dispersion of the intrinsic colors caused by the variation of metallicity. For giants, the differences are much larger, especially at low T_{eff}. The dispersion rises to 0.04 for 4000 K < T_{eff} < 5200 K. At low T_{eff}, the dispersion increases for both dwarfs and giants, reaching almost 0.1 mag for giants when T_{eff} < 4000 K. But it may partly come from the uncertainty of the stellar parameters at low T_{eff} in addition to metallicity.

![Figure 3. Uncertainties of the intrinsic colors caused by the errors of the photometry and T_{eff}, derived from the Monte Carlo simulation.](image)

![Figure 4. Influence of [Fe/H] on the intrinsic colors of dwarfs (left) and giants (right). In the upper section of each panel, the intrinsic colors derived from the different [Fe/H] bins are presented in different colors and line styles; the black solid line presents the result derived using all of the [Fe/H] samples. In the lower section of each panel, the colored lines show the differences between the corresponding bins and the result from all of the samples.](image)

We prefer to take these uncertainties (0.02 for dwarfs and 0.04 for giants) as part of the total uncertainty of our intrinsic color model rather than deriving the relation between them. This is because (1) T_{eff} is the dominant factor for intrinsic colors while [Fe/H] has a much weaker effect in the NIR, (2) the mean error of [Fe/H] for dwarfs is about 0.14 dex, which constrains the bin box size, and (3) there are not enough metal-poor and -rich stars to complete the fitting.

### 3.2. A_{Ks}: Interstellar Extinction in the Ks Band

The color excess is calculated straightforwardly after subtracting the intrinsic color from the observed one. The extinction in the Ks band, A_{Ks}, must also be derived in order to calculate the stellar distance. The conversion from the color excess, E_{JKS}, to the extinction, A_{Ks}, depends on principle on the extinction law. The NIR extinction law (Wang & Jiang 2014) makes it convenient to convert the color excess into the absolute extinction in the Ks band. Based on all-sky survey data, Xue et al. (2016) derived an average E_{HI}/E_{JKS} = 0.652, which corresponds to α = 1.79 and A_{J}/A_{Ks} = 2.72. This conversion factor is adopted to convert E_{JKS} to A_{Ks}. The uncertainty of A_{Ks} is then

$$\sigma_{A_{Ks}} = \frac{\sigma_{E_{JKS}}}{1.72},$$

and

$$\sigma_{E_{JKS}} = \sqrt{\sigma_J^2 + \sigma_{Ks}^2 + \sigma_{(J-Ks)_0}^2},$$

where \(\sigma_{(J-Ks)_0}\) is the uncertainty of the intrinsic color discussed in Section 3.1, and \(\sigma_J\) and \(\sigma_{Ks}\) are the observed errors.

### 3.3. The Absolute Magnitude

We use the PARSEC to compute stellar absolute magnitudes. The new PARSEC is an update of the Padova database, which can calculate sets of stellar evolution tracks (Bressan et al. 2012). We obtain stellar evolution tracks calculated by PARSEC through CMD 3.0. CMD 3.0\(^1\) is a set of routines that provides interpolated isochrones in a grid, together with stellar parameters and absolute magnitudes transformed into various photometric systems (see Girardi et al. 2002, 2004). The isochrone grids we use in this work have a metallicity step of 0.001 dex between 0.005 < Z < 0.048 and an age spacing of Δ log(t) = 0.05 Gyr.

For each star, we select the isochrone closest in metallicity, and then the Ks-band absolute magnitude, M_{Ks}, is calculated by using a two-dimensional cubic interpolation with neighboring grid points in the corresponding T_{eff} and log g plane, rather than by directly adopting the closest point. In this way, the accuracy of M_{Ks} is improved in the low-density area. Additionally, for a query star with a specific type, the grid points are filtered by the parameter “stage,” which indicates the stellar evolution phase, to alleviate the contamination by the other star types. If a star lies out of the network constructed by the theoretical isochrones, the grid points will focus on one side of it and extrapolation is needed to calculate M_{Ks}. In such a case, no

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\(^1\) CMD is being extended/updated every few months, and the last version is always linked in [http://stev.oapd.inaf.it/cmd](http://stev.oapd.inaf.it/cmd).
calculation is done for this star because the errors and uncertainties would be unpredictable.

The typical uncertainty of $M_K$ calculated by the PARSEC code is composed of two parts:

$$
\sigma_{\text{total}} = \sqrt{\sigma_{\text{para}}^2 + \sigma_{\text{inter}}^2},
$$

where $\sigma_{\text{para}}$ is the contribution by the stellar parameters’ error and $\sigma_{\text{inter}}$ is caused by the interpolation.

Schultheis et al. (2014) present a simple method to estimate $\sigma_{\text{para}}$. For each star, a new set of stellar parameters is constructed by adding the errors, i.e., $T_{\text{eff}} \pm \Delta T_{\text{eff}}$, $\log g \pm \Delta \log g$, and $[\text{Fe/H}] \pm \Delta [\text{Fe/H}]$, which is taken as a new input to calculate the lower and upper limits of $M_K$. Consequently, the range of $M_K$ is calculated, and the half difference of the lower and upper limits with $M_K$ is regarded as the uncertainty. This method is applied to the 2725 subsample stars mentioned in Section 2.3, and $M_K$ is successfully derived for 2218 stars. Because the remainder lie out of the theoretical network, as mentioned above, they are beyond calculation and dropped.

Figure 5 presents the variation of the error $\sigma_{M_K}$ with $M_K$. The sample stars gather into three distinct parts associated with their data sources and stellar types. There is no correlation between $\sigma_{M_K}$ and $M_K$, while stars observed by LAMOST generally have significantly higher $\sigma_{M_K}$ than APOGEE. This can be understood by the larger error in the stellar parameters of the LAMOST survey, in particular the apparently lower quality in $\log g$ and $[\text{Fe/H}]$ than those in the APOGEE survey.

For a sample star, we take the interpolated error of its closest grid point as its $\sigma_{\text{inter}}$. The interpolated error equals the difference between the intrinsic value of the $M_K$ of the grid point and the interpolated value calculated with the adjacent ones with $\Delta T_{\text{eff}} < 200$ K and $\Delta \log g < 0.2$ dex. Mostly, $\sigma_{\text{inter}}$ is smaller than 0.05 and negligible in comparison with $\sigma_{\text{para}}$.

The errors we discuss above do not include the contribution of the PARSEC itself. Schultheis et al. (2014) discussed the differences between the PARSEC isochrones and the Base3.1 model library (Lejeune et al. 1997). They suggest that systematic differences exist in calculating the magnitudes and distances between the two libraries, which are significant for cool, metal-poor M giants. Fortunately, we only make use of the G- and K-type giants, which may not be seriously affected.

### 3.4. The Stellar Distance

The distance to an individual star is calculated from

$$
D(\text{pc}) = 10^{[m_{M_K}+5-M_K-A_{M_K}]/5},
$$

where $m_{M_K}$, $M_{K_S}$, and $A_{M_K}$ are the apparent magnitude, absolute magnitude, and extinction magnitude in the $K_S$ band, respectively. According to the error analysis above, the relative uncertainty of the distance is

$$
\sigma_D/D = 0.46 (\sigma_{m_{M_K}} + \sigma_{M_{K_S}} + \sigma_{A_{M_K}}).
$$

For the 2218 sample stars with $M_K$ available, the relative error of the distance is shown in Figure 6. As predicted, the errors for the LAMOST stars (both dwarfs and giants) are significant, mostly above 50% from the uncertainty of the derived absolute magnitude $M_K$. On the other hand, the APOGEE giants appear with a much smaller uncertainty, mostly around 2%–5% and never superseding 20%, even when the distance reaches 8 kpc. Consequently, the LAMOST dwarfs may be problematic in describing the run of reddening toward the targets. Meanwhile, as most dwarfs are located within 1 kpc, this effect is weak for the Monoceros and Rosette nebulae, while it is non-negligible for the closer object, NGC 2264.

### 3.5. The Distance from Parallax

The first version of data from the European Space Agency’s (ESA) Gaia mission was recently released (Gaia Collaboration et al. 2016a, 2016b). It contains the Tycho-Gaia Astrometric Solution (TGAS; Michalik et al. 2015) catalog, which provides stellar parallaxes for about 2 million stars. The distances
computed from parallaxes are independent of the stellar parameters and stellar model, which is a very good examination of the distances derived by our method.

With the requirement that the error of the parallactic distance be less than 20%, matching TGAS with LEGUE and APOGEE results in 38,222 dwarfs and 1468 giants (996 from LEGUE, 472 from APOGEE). Among them, there are 143 dwarfs and 4 giants in our target region.

Figure 7 compares the distance differences, where the dashed lines delineate the 20% borders. It can be seen that most dwarfs have differences less than 20%, comparable to the error of TGAS. The mean difference is close to zero, and a systematic deviation occurs when \( d > 0.6 \) kpc with a tendency that the model distance is larger than the parallactic distance. Dwarfs in our target regions (green crosses) show a similar tendency. For giants in the right panel of Figure 7, the difference is on the same order as the dwarfs, and has no clear difference between the LEGUE and APOGEE data. Recalling that the estimated errors of the distances for the LEGUE stars are generally larger than 50% in Section 3.4, the distance errors must be greatly overestimated as a result of the overestimation of \( \Delta \log g \) derived from the LAMOST spectra. There is a tendency for the model distance to become larger than the parallactic linearly with the distance when it is greater than 0.6 kpc. This tendency is visible for both dwarfs and giants, while it is more significant for giants at larger distance. This means that our method tends to yield a larger distance for relatively distant stars in comparison with TGAS data. This may lead to the overestimation of distances. On the other hand, Davies et al. (2017) found that the TGAS distance showed a systematic deviation to larger distances at \( d > 0.5 \) kpc for the Kepler field of view. Stassun & Torres (2016) also reported that the Gaia distance is offset to large values. The Gaia distance, when \( > 0.5 \) kpc, needs better calibration. It is puzzling that the Gaia distance is smaller than our model distance when \( > 0.6 \) kpc. If the problem lies in the model distance, the systematic deviation should also occur in the small-distance stars, but it does not.

4. The Distance to and Extinction of the Monoceros SNR

The distance to the Monoceros SNR can now be derived based on the extinction of and distances to individual stars in this sightline. The pre-assumption is that interstellar extinction increases monotonically with distance at a given sightline, which is very reasonable as the extinction is an integral parameter along the sightline. There will be a sharp increase at the position of the Monoceros SNR because it has a higher dust density than the foreground diffuse ISM. The position of the sharp increase will give the distance to the nebula.

4.1. The Foreground Extinction

Because extinction is an integral effect, the foreground extinction must be subtracted in order to measure the extinction produced by the SNR alone. For a precise determination of the foreground extinction, eight DFs are selected as described in Section 2.3. The change of extinction with distance for the stars in these eight DFs are shown in Figure 8, and a linear fitting is performed for simplicity, along with a 3σ uncertainty region. It can be seen that the slopes agree with each other for DF1, DF3, and DF4, with a value of about 0.02 mag/kpc in \( A_{K_S} \), as well as for DF2 and DF8, with a slightly smaller value of about 0.01 mag/kpc. Meanwhile, the DF5 to DF7 variations have a much higher slope, being about 0.05 mag/kpc. This is caused by the Galactic latitude as DF1–DF4 and DF8 have a slightly higher latitude, while the variation of slopes between them, from 0.009 to 0.025, is mainly due to the local environment. Considering that the average rate of interstellar extinction in the \( V \) band is usually taken to be 0.7–1.0 mag/kpc (Gottlieb & Upson 1969; Milne & Aller 1980) and the \( K_S \) band extinction is about 10% of the \( V \) band, the derived foreground extinction rate does mean a diffuse foreground.

For the foreground extinction of the Monoceros SNR, a \( 1.25 \times 2^\circ \) reference region (marked by the black dotted–dashed lines in Figure 1) is chosen with the center at \(( l, b) = (208^\circ 25', +0^\circ 5), \) including DF5 and DF6, for its similar latitude (Figure 9). This foreground will also be applied to the Rosette Nebula and NGC 2264. The extinction of a star, within the uncertainty (3σ) of the linear fitting, is mainly produced by the diffuse ISM rather than by the nebula. We must take out this part of the extinction to study the extinction and NIR color excess ratios for the nebulae in Section 5.

4.2. The Nebular Distance and Extinction

The change of the stellar extinction \( A_{K_S} \) with distance \( D \) is shown in Figures 10–12 for the three selected nebular regions. To be reasonable, only stars with \( E_{B-V} > 0 \) and \( E_{JH} > 0 \) are regarded as the correct indicators. For better accuracy, \( \sigma_D/D < 100\% \) is also required. For the Monoceros SNR, it can be seen that there are three stars (located in the green box in Figure 10) whose extinctions clearly jump around 2.0 kpc. In order of distance, they are (1) \( A_{K_S} = 0.26 \) at 1.98 kpc, (2) \( A_{K_S} = 0.36 \) at 2.31 kpc, and (3) \( A_{K_S} = 0.35 \) at 2.32 kpc. As the nebular extinction shows up only when the star lies behind, the stellar distance should be the upper limit of the Monoceros SNR. The three stars thus indicate the upper limit of the distance. We tend to believe that the closest distance, i.e., 1.98 kpc, is the nebular distance, and the other two stars are behind the SNR. The dispersion of the extinction is mainly caused by the inhomogeneity of the SNR. On the other hand, the tracers are located densely around 2.0 kpc; this distance should be very close to the position of the SNR nebula. In addition, there is no apparent increase of extinction up to at least 1.9 kpc. Therefore, the distance to the Monoceros Nebula is between 1.90 and 1.98 kpc.

The extinction of the Rosette Nebula, \( \Delta A_{K_S} \approx 0.5 \) mag, is twice that of the Monoceros SNR. From Figure 11, the distance to Rosette can be determined to be less than 1.55 kpc as a star at 1.55 kpc has an apparent increase in \( A_{K_S} \), with \( \Delta A_{K_S} > 0.5 \) mag, which is followed by several stars (in the green box in Figure 11) with a similarly steeply rising extinction. NGC 2264 has an extinction jump of \( \Delta A_{K_S} \approx 0.25 \) mag at 1.20 ± 0.03 kpc (Figure 12), which sets the distance at 1.20 kpc. However, there is one dwarf (the blue cross in Figure 12) with a distance of 0.35 kpc and \( A_{K_S} = 0.24 \) mag, which is obviously larger than that of other dwarfs nearby. We suspect that this star is misclassified as a dwarf as it may be a giant star at a much larger distance. No cloud is claimed at this distance at this sightline. In addition, no neighbor stars follow this tendency, and this distance is much smaller than previous results. Instead, there are quite a few stars showing up above the foreground and background extinction after the star at 1.20 kpc. So, 1.20 kpc should be the distance to NGC 2264.

Table 5 compares the derived distances to the three nebulae with those from previous studies. The distance to the Mono-
cotos SNR is 1.98 kpc, appearing larger than the previous value of \( \sim 1.6 \) kpc. Meanwhile, the distance to the Rosette Nebula, 1.55 kpc, coincides with previous results. According to our new determinations of the distances, there should be no interaction between these two nebulae as their distance difference is about 0.4 kpc. The distance to NGC 2264, 1.2 kpc, is larger than previous results, but quite close to the result of Morgan et al. (1965), 0.95 kpc. Overall, the positional relation of the three nebulae is consistent with Davies et al. (1978), i.e., the Monoceros Nebula is the farthest, NGC 2264 the closest, and the Rosette Nebula in between.

The location of the nebular tracers is shown in Figures 13(a) –(c). There are no stars in the highest 60 \( \mu \)m emission regions for all three nebulae, very possibly because of too high extinction in comparison with the depth of observation. The tracers are mainly distributed near the southern edge of the Monoceros SNR, while the foreground stars with low extinction are spread out in a wide distance range. No extinction jump is found for these foreground stars in Figure 10, which indicates that the sharp increase in extinction at 1.90–1.98 kpc can only be attributed to the SNR. Although tracers of the Rosette Nebula are more scattering, the crucial ones still have nearby foreground stars to ensure the distance estimation. As for NGC 2264, which has fewer stars, it is hard to exclude the existence of a foreground cloud. But NGC 2264 itself contains a massive dark cloud, and previous work implies a nearest distance of 0.8 kpc, so the possibility is low for a comparable dust cloud in a nearby region.

The nebular dust not only causes extinction of the background stars, but also emits infrared radiation, thus a correlation between the nebular extinction and infrared emission is expected. Figure 13 compares the extinction of stars behind the nebulae and the infrared flux of the nearest pixel as per the IRAS 60 \( \mu \)m (middle panels) and 100 \( \mu \)m (right panels) images, respectively. We made no intention to subtract the background emission from the infrared images because it would be non-uniform for a large extended nebula, such as Monoceros, and consequently hard to model. No correlation is found between the extinction and the 60 \( \mu \)m emission or the 100 \( \mu \)m emission. Although both the extinction and emission are proportional to dust mass, the emission depends sensitively on dust temperature. The 60 and 100 \( \mu \)m emission is dominated by warm dust, which makes up only a small fraction of the total dust in SNRs (see the dust mass estimation of Gomez et al. 2012 and De Looze et al. 2017). It also implies that the warm and cold dust do not spatially coincide completely, which is suggested by the dust map of De Looze et al. (2017). A check of the dust emission at longer wavelengths may reveal whether the excess extinction is due to the nebular dust. Fortunately, the eastern part of the Rosette Nebula was observed by the Herschel Space Observatory (Pilbratt et al. 2010), with its Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) at 250, 350, and 500 \( \mu \)m. We obtained the reduced SPIRE data through the Herschel Interactive Processing Environment (Ott 2010). Figure 14(a) shows the Herschel 500 \( \mu \)m image of the Rosette Nebula together with the sample stars and the nebula border. Most tracing stars are located in the region with the intensity of 30–50 MJy/sr, while the dense region is not covered again due to its severe extinction. The distances to individual stars and the background emission have much smaller influence at the FIR, which is dominated by the nebular cold dust. It can be seen that there exists tight linear correlations between the nebular stellar extinction, \( A_K \), and the dust emission at 250, 350, and 500 \( \mu \)m (Figure 14(b)), which yields linear correlation coefficients greater than 0.96. This result shows that the extinction-producing dust is identical to the FIR emission dust.

5. The Near-infrared Extinction Law

Although the NIR extinction law takes the form of a power law, the power index \( \alpha \) is very sensitive to the adopted wavelengths of the \( JHK_s \) bands. So, the color excess ratio, \( E_{HI}/E_{IK_s} \), is a more stable and reliable description of the NIR extinction law. Wang & Jiang (2014) and Xue et al. (2016) have already derived the mean \( E_{HI}/E_{IK_s} \) of the Milky Way, which are 0.64 and 0.652, respectively, and consistent with each other, and the result by Xue et al. (2016) is more preferable for their better determination of the intrinsic color indices.
Stars behind the nebula are obscured by dust both from the nebula and the diffuse foreground ISD. But the nebula is inhomogeneous—they experience different extents of extinction by the nebula. The extinction by the nebula is calculated by subtracting the interstellar foreground extinction. With the nebular distance derived above, stars farther than this distance are chosen to study the extinction law of the nebula. Moreover, only the stars with apparent extinction by the nebula are taken as tracers. In Figure 10, the red dots with error bars denote the extinction tracers that lie above the 3σ level of the background extinction and are used as the tracer stars of the nebular extinction. The same is shown for the Rosette nebula and NGC 2264 in Figures 11 and 12. After subtracting the contribution by the background ISM, the color excess ratio, $E_{J H}/E_{JKS}$, is derived by a linear fitting between $E_{JH}$ and $E_{JKS}$ as shown in Figures 15 and in Table 6.

The color excess ratio $E_{JH}/E_{JKS}$ is $0.657 \pm 0.056$ for the Monoceros SNR and $0.658 \pm 0.018$ for the Rosette Nebula, which agree with each other, and also with $0.652$ by Xue et al. (2016). As Monoceros is an old faint SNR, $E_{JH}$ and $E_{JKS}$ span a narrow range, which leads to a relatively large uncertainty (0.056) and a low correlation coefficient ($r = 0.89$). NGC 2264 has a smaller ratio, $E_{JH}/E_{JKS} = 0.617$, but with an error of 0.061; it is still consistent with the mean value of 0.652. Wang & Jiang (2014) suggest that the NIR extinction law is universal based on the fact that there is no visible change of $E_{JH}/E_{JKS}$ with $E_{JKS}$ in the range [0.3, 4.0]. The Monoceros SNR shows no significant difference in the NIR extinction law from the mean law of the Milky Way, which confirms the universality of the NIR extinction law. However, a supernova explosion is a very violent event that releases numerous high-energy particles and photons, which can destroy the surrounding dust grains. Moreover, the supernova ejecta produce dust grains that may differ from the dust in the diffuse medium. In principle, the properties of the SN dust are expected to differ, and thus the extinction law. The highly consistent NIR extinction law of the two environments does not necessarily mean that the SN dust is the same as others or that the SN explosion has no effect on the surrounding dust grains. One possibility is that the Monoceros SNR is very old (10^5 yr) that the dust observed is almost the normal ISD, which is affected very little by SN explosion. The other possibility is that the NIR bands cannot trace the difference between the dust. The other bands, in particular the visual and UV bands, may better reflect the difference between the dust.

6. Dust Mass of the Monoceros SNR

In principle, the dust mass of the Monoceros SNR can be derived from its extinction because the extinction is proportional
to the dust column density. A precise determination of the dust mass needs information on the extinction at all wavelengths from which the dust property can be precisely constrained. Nevertheless, a rough estimation of the dust mass can still be derived with the extinction known only in the NIR if an extinction law is assumed.

Adopting the WD01 (Weingartner & Draine 2001) dust model for the Galactic interstellar extinction law ($R_V = 3.1$), the mass...
Figure 11. The same as Figure 10, but for the Rosette Nebula. The jump of $A_{KS}$ can be clearly seen at 1.55 kpc, followed by several high-extinction stars in the green box. The blue point represents a dwarf above the uncertainty region.

Figure 12. The same as Figure 10, but for NGC 2264.
extinction coefficient for the V band, $K_{\text{ext,}V} = A_V/\Sigma_{\text{dust}}$, is

$$K_{\text{ext,}V} = 2.8 \times 10^4 \text{ mag cm}^2 \text{ g}^{-1}. \quad (11)$$

With a surface mass density $\Sigma_{\text{dust}} = A_V/K_{\text{ext,}V}$, the dust mass is then

$$M_{\text{dust}} = \Sigma_{\text{dust}} \times A_{\text{eff}} = \frac{A_V}{K_{\text{ext,}V}} \times A_{\text{eff}}, \quad (12)$$

where $A_{\text{eff}}$ is the effective surface area.

As a test of this method, we first apply it to the SN dust in the Crab Nebula, which appears to be a $4.0 \times 2.9 \text{ pc}$ ellipsoid (Hester 2008). Owen & Barlow (2015) presented a detailed description of the nebular geometry. To calculate $A_{\text{eff}}$, we follow the dust distribution of their favored models (Van & V I): a clumped shell starts at inner axis diameters of $2.3 \times 1.7 \text{ pc}$, and extends to the $4.0 \times 2.9 \text{ pc}$ outer boundaries, with a volume filling factor ($F_{\text{fil}}$) of 0.10. If we adopt the $A_V = 1.6 \pm 0.2$ mag derived by Miller (1973), the resultant dust mass is $0.658 \pm 0.082 \odot M_{\odot}$ (the uncertainty is simply derived by using $\Delta A_V = 0.2$). This value is in agreement with that by Owen & Barlow (2015), who obtained a result of $0.11 - 0.13 \odot M_{\odot}$ of amorphous carbon and $0.39 - 0.47 \odot M_{\odot}$ of silicate from the infrared emission by using a mixed-dust chemistry model. However, assuming a single dust species of carbon grains, Gomez et al. (2012) derived warmer ($64 \pm 4 \text{ K}$) and cooler ($34 \pm 2 \text{ K}$) components of $0.006 \pm 0.02$ and $0.11 \pm 0.02 M_{\odot}$, respectively, and Owen & Barlow (2015) derived $0.18 - 0.27 M_{\odot}$ of amorphous carbon from clumped models. Both results are lower than our estimate. The discrepancy may be attributed to the value of $K_{\text{ext,}V}$, which is affected by the species and size distribution of dust grains. Nozawa & Fukugita (2013) construct a graphite–silicate model with a power-law size distribution,

### Table 5

| The Nebular Distances (in kpc) Compared with Previous Works |
|-------------------------------------------------------------|
|                | Monoceros SNR | Rosette Nebula | NGC 2264 |
| This work (upper limit) | 1.98 | 1.55 | 1.2 |
| Johnson (1962) | ... | 1.66 | ... |
| Becker & Ferrari (1963) | ... | 2.2 | 0.715 |
| Morgan et al. (1965) | ... | 1.7 | 0.95 |
| Davies et al. (1978) | 1.6 ± 0.3 | 1.6 | 0.8 |
| Graham et al. (1982) | 1.6 | ... | ... |
| Leahy et al. (1986) | 1.5 | ... | ... |

Figure 13. Left panels: the distribution of the sample stars. The red dots are the tracing stars, the black ones are the foreground stars, and the blue ones are the stars behind the nebulae, which are mainly obscured by interstellar dust. The contours and nebular borders are the same as in Figure 1. Middle and right panels: the correlation between the extinction, $A_{KS}$, and the 60 and 100 $\mu$m flux from IRAS for the three nebulae, respectively.
which is similar to the mixed models of Owen & Barlow (2015), and obtain $K_{s, V} = (3.7 \pm 0.5) \times 10^4 \text{ mag cm}^{-2} \text{ g}^{-1}$, which would make our estimation of dust mass be $0.498 M_\odot$ and effectively reduce the discrepancy.

Figure 14. Left: the SPIRE 500 μm image of part of the Rosette Nebula with our sample stars in this sightline and the nebular border (the cyan profile). The green crosses are the foreground stars, and the red and black dots are the same as in Figure 13. Right: the linear correlations between the extinction $A_K$, and the infrared emission intensity of the Rosette Nebula at 250, 350, and 500 μm. The correlation coefficients ($r$) are shown in the legend box.

Figure 15. Color excess ratio, $E_{HI}/E_{JK}$, for the three target nebulae and their comparison. The red solid line is the linear fitting result, and the blue dashed lines bound the 3σ uncertainty region.

According to the distribution of the nebular tracers, a similar clumped-shell geometry as described by Owen & Barlow (2015) can be applied to the Monoceros SNR. The SN explosion cleared an inner region around the central point so it
is free of dust now, while the ISD has been swept-up into the outer dense shell, i.e., the clumped shell. Figure 13(a) shows a lack of significant extinction in the central part of the SNR, consistent with the presumed scenario. The Monoceros SNR has an angular diameter of 220’, corresponding to a radius of 63.36 pc at the derived distance of 1.98 kpc. We assume a circular shell for simplicity. The dust clumps start at the inner radius, \( R_{\text{in}} \). From Figure 10, it can be seen that the nebular extinction varies from about 0.01 to 0.15 in \( A_K \). For a rudimentary estimation, an average extinction of 0.05 in the \( K \) band is adopted, which corresponds to 0.5 mag in \( A_V \). Then, the mass of the dust \( (M_{\text{dust}}) \) clumped in the shell is

\[
M_{\text{dust}} = \frac{0.5 \times \pi \times (R_{\text{out}}^3 - R_{\text{in}}^3) \times F_{\text{fil}}}{K_{\text{ext},V}}
\]

\[
= \left( 1073.595 - 0.26743 (R_{\text{in}} \text{ pc})^2 \right) F_{\text{fil}} M_\odot .
\]  

Because our extinction map is incomplete for the SNR due to the lack of data, it is hard to determine the boundary of the inner ring. If the filling factor \( F_{\text{fil}} \) equals to 0.1 as Barlow et al. (2010), the dust mass is from 38.65 \( M_\odot \) to 80.52 \( M_\odot \) if \( R_{\text{in}} \) is 50%–80% of the \( R_{\text{out}} \) estimated from Figure 13(a). Since the supernova dust is usually on the order of a few percent to at most a couple of tenths of solar mass, the dust mass is mostly contributed by normal ISD. This fact can be understood from the old age of the Monoceros SNR, which is able to sweep a large region of the ISM. This result is also consistent with the fact that the NIR extinction law agrees with the mean law as discussed in the previous section. In this case, the characteristics inhibited in the SN explosion is obliterated when the ISD absolutely dominates during the long evolution after the explosion. This method can be improved by an extinction law covering a complete wavelength range instead of only the \( V \)-band. We will modify our method in future work.

### 7. Summary

The goal of this work is to investigate the dust property of the SNRs from the nebular extinction and its law. The present work determines the distance to and the NIR extinction law of the Monoceros SNR and its two nearby nebulae—the Rosette Nebula and NGC 2264. By taking the stars in the sightlines corresponding to the extinction tracers, the distance of a nebula is found at the position of the sharp increase of the stellar extinction with distance. The stellar extinction is calculated by using the color excess with the intrinsic color index derived from its stellar parameters (mainly \( T_{\text{eff}} \)) based on spectroscopic surveys. Its distance is calculated from the absolute magnitude \( M_V \). The \( T_{\text{eff}} \) and \( \log g \) after subtracting interstellar extinction. The distance to the Monoceros SNR is 1.98 kpc, which is larger than previous results. The distance to the Rosette Nebula, 1.55 kpc, agrees with some previous values. The large difference between these two nebulae, 0.4 kpc, implies low possibility that they are interacting with each other. For NGC 2264, the distance, 1.2 kpc, is slightly larger than previous results. The relative positions of the three nebulae coincide with the Davies et al. (1978) result, i.e., with the Monoceros SNR being the farthest and NGC 2264 the closest. The nebular extinction is derived by subtracting the foreground extinction, which is calculated from a reference DF with comparable Galactic latitude. The NIR extinction law of the Monoceros SNR as well as the two nearby nebulae shows no apparent difference with the mean NIR extinction law. This fact may be a piece of evidence for the universality of the NIR extinction law. On the other hand, the old age (\( \sim 10^7 \) year) and the large mass (\( \sim 50 \ M_\odot \) on average) of the Monoceros SNR signify that the material of this SNR is absolutely dominated by the ISD rather than the SN ejecta. The work needs to be extended to the UV/visual extinction law and to a more accurate estimation of the property of SNRs.

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Software: PARSEC, CMD (v3.0; http://stev.oapd.inaf.it/cmd).

### ORCID iDs

He Zhao [https://orcid.org/0000-0003-2645-6869](https://orcid.org/0000-0003-2645-6869)

Biwei Jiang [https://orcid.org/0000-0003-3168-2617](https://orcid.org/0000-0003-3168-2617)

Shuang Gao [https://orcid.org/0000-0003-0300-6857](https://orcid.org/0000-0003-0300-6857)

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