Properties of Interstellar Dust Responsible for Steep Extinction Curves toward Type Ia Supernovae

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Type Ia supernovae (SNe Ia) show remarkable homogenity in terms of their absolute magnitude and spectral energy distribution. As such, they are ideal objects not only for measuring the cosmic expansion as standard candles but also for extracting the extinction properties caused by interstellar dust in their host galaxies. It has been known, however, that the extinction curves observed for SNe Ia are very steep with unusually low total-to-selective extinction ratios of R_V = 1.0–2.5 [1], compared to the average value of R_V = 3.1 in the Milky Way (MW) [2]. The origin of such highly low R_V values casts challenging problems in modelling the nature and evolution of interstellar dust in external galaxies, which has been invoked as one of the critical issues for improving the current precision of cosmological parameters [3].

In order to reveal the properties of interstellar dust that causes steep extinction laws toward SNe Ia, we search for physical dust models that lead to good fits to the extinction curves obtained from the empirical formula (called the CCM formula) by Cardelli et al. (1989) [2] with R_V = 2.0, 1.5, and 1.0 [4]. In the fitting calculations, we apply a two-component dust model composed of graphite and silicate, and consider the power-law grain size distribution. For simplicity, we assume that graphite and silicate grains have the same size distribution, in which the important quantities to be assigned are the power-law index q, the maximum cut-off radius $a_{\max}$, and the graphite-to-silicate mass ratio $f_{\rm gs}$.

We find that the steep extinction curves with R_V = 2.0, 1.5, and 1.0 can be reasonably explained even by the simple power-law grain size distribution with a fixed index of $q = -3.5$ by taking the maximum cut-off radii of $a_{\max}$ = 0.13 μm, 0.094 μm, and 0.057 μm, respectively (Fig. 1). These maximum cut-off radii are smaller than $a_{\max} \simeq 0.25\,\mu$m considered valid in the MW [5,6], clearly demonstrating that the interstellar dust responsible for steep extinction curves is biased to smaller sizes. The mass ratios of graphite to silicate grains are in a narrow range of $f_{\rm gs}$ = 0.45–0.60, indicating that the chemical composition of interstellar dust is not changed dramatically for different R_V. This is the first study to quantitatively reveal the properties of interstellar dust that arises the steep extinction curves.

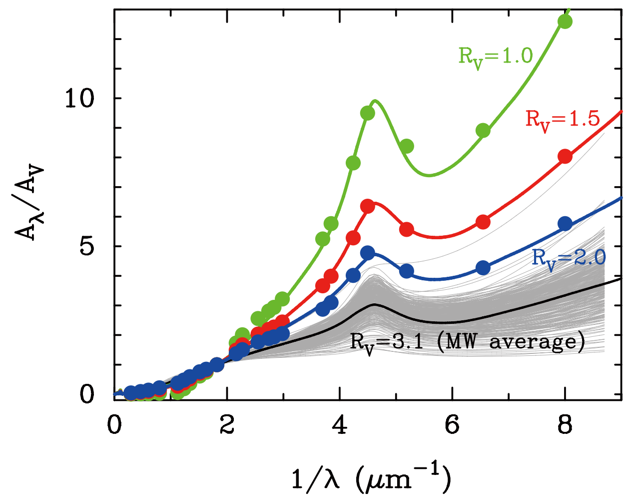

Figure 1: Extinction curves calculated from the best-fit values of $a_{\max}$ and $f_{\rm gs}$ for a two-component dust model following the power-law size distribution with an index of q = −3.5. The filled circles are the data of extinction at wavelengths of representative photometric bands from ultraviolet to near-infrared, derived from the CCM formula [2] for each R_V value. For reference, the average MW extinction curve (R_V = 3.1) is drawn by the black line, and the gray thin lines plot the extinction curves measured along a variety of lines of sight in our Galaxy [7]. The steep extinction curves with R_V = 1.0 (green), 1.5 (red), and 2.0 (blue) as suggested for SNe Ia can be nicely fitted by power-law grain size distributions with the maximum cut-off radii of $a_{\max}$ = 0.057 μm, 0.094 μm, and 0.13 μm, respectively, which indicates that the maximum cut-off radius is an important quantity to describe the variety of extinction curves.

References

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