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On the Atmospheric Extinction Reduction Procedure in Multiband Wide-Field Photometric Surveys

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ABSTRACT

We propose an improved method for the atmospheric extinction reduction within optical photometry. Our method is based on the simultaneous multicolor observations of photometric standards. Such data are now available within the modern wide-field sky surveys and contain a large amount of information about instant atmospheric conditions. So, it became possible to estimate the extinction parameters on the basis of a quite short observational dataset and, hence, to trace the rapid stars twinkling accurately. Having been developed for a new MiniMegaTORTORa observational system, the proposed method can be adopted for a wide range of modern observational programs.

Key words: *Techniques: photometric – Surveys*

1. Introduction

Large-scale photometric surveys (both ground- and space-based) have recently become a common method for the investigation of astronomical sources variability and for standardized multiband photometry. Many of them are inexpensive and easy to be implemented since their design is based on the usage of small telescopes. At the same time these surveys deliver a large amount of homogeneous observational data that can be processed and analyzed automatically. Typical exposure times are becoming shorter in the course of the years making it possible to investigate astrophysical phenomena with high temporal resolution.

The examples of such modern multiband optical sky surveys are large-scale LSST (Ivezic *et al.* 2008), PanSTARRS (Kaiser *et al.* 2002), Gaia (Lindegren and

Perryman 1996) and more specialized, relatively small ASAS (Pojmański 1997), MASTER (Lipunov *et al.* 2010) and new photopolarimetric system with high temporal resolution MiniMegaTORTORA - MMT (Beskin *et al.* 2013, Biryukov *et al.* 2015).

The photometric datasets of ground-based surveys are highly affected by atmospheric extinction. Since the atmosphere is not stationary on time-scales as short as 0.001–1 s (*e.g.,* Dravins *et al.* 1997), it influences significantly the observed fast variability of astronomical sources. The study of some rapid, irregular phenomena like star flares, transients, occultations etc., becomes difficult, which makes the accurate atmospheric extinction reduction important.

Many methods of dealing with atmospheric extinction have been suggested so far (*e.g.,* Straizys 1992), but they typically require subsequent observations of one or more sources that usually takes a longer time than atmospheric non-stationarity scale and as a result an additional error is introduced to the de-extincted photometric magnitudes. For observations with high temporal resolution one needs a new, improved de-extinction procedure based on data obtained in a sufficiently short time.

There are several catalogs that contain reduced ("extra-atmospheric", de-extincted) magnitudes of a large number of stars. They are based either on measurements obtained during an orbital mission (like Hipparcos) or on calculations using large number of observations and monitoring of the local atmosphere (*e.g.,* catalog of bright stars by Kroussanova *et al.* 2013). Such *a priori* information, as well as a list of photometric standards measured in various bands, can greatly simplify the calculation of extra-atmospheric magnitudes and, finally, provide a method for rapid, but accurate, ground-based photometry.

In this paper we propose a prospective self-consistent method for atmospheric extinction reduction and a study of local atmosphere within wide-field multicolor sky observations using extra-atmospheric magnitudes of photometric standards.

2. Method Description

Our method requires that two conditions are met. First, the observations of the source (or field) in different photometric bands have to be undertaken (quasi) simultaneously. It is sufficient if the time interval between exposures taken in different bands is shorter than the typical atmospheric instability time. It can be achieved through either simultaneous observations in several bands by independent telescopes (as implemented in the MMT, see Section 3 for details) or a series of rather short exposures made by the same instrument.

The second condition is the availability of a list of photometric standards with known extra-atmospheric magnitudes in the same bands as used in the observations. The instrumental photometric system, however, does not have to coincide with that of the catalog of standards. (The instruments are always affected by the external conditions like air temperature, pressure etc., anyway.) If the spectral transmission curves for all bands of both ("instrumental" and "standard") systems are known, it is possible to convert the apparent magnitudes of stars from one system to another.

The relationship between the magnitudes in both systems can be presented in the form of widely-used photometric (color) polynomials. The calculation of their coefficients is a well-known though quite complicated procedure. It requires the knowledge of "typical" spectra of stars (patterns) for different spectral and luminosity classes (*e.g.,* Pickles 1998) and interstellar medium transmitting spectral curve (*e.g.,* Fitzpatrick 1999). All of these data easily can be found in the literature. Using such converting polynomials, a catalog of extra-atmospheric magnitudes of standard stars in the instrumental photometric system can be built for any telescope and detector.

The atmospheric extinction reduction procedure, used in our method is as follows. Let m_0 be an extra-atmospheric magnitude of an observed photometric standard in one of instrumental photometric bands, while m – is its actually observed (ground-based) magnitude in the same band. For the star observed at the air mass $M(z)$ (where z is the zenith distance):

$$m = m_0 + a_m \cdot M(z) + C_m \tag{1}$$

where a_m is an atmospheric extinction coefficient for the instrumental color band m, and C_m is a parameter, which characterizes the current telescope (and detector) state and does not depend on the azimuthal coordinates of the star. Furthermore, let

$$a_{m,0} = (m - m_0)\,|_{M(z)=1} \tag{2}$$

be the extinction coefficients, calculated for each standard star assuming some known atmospheric extinction model. Such a model has to be calculated independently and appears as an initial approximation of the real state of the atmosphere.

Thus, Eq.(1) can be rewritten as:

$$m = m_0 + [a_{m,0} + \Delta a_m] \cdot M(z) + C_m \tag{3}$$

where Δa_m is an unknown correction to the initially assumed atmospheric extinction model for the current observational set. Note that coefficients a_m generally depend on the extra-atmospheric spectrum of the standard, so:

$$\Delta a_m(CI_{i,0}) = \sum_i \sum_{k=0}^{k_{\max}} c_{ik} CI_{i,0}^k \tag{4}$$

where $CI_{i,0}$ are extra-atmospheric color indices within the instrumental photometric system and c_{ik} are coefficients.

The value of m in Eq.(3) is known directly from the observations, the values of m_0 and $a_{m,0}$ are precalculated and air mass $M(z) \approx \sec z$ depends on the zenith distance in a common manner. The solution of the system of Eqs.(3) written for all photometric standards observed simultaneously in the same field and various color bands, is the set of values of corrections Δa_m. More precisely, this solution contains the parameters c_{ik} – *i.e.,* the dependence of Δa_m on the colors of standards. The instrumental parameter C_m is also a part of the full solution of Eqs.(3). This shows that the multiband simultaneous observations of standard stars allow us to obtain parameters of a current real state of the atmospheric extinction and observational equipment.

Finally, since values of $\Delta a_m(CI_{i,0})$ and C_m are now known for different instrumental color bands, one can calculate the extra-atmospheric magnitudes m_0 of other (non-standard) field stars. For a star with observed magnitudes m and color indices CI_i:

$$m_0 = m - [a_{m,0}(CI_{i,0}) + \Delta a_m(CI_{i,0})] \cdot M(z) - C_m \tag{5}$$

where polynomials $a_{m,0}(CI_{i,0})$ are precalculated with the same method as was used above for a_m computing.

Note that extra-atmospheric color indices $CI_{i,0}$ are initially unknown for the observed stars (with the exception of photometric standards), but due to the smallness of the correction Δa_m one can use an iterative procedure to estimate m_0. Let us assume that $CI_{i,0} \equiv CI_i$ at the first step. The value of m_0 obtained in this approximation should be used to calculate the next approximation of extra-atmospheric colors of the star $CI_{i,0}$. Iterations have to be continued until the set of m_0 for different color bands corresponds to Δa_m.

3. Method Implementation

The method described above has been developed as a part of data reduction procedure for MMT photopolarimetric system.

MMT is a complex of 9 robotic telescopes, which is able to provide simultaneous bvr[1] wide-field observations of stars with v up to 11 mag for 0.1 s exposure. The MMT bvr bands are very close to those of classical Johnson-Cousins photometric bands (Johnson and Morgan 1953, Bessel 1990): $b \sim B$, $v \sim V$ and $r \sim R$. The response curves of both systems are shown in Fig. 1. We use solid lines for the standard *BVR* system and dashed lines for the MMT bvr filters.

Each channel (separate telescope) of MMT is equipped with a standard Canon 70 mm lens and Neo sCMOS 5Mpix detector from Andor Technology. An individual channel field of view size is about 100 square degrees, while the whole system's FOV within monitoring regime is about 900 square degrees. The detection limit $(\mathrm{S/N} = 5)$ in the panchromatic band $B = 12.0$ mag in 0.1 s (14.5 mag and 17 mag in 10 s and 1000 s, respectively). In the narrow-field regime of follow-up observations of individual objects, the size of the field of view decreases to 100 square

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[1] Within this paper we will mark intrinsic color bands of MMT by small characters: b – for blue band, v – for visible band, and r – for red band.

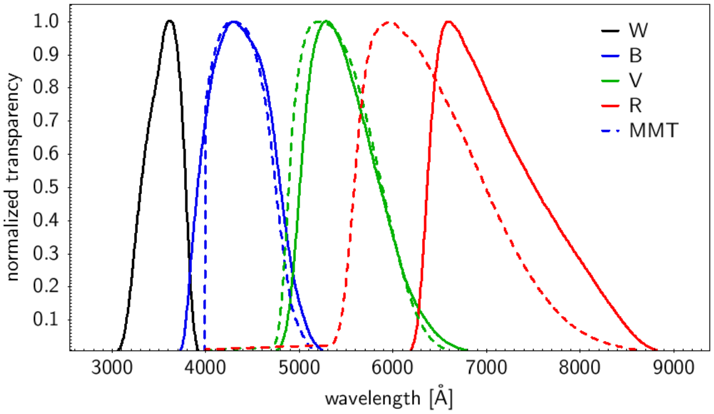

Fig. 1. Spectral response of filters *W, B, V* and *R* of Alma-Ata photometric system (continuous lines) and bvr filters of MMT complex (dashed lines). The MMT photometric system consists of three filters that are close respectively to Johnson-Cousins *B, V* and *R*. The *W*-band of Alma-Ata system was initially introduced by Straizys (see Straizys 1999 for review) as alternative to Johnson's *U*. Being revised, this band excludes the high influence of the Balmer jump on the measured ultra-violet magnitude.

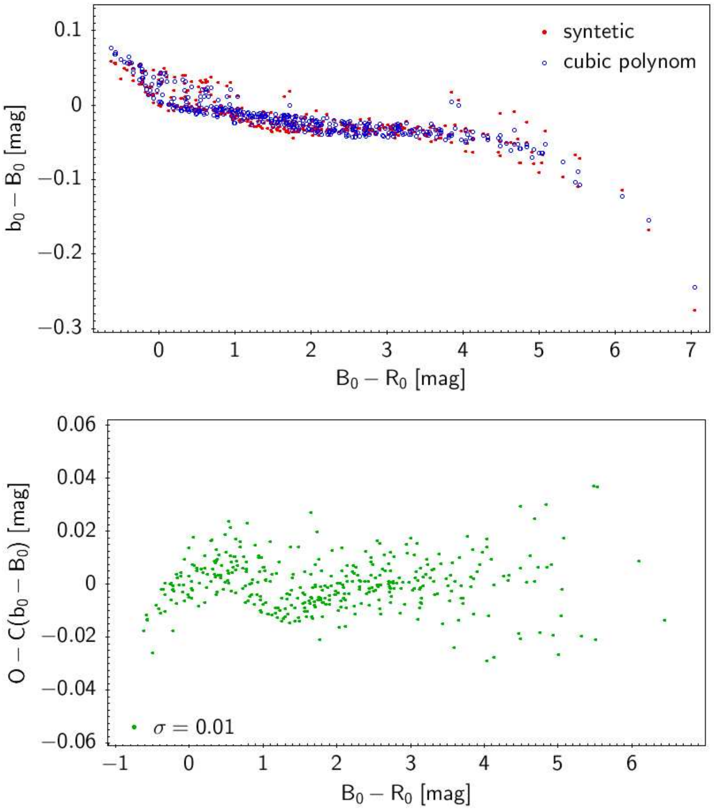

Fig. 2. *Upper panel:* the difference between de-extincted (extra-atmospheric) magnitude b_0 (in MMT photometric system) and B_0 (in *WBVR* system) – calculated directly from synthetic spectra (red points) and using obtained cubic photometric polynomial (blue points). *Lower panel:* residuals for $b_0 - B_0$ corrections obtained with direct calculations and photometric polynomial.

degrees, and the detection limit, which depends on the combination of color and polarization filters, falls within the range of 10.5–13.5 mag in 0.1 s and reaches 18 mag in 1000 s.

The MMT system collects up to 30Tb of raw data every night. Only an automatic reduction procedure makes possible the analysis of accumulated data. Thus, the specific software has been developed for rapid classification, astrometry and photometry of the observed phenomena. The photometric module needs a highly efficient method for atmospheric twinkling reduction – like that described in Section 2.

Within photometric calibration of MMT data, the catalog of photometric standards obtained in $WBVR$ Alma-Ata 4-band system (Kroussanova *et al.* 2013) is used. It contains ≈ 6500 stars of the northern sky ($\delta > -15^\circ$) with $V \approx 6 \div 7$ mag. The review of the *WBVR* photometric system and the corresponding sky survey can be found in Kornilov *et al.* (1991, 1996) and Kornilov (1998). The main advantage of this catalog is that it contains already de-extincted stellar magnitudes of stars more or less isotropically distributed over the northern sky. This catalog can be used as a basis for automatic reduction of MMT wide-field observations.

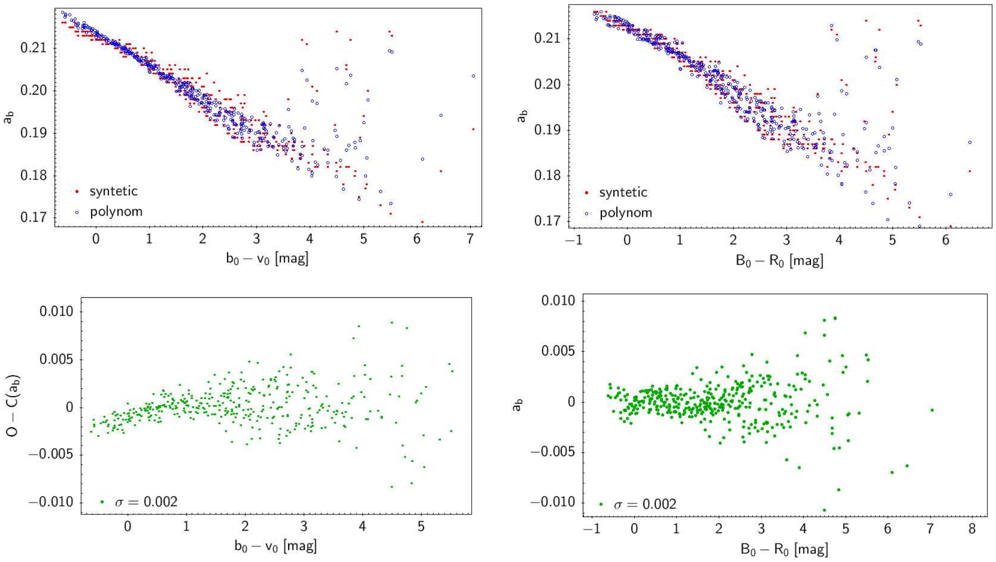

Fig. 3. Atmospheric extinction coefficients a_b for MMT band b, calculated directly from synthetic spectra (red points) and using obtained cubic photometrical polynomial (blue points).

Using the atlas of synthetic spectra compiled by Pickles (1998), the interstellar extinction model provided by Fitzpatrick (1999) and the model of atmospheric extinction which is relatively close to that of the MMT site,[2] we have calculated the photometric polynomials that provide the relation between de-extincted $WBVR$ and bvr magnitudes (see Fig. 2), and between atmospheric extinction coefficients

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[2] A. Mironov, private communication

$a_{m,0}$ and color indices $b_0 - v_0$, $v_0 - r_0$ (see Fig. 3). Using these polynomials one can calculate actual de-extincted magnitudes of the stars observed with MMT and investigate the atmospheric conditions over the telescope site.

The quite small differences ($\approx 0.1 - 0.2$ mag) between "real" (synthetic) and calculated de-extincted magnitudes and colors of the stars represent the expected accuracy of the described method.

4. Discussion and Conclusions

High precision photometry with accurate atmospheric extinction modeling is crucial for investigating various astrophysical phenomena accompanied by fast optical variability. Non-stationary processes in the atmospheres of Sun-like stars and the main sequence red dwarfs may serve as an example. These objects are important in the context of the search for earth-like exoplanets located in habitable zones (Kasting *et al.* 1993, Quintana *et al.* 2014). The observed activity of such stars is partially due to spots on their surfaces (Gershberg 2005, Maehara *et al.* 2012) which affects the locations and widths of their habitable zones. To investigate this effect, the long-term optical monitoring of a large subset of the main sequence stars is needed. Such monitoring should be performed with a high temporal resolution and precise photometry in different color bands. This is one of the main tasks of the MMT system, and the method described in this paper is expected to substantially improve the efficiency of such observations.

We have proposed a new, self-consistent method of atmospheric extinction reduction and the study of local atmosphere within wide-field multicolor sky observations using *a priori* information about extra-atmospheric magnitudes of photometric standards. We have also calculated coefficients of cubic photometric polynomials which are necessary for the implementation of this method for the new photopolarimetric wide-field telescope system MMT (Biryukov *et al.* 2015). We conclude that the calculated synthetic polynomials are able to provide the atmospheric correction with the accuracy of the order of 0.1–0.2 mag. In the real observations this accuracy will slightly decrease and will highly be dependent on the signal-to-noise ratio for observed stars. For a sufficiently high S/N the final accuracy of stellar de-extincted photometry will be close to that of the method. In any case, the 0.1–0.2 mag precision for high temporal resolution data (the typical MMT exposure is just 0.1 s) can be considered as a major breakthrough in the stellar photometry.

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