BVRI Photometry of Space Debris Objects at the Astronomical and Geophysical Observatory in Modra

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ABSTRACT

In Fall 2016 there has been deployed a new 0.7-meter aperture Newtonian telescope (AGO70) at the Astronomical and geophysical observatory in Modra (AGO). This system belongs and is operated by the Faculty of Mathematics, Physics and Informatics of Comenius University in Bratislava, Slovakia (FMPI). The major research focus of AGO70 is dedicated to the observations of space debris which are objects such as defunct satellites, rocket bodies and fragmentation pieces. AGO70 is equipped with commonly used BVRI Johnson-Cousins filters, which provide an opportunity to perform color photometry. The main motivation of research in field of color photometry is to obtain data for characterization of objects depending on their surface properties and their changes over time. Data acquired from this telescope was processed with the photometric reduction routine, which was developed by our team. We used Landolt's catalogue of standard stars, to obtain necessary coefficients for transformation to standard system of magnitudes, as a zero-point of telescope, an extinction coefficient and a color transformation coefficient. Using the least-squares method we estimated values of the coefficients for each selected photometric night and used them to transform object's intensity from instrumental to standard system of magnitudes.

We chose eleven stable attitude-controlled satellites on GEO orbit, to test the developed photometric reduction routine and to estimate and evaluate the error propagation during the data processing. We acquired and monitored changes in the object's color indices over time, to see effects of slow rotation, space-weathering and phase angle dependency. These satellites were also used to define a "reference plane" of our system for future measurements.

Our primary focus is processing of observations of fast rotating and debris objects. To select proper targets for such analysis we used our internal database of space debris light curves, to select potentially interesting objects according to their rotational period and instrumental brightness. These light curves were obtained in simultaneous program of aperture photometry performed with AGO70. Our routine was applied on several objects observed with all four filters. We obtained four phase functions (phase diagrams), one for each filter, by processing the data simultaneously and we acquired the dependency of the color indices as a function of phase function. The developed methodology may be used for any rotating object, to obtain material characteristics and incorporate them to the groups according to their surface properties.

In our work we will present the developed methodology and its validation, as well the obtained results for attitude stabilized GEO spacecraft and exemplary rotating objects.

1. INTRODUCTION

BVRI or color photometry is an astronomical method based on light's capturing in different passband of the visible and near infrared portion of the light spectra. It also can be understood as ultra-low resolution spectroscopy. In the field of space debris the detected light does not belong to object itself, but it comes from the Sun. The object reflects the light, so its characteristics will be affected by the object's surface properties. These effects can be described by the term of the color index, which is numerical expression of the object's color. According to the similarities in the color index, observed objects can be divided into three groups, which help us to with identification and description of the surface properties. In this work we will present the application of by us developed light curve processing program on the data acquired with Johnson/Cousins photometric filters.

The obtained color indices are compared to the results from article [1]. Authors divided Earth's artificial satellites to three different groups according to their reflective spectra (Fig 1). Specified categories in color index system R-I vs. B-V are [1]:

- I.Solar cell category - monotonic increasing with concave up shape.
- II.Gold similar category - monotonic increasing with concave down shape.
- III.Silver similar category - relatively flat with possible negative slope in blue range.

This categorization can serve for first identification of object's surface properties, whether the reflected light dominantly origins from the reflective solar panel or from the insulating foil of satellite's body.

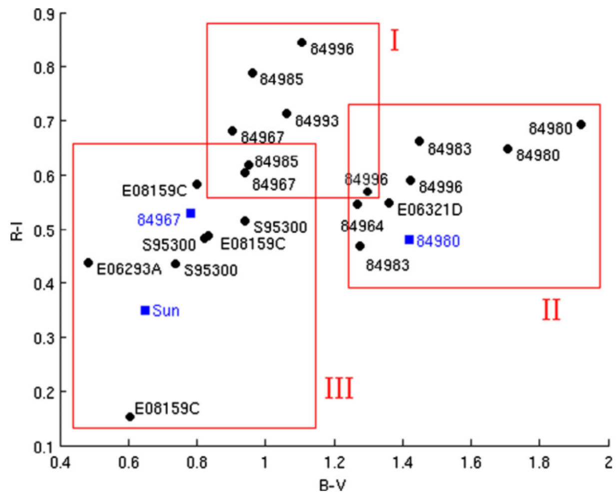


Fig. 1: Plot of color indices' digram B-V vs R-I of unknown debris objects from AIUB database. Red rectangles mark the area belonging to particular category. We can see that objects are grouped together. Credit:[1]

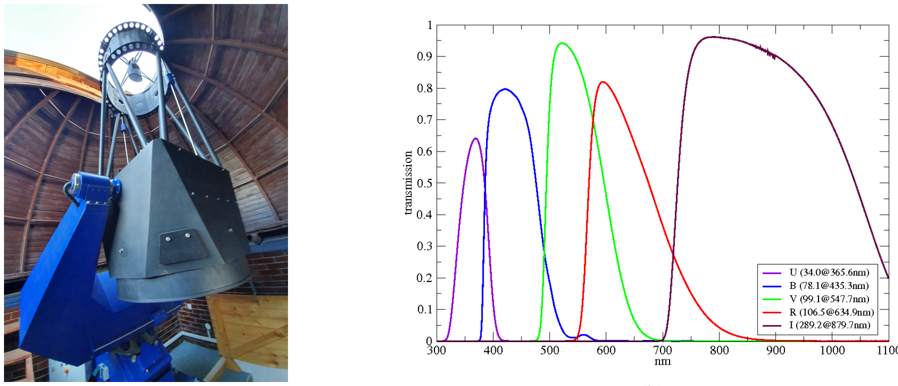
2. OUR OPTICAL SYSTEM

Since 2016 we are operating our own optical telescope, the Newtonian reflector (AGO70) installed on an equatorial mount with primary mirror with the diameter of 70 cm and the focal length of 2.9 m. AGO70 is installed at the Astronomical and Geophysical observatory in Modra, Slovakia (AGO) and is operated by the Faculty of Mathematics, Physics and Informatics of Comenius University in Bratislava, Slovakia (FMPI) (Fig.2a). Its main specialisation is the space debris and near-Earth asteroid observations. The light from the telescope is detected by the CCD camera FLI-ProLine KAF-1001E Grade 1 front-illuminated full frame monochrome CCD Camera with 65 mm shutter and resolution of 1024x1024 pixels with pixel size 24 μm. The resulting effective field of view is 29.1$'$x29.1$'$ and pixel's field of view is 1.67$''$x1.67$''$ [2].

The installed filter wheel contains Johnson/Bessel's BVRI filters (Fig.2b). The peak values and full width in half of maximum (FWHM) of the transmitted light respectively to the filters are: B-band - 435.3 nm - FWHM 78.1 nm, V-band - 547.7 nm - FWHM 99.1 nm, R-band - 634.9 nm - FWHM 106.56 nm, I-band 879.7 nm FWHM 289.2 nm [3].

3. LIGHT CURVE DATABASE

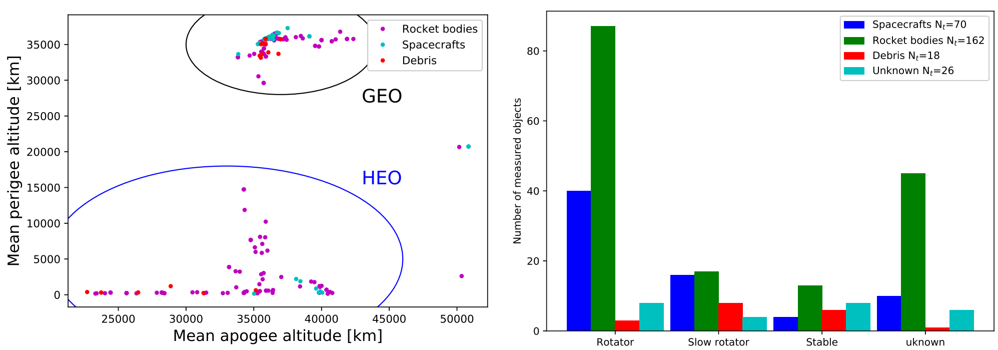
Photometric data acquired by AGO70 optical system are calibrated using routine astronomical calibration and then we construct the light curves using the image processing software AstroImageJ [5]. In the next the light curves are processed for the time series analysis. Using methods as Fast Fourier Transform and Lomb-Scargle method [6] we determine a potential apparent rotational period. The obtained value serves as input parameter to phase dispersion minimisation method [7]. The general condition for the processed light curve is, that it has to cover at least one and half of the phase. If the condition is fulfilled, the process provides us reconstructed phase function of the whole rotational period, which is in the next step fitted by the Fourier function of the eighth degree to determine the amplitude



(a) (b)

Fig. 2: a) Newtonian reflector AGO70. b) Spectral response of the Johnson/Bessel's photometric filters installed on AGO70. Credit:[4]

of phase. The found Fourier function is also used for estimation of the uncertainties in the obtained amplitude, apparent period and phase. The phase diagrams along with the estimated uncertainties are then stored in the FMPI's light curve catalogue [8]. Currently, the database consists of 276 light curves of 209 single objects, non-functional spacecraft, rocket bodies and also debris objects. The database covers objects placed on GEO and highly eccentric orbits.



(a) (b)

Fig. 3: a) Spatial distribution of observed objects. b) Distribution of apparent rotational period of catalogued objects. Data taken from the FMPI's light curve catalogue. Credit: [8]

Catalogued objects can be divided according to their apparent rotational period to following groups: rotators, slow rotators, stable, and objects with unknown period. This division is crucial during the target selection for the BVRI photometry, because the rotational period of chosen body should be long enough to be reliably sampled during the observation.

4. PHOTOMETRIC REDUCTION

To get from the obtained instrumental magnitude system to the standard system of BVRI filters we use the general transformation equations which considers effect of telescope's zero point (ZP), atmospheric exctinction (k) and color term (t_f) (Eq. 1):

$$M - m = k \cdot X - ZP - t_f \cdot (CI), \quad (1)$$

where M represents the calculated standard magnitude, m is the measured instrumental magnitude, X is the airmass calculated as secant of the zenith angle and CI stands for selected color index. Eq. 1 is a linear equation with three unknown parameters (k, X, t_f).

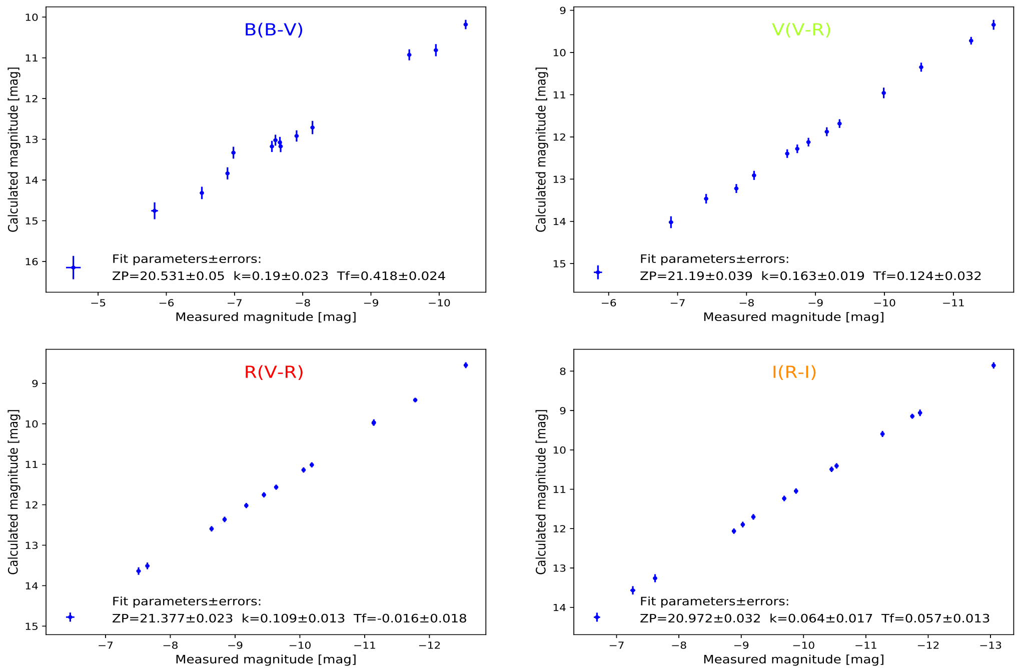


Fig. 4: Example of result from the optimization of the transformation equation from night 13/05/2018 with single values of the coefficients. In the brackets are showed the selected color index for optimization.

To estimate the unknown parameters in Eq.1 we observe the standard stars from the Landolt's catalogue ([9]) and [10]). Fields of the standard stars are selected to reliably satisfy the interval of the airmass and intensity airmass and intensity values obtained for the debris objects. The instrumental intensities of the standard stars are then converted to logarithmic scale and fitted using the least squares method and the catalogued values of their standard magnitudes. Thanks to this fit we are able to compute the transformation coefficients together with their uncertainties.

The AstroImageJ provides us also the formal uncertainty of each measurement [5], which is then propagated through our calculations. We consider every single variable in our calculation process as dependent on the data originated from the single instrument AGO70 [11]. This assumption allow us to consider only linear propagation of the uncertainty through the transformation equation and through the equation of the conversion to logaritmic scale.

Using this methodology, we obtain the solution of the transformation equation independently for each filter and also resulting uncertainty of the measurements (Fig.4). This solution is after that applied to transform the object's instrumental intensity to the standard system of magnitudes.

5. RESULTS

In this section we will present our two approaches to the BVRI photometry. In the first approach we can extract the average color indices from the selected target. It can be used for monitoring of the ageing, space-weathering effects or phase angle dependency effects and also to define the mentioned "reference plane". The targets for the second approach are rotating objects with well-known rotational period. Using this method we can see the changes of the color indices along the phase.

5.1 Attitude-controlled satellites

The first stage of the methodology is calculation of the average color index. Suitable targets are are operational GEO satellites which are attitude- and position-controlled. During the observation we acquire from five to ten images in each frame, with exposure time set to integrate a dominant part of the object's rotational period. The filter rotation starts and also end with the R filter to check, whether the conditions e.g., phase angle influence, object's rotation axis alignment toward observer are similar before and after the observation. The instrumental intensities in each filter are averaged and transformed to standard system of magnitudes and also the formal uncertainty of their measurements is propagated through each equation. The color indices are computed as difference between standard magnitudes in selected filters (Fig.5). During one night we acquire data for one object in three phase angles.

We also selected fourteen stable satellites from the public catalogue, which are functional with fixed positoin above a geodetic point. The advantage of these satellites is that they will be functional for many years and can be periodically monitored and we are able to set a "reference plane" by them in the instrumental system, which can be after that used for fast first guess transformation. The long-term monitoring should also show the effects of space-weather and ageing processes on surface materials.

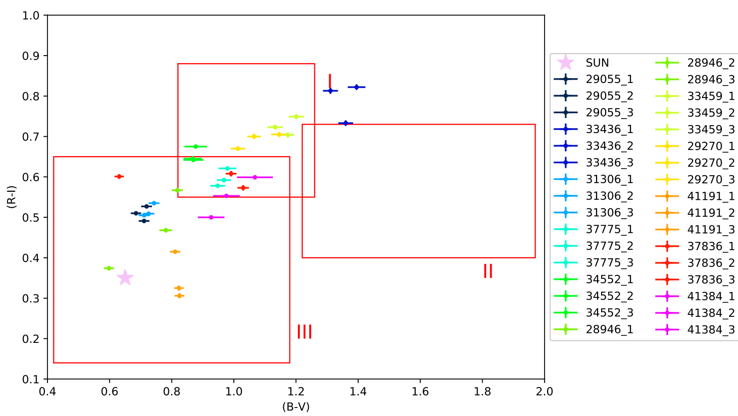


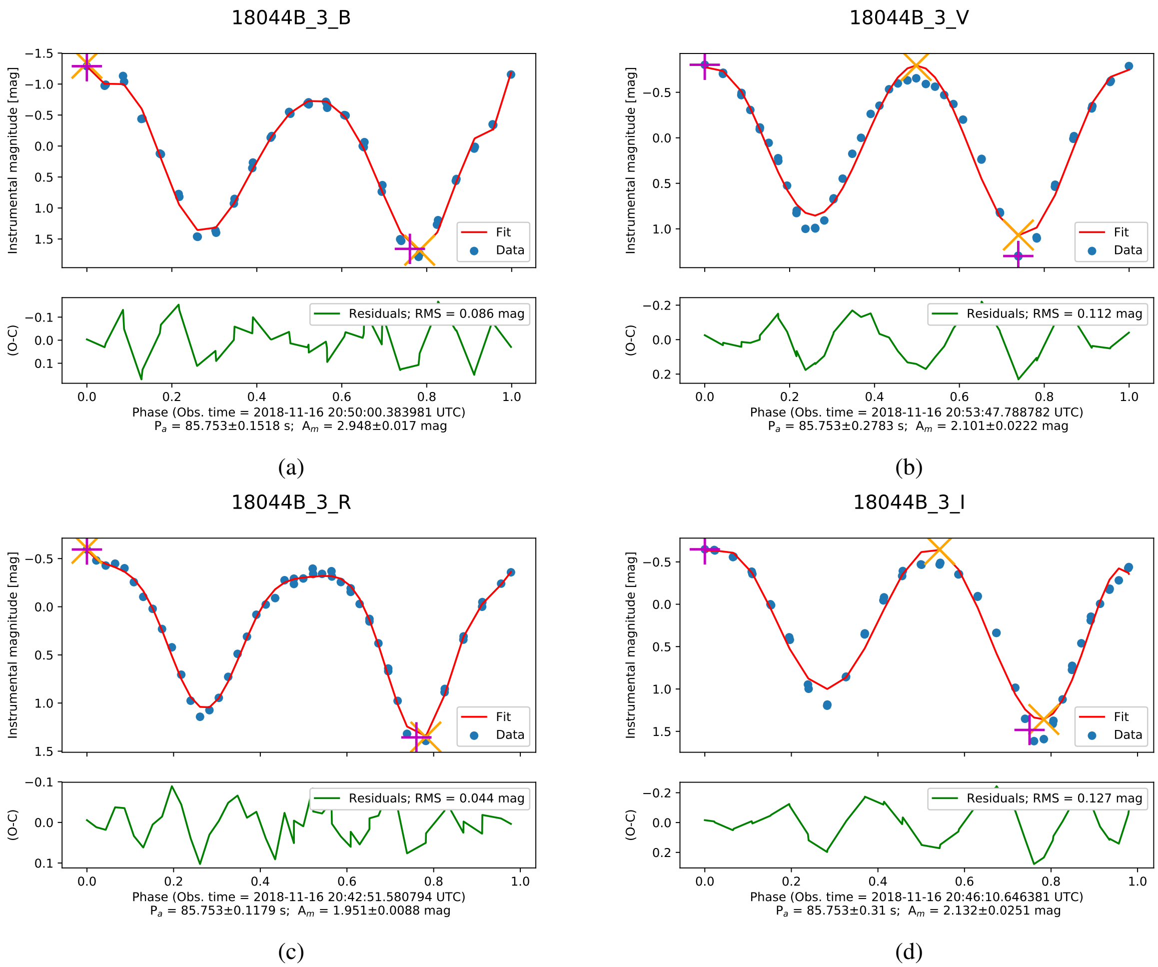
Fig. 5: Resulting color indices of reference satellites from night 24/07/2019. Each object was measured in three different phase angles. Plotted are also three material categories from [1]

In the Fig. 5 are eleven attitude-controlled satellites measured in three different phase angles during one observational night. It can be seen that color indices are slightly different in each phase angle, but their position holds in the same material category. The new and functional satellites, which were targets of this observation, lies primarily in the first and third category from article [1]. So, the dominantly reflecting surfaces are materials close to the solar panel and aluminium or silver insulation foil from the objects body. We expect that periodical long-term observations will show some redding effects as a result of the space-weathering and ageing processes. So, the objects should move slightly to the second "copper" category.

5.2 Rotating objects

The color indices of the rotating object along its rotational phase must be obtained differently than in the case of the stable satellites. The crucial part of the processing is, that the exact position of the measured point in the phase must be taken into account. This can be done using our internal light curve processing routine by using the phase dispersion minimization (Fig.6). The light curves observed in all filters are processed simultaneously to ensure that the resulting phase functions will be reliably aligned. From phase dependence of the color index we can see the motion of the objects in the indices' plane, between or in the material groups. We are unable to perform the simultaneous observation in different filters, but using this methodology we are can calculate the color index during the whole rotational phase.

Objects suitable for this method should well known rotational period, which can be narrowly and regularly sampled. The observational strategy is similar as in the previous case, but the exposures are much shorter to avoid any changes in amplitude due to the long integration of the intensity in one point. The observation series starts and ends with the data acquired in R filter to assure that the conditions, e.g., phase angle influence, object's rotation axis alignment toward observer, did not change significantly. One filter rotation usually takes from 20 to 25 minutes.



(a) (b) (c) (d)

Fig. 6: Plotted output of our light curve processing routine. We can see the fitted phase function with determined mathematical (orange cross) and data (purple plus) global extremes. On the bottom of the images we can see determined apparent rotational period and the data amplitude with their uncertainties.

In the next step are the color light curves transformed to standard system of magnitudes using the solution discussed in the section 4. The measured datasets are then fitted by Fourier function of the eighth degree, to obtain the mathematical expression of the phase functions. An example of such a case is shown in Fig. 6 for the object 18044B which was observed during the night 11/16/2018. The color indices are then calculated as the difference between these mathematical expressions.

In the Fig. 8a can be seen the material categories from the article [1] and plotted the R-I vs. B-V dependency along the phase of the Falcon 9 R/B. The color scale represents the objects motion in the color indices' plane. Plotted are also the values of the color indices in the maxima and minima of the reference R filter phase function. It can be seen that these points lies in the back-set points and that the dominant part of the curve lies in the third category. This "silver-like" category suits for the materials, which are strongly reflective and do not change markedly the spectrum of the incoming light. Because the Falcon 9 R/B have dominant white reflective coating, its position in the R-I vs. B-V can be expected in or near the third category.

6. CONCLUSION

In this work were used data acquired by 70 cm Newtonian reflector AGO70, equipped with filter changing wheel with Johnson/Cousins B, V, R$_c$, I$_c$ photometric filters, which is situated at the Astronomical and Geophysical Observatory

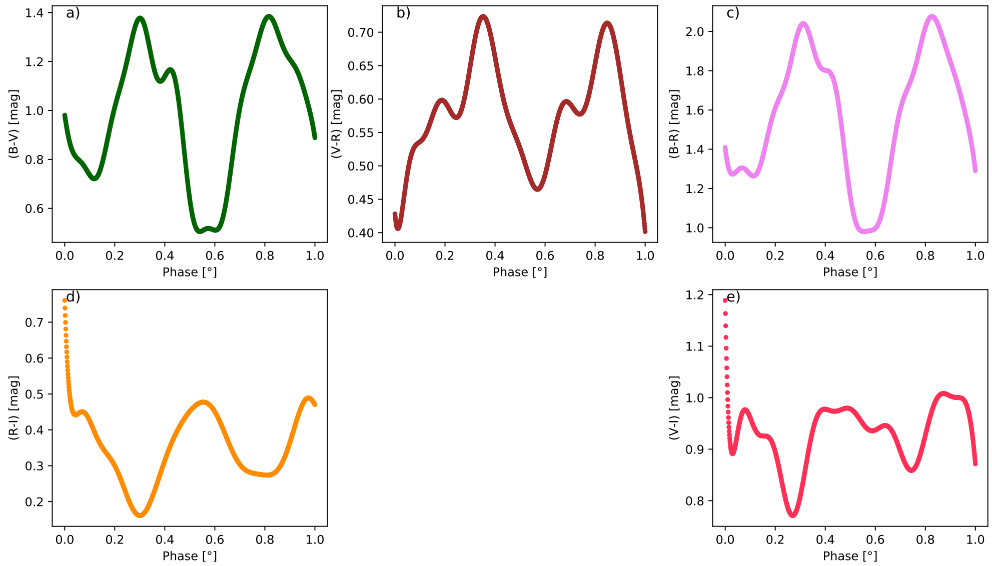


Fig. 7: Phase dependence of the color indices a) to e). The color indices were calculated from optimized data.

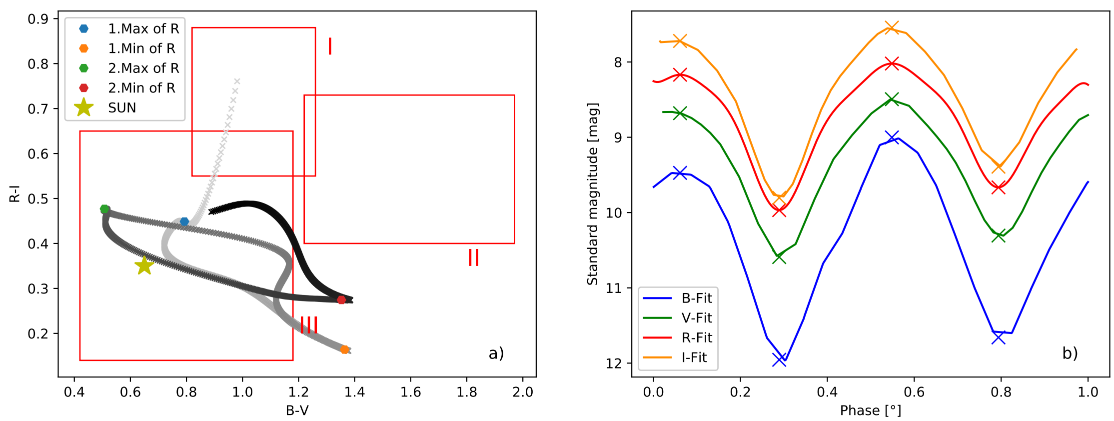


Fig. 8: a) R-I vs. B-V diagram with boxed marking different material categories defined in [1]. Marked are the values of the color indices in the 1^{st} and 2^{nd} local maxima and minima of the phase function in R filter. The color path represents the dependency of the object's indices on phase function (interval from 0.0 for lighter colors to 1.0 for black color; b) Fourier function of the aligned phase functions with marked maxima and minima.

in Modra, Slovakia (AGO). Its field of study is dedicated mainly for space debris observations, light curve cataloguing and astrometry. In this article we present the usage of AGO70 for specific astronomical method named BVRI or color photometry.

Our general goal is to establish a routine color photometry program of the space debris objects with intention of creating a public catalogue of color indices. This required to develop the observation and image reduction methodology for the transformation from the instrumental to the standard magnitude system by using Landolt's standard stars.

In our work we focused on two types of objects. The attitude-controlled satellites help to define the reference frame in instrumental system for the future observations, they help to better understand the effect of the phase angle change on the color indices and their long-term monitoring can reveal effect of space-weather. The rotating objects such as upper stages and non-functional satellites are the objects of interest where we investigate the color index as a function of the object's rotational phase. We presented average color indices obtained for 11 geosynchronous satellites and one example of rotating object Falcon 9 upper stage where we showed the R-I and B-V as a function of phase.

By using our public catalogue of light curves, we will perform an extensive observation campaign to the best candidates with goal to extract for them the R-I and B-V dependency on phase function by also focusing on the change of phase angle during the observations. Last but not least we plan to establish our own public catalogue of color indices for space debris to be made available for wider scientific community.

7. REFERENCES

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