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Parameterization of stars and determination of interstellar extinction from multicolor photometry

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We have developed a method for the determination of stellar parameters and interstellar extinction values from multicolor photometry. The application of this method to a set of stars in a small area in the sky allows us to determine an increase of interstellar extinction with distance in that direction and, consequently, to construct a 3D extinction map of the Milky Way Galaxy.

Keywords: Cross-matching, sky surveys, photometry, interstellar extinction

1 Introduction

Three-dimensional (3D) extinction models have been constructed using spectral and photometric stellar data, open cluster data, star counts, Galactic dust distribution models. The standard approach to construct a 3D extinction model has been to parcel out the sky in angular cells, each defined by boundaries in Galactic coordinates (l,b). The visual extinction (A_V) in each cell may then be obtained as a function of distance (d): A_V (l,b,d) from the stars in the cells. The angular size of the cells has varied from study to study, although each cell was generally chosen to be large enough to contain a statistically significant number of calibration stars at different distances.

Published 3D models, using spectral and photometric data, were based on 10^4–10^5 stars, or were constructed for a very limited area in the sky (see, e.g., [37], [17], [23];

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the earlier studies were reviewed in [31]). Modern large surveys contain photometric (3 to 5 bands) data for 10^7–10^9 stars. However, to make those data (obtained at different wavelengths and with different observational techniques) useful for a 3D extinction model construction, one needs to run a correct cross-identification of objects between surveys. Such cross-identification was laborious and time consuming, but using Virtual Observatory (VO) data access and cross-correlation technologies, a search for counterparts in a subset of different catalogues can now be carried out in a few minutes. It is now feasible to obtain information on interstellar extinction from modern large photometric surveys.

In Section 2 we give a review of sky surveys, and present principles of their cross-matching. Section 3 contains description of our procedure for parameterization of stars, and in Section 4 we present principles and pilot results of determination of interstellar extinction. We draw our conclusions in Section 5.

2 Sky surveys and cross-matching

2.1 Sky surveys selection

The number of surveys available at any wavelength is large enough to construct detailed spectral energy distributions (SED) for any kind of astrophysical object. Sky surveys we select for parameterization of stars should satisfy the following criteria:

- the number of objects exceeds $\sim 10^7$,
- the survey covers a large area in the sky,
- the photometric accuracy is better than about 0.05 mag,
- the depth of the survey exceeds $V \sim 20$ mag.

The following sky surveys are selected for our study.

- The DENIS database [11]
- 2MASS All-Sky Catalog of Point Sources [10]
- The SDSS Photometric Catalogue, Release 12 [1]
- GALEX-DR5 (GR5) sources from AIS and MIS [4], [5]
- UKIDSS-DR9 LAS, GCS and DXS Surveys [24]
- AllWISE Data Release [9]
- IPHAS DR2 Source Catalogue [3]
- The Pan-STARRS release 1 (PS1) Survey – DR1 [8]
- Gaia DR2/EDR3 [15], [2], [16].

Some information on the surveys is given in Table 1, their photometric systems response curves are shown in Fig. 1.

The presented surveys basically satisfy the criteria listed above. The number of objects varies from $\sim 10^8$ to $\sim 10^9$. The most local survey, IPHAS, covers a relatively small but important area in the sky. The photometric accuracy of all surveys (except, probably, ultraviolet GALEX) is better than 0.05 mag. The limiting magnitudes, converted to V-band, are not less than $\sim$20 mag.

Table 1 Large photometric surveys

Survey	N^a	Sky coverage	Photometric bands	Limiting magnitude
DENIS	355	Southern hemisphere	Gunn-i, J, K_S	18.5, 16.5, 14.0
2MASS	471	All sky	J, H, K_S	15.8, 15.1, 14.3
SDSS 12	325	25%	u, g, r, i, z	g,r = 22.2
GALEX DR5 (AIS+MIS)	78	90%	FUV, NUV	∼25
UKIDSS DR9 LAS	83	15%	Z, Y, J, H, K	K = 18.3
AllWISE	748	All sky	W1, W2, W3, W4	16.6, 16.0, 10.8, 6.7
IPHAS DR2	219	Northern Galactic plane	r, i, H_α	r = 21–22
Pan-STARRS PS1 – DR1	1919	All sky but southern cap	g, r, i, z, y	i ∼ 20
GAIA DR2/EDR3	1693	All sky	G, BP, RP	G = 20

[a] N is the number of objects, 10^6.

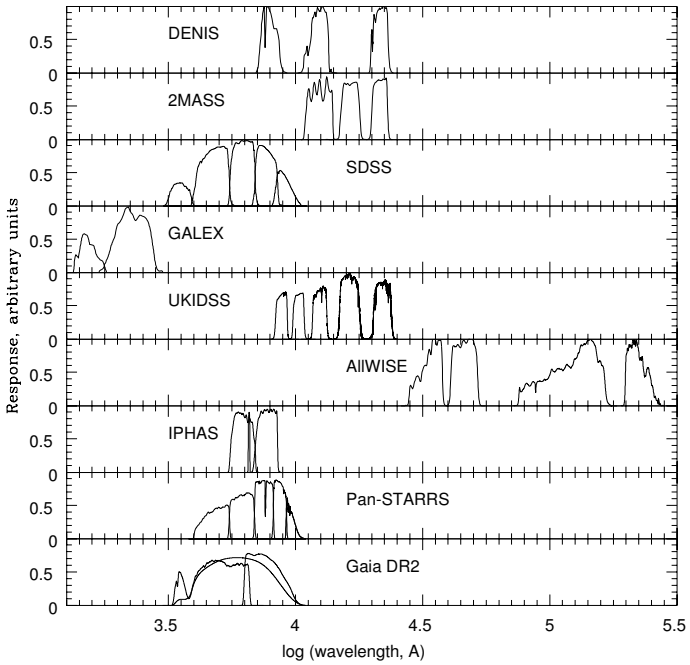


Figure 1 Response curves of the photometric surveys.

2.2 Cross-matching of surveys

Different surveys/instruments have different positional accuracy and resolution. In addition, the depth of each survey is different and, depending on sources brightness and their SED, a given source might or might not be detected at a certain wavelength. All this makes the pairing of sources among surveys not trivial, especially in crowded fields.

We have implemented an algorithm of fast positional matching of some of the sky surveys in small (up to one degree) areas with filtering of false identification [28]. In particular, for each area and each pair we estimated the matching radius. As a result, we drew in a number of 0.1-degree radius areas samples of point-like objects' counterparts from the DENIS, 2MASS, SDSS, GALEX, and UKIDSS surveys, and performed a cross-identification within these surveys [20, 27]. We have compiled the corresponding subcatalogues in the VOTable format. The tool developed as a result of this work can be used to cross-identify objects in arbitrary sky areas for the further classification and determination of stellar parameters, including the measurement of the amount of interstellar extinction.

In some surveys (e.g., GALEX, SDSS, UKIDSS) more than one observation per object was made and, consequently, more than one entry per object is present in the survey. In such cases we use weighted average values for the photometry.

In the cross-identification process (and later for the parameterization) we use all positional information and all photometry available in surveys. To select objects for further study we also pay attention to various flags presented in the surveys. The flags can indicate quality of observations and provide information on the nature of object (duplicity, variability, extended shape). As it was mentioned above, at this stage we do not use trigonometric parallax as an input parameter.

It can be seen from Fig. 1 that response curves of photometric bands in different surveys are sometimes the same or similar (e.g., K_S-band in DENIS and K_S-band in 2MASS). The comparison of brightness of objects in such pairs of bands provides us an additional filter to discard objects irrelevant for the parameterization: a large magnitude difference may indicate variability, a rare evolutionary stage, or non-stellar nature of the object.

We have to remove all non-stellar objects, unresolved photometric binaries, variable stars and other contaminating objects, based on flags included in the original surveys. Too bright and too faint objects for this particular survey (i.e., overexposed and underexposed, respectively) can also be spotted and omitted at this stage.

3 Multicolor photometry and parameterization of stars

We studied a problem of classification and parameterization of stars from multicolor photometry in detail (see, e.g., [41], [42]). In particular, a problem of binary stars parameterization was studied in [33] and [32].

We have developed a method, which allows us to determine stellar parameters from multicolor photometry. For the studied objects MK (Morgan–Keenan) spectral types (SpT), distances (d) and interstellar extinction values (A_V) can be estimated,

minimizing the function

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{m_{obs,i} - m_{calc,i}}{\sigma m_{obs,i}} \right)^2, \quad (1)$$

where $m_{obs,i}$ and $\sigma m_{obs,i}$ are the apparent magnitude and its observational error, respectively, in the i-th photometric band from a given survey. The summation is over up to N∼30 photometric bands (see Table 1), and

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

Here $A_i = f(A_V)$ is the extinction in the i-th photometric band, and can be determined from the interstellar extinction law ([14], [6], [13]).

A calibration relation M_i(SpT) should be available for each of the i photometric bands included in the original surveys. It is true for 2MASS, SDSS and GALEX photometric systems ([22], [12]) but corresponding calibration tables for UKIDSS and other surveys cannot be found in literature. In the absence of such information, it is necessary to construct corresponding relations from theoretical spectral energy distributions (SED) and photometric system response curves. The best source for theoretical SED are libraries of synthetic spectra [25], [7], [18], and the SEDs are computed there for a given set of atmospheric parameters ($\log T_{\rm eff}$, $\log g$, $[M/H]$) rather than spectral classes. Thus, for the decision of this problem it is necessary to design relations between spectral class and atmospheric parameters for different luminosity classes.

Another source of SED for different types of stars (which can be used to model observational photometry), are empirical spectrophotometric atlases (e.g., [36], [44]). We have made a comparative analysis of the most known semi-empirical and empirical spectral atlases. The results show that the standard error of synthesized stellar magnitudes calculated with SED from best spectral atlases reaches 0.02 mag. It has also been found that some modern spectral atlases are burdened with significant systematic errors [21].

To properly obtain astrophysical parameters from catalogued photometry one also needs to study the possibility and sphere of application of the parameterization method. We indicate areas in the parameter space (effective temperature $\log T_{\rm eff}$, gravity $\log g$, metallicity $[Fe/H]$, visual extinction A_V, total-to-selective extinction ratio R_V), where observational photometry precision, achieved in modern large multicolor surveys, allows us to obtain astrophysical parameters with acceptable accuracy [40].

4 Determination of interstellar extinction

Using the method of parameterization, described in Section 3, one can construct A_V(l,b,d) relation. This method allows one to plot parameterized objects in the distance-extinction (d-A_V) plane, approximate them (by the cosecant law or a more complicated function) and estimate interstellar extinction parameters in a given direction on the sky.

Note that for high galactic latitude areas ($|b| > 15^\circ$ or so) the interstellar extinction is thought to be (roughly) uniformly distributed and to satisfy the so-called cosecant (barometric) law suggested by Parenago in [34]. That function should be modified (complicated) for lower latitudes, as dust clouds concentrated in the Galactic plane will have to be taken into account.

A preliminary analysis of applicability of SDSS and 2MASS photometry for determining the properties of stars and interstellar extinction was made in [39].

Then to test the procedure described in Section 3, we have selected sky areas which are interesting from the astrophysical point of view and where our results can be compared with independent studies. In particular, it is instructive and useful to apply the model to estimate interstellar extinction for several areas of the sky where individual estimates were made by [38] and used to calculate extinction for SNs in the Universe accelerating expansion study [35].

In our study [29] we have cross-matched objects in 2MASS, SDSS, GALEX and UKIDSS surveys in selected areas at high galactic latitudes, using Virtual Observatory facilities. As a result of the cross-matching, we obtained multi-wavelength ($i = 9$ to 13 bands) photometric data for each object. We have applied the method, described in Section 3, to parameterize the stars and to construct A_V(l,b,d) relations for selected areas in the sky.

We have compared our results with LAMOST [26] data and extinction values to distant SNs (based on IRAS and DIRBE microwave data), available in the literature. The comparison exhibits a good agreement (see [29] for details). A comparison of our results with recently released Gaia DR2/EDR3 data also demonstrates a good agreement for stars as faint as $19^m.6$ g_{SDSS}, and shows that our method allows us to determine spectral type, distance and interstellar extinction of objects out to 4.5 kpc [30]. It indicates that the proposed algorithm (after some modifications required for low galactic latitudes) can be used for construction of a 3D map of interstellar extinction in the Milky Way Galaxy.

5 Conclusions

The study of the stellar physical properties as well as the spatial distribution of interstellar extinction is important for many investigations of galactic and extragalactic objects. We have developed a method for determination of stellar parameters and interstellar extinctions from multicolor photometry. This method was applied to objects drawn from modern large photometric surveys and, in this work, we give a review of the surveys and discuss problems of cross-identification.

Our procedure may be modified to use the astrometric and spectral information on the studied objects as input parameters. In particular, our procedure can be modified to determine stellar parameters and interstellar extinction values from not only multicolor photometry but also using additional information such as precise parallaxes and spectral classification where available, thus reducing the number of unknowns in Eq. (2). One notable improvement has come with the recent release of the Gaia DR2/EDR3 set of parallaxes, which allows us to use distance as an input (rather than as free) parameter. It should significantly increase the accuracy of our results, especially when we can substitute the more precise parallaxes from Gaia

DR3 for the DR2/EDR3 data we currently use. Our procedure can also be modified for stars with spectral classification available from LAMOST [26], the largest source of spectral classification of objects in the northern sky. LAMOST Data Release 4 contains data on 7.6×10^6 objects and is available through VizieR database (V/153).

Also, our experience is thought to be a practical guide to issues that will be of particular importance as soon as new surveys will become available (LSST [19], SAGE [45], UVIT [43]).

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