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Wide-Field Variability Surveys: A 21st Century Perspective

Time-series surveys and pulsating stars: The near-infrared perspective

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Abstract. The purpose of this review is to discuss the advantages and problems of near-infrared surveys in observing pulsating stars in the Milky Way. One of the advantages of near-infrared surveys, when compared to optical counterparts, is that the interstellar extinction is significantly smaller. As we see in this review, a significant volume of the Galactic disk can be reached by infrared surveys but not by optical ones. Towards highly obscured regions in the Galactic mid-plane, however, the interstellar extinction causes serious problems even with near-infrared data in understanding the observational results. After a review on previous and current near-infrared surveys, we discuss the effects of the interstellar extinction in optical (including *Gaia*) to near-infrared broad bands based on a simple calculation using synthetic spectral energy distribution. We then review the recent results on classical Cepheids towards the Galactic center and the bulge, as a case study, to see the impact of the uncertainty in the extinction law. The extinction law, i.e. the wavelength dependency of the extinction, is not fully characterized, and its uncertainty makes it hard to make the correction. Its characterization is an urgent task in order to exploit the outcomes of ongoing large-scale surveys of pulsating stars, e.g. for drawing a map of pulsating stars across the Galactic disk.

1 Introduction

What we call "near-infrared" (hereafter near-IR) here is the wavelength range covered by the photometric bands of JHK. A broad and general review on the photometric bands is found in [3]. Note that the K band, at around 2 μm, has variations of filter transmission in different systems, and we mainly consider the $K_{\rm s}$ band which lacks the longest-λ part ($\lambda > 2.3$ μm) of the broader K in the following discussions. The wavelength around 3.5 μm will be called "mid-IR", partly because most important datasets in this range tend to be collected with space facilities rather than ground-based telescopes today, but we also discuss some results obtained in this mid-IR range. A review on studies in the shorter-λ (I-band and shorter) range is given by Soszyński in this volume ([93]).

There are mainly three advantages of IR data for observations of pulsating stars. First, they are less affected by interstellar extinction. At around 2 μm, for example, the extinction is around 10% of that at the optical V band ([10, 80]) or even smaller (~1/16, [72]). Secondly, some objects are enshrouded in circumstellar dust, so that they are only visible or bright in the IR ([95, 96]). IR data are crucial to study properties of such dust. Thirdly, we know pulsating stars tend to show simpler characteristics in

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the IR. In particular, the period-luminosity relation of Cepheids is known to be tight and less affected by metallicity. There has been a wealth of literature on its advantage (e.g., [5, 8, 35, 42, 89]). This is of great value for high precision cosmology ([81]) and for other applications.

The following five facilities have been actively used for observing pulsating stars in the IR: Infrared Survey Facility (IRSF) in South Africa, VISTA in Chile, *Hubble Space Telescope*, *Spitzer Space Telescope*, and CTIO 1.5-m telescope with CPAPIR camera. Catalogs from all-sky surveys like 2MASS[1] and WISE[2] are very conveniently used and naturally making a giant impact on studies of pulsating stars, but they are not discussed in this review.

- The 1.4-m telescope IRSF is working with SIRIUS near-IR camera in the SAAO Sutherland Observatory, South Africa ([69, 70]). Even with the moderate field-of-view, $7.7' \times 7.7'$, the efficiency of the three detectors taking simultaneous images in three bands (JHK_s) has been producing important catalogs of variable stars with color information for many stellar systems and regions: the Galactic center and bulge ([46, 47, 49, 51]), globular clusters ([45, 91]), the Magellanic Clouds ([36, 37]), and nearby dwarf galaxies ([21, 54, 56–59, 100, 101]). Some of these results will be discussed in more detail below.
- VISTA is a 4.1-m telescope in the ESO Cerro Paranal Observatory, Chile, and is working with a wide-field near-IR camera VIRCAM. The sixteen detectors, 67 million pixels effectively covering $\sim$0.6 deg^2, together with the relatively large telescope aperture have a very high survey ability ([94]). Among the six public surveys, two surveys are targeted at surveying pulsating stars: VISTA Variables in the Via Lactea (VVV, [60]) and VISTA survey of the Magallanic Clouds (VMC, [12]). See also Minniti et al. ([65]) and Cioni et al. ([15]) in these proceedings. While the comprehensive photometric catalog provided by the VVV has been used in many investigations about the Galactic bulge and disk ([9, 29, 30, 61, 87, 98]), its time-series data have led to new discoveries and insights into various pulsating stars like classical Cepheids ([11, 18, 19]) and RR Lyrs ([1, 17, 31, 32, 62–64]). VMC has been also providing very useful near-IR datasets for pulsating stars, classical Cepheids ([44, 68, 82, 84]), type II Cepheids ([83]), and RR Lyrs ([67]) as well as other topics such as star formation history in the Magellanic Clouds ([39, 85, 86]). In addition to time variations in brightness, both of the VVV and VMC surveys are providing proper motions ([13, 14, 33, 40]) which will be very useful to discuss the nature of variable stars and other populations. Besides the two large surveys, there is an important contribution (and will be more) from VISTA: McDonald et al. ([52, 53]) studied variable stars in the Sagittarius dwarf spheroidal galaxy.
- *Spitzer Space Telescope* is actively used to obtain important time-series datasets in the mid IR through some conspicuous projects. The Carnegie Chicago Hubble Program has been making a considerable effort on establishing the period-luminosity relation of Cepheids in the mid IR (see e.g. [25, 26, 88, 89]). The *Spitzer* Legacy Program "Surveying the Agents of a Galaxy's Evolution" (SAGE, [55]) and its related programs (SAGE-Var, in particular; [79]) collected a comprehensive dataset in the mid IR for pulsating stars and other objects in the Magellanic Clouds ([77–79]). In this proceedings book, Whitelock et al. ([102]) discuss mid-IR characteristics of large amplitude variables in the LMC and IC 1613 by combining the SAGE-Var data and other datasets.
- *Hubble Space Telescope (HST)* has been also producing important results on pulsating stars mainly for the purpose of cosmology and determining the H_0 constant in particular. While the *HST* Key Project to measure H_0 in the 1990s used optical data for detecting Cepheids in distant galaxies as much as possible ([24], and references therein), Riess and collaborators have been using near-IR data exclusively collected with an identical instrument to reduce the systematic uncertainties caused

[1]`http://irsa.ipac.caltech.edu/Missions/2mass.html`
[2]`http://irsa.ipac.caltech.edu/Missions/wise.html`

by the intrinsic characteristics of Cepheids like the metallicity effect on the period-luminosity relation and by the cross-instrument errors ([81]).

- The CPAPIR near-IR camera attached to the CTIO 1.5-m telescope was used to carry out the LMC Near-IR Synoptic Survey ([41]). Its good collection of time-series data for a wide area of the LMC has been producing important results on classical Cepheids and type II Cepheids ([4–7]).

It is clear that these surveys are providing us with useful data on pulsating stars. The IR surveys are particularly useful for exploring the large space of the Milky Way including the disk obscured by interstellar extinction, which is the main focus of the following discussions. When interesting and reddened objects are found in obscured regions, follow-up spectroscopy in the IR will be important. The demands for IR spectrographs will grow rapidly considering that a large number of pulsating stars and other objects are being found in IR surveys. APOGEE and its successor APOGEE-2 ([43]) together with other modern near-IR high-resolution spectrographs like GIANO ([74]) and WINERED ([34, 75]) will play important roles in collecting detailed information such as radial velocities and chemical abundances of pulsating stars, but this is beyond the scope of this review.

2 Expected limits of optical and near-IR surveys

In this section, we discuss limits of optical and near-IR surveys by calculating broad-band photometry with different extinction laws. We consider classical Cepheids and examine how far surveys can reach. Previous surveys of Cepheids are far from complete (see, e.g., Fig. 1 in [48]), which is mainly due to the interstellar extinction. Windmark et al. ([103]) predicted the total number and the distribution of Cepheids which can be detected in the *Gaia* survey. They obtained ∼20000 based on a simple exponential-disk model[3] and the local density. They also predicted about half of them will be detected by *Gaia* with the limiting magnitude of $G = 20$ mag. While *Gaia* will detect a large number of new Cepheids, such an optical survey is affected by the interstellar extinction and is limited up to several kpc along the Galactic plane. The accurate limit, however, depends on the extinction law as we see below.

In order to see the effects of the extinction on the broad-band photometry, we present results of integrating the spectral energy distribution after the extinction applied. This calculation is summarized as

$$m_\lambda = \int F_\lambda A_\lambda T_\lambda d\lambda, \tag{1}$$

where F_λ, A_λ, and T_λ indicate flux density, wavelength-dependent extinction function, and filter transmission, respectively. For F_λ, we adopt the synthetic spectrum[4] of the Sun whose effective temperature is within the range of Cepheids' temperatures. For comparing the effects of different extinction laws, we here consider a power law, $A_\lambda \propto \lambda^{-\alpha}$, with $\alpha = 2$, and the law of Cardelli ([10]). The former is close to the extinction law in Nishiyama et al. (2006, [71]), which we call the N06 law hereinafter, while the Cardelli law (henceforth C89) corresponds to a power law with $\alpha = 1.61$, significantly shallower than the N06 law. We consider the filters, V, G, J, H and K_s for T_λ. The transmission curves are taken from [3] for V, [38] for G, and the technical information on the SIRIUS camera for JHK_s. Figure 1 plots the SED with varying amounts of extinction, i.e. $F_\lambda A_\lambda$, from $A_{K_s} = 0$ to 10 mag, in addition to the filter transmission, T_λ. Note that in our calculation the integration of the SED is done after the λ-dependent extinction is applied.

[3]Such a simple exponential disk, see their prediction in Figure 5 of [103], is not consistent with the distribution of Cepheids we found as described in Section 3.

[4] The solar spectrum obtained by using the ATLAS9 code with the solar abundance in [2] was taken from `http://wwwuser.oats.inaf.it/castelli/sun.html`.

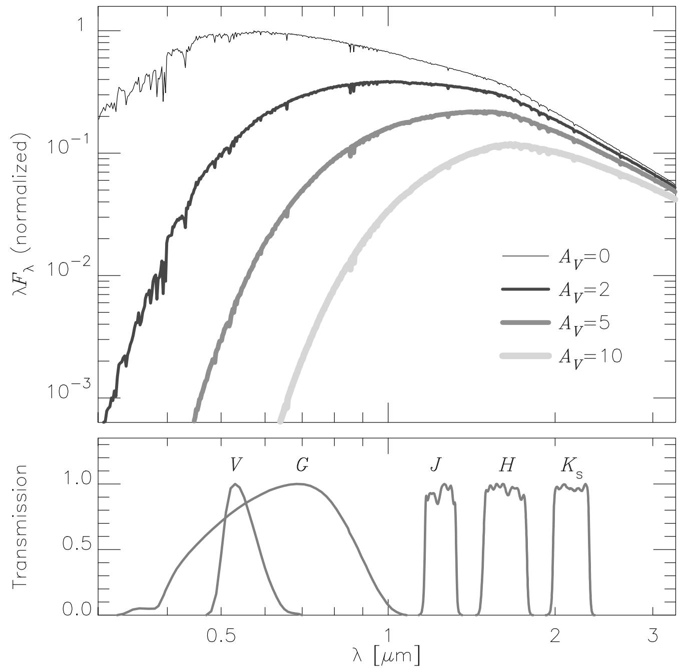

Figure 1. (Top) The synthetic spectrum of the Sun based on ATLAS9 by Kurucz and Castelli and those affected by the power law extinction, $\sim \lambda^{-2}$. (Bottom) Filter transmission curves, normalized to the peak of each bandpass.

Figure 2 plots the extinctions in V and *Gaia*'s G bands against that in K_s. For example, A_V/A_{K_s} is around 14 with the N06 law (almost consistent with the result in [72], ~16) and around 8 with the C89 law. The extinction in G is clearly smaller than that in V. *Gaia* can reach relatively deeper than previous V-band surveys in obscured regions of the Milky Way. Furthermore, the curves for A_G/A_{K_s} in Figure 2 get shallower towards the larger A_{K_s}. This is because the G band is broad and the effective wavelength changes with increasing the amount of extinction. The central wavelengths of G and V bands are 0.673 and 0.551 μm respectively ([38]). The SED affected by a large extinction, however, keeps more photons in the longer wavelength part of the G band, as illustrated in Figure 1, so that the sensitivity to the extinction gets closer to that of a photometric band at for a longer-λ range. This leads to an even larger difference between A_V/A_{K_s} and A_G/A_{K_s} at a larger A_{K_s}; at around $A_{K_s} = 2.5$ mag, A_G gets nearly half of the corresponding A_V.

2.1 How deep will *Gaia* and optical surveys be able to reach?

Figure 3 plots the maximum extinction that can be reached with a given magnitude in each photometric band as a function of distance. The limiting magnitudes of $G = 20$, $V = 20$, $H = 15$, and $K_s = 14$ mag are adopted as an example. The interstellar extinction varies from one line of sight to another, and we here consider two cases: the three-dimensional extinction map towards the bulge taken from [90] and a moderate increase of extinction at the rate of 0.1 mag/kpc. With the N06 law adopted (indicated by the gray filled curve), the *Gaia*'s limiting magnitude ([99]) allows one to detect Cepheids with $A_{K_s} \sim 1.2$ mag at ~6.5 kpc towards the bulge or at over 10 kpc in the latter case of the moderate

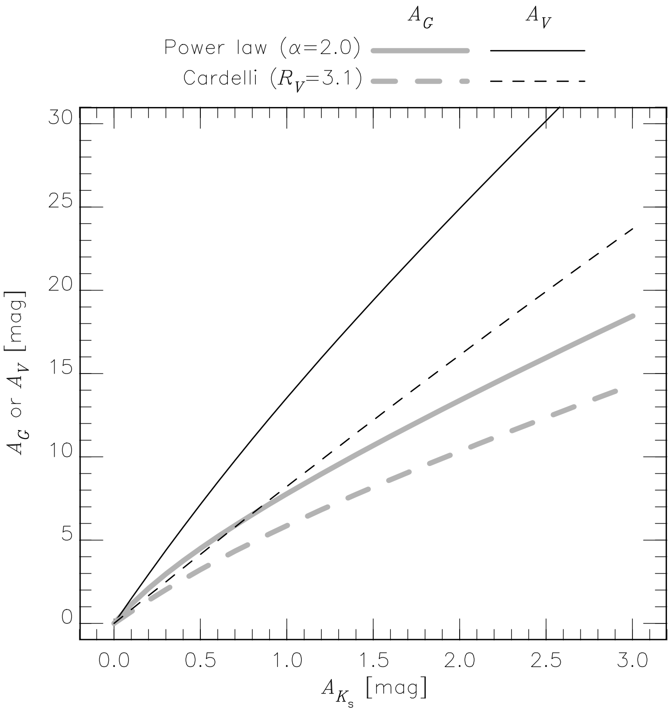

Figure 2. The optical extinctions, A_G (gray) and A_V (black), are plotted against A_{K_s}. The filled curves are obtained for the power law with $\alpha = 2$ while the dashed curves for the Cardelli law with $R_V = 3.1$ as indicated in the legend.

extinction. These limits are significantly deeper than a *V*-band survey. If the extinction law were closer to the C89 law, the limits would be even deeper, but at least towards the bulge the N06 law is considered to be more likely ([72]). Towards less obscured regions, *Gaia* and some other optical surveys can see to larger distances. The sensitivity of *Gaia* and more importantly its all-sky coverage will extend the frontier of the variability survey. Other current and future optical surveys will also make important contributions to finding new variables and exploring their population in the wide range of the Milky Way. For example, Feast et al. ([22]) identified classical Cepheids, among OGLE-III Cepheids ([92]), which are located in the flared part of the Galactic disk beyond the bulge. These objects are slightly off the Galactic mid-plane ($2° < |b| < 5°$). The extinctions of these objects, 0.17–0.57 mag, at the distances of 22–30 kpc correspond to roughly 0.01 mag/kpc but with a scatter of 50%. The OGLE-IV survey for the Galactic disk has actually revealed a rich population of Cepheids in the southern hemisphere as presented by Udalski et al. in this volume ([97]). In their maps, however, newly found Cepheids and RR Lyrs have patchy distributions which clearly shows the limit of optical surveys and the needs of IR surveys.

2.2 How deep can near-IR surveys reach?

Even with the moderate limiting magnitudes, *H*- and K_s-band surveys can reach significantly further than 10 kpc except through thick molecular clouds. The extinctions of objects towards the Galactic

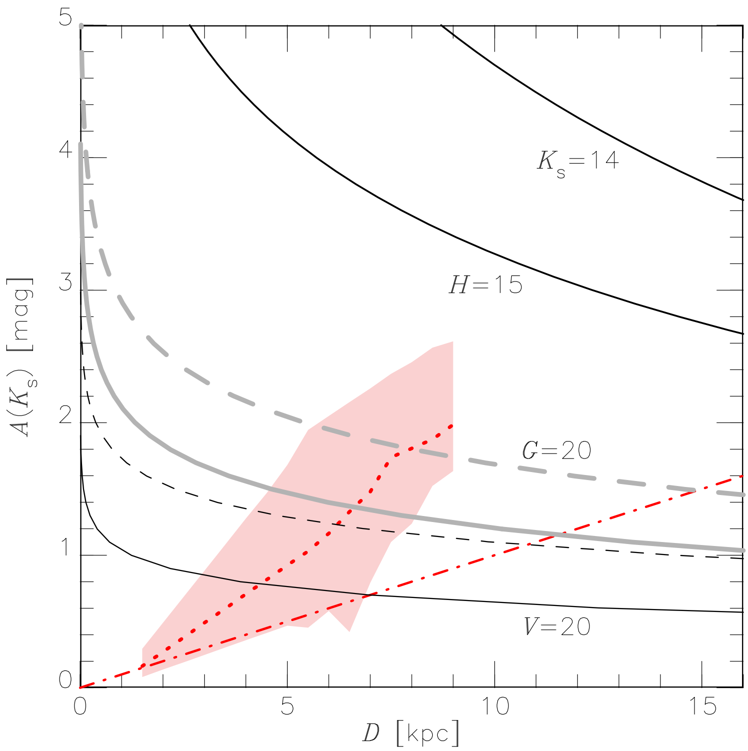

Figure 3. The maximum extinction, A_{K_s}, with which a Cepheid with P = 10 days can be detected with a given limiting magnitude. The limiting magnitudes are given within the figure, while a Cepheid with P = 10 days has absolute magnitudes of −4, −4, −5.6, and −5.7 mag in $VGHK_s$ bands, respectively. For V and G, the same styles are used as in Figure 2: filled curves when the power law with α = 2 is used and dashed curves with the Cardelli law used. Only the power law is used for the H and K_s bands. The red dotted curve and the shaded area illustrate the three-dimensional extinction map by [90] towards the bulge (see also Fig. 3 of [51]), while the dashed-dotted line indicates the extinction increasing at the rate of 0.1 mag/kpc.

center are ~2.5 mag in A_{K_s}, which makes it impossible to detect them in the optical ranges. The *Gaia* all-sky map, accompanying its first data release, clearly shows the dark lane caused by the disk extinction (Fig. 2 in [27]). The Galactic plane within 1 deg tends to have the extinctions around 1 mag in A_{K_s} or stronger ([20, 90]) and thus near-IR surveys are more effective than optical surveys at around 5 kpc and further. As mentioned in the Introduction, some results from near-IR surveys carried out with IRSF and VISTA have already demonstrated that many obscured variables can be found in a large space of the Galactic mid-plane. Such surveys seeing through the Galactic plane is necessary, in particular, to study the thin disk component; the Galactic latitude of 1 deg corresponds to the distance of 140 pc from the plane at the distance of 8 kpc. It is difficult to predict how much we can ultimately see through the entire range of the disk. Towards the Galactic center and bulge, for example, if the same amount of extinction needs to be overcome on the opposite side of the disk, we would expect an extinction of $A_{K_s} \sim 5$ mag. It is possible to observe such reddened objects if they are intrinsically bright, although thick molecular clouds may well interrupt the lines of sight to prevent us from reaching to the opposite end even in the IR.

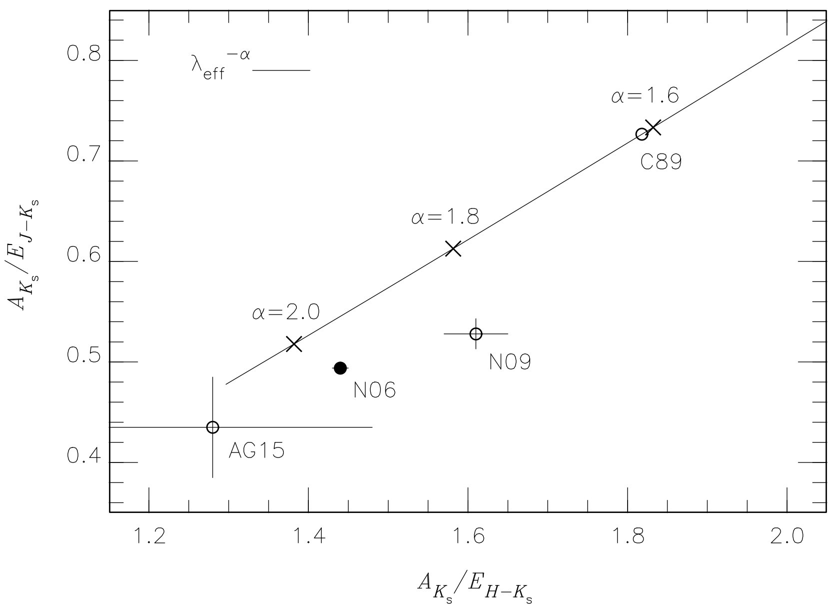

Figure 4. Comparison of the extinction coefficients, A_{K_s}/E_{J-K_s} and A_{K_s}/E_{H-K_s}. The straight line gives the relation between the two coefficients with varying power α as indicated by crosses. The points with the labels of AG15, C89, N06, and N09 indicate the values obtained by [1], [10], [71], and [73], respectively. The C89 law corresponds to the power law with $\alpha = 1.61$.

3 Impact of the uncertainty in the extinction law

The near-IR surveys will open our path to the obscured regions of the Milky Way as we discussed in the previous section, but the interstellar extinction still poses a serious problem with interpreting observational data we'll obtain. For many applications, we need to make corrections of the extinction and reddening, and this requires using a proper law of extinction. When we combine H- and K_s-band data with the period-luminosity relation of Cepheids to estimate the distances and foreground extinctions, for example, we need to derive the amount of extinction, A_{K_s}, considering an extinction coefficient, A_{K_s}/E_{H-K_s}, and the reddening, $E_{H-K_s} = (H - K_s) - (M_H - M_{K_s})$, where M_H and M_{K_s} are predicted by the period-luminosity relation[5]. Figure 4 plots some extinction coefficients in the near IR in the literature and shows a large scatter among them. Figure 5 illustrates how the different extinction laws (N06 and C89) give different reddening vectors on the color-magnitude diagram (left) and the color-color diagram (right). For example, a reddening of $E_{H-K_s} = 1.5$ mag would give $A_{K_s} = 2.16$ and 2.73 mag with the N06 and C89 laws, respectively. The differences in the extinction laws thus introduce large uncertainties in estimating distances of such reddened objects (the reddenings of stars at around the Galactic center are around 1.5–2 mag in E_{H-K_s}). On the other hand, Figure 5 also indicates that the reddening vector on the color-color diagram is relatively insensitive to the difference in the extinction law; the N06 and C89 laws would predict different $(H - K_s,\ J - H)$ by only ~0.2 mag for the stars at around the Galactic center.

[5]When one uses the relation of a Wesenheit index, e.g. $W_{K_s} = K_s - \alpha(H - K_s)$, which is often considered as a reddening-free index, it is still necessary to decide the coefficient α properly in order to make this index reddening free.

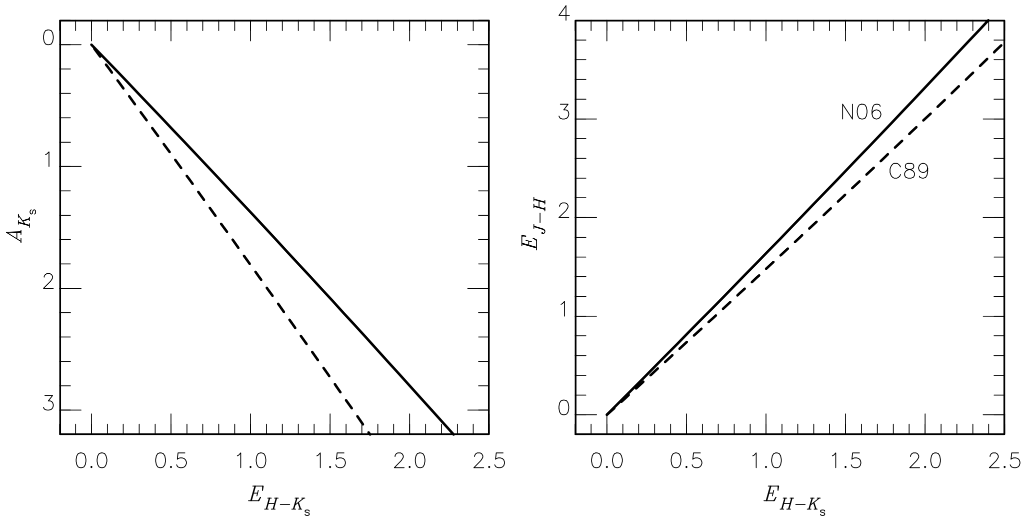

Figure 5. Reddening vectors according to the extinction laws of C89 ([10], dashed) and N06 ([71], solid) on the color-magnitude diagram (left) and the color-color diagram (right).

A good example of the impact of the extinction law is found and discussed in [51]. Dékány et al. ([19]) reported a few dozens of classical Cepheids towards the Galactic bulge and concluded that they form a thin disk surrounding the Galactic center. Matsunaga et al. ([51]), however, reported their discoveries of classical Cepheids which are located behind the bulge and concluded that the region around the Galactic center lacks classical Cepheids. Some of the Cepheids are common in the two works, but they obtained significantly different distances for the Cepheids, $\Delta\mu_0 = 0.4$–0.5 mag. Matsunaga et al. ([51]) found that such a large difference was caused because two different extinction laws were used: the N06 law in [51] and the N09 law from Nishiyama et al. (2009, [73]) in [19]. The A_{K_s}/E_{H-K_s} in the N06 and N09 laws are 1.44 and 1.61 (Fig. 4), respectively, and these led to offsets of ~0.3 mag and the significantly different conclusions on the distribution of the Cepheids.

Readers are referred to [51] for details, but we here outline how the extinction law towards the Galactic bulge can be constrained together with adding a new plot which supports our conclusion. An important group of Cepheids are four classical Cepheids which belong to the nuclear stellar disk (NSD, henceforth). The NSD is a disk-like system around the Galactic center, with a radius of about 200 pc. This region is also known as the Central Molecular Zone (CMZ). Unlike the more extended bulge, this region is known to host young stars like the famous massive clusters Arches and Quintuplet, and those young stars are rotating within this disk. We can conclude that the four Cepheids belong to the NSD for a few reasons: the projected distances, similarity in the physical parameters of Cepheids, the fact that their distances must be similar independent of the adopted extinction law, and that their radial velocities are consistent with the rotation of the NSD. These strongly indicate that their distances should agree with that of the Galactic center ($R_0 = 8.0 \pm 0.5$ kpc, [16, 28]) within the size of the NSD (~0.2 kpc). Note that some estimates of R_0, e.g. the orbit modeling of the S stars around the central black hole ([28]), are independent of the extinction law. As illustrated in the left panel of Figure 6, A_{K_s}/E_{H-K_s} should be around 1.44, rather than 1.61, in order to keep the four Cepheids at around 8 kpc. Note that, with the period-luminosity relations and observed magnitudes given, the location of each Cepheid on this diagram doesn't depend on the adopted extinction law or its distances. The four

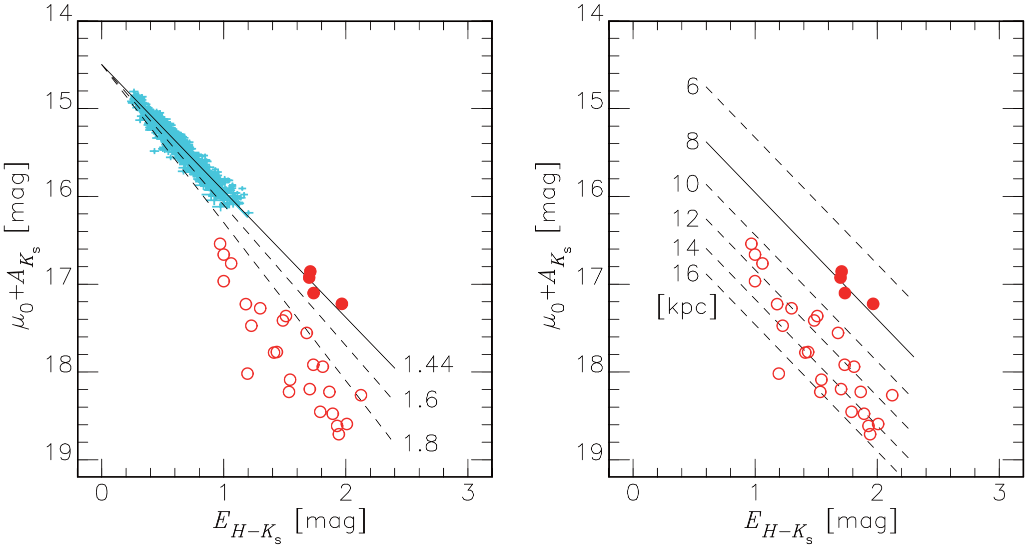

Figure 6. (Left) Reddening vectors on the color-magnitude diagram with different coefficients of A_{K_s}/E_{H-K_s} starting from the distance of the Galactic center, 8 kpc, at the zero color excess, $E_{H-K_s} = 0$ mag. The sequence of cyan points near the top-left corner, taken from N06 [71], indicates the red clump peaks affected by various amounts of reddening. Filled circles indicate the four classical Cepheids in the nuclear stellar disk ([47, 50]), and open circles indicate the other classical Cepheids reported in [51]. (Right) Same as the left panel, but lines have the slope of $A_{K_s}/E_{H-K_s} = 1.44$ and correspond to different distances from 6 to 16 kpc.

NSD Cepheids are precisely on the extension of Nishiyama's fit to the red clumps. Assuming that the Cepheids and the red clumps are at the same distance, this strongly supports the extinction value of 1.44. Once the coefficient of 1.44 is adopted, the distances of other Cepheids can be determined as one can see on the right panel of Figure 6. The vertical offset in this panel corresponds to the offset in distance. Other Cepheids are located significantly further than the Galactic Center, showing the gap between the NSD (marked down by the four Cepheids) and the inner edge of the distribution of disk Cepheids. Also, we found no Cepheids on the nearer side, which supports the absence of Cepheids around the Galactic Center; the saturation limit of our survey could have allowed us to detect Cepheids between ∼5 and 8 kpc from the Sun if the density were high enough. These support our conclusion on the lack of Cepheids within 2.5 kpc around the Galactic center except the NSD. More details are given in the original paper ([51]) as mentioned above, and some remarks are also found in the conference summary for this conference ([23]).

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References

[1] Alonso-García, J., Dékány, I., Catelan, M., Contreras Ramos, R., Gran, F., Amigo, P., Leyton, P., & Minniti, D., AJ, **149**, 99 (2015)

[2] Asplund, M., Grevesse, N., & Sauval, A. J., ASPC, **336**, 25 (2005)

[3] Bessell, M. S., ARA&A, **43**, 293 (2005)
[4] Bhardwaj, A., Kanbur, S. M., Singh, H. P., Macri, L. M., & Ngeow, C.-C., AJ, **447**, 3342 (2015)
[5] Bhardwaj, A., Kanbur, S. M., Macri, L. M., Singh, H. P., Ngeow, C.-C., Wagner-Kaiser, R., & Sarajedini, A., AJ, **151**, 88 (2016a)
[6] Bhardwaj, A., Kanbur, S. M., Macri, L. M., Singh, H. P., Ngeow, C.-C., & Ishida, E. E. O., MNRAS, **457**, 1644 (2016b)
[7] Bhardwaj, A., Macri, L. M., Rejkuba, M., Kanbur, S. M., Ngeow, C.-C., & Singh, H. P., AJ, **153**, 154 (2017)
[8] Bono, G., Caputo, F., Marconi, M., & Musella, I., ApJ, **715**, 277 (2010)
[9] Borissova, J., Chené, A.-N., Ramírez Alegría, S., et al., A&A, **569**, A24 (2014)
[10] Cardelli, J. A., Clayton, G. C., & Mathis, J. S., ApJ, **345**, 245 (1989)
[11] Chen, X., de Grijs, R., & Deng, L., MNRAS, **464**, 1119 (2017)
[12] Cioni, M.-R. L., Clementini, G., Girardi, L., et al., A&A, **527**, A116 (2011)
[13] Cioni, M.-R. L., Girardi, L., Moretti, M. I., et al., A&A, **562**, A32 (2014)
[14] Cioni, M.-R. L., Bekki, K., Girardi, L., et al., A&A, **586**, A77 (2016)
[15] Cioni, M. R.,L., these proceedings (`arXiv:1703.06769`) (2017)
[16] de Grijs, R., & Bono, G., ApJ, **227**, 5 (2016)
[17] Dékány, I., Minniti, D., Catelan, M., Zoccali, M., Saito, R. K., Hempel, M., & Gonzalez, O. A., ApJL, **776**, L19 (2013)
[18] Dékány, I., Minniti, D., Majaess, D., et al., ApJL, **812**, L29 (2015a)
[19] Dékány, I., Minniti, D., Hajdu, G., et al., ApJL, **799**, L11 (2015b)
[20] Dutra, C. M., Santiago, B. X., Bica, E. L. D., & Barbuy, B., MNRAS, **338**, 253 (2003)
[21] Feast, M. W., Whitelock, P. A., Menzies, J. W., & Matsunaga, N., MNRAS, **421**, 2998 (2012)
[22] Feast, M. W., Menzies, J. W., Matsunaga, N., & Whitelock, P. A., Nature, **509**, 342 (2014)
[23] Feast, M. W., these proceedings (`arXiv:1702.07147`) (2017)
[24] Freedman, W. L., Madore, B. F., Gibson, B. K., et al., ApJ, **553**, 47 (2001)
[25] Freedman, W. L., Madore, B. F., Scowcroft, V., et al., AJ, **142**, 192 (2011)
[26] Freedman, W. L., Madore, B. F., Scowcroft, V., Burns, C., Monson, A., Persson, S. E., Seibert, M., & Rigby, J., ApJ, **758**, 24 (2012)
[27] Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al., A&A, **595**, A2 (2016)
[28] Gillessen, S., Eisenhauer, F., Fritz, T. K., Pfuhl, O., Ott, T., & Genzel, R., IAUS, **289**, 29 (2013)
[29] Gonzalez, O. A., Rejkuba, M., Zoccali, M., Valenti, E., Minniti, D., & Tobar, R., A&A, **552**, A110 (2012)
[30] González-Fernández, C., Asensio Ramos, A., Garzón, F., Cabrera-Lavers, A., & Hammersley, P. L., ApJ, **782**, 86 (2012)
[31] Gran, F., Minniti, D., Saito, R. K., Navarrete, C., Dékány, I., McDonald, I., Contreras Ramos, R., & Catelen, M., A&A, **575**, A114 (2015)
[32] Gran, F., Minniti, D., Saito, R. K., et al., A&A, **591**, A145 (2016)
[33] Gromadzki, M., Kurtev, R., Geamín, J. C., et al., AcA, **66**, 293 (2016)
[34] Ikeda, Y., Kobayashi, N., Kondo, S., et al., Proc. SPIE, **9908**, 5 (2016)
[35] Inno, L., Matsunaga, N., Bono, G., et al., ApJ, **764**, 84 (2013)
[36] Ita, Y., Tanabé, T., Matsunaga, N., et al., MNRAS, **347**, 720 (2004a)
[37] Ita, Y., Tanabé, T., Matsunaga, N., et al., MNRAS, **353**, 705 (2004b)
[38] Jordi, C., Gebran, M., Carrasco, J. M., et al., A&A, **523**, A48 (2010)
[39] Kerber, L. O., Girardi, L., Rubele, S., & Cioni, M. R. L., A&A, **499**, 697 (2009)

[40] Kurtev, R., Gromadzki, M., Beamín, J. C., et al., MNRAS, **464**, 1247 (2017)
[41] Macri, L. M., Ngeow, C.-C., Kanbur, S. M., Mahzooni, S., & Smitka, M. T., AJ, **149**, 117 (2015)
[42] Madore, B. F., & Freedman, W. L., PASP, **103**, 933 (1991)
[43] Majewski, S. R., APOGEE Team, & APOGEE-2 Team, AN, **337**, 863 (2016)
[44] Marconi, M., Molinaro, R., Ripepi, V., et al., MNRAS, **466**, 3206 (2017)
[45] Matsunaga, N., Fukushi, H., Nakada, Y., et al., MNRAS, **370**, 1979 (2006)
[46] Matsunaga, N., Kawadu, T., Nishiyama, S., Nagayama, T., Hatano, H., Tamura, M., Glass, I. S., & Nagata, T., MNRAS, **399**, 1709 (2009)
[47] Matsunaga, N., Kawadu, T., Nishiyama, S., et al., Nature, **188**, 477 (2011)
[48] Matsunaga, N., Journal of Physics: Conference Series, **372**, 12026 (2012)
[49] Matsunaga, N., Feast, M. W., Kawadu, T., et al., MNRAS, **429**, 385 (2013)
[50] Matsunaga, N., Fukue, K., Yamamoto, R., et al., ApJ, **799**, 46 (2015)
[51] Matsunaga, N., Feast, M. W., Bono, G., et al., MNRAS, **462**, 414 (2016)
[52] McDonald, I., Zijlstra, A. A., Sloan, G. C., et al., MNRAS, **436**, 413 (2013)
[53] McDonald, I., Zijlstra, A. A., Sloan, G. C., Kerins, E., Lagadec, E., & Minniti, D., MNRAS, **439**, 2618 (2014)
[55] Meixner, M., Gordon, K. D., Indebetouw, R., et al., AJ, **132**, 2268 (2006)
[54] Menzies, J. W., Feast, M. W., Tanabé, T., Whitelock, P. A., & Nakada, Y., MNRAS, **335**, 923 (2002)
[56] Menzies, J. W., Feast, M. W., Whitelock, P. A., Olivier, E., Matsunaga, N., & Da Costa, G., MNRAS, **385**, 1045 (2008)
[57] Menzies, J. W., Whitelock, P. A., Feast, M. W., & Matsunaga, N., MNRAS, **406**, 86 (2010)
[58] Menzies, J. W., Feast, M. W., Whitelock, P. A., & Matsunaga, N., MNRAS, **414**, 3492 (2011)
[59] Menzies, J. W., Whitelock, P. A., & Feast, M. W., MNRAS, **452**, 910 (2015)
[60] Minniti, D., Lucas, P. W., Emerson, J. P., et al., New Astronomy, **15**, 433 (2010)
[61] Minniti, D., Saito, R. K., Alonso-García, J., Lucas, P. W., & Hempel, M., ApJL, **733**, L43 (2011)
[62] Minniti, D., Contreras Ramos, R., Zoccali, M., Rejkuba, M., Gonzalez, O. A., Valenti, E., & Gran, F., ApJL, **830**, L14 (2016)
[63] Minniti, D., Palma, T., Dékány, I., et al., ApJL, **838**, L14 (2017a)
[64] Minniti, D., Dékány, I., Majaess, D., et al., AJ, **153**, 179 (2017b)
[65] Minniti, D., these proceedings (2017)
[66] Monson, A. J., Freedman, W. L., Madore, B. F., Persson, S. E., Scowcroft, V., Seibert, M., & Rigby, J. R., ApJ, **759**, 146 (2012)
[67] Moretti, M. I., Clementini, G., Muraveva, T., et al., MNRAS, **437**, 2702 (2014)
[68] Moretti, M. I., Clementini, G., Ripepi, V., et al., MNRAS, **459**, 1687 (2016)
[69] Nagashima, C., Nagayama, T., Nakajima, Y., et al., Proc. "Star Formation 1999", 397 (1999)
[70] Nagayama, T., Nagashima, C., Nakajima, Y., et al., Proc. SPIE, **4841**, 459 (2003)
[71] Nishiyama, S., Nagata, T., Kusakabe, N., et al., ApJ, **638**, 839 (2006)
[72] Nishiyama, S., Nagata, T., Tamura, M., Kandori, R., Hatano, H., Sato, S., & Sugitani, K., ApJ, **680**, 1174 (2008)
[73] Nishiyama, S., Tamura, M., Hatano, H., Kato, D., Tanabé, T., Sugitani, K., & Nagata, T., ApJ, **696**, 1407 (2009)
[74] Origlia, L, Oliva, E., Baffa, C., et al., Proc. SPIE, **9147** , 1 (2014)
[75] Otsubo, S., Ikeda, Y., Kobayashi, N., et al., Proc. SPIE, **9908**, 79 (2016)

[76] Palma, T., Minniti, D., Dékány, I., Clariá, J. J., Alonso-García, J., Gramajo, L. V., Ramírez Alegría, S., & Bonatto, C., New Astronomy, **424**, 1807 (2012)
[77] Polsdofer, E., Seale, J., Sewilo, M., Vijh, U. P., Meixner, M., Marengo, M., & Terrazas, M., AJ, **149**, 78 (2015)
[78] Riebel, D., Meixner, M., Fraser, O., Srinivasan, S., Cook, K., & Vijh, U., ApJ, **723**, 1195 (2010)
[79] Riebel, D., Boyer, M. L., Srinivasan, S., et al., 2015, ApJ, **807**, 1 (2015)
[80] Rieke, G. H., & Lebofsky, M. J., ApJ, **288**, 618 (1985)
[81] Riess, A. G., Macri, L. M., Hoffmann, S. L., et al., ApJ, **826**, 56 (2016)
[82] Ripepi, V., Moretti, M. I., Marconi, M., et al., MNRAS, **424**, 1807 (2012)
[83] Ripepi, V., Moretti, M. I., Marconi, M., et al., MNRAS, **446**, 3034 (2015)
[84] Ripepi, V., Marconi, M., Moretti, M. I., et al., ApJS, **224**, 21 (2016)
[85] Rubele, S., Kerber, L., Girardi, L., et al., A&A, **537**, A106 (2012)
[86] Rubele, S., Girardi, L., Kerber, L., et al., MNRAS, **449**, 639 (2015)
[87] Saito, R. K., Zoccali, M., McWilliam, A., Minniti, D., Gonzalez, O. A., & Hill, V., AJ, **142**, 76 (2011)
[88] Scowcroft, V., Freedman, W. L., Madore, B. F., Monson, A. J., Persson, S. E., Seibert, M., Rigby, J. R., & Melbourne, J., ApJ, **773**, 106 (2013)
[89] Scowcroft, V., Seibert, M., Freedman, W. L., Beaton, R. L., Madore, B. F., Monson, A. J., Rich, J. A., & Rigby, J. R., MNRAS, **459**, 1170 (2016)
[90] Schultheis, M., Chen, B. Q., Jiang, B. W., et al., A&A, **566**, A120 (2014)
[91] Sloan, G. C., Matsunaga, N., Matsuura, M., et al., ApJ, **719**, 1274 (2010)
[92] Soszyński, I., Udalski, A., Pietrukowicz, P., et al., AcA, **61**, 285 (2011)
[93] Soszyński, I., these proceedings (2017)
[94] Sutherland, W., Emerson, J., Dalton, G., et al., A&A, **575**, A25 (2015)
[95] Tanabé, T., Nishida, S., Matsunaga, S., et al., Nature, **385**, 509 (1997)
[96] Tanabé, T., Kučinskas, A., Nakada, Y., Onaka, T., & Sauvage, M., ApJS, **155**, 401 (2004)
[97] Udalski, A., these proceedings (`arXiv:1703.02980`) (2017)
[98] Valenti, E., Zoccali, M., Gonzalez, O. A., et al., A&A, **587**, L6 (2016)
[99] van Leeuwen, F., Evans, D. W., De Angeli, F., et al. A&A, **599**, A32 (2017)
[100] Whitelock, P. A., Menzies, J. W., Feast, M. W., Matsunaga, N., Tanabé, T., & Ita, Y., MNRAS, **394**, 795 (2009)
[101] Whitelock, P. A., Menzies, J. W., Feast, M. W., Nsengiyumva, F., & Matsunaga, N., MNRAS, **428**, 2216 (2013)
[102] Whitelock, P. A., Kasiwal, M., & Boyer, M., these proceedings (`arXiv:1702.06797`) (2017)
[103] Windmark, F., Lindegren, L., & Hobbs, D., A&A, **530**, A76 (2011)