Research Article

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# Interstellar extinction from photometric surveys: application to four high-latitude areas

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**Abstract:** Information on interstellar extinction and dust properties may be obtained from modern large photometric surveys data. Virtual Observatory facilities allow users to make a fast and correct cross-identification of objects from various surveys. It yields a multicolor photometry data on detected objects and makes it possible to estimate stellar parameters and calculate interstellar extinction. A 3D extinction map then can be constructed. The method was applied to 2MASS, SDSS, GALEX and UKIDSS surveys. Results for several high-latitude areas are obtained, compared with independent sources and discussed here.

**Keywords:** Extinction, Surveys, Photometry, Supernovae

## 1 Introduction

One of the main problems of astrophysics is the study of physical properties of the surface layers of stars. Stars are observed through the interstellar dust, therefore their light is dimmed and reddened. This fact complicates the parameterization and classification of stars. Parameters of a star, as well as interstellar reddening, can be obtained from its spectrum. However, to get spectral energy distribution with good dispersion and sufficient accuracy one needs to use large telescope unless the investigated object is bright enough. This work was performed by various authors, and a number of empirical atlases were constructed (Straizys and Sviderskiene (1972), Glushneva et al. (1992), Alekseeva et al. (1996), Alekseeva et al. (1997), Pickles (1998), Bagnulo et al. (2003), Le Borgne et al. (2003), Valdes et al. (2004), Heap and Lindler (2007), Falcón-Barroso et al. (2011), Wu et al. (2011)). However Mironov et al. (2014) made a critical analysis, compared data for stars included in several atlases, and found a large number of discrepancies.

Another way to construct a map of interstellar extinction is the estimation of extinction (as well as stellar parameters) from evolutionary tracks. Corresponding procedures were developed in Sichevsky and Malkov (2016), Sichevskij (2016), Sichevskij (2017a) and applied to LAMOST data by Sichevskij (2017b). However, a knowledge of stellar atmospheric parameters is highly desirable for application of these procedures. It significantly limits a number of stars used for such a parameterization.

Therefore, the solution of the problem of parameterization of stars based on their photometry is a topical issue. It was preliminary studied in Malkov (2003). A great variety of photometric systems (see, e.g., Straižys (1992) for references) and recently constructed large photometric surveys as well as VO-tools for cross-matching their objects provide us with a possibility to get multicolor photometric data for millions of objects. Consequently, it allows user to

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parameterize objects and determine interstellar extinction in the Galaxy.

We present a method and results of obtaining the most reliable stellar parameters based on multicolor 2MASS, SDSS, GALEX and UKIDSS photometry. Also, the method allows us to estimate interstellar extinction value and distance to the star, and, consequently, to construct a 3D model of the galactic interstellar extinction.

We have made a comparative analysis of available 3D maps of interstellar extinction Kilpio and Malkov (1997a) and found that the investigated maps often demonstrate contradictory results. As a temporary solution of that problem, a synthetic map of the galactic interstellar extinction can be compiled Kilpio and Malkov (1997b), Hakkila et al. (1997), Malkov and Kilpio (2002).

Early dust maps used the correlation between the dust column density and the distribution of neutral hydrogen Burstein and Heiles (1982). These data were supplanted by the dust maps produced by Schlegel et al. (1998), who used full sky microwave data made available by the IRAS satellite and the DIRBE (Diffuse Infrared Background Experiment) instrument on the COBE mission. Mapping the dust column densities via the calibrated dust temperature, the extinction maps, assuming a standard reddening law, were shown to be at least twice as accurate as those of Burstein and Heiles (1982). An advantage of this method is that it does not rely on a predefined model for the stellar population.

Different aspects and pilot results of parameterization of stars from multicolor photometry are presented here. Construction of a 3D map of galactic interstellar extinction is also discussed.

This paper is organized as follows. Cross-matching of surveys is discussed in Section 2. Section 3 covers the basic theory of our approach and describes the method used. We illustrate the practical application procedure in Section 4, detailing selection and features of the data. We quantify the performance of the method in Section 5, comparing our results with observational data. We make conclusions and discuss our future plans in Sections 6 and 7, respectively.

## 2 Cross-matching of surveys

To get all available multicolor photometry for investigated objects we have constructed a tool for cross-matching of objects in most known and widely used surveys. The principal aim is to reliably link the same object data in different surveys, having (i) different sky coverage, (ii) different detection limits, and (iii) different object densities. To achieve this goal an algorithm of fast positional matching of large astronomical catalogues in small areas with false solution filtering was developed.

To test the tool it was applied to several 0.1 degree areas, where objects from DENIS, 2MASS, SDSS, GALEX, UKIDSS surveys were selected and cross-matched. Corresponding sub-catalogues were compiled in the VOTable format (Malkov and Karpov (2011), Karpov et al. (2012), Malkov et al. (2012)).

To perform the analysis described later in Section 3, a set of photometric data is required. We use stars selected from the 2MASS Skrutskie et al. (2006), GALEX Martin et al. (2005), United Kingdom Infrared Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS; Lawrence et al. (2007)) and SDSS Aihara et al. (2011).

By using real data, we are able to use the proper photometric errors and intrinsic scatter, instead of depending on synthetic estimates. We perform a cross-match to generate a catalogue of stars with photometry in (maximum thirteen) bands. The bands ugriz are from SDSS, $JHK_S$ are from 2MASS, FUV and NUV are from GALEX, and YJHK are covered by UKIDSS LAS. In principle, we can also use (or combine) other surveys, as our method can easily be trained on further photometric data.

## 3 Model

To find spectral type SpT, distance $d$ and interstellar extinction $A_V$ we minimize the functional

$$D^2 = \sum_{i=1}^{N} \left( \frac{m_{obs,i} - m_{calc,i}}{\Delta m_{obs,i}} \right)^2 , \qquad (1)$$

where summation goes over all photometric bands (N=13 at most, see Section 2), and

$$m_{calc,i} = M_i(\mathrm{SpT}) + 5 \log \mathrm{d} - 5 + \mathrm{A_i(A_V)}, \qquad (2)$$

Here $m_{obs,i}$ and $\Delta m_{obs,i}$ are apparent magnitude in i-th photometric band from a survey and its observational error, respectively. $A_i(A_V)$ is the interstellar extinction law (see Section 3.1), and $M_i$(SpT) is the absolute magnitude in i-th photometric band taken from calibration tables (see Section 3.2).

### 3.1 Interstellar extinction law

To predict the star's colors in our model we need extinction coefficients for photometric bands of the used surveys, listed in Section 2. To compute extinction in a photometric band, in turn, one needs to know the passband function of the corresponding filter and extinction curve (for extinction curves see, e.g., Fluks et al. (1994), Cardelli et al. (1989), Fitzpatrick (1999), Fitzpatrick and Massa (2007)). Such calculations of extinction for classical and modern photometric systems were made, e.g., by Heiser (1977), Rieke and Lebofsky (1985), Schlegel et al. (1998), Draine (2003), Wright et al. (2010), Schlafly and Finkbeiner (2011), Yuan et al. (2013).

We have used data from the last two studies: data for 2MASS, SDSS and GALEX were taken from Yuan et al. (2013) whereas data for UKIDSS and Johnson V-band were adopted from Schlafly and Finkbeiner (2011). Both teams have made calculations for SDSS photometry, and our comparison shows a very good agreement between their results.

As is customary, we used a fixed value of the total to selective extinction ratio $R_0 = 3.1$, which in reality is only a mean value for the diffuse ISM (e.g. Savage and Mathis (1979), Seaton (1979), Wegner (1989), Berdnikov and Pavlovskaya (1991), Stasińska et al. (1992), Zasowski et al. (2009), Schlafly and Finkbeiner (2011) rather than any individual line of sight in the Galaxy. Variations of $R_0$ in some individual directions were studied, e.g., in Tovmassian et al. (1994), Gómez de Castro et al. (2015).

## 3.2 Absolute magnitude calibration

To properly parameterize objects cross-matched in the used surveys (Section 2), one needs absolute magnitudes of stars of different spectral types in the corresponding photometric systems. Such data for various surveys can be found, e.g., in Covey et al. (2007), Kraus and Hillenbrand (2007), Findeisen and Hillenbrand (2010), Findeisen et al. (2011), Pecaut and Mamajek (2013)). Data for M-stars can also be found in Bochanski et al. (2007) and West et al. (2011). We have compiled a table of absolute magnitudes in 2MASS, SDSS and GALEX surveys using Kraus and Hillenbrand (2007), and Findeisen et al. (2011) data. The resulting table contains magnitudes for B8V-L0V stars (B8V-K5V for GALEX FUV and NUV filters).

Due to lack of published data, UKIDSS absolute magnitudes were calculated from 2MASS magnitudes and 2MASS-UKIRT relations from Hodgkin et al. (2009). This can lead to the appearance of internal correlations, which should be taken into account. However, as we found later, 2MASS data can be ignored if other three surveys are used.

In the current study we consider only MS-stars. Synthetic SDSS/2MASS photometry for giants and supergiants

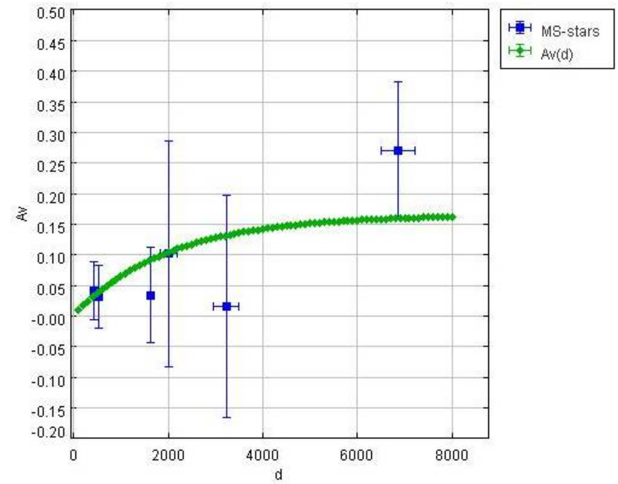


**Fig. 1.** $A_V(d)$ relation for area 1

are available in Covey et al. (2007), however, we consider an absence of UV (i.e., GALEX) photometry as a serious impediment to correct parameterization of stars.

## 3.3 Error budget

To calculate errors of the resulting parameters, we assume

$$\sigma_{Av}^2 = \sum_{i=1}^{N} \left(\Delta m_{obs,i}\right)^2, \tag{3}$$

and

$$\sigma_{log(d)} = 0.2\sigma_{Av}, \tag{4}$$

Certainly, here we underestimate the error values. To calculate errors more correctly, one should take into account also calibration tables errors and relations errors

Belikov and Röser (2008), estimating stellar astrophysical parameters from Johnson and 2MASS photometry (and based on stellar atmospheres models), found that, when mean errors of input colors are better than 0.01 mag, the best results are achieved for MS mid-G to late-K stars.

Hanson and Bailer-Jones (2014), combining SDSS and UKIDSS surveys, obtained a residual mean absolute error for extinction $A$ of 0.23 mag, and they mentioned that this value is up to 50 per cent better than just using SDSS photometry.

# 4 Application of the model

We now apply the model to estimate interstellar extinction for several areas of the sky where individual estimates were made by Schlegel et al. (1998), and used to calculate

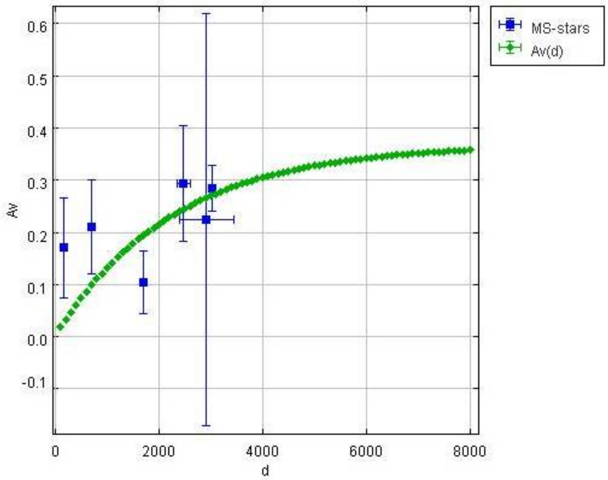


**Fig. 2.** $A_V(d)$ relation for area 2

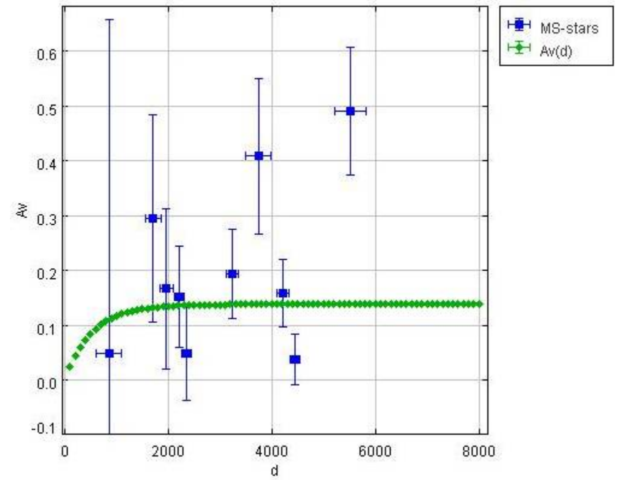


**Fig. 3.** $A_V(d)$ relation for area 5

**Table 1.** Most distant SN data from Perlmutter (1999)

| N | SN name | l | b | $A_R$ | $A_V$ |
|---|---|---|---|---|---|
| 1 | SN 1997ap | 334 | +61.9 | 0.13 | 0.17 |
| 2 | SN 1996cl | 257 | +48.7 | 0.18 | 0.24 |
| 3 | SN 1997G | 202 | −26.5 | 0.20 | 0.27 |
| 4 | SN 1997R | 257 | +48.5 | 0.11 | 0.15 |
| 5 | SN 1996ck | 301 | +62.1 | 0.13 | 0.17 |
| 6 | SN 1995at | 129 | −58.1 | 0.07 | 0.09 |

N is the area number; l,b are galactic coordinates. Interstellar extinction in R-band is taken from Perlmutter et al. (1999), and $A_V = A_R/0.751$ (see, e.g., Rieke and Lebofsky (1985); Cardelli et al. (1989)).

**Table 2.** Interstellar extinction parameters

| N | Ob | MS | $a_0$ | $\beta$ | $A_{V,\infty}$ | $A_{V,SN}$ |
|---|---|---|---|---|---|---|
| 1 | 44 | 6 | 0.08 | 1800 | 0.16 | 0.17 |
| 2 | 49 | 6 | 0.16 | 1720 | 0.36 | 0.24 |
| 5 | 58 | 10 | 0.25 | 480 | 0.14 | 0.17 |
| 6 | 100 | 4 | 0.25 | 240 | 0.07 | 0.09 |

N is the area number; Ob and MS, respectively, are number of objects and number of MS-stars among them, used for approximation. Parameters $a_0$ and $\beta$ (see Eq (5)), are derived from approximation. $A_{V,\infty}$ values are calculated from Eq. (6), meanwhile $A_{V,SN}$ are values from Perlmutter et al. (1999), for comparison.

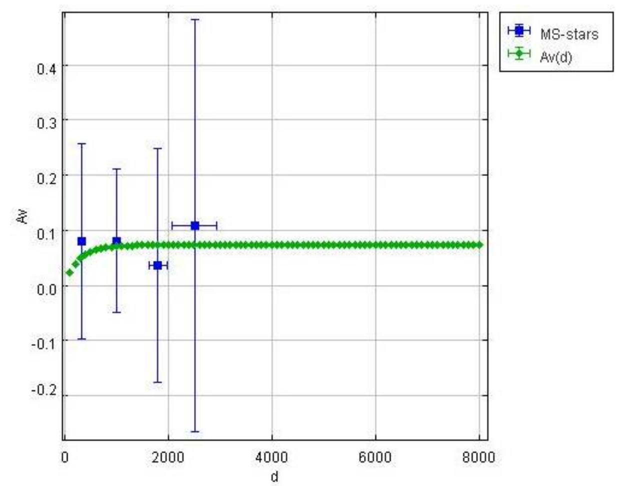


**Fig. 4.** $A_V(d)$ relation for area 6

extinction for SNs in the Universe accelerating expansion study Perlmutter et al. (1999). The data are presented in Table 1. Areas 3 and 4 were disregarded, as they are not covered by UKIDSS (area 4 is not also covered by SDSS). For four remaining areas parameterization was performed. Objects were cross-matched in 5-arcmin radius from the points listed in Table 1. Altogether 251 objects were found (and cross-matched) in the areas, but only 26 of them were successfully parameterized. Principles of objects rejection are presented in the next Section.

## 4.1 Selection of objects for further analysis

There is a number of reasons to remove objects from further consideration. First, original surveys contain various flags, namely, “Binary object” (2MASS, UKIDSS), “Non-stellar/extended object” (2MASS, SDSS, GALEX, UKIDSS), “Observation of low quality” (SDSS). Secondly, we did not consider too bright objects and objects with large observational errors.

Also, in the current study we deal with areas located at relatively high galactic latitudes ($|b| > 45^o$). Consequently, $A_V$ is assumed to be within 0.5 mag, and distance $d$ is assumed to be within 8000 pc. We have removed objects demonstrated larger values for those parameters from the further consideration. Certainly, we have also removed object with formally negative $A_V$ or $d$ value (possible reasons for such solutions are discussed in Section 5).

Finally, for every object we have performed a rough parameterization (based on 2MASS+SDSS photometry only) with Covey et al. (2007) absolute magnitude tables (see Section 3.2). Object was removed if this procedure showed that there was a high probability for it to be a non-MS star (giant or supergiant). We remind that here we consider MS-stars only.

### 4.2 Construction of $A_V(d)$ relations

After parameterization of individual stars we can construct an interstellar extinction – distance ($A_V(d)$) relation for a given area in the sky. It is assumed that this relation is kept unchanged in the whole area. Cosecant law Parenago (1940) seems to be a good approximation for high galactic latitudes $b$:

$$A_V(d,b) = \frac{a_0\beta}{\sin|b|}\left(1 - e^{\frac{-d\sin|b|}{\beta}}\right), \qquad (5)$$

where $a_0$ (magnitude of the absorption per kpc) and $\beta$ (vertical scale of absorbing matter distribution) are parameters, which we should estimate for each area.

Note that, in accordance with Eq. (5)

$$A_V(b) \to \frac{a_0\beta}{\sin|b|} \qquad (6)$$

at $d \to \infty$.

Resulting $A_V(d)$ relations are shown in Figs. 1-4 and calculated values are listed in Table 2.

One can see that our 5'-circle areas contain 4 to 10 successfully parameterized stars. This is a strong proof of advantage of combination of multicolor photometry from large modern surveys, as without these data, in previous models one could use, on average, 0.0025 objects per 5'-circle.

Analysis of interstellar extinction parameters in the areas (see Table 2) and areas' coordinates (see Table 1) shows that there is no correlation between $a_0$ or $\beta$ and galactic longitude. However we should note that four areas do not provide enough data for reliable conclusion on such a correlation.

## 5 Comparison with observational data and discussion

To obtain quantitative estimate of credibility of the presented model, we compare the computed stellar parameters with those from LAMOST DR4. We managed to find in LAMOST database six stars, among successfully parametrized in the current study. The results (recalculated from spectral type to $M_{bol}$ according to Kraus and Hillenbrand (2007)) are presented in Fig. 5 and demonstrate a satisfactory agreement.

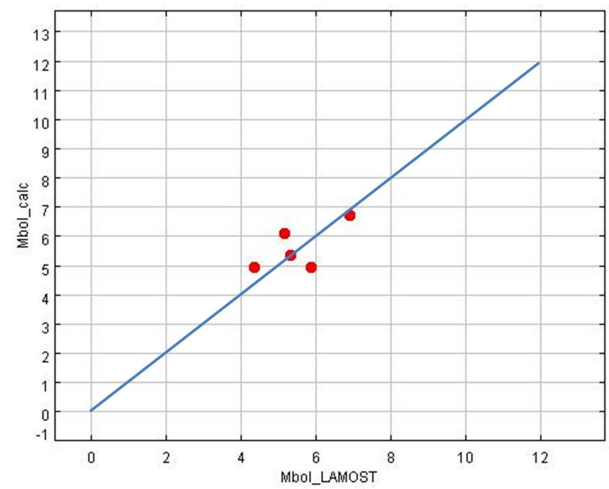


**Fig. 5.** Comparison of our results with LAMOST data. Errors are about 0.1 and 0.3 mag on X- and Y-axes, respectively. Axes range corresponds to SpT range (B8V-L0V) used in calibration tables (see Section 3.2). Note that LAMOST uses a smaller scale SpT grid than one, used in our calibration tables. Left bottom point represents two objects.

On the other hand, we should note that a preliminary comparison shows that results of previous studies, where 3D maps were constructed (Sharov (1964); Arenou et al. (1992)), which contradict our results at least in those four areas.

On the whole, the results are consistent with how we expect the model to function, with results obtained from LAMOST and data from SNs that deliver the integrated extinction to the edge of the Galaxy.

For one region (see Fig. 2) Schlegel et al. (1998) predict lower extinction than we do. This can have several reasons, one being the fact that some stars are unresolved binaries: close binaries, which can be resolved neither photometrically (unless they exhibit mutual eclipses) nor astrometrically. Unresolved binaries with components of different temperature can exhibit colors different enough from ones of single stars. Such binaries can be separated from single stars in some color index diagrams. We have investigated this problem and specified photometric bands, where the single-binary star separation is possible in Malkov et al. (2011).

There is a number of other reasons for the disagreement between the simulated and catalogued photometry: observational photometric uncertainties, catalogs misprints, cross-match errors, variability or non MS evolutionary state or stars, non-stellar nature of objects, non-standard behaviour of the interstellar extinction law in the area or non-uniform extinction behavior within the area, etc.

In the current study only high latitude areas are evaluated. Here one can expect reasonable low values of extinction, also one can assume that cosecant law satisfactory describes the extinction at such high latitudes.

We should note that our study is done in V band. Longer wave bands exhibit other behaviors, in particular, the Galaxy is almost transparent in K-band till 4-5 kpc.

Also, we have found that 2MASS data can be ignored if other three surveys cover the area. In these cases results with 2MASS photometry and without it do not significantly differ.

## 6 Conclusions

The presented method allows us to construct $A_V(d)$ relations at least for high galactic latitudes, to approximate them by the cosecant law and estimate $a_0$ and $\beta$ parameters.

We prove that with sufficiently-good-quality photometry, one could compute a 3D extinction map by comparing catalogued multicolor photometry with photometry derived from distance modulus equation, interstellar extinction law, calibration tables for absolute magnitudes, going through reasonable spectral type, extinction and distance values. The lack of self-consistent photometry for stars, listed in a single survey, previously prevented such determination, but it became possible in the modern large multicolor surveys and Virtual Observatory era.

With the advent of large, existing and coming, photometric surveys and the evolution of computing power and data analysis techniques (in particular, VO-tools for cross-matching), extinction can now be computed for millions of stars in a reasonable amount of time. Good agreement of our results with LAMOST data and extinction values to distant SNs indicates that the proposed algorithm can be used for construction of a 3D map of interstellar extinction in the Milky Way Galaxy.

## 7 Future plans

The described method requires assuming the interstellar extinction law. However, the extinction law can be determined by the method itself. In principle, the total-to-selective extinction ratio ($R_V$) can also vary, together with other parameters. Hanson and Bailer-Jones (2014) varied it, among other parameters, and achieved an accuracy of 0.73 in $R_V$. So it can be advantageous in further study to keep the $R_V$ parameter in the interstellar extinction law variable.

Among other plans are to include data from other surveys: WISE (Wright et al. (2010)), DENIS (Epchtein et al. (1997)), Pan-STARRS (Kaiser et al. (2002)) and others, as well as modern UV data (UVIT, Kumar et al. (2012)). We will also verify our results with coming Gaia DR2 data.

Used calibration tables can be extended to hotter/cooler temperature classes, to other luminosity classes, and to YJHK UKIRT photometry.

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