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Cross-Matching of Objects in Large Sky Surveys

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Abstract. 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.

Keywords: Cross-matching · Sky surveys · Photometry · Interstellar extinction

1 Introduction

An outstanding problem of astrophysics is the study of the stellar physical properties. Because the stars are observed through interstellar dust, their light is dimmed and reddened, complicating their parameterization and classification. The parameters of a given star, as well as the interstellar reddening, may be obtained from its spectrum but one must either use a large telescope or only observe bright objects in order to get spectral energy distributions with good resolution and sufficient accuracy. On the other hand, recently constructed large photometric surveys with new tools for cross-matching objects provide us with the possibility of getting multicolor photometric data for hundreds of millions of objects. From these, we may not only parameterize objects but also determine the 3-dimensional interstellar extinction in the Galaxy.

We have developed a method for the determination of stellar parameters and interstellar extinction values from multicolor photometry. The application of this

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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 3-d extinction map of the Milky Way Galaxy.

Published interstellar extinction maps are described in Section 2. Section 3 contains description of our procedure for parameterization of stars. In Section 4 we give a review of sky surveys, and present principles of their cross-matching. Our future plans are discussed in Section 6 with the conclusions in Section 7.

2 Interstellar Extinction Maps

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., [36], [16], [21], the earlier studies were reviewed in [28]). 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.

To properly obtain astrophysical parameters from catalogued photometry one 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 multi-color surveys, allows us to obtain astrophysical parameters with acceptable accuracy [40].

3 Multicolor Photometry and Parameterization of Stars

3.1 Parameterization Procedure

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 [30] and [29].

We have developed a method, which allows us to construct $A_V(l, b, d)$ relations from multicolor photometry. Varying (i) the spectral type of the star (SpT), (ii) its distance (d), and (iii) interstellar extinction value (A_V), we simulate the observational brightness, m, with the distance modulus equations

$$m = M_i(\mathrm{SpT}) + 5\log d - 5 + A_i(A_V) \quad (1)$$

for every photometric band, and, based on the quality of the simulation process, choose the most appropriate SpT-d-A_V set. A calibration relation M_i(SpT) and interstellar extinction law $A_i(A_V)$ should be available for each of the i photometric bands included in the original surveys.

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 with flags from our simulation techniques.

This method of simulation/parameterization, as described above, allows one to plot parameterized objects in the distance-extinction (d-A_V) plane, approximate them (by the cosecant law or more complicated function) and estimate interstellar extinction parameters in a given direction on the sky.

Note that for high galactic latitude areas ($|b| > 15^o$ 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 [32]. That function should be modified (complicated) for lower latitudes, as dust clouds concentrated in the Galactic plane, will have to be taken into account.

3.2 Modifications of the Procedure

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. 1.

One notable improvement has come with the recent release of the Gaia DR2 (see Table 1) set of parallaxes, which allows us to use distance as an input (rather than as a 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 data we currently use.

Our procedure can also be modified for stars with spectral classification available from LAMOST [23], 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).

4 Sky Surveys and Cross-matching

4.1 Sky Surveys Selection

The following sky surveys are selected for our study:

- The DENIS database [12];
- 2MASS All-Sky Catalog of Point Sources [9];
- The SDSS Photometric Catalogue, Release 12 [1];
- GALEX-DR5 (GR5) sources from AIS and MIS [4], [5];
- UKIDSS-DR9 LAS, GCS and DXS Surveys [22];
- AllWISE Data Release [10];
- IPHAS DR2 Source Catalogue [3];
- The Pan-STARRS release 1 (PS1) Survey - DR1 [7];
- Gaia DR2 [15], [2].

Some information on the surveys is given in Table 1, their photometric systems response curves are shown in Fig. 1 (the mid-IR AllWISE photometric bands are located in the 26,000 − 280,000 Å area and are not shown here).

Table 1. Large photometric surveys

Survey	Number of objects, 10^6	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	1693	All sky	G, BP, RP	G=20

The selected surveys satisfy the following criteria:

- the number of objects exceeds 10×10^6;
- the survey covers a large area in the sky (the only exception is IPHAS, which covers a relatively small but important area in the sky);
- the photometric accuracy is better than about 0.05 mag;

– the depth of the survey exceeds V∼20 mag.

For every survey the following information should be available: absolute magnitude – spectral type (M_λ – SpT) calibration tables and $A_\lambda(A_V)$ relations for every photometric band λ. If these information is not available in literature, we construct it using response curves of photometric bands and spectral energy distribution (SED) for every spectral type, as well as the interstellar extinction law ([14], [6], [13]). Besides, relations between spectral type and atmospheric parameters (effective temperature $\log T_{\rm eff}$ and surface gravity $\log g$) for stars of different luminosity classes should be available.

To model observational photometry one needs to know spectral energy distribution, and a number of spectrophotometric atlases are designed to meet that requirement (e.g, [34], [46]). 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 SEDs from best spectral atlases reaches 0.02 mag. It has been also found that some modern spectral atlases are burdened with significant systematic errors [19].

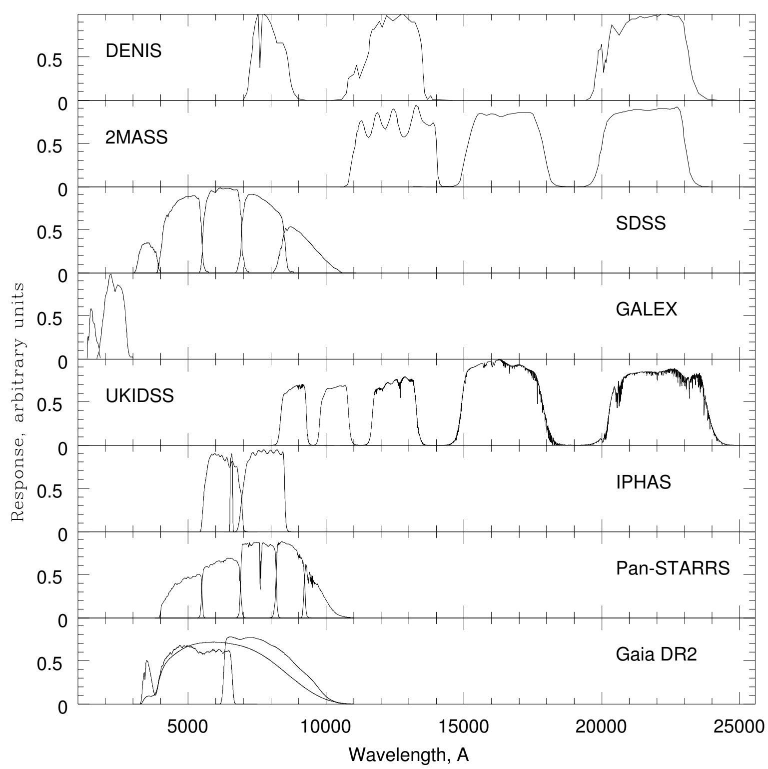

Fig. 1. Response curves of the photometric surveys

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

4.2 Cross-matching of Surveys

The number of surveys available at any wavelength is large enough to construct detailed Spectral Energy Distributions (SEDs) for any kind of astrophysical object. However, 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 catalogues not trivial, especially in crowded fields.

We have implemented an algorithm of fast positional matching of large astronomical catalogs in small (up to one degree) areas with filtering of false identification [25]. In particular, for each area and each pair we estimated the matching radius. As a result, we drew in a number 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 [18], [24]. We have compiled the corresponding subcatalogues in the VOTable [31] 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 catalogue. 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 a nature of object (duplicity, variability, extended shape). As it was mentioned above, on this stage we do not use trigonometric parallax as an input parameter.

Response curves of photometric bands of the surveys are shown in Fig.1. It can be seen that some bands in different surveys are 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. 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.

4.3 Selection of Sky Areas

To test our procedure, we have to select sky areas which are interesting from various astrophysical points of view and where our results can be compared with independent studies.

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 [33].

Among other interesting objects, RR Lyr-type variable stars (variables) were selected for the study. RR Lyr-type pulsating variables satisfy a period-luminosity relation (PLR) that simplifies estimation of their distances (and, consequently, distances to stellar systems they reside). However, PLR is not yet well calibrated, and our study of dust distribution in the RR Lyr-type variables directions is intended to improve the situation. Several hundreds of RR Lyr-type variables with available spectral classification were selected for our study from the General Catalogue of Variable Stars [37].

Another interesting direction in the sky to study is the solar apex, i.e., the direction that the Sun travels with respect to the mean motion of material in the Solar neighborhood. The solar apex is in the constellation of Hercules, the approximate galactic coordinates are l=$56^o.24$, b=$22^o.54$. There is a practical interest in the study of dust distribution in the Galaxy in that direction. The movement of the Solar system through the clots of interstellar gas could lead to the direct invasion of a dense mixture of gas and dust into the Solar system. That has such potential consequences as global glaciation and reducing the size of the heliosphere (up to the Earth's orbit) which protects us from cosmic rays.

5 Results and Discussion

In our pilot study [26] we applied this method to construct $A_V(l, b, d)$ relations for selected areas at high galactic latitudes. We have cross-matched objects in 2MASS, SDSS, GALEX and UKIDSS surveys in selected areas in the sky, using Virtual Observatory facilities. As a result of the cross-matching, we find multi-wavelength ($i = 9$ to 13 bands) photometric data for each object.

We have compared our results with LAMOST [23] 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 [26] for details). A comparison of our results with recently released Gaia DR2 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 [27]. 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.

6 Future Plans

6.1 Coming Photometric Surveys

Our experience is thought to be a practical guide to issues that will be particular important as soon as the new surveys will become available. In particular, the following surveys can be mentioned here.

LSST. Large Synoptic Survey Telescope (LSST) is the most ambitious survey currently planned in the optical [17]. LSST will be a large, wide-field ground-based system designed to obtain repeated images covering the sky visible from northern Chile. The telescope will have an 8.4 m (6.5 m effective) primary mirror, a 9.6 $\deg^2$ field of view, a 3.2-gigapixel camera, and six filters (ugrizy) covering the wavelength range 320-1050 nm. The project is in the construction phase and will begin regular survey operations by 2022. A 18,000 $\deg^2$ region will be uniformly observed during the anticipated 10 yr of operations and will yield a co-added map to r $\sim$ 27.5. These data will result in databases including about 32 trillion observations of 20 billion galaxies and a similar number of stars, and they will serve the majority of the primary science programs.

SAGE. Stellar Abundance and Galactic Evolution (SAGE) project aims to study the stellar atmospheric parameters of $\sim$0.5 $\times 10^9$ stars in the $\sim$12.000 $\deg^2$ of the northern sky, with declination $\delta > -5^o$, excluding the bright Galactic disk ($|b| < 10^o$) and the sky area of $12 < R.A. < 18$ hr [48]. The survey uses a self-designed SAGE photometric system, which is composed of eight photometric bands Stromgren-u, SAGE-v, SDSS g,r,i, $H_\alpha$wide, $H_\alpha$narrow, and DDO-51.

UVIT. The UVIT instrument on-board the Indian space observatory ASTROSAT consists of two 38-cm telescopes — one for the FUV and the other for the NUV and visible bands. It has a circular field of view $\approx 28'$ in diameter. It collects data in three channels simultaneously, in FUV, NUV and Visible bands corresponding to λ = 1300-1800 A, 2000-3000 A and 3200-5500 A, respectively. Full details of the instrument and calibration results can be found in [45]. UVIT does not provide data for *large* number of objects, however, its data will be used as the UV spectral range is very important for the study of the interstellar extinction.

Another aspect which we can tackle is how the accuracy of the results depend on missing data (in fact the larger the number of the surveys cross-matched, the larger should be the fraction of missing data). According to our preliminary results [26], the presence or absence of 2MASS data in the set (subject to the availability of SDSS, GALEX and UKIDSS data) does not significantly change the result, but this issue needs a further study.

6.2 Use of Spectral Surveys in Parameterization

Ongoing (LAMOST [23], APOGEE (all-sky, $\sim$450,000 objects) [35], SEGUE (northern sky, $\sim$350,000 objects) [47], RAVE (southern sky, $\sim$460,000 objects)

[20] and upcoming (4MOST [11], MOONS [8], WEAVE [44]) spectroscopic surveys can serve as an exceptional sources not only of stellar parameter values, but also of the nature of interstellar dust and its distribution in the Milky Way. Atmospheric parameters ($T_{\rm eff}$, $\log g$) and/or spectral classifications — obtained from spectroscopy combined with observational photometry — allow us to determine distances and interstellar extinctions for stars with high accuracy and thereby to construct a 3D map of interstellar extinction.

7 Conclusion

The parameterization of stars is a well known problem and used for various purposes in astronomy (e.g., while solving the problem of searching for well defined stars to be used for secondary photometric standards [43]). We have shown that multicolor photometric data from large modern surveys can be used for parameterization of stars. A comparison of our results with independent data shows a good agreement. We prove that with sufficiently good quality photometry, one may compute a 3D extinction map by comparing catalogued multicolor photometry with photometry derived from the secondary estimators such as the distance modulus and the interstellar extinction law with suitable calibration tables for absolute magnitudes with reasonable spectral types, extinctions and distances.

With the advent of large, existing and coming, photometric surveys and the evolution of computing power and data analysis techniques (in particular, Virtual Observatory tools for cross-matching), interstellar extinction can now be computed for hundreds of millions of stars in a reasonable amount of time, and a 3D interstellar extinction map can be constructed.

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