Dust extinction map of the Galactic plane based on the VVV survey data

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ABSTRACT

Dust extinction is one of the most reliable tracers of the gas distribution in the Milky Way. The near-infrared (NIR) Vista Variables in the Vía Láctea (VVV) survey enables extinction mapping based on stellar photometry over a large area in the Galactic plane. We devise a novel extinction mapping approach, XPNICER, by bringing together VVV photometric catalogs, stellar parameter data from StarHorse catalogs, and previously published Xpercentile and PNICER extinction mapping techniques. We apply the approach to the VVV survey area, resulting in an extinction map that covers the Galactic disk between $295^\circ \lesssim l \lesssim 350^\circ$ and $-2^\circ \lesssim b \lesssim 2^\circ$, and the Galactic bulge between $-10^\circ \lesssim b \lesssim 5^\circ$. The map has 30$''$ spatial resolution and it traces extinctions typically up to $A_V \sim 10-20$ mag and maximally up to $A_V \sim 30$ mag. We compare our map to previous dust based maps, concluding that it provides a high-fidelity extinction-based map, especially in its ability to recover both the diffuse dust component of the Galaxy and moderately extincted giant molecular cloud regions. The map is especially useful as independent, extinction-based data on the Galactic dust distribution and applicable for a wide range of studies from individual molecular clouds to the studies of the Galactic stellar populations.

Key words: dust, extinction – infrared: ISM – infrared: stars – Galaxy: structure

1 INTRODUCTION

Dust is a crucial component of the interstellar medium (ISM), important as a tracer of the Galactic ISM, a diagnostic tool of the physical properties of the ISM, and as a foreground for extragalactic observations. The spatial distribution of the Galactic dust has been mapped using thermal dust emission with many datasets (Schlegel et al. 1998; Planck Collaboration et al. 2014b; Marsh et al. 2017). For example, Schlegel et al. (1998, SFD hereafter) presented a full-sky reddening map with the spatial resolution of $\sim 6'$ using the Cosmic Background Explorer (COBE, Boggess et al. 1992) and the Infrared Astronomical Satellite (IRAS, Neugebauer et al. 1984) emission maps. The SFD map is currently the most widely-used large-scale dust reddening map. However, converting thermal dust emission to dust column density requires assumptions about both the dust emissivity and the line-of-sight dust temperature distribution (Draine 2009; Padoan et al. 2014) that usually have large uncertainties due to the lack of detailed information about dust properties (Ossenkopf & Henning 1994).

Another commonly-used dust mapping technique is measuring the reddening and extinction towards a large number of stellar objects, which is then treated as a discrete sampling of a continuous dust distribution. The extinction towards an individual star can be obtained by comparing its observed spectral energy distribution (SED) to intrinsic SED (Lada et al. 1994), which, in principle, requires detailed stellar spectroscopic information, but does not depend on the assumptions about dust temperature and properties. Therefore, dust extinction can be more reliable probe of column density compared to thermal dust emission and gas tracers such as $^{13}$CO (Goodman et al. 2009).

In the optical regime, a large number of works (Green et al. 2014; Andrae et al. 2018; Anders et al. 2019; Bai et al. 2020; Queiroz et al. 2020) have attempted to determine the stellar parameters, distance, and reddening based on the modern wide-field optical photometric and spectroscopic survey data (York et al. 2000; Keller et al. 2007; Zhao et al. 2012; Chambers et al. 2016; Gaia Collaboration et al. 2018) and the stellar evolutionary models (Bressan et al. 2012; Hidalgo et al. 2018). The obtained stellar parameter catalogs can be naturally used to map the three-dimensional (3D) dust distribution (Sale et al. 2014; Rezaei Kh. et al. 2018; Chen et al. 2019; Green et al. 2019; Lallement et al. 2019; Leike & Enßlin 2019; Leike et al. 2020). However, the dynamical range of the dust maps based on optical surveys is limited, only up to a few to $\sim 10$ magnitudes of visual extinction, and thus not enough to trace the high column density regions closely connected to the star formation process (Gao & Solomon 2004; Lada et al. 2010; Zhang et al. 2019).

Since extinction decreases with wavelength, we can expect to detect more background stars at longer wavelength. Indeed, extinction mapping with the NIR multi-band photometric survey data (Skrutskie et al. 2006; Lawrence et al. 2007; Minniti et al. 2010) can measure the dust column density with a dynamic range $\sim 5-10$ times larger than the optical extinction maps (Lada et al. 1994). However, due to the lack of large NIR spectroscopic and astrometry surveys, it is difficult to derive accurate stellar parameters for NIR sources. The NIR extinction towards individual stars are usually obtained by simply comparing the observed NIR colors and the average intrin-
sic colors. This is facilitated by two observationally confirmed facts: 1) the dispersion of the stellar intrinsic colors is relatively small at NIR wavelength (Lombardi & Alves 2001; Girardi et al. 2005; Davenport et al. 2014); and 2) the variation of the NIR extinction law is small (Cardelli et al. 1989; Wang & Jiang 2014; Meingast et al. 2018; Wang & Chen 2019). In practice, the intrinsic colors of stars are usually inferred with the nearby, supposedly extinction-free reference fields.

Based on above well-established approach, several two-dimensional (2D) extinction mapping techniques have been developed, each employing a somewhat different detailed formalism (NICE: Lada et al. 1994; NICER: Lombardi & Alves 2001; NICEST: Lombardi 2009; PNICER: Meingast et al. 2017; XNICER: Lombardi 2018; see also, e.g., Cambresy et al. 2002; Gutermuth et al. 2009 for further variants). These techniques have been used extensively to investigate column density structures of nearby star forming regions (e.g., Kainulainen et al. 2006, 2007, 2009; Lombardi et al. 2006, 2008, 2010; Gutermuth et al. 2011; Schneider et al. 2011; Alves et al. 2014), but they are rarely applied to study the Galactic plane. This is because extinction mapping methods are usually inferred with the nearby, supposedly extinction-free reference fields. Which makes extinction mapping prohibitively difficult (e.g., Lombardi 2005; Kainulainen et al. 2011; Juvela & Montillaud 2016). To improve on this point, Dobashi et al. (2008) developed a technique named "X percentile method" as an extension of the NICE method. The X percentile method selects the X percentile reddest stars along the line of sight as the background stars and thus can efficiently remove the contamination by foreground sources, which makes it suitable to estimate the extinction towards distant and/or dense dust clouds located behind a large number of foreground stars. Dobashi (2011) applied the X percentile method to the Two Micron All-sky Survey catalogs (2MASS, Skrutskie et al. 2006) and obtained an all-sky extinction map that had a variable spatial resolution of 1°–12° and a dynamical range of up to AV ~ 20 mag, limited by the relatively poor resolution and sensitivity of 2MASS survey. In general, the map is still not refined enough to trace the fine dust structures in the Galactic plane. In summary, the complementary view of Galactic dust provided by NIR extinction mapping is largely missing towards the Galactic plane.

In this paper, we make progress by deriving a new extinction-based dust map that can trace the dust distribution in the Galactic plane better than its predecessors. To do this, we develop a new NIR extinction mapping technique, XPNICER, that is based on PNICER (Meingast et al. 2017) and Xpercentile (Dobashi et al. 2008) methods. We will apply XPNICER to the VVV survey (Minniti et al. 2018) photometric catalogs (Zhang & Kainulainen 2019) and obtained a 2D extinction map with the spatial resolution of 30′′ and the dynamical range up to AV ~ 30 mag, covering the whole VVV survey area in the Galactic plane. In Sect. 2 we described the source catalogs that we used, including the VVV DaoPHOT catalog (Zhang & Kainulainen 2019) that has been recalibrated with the aim to decrease the zero magnitude bias. We described the XPNICER technique in Sect. 3 and presented the extinction map in Sect. 4. In Sect. 5 we compared our extinction maps with several previous dust based maps and gave some suggestions and caveats to the usage of our map. Finally, we summarized our results and conclusions in Sect. 6.

2 DATA

2.1 VVV photometric catalogs

We use in this paper photometric data from the VVV survey as the main data to derive our extinction map. We describe below the survey and the data to the degree relevant to this work. For more detailed descriptions we refer to the respective survey and instrument papers.

The VVV survey uses VIRCAM (VISTA InfraRed CAMera; Dalton et al. 2006; Emerson & Sutherland 2010) equipped on the VISTA telescope (Sutherland et al. 2015) to map ~562 square degrees in the inner Galactic plane, including the Galactic bulge (-10 ≤ l ≤ 10, -10 ≤ b ≤ 5) and part of the adjacent Galactic plane (-65 ≤ l ≤ -10, -2 ≤ b ≤ 2). The survey covers five bands, $Z, Y, J, H, K_s$, and it extends over the time period of five years (Minniti et al. 2010; Saito et al. 2012).

VIRCAM is equipped with a 4×4 detector array and each detector has 2048×2048 pixels$^2$ in size with a pixel scale of 0.339″. A single pointing with the detector array is called a pawprint and six pawprints can be combined to construct a contiguous field of ~1.687 deg$^2$ named a tile. The whole VVV survey consists of 348 tiles, including 196 bulge tiles (names start with "b"), and 152 disk tiles (names start with "d"). The tile names and coordinates can be found in Saito et al. (2012).

Several works have used the VVV data to produce photometric catalogs. Saito et al. (2012) released a catalog based on aperture photometry with the 5σ limiting magnitude of $K_s$ ~ 17-18 mag for most tiles and $K_s$ ~ 15-16 mag in the crowded fields. Alonso-García et al. (2018) presented a PSF photometric catalog based on DoPHOT algorithm (Mateo & Schechter 1989; Schechter et al. 1993) with the limiting magnitude (5σ) of $K_s$ ~ 17-18 mag. Zhang & Kainulainen (2019) performed the PSF photometry on the stacked VVV survey images using DaoPHOT algorithm (Stetson 1987) and presented a catalog that was about one magnitude deeper than the DoPHOT photometric catalog released by Alonso-García et al. (2018). To detect more faint background sources, we decided to use the PSF photometric catalog presented by Zhang & Kainulainen (2019).

We note that Zhang & Kainulainen (2019)’s DaoPHOT photometric catalog was calibrated with Alonso-García et al. (2018)’s DoPHOT catalog, which in turn was calibrated with Saito et al. (2012)’s aperture photometric catalog. The flux of sources in the aperture photometric catalog was calibrated with the 2MASS sources (González-Fernández et al. 2018). Specifically, González-Fernández et al. (2018) constructed the empirical transformations between 2MASS and VISTA photometric systems, considering the effect of interstellar reddening. Then the 2MASS sources with VISTA counterparts were transformed to the VISTA system and treated as the local secondary standard stars to calibrate the VVV aperture photometric catalog tile by tile. However, Hajdu et al. (2020) has pointed out that there is bias in the photometric zero-points of the calibrated VVV aperture photometric catalog. The sources of the bias were identified as 1) artifacts in some detector images due to the high level of sky background; 2) high blending effect of 2MASS sources in the crowded fields. Given the calibration chain, the DaoPHOT catalog released by Zhang & Kainulainen (2019) should also have the similar zero magnitude bias.

We re-calibrated the VVV DaoPHOT catalog (Zhang & Kainulainen 2019) using the method suggested by Hajdu et al. (2020). First, the 2MASS photometry was converted to the VISTA system with the transformations suggested by González-Fernández et al. (2018) and Hajdu et al. (2020). Here we only consider the high reliable 2MASS sources with the photometric
quality flags\footnote{https://old.ipac.caltech.edu/2mass/releases/allsky/doc/sec1_60.html} of “AAA”. Second, the converted 2MASS catalog was cross-matched with the DaoPHOT catalog with a tolerance of 0.15\arcsec that was suggested by Hajdu et al. (2020). Such a small tolerance helps to filter out the mismatch between 2MASS and VVV because several VVV sources can be blended into the same 2MASS source in the crowded fields if using a large tolerances. González-Fernández et al. (2018) allowed a relatively large cross-match radius of 1\arcsec between 2MASS and VVV catalogs to calculate the zero magnitude of VVV aperture photometric catalog, which resulted in the mismatches and thus bias of zero points in the crowded fields (Hajdu et al. 2020). Figure 1 shows the photometric difference between DaoPHOT $J$ magnitudes and converted 2MASS magnitudes in four tiles that are located in the disk and bulge areas, covering different Galactic latitudes and thus represent regions with different crowding conditions. We can see obvious patterns that show the systematic large offsets in the bottom-left corner of each tile. We believed that this bias was due to the variable quantum efficiency (QE) of detector 16\footnote{http://casu.ast.cam.ac.uk/surveys-projects/vista/technical/technical.html\#AppendixA}, which was quite small, the StarHose code can be used to estimate $J$ and $\chi$ percentile (Anders et al. 2019), LAMOST DR5 (Zhang & Kainulainen 2019), RA6 (Steinmetz et al. 2020a,b), and GES DR3 (Gilmore et al. 2012), together with the photometric catalogs of Gaia DR2, Pan-STARRS1, APASS (Henden & Munari 2014), 2MASS and AllWISE. The typical uncertainties of distances and visual extinctions are $\sim$3-5\% and 0.05-0.16 mag, individually.

We combined the StarHorse2019 and StarHorse2020 catalogs to produce a new StarHorse catalog. Specifically, the sources in StarHorse2019 that have counterparts in StarHorse2020 were replaced with the entries of StarHorse2020 due to the relatively small uncertainties of distances and extinctions of StarHorse2020. The StarHorse2020 sources that have no StarHorse2019 counterparts were just added as new entries to the new StarHorse catalog.

2.2 StarHorse catalogs

In this paper, we also use the StarHorse catalogs (Anders et al. 2019; Queiroz et al. 2020) as ancillary data. In the StarHorse catalogs, there are several hundreds of million sources with the Bayesian stellar parameters, distances, and extinctions. We use these stars as the reference sources in our extinction mapping process (see Sect. 3.1).

The StarHorse catalogs were constructed with the StarHorse code (Santiago et al. 2016; Queiroz et al. 2018). By comparing a number of observed quantities, e.g., multi-band photometry, spectroscopically determined parameters like effective temperatures, or parallaxes, to the stellar evolutionary models (Bressan et al. 2012; Hidalgo et al. 2018), the StarHorse code can be used to estimate the stellar parameters, distances and extinctions of stars with the Bayesian method.

Anders et al. (2019, StarHorse2019 hereafter) applied the StarHorse code to the precise parallaxes and multi-band photometry released by the Gaia DR2 (Gaia Collaboration et al. 2018, Pan-STARRS1 (Chambers et al. 2016), 2MASS, and AllWISE (Wright et al. 2010; Marrese et al. 2019) surveys. They finally obtained the distances and extinctions for $\sim$265 million sources in the whole sky with a median accuracy of $\sim$5-16\% in distance and $\sim$0.2 mag in visual extinction.

Queiroz et al. (2020, StarHorse2020 hereafter) also obtained the distances and extinctions for more than 5 million sources by applying the StarHorse code to the spectroscopic surveys of APOGEE DR16 (Ahumada et al. 2020), GALAH DR2 (Buder et al. 2018), LAMOST DR5 (Xiang et al. 2019), RAVE DR6 (Steinmetz et al. 2020a,b), and GES DR3 (Gilmore et al. 2012), together with the photometric catalogs of Gaia DR2, Pan-STARRS1, APASS (Henden & Munari 2014), 2MASS and AllWISE. The typical uncertainties of distances and visual extinctions are $\sim$3-5\% and 0.05-0.16 mag, individually.

2.3 Final input catalog for the extinction mapping

We generated a matched catalog by combining the re-calibrated VVV DaoPHOT catalog (see Sect. 2.1) and the combined StarHorse catalog (see Sect. 2.2) as the input of our extinction mapping procedure that was described in the subsequent section (Sect. 3). We used a matching radius of 0.5\arcsec to match the StarHorse catalog to the VVV DaoPHOT catalog. We also required the photometric uncertainties of $<0.35$ mag in all $I$, $H$, and $K_s$ bands and excluded the possible spurious detections, i.e., sources that have any of nine spurious detection flags equaling 1 (see Sect. 3.2.4 of Zhang & Kainulainen 2019 for details). Finally we obtained $\sim$820 million NIR sources in the VVV survey area, of which $\sim$3\% have StarHorse extinction estimates.

3 METHOD

Our extinction mapping technique, XPNICER, is based on the PNICER (Meingast et al. 2017) and X percentile (Dobashi et al. 2008) methods. In brief, the extinctions towards individual stars are estimated by comparing their observed colors to intrinsic colors that are inferred statistically from the StarHorse sources in the same area (elaborated below in Sect. 3.1). Then we group stars into discrete sightlines and select possible background sources along different lines of sights with the X percentile method (elaborated below in Sect. 3.2). The selected background stars are used to map the spatial distribution of the integrated dust extinction.

3.1 Single-star extinction estimation

In our input catalog (see Sect. 2.3), about 23 million sources have StarHorse extinction estimates. We checked the quality flags for these sources in the original StarHorse2019 and StarHorse2020 catalogs. The StarHorse2019 catalog used “SH_OUTFLAG” (see Sect. 3.4.4 of Anders et al. 2019) to mark the sources with unreliable extinction values or large $A_V$ uncertainties while the StarHorse2020 catalog labeled the sources with bad extinction estimates using the flag of “SH_OUTPUTFLAGS” (see Table A.2 of Queiroz et al. 2020). We noted that the StarHorse extinction and distance of each source were in Table A.2 of Queiroz et al. 2020.
Figure 1. Photometric difference between VVV DaoPHOT $J$-band magnitude and converted 2MASS magnitude in four tiles.

We then used the quantiles to calculate the means and standard deviations of extinction ($\mu_{AV}$, $\sigma_{AV}$) and distance ($\mu_{dist}$, $\sigma_{dist}$) assuming a Gaussian error for them:

\begin{align}
\mu_{AV} &= \frac{1}{2}(av_{16} + av_{84}) \\
\sigma_{AV} &= \frac{1}{2}(av_{84} - av_{16}) \\
\mu_{dist} &= \frac{1}{2}(dist_{16} + dist_{84}) \\
\sigma_{dist} &= \frac{1}{2}(dist_{84} - dist_{16}).
\end{align}

We also obtained the dereddened NIR colors of $[J - H]_0$ and $[H - K_s]_0$ using $\mu_{AV}$ based on the extinction law suggested by Wang & Chen (2019). Furthermore, we applied the following criteria to the selected 17.6 million StarHorse sources:

\begin{align}
-1 &< [J - H]_0 < 1.5 \\
-1 &< [H - K_s]_0 < 1.5 \\
\mu_{dist} &> \sigma_{dist} \\
\mu_{dist} &< 20 \text{ kpc}.
\end{align}

Finally we obtained about 17.47 million DaoPHOT sources which have high-quality (hq) StarHorse extinction estimates.

For the DaoPHOT sources without hq StarHorse extinction estimates, we used PNICER method to estimate their extinction values. Meingast et al. (2017) presented an unsupervised machine learning technique, PNICER, which determined the probability distribution of extinction through fitting the features in color space of sources in the reference field. PNICER decreases the variance of intrinsic color measurements and thus can offer more accurate extinction estimation than NICER (Lombardi & Alves 2001). Meingast et al. (2018) also successfully applied PNICER to Orion A based on the Vienna Survey In OrioN (VISION, Meingast et al. 2016) data. A necessary input of PNICER is the intrinsic colors of sources, which are usually inferred with an extinction-free region close to the target field. However, it is quite difficult to identify such extinction-free reference fields in the Galactic plane. Therefore, we directly adopted the DaoPHOT sources with hq StarHorse estimates as the reference stars. In specific, the extinctions towards DaoPHOT sources without hq StarHorse estimates ($\mu_{control:Starhorse}$) in one tile were obtained by comparing their observed colors to the de-reddened colors of DaoPHOT sources with hq StarHorse extinction estimates in the same tile using the PNICER python package\(^3\) based on the extinction law suggested by Wang & Chen (2019). The uncertainties of $\mu_{V,PNICER}$ were mainly due to the photometric uncertainties and the variations of intrinsic colors.

The above PNICER process relied on the assumption that the probability density distributions of intrinsic colors of observed DaoPHOT

\(^3\) https://github.com/smeingast/PNICER
Figure 2. The $J$, $H$, and $K$ band smoothed maps of photometric difference between the VVV and converted 2MASS magnitudes over the whole VVV survey area.

Sources can be well-represented by the de-reddened color distributions of reference stars. However, the DaoPHOT sources with hq StarHorse extinction estimates as reference stars were selected from all DaoPHOT sources with a bias to the bright and nearby stellar objects, which, obviously, introduced additional uncertainties in the PNICER extinction determination process. Subsequently, we tried to quantify these additional uncertainties using the Besançon model of stellar population synthesis of the Galaxy (Robin et al. 2003). Here we have ignored the contamination of galaxies in the DaoPHOT catalogs because the high star, dust, and gas density of the Galactic plane obscure most of extragalactic objects (Flores Carrubio 2020). Actually, Amôres et al. (2012) identified 204 galaxy candidates in tile "d003" by visual inspection on the VVV images, resulting in a surface density of $\sim124.7$ galaxies per deg$^2$. Baravalle et al. (2018) also searched extragalactic sources in VVV tiles "d010" and "d115" by their photometric procedures and finally detected 345 and 185 extragalactic candidates in 752,233 and 310,283 photometric sources. Baravalle et al. (2021) then applied Baravalle et al. (2018)'s method to the disk parts of $\sim220$ deg$^2$ covered by the VVV survey and finally identified 5563 galaxies. Amôres et al. (2012) estimated that $\sim15,000$ galaxies can be detected among about a billion point sources in the whole VVV survey area based on the semi-analytic galaxy formation model (Bower et al. 2006) and the Galactic interstellar extinction model (Amôres & Lépine 2005), which suggested that only 1 (0.02%) out of $\sim5000$ objects was a galaxy. Thus the contamination of galaxies in the DaoPHOT catalogs is negligible.

We selected a 15'×15' central region in each tile and extracted the pseudo-stars from the Besançon Galactic model (Robin et al. 2003). Due to the lack of information about the extinction distribution profile along the line of sight, we assumed a simple linear relation of $A_V = aD$, where $A_V$ is the total extinction along one sightline till the distance of $D$ kpc. We constructed 60 synthetic color-color diagrams (CCDs) and color-magnitude diagrams (CMDs) with the pseudo-stars based on the different $a$ values from 0.1 to 6 with the step of 0.1 mag per kpc. The best pseudo-star model of observed DaoPHOT sources can be obtained by minimizing the differential CCDs and CMDs that were built by subtracting the synthetic number density map from the observed number density
Figure 3. Histograms of photometric difference between VVV DaoPHOT \( J \)- (left), \( H \)- (middle), \( K \)- (right) magnitudes and converted 2MASS magnitudes in the whole VVV survey area before (top) and after (bottom) re-calibration. The red solid lines show the gaussian fittings to the histograms and the fitting parameters, \( \mu \) and \( \sigma \) (gaussian mean and sigma), are also marked in the corresponding panels.

map in the color space. Figure 4 shows the CCDs and CMDs constructed with observed DaoPHOT sources and best pseudo-stars from the Besançon Galactic model in the \( 15' \times 15' \) central region of tile "d003". We used these best pseudo-star models to describe the intrinsic color distribution of the corresponding DaoPHOT sources. Figure 5 shows the distributions of de-reddened magnitudes, distances, and intrinsic colors for the DaoPHOT sources with \( h_q \) Starhorse estimates and for the pseudo-stars from the best-fitting Besançon Galactic model in the \( 15' \times 15' \) central region of tile "d003". Obviously, the DaoPHOT sources with \( h_q \) Starhorse extinction estimates were significantly biased to the bright and close stars as a selected sub-sample from all DaoPHOT sources. We also calculated extinctions towards DaoPHOT sources (\( A_{\text{V,PNICER}}^{\text{control,Besançon}} \)) in the \( 15' \times 15' \) central region of each tile with PNICER method using the pseudo-stars predicted by the best-fitting Besançon model as the reference stars. Figure 6 shows the histogram of difference between \( A_{\text{V,PNICER}}^{\text{control,Starhorse}} \) and \( A_{\text{V,PNICER}}^{\text{control,Besançon}} \) in the \( 15' \times 15' \) central region of tile "d003". We adopted the standard deviation (\( \sigma_{\Delta A_V} \)) of \( \Delta A_V = A_{\text{V,PNICER}}^{\text{control,Besançon}} - A_{\text{V,PNICER}}^{\text{control,Starhorse}} \) as the additional uncertainty introduced by the bias of reference stars in each tile, e.g., \( \sigma_{\Delta A_V} = 1.51 \) mag in tile "d003" which has been marked in Fig. 6. Therefore, \( \sigma_{\Delta A_V} \) in the whole VVV survey area was a function of tile positions. We finally smoothed the \( \sigma_{\Delta A_V} \) map using a Gaussian kernel with the full width at half maximum (FWHM) of 1.5' to avoid the edge effect. The total error (\( \sigma_{\text{total}} \)) of \( A_V \) of the DaoPHOT sources without \( h_q \) Starhorse extinction estimates was the combination of error given by PNICER method (\( \sigma_{\text{PNICER}} \)) and that due to the bias of reference stars (\( \sigma_{\Delta A_V} \)), i.e., \( \sigma_{\text{total}} = \sqrt{\sigma_{\text{PNICER}}^2 + \sigma_{\Delta A_V}^2} \). During the above process, we have ignored the systematic difference of \( \Delta A_V \) that can be seen in Fig. 6 because it is sensitive to the assumed dust distribution along the line of sight and thus difficult to quantify without the knowledge of 3D dust distribution. Because the systematic difference affected the zero point of our extinction map, we revisited it in Sect. 4.2.1.

3.2 Background source selection and extinction mapping

To map the integrated Galactic extinction, we must isolate the background sources that are as far as possible, i.e., are on the background of as much dust as possible. In principle, the optimal way would be to use the stars at the far-side of the Galaxy, which is of course, impossible without the distance information of stars. However, a reasonable approach is to select the most extincted stars as the background stars, based on the fact that on average the total extinction increases with the distance from the Sun. We note that this approach ignores any structure within the resolution element.

We used the "X percentile method" to derive the extinction maps. The key of this method is to utilize the color of the X percentile reddest star to measure the color excess of a sightline cell. The full description of the X percentile method can be found in Dobashi et al. (2008), we only summarize our implementation here. First, we gridded the whole VVV survey area into discrete square sightline cells.
The size of grid cell was selected to be 30″ and 60″ based on our experience. Figure 7 shows the cumulative density function (CDF) of DaoPHOT source number density (Σcell) at 30″ and 60″ grids. The 50% percentiles of Σcell were 100 and 401 counts at 30″ and 60″ grids, respectively. About 2-3% of grid cells have Σcell ≤ 10. The 30″ grid can offer higher spatial resolution while the 60″ grid can give lower AV noise level for the final extinction maps. Actually, the selection of these two grids (30″ and 60″) can make sure that there is at least one DaoPHOT source in >99.97% beams of the final extinction maps.

Second, we located the DaoPHOT sources in each grid cell. Then we sorted the stars according to their AV values in the ascending order and denoted the q-th percentile of AV as AV(q). Considering X₀- and X₁-th percentiles (0% ≤ X₀ < X₁ ≤ 100%) of AV, i.e., AV(X₀) and AV(X₁), we can select DaoPHOT sources in each grid cell with AV(X₀) ≤ AV ≤ AV(X₁) as the background sources. The classical NICER method (Lombardi & Alves 2001) usually uses the spatial averages (or medians) of extinctions towards all detected stars, which is equivalent to setting X₀ = 0% and X₁ = 100%. In general, higher X₀ and X₁ values are more helpful to select the true background sources, especially for the clouds that are heavily contaminated by the foreground stars. Assuming a cloud located at a distance with the uniform density distribution along a line of sight, Dobashi et al. (2008) modelled the cloud color excess as a function of X₀, i.e., E(X₀), and found that E(X₀) is close to the true cloud color excess when X₀ ≥ 70%. Dobashi et al. (2008) and Dobashi et al. (2009) obtained the extinction maps for the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) using the X percentile method with different X₀ based on 2MASS source catalog. By comparing to the CO maps of LMC and SMC (Mizuno et al. 2001a, b), they also found that X₀ = 80% gives a reasonable moderate noise level and should trace the cloud extinction best. Therefore, we decided to adopt the suggestions from Dobashi et al. (2008) and Dobashi et al. (2009) and use X₀ = 80% to select the background sources. However, for some distant and/or very dense dust clouds, X₀ = 80% was still not high enough to select the true background sources. Thus we also used the configuration of X₀ = 90%, but only for 60″ grid.

We also set X₁ = 95% to remove the sources with infrared excess. The intrinsically red sources such as young stellar objects (YSOs) and asymptotic giant branch stars (AGBs) also contaminated our selected background sources because their infrared excess results in a serious overestimation of their true color excess and extinctions. Marton et al. (2016) presented an all-sky catalog of sources with infrared excess as the YSO candidates using the support vector machine algorithm based on 2MASS and AllWISE catalogs (Wright et al. 2010). The whole catalog includes 133, 980 Class I/II candidates and 608, 606 Class III candidates, of which 363, 564 YSO candidates are located in the VVV survey area. However, considering the limited sensitivity of 2MASS and WISE, we should expect more infrared excess sources in our VVV DaoPHOT source catalogs.
(2019) revisited the YSO candidates in the Orion A molecular clouds based on the NIR VISION data and mid- and far-infrared survey data such as Spitzer (Megeath et al. 2012), WISE, and Herschel (Furlan et al. 2016). They compared the YSO candidates selected with Spitzer/VISTA data and that identified with WISE/VISTA data in L1641 and found that the WISE selection method recovers about 59% of the YSOs identified with Spitzer/VISTA data. Therefore, there could be about 0.6 million contaminants with infrared excess of our DaoPHOT sources, which gives a low contamination fraction of \( \sim 1\% \). The Galactic AGB stars could have an universal spatial distribution (Jackson et al. 2002; Robitaille et al. 2008), but the YSOs usually cluster in the dense gas regions (Lada et al. 2010), which suggests that the above contamination fraction increases towards the higher extinction regions. Zhang et al. (2019) searched through several tens of million VVV/Spitzer/Herschel sources and identified 36,394 sources with the infrared excess in 57 giant molecular filaments (GMFs) that are roughly defined as the filamentary structures with \( A_V > 3 \) mag. We located their YSO sample in a 5′ grid of the VVV survey area and calculated the infrared excess source fraction per grid cell, i.e., \( f_{\text{IRex}} \). Figure 8 shows the cumulative density distribution of \( f_{\text{IRex}} \), which has a median value of <1%, but can be close to 1% in some regions with active star formation. Therefore, \( X_1 = 95\% \) can efficiently exclude the sources with infrared excess in each grid cell. We note that the \( X_1 \) value of 95% is also the same as that suggested by Dobashi et al. (2008), Dobashi et al. (2009), and Dobashi (2011). Using the configuration of \( X_0 = 80\% \) (90%) and \( X_1 = 95\% \) we obtained about 120 (41) million DaoPHOT background sources in the VVV survey area.

Finally, we smoothed the \( A_V \) values of selected background sources with a Gaussian kernel to obtain the extinction maps. The FWHMs of Gaussian kernels were 30′′ and 60′′ for the background sources selected from 30′′ and 60′′ grids, respectively. To decrease the calculation time, we also set a radius of 2 × FWHM to truncate the smoothing. The pixel size of the extinction map was defined as the half of the FWHM of Gaussian kernel. This smoothing process actually assumed that the dust density distribution was smooth on small scales, i.e., if a dust cloud appears in one sightline it is likely to appear in neighboring sightlines.

The uncertainties of the extinction maps were estimated with a Monte Carlo method as suggested by Dobashi et al. (2008). Assuming a Gaussian error for \( A_V \) values of DaoPHOT sources, we can generate a random \( A_V \) measurement for each DaoPHOT source and produce a simulated DaoPHOT catalog. Then we located the simulated DaoPHOT sources into a grid and selected the background sources in each grid cell with the XPNICER technique described above. The extinction maps can be obtained by smoothing the \( A_V \) measurements of the simulated background sources. By repeating the simulation 100 times we can obtain 100 extinction maps. The final extinction map and the associated uncertainty map were adopted as

\[ \text{Figure 5. Top panels: PDFs of de-reddened } K \text{-band magnitudes (top left) and distances (top right) for the DaoPHOT sources with hq Starhorse estimates and the pseudo-stars from the best-fitting Besançon Galactic model; bottom panels: intrinsic } [H - K]_0 \text{ vs. } [J - H]_0 \text{ CCDs built with DaoPHOT sources with hq Starhorse estimates (bottom left) and pseudo-stars from the best-fitting Besançon Galactic model (bottom right); in the 15′×15′ central region of tile "d003".} \]
Thus, the VVV survey can see the stars as far as 12-16 kpc. The estimate was done using the TRILEGAL,4 model, which is a stellar population code that can simulate the stellar photometry of any Galactic field (Girardi et al. 2005). Thus, the VVV survey can see the stars as far as ~12-16 kpc, if only considering a simple model for the diffuse dust distribution in the Galaxy. This can be treated as the upper limit of $d_{\text{limit}}$.

We also use an indirect way to estimate the lower limit of $d_{\text{limit}}$ using a published 3D extinction map. Chen et al. (2019) presented a 3D dust extinction map of the Galactic plane ($0^\circ < l < 360^\circ, |b| < 10^\circ$) based on the Gaia DR2, 2MASS, and WISE data. They obtained the color excesses of over 56 million stars and mapped the Galactic dust distribution up to $\sim$4-6 kpc at 6′ resolution. Chen et al. (2019) defined the reliable depth of each pixel as the maximum distance, $d_{\text{limit,chen2019}}$, of all stars in that pixel. Fig. 13 shows the pixel-to-pixel comparison of our XPNICER map at 6′ resolution to the $d_{\text{limit,chen2019}}$ map. We found the value of $d_{\text{limit,chen2019}}$ in the range of 0.8-6 kpc with a median value of $\sim$3.5 kpc. Compared with Gaia and 2MASS data, the VVV survey detected much more faint and distant stars. Thus $d_{\text{limit,chen2019}}$ can be treated as the conservative lower limit of $d_{\text{limit}}$, which results in 0.8-6 kpc $< d_{\text{limit}}$ $<$ 12-16 kpc depending on the line of sight. One can get the exact estimate of $d_{\text{limit}}$ for individual lines of sight from Chen et al. (2019).

There are several types of defects and artifacts in our XPNICER extinction maps, including defects by bright stars, absorption-like features in high extinction regions, artifacts caused by detector de-

4 http://stev.oapd.inaf.it/cgi-bin/trilegal

4 RESULTS

4.1 Dust extinction maps

Figures 9 and 10 show our XPNICER extinction maps of the Galactic disk and bulge areas covered by the VVV survey in units of $A_V$. Figures 11 and 12 show the corresponding uncertainty. The maps were obtained using the configuration of $X_0 = 80$% and $X_1 = 95$% with the spatial resolution of 30″. In the following, we refer to the extinction and uncertainty maps as $A_{V,30}^0(X_0 = 80)$ and $\delta A_{V,30}^0(X_0 = 80)$, respectively.

The basic statistics of $A_{V,30}^0(X_0 = 80)$ and $\delta A_{V,30}^0(X_0 = 80)$ are shown in Table 1. The maps can trace dust extinction up to $A_V \sim 30$ mag with a typical uncertainty of $\sim$0.2 mag. Figures 9 and 10 reveal a wealth of complex structures at different scales.

By construction, the maps describe the extinction integrated to some limiting distance, $d_{\text{limit}}$, along the line of sight. Obviously, $d_{\text{limit}}$ is a function of Galactic longitude and latitude and related to the detection limit of the VVV survey and the 3D dust distribution. It is impossible to fully quantify $d_{\text{limit}}$ without an actual 3D model of the Galactic dust. Therefore, here we only gave the rough estimation of the range within which $d_{\text{limit}}$ is likely to be. To make the estimates, we selected two 1°×1° low extinction regions towards $[l = 0^\circ, b = -9^\circ]$ and $[l = 330^\circ, b = -1.5^\circ]$. Assuming a constant dust distribution profile of $A_V \sim 0.7$ mag kpc$^{-1}$ (Robin et al. 2003) in these two regions, we estimated the $d_{\text{limit}}$ that corresponds to the detection limit, $K = 18.7$ mag, of the VVV DaoPHOT catalog (Zhang & Kainulainen 2019) to be 12-16 kpc. The estimate was done using the TRILEGAL,4 model, which is a stellar population code that can simulate the the stellar photometry of any Galactic field (Girardi et al. 2005). Thus, the VVV survey can see the stars as far as $\sim$12-16 kpc, if only considering a simple model for the diffuse dust distribution in the Galaxy. This can be treated as the upper limit of $d_{\text{limit}}$.
fected, and tile patterns in the maps. The detailed description and examples of the defects can be found in the Appendix A.

4.2 Uncertainties of the derived maps

We have presented the uncertainty maps (see Fig. 11 and 12) in Sect. 4.1. The sources of uncertainties are also discussed in Sect. 3.1, including 1) observed photometric uncertainties, 2) variations of intrinsic colors, and 3) bias of reference stars, which, however, do not include the systematic uncertainties. In this section we discussed two main sources of the systematic uncertainties.

4.2.1 Uncertainties of extinction map zero point

We used DaoPHOT sources with hq StarHorse extinction estimates to infer the intrinsic colors of all DaoPHOT sources. Because the StarHorse sources were biased to bright and nearby stars, there was systematic difference between the de-reddened colors of StarHorse sources and the true intrinsic colors of DaoPHOT sources, which also resulted in the systematic error of zero point of our extinction maps. Due to the lack of 3D image of Galactic dust we did not investigate the systematic difference with the Besançon Galactic model in Sect. 3.1. Here we give a rough estimation of the systematic error of zero point of our extinction maps by comparing the PNICER extinction measurements of background DaoPHOT sources with the corresponding StarHorse2020 estimates.

There are 5688 sources with hq StarHorse2020 extinction estimates out of 120 million DaoPHOT background sources selected with $X_0 = 80\%$ and $X_1 = 95\%$ from 30$''$ grid. Figure 14 shows the comparison of extinction values obtained by PNICER method ($A_{\nu,\text{PNICER}}$) and from StarHorse2020 catalog ($A_{\nu,\text{StarHorse2020}}$). Considering that $A_{\nu,\text{StarHorse2020}}$ was estimated based on the spectroscopic observations and more reliable than $A_{\nu,\text{PNICER}}$, our PNICER method overestimated the source extinction by about 1 mag. Therefore, the zero point of our $A_{\nu}$ extinction maps is about $\pm 1.4$ mag, which means that our extinction maps could systematically overestimate the integrated extinction.

4.2.2 Uncertainties due to extinction laws

Our work currently assumed an universal NIR extinction law suggested by Wang & Chen (2019) for the entire VVV survey area. The extinction laws in the NIR were commonly described with a power-law relation as $A_{\lambda} \propto \lambda^{-\alpha}$, where $\lambda$ is the wavelength and $\alpha$ is a dimensionless parameter that defines a specific extinction law. Wang & Chen (2019) combined the data from different large-scale spectroscopic, astrometric, and photometric surveys to derive a relative extinction curve from optical to mid-infrared bands, which gave $\alpha = 2.07 \pm 0.03$ at NIR.

We note that other works usually suggested different values of $\alpha$, from 1.61 (Rieke & Lebofsky 1985), 1.99 (Nishiyama et al. 2006), 2.11 (Fritz et al. 2011), up to 2.47 (Alonso-Garcia et al. 2017). Apparently, the variation of NIR extinction law can also cause uncertainties of the extinction estimation. A direct idea is to use the standard deviation of $\alpha$ values from different works to estimate the variation of the NIR extinction law. However, because the different $\alpha$ values were obtained based on different datasets and methods, we can not use them to quantify the variation of NIR extinction law without the cross-calibration between them (Wang & Jiang 2014; Maíz Apellániz et al. 2020). In fact, whether the NIR extinction law is universal is still under debate.

Wang & Jiang (2014) determined accurately the intrinsic colors of ~6000 giants based on the APOGEE spectroscopic survey that covered the area of $0^\circ < l < 220^\circ$. They revisited the NIR extinction law and obtained an $\alpha$ value of about $1.95 \pm 0.02$. Wang & Jiang (2014) also found that the NIR extinction law showed no dependence on the color excess of $E(J-K_s)$ in the range of $0.3 < E(J-K_s) < 4-5$, which indicated an universal NIR extinction law from diffuse to dense (up to $A_V \sim 20-30$ mag) regions. However, Wang & Jiang (2014) could underestimate the uncertainty of $\alpha$ due to their small sample size, especially for the dense regions. Maíz Apellániz et al. (2020) also analyzed the NIR extinction with the all-sky 2MASS stellar catalog with high-quality photometry. They tried to select a clean red giant sample with the help of Gaia DR2 data and finally reached a NIR extinction of $\alpha \sim 2.27$ with the uncertainty of a few hundredths of a magnitude. Maíz Apellániz et al. (2020) found no significant spatial variation of NIR extinction law towards different sightlines. Therefore, above large-scale investigations suggested an universal NIR extinction law in most regions with typical environments in the Galactic plane although they gave different $\alpha$ values. On the other hand, it is possible that there are different NIR extinction laws in some specific environments such as the molecular clouds associated with star formation. For example, Racca et al. (2002) obtained a NIR extinction law with $\alpha = 2.52$ in the Coalsack globule 2 that is the highest-density region in the Coalsack molecular cloud. Wang et al. (2013) obtained the different $\alpha$ values for the diffuse ($\alpha = 1.73$) and dense ($\alpha > 2$) environments in the Coalsack nebula. Meingast et al. (2018) investigated the NIR extinction curve in Orion A and found a significant evidence that the extinction law varied ~3% across the cloud. They suggested that this variation could be due to the influence of massive stars on their ambient medium.

Therefore, our assumption of an universal NIR extinction law should be valid in most VVV survey area. Based on the value of $\alpha = 2.07 \pm 0.03$ that we adopted, the uncertainties of visual extinctions due to the error of $\alpha$ were within 3%. From diffuse to dense environments, the variation of NIR extinction law can be from <2% (Wang & Jiang 2014) to up to ~30% (Wang et al. 2013), which was still not well quantified. However, the dense regions in our extinction maps tend to suffer the problem due to the contamination of foreground sources (see Sect A3), which should be the main source of uncertainties of extinctions. Of course, adopting other NIR extinction laws rather than the one with $\alpha = 2.07$ results in the systematic under- or over-estimation of the extinction. The systematic error due to different $\alpha$ values from different works can be up to 20-30% (Wang & Chen 2019).

5 DISCUSSION

5.1 Comparisons with previous dust based maps

In this section, we compare our XPNICER extinction maps with...

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Table 1. Statistics of the visual extinction maps and their associated uncertainty maps of the Galactic plane covered by the VVV survey

| Maps              | min (mag) | max (mag) | mean (mag) | median (mag) |
|-------------------|-----------|-----------|------------|--------------|
| disk $A_V^{\text{m}} (X_0 = 80)$ | -6.66     | 28.89     | 11.55      | 10.84        |
| bulge $A_V^{\text{m}} (X_0 = 80)$ | -4.64     | 34.12     | 7.25       | 5.08         |
| disk $\delta A_V^{\text{m}} (X_0 = 80)$ | 1.55x10^{-4} | 4.72 | 0.27 | 0.26 |
| bulge $\delta A_V^{\text{m}} (X_0 = 80)$ | 2.83x10^{-5} | 4.52 | 0.19 | 0.18 |
Figure 9. The XPNICER extinction maps obtained using $X_0 = 80\%$ and $X_1 = 95\%$ with the spatial resolution of 30\arcsec for the Galactic disk area.

For brevity, we refer to our XPNICER extinction map as $A_V$ (XPNICER) and to the other dust-based maps by Dobashi (2011), Juvela & Montillaud (2016), Schlegel et al. (1998), Planck Collaboration et al. (2014b), Marsh et al. (2017), Gonzalez et al. (2012, 2018), Nidever et al. (2012), Soto et al. (2019), Schultheis et al. (2014), and Surot et al. (2020) as $A_V$ (Dobashi), $A_V$ (M2b), $A_V$ (SFD), $\tau_{353}$ (Planck), $\tau_{353}$ (PPMAP), $A_V$ (BEAM), $A_V$ (RJCE12), $A_V$ (RJCE19), $A_V$ (Schultheis), and $A_V$ (Surot), respectively. Table 2 summarizes the basic information of the ten maps. We note that the maps have been derived with different techniques and datasets and thus have different units. To better understand the differences between them and our XPNICER map, we summarize the different mapping processes in Appendix B to the degree relevant to perform meaningful comparisons. The detailed descriptions can be found in the respective papers. We also converted the units of all previous dust extinction maps to the visual extinction ($A_V$). The details of the conversion process can be found in the following individual comparison sections (Sect. 5.1.2-5.1.9).

We first present visual comparisons of the $A_V$ (XPNICER) and ten other maps in Sect. 5.1.1. Then, the sections 5.1.2-5.1.9 describe the quantitative pixel-to-pixel comparisons, both for the whole $A_V$ (XPNICER) coverage area and a few selected sub-regions.

5.1.1 Visual comparison

Figure 15 shows the zoom-in view of a region with the giant filament GMF 324.5-321.4b (GMF 324b, Abreu-Vicente et al. 2016) in $A_V$ (XPNICER), $A_V$ (Dobashi), $A_V$ (M2b), $A_V$ (SFD), $\tau_{353}$ (Planck), $\tau_{353}$ (PPMAP), $A_V$ (RJCE12), and $A_V$ (RJCE19), respectively. We
Figure 10. The XPNICER extinction map obtained using $X_0 = 80\%$ and $X_1 = 95\%$ with the spatial resolution of $30''$ for the Galactic bulge area.

Table 2. Basic information of the ten dust-based maps compared with our data.

| Maps       | Type             | Resolution | Units       | References                  |
|------------|------------------|------------|-------------|-----------------------------|
| $A_V$(Dobashi) | dust extinction | $1'-12'$  | $A_V$       | Dobashi (2011)              |
| $A_V$(M2b)  | dust extinction  | $3'$       | $A_V$       | Juvela & Montillaud (2016)  |
| $A_V$(SFD)  | dust extinction  | $6'$       | $E(B-V)$    | Schlegel et al. (1998)      |
| $\tau_{353}$(Planck) | dust emission | $5'$       | optical depth | Planck Collaboration et al. (2014b) |
| $\tau_{353}$(PPMAP) | dust emission | $12''$     | optical depth | Marsh et al. (2017)         |
| $A_V$(BEAM) | dust extinction  | $1'-6'$    | $E(J-K_s)$  | Gonzalez et al. (2012, 2018) |
| $A_V$(RJCE12) | dust extinction | $2'$       | $A_{K_s}$   | Nidever et al. (2012)       |
| $A_V$(RJCE19) | dust extinction | $1'$       | $A_{K_s}$   | Soto et al. (2019)          |
| $A_V$(Schultheis) | dust extinction | $6'$       | $E(J-K_s)$  | Schultheis et al. (2014)    |
| $A_V$(Surot) | dust extinction  | $\sim 10''-2'$ | $E(J-K_s)$  | Surot et al. (2020)         |

also selected six other regions for visual comparisons, shown in Appendix C. These selected regions are located at different Galactic longitudes and latitudes, representing different conditions in the Galactic plane.

Compared to $A_V$(Dobashi), $A_V$(M2b), $A_V$(SFD), $\tau_{353}$(Planck), $A_V$(BEAM), $A_V$(RJCE12), $A_V$(RJCE19), and $A_V$(Schultheis), our $A_V$(XPNICER) has higher spatial resolution and it can trace finer structures. We note that $A_V$(Surot) reaches the significant higher resolution ($<10''$) than our $A_V$(XPNICER) map in the area close to the Galactic midplane ($b = 0^\circ$), but $A_V$(Surot) only covers the Galactic bulge area. When comparing $A_V$(XPNICER) with $\tau_{353}$(PPMAP), we can see two main differences. First, $\tau_{353}$(PPMAP) shows more small-scale structures due to its higher resolution ($12''$). Second, the very dense regions in $\tau_{353}$(PPMAP) commonly correspond to absorption-like features in our $A_V$(XPNICER) that are artifacts due to the contamination of foreground sources (see Appendix A3). This is due to the limitations of our XPNICER method that runs out of background stars at high column densities. The dust emission based $\tau_{353}$(PPMAP) can better trace the total column density, reaching regions with higher densities. Overall, considering the spatial resolution and coverage, the comparison of the dust extinction based...
maps indicates that our $A_V$ (XPNICER) map provides a high-fidelity extinction map of the Galactic plane.

Another obvious difference is the systematic offset between maps. The $A_V$ values of $A_V$ (XPNICER) are usually significantly higher than that of $A_V$ (Dobashi), $A_V$ (M2b), and $\tau_{353}$ (PPMAP), but lower than that of $A_V$ (SFD). When comparing with $A_V$ (BEAM), $A_V$ (RJCE12), $A_V$ (RJCE19), $A_V$ (Schultheis), and $A_V$ (Surot), $A_V$ (XPNICER) usually has slightly higher $A_V$ values. The offsets result from the different dust tracers and mapping techniques. In sections 5.1.2-5.1.9 we will discuss these offsets quantitatively.

5.1.2 Detailed comparisons with NIR extinction maps by Dobashi (2011) and Juvela & Montillaud (2016)

Both $A_V$ (Dobashi) and $A_V$ (M2b) significantly underestimate, by construction, the extinction from diffuse dust (see Appendix B). In contrast, our XPNICER map measures the integrated extinction until some limiting depth (see Section 4.1). The offsets between $A_V$ (XPNICER), $A_V$ (Dobashi), and $A_V$ (M2b), shown in Fig. 15, should mainly reflect the extinction from diffuse dust.

To better understand the difference between our XPNICER map and $A_V$ (Dobashi) and $A_V$ (M2b), we need to understand the effect of the mapping techniques on the diffuse dust component. To study this, we make a simple model for the diffuse dust component and subtract it from the XPNICER map. Of course, the precise modelling needs the full knowledge of 3D dust distribution in the Galactic plane, which is beyond the scope of this paper. Here we simply assumed that the diffuse dust distribution causes a smooth large-scale background in $A_V$ (XPNICER) and used two different methods (see Appendix D) to estimate this background, i.e., $A_V$ (BG1) and $A_V$ (BG2).

Figure 16a shows the comparisons of $A_V$ (XPNICER) $- A_V$ (BG1) with $A_V$ (Dobashi) for the whole map. We calculated the Pearson correlation coefficient ($r$) between them and obtained a value of 0.64, which indicated a weak correlation. The median and standard deviation of $A_V$ (XPNICER) $- A_V$ (BG1) $- A_V$ (Dobashi) are 0.05 and 0.96 magnitude, respectively. Figures 17a, and 18a show the similar comparisons for two sub-regions, GMF 324b and Pipe (see Fig. C6). Their $r$ values also indicate correlations. However, there are system-
Figure 12. The associated uncertainty map of the extinction map shown in Fig. 10.

Figure 13. Pixel-to-pixel comparison of our XPNICER extinction map at 6′ resolution and Chen et al. (2019)'s reliable depth map ($d_{\text{limit,chen2019}}$). The orange solid line represents medians in the individual bins while the orange dashed lines mark 16% and 84% percentiles in the individual bins.

atatic offsets between $A_V(\text{XPNICER})-A_V(\text{BG1})$ and $A_V(\text{Dobashi})$ in sub-regions (also see Figs. E1-E5).

Figure 16b shows the relation between $A_V(\text{XPNICER})-A_V(\text{BG2})$ and $A_V(\text{M2b})$ for the whole $A_V(\text{XPNICER})$ map. We can see a correlation between them ($r = 0.71$). The median and standard deviation of $A_V(\text{XPNICER})-A_V(\text{BG2})-A_V(\text{M2b})$ are -0.58 and 1.63 magnitude, respectively. Similar correlations can also be found in the sub-regions and the systematic offsets are also significant (see Figs. 17b, 18b, and Figs. E1-E5).

Overall, our XPNICER map is roughly in agreement with the extinction maps presented by Dobashi (2011) and Juvela & Montillaud (2016), if a smooth background is subtracted from our XPNICER map. However, there are systematic offsets at different scales that could be due to the oversimplified diffuse dust model we used.

5.1.3 Detailed comparison with SFD map

The original SFD map has been calibrated to the color excess units (see Appendix B). We retrieved the original SFD map with the python interface of DUSTMAPS (Green 2018) and converted it to $A_V$ units using $A_V = 2.742 E(B-V)$. We note that the extinction law used to calibrate SFD map (Schlafly & Finkbeiner 2011) was close to the law suggested by Fitzpatrick (1999) and different from the one that we used (Wang & Chen 2019). To decrease the systematic difference due to extinction laws, we scaled $A_V(\text{XPNICER})$ by a factor of $\frac{2.742}{2.1}$. Figures 16c, 17c, and 18c show the pixel-to-pixel comparisons
Figure 14. Left: comparison of DaoPHOT source extinction estimates obtained with PNICER method and from StarHorse2020 catalog (Queiroz et al. 2020). The red dashed line shows the one-to-one relation. Right: histogram of extinction difference between PNICER measurements and StarHorse2020 estimates. The median value and standard deviation are also marked on the panel.

Figure 15. Zoom-in view of a region with the giant filament GMF 324b of (a): our $A_V^{30}(X_0 = 80)$ map; (b): extinction map by Dobashi (2011); (c): extinction map by Juvela & Montillaud (2016); (d): SFD map (Schlegel et al. 1998); (e): Planck dust map (Planck Collaboration et al. 2014b) in units of dust optical depth at 353 GHz; (f): Herschel column density map obtained with PPMAP technique (Marsh et al. 2017); (g): extinction map constructed with the RJCE method (Majewski et al. 2011) by Nidever et al. (2012); and (h): extinction map obtained with the RJCE method by Soto et al. (2019). The PPMAP has been converted to the $A_V$ units with the relation of $N(H_2) = 0.94 \times 10^{21} A_V$ (Bohlin et al. 1978).
Figure 16. Pixel-to-pixel comparisons of our XPNICER extinction map with (a): extinction map by Dobashi (2011); (b): extinction map by Juvela & Montillaud (2016); (c): SFD dust map (Schlegel et al. 1998); (d): Planck dust map (Planck Collaboration et al. 2014b); (e): Herschel PPMAP (Marsh et al. 2017); (f): BEAM extinction map by Gonzalez et al. (2012, 2018); (g): RJCE extinction map by (Nidever et al. 2012); (h): RJCE extinction map by Soto et al. (2019); (i): 2D extinction map integrated from the 3D dust map by Schultheis et al. (2014); and (j): extinction map by Surot et al. (2020). The comparison is for the whole map. The red lines mark the one-to-one relation. The black solid lines show the linear fits with the slope of $\gamma$ and the intercept of $\delta$. In the panels d and e, we limited the fit to $\tau_{353} < \tau_{353} \times 10^{-4}$ that were marked with the vertical black dashed lines. The Pearson correlation coefficient ($r$) or the fitting parameters are also labeled on the corresponding panels.
between $A_V$ (XPNICER) and $A_V$ (SFD) for the whole map and sub-regions of GMF 324b and Pipe, respectively (also see Figs. E1-E5 for the comparisons in other sub-regions). We can immediately get two main results: first, there is an approximate one-to-one relation between $A_V$ (XPNICER) and $A_V$ (SFD) in the range of $A_V \lesssim 10-20$ mag (depending on different sub-regions), but with a systematic difference of $A_V$ (XPNICER) - $A_V$ (SFD) -1 mag. The systematic difference could result from the adopted different extinction laws, uncertainty of zero point of our extinction map (see Sect. 4.2.1), and the uncertainties of the SFD map (see Appendix B); second, $A_V$ (SFD) is significantly higher than $A_V$ (XPNICER) when $A_V \gtrsim 10-20$ mag. In Sect. 4.1 we discussed that $A_V$ (XPNICER) traces the total dust extinction integrated to the distance of $d_{\text{limit}}$ and that $d_{\text{limit}}$ could be only a few kpc towards the regions with dense molecular clouds (also see Appendix A3). However, it was commonly believed that $A_V$ (SFD) trace the total dust column density. Therefore, the discrepancy between $A_V$ (XPNICER) and $A_V$ (SFD) at $A_V \gtrsim 10-20$ mag should reflect the limitation of our XPNICER extinction mapping technique.

Overall, our XPNICER extinction map is roughly consistent with the SFD map in the range of $A_V \lesssim 10-20$ mag, but there is significant discrepancy when $A_V \gtrsim 10-20$ mag. The discrepancy could
result from, on the one hand, the large uncertainties of SFD map at low Galactic latitude (see Appendix B, also see Schlegel et al. 1998; Gonzalez et al. 2012). On the other hand, considering that our XPNICER map can not trace the total dust extinction along some lines of sights towards the dense molecular clouds, the discrepancy also reflects the limitation of our XPNICER extinction mapping technique.

5.1.4 Detailed comparison with Planck dust map

We downloaded the $\tau_{353}$ (Planck) with the Python interface of DUSTMAPS (Green 2018). For convinence, we also converted $A_V$ (XPNICER) back to the $A_K$ units, i.e., $A_K$ (XPNICER), with the reddening law suggested by Wang & Chen (2019). Figure 16d shows the pixel-to-pixel comparison between $A_K$ (XPNICER) and $\tau_{353}$ (Planck) for the whole $A_K$ (XPNICER) map. There is roughly a linear relation in the range of $\tau_{353}$ (Planck) $\lesssim 5 \times 10^{-4}$, but significant discrepancy when $\tau_{353}$ (Planck) $\gtrsim 5 \times 10^{-4}$. When we focus on the sub-regions (Figs. 17d, 18d and Figs. E1-E5), the approximating linear relations can retain in the range of $\tau_{353}$ (Planck) $\lesssim (4-7) \times 10^{-4}$. As mentioned in Sect. 5.1.3, the discrepancy between $A_K$ (XPNICER) and $\tau_{353}$ (Planck) in the dense...
regions could result from the bias of $A_K$ (XPNICER) due to the limitation of our extinction mapping technique. We also fitted $A_K$ (XPNICER) versus $\tau_{353}$ (Planck) with a linear relation:

$$A_K (\text{XPNICER}) = \gamma \tau_{353} \text{(Planck)} + \delta.$$  

(9)

The fitting was limited in the range of $\tau_{353} \text{(Planck)} < \tau_{\text{cut}} \times 10^{-4}$, where $\tau_{\text{cut}}$ has different values of 4–7 in different sub-regions. The returned $\gamma$ has values of 1000–3000 while $\delta$ has values of 0.1–0.6.

The intercept $\delta \sim 0.1–0.6$ indicates that $A_K$ (XPNICER) could systematically overestimate the $A_K$ values by about 0.1–0.6 in the low extinction regions, corresponding to an $A_V$ value of $\sim$1–7 mag. This systematic offset can be explained by the zero point uncertainty of our extinction map (see Sect. 4.2.1) and the uncertainty of the Planck dust maps. However, the slope of the linear fit, $\gamma$, was proportional to the ratio of dust opacity and extinction coefficient as suggested by Lombardi et al. (2014):

$$\gamma = 1.0857 \frac{C_{2,2}}{k_{850}} = 1.0857 \frac{C_{2,2}}{k_{250}} \left( \frac{850 \mu m}{250 \mu m} \right)^{\beta},$$  

(10)

where $C_{2,2}$ was the extinction coefficient at 2.2 $\mu m$, $k_{850}$ and $k_{250}$ were the dust opacity at 850 and 250 $\mu m$, respectively. $C_{2,2}$ and $k_{850}$ were dependent on the dust properties such as composition and grain size distribution (Ossenkopf & Henning 1994). Thus different values of $\gamma$ could be related to the variation of dust properties, which has been observed in many different regions. For example, Kramer et al. (2003) measured variation of opacity ratios towards different prestellar cores, corresponding $\gamma$ value from $\sim$1000 to 5700. Lombardi et al. (2014) obtained $\gamma = 2640$ in Orion A and $\gamma = 3460$ in Orion B while Meingast et al. (2018) obtained a slightly larger $\gamma$ value of 3042 in Orion A. Zari et al. (2016) also obtained $\gamma = 3931$ in Perseus. The $\gamma$ values of $\sim$1000–3000 obtained by us are consistent with the previous studies.

A linear fit for the entire VVV survey area yielded an average value of $\gamma = 2043$. The median $\beta$ value for the area is $\sim$1.68, based on the Planck $\beta$$_{\text{obs}}$ map (see Appendix B). If adopting $C_{2,2} \approx 254.7$ from Mathis (1990), we can calculate a $\gamma$ value of $\sim$2160 with Eq. 10. We note that our fitting value of $\gamma = 2043$ is very close to this value of 2160, which indicates that our XPNICER map is globally consistent with the Planck dust model (Planck Collaboration et al. 2014b).

5 https://www.astro.cf.ac.uk/research/ViaLactea/

### 5.1.5 Detailed comparison with Herschel PPMAP

We downloaded the Herschel PPMAPs, but here only used the integrated column density maps. We also note that Marsh et al. (2017) assumed $k$($\lambda$) = 0.1 cm$^2$ g$^{-1}$ (500 $\mu$m)$^{-\beta}$ and $\beta = 2$ to convert the dust optical depth to the column density. To decrease the uncertainty introduced by the former conversion, we transformed the Herschel PPMAPs from column density units back to the optical depth and obtained $\tau_{353}$ (PPMAP).

To compare $A_K$ (XPNICER) to $\tau_{353}$ (PPMAP), we firstly calibrate $\tau_{353}$ (PPMAP) with $\tau_{353}$ (Planck) that was obtained in Sect. 5.1.4 using a simple method described in Appendix F. Figures 16e and 17e show the pixel-to-pixel comparison for the whole map and the region with GMF 324b (see Figs. E1-E5 for the comparison in five other sub-regions). The behavior of $A_K$ (XPNICER) versus $\tau_{353}$ (PPMAP) is similar to that of $A_K$ (XPNICER) versus $\tau_{353}$ (Planck), but with larger scatter. We also fitted the data with $\tau_{353}$ (PPMAP) $< \tau_{\text{cut}} \times 10^{-4}$ with a linear function as described in Eq. 9 and obtained similar $\gamma$ and $\delta$. Thus our XPNICER map is also roughly consistent with the Herschel PPMAPs in the low extinction area. However, due to the oversimplified calibration method (see Appendix F), we did not discuss the pixel-to-pixel comparison between $A_K$ (XPNICER) and $\tau_{353}$ (PPMAP) in detail.

### 5.1.6 Detailed comparison with reddening map by Gonzalez et al. (2012, 2018)

We downloaded the reddening map presented by Gonzalez et al. (2012, 2018) through the Bulge Extinction and Metallicity (BEAM) Calculator. The $E(J-K_s)$ map obtained by Gonzalez et al. (2012) and Gonzalez et al. (2018) were constructed based on the aperture photometric catalog (Saito et al. 2012) and the DoPHOT catalog (Alonso-García et al. 2018), respectively. As mentioned in Sect. 2.1, these catalogs have bias in the photometric zero-points. Thus we firstly corrected the $E(J-K_s)$ using our correction maps shown in Fig. 2 and then converted the color excess units to $A_V$ with the extinction law suggested by Wang & Chen (2019).

Figures 16f and 18e show the pixel-to-pixel comparisons between $A_V$ (XPNICER) and $A_V$ (BEAM) for the whole map and sub-region of Pipe, respectively (also see Fig. E5 for the comparison in another sub-region). We can see an approximate one-to-one relation between $A_V$ (XPNICER) and $A_V$ (BEAM), but with a systematic difference. The median value of $A_V$ (XPNICER)$-A_V$ (BEAM) is about 2.8 mag for the whole map while about 1.6–2.5 mag for the sub-regions. This ~1–3 mag systematic offset could result from the uncertainty of zero point of $A_V$ (XPNICER) and the uncertainties of $A_V$ (BEAM).

We also note that $A_V$ (XPNICER) values are significantly lower than $A_V$ (BEAM) in some high extinction regions. This discrepancy could result from different stellar populations that were used to construct the maps. Our XPNICER map is produced with all stars and underestimate the $A_V$ values of many high density regions due to the contamination of foreground sources (e.g., main sequence (MS) stars, see Appendix A3). However, $A_V$ (BEAM) was constructed with the red clump (RC) giants, which can naturally eliminate the contamination of foreground MS stars and thus trace the high extinction regions more reasonably in the bulge area.

Overall, considering that $A_V$ (XPNICER) overestimates the $A_V$ values of $\sim$1±1.4 mag (see Sect. 4.2.1), our XPNICER map is consistent with $A_V$ (BEAM) in the majority of the Galactic bulge area.

### 5.1.7 Detailed comparisons with RICE maps by Nidever et al. (2012) and Soto et al. (2019)

We downloaded the $A_K$ (RICE12)$^7$ and $A_K$ (RICE19)$^8$ that were presented by Nidever et al. (2012) and Soto et al. (2019). The RICE method is based on the extinction laws suggested by Indebetouw et al. (2005) and Zasowski et al. (2009). To match the reddening law that we used (Wang & Chen 2019), the RICE maps were scaled by a factor of 0.9743 and then converted to the visual extinction units.

Figures 16g, 17f, and 18f show the pixel-to-pixel comparisons between $A_V$ (XPNICER) and $A_V$ (RICE12) for the whole map and two sub-regions with GMF 324b and Pipe, respectively (also see Figs. E1-E5 for the comparisons in other sub-regions). There is a good correlation between $A_V$ (XPNICER) and $A_V$ (RICE12), but with a systematic offset of $A_V$ (XPNICER)$-A_V$ (RICE12)$\sim$0.3–2 mag at

6 https://www.oagonzalez.net/beam-calculator
7 http://www.astro.virginia.edu/rjce/
8 http://www.astro.uda.cl/msoto/extinction/ab.php
different scales. This systematic difference can be explained with the uncertainty of zero-point of our XPNICER map (see Sect. 4.2.1). Therefore, our XPNICER map agrees well with the RJCE map by Nidever et al. (2012). Figures 16h shows the comparison between $A_V$ (XPNICER) and $A_V$ (RJCE19) for the whole map. We can also see a correlation. However, the median value of $A_V$ (XPNICER)−$A_V$ (RJCE19) is about 3.4 mag for the whole map, which is significantly higher than that of $A_V$ (XPNICER)−$A_V$ (RJCE12). For the sub-regions (see Fig. 17g and Figs. E1-E4), the medians of $A_V$ (XPNICER)−$A_V$ (RJCE19) are in the range of $\sim 2$−4 mag which is also $\sim 1$−2.5 mag higher than that of $A_V$ (XPNICER)−$A_V$ (RJCE12) individually. Actually, Soto et al. (2019) also compared $A_K_S$ (RJCE19) with $A_K_S$ (RJCE12) and found a systematic offset of $A_K_S$ (RJCE12)−$A_K_S$ (RJCE19)−0.2 mag, corresponding to $A_V$ $\sim 2$ mag in a VVV tile (b328). They suggested that the discrepancies could arise from the selection effects based on the techniques and data employed, e.g., the different stellar samples used to construct the maps. Therefore, considering the uncertainties of zero-point of our XPNICER map (see Sect. 5.1.6), these discrepancies could result from the uncertainties of zero-points of $A_V$ (XPNICER) and $A_V$ (Surot) in the whole map and the different stellar population used to map the extinction.

5.2 On the advantages and caveats of the XPNICER maps

We performed comparisons between our XPNICER maps and ten previous dust based maps in Sect. 5.1. Here we summarize the main advantages and caveats of our XPNICER map and give some suggestions for its use.

One advantage of the XPNICER map over the previous extinction maps is that it traces the total dust extinction integrated to a distance of $d_{\text{limit}}$. In low extinction regions, the value of $d_{\text{limit}}$ can be up to $\sim 12$−16 kpc (see Sect. 4.1), which approaches the “total Galactic dust extinction”. Previous large-scale NIR extinction maps such as that by Dobashi (2011) and Juvela & Montillaud (2016) do not measure the total dust extinction along the line of sight and usually significantly underestimate the extinction from diffuse dust component.

Another advantage of our XPNICER map is its high spatial resolution (30″) and large coverage. Previous dust-based maps with large coverage such as that presented by Schlegel et al. (1998); Dobashi (2011); Nidever et al. (2012); Planck Collaboration et al. (2014b); Juvela & Montillaud (2016) usually have spatial resolutions of $>1′$.

The reddening map presented by Surot et al. (2020) can achieve $\sim 10″$ resolution in the area close to the Galactic midplane, but their map only covers the Galactic bulge. The Herschel PPMAP data presented by Marsh et al. (2017) have the resolution of 12″ and a coverage of $\sim 720$ deg2, but it only covered the central Galactic midplane with $|b| \lesssim 1°$ ($|b| \lesssim 2.2°$ for our XPNICER map). The higher Galactic latitudes are crucial for a variety of studies, e.g., of the stellar populations in the disk, gas content of the Milky Way, nearby molecular clouds, and studies of extragalactic sources. Our map can be highly beneficial in these regions.

Finally, for studies of Galactic extinction, our XPNICER map measures actual extinction. The emission-based maps, i.e., SFD, Planck, and PPMAP maps measure emission that needs to be converted to column density and further to extinction. Thus, our XPNICER map provides a highly complementary, direct way to measure Galactic extinction. The extinction and emission based methods can be significantly different in specific regions, such as supernova remnants or star-forming regions, because dust extinction and emission are sensitive to dust properties such as composition, grain size distribution, temperature distribution, and interstellar radiation field (Draine 2003). As a result, compared with many previous dust-based maps, our XPNICER map offers a better estimation for the "total Galactic dust extinction".

The main disadvantage of our XPNICER map is that it can not trace the dense and/or distant dust features because the sensitivity of the VVV survey is not good enough to detect sufficient number of stars behind the dense clouds. A very dense nearby cloud could result in an almost total lack of sources and thus a "hole" in our XPNICER map while a distant dense cloud could result in an absorption-like feature in our XPNICER map as described in Appendix A3. Identifying or masking such artifacts is a nontrivial task, as it needs the knowledge of the dense dust structure distribution. Comparisons with other dust tracers can be used to study reliability of different lines of sight. For example, the comparisons with previous dust based maps in Sect. 5.1 suggested linear correlations between our XPNICER map and sev-

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5.1.8 Detailed comparison with 3D reddening map by Schultheis et al. (2014)

We accessed the 3D $E(J−K_s)$ reddening map through the VizieR server and then integrated it up to a distance of 10 kpc to obtain a projected $E(J−K_s)$ map. Because this 3D map is constructed with the VVV aperture photometric catalog (Saito et al. 2012), we corrected the 2D $E(J−K_s)$ map for the bias in the photometric zero-points as described in Sect. 5.1.6. Finally we obtained the 2D extinction map of $A_V$ (Schultheis) using the reddening law suggested by Wang & Chen (2019).

Figure 16i, 18g show the pixel-to-pixel comparisons between $A_V$ (XPNICER) and $A_V$ (Schultheis) for the whole map and the sub-region with the Pipe, respectively (also see Fig. E5 for the comparison in another sub-region). The relations between $A_V$ (XPNICER) and $A_V$ (Schultheis) are close to the one-to-one relation, but with a systematic offset of $\sim 1$−2 mag. Considering that $A_V$ (XPNICER) overestimates the extinction values by $\sim 1$ mag, there should be a good agreement between $A_V$ (XPNICER) and $A_V$ (Schultheis).

5.1.9 Detailed comparison with reddening map by Surot et al. (2020)

We downloaded the $E(J−K_s)$ reddening map presented by Surot et al. (2020) through the VizieR server. We did not try to correct for the photometric bias as described in Sect. 5.1.6 because Surot et al. (2020) has applied the internal and absolute calibrations to their color excess maps (see Appendix. B10). We just converted $E(J−K_s)$ to the visual extinction units using the extinction law suggested by Wang & Chen (2019).

Figures 16j and 18h show the pixel-to-pixel comparisons between $A_V$ (XPNICER) and $A_V$ (Surot) for the whole map and the sub-region with the Pipe, respectively (also see Fig. E5 for the comparison in another sub-region). The behavior of $A_V$ (XPNICER) versus $A_V$ (Surot) is similar to that of $A_V$ (XPNICER) versus $A_V$ (BEAM) because $A_V$ (Surot) was calibrated with $A_V$ (BEAM) (Surot et al. 2020). The medians of $A_V$ (XPNICER)−$A_V$ (Surot) in the whole map
eral dust emission based maps in the range of $A_V \lesssim 10-20$ mag or the optical depth $\tau_{553} < (4-7) \times 10^{-4}$. The pixels in our XPNICER map with values that correspond to $A_V \gtrsim 10-20$ mag or $\tau_{553} > (4-7) \times 10^{-4}$ have relatively large uncertainties and should be treated with caution.

The main objective of this work is to provide a data product in which the dust extinction towards any line of sight of the inner Galactic plane can be easily and conveniently obtained. We believed our XPNICER map to be useful in many studies, at least as the first step towards more detailed analysis of the Galactic dust distribution or stellar populations. For example, our XPNICER map can be used to identify the dust structures at cloud scale as a searching map or investigate the diffuse dust distribution at large scales. Many studies with the aim to investigate the stellar properties can also use our map as a quick check to estimate the initial values of the reddening of stars. By comparing with other gas tracer maps (McClure-Griffiths et al. 2009; Barnes et al. 2015; Schuller et al. 2017), our XPNICER map can be also used to analyze the relation between gas and dust, and even constrain the properties of "CO-dark" gas (Wolfire et al. 2010).

6 SUMMARY AND CONCLUSIONS

We have presented a 2D dust extinction map with the spatial resolution of 30″ based on the previously released DaoPHOT photometric catalog (Zhang & Kainulainen 2019), covering the whole VVV survey area of ~562 deg$^2$ in the Galactic plane. The map was derived with the XPNICER technique that was developed based on the previous PNICER (Meingast et al. 2017) and Xpercentile (Dobashi et al. 2008) methods. Our main results and conclusions are as follows:

1. To decrease the bias in the photometric zero-points, we recalibrated the Zhang & Kainulainen (2019)’s DaoPHOT catalogs with the method suggested by Hajdu et al. (2020). The new calibrated DaoPHOT catalogs have no significant systematic photometric offset compared with the 2MASS photometry and the photometric accuracy of new DaoPHOT catalog is about 60-70 mmag.

2. We derived a novel dust extinction map that covers the VVV survey area. To do this, we developed the XPNICER method (see Sect. 3). The map has a spatial resolution of 30″ and it can trace the dust extinction up to $A_V \sim 30$ mag, although, it is generally less reliable above $A_V \sim 10-20$ mag. The map describes the total extinction up to the distance of $d_{\text{limit}}$. This limiting distance varies strongly, but is typically higher than 3 kpc and can reach up to 12-16 kpc, depending on the line of sight.

3. The typical uncertainty of our XPNICER $A_V$ map is about 0.2 mag. The sources of uncertainties include the observed photometric uncertainties, the variations of intrinsic colors, and the bias of reference stars. In addition to these, the zero point uncertainty of our XPNICER map is about 1±1.4 mag, and the systematic uncertainty due to different extinction laws can be up to 20-30%. In addition to the uncertainties, we describe the typical artifacts in the map that can make it locally unreliable.

4. Compared to most previous dust based maps, our XPNICER map has higher spatial resolution and it can better trace the total dust extinction, including the extinction from diffuse dust that is usually underestimated by the previous extinction maps. Thus, it provides useful data for a variety of studies ranging from individual objects to the stellar population of the Milky Way. It represents a high fidelity extinction-based map and can be highly complementary as an independent measure of dust column densities.

Even if our extinction map represents a clear step onwards, it still cannot trace well the dense dust structures, especially at the Galactic latitude of $|b| \lesssim 1°$. In the future, one solution is to perform deeper optical or infrared imaging surveys, which can be expected from the ground-based or space projects such as LSST and JWST. Another way forward is to combine dust extinction and emission data as suggested by Lombardi et al. (2014). We are working on the combination of the extinction map presented in this work and the Herschel PPMAP mentioned in Sect. 5.1.5. This work is part of the PROMISE: program that derives high-dynamical-range column density data for molecular clouds by combing mid-infrared extinction, far-infrared dust emission, and near-infrared extinction data.

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DATA AVAILABILITY

We released the extinction maps and their associated uncertainty maps derived with XPNICER technique based on the VVV photometric catalogs in http://paperdata.china-vo.org/miaomiaozhang/VVVextmap/VVVextmap. It is a multi-extension FITS file and self-explained in its header.

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10 http://promise.jouunikainulainen.com
11 http://www.astropy.org
APPENDIX A: DEFECTS AND ARTIFACTS IN OUR XPNICER EXTINCTION MAPS

A1 Pixels with negative extinction values

We note that there are 66 pixels with negative values in the $A_V^{30}(X_0 = 80)$ map, about half of which are located at the edge of maps and thus treated as the unreliable measurements. Other half of negative pixels are concentrated in several "holes" as shown in Fig. A1 (top panels). We found that these negative "holes" are in the vicinity of very bright sources that are saturated in the VVV survey images and thus are artifacts due to the lack of reliable photometry around the saturated sources.

A2 Defects by bright stars

The bright stars usually cause the artifacts in the detectors like saturation, non-linearity, and diffraction patterns. Thus there are often many spurious detections and very few reliable photometric sources around them. Such a lack of stars in the vicinity of the bright sources results in the "holes" in our extinction maps. Figure A1 shows some examples in the $A_V^{30}(X_0 = 80)$ map. The "holes" usually have point-like morphology and their sizes are related to the brightness of the corresponding bright stars. Several very bright stars ($K_s < 2$ mag) result in the negative "holes" (also see Sect. A1).

A3 Absorption-like features in high extinction regions

There are also many irregular "holes" in the center of high extinction regions, especially the area at low Galactic latitudes (see Fig. 9 and 10), which look like the absorption-like features on the high extinction background. These absorption-like features should arise from an underestimation of the true integrated extinction due to contamination of foreground sources and can be improved by using higher $X_0$ percentile values.

Figure A2 shows a zoom-in region with the Nessie that was identified as a giant filament with the length of $\sim 80$ pc and width of only $\sim 0.5$ pc (Jackson et al. 2010; Ragan et al. 2014; Mattern et al. 2018) presented a high resolution ($\sim 2''$) extinction map of Nessie by combining the NIR and mid-infrared (MIR) extinction maps with the method suggested by Kainulainen et al. (2011), Butler & Tan (2012), and Kainulainen & Tan (2013). Their combined extinction map has a large dynamical range and can trace the dust extinction up to $A_V \sim 100$ mag. Figure A2 (top panel) shows their map and we can see the high-extinction skinny filamentary structures. Figure A2 (middle panel) shows our extinction map, $A_V^{30}(X_0 = 80)$. Obviously, the absorption-like features in $A_V^{30}(X_0 = 80)$ exactly match the high-extinction filamentary structures in Mattern et al. (2018)'s map, which means that $X_0 = 80$ is not high enough to select the background sources that are located behind the dense part of Nessie. We also obtained the extinction map using $X_0 = 90$, i.e., $A_V^{90}(X_0 = 90)$, which has a lower spatial resolution of $60''$ and is shown in Fig. A2 (bottom panel). Apparently, some absorption-like features in $A_V^{30}(X_0 = 80)$ have disappeared in $A_V^{90}(X_0 = 90)$, but there are still absorption-like features remaining in $A_V^{90}(X_0 = 90)$. Therefore, $X_0 = 90$ is not high enough yet to exclude the contamination of foreground sources for the very dense part of Nessie.

In general, the absorption-like features in high extinction regions of our map are artifacts due to the contamination of foreground sources. They usually correspond to the very dense and/or distant molecular clouds. Increasing $X_0$ percentile value is helpful to remove some of absorption-like features. However, if a cloud has a total extinction sufficient to darken the background stars beyond the detection limit of the VVV survey, its density distribution can not be mapped by our extinction mapping technique.

A4 Artifacts caused by detector defects

The defects of VIRCAM also result in some artifacts in our extinction maps. Figure A3 shows the $A_V^{30}(X_0 = 80)$ map for a bulge tile "b230". The six spots marked with orange circles in the top-right corner of Fig. A3 are due to the bad pixels of VIRCAM detector #12. There are also two stripes labeled with orange ellipses in the bottom-left corner of Fig. A3. They arise from the variable QE of VIRCAM detector #16. Although we tried to remove these QE variant through re-calibrating the Daophot catalog (see Sect 2.1), the residuals still exist in our extinction maps. We note that these artifacts appear in many tile regions of our extinction maps. However, their unchanging patterns can be used to distinguish them from the true dust features.

A5 Tile patterns in the maps

Figure 9-12 show obvious tile patterns in the $A_V^{30}(X_0 = 80)$ and $\delta A_V^{30}(X_0 = 80)$ maps, especially the bulge area at high Galactic latitude. The tile patterns should arise from the varying sensitivity of the

http://casu.ast.cam.ac.uk/surveys-projects/vista/technical/known-issues
APPENDIX B: SHORT DESCRIPTIONS OF PREVIOUS TEN DUST-BASED MAPS

B1 Dobashi (2011)

Dobashi (2011) obtained an all-sky extinction map with the “X percentile” method based on the 2MASS point source catalog (PSC). To estimate the intrinsic colors of the background sources, Dobashi (2011) assumed that bright and faint stars were nearby and distant stars, respectively, and estimated the intrinsic colors of faint stars with the intrinsic color of nearby stars and a color correction item. The intrinsic color of nearby stars was resembled with the colors of stars in the polar area ($|b| > 80^\circ$) while the color correction item was estimated using stars in the high latitude regions without the molecular clouds. However, Dobashi et al. (2013) found that the assumption of a constant intrinsic color of nearby stars was not valid at large scales and they used the Besançon Galactic model to calibrate the intrinsic colors of background sources. Because the Besançon Galactic model can not precisely simulate the 2MASS PSC without the full information of 3D dust distribution, Dobashi et al. (2013) found that the obtained color excess maps significantly underestimated the extinction from large-scale diffuse dust.

B2 Juvela & Montillaud (2016)

Juvela & Montillaud (2016) also presented an all-sky extinction map using the NICER technique (Lombardi & Alves 2001) based on the 2MASS PSC. They offered three extinction maps based on the different methods that were used to estimate the intrinsic colors of background stars. The M1 map used the average colors of all 2MASS stars at Galactic latitude of $|b| > 60^\circ$. The M2a map employed the average colors of all simulated stars from the Besançon model within a distance of 8 kpc as the reference colors. For the M2b map, the intrinsic colors of the simulated Besançon stars were firstly reddened by a simple diffuse dust model of $f(z) \propto 1.0 \text{mag kpc}^{-1} \times e^{-\frac{|z|}{150 \text{pc}}}$, where $z$ was the Galactic height. Then the reddened colors were used as the reference colors, which also meant that M2b map did not include the extinction from diffuse dust component. M1 map was not appropriate to trace the dust extinction in the Galactic plane because it ignored the variation of the intrinsic colors of background stars at low Galactic latitude. Compared with M2a, M2b considered the 3D dust distribution and thus the simulated Besançon stars used for M2b were more analogous to the 2MASS PSC. Therefore, in this paper we only consider the M2b map.

B3 Schlegel et al. (1998)

The SFD dust map was derived from the 100 $\mu$m thermal emission maps from IRAS and DIRBE/COBES surveys. Schlegel et al. (1998) used the flux ratio map of DIRBE 100 $\mu$m to 240 $\mu$m to constrain the dust temperature and transformed the IRAS 100 $\mu$m map to a normalized dust column density map which was then calibrated to the color excess $E(B - V)$ units using about 400 galaxies with Mg$_2$ indices and photometric color measurements (Faber et al. 1989). Schlafly & Finkbeiner (2011) investigated the reddenings towards individual stars based on the SDSS photometric and spectroscopic survey data (Adhara et al. 2011), which were used to recal-
brace the SFD map. They provided a set of conversion coefficients from the SFD $E(B-V)$ units to extinction in different passbands, e.g., $A_V = 2.742E(B-V)$ assuming $R_V = 3.1$.

Schlegel et al. (1998) mentioned that most contaminating unresolved sources such as stars, planetary nebulae, and extragalactic sources were not removed from the SFD dust map at low Galactic latitudes ($|b| < 5^\circ$), which usually results in anomalous bright blobs in the map. Moreover, the temperature distribution of the Galaxy is not well resolved (see Appendix C of Schlegel et al. 1998). Thus the SFD map at low Galactic latitudes has large uncertainties.

**B4 Planck Collaboration et al. (2014b)**

Planck Collaboration et al. (2014b) fitted the emission from Planck 353, 545, 857 GHz, and IRAS 100 $\mu$m survey data with an all-sky dust model. Their model described the SED of emission with a modified blackbody assuming thermal equilibrium in the optically thin limit:

$$I_\nu = \tau_{v_0}B_\nu(T_{\text{obs}}) \left( \frac{\nu}{v_0} \right)^{\beta_{\text{obs}}},$$

where $I_\nu$ is the specific intensity at frequency $\nu$, $B_\nu(T_{\text{obs}})$ is the Planck function at temperature $T_{\text{obs}}$, $\tau_{v_0}$ is the optical depth at a reference frequency $v_0$, and $\beta_{\text{obs}}$ defines a commonly-used power law relation of $\tau_\nu = \tau_{v_0}(\nu/v_0)^{\beta_{\text{obs}}}$. Planck Collaboration et al. (2014b) selected a reference frequency $v_0 = 353$ GHz ($\sim 850$ $\mu$m) and presented the all-sky maps of $\beta_{\text{obs}}$ at 30', $T_{\text{obs}}$ and $\tau_{353}$ at 5' resolution.

**B5 Marsh et al. (2017)**

Marsh et al. (2015) used the point process mapping (PPMAP) technique to decompose an astrophysical structure into a set of small building-block components that were parameterized by the variables...
of angular positions and dust temperature. Marsh et al. (2017) applied this technique to all Herschel infrared Galactic Plane (Hi-GAL) survey (Molinari et al. 2010) images and constructed a set of separate column density maps in twelve dust temperature intervals at a spatial resolution of 12″.

B6 Gonzalez et al. (2012, 2018)

Gonzalez et al. (2011) developed a method of obtaining the reddening maps based on the VVV photometric catalogs, which derives the mean color excess $E(J - K_s)$ maps by comparing the observed $J - K_s$ colors of the RC giants to the color of RC stars in Baade’s window. The RC giants can be selected on the CMDs with the appropriate criteria and Baade’s window is a low extinction region at $l = 1.14^\circ$, $b = -4.18^\circ$ with the known reddening value of $E(B-V) = 0.55$ (Zoccali et al. 2008). Gonzalez et al. (2012) applied this method to the VVV aperture photometric catalog (Saito et al. 2012) and obtained a $E(J - K_s)$ reddening map for the bulge area, i.e., $-10.0^\circ \leq l \leq 10.4^\circ$, $-10.3^\circ \leq b \leq 5.1^\circ$. The reddening map has variant resolutions: 6′ for $-10^\circ \leq b \leq -7^\circ$; 4′ for $-7^\circ \leq b \leq -3.5^\circ$; and 2′ for $-3.5^\circ \leq b \leq 5^\circ$. Gonzalez et al. (2011) also applied Gonzalez et al. (2011)’s method to the VVV DoPHOT PSF photometric catalog (Alonso-García et al. 2018) and derived a reddening map with the spatial resolution of 1′ for the central Galactic bulge area, i.e., $-10^\circ < l < 10^\circ$, $-1.5^\circ < b < 1.5^\circ$.

B7 Nidever et al. (2012)

Majewski et al. (2011) developed the RJCE method to obtain the foreground reddening of any normal star by combining the NIR photometry such as 2MASS and the mid-infrared (MIR) photometry such as Spitzer/IRAC. The MIR filters sample the Rayleigh-Jeans tail of a star’s SED. Because the slope of the tail is nearly independent of stellar temperature, the variation of intrinsic colors in MIR or NIR-MIR is significantly smaller than that in NIR. Taking advantage of these NIR-MIR color properties, the RJCE method can produce reliable estimates of the foreground reddening towards each individual star through adopting an optimal single NIR-MIR color, i.e., $H - [4.5]$, where $[4.5]$ represents Spitzer 4.5 μm band. Using the extinction law suggested by Zasowski et al. (2009) and Indebetouw et al. (2005), the extinction of an individual star can be obtained with:

$$A_{K_s} = 0.918 \times (H - [4.5] - 0.08)$$  \hspace{1cm} (B1)

Nidever et al. (2012) applied the RJCE method to the 2MASS and Spitzer GLIMPSE data (Benjamin et al. 2003; Churchwell et al. 2009; Majewski et al. 2007) and obtained a 2′ resolution extinction map in the Galactic plane, covering the area of $256^\circ < l < 65^\circ$ and $|b| \leq 1^\circ$ (extending $|b| < 4^\circ$ in the bulge). Specifically, Nidever et al. (2012) split the stellar sample into three subsamples: MS dwarfs, RC giants, and red giant branch (RGB) giants based on their intrinsic colors of $[J - K_s]_0$. For each of these three sub-samples, two extinction maps were created using the median and 90% percentile values of $A_{K_s}$ measured within each pixel. Nidever et al. (2012) suggested that the 90% percentile maps probably provide the most reliable estimates of the total integrated extinction due to the low fraction of foreground sources in the lines of sight. Considering the spatial distributions of different stellar populations, the maps produced by different sub-samples actually trace the dust column to different distances: $\sim$2-4 kpc for MS maps; $\sim$6-10 kpc for RC maps; and $\sim$15-24 kpc for RGB maps. On the other hand, the RC maps have the highest signal-to-noise ratio because the vast majority of sources in the data set are RC giants. Therefore, in this paper we only consider the 90% percentile extinction maps produced with the RC giants.

B8 Soto et al. (2019)

Soto et al. (2019) applied the RJCE method (Majewski et al. 2011, see the description in Sect. B7) to the VVV aperture photometric catalog (Saito et al. 2012), 2MASS, and Spitzer GLIMPSE data. They finally obtained the $A_{K_s}$ extinction maps with the spatial resolution of 1′. The maps cover $\sim$148 deg$^2$ in the Galactic disk, i.e., the area of $295^\circ \leq l \leq 350^\circ$, $-1.0^\circ \leq b \leq 1.0^\circ$ (extending to $|b| \leq 2.25^\circ$ at some longitudes). Soto et al. (2019) constructed the extinction maps with all sources, MS stars, RC giants, and RGB giants as suggested by Nidever et al. (2012), respectively, but they only release the $A_{K_s}$ map produced by all stars.

B9 Schultheis et al. (2014)

Schultheis et al. (2014) presented a 3D extinction map with a spatial resolution of 6′ in the Galactic bulge by comparing the VVV photometric catalog (Saito et al. 2012) to the Galactic Besançon model (Robin et al. 2003, 2012). Specifically, the sources from the VVV photometric catalog and the Besançon model were located into the 6′ grid of the Galactic bulge area. In each cell, the extinction can be obtained by comparing the observed color to the simulated intrinsic color while the distance can be also calculated with the distance-color relation constructed with the simulated data. Repeat this calculation iteratively until the reddened simulated color can well mimic the observed color distribution. The final 3D extinction map can trace the dust column till 10 kpc, covering the whole VVV bulge area, i.e., $-10^\circ < l < 10^\circ$, $-10^\circ < b < 5^\circ$.

B10 Surot et al. (2020)

Surot et al. (2020) presented a $E(J - K_s)$ color excess map in the Galactic bulge based on their VVV MW-BULGE-PSFPHOT catalogs (Surot et al. 2019). In each VVV tile, they selected the RC and RGB giants manually on the $J - K_s$ versus $K_s$ CMDs and then obtained the color map in a 610×500 pixel grid. All 196 color maps were

Figure A3. The $A_{K_s}^\text{RC}(X_0 = 80)$ map for the tile region "b230". The orange ellipses mark the artifacts caused by the defects of detector VIRCAM.
firstly self-calibrated maps were used by applying the absolute calibration with the reference $E(J - K_s)$ map presented by Gonzalez et al. (2012, 2018). The final color excess maps covers the whole VVV bulge area, i.e., $|l| < 10^\circ$, $-10^\circ < b < 5^\circ$, with the variant resolution of $\sim 2''-10''$.

**APPENDIX C: GLIMPSE OF VISUAL COMPARISONS OF OUR XPNICER EXTINCTION MAPS TO THE PREVIOUS DUST-BASED MAPS**

**APPENDIX D: BACKGROUND ESTIMATION FOR $A_V$ (XPNICER)**

We used two methods to estimate the background of $A_V$ (XPNICER) and obtained two backgrounds, i.e., $A_V$ (BG1) and $A_V$ (BG2).

$A_V$ (BG1) was obtained by smoothing $A_V$ (XPNICER) with a box kernel. We tried some different sizes of box kernels from $5''$ to $30''$ and found that a $25''$ box kernel can minimize the $\chi^2$ that was defined as:

$$\chi^2 = \frac{\sum_{\text{pixels}} \left[ A_V (\text{XPNICER}) - A_V (\text{Dobashi}) \right]^2}{\sigma^2 (\text{XPNICER}) + \sigma^2 (\text{Dobashi}) + \sigma^2 (\text{BG1})},$$

where $\sigma (\text{XPNICER})$ and $\sigma (\text{Dobashi})$ were the uncertainty maps of $A_V (\text{XPNICER})$ and $A_V (\text{Dobashi})$, respectively, while $\sigma (\text{BG1})$ was the noise map of $A_V (\text{BG1}).$

We note that $A_V (\text{M2b})$ was obtained by assuming a diffuse dust model that was only related to the Galactic height. We used a similar model to fit $A_V$ (XPNICER) as a slab. The model was defined as:

$$A_V (\text{BG2}) = c + A \times e^{-|b|/h},$$

where $b$ was the Galactic latitude while $c$, $A$, and $h$ were free parameters. We fitted the median profile calculated over all Galactic longitudes of $A_V$ (XPNICER) with the above model and obtained $c = 4.38$ mag, $A = 16.05$ mag, and $h = 1.41^\circ$.

**APPENDIX E: QUANTITATIVE COMPARISONS BETWEEN OUR XPNICER MAP AND PREVIOUS DUST-BASED MAPS IN FIVE SUB-REGIONS**

**APPENDIX F: CALIBRATING HERSHEY S PPMAPS WITH PLANCK DUST MAPS**

The archival Herschel data have been corrected by comparing to the Planck data (Planck Collaboration et al. 2014a). The absolute flux calibration applied a constant-offset correction to the Herschel images, which assumed a average zero-level flux value over a given map (Bernard et al. 2010). The Herschel PPMAPS were constructed with the Herschel images that were calibrated with the constant-offset correction.

However, Abreu-Vicente et al. (2017) pointed out that the constant-offset correction actually assumed that the absolute calibration was independent of angular scale. Unfortunately, the Herschel and Planck flux distribution could vary significantly within a given image, especially for the Hi-GAL images towards the Galactic mid-plane. Abreu-Vicente et al. (2017) improved a spatial dependence correction method based on Fourier transforms, which combined Planck model on large scales with the Herschel images on smaller scales. They compared these two different correction methods and found significant differences ($\gtrsim 20\%$) over $\sim 15\%$ area of a given map at low column densities and high temperatures. The ratio of column densities corrected with their Fourier transforms method and constant-offset corrected column densities can be down to $< 0.3$ and up to $> 1.1$ at different spatial scales. Therefore, the zero-point of PPMAPS could be not uniform due to the inaccurate absolute flux calibration of the Herschel Hi-GAL images.

We compared $\tau_{353}$ (PPMAP) with the $\tau_{353}$ (Planck) map (obtained in Sect. 5.1.4) at $5''$ resolution. We limited the comparison in the VVV survey area (only $|b| \lesssim 1$ due to the Herschel Hi-GAL coverage). Figure F1 shows the pixel-to-pixel relation between $\tau_{353}$ (PPMAP) and $\tau_{353}$ (Planck) for whole map and six sub-regions (see Figs. C1-C5). There are linear relations that can be fitted with the function of

$$\tau_{353} (\text{PPMAP}) = \gamma' \tau_{353} (\text{Planck}) + \delta'. \quad (F1)$$

The returned $\gamma'$ is in the range of $\sim 0.5-1$ while $\delta'$ is in the range of $\sim (1-0.3) \times 10^{-3}$. On average there is a approximating one-to-one relation between $\tau_{353}$ (PPMAP) and $\tau_{353}$ (Planck), but the ratio of $\tau_{353}$ (PPMAP) to $\tau_{353}$ (Planck) is quite different in different sub-regions, i.e., different spatial locations and scales. Therefore, $\tau_{353}$ (PPMAP) and $\tau_{353}$ (Planck) vary significantly at different angular scales. We consider this variance could result from the constant-offset absolute flux calibration of the Herschel images.

In principal, to eliminate the variance between $\tau_{353}$ (PPMAP) and $\tau_{353}$ (Planck) we need to re-calibrate the Herschel Hi-GAL images as suggested by Abreu-Vicente et al. (2017) and then construct $\tau_{353}$ (PPMAP) again with the method suggested by Marsh et al. (2017), which is obviously beyond the scope of this paper. To compare our XPNICER map and the PPMAPS, we simply calibrate $\tau_{353}$ (PPMAP) with $\tau_{353}$ (Planck) using the relations of Eq.1 for the whole map and the sub-regions. For example, Fig. F1b shows the relation between $\tau_{353}$ (PPMAP) and $\tau_{353}$ (Planck) in the region with GMF 324b (see Fig. 15). The linear fitting returns $\gamma' = 0.56$ and $\delta' = 0.00$. We calibrated $\tau_{353}$ (PPMAP) of the region with GMF 324b by multiplying it by the factor of 1.0, 56$\sim$1.8.

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Figure C1. Zoom-in view of a $2\degree \times 1\degree$ region towards $l = 299\degree$ and $b = -0.3\degree$. Others are the same as Fig. 15.

Figure C2. Zoom-in view of a $1.5\degree \times 0.8\degree$ region towards $l = 319.7\degree$ and $b = 0.9\degree$. Others are the same as Fig. 15.
Figure C3. Zoom-in view of a $\sim 2.5^\circ \times 1.6^\circ$ region towards $l = 340.75^\circ$ and $b = 0.0^\circ$. Others are the same as Fig. 15.

Figure C4. Zoom-in view of the region with RCW 120. Others are the same as Fig. 15.
Figure C5. Zoom-in view of a $\sim 3^\circ \times 2.5^\circ$ region towards $l = 352.5^\circ$ and $b = 0.25^\circ$. Others are the same as Fig. 15, except the panels (g) is the BEAM extinction map by Gonzalez et al. (2012, 2018); (h) is the extinction map obtained with RJCE method by Nidever et al. (2012); (i) is the integrated 2D extinction map by Schultheis et al. (2014); and (j) is the extinction map by Surot et al. (2020).
Figure C6. Zoom-in view of the region with the Pipe molecular cloud. Others are the same as Fig. 15, except the panels (f) is the BEAM extinction map by Gonzalez et al. (2012, 2018); (g) is the extinction map obtained with the RJCE method by Nidever et al. (2012); (h) is the integrated 2D extinction map by Schultheis et al. (2014); and (i) is the extinction map by Surot et al. (2020).
Figure E1. Pixel-to-pixel comparisons of our XPNICER extinction map with previous dust-based maps in sub-region 1 (see Fig. C1), including the extinction maps from Dobashi (2011, $A_v$ (Dobashi)) and Juvela & Montillaud (2016, $A_v$ (M2b)), the SFD map (Schlegel et al. 1998, $A_v$ (SFD)), the Planck dust map (Planck Collaboration et al. 2014b, $A_v$ (Planck)), the Herschel PPMAPS (Marsh et al. 2017, $A_v$ (PPMAP)), RJCE extinction map by Nidever et al. (2012, $A_v$ (RJCE12)), and RJCE extinction map by Soto et al. (2019, $A_v$ (RJCE19)). Others are the same as Fig. 16.
Figure E2. Pixel-to-pixel comparisons of our XPNICER extinction map with previous dust-based maps in sub-region 2 (see Fig. C2), including the extinction maps from Dobashi (2011, $A_V$ (Dobashi)) and Juvela & Montillaud (2016, $A_V$ (M2b)), the SFD map (Schlegel et al. 1998, $A_V$ (SFD)), the Planck dust map (Planck Collaboration et al. 2014b, $A_V$ (Planck)), the Herschel PPMAPs (Marsh et al. 2017, $A_V$ (PPMAP)), RJCE extinction map by Nidever et al. (2012, $A_V$ (RJCE12)), and RJCE extinction map by Soto et al. (2019, $A_V$ (RJCE19)). Others are the same as Fig. 16.
Figure E3. Pixel-to-pixel comparisons of our XPNICER extinction map with previous dust-based maps in sub-region 3 (see Fig. C3), including the extinction maps from Dobashi (2011, $A_V$ (Dobashi)) and Juvela & Montillaud (2016, $A_V$ (M2b)), the SFD map (Schlegel et al. 1998, $A_V$ (SFD)), the Planck dust map (Planck Collaboration et al. 2014b, $\tau_{353}$ (Planck)), the Herschel PPMAPs (Marsh et al. 2017, $\tau_{353}$ (PPMAP)), RJCE extinction map by Nidever et al. (2012, $A_V$ (RJCE12)), and RJCE extinction map by Soto et al. (2019, $A_V$ (RJCE19)). Others are the same as Fig. 16.
Figure E4. Pixel-to-pixel comparisons of our XPNICER extinction map with previous dust-based maps in sub-region 4 (see Fig. C4), including the extinction maps from Dobashi (2011, $A_v$ (Dobashi)) and Juvela & Montillaud (2016, $A_v$ (M2b)), the SFD map (Schlegel et al. 1998, $A_v$ (SFD)), the Planck dust map (Planck Collaboration et al. 2014b, $\tau_{353}$ (Planck)), the Herschel PPMAPs (Marsh et al. 2017, $\tau_{353}$ (PPMAP)), RJCE extinction map by Nidever et al. (2012, $A_v$ (RJCE12)), and RJCE extinction map by Soto et al. (2019, $A_v$ (RJCE19)). Others are the same as Fig. 16.
Figure E5. Pixel-to-pixel comparisons of our XPNICER extinction map with previous dust-based maps in sub-region 5 (see Fig. C5), including the extinction maps from Dobashi (2011, \(A_V\) (Dobashi)) and Juvela & Montillaud (2016, \(A_V\) (M2b)), the SFD map (Schlegel et al. 1998, \(A_V\) (SFD)), the Planck dust map (Planck Collaboration et al. 2014b, \(\tau_{353}\) (Planck)), the Herschel PPMAPs (Marsh et al. 2017, \(\tau_{353}\) (PPMAP)), BEAM extinction map by Gonzalez et al. (2012, 2018, \(A_V\) (BEAM)), and RICE extinction map by Nidever et al. (2012, \(A_V\) (RICE12)), 2D extinction map integrated from the 3D dust map by Schultheis et al. (2014, \(A_V\) (Schultheis)), and extinction map by Surot et al. (2020, \(A_V\) (Surot)). Others are the same as Fig. 16.
Figure F1. Pixel-to-pixel comparisons of the Planck dust maps and the Herschel PPMAPs in the whole VVV survey area and six sub-regions. The solid black lines show the linear fits with the slope of $\gamma'$ and the intercept of $\delta'$. The values of $\gamma'$ and $\delta'$ are also marked on each panel.