Research Article

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Fitting procedure for estimating interstellar extinction at high galactic latitudes

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Abstract: We determine the interstellar extinction in the selected high-latitude areas of the sky based on Gaia EDR3 astrometry and photometry and spectroscopic data from RAVE survey. We approximate the results with the cosecant law in each area thus deriving the parameters of the barometric formula for different lines of sight. The distribution of the parameters over the entire sky is described using spherical harmonics. As a result, we get a mathematical description of the interstellar visual extinction for different lines of sight and distances from the Sun which can be used for estimating interstellar extinction.

Keywords: interstellar extinction, surveys

1 Introduction

Taking extinction into account is an essential step in almost every astronomical, and particularly astrophysical, research. For this reason, 3D interstellar reddening or extinction maps and models are tools of great usage. Moreover, the distribution of interstellar dust, which is mostly responsible for an extinction, is itself interesting in a context of Galaxy evolution and structure studies.

The results of 3D mapping are usually presented in a form of a discrete set of extinction values corresponding to different distances from the Sun in a certain direction on the celestial sphere. Marshall *et al.* (2006) implies the population synthesis Besançon model of the Galaxy along with 2MASS photometry. The 3D map constructed is available as a table in Vizier. Sale *et al.* (2014) produced a 3D map based on hierarchical Bayesian model using the IPHAS photometric data. Both works mentioned above are focused only on low-latitude areas of the sky, mainly the part of the Galactic plane, which makes them unsuitable for the high-latitude estimation of the interstellar extinction.

Green *et al.* (2019) also constructed a 3D map using the Bayesian method, Gaia, Pan-STARRS 1, and 2MASS data.

The results can be downloaded for the particular lines of sight or en bloc for all available directions. It covers roughly a three quarters of the sky and has a minimum reliable distance due to saturated Pan-STARRS stars. The typical value for that minimum is about 300 pc, that is, behind the main fraction of the dust in high galactic latitudes.

Lallement *et al.* (2014) implied regularized Bayesian approach to color excesses datasets based on Strömgren catalogs, the Geneva photometric database, and the Geneva-Copenhagen survey. Later, Lallement *et al.* (2019) used 2MASS photometry and Gaia DR2 astrometry to produce a map of interstellar dust within 3 kpc. Both maps are available as tables. The first work mentioned has an online service to extract the reddening for the particular line (or lines) of sight. The second one is a table constructed in Euclidean coordinates with no extraction for a particular line of sight provided.

Unlike maps, models are defined by some formulas, which makes them easier to use. Nonetheless, various parameters of the formulas can be also given in a tabular form, since their difference on the different parts of the sky can be significant. Here we also take a quick look at the reliable models to date.

The first one, developed by Parenago (1940), considers a barometric (exponential) function:

$$A_V(b, d) = \frac{a_0 \cdot \beta}{\sin |b|} \left(1 - \exp \left(\frac{-d \cdot \sin |b|}{\beta} \right) \right), \quad (1)$$

It represents the classical model of a homogeneous, semi-infinite absorbing layer with a density exponentially distributed with height. The parameter β is the scale height, and a_0 is the extinction per unit length in the Galactic plane.

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Although the formula is still relevant for the lines of sight individually, Parenago (1940) implied the constant parameters on the sphere, which is obviously not the case.

The model constructed by Arenou *et al.* (1992) uses a quadratic distance function with the coefficients of the function listed in the table for different directions of the sky. The values of A_V calculated with this model actually become constant in polar caps due to the low number of stars used there.

Gontcharov (2009) presented a model of interstellar extinction that takes into account the Gould Belt – an additional extinction layer. Author implies that the change in the extinction over longitude (separately along the equatorial Galactic plane and in the Gould Belt) has a sinusoidal function. The extinction across the layers varies according to Eq. (1). The model has shown a good agreement with several existing maps of interstellar extinction.

Lately, Gontcharov and Mosenkov (2021a) and Gontcharov and Mosenkov (2021b) have built the model of interstellar extinction based on the Gaia DR2 parallaxes and Gaia and WISE photometry for over a hundred thousand of giants and proposed the 3D dust distribution for this model. The model is a highly improved and refined version of Gontcharov (2009) and Gontcharov (2012) models with an elliptical and off-centred dust layer in the Gould belt.

Present work follows the approach developed in Nekrasov *et al.* (2021). Authors used the cosecant law (Eq. (1)) to describe the change of interstellar extinction in radial direction, as most of the models mentioned above do, but the variations on the sphere were described with the harmonic functions. The work was based on the Gaia EDR3 photometry and spectroscopic parameters from the LAMOST data.

Since the LAMOST data covers only the Northern hemisphere, the Nekrasov *et al.* (2021) lacks the approximation points in the Southern sky, which reduces the reliability of the model in this area. We use the RAVE DR6 (McMillan 2020) data, which covers the Southern sky, to perform the same research and enhance the Nekrasov *et al.* (2021) model. We calculate the visual extinction A_V in 40 different high-latitude areas of the Southern sky on the basis of RAVE DR6 temperatures of the stars and Gaia EDR3 photometry and astrometry (Prusti *et al.* 2016), (Brown *et al.* 2021). Then we estimate the parameters a_0 and β of the Eq. (1) for each of the selected area. We approximate the parameters estimated in this work along with the ones found by Nekrasov *et al.* (2021) by spherical harmonics over the entire sky.

The paper is organised as follows. In Section 2 we describe the data that was used and calculate the visual extinction of objects at individual areas of the sky. Section

3 contains the description of approximation methods and the resulting parameters a_0 , β . In Section 4 we present the results of approximation over the entire sky. Finally, in Section 5 we discuss the perspectives of this work.

2 Observational data and obtaining the extinction

We have selected 40 different areas in the RAVE coverage at high ($|b| > 20^\circ$) latitudes (see Figure 1). A limit of $|b|$ was chosen because the cosecant law is believed to satisfactorily reproduce the $A_V(d)$ dependence at high latitudes far from the Galactic plane. Each area is a cone of 80 arcsec radius, defined by its center.

Figure 1. The distribution of selected areas over the sky in galactic coordinates. Aitoff projection.

We made a cross-match of RAVE DR6 and Gaia EDR3 objects within every area. For each object distances were adopted from Bailer-Jones *et al.* (2021) catalogue. We have chosen BDASP catalogue of RAVE DR6 (https://www.rave-survey.org/metadata/ravedr6/dr6_bdasp/) to get the spectroscopic parameters of stars.

For individual stars in each area we have calculated the visual extinction, using the following formula:

$$A_V = \frac{c_1}{c_2} \cdot ((BP - RP) - (BP - RP)_0), \quad (2)$$

where c_1 is A_G to $E(BP - RP)$ ratio and c_2 is an absorption coefficient, A_G to A_V ratio. A_G is the interstellar extinction in G-band of Gaia. According to (Danielski *et al.* 2018) $c_2 = 0.84$. The coefficient $c_1 = 2.02$ was calculated according to Cardelli *et al.* (1989) assuming that the R_V value equals to 3.1.

In fact, c_1 and c_2 are not constants due to broad G-band of Gaia (Danielski *et al.* 2018); also see <https://www.cosmos.esa.int/web/gaia/edr3-extinction-law>. If A_0 is the interstellar extinction at $\lambda = 550$ nm, A_G/A_0 , A_{BP}/A_0 , A_{RP}/A_0 may vary depending on effective temperature and $\log g$ of a star, and on A_0 itself. Basically, $A_k/A_0 < 1$. How-

Figure 2. Comparison of our extinctions with three different 3D maps or models of interstellar extinction. Green solid line is made from values provided by Stilism (Lallement *et al.* (2014)). Orange dash-dotted line adopted from Arenou *et al.* (1992). Red dashed line refers to a Gontcharov and Mosenkov (2021b) model, according to authors, uncertainties of A_V are less than 0.03 mag.

ever, extinctions at the high galactic latitudes we consider are under 1 mag, and due to reasons described below in this paragraph we do not take into account stars of spectral type later than K6. Moreover, both coefficients c_1 , c_2 vary consistently so for its ratio in Eq. (2) variations are negligible. In present work, we neglect it.

The intrinsic colours $(BP - RP)_0$ were calculated according to Pecaut and Mamajek (2013) (the table is published also on a <http://www.pas.rochester.edu/~emamajek/>

EEM_dwarf_UBVIJHK_colors_Teff.txt), where the intrinsic colours provided for different effective temperatures. For this purpose we have used the effective temperatures T_{eff} of RAVE DR6 BDASP catalogue. In the intervals between the values given in the table we performed a linear approximation.

In some areas the overall extinction trend with distance turned out to be negative due to low values of extinction to distant objects. We associate this with improper temperature derivation for some objects in RAVE data. To eliminate the stars with outrageously low extinctions at far distances, we set the following restrictions on the data used for the work: $1.6 > BP - RP > 0.8$ and $\log g > 3.5$. Other data issues and possible reasons are discussed in the Section 3.1.

We compared our extinctions remaining after sifting with three different models or 3D maps of interstellar extinction in four different areas of the sky. The comparison is presented in Figure 2.

3 Deriving the parameters of the cosecant law in individual areas

To obtain the parameters a_0 and β of the cosecant law we have minimized the following χ^2 functional:

$$\chi^2 = \sum_{n=1}^N \left(\frac{A_V(d_n) - A_{V,n}}{\epsilon_n(d_n, A_{V,n})} \right)^2 \quad (3)$$

Here $A_{V,n}$ are the extinction values we have calculated in Section 2; $A_V(d_n)$ – values, predicted by the cosecant law (1) for a distance d_n ; ϵ_n – uncertainty of extinction and distances, N is the total number of objects in the area.

We used two methods for finding the minimum of the functional: beat-fit χ^2 minimization and χ^2 scan. Methods are described below.

3.1 Best-fit χ^2 minimization

The minimization of Eq. (3) was performed with lmfit package of Python (Newville *et al.* 2014). We have used the Levenberg-Marquardt algorithm. The standart errors are 1σ uncertainty, estimated by inverting the Hessian matrix, calculated also with lmfit package. Examples of successful estimation of a_0 and β parameters are presented in Figure 3.

The approximation was performed successfully for 36 of 40 areas. In three other areas there was no solution found. It could be both due to the number of negative values of extinction and the inadequate trend of extinction, non-

Figure 3. Examples of χ^2 minimization. Galactic coordinates of the center of the region are on top of each graph. Green line is the result of approximation with best-fit χ^2 minimization and the red one is the solution obtained with χ^2 -scan.

monotonic or decreasing. Another one area we have eliminated is the one with doubtfully low value of a_0 . We have kept the solutions with preposterous values of uncertainties such as areas number 3, 20 and 37 (these numbers can be found in Table 1) because they have reasonable values of a_0 and β and thus can contribute to the all-sky approximation.

We assume the main problem with approximation in “bad” regions is due to systematic effects affecting values of T_{eff} in RAVE catalogue. We believe so since the temperatures adopted from the LAMOST data and the RAVE data for the same objects from the intersection of the surveys differ systematically. While the research of Nekrasov *et al.* (2021) based on the LAMOST data did not show this strong discrepancies with the cosecant law, our present research based on the RAVE DR6 data, sometimes shows the result inconsistent with Eq. (1). The offsets in LAMOST–RAVE overlapping data have been noticed earlier Vickers and Smith (2018) for the radial velocities. The comprehensive analysis of temperatures offset will be made and published in a subsequent paper.

3.2 χ^2 scan

Additionally to Levenberg-Marquardt algorithm of minimization we calculated the χ^2 values on the (a_0, β) grid and found the χ^2 minimum via brute-force search. We have calculated the standard errors as a 1σ – contour. Figure 4 shows a χ^2 maps for the same areas on the sky as in Figure 3. The results are also indicated in Figure 3 as red lines. If there are only one green line visible on the plot, then two solutions coincide.

Figure 4. Examples of χ^2 -scan solutions for the same areas as in Figure 3.

Size and shape of blue area on the χ^2 map represents the degeneracy of the parameters, *i.e.* the range of the parameters a_0 and β , corresponding to the χ^2 values close to the minimum, could be quite broad. That results in large standard errors. Note that in this method errors are naturally restricted by the size of the grid and not always represent the actual uncertainty.

Large blue regions on the χ^2 maps can also be associated with the data reliability, discussed in previous subsection.

3.3 The results of approximation within the areas

In both methods, the χ^2 is calculated. We chose between the two methods in each area the method which provide the minimal χ^2 value. Final results are presented in Table 1.

We have also calculated the estimation for the total Galactic extinction. The total Galactic visual extinction A_{Gal} , *i.e.* the extinction in V band, produced by the interstellar medium, is of particular interest in the context of extragalactic researches. Moreover, it plays crucial role in distance scaling, because the scale relies on the distance to reference objects and depends on their absolute magnitudes, which require knowledge of the total Galactic extinction.

The Galactic extinction could be estimated from the Parenago formula (1) if distance tends to infinity:

$$A_{Gal}(l, b) = \frac{a_0 \cdot \beta}{\sin |b|} \quad (4)$$

We have calculated values of A_{Gal} for each of our areas. The results are also presented in Table 1. We compared A_{Gal} val-

Table 1. Interstellar extinction in the selected areas

Area	l	b	a_0 , mag/kpc	β , pc	A_{Gal}
1	5.0	-30.0	6 ± 16	14 ± 32	0.18 ± 0.66
2	30.0	-30.0	0.8 ± 0.4	55 ± 32	0.09 ± 0.03
3	230.0	-30.0	$7 \pm 9e5$	$3 \pm 4e5$	0.05 ± 900
5	280.0	-30.0	5 ± 13	15 ± 37	0.16 ± 0.56
6	305.0	-30.0	15 ± 54	11 ± 41	0.35 ± 1.75
7	330.0	-30.0	0.7 ± 0.2	216 ± 110	0.31 ± 0.18
8	17.0	-45.0	3.4 ± 31.4	19 ± 172	0.09 ± 1.17
9	46.0	-45.0	0.5 ± 0.2	330 ± 397	0.23 ± 0.29
10	195.0	-45.0	3.5 ± 8.5	32 ± 79	0.16 ± 0.55
12	270.0	-50.0	0.22 ± 0.24	210 ± 440	0.06 ± 0.14
13	290.0	-45.0	0.9 ± 2.4	40 ± 115	0.05 ± 0.19
15	335.0	-45.0	0.2 ± 0.9	70 ± 360	0.02 ± 0.14
16	26.0	-56.9	0.05 ± 2.2	50 ± 2000	0.003 ± 0.18
17	96.7	-72.9	1.6 ± 2.9	60 ± 120	0.1 ± 0.3
18	200.0	-60.0	2 ± 15	30 ± 220	0.08 ± 0.7
19	290.0	-60.0	5 ± 520	12 ± 1300	0.1 ± 10
20	20.0	-70.0	$6 \pm 7e4$	$7 \pm 8e4$	0.05 ± 800
22	340.0	-70.0	0.21 ± 0.04	190 ± 700	0.04 ± 0.17
23	275.0	30.0	3.2 ± 8.5	15 ± 43	0.1 ± 0.4
24	290.0	30.0	0.9 ± 0.5	115 ± 114	0.2 ± 0.2
25	320.0	30.0	6 ± 390	9 ± 590	0.1 ± 9.5
26	350.0	30.0	9.2 ± 8.1	15 ± 13	0.28 ± 0.35
27	10.0	30.0	10.5 ± 2.2	29.3 ± 6.6	0.61 ± 0.19
28	113.0	-85.0	0.1 ± 0.5	140 ± 1000	0.014 ± 0.119
29	260.3	46.3	0.5 ± 0.9	100 ± 200	0.07 ± 0.19
30	279.5	45.8	0.42 ± 0.45	110 ± 170	0.07 ± 0.12
31	305.0	45.0	6 ± 30	20 ± 100	0.17 ± 1.25
32	330.0	45.0	2.50 ± 1.15	55 ± 28	0.19 ± 0.13
33	242.0	-22.0	2.3 ± 25.0	10 ± 110	0.06 ± 0.92
34	269.0	-23.0	6.4 ± 21.0	13 ± 45	0.2 ± 1.0
35	310.0	-22.0	4.8 ± 1.6	41 ± 19	0.5 ± 0.3
36	19.9	-24.8	6.9 ± 3.5	28 ± 16	0.5 ± 0.4
37	262.3	22.3	$19 \pm 7e6$	$1.5 \pm 5e5$	$0.07 \pm 4e5$
38	335.0	-26.5	7.5 ± 2.6	22 ± 8	0.37 ± 0.19
39	283.9	-22.4	1.91 ± 1.98	31 ± 39	0.16 ± 0.25
40	245.4	-20.3	4.3 ± 7.6	20 ± 38	0.26 ± 0.68

Figure 5. Galactic extinction A_{Gal} in comparison with Schlafly and Finkbeiner (2011). The one-to-one relation is shown as a solid line.

ues with the values, predicted by Schlafly and Finkbeiner (2011) (Figure 5).

4 Approximation of cosecant law parameters over the entire sky and final formula

Finally, we have approximated the parameters a_0 , β and the total Galactic extinction A_{Gal} by a polynomial composed of spherical harmonics of degree and order 2:

$$f(l, b) = A_{00}Y_0^0\left(l, \frac{\pi}{2} - b\right) + A_{10}Y_1^0\left(l, \frac{\pi}{2} - b\right) + A_{11}Y_1^1\left(l, \frac{\pi}{2} - b\right) + A_{20}Y_2^0\left(l, \frac{\pi}{2} - b\right) + A_{21}Y_2^1\left(l, \frac{\pi}{2} - b\right) + A_{22}Y_2^2\left(l, \frac{\pi}{2} - b\right) \quad (5)$$

For the approximation, we used the parameters for 36 out of 40 areas. They are listed in Table 1. We also used the data obtained from Nekrasov *et al.* (2021). The coefficient of the polynomial for a_0 , β and A_{Gal} approximation are presented in Table 2.

Table 2. The coefficients of the polynomial approximation for a_0 , β and A_{Gal} . The approximation results are only valid for areas with $|b| > 20^\circ$. Also, they can not be used in the areas marked as blank spaces in Figure 6.

$f(l, b)$	a_0	β	A_{Gal}
A_{00}	10.0 ± 1.5	811.4 ± 210.2	0.967 ± 0.113
A_{10}	-0.9 ± 1.5	495.3 ± 212.4	-0.148 ± 0.114
A_{11}	-6.64 ± 2.18	715.7 ± 298.9	0.02 ± 0.16
A_{20}	-4.0 ± 1.8	336.3 ± 250.6	-0.51 ± 0.13
A_{21}	-2.6 ± 1.9	520.2 ± 266.8	-0.43 ± 0.14
A_{22}	0.77 ± 2.19	32.4 ± 300.5	0.56 ± 0.16

Substituting the values of the coefficients A_{ij} into the Eq. (5) and then into the cosecant law (Eq. (1)), one could get an analytical expression to estimate the interstellar extinction in particular line of sight at particular distance.

We should note, that due to the harmonic form of the function, there are areas in approximation where the values of parameters become negative. They are shown in Figure 6 with blank spaces. In these areas we either can say nothing about the extinction or it is approximately equals to zero (as on polar region). We do not recommend to use the approximation within these areas. We also want to emphasise that present approximation provides estimates only for galactic latitudes $|b| > 20^\circ$.

Figure 6. Approximation of parameters over the sky. The areas with negative values are indicated as blank spaces.

4.1 Uncertainties

The uncertainties of a_0 , β and A_{Gal} depend on latitude and longitude of the line of sight and can be calculated as follows:

$$\delta f(l, b) = \left[\delta A_{00}^2 \cdot k_{00}^2 + \delta A_{10}^2 \cdot k_{10}^2 + \delta A_{11}^2 \cdot k_{11}^2 + \delta A_{20}^2 \cdot k_{20}^2 + \delta A_{21}^2 \cdot k_{21}^2 + \delta A_{22}^2 \cdot k_{22}^2 \right]^{1/2} \quad (6)$$

where $k_{i,j} = Y_i^j(l, \frac{\pi}{2} - b)$.

One can also estimate the relative uncertainty of A_V with this formula which depends on latitude, longitude and distance:

$$\frac{\delta A_V}{A_V}(l, b, d) = \left[\frac{\delta a_0^2}{a_0^2} + \frac{\delta \beta^2}{\beta^2} \cdot \left(1 + \frac{d \cdot \sin(|b|)}{\beta} \cdot \frac{\exp(-\frac{d \cdot \sin(|b|)}{\beta})}{(1 - \exp(-\frac{d \cdot \sin(|b|)}{\beta}))} \right) \right]^{1/2} \quad (7)$$

Figure 7. The examples of the visual extinction to distance dependence, calculated with our formula (Eq. 5). The uncertainties were also calculated and shown as a colour-filled area.

The examples of the interstellar extinction A_V calculated with the uncertainty are shown in Figure 7. Generally, the relative uncertainty tends to be larger on higher latitudes, although it depends on the longitude as well.

5 Summary and future plans

We have obtained the interstellar visual extinction of objects in 40 areas of the southern sky with Gaia EDR3 and RAVE DR6 data. Comparison of calculated extinctions with various interstellar extinction models or maps shows qualitative similarity, which indicates the adequacy of chosen method of extinction determination.

Approximation in areas showed that the quality of data is not satisfying. In some areas no successful approximation has been performed due to odd trend. We assume that this problem is caused by inadequate RAVE temperatures. Hopefully, homogenisation will be made and eliminate that problem.

The all-sky approximation with spherical harmonics was made and the approximate analytical description was obtained. Nonetheless, there are regions where the solution tends to zero within the margin of error (regions with negative values of parameters), so no reasonable solution can be found. It is necessary to reduce the approximation error by an order of magnitude to obtain reasonable solutions for areas with low total extinction. Additionally, present investigation is based on data for high galactic latitudes, and its results apply only to areas with $|b| > 20$.

The issue with the discrepancy of effective temperatures adopted from LAMOST and RAVE surveys still remains. Using other surveys (like APOGEE or SEGUE) will probably help us to get an additional information and draw the conclusions about the reliability of the data used by comparing temperatures.

We also plan to include stars from the outside of main sequence both in Southern and Northern sky. Moreover, we want to extend our investigation to low galactic latitudes probably with more complex $A_V(d)$ law. For instance, we want to take into account the Gould Belt as an another light absorbing structure with its own a_0 , β parameters.

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