The Optical – Mid-infrared Extinction Law of the l165° Sightline in the Galactic Plane: Diversity of Extinction Law in the Diffuse Interstellar Medium

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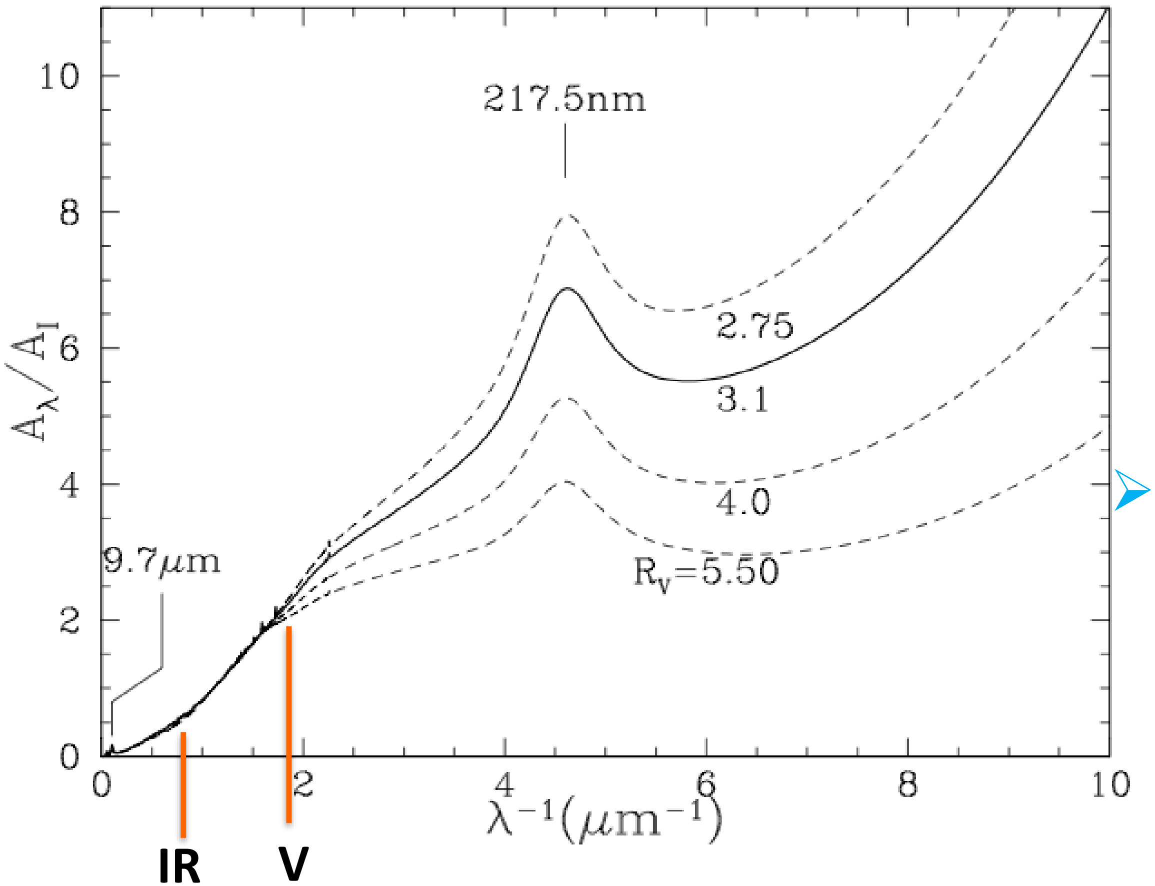
Outline

- Background
  - Interstellar Extinction

- Our work
  - revealing the diversity of the extinction law in diffuse regions
  - photometric data and spectroscopic data
  - red clump stars
  - diversity of extinction

UV/Optical Interstellar Extinction

extinction curves for different values of $R_V \equiv A_V/E(B-V)$
normalized to extinction at I = 0.9 μm

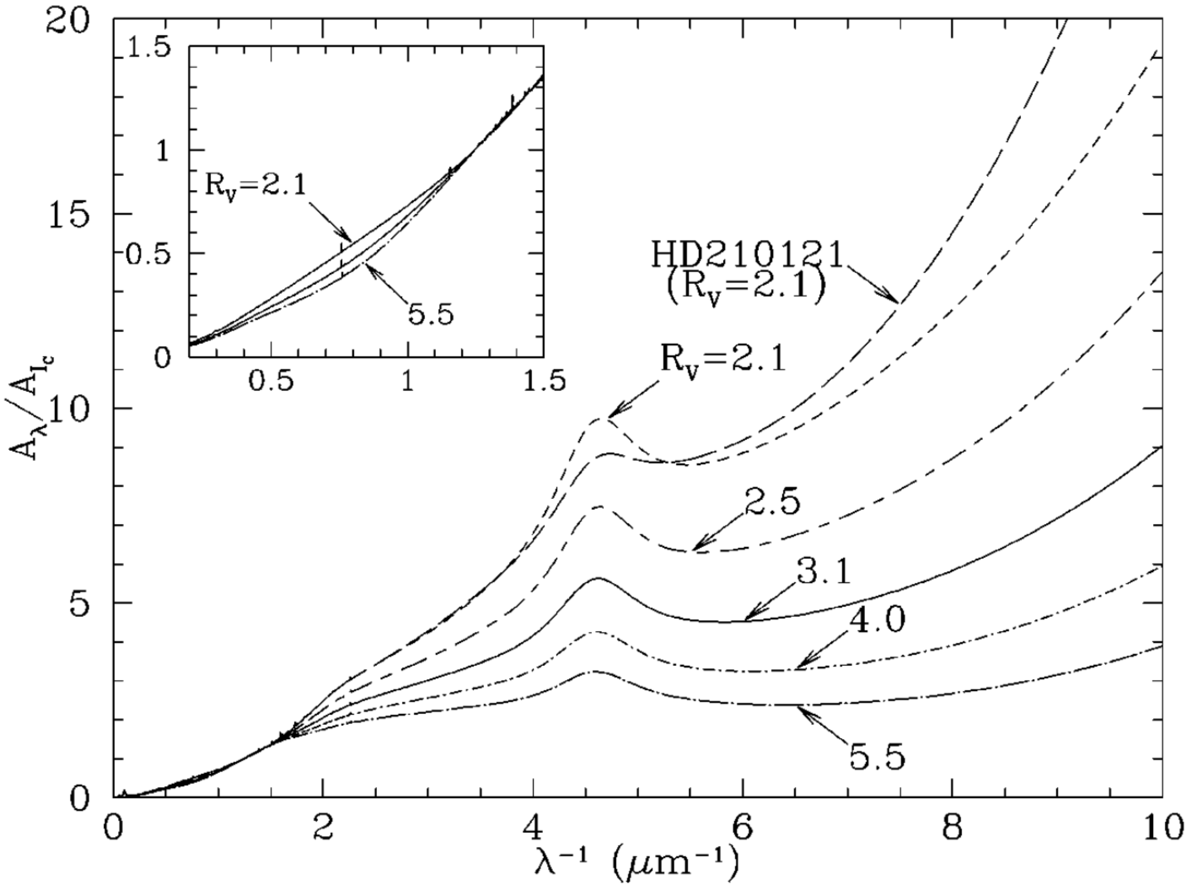


- Extinction Law A_λ/A_I
  - depends on only one parameter: **$R_V = A_V/E(B-V)$** (Cardelli et al. 1989, CCM89)
  - Far-UV (λ^{-1}>5.9μm^{-1}), steeply increases with λ^{-1}
  - 2175Å extinction bump
- Varying in different interstellar environments
  - Denser clouds tend to have larger values of R_V
  - Diffuse ISM , R_V =3.1
  - Dense clouds, $R_V \approx 5.5$

- CCM89 $R_V = 3.1$ extinction curve represents the average extinction law of diffuse regions, it is commonly used to correct observations for the diffuse ISM sightlines.

- However, a given value of R_V may not be able to reflect the true interstellar environment
  - the star Cyg OB2 12
    - Rv = 2.65, $A_V = 10.18$ (Clark et al. 2012)
    - Rv = 3.04, $A_V = 10.20$ (Torres et al. 1991)

- There exists apparent deviation from the CCM89 curve calculated for a given value of R_V
  - HD 210121, $R_V = 2.1$ curve



- HD 210121, can be best fitted by the CCM89 R_V = 2.1 curve
- compared with the average behavior for normal CCM89 R_V = 2.1
  - a significantly lower bump at 2175Å
  - a much steeper rise in the far-UV

This Work

- This work aims at revealing the diversity of the extinction law in diffuse regions by carefully examining a very diffuse sightline covering an area of four square degrees.

The Diffuse Region: Gl165.0 + 0.0

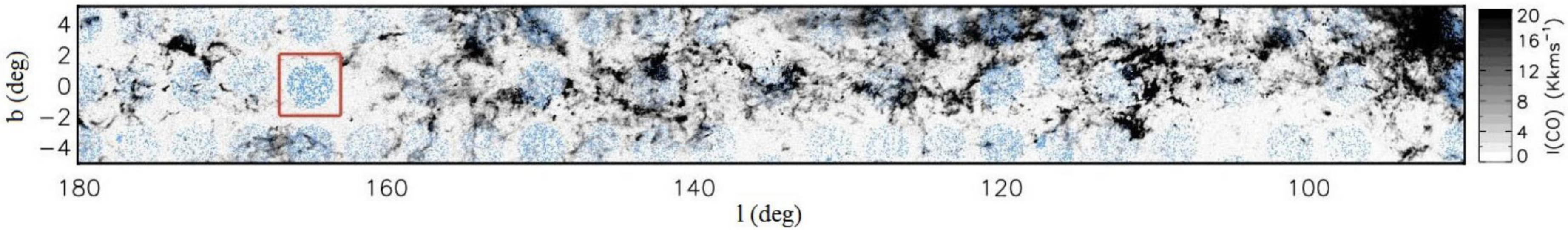


Fig. 1.— The *Planck* velocity-integrated CO (1–0) emission intensity contour of galactic plane $|b| \leq 5°$. Blue dots: the APOGEE giants; red square: the selected G$l165° \pm 0$ region.

- The CO gas emission intensity (I_{CO})
  - is proportional to the dust column density
- extinction tracers: red clump stars
  - diffuse region should be observed by the APOGEE survey
  - overlay the APOGEE stars on the CO emission map
- one diffuse region candidate "l165°"
  - centering around (l = 165.0°, b = 0.0°)

Optical to Infrared Photometric Data

- The APASS (AAVSO, American Association of Variable Star Observers, Photometric All-Sky Survey) survey
  - *B, V*
- The XSTPS-GAC (Xuyi 1.04/1.20 m Schmidt Telescope Photometric Survey of the Galactic Anticentre) survey
  - *g, r, i*
- The 2MASS (Two Micron All Sky Survey) is a near-IR ground-based whole sky survey using two 1.3 m aperture telescopes
  - *J, H, Ks*
- The WISE (Wide-Field Infrared Survey Explorer) survey is an entire sky mid-infrared survey by a 40 cm telescope board on the satellite
  - *W1, W2*

Spectroscopic Data: the SDSS/APOGEE Survey

- The APOGEE is a near-IR H band (1.51-1.70 μm), high-resolution (R~22500), spectroscopic survey.
  - stellar parameters
    - > effective temperature T_{eff} (accuracy of 50 to 100 K)
    - > surface gravity **log *g*** (accuracy of 0.2 dex)
    - > metal abundance **Fe/H** (accuracy of 0.03 to 0.08 dex)
- APOGEE red–clump (APOGEE–RC) catalog
  - RC stars are selected by their position in the color-metallicity-surface-gravity-effective-temperature space
  - contains about 20,000 likely RC stars with a lower than 3.5% estimated contamination

Tracers： Red Clump Stars

- a high quality RC stars sample
  - photometric error
    - > in B, $V \leq 0.1$
    - > in g, r, i, J, H, Ks, $W1$, $W2 \leq$ 0.05
  - metallicity Fe/H ＞ -0.5
  - clumping in the Teff –log g contour map for APOGEE data
    - > 4550 K ≤ Teff ≤ 5050 K and 2.3 ≤ log g ≤ 3.0.
- APOGEE–RC catalog
  - not all RC candidates are included in the APOGEE–RC catalog
- only 18 RC stars with the full ten-band data of high quality

Method

- indicator of the extinction law
  - color-excess ratio $E(V-\lambda x)/E(B-V)$
  - R_V value fitted by CCM89 equations

- color excess $E(V-\lambda x) = (V-\lambda x) - (V-\lambda x)_0$
  - photometric data → the observed color index $(V-\lambda x)$

- key problem
  - determine the intrinsic color index $(V-\lambda x)_0$
    - T_{eff} – Intrinsic Color Relation

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- T_{eff} vs. observed color index diagrams
  - The bluest stars are considered to have little or no extinction
  - a series of discrete [< Teff >, < (B-V) >] in T_{eff} bin=50K
  - A quadratic function to fit the bluest color

$$[\lambda 1] - [\lambda 2] = a + b \cdot T_{\text{eff}} + c \cdot T_{\text{eff}}{}^2$$

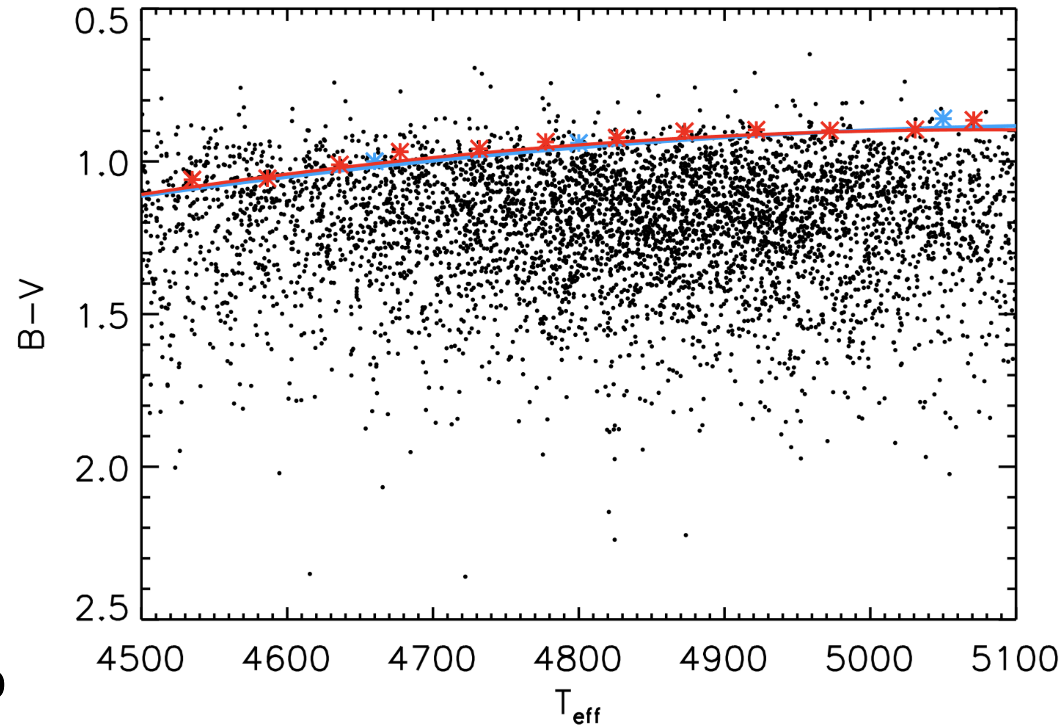

Fig. 2---Teff vs. observed color (B-V) diagram. Black dots are the selected K-type giants, red asterisks show the median values of the bluest stars in bins of Teff=50 K. The red solid line denotes the quadratic fit result to these red asterisks. For comparison, the blue line is the quadratic fit result using discrete intrinsic color data (blue asterisks) given by Johnson (1966, ARAA 4, 193).

Results

- the range of R_V values
  - mean R_V value: 2.8
  - lowest: 1.7 (No.3) is lower than the previously published lowest R_V = 2.1 in the Milky Way.
  - highest: 3.8 (No.18)
- the average error in R_V is about 13.4%
- The diversity in R_V is much larger than the error
- conclusion: the variation in R_V is real and cannot be attributed merely to errors

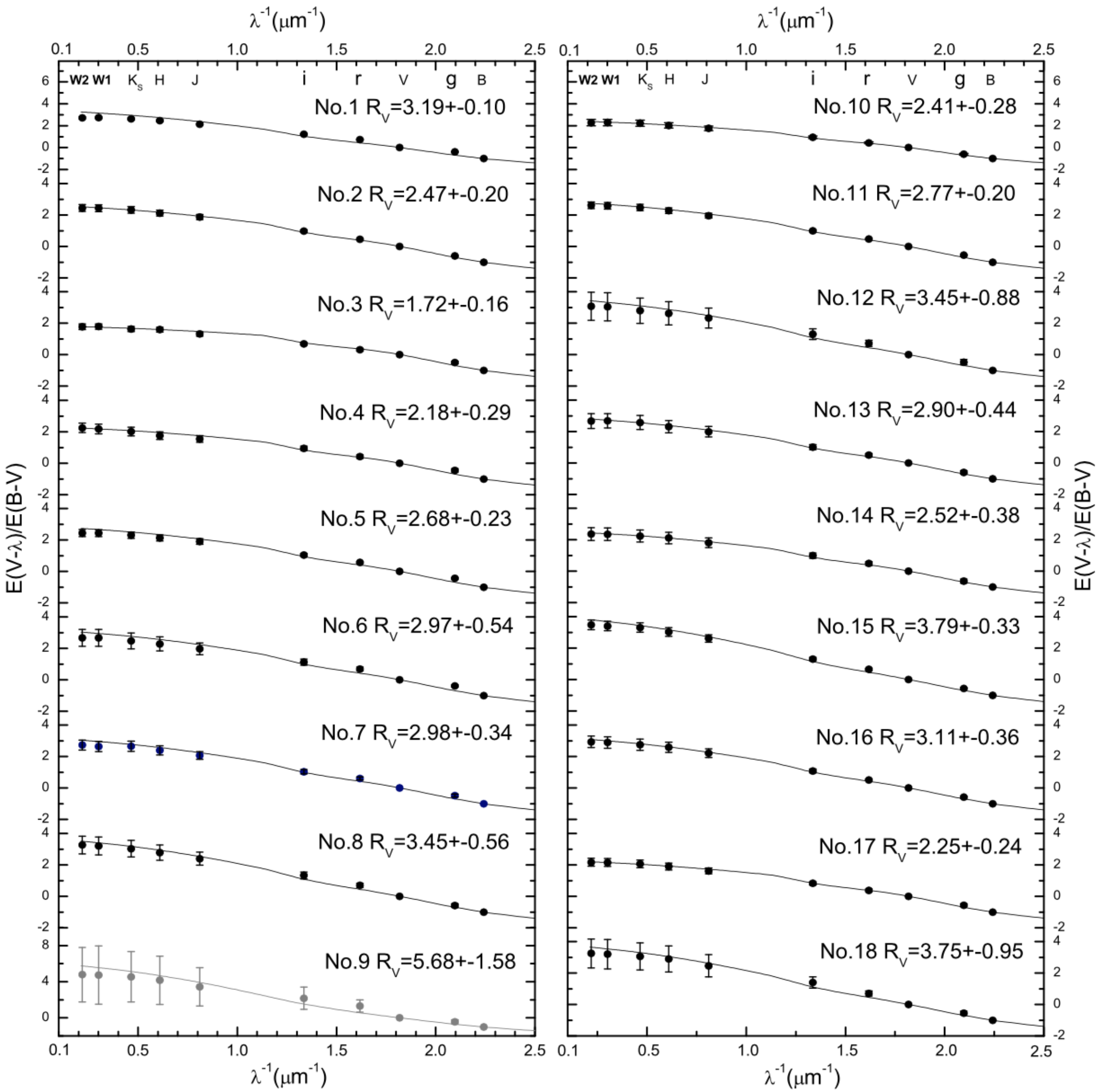

Fig. 4.— Multi-band extinction and corresponding R_V values for the 18 RC stars. Color excesses have been determined by adopting intrinsic colors based on the analytic T_{eff}–$C^0_{\lambda1\lambda2}$ relation. The black line is the best-fitting results based on using CCM89's equations. The error bar associated with the R_V values were derived based on 20,000 Monte-Carlo simulations.

Distances to the RC stars

- The variation in R_V is usually related to the interstellar environment, whether diffuse or dense.
- the sightlines in the l165◦ region are essentially diffuse, the extinction law still exhibits significant variation.

- the degree of diffusivity
  - distance
  - the specific extinction per kpc

- RC stars: standard candles
  - M_{Ks} with a weak dependence on metallicity
  - The derived distances range from 2.67 kpc to 4.49 kpc.

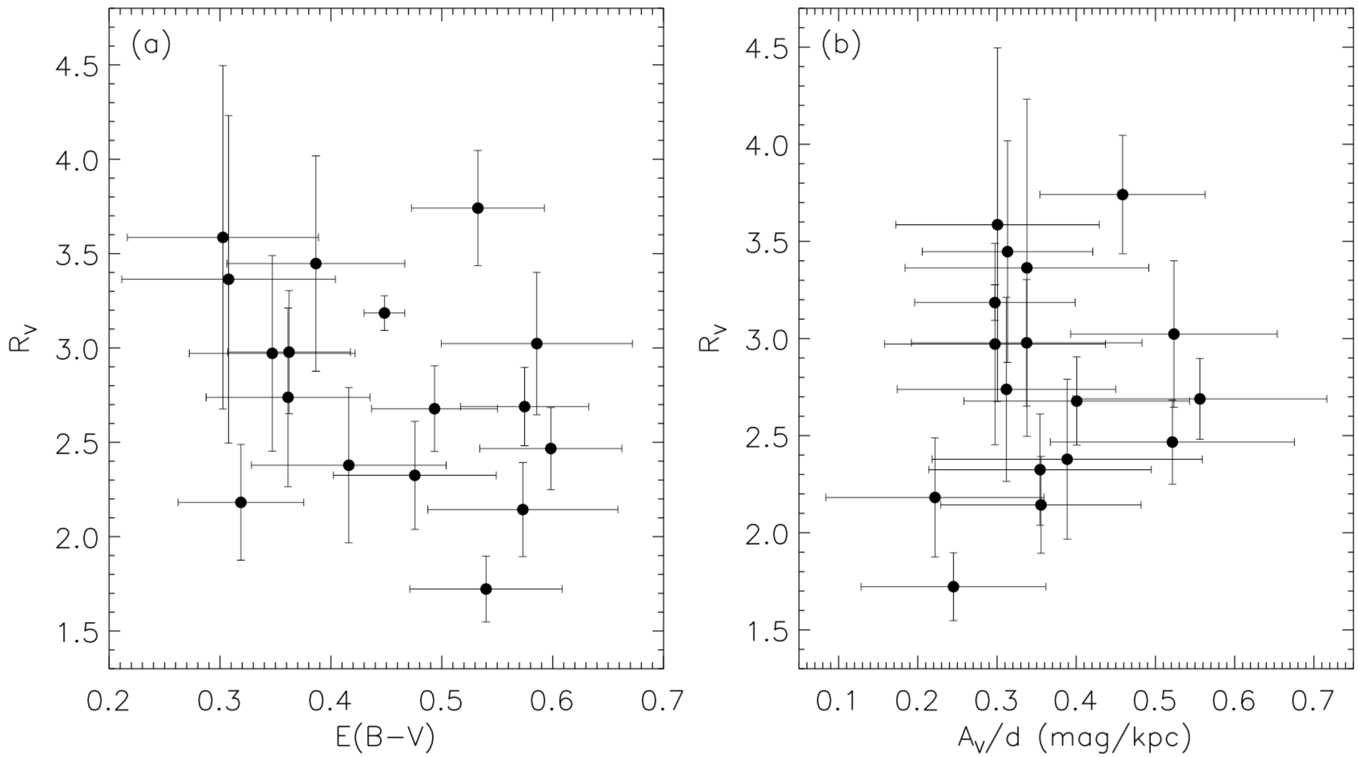

Fig. 6.— The distribution of reddening R_V with color excess E_{BV} (a) and with specific visual extinction per kiloparsec A_V/d (b) for the 17 RCs in $l165°$ region.

- The average specific extinction A_V/kpc is 0.37 mag kpc^{-1}
  - The highest one is ~ 0.56 mag kpc^{-1}
- the average rate of diffuse interstellar extinction: 0.7–1.0 mag kpc^{-1}
- There is no apparent trend for R_V with E(B − V) or A_V /d.

Summary

- The optical-to-mid-IR extinction law has been derived for the diffuse l165° region in *B*, *V*, *g*, *r*, *i*, *J*, *H*, *Ks*, *W1*, *W2* bands using RC stars as extinction tracers.
- Diversity of extinction law in the diffuse ISM
  - R_V values range from 1.7 to 3.8
    - > The lowest value is lower than the previously published lowest $R_V = 2.1$ in the Milky Way.
  - distances to RCs range from 2.67 kpc to 4.49 kpc
  - The average A_V /d is 0.37 mag kpc^{-1}
    - > lower than the average value for the Milky Way

Thank you