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Influence of replacing discharge lamps with LED sources in outdoor lighting installations on astronomical observations

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Abstract. Light pollution has a detrimental effect on astronomy. Artificial light emitted from outdoor lighting increases the brightness of the night sky, making it difficult to observe astronomical objects. The spectral power distribution of artificial light sources is one of the key factors determining how much the night sky is deteriorated by light pollution. The ongoing replacement of discharge lamps with LED sources may have a major impact on astronomy because LED spectra usually cover the entire visible radiation range. This paper provides an analysis of the impact of LED sources with correlated color temperature in the range from 1000 K to approximately 10 000 K on visual and instrumental astronomical observations. For each analyzed artificial source, the Starlight Contamination Degree (SCD) index, i.e. a quantity that allows for quick evaluation of the impact of the sources on the night sky, is calculated. The reflection of artificial light from different ground surfaces and its scattering in the atmosphere was included in the calculation of the SCD index. LED lamps with very low values of correlated color temperature (CCT) and color rendering index (CRI) were found to possibly have a similar or even smaller impact on astronomical observations than sodium discharge lamps. Moreover, professional astronomical observations are more affected by LED lamps than visual observations, even for lamps with the lowest CCT and CRI. Thus, additional measures (e.g. reducing lumen output) should be applied to protect observational conditions. The results of the study help to assess which LED lamps can be used, and which should be avoided in the protection zones around astronomical observing sites.

Key words: outdoor lighting; LED sources; light pollution; astronomical observations; Starlight Contamination Degree.

1. INTRODUCTION

Electromagnetic radiation, including light, emitted, absorbed by, or reflected from celestial objects, carries key information about these objects. Astronomy aims to extract this information by collecting and analyzing electromagnetic radiation properly. In the process of collecting the radiation, celestial objects are observed using different facilities like telescopes and detectors. There are astronomical observations made from the surface of the Earth (ground-based observatories) and others from space (space observatories). Despite the growing role of space observatories, ground-based studies remain equally important for astronomy. The night sky, unpolluted by artificial light, is one of the crucial factors in facilitating ground-based observations. In other words, the night sky is an essential resource for astronomy.

Artificial outdoor lighting has many important purposes, e.g. safety [1, 2], or architectural lighting [3–6]. However, its extensive use may lead to several adverse phenomena known collectively as light pollution (LP). From a biological standpoint, artificial light at night (ALAN) may exert significant harmful impacts on flora and fauna [7–10]. In the case of astronomy, ALAN leads to an increase in the brightness of the night sky [11–14]. This increase is due to the light scattering in the atmosphere. More ALAN means a brighter sky. The brighter the sky, the lower the contrast between the background and celestial object. If the contrast is too low, observations become difficult or impossible to conduct (Fig. 1). The International Astronomical Union states that the maximum tolerable increase in the night sky brightness because of artificial light must not exceed 10 percent of the natural brightness level. As shown by a recent study [15], clear night skies over 18 of 28 major world astronomical observatories are already brighter than this limit. It is a deeply concerning situation that could get worse shortly.

The amount of artificial light is not the only factor determining the level of deterioration of the night sky. Spectral power distribution (SPD) of artificial light sources also plays an important role. Sources with SPDs as narrow as possible (almost monochromatic) and peaking in the long wave part of the visible spectrum are the least harmful to astronomy. Such sources leave part of or most of the visible spectrum uncontaminated by ALAN. That facilitates (almost) undisturbed observations at least at some wavelengths. Moreover, long-wave light scatters less in the atmosphere than the short wave, which means a relatively lower increase in the sky brightness. This is especially true for shorter distances from artificial light sources [16]. A good example of such sources is low-pressure sodium (LPS) lamps and to a lesser extent high-pressure sodium (HPS) lamps. However, these lamps are gradually being replaced with new, more efficient sources – light-emitting diodes (LED).

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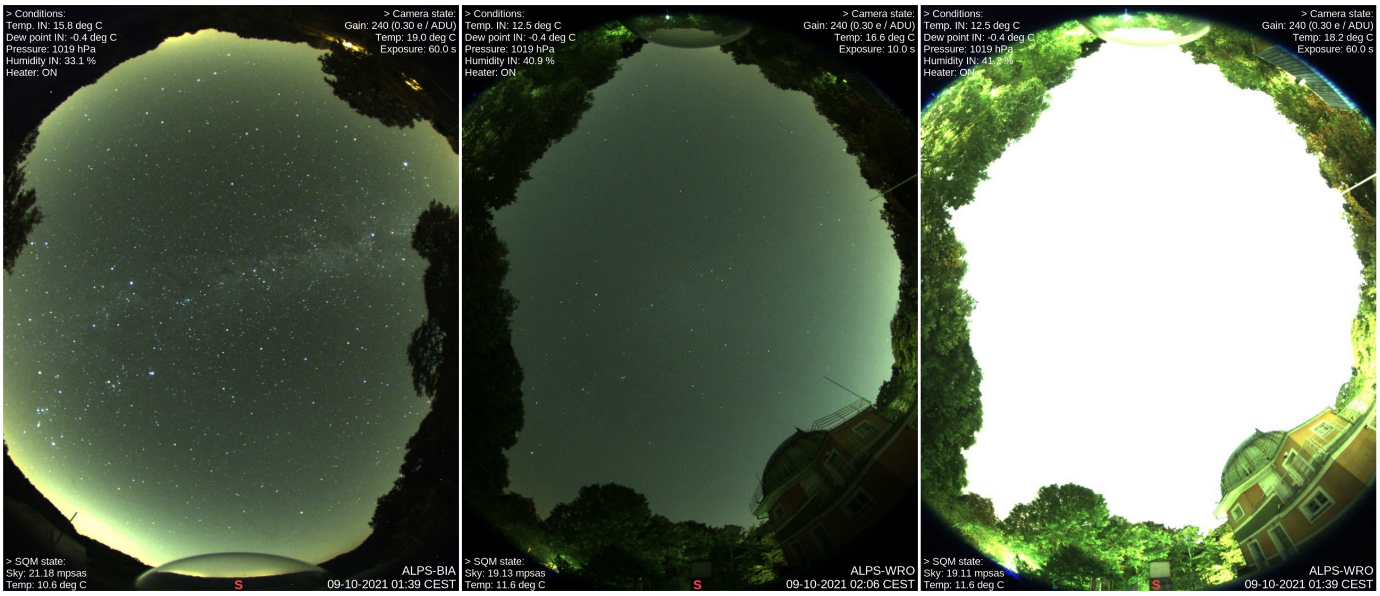

Fig. 1. Light emitted by outdoor lighting causes an increase in the brightness of the night sky. These all-sky photos show visual effect of the artificial increase. The image on the left was taken at Białków Astronomical Observatory (University of Wrocław). Exposure time: 60 sec. The sky in Białków has low light pollution and represents typical rural night sky in Poland. Image in the middle was taken in Wrocław, less than 4 km away from the city center (location of the Astronomical Institute of the University of Wrocław). Exposure time: 10 sec. This is a typical city night sky with high level of light pollution. Far fewer stars are seen on the image from Wrocław and Milky Way is invisible here (the belt of dim light running across the Białków image). Image on the right was taken at the same location as image in the middle but with exposure time the same as the image from Białków. Thus, the left and the right images show real visual comparison of the effect of light pollution on the sky in these two sites. All images were taken during the same night at a similar time by two monitoring stations of ALPS network (All-sky Light Pollution Survey [17–19])

Light-emitting diodes do not produce white light directly. To make it possible, it is necessary to apply appropriate technical measures. There are different methods of obtaining white light. The most popular one is producing blue light (of spectral range from 430 to 480 nm), which excites the phosphor placed on the diode. The light produced by the phosphor is mixed with blue light, which results in white light. Depending on the chemical composition of the phosphor, it is possible to produce light with different spectral distributions and, consequently, with different correlated color temperature (CCT) values. The manufacturers of LED sources offer a wide range of color temperatures, from low (warm color) to high (cold color). The transformation of blue light by the phosphor lowers the luminous efficacy. Due to economic pressure, favoring lighting with high luminous efficacy, light sources with high values of the closest color temperature (cold light) are preferred in outdoor lighting. The development and popularization of LED lighting is inevitable. As a result of technological progress, electricity can be used more efficiently.

From astronomical perspective, it is vital to learn how these LED sources will affect the night sky brightness. Some studies have already tackled this topic. For example, a model of the global map of artificial night sky brightness was computed based on satellite images of artificial nighttime sources [11]. In the same paper, the authors forecast Europe's sky brightness after the full transition from HPS lamps to 4000 K white LEDs in outdoor lighting. The authors assumed that photopic flux and upward emission of light remain the same as in the case of currently installed lamps. This forecast concludes that such a transition would result in about a 2.5-time increase in the night sky brightness as perceived by the dark-adapted human eye.

Another example of an analysis of LED impact on astronomy [20] quantitatively assessed the impact of different light sources, including LPS, HPS, and a few white LEDs (see section 2.F for details). The conclusion is that white LED sources may cause up to a 10-fold increase in the sky brightness for the human eye compared to LPS lamps.

It is also worth mentioning another aspect of LED lighting – the impact on how astronomers measure the deterioration of the night. The spectra of LED sources are characterized by a great variety. Thus, sky brightness changes due to LP cannot be accurately measured with the use of single-band photometers. More complex multi-band photometers, like color cameras, are needed [21].

In this paper, a detailed analysis of the projected impact of over 150 different LED sources on visual and instrumental astronomical observations is presented. An index that allows for rapid evaluation of this impact was constructed.

2. METHODS

Let us consider an observing site for amateur or professional astronomers. In the best scenario, outdoor lighting should not be present in the area around the site. This is not always possible, especially in countries with a high population density. In many European astronomical observatories, villages and towns are within a short distance, e.g. 10–20 km.

What outdoor lighting installed in that site nearest neighborhood will have a lesser adverse impact on the sky brightness? The answer is not straightforward. Many parameters of outdoor lighting and properties of surroundings will affect the final apparent condition of the sky, e.g.:

- Total installed luminous flux.
- Spectral power distribution of sources.
- Type of luminaires (luminaire photometric intensity curve).
- Type of lighting (road/street lighting, sports lighting, floodlighting of buildings, advertising lighting, etc.).
- Type of ground surfaces (reflection of light).
- Terrain masking (e.g. hills).
- The presence of obstacles (trees, buildings).
- The state of the atmosphere (aerosols, clouds).

If one's goal is to predict night sky brightness, all or most of the above-mentioned factors should be included in a model. Such comprehensive models (e.g. [11]) provide quite accurate results. However, computations are time-consuming because the contribution of artificial light coming from all directions must be taken into account to calculate night sky brightness in a given location. Any significant change in model parameters means that the model needs to be recalculated.

This paper focuses on the spectral power distribution of light sources. A situation in which existing outdoor lighting nearest to the observing site will be replaced with LED sources is assumed. Other parameters of the lighting and properties of surroundings will not be changed. It would not be feasible to calculate a complex model for a larger number of LED sources used in outdoor lighting. Thus, we had to use a simplified, easy-to-calculate model which, however, can provide reliable results. The presented model does not calculate the brightness of the sky. It estimates a degree of contamination of the observed part of the spectrum of a celestial object with artificial light. Details of the model are described in the next sections.

2.1. Model

Figure 2 shows two models estimating the impact of ALAN on professional and amateur astronomy.

- Instrumental observations conducted by professional astronomers. Light from astronomical objects is collected by a telescope and directed to a detector to be digitally recorded for analysis.
- Visual observations conducted by amateur astronomers. Light from an astronomical object is recorded by the human eye. These observations can be done with the naked eye or using a telescope.

In both situations, we assume the presence of outdoor lighting near the observation site. Artificial light is reflected from the ground and propagates up in the atmosphere. Here, the light is scattered and partially directed toward the observing site. Thus, the observer receives a mixture of scattered artificial light and light from an observed celestial object. The light of the observed object is contaminated with artificial light. How does the contamination shift in response to the SPD of artificial sources?

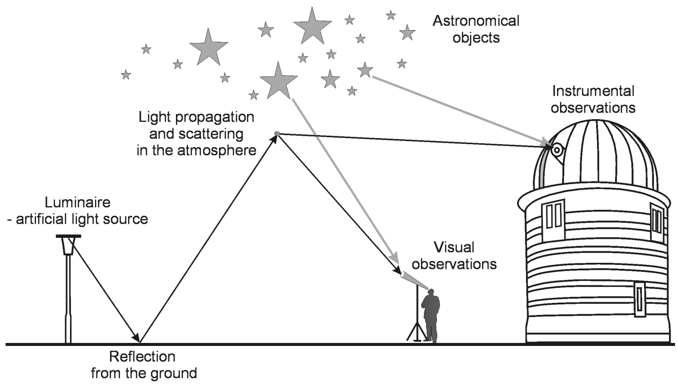

Fig. 2. Schematic model of situations considered in this paper – artificial light contaminates light of observed celestial objects. See the text for more details

In our calculations, we assume that artificial light cannot reach an observing site directly. This is because the light can be blocked by different obstacles, e.g. trees, buildings, and hills.

The sky closer to the zenith, higher than 30°–40° above the horizon, is the most critical for observations. In the lower part of the sky, atmospheric extinction and astronomical seeing (blurring of the image of astronomical objects as a result of atmospheric turbulence) significantly worsen the conditions for observation. It was shown by other authors (e.g. [22]) that closer to the zenith artificial sky brightness is dominated by ground-reflected light emitted from outdoor lighting and installed near the observing site. Thus, artificial light that disturbs observations has a spectrum different from that of the SPD of lamps. The SPD is modified by ground reflection and atmospheric scattering. In general, both processes are wavelength dependent.

In the next sections, we will follow artificial light from its source to an observer and explain adopted parameters and assumptions.

2.2. Artificial light sources

In the case of outdoor lighting, energy efficiency plays a vital role. The level of electricity consumption for lighting purposes is determined, among other factors, by the type of light source used. In the past years, the most popular light sources used in outdoor luminaires were discharge lamps. Low-pressure sodium lamps show the highest light efficiency. The light emitted from the arc discharge in sodium vapors of low pressure is nearly monochromatic (Fig. 3), which makes it difficult to determine the color rendering of the illuminated objects [23, 24]. As mentioned in the introduction, these lamps produce the least interference with astronomical observations. Thus, we decided to include these lamps in our analysis as a reference point.

High-pressure sodium lamps are commonly used in road and outdoor lighting. They are characterized by high luminous efficiency and better color rendering. The discharge in sodium vapor makes the color of the light yellow with the closest color temperature equal to circa 2000 K. The spectral power distribution of this type of sodium lamp is not continuous, with visible peaks in the range from 560 nm to 610 nm.

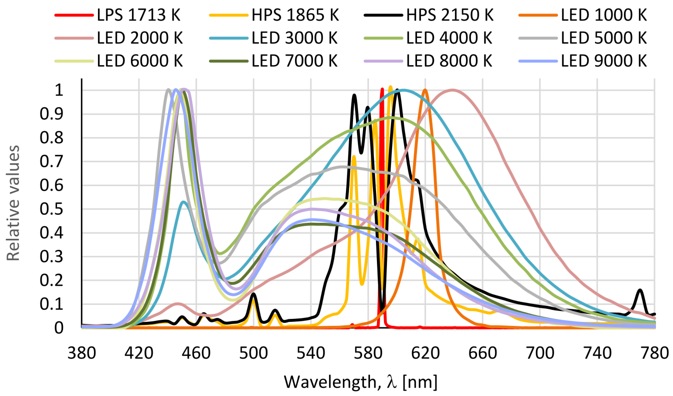

Fig. 3. Spectral characteristics of sodium lamps and selected LED sources with different correlated color temperature values

Semiconductor light sources are currently the fastest-growing and the most energy-efficient group of light sources used in lighting technology [25]. The luminous efficiency of modern luminaires with LED sources is higher than that of sodium lamps [26, 27]. Systematic modernization of lighting is carried out both in cities and municipalities. The most common premise for the modernization of outdoor lighting is the improvement of energy efficiency. The idea behind the functioning of white LEDs is to transform blue light generated by the chip via phosphor. Depending on the phosphor's chemical composition, it is possible to obtain light colors with distinct color temperatures. In other words, the phosphor acts as a blue-light-to-white-light converter. The consequence of such a mechanism of producing light results in two "peaks" visible in the spectral power distribution. The first, the maximum of which is usually in the wavelength range between 430 nm and 480 nm, is the radiation emitted by the blue diode while the second is the result of the phosphor response.

Our considerations include one LPS lamp, two HPS lamps, and 156 actual spectral characteristics of LED sources with a wide range of the closest color temperature (from 1000 K to almost 10 000 K). Due to the large number of analyzed LED sources, it was decided to include only selected spectral characteristics of the lamps in Fig. 3. The spectral characteristics of the lamps were taken from [23].

In outdoor lighting installations, color temperatures of the light sources are typically in the range of 2000 K to 6500 K. It is worth mentioning that in the case of LED sources increasing the luminous efficiency, the closest color temperature also increases. From the perspective of energy efficiency, these sources are the most attractive. Therefore, there are solutions where LED sources with values exceeding 6500 K are used.

LED technology can also produce light with a very warm color that is visually similar to traditional sodium lamps. Due to the lower luminous efficiency, these sources are not very popular, but from the viewpoint of limiting the increase in the brightness of the night sky, they can serve as an alternative to sodium lamps. To broaden the scope of considerations, the authors decided to take into account a greater range of color temperatures of LED sources than that usually used in practice. However, the considerations did not include the impact of ambient temperature on the change of photometric parameters of the light sources [28].

2.3. Ground surfaces

As a result of the interaction of light with the ground, part of the visible radiation will be reflected and directed towards the sky. In the lighting technique, the properties of a given surface are characterized by the spectral reflectance. This quantity provides information on the ability to reflect individual wavelengths of the illuminating light from a given surface. It is worth mentioning that all surfaces show nonlinear spectral reflection characteristics. Figure 4 shows the spectral reflectance waveforms of four typical substrates: asphalt, grass, paving stones, and snow. The first three are typical foundations of built-up areas (cities, villages). In our considerations, we assume such areas are in the vicinity of the observation site. Snow is typical of winter ground in mid to high latitudes. The spectral reflectance of asphalt, grass, and snow was taken from the Jet Propulsion Laboratory (JPL) spectral library, which is available from the National Aeronautics and Space Administration (NASA) [29], while the spectral reflectance of paving stones is a result of own laboratory measurements.

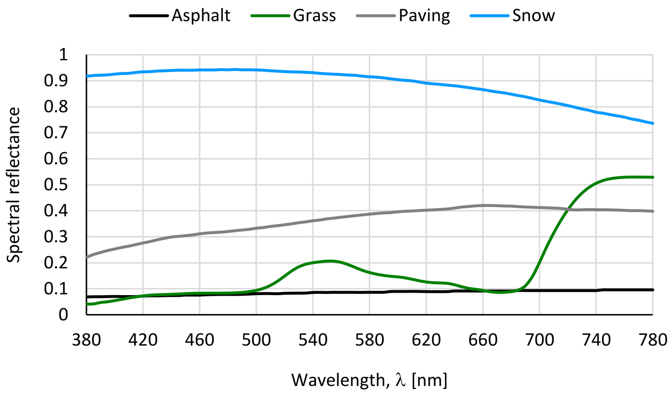

Fig. 4. Spectral reflectance of selected grounds. See the text for more details

The courses of the individual curves differ significantly, which in practice means that the individual wavelengths of light falling on the substrate are reflected differently. The light reflects the least in the case of asphalt. The maximum value does not exceed 0.1. A high stability of the spectral reflection coefficient is noticeable here, which means that all wavelengths of radiation in the visible range are reflected in the same way. In the case of grass, the reflectance value increases in the wavelength range from 500 to 650 nm and even above 690 nm. This means that the wavelengths corresponding to the red color will be reflected the most. In the case of paving stones, an increase in the spectral reflectance can be observed with increasing wavelength. The highest values of the spectral reflectance coefficient occur when snow covers the ground. Light reflection deteriorates with increasing wavelength.

Knowing the spectral reflectance of the substrate and the spectral characteristics of the radiation emitted by the lamp, the spectral characteristics of the radiation emitted towards the sky can be determined.

2.4. Atmospheric scattering

The light propagating through the atmosphere interacts with its components: molecules, aerosols, and clouds. We assume good observing conditions, i.e. no clouds. The scattering on the molecules strongly depends on the wavelength. According to Rayleigh's theory, the amount of the scattering is proportional to λ^{-4}. On the other hand, scattering on aerosols is much less dependent on the wavelength [30]. In real conditions, both processes are present. Approximately, the total scattering (molecules plus aerosols) will be proportional to λ^{-a}, where the exponent a is in the range of 1 to 4. In the paper [22] the authors showed that a depends on the distance between an observer and a lit area, e.g. a town. For shorter distances up to 20 km and good observing conditions (clear atmosphere, low abundance of aerosols), the exponent $a \approx 3.6$. This value was adopted in our main calculations. In addition, we repeated our analysis for a more turbid atmosphere (higher abundance of aerosols) using the exponent $a = 2.0$. This case represents areas with more air pollution. In both cases (clear and turbid), we expect that short-wavelength light will be scattered significantly more causing a higher increase in the sky brightness than long-wavelength light.

2.5. Observer's spectral response

At the end of its path, artificial light reaches an observer (eye or instrument). Usually, observations are conducted in a selected portion of the visible spectrum. For visual observations, we assumed an observer with fully dark-adapted eyes. Therefore, we used the scotopic vision curve adopted by the CIE [31] in our calculations (see Fig. 5).

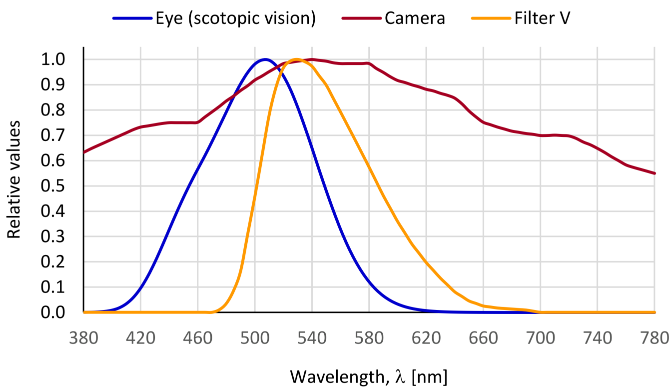

Fig. 5. Spectral characteristic of the fully dark-adapted human eye (scotopic vision), the V filter of the Johnson–Cousins photometric system, and the selected CCD camera. See the text for more details

The case of professional instrumental observations is more complex. First, the light goes through a telescope. Here we assumed that optical elements of a telescope do not change the spectral distribution of light. The next step depends on the type of observations. We consider photometric observations, where the brightness of a celestial object is measured. The light passes through a specialized optical bandpass filter before reaching a photometer. There are many photometric systems commonly used in professional astronomy. A photometric system is a set of well-defined optical filters. The spectral characteristic of these filters is standardized. For our calculations, we assumed that photometric observations are conducted with the V filter of the Johnson–Cousins photometric system [32]. Spectral transmission of the V filter is shown in Fig. 5. To avoid confusion with the scotopic curve $V'(\lambda)$, the V filter will be written with JC subscript (V_{JC}). Finally, light is received by a detector (photometer). At present CCD cameras are used in astronomical photometry. CCD cameras have different spectral responses (called quantum efficiency). For our calculation, we adopted the spectral response of an arbitrarily selected CCD camera (Fig. 5).

2.6. Starlight Contamination Degree index

In the paper [20] the authors constructed an index to quantitatively assess the impact of artificial light on star visibility in the case of different light sources, including LPS, HPS, and a few white LEDs. The index, named Star Light Index (SLI), is a ratio of two integrals (see Equation 1).

$$\mathrm{SLI} = \frac{\int_{380}^{730} S(\lambda)_{n\mathrm{Lamp}} V'(\lambda)\,\mathrm{d}\lambda}{\int_{380}^{730} S(\lambda)_{n\mathrm{D65}} V'(\lambda)\,\mathrm{d}\lambda}, \tag{1}$$

where $S(\lambda)_{n\mathrm{Lamp}}$ is the normalized spectral distribution of a lamp, $V'(\lambda)$ – scotopic efficiency function, and $S(\lambda)_{n\mathrm{D65}}$ – normalized spectral distribution of standard CIE illuminant D65. The normalization was done to exclude differences in the luminous flux of different lamps, so the perceived power of their light is the same. Thus, the SLI is a ratio of two scotopic luminous fluxes of normalized SPD.

The illuminant D65, which represents the typical midday spectrum of solar radiation in Europe, is a reference point in the SLI. The authors justify the adoption of such a reference point based on the fact that life on Earth (including human sight) evolved under the Sun. However, we think that the spectral distribution of an observed celestial object is a better reference point. We need to know to what extent the observed part of the spectrum of a celestial object is contaminated with artificial light.

The second modification we want to introduce is ground reflectance which is not present in the SLI. The justification to include the reflectance was presented in Section 2.1.

Originally the SLI was calculated for direct lighting (artificial light reaches an observer directly) and for indirect lighting (artificial light reaches an observer after being scattered in the atmosphere). In the second case, the authors also included the scattering in the denominator. In our modification, the scattering of light of a celestial object is not present. This is because an observer receives (needs to receive) direct light of the object, not its scattered light.

After the application of the aforementioned modifications, we introduce a new index – Starlight Contamination Degree (SCD). The name is different to avoid confusion with the original SLI. In the case of visual observations we have the visual SCD:

$$\mathrm{vSCD} = \frac{\int_{380}^{780} S(\lambda)_{n\,\mathrm{Lamp}} r(\lambda) V'(\lambda) p \lambda^{-a} \, \mathrm{d}\lambda}{\int_{380}^{780} S(\lambda)_{n\,\mathrm{Star}} V'(\lambda) \, \mathrm{d}\lambda}, \tag{2}$$

where $S(\lambda)_{n\,\mathrm{Lamp}}$ is the normalized spectral distribution of a lamp, $V'(\lambda)$ – scotopic efficiency function, $r(\lambda)$ – ground reflectance, λ^{-a} – atmospheric scattering, p – arbitrary scaling parameter for the scattering, $S(\lambda)_{n\,\mathrm{Star}}$ – normalized spectral distribution of a star.

In the case of instrumental observations (photometry with the use of the V_{JC} filter), the equation takes the following form:

$$\mathrm{iSCD} = \frac{\int_{380}^{780} S(\lambda)_{n\,\mathrm{Lamp}} r(\lambda) C(\lambda) F(\lambda) p \lambda^{-a} \, \mathrm{d}\lambda}{\int_{380}^{780} S(\lambda)_{n\,\mathrm{Star}} C(\lambda) F(\lambda) \, \mathrm{d}\lambda}, \tag{3}$$

where $C(\lambda)$ is the spectral responses of the CCD camera, and $F(\lambda)$ – spectral transmission of the V_{JC} filter. In equations (2) and (3) the integration range from 380 nm to 780 nm was adopted. This is because usually this wavelength range is taken as visible radiation.

Three stars of different spectral distributions were included in the calculations of both SCD indices. Stellar spectra were downloaded from Sternberg Spectrophotometric Catalog [33] and are presented in Fig. 6. Typical stars were selected:

- A star of spectral type A0V (effective temperature 9500 K) represents a population of hot stars.
- A star of spectral type G0V (effective temperature 6050 K) represents a population of stars of intermediate temperatures (solar-like).
- A star of spectral type K7V (effective temperature 4050 K) represents a population of cool stars.

Effective temperature, T_{eff}, can be regarded as a rough estimation of the temperature of the gaseous surface of a star. The effective temperature of a star is the temperature of a black body emitting the same total amount of electromagnetic radiation as this star.

The spectra do not cover the entire visible range. There are no data for a small part of the range, close to its red end (see Fig. 6). However, this does not affect our calculations because for wavelengths > 700 nm, the V filter transmission curve and scotopic vision curve have almost a value of zero.

The measured spectral distribution of a star is altered by atmospheric extinction. In this process, light in shorter wavelengths is extinguished more than in longer wavelengths. Thus, the shape of the stellar spectrum changes. The magnitude of this phenomenon depends on the angular height (elevation) of a star above the horizon. The lower the elevation, the greater the effect of the extinction. However, the change in the shape of the spectrum is not significant from our point of view because the consideration is limited to elevation angles $> 30°–40°$. Moreover, the change is smaller than the differences in spectra of the considered stars. Thus, the effect of atmospheric extinction on the stellar spectra is not included.

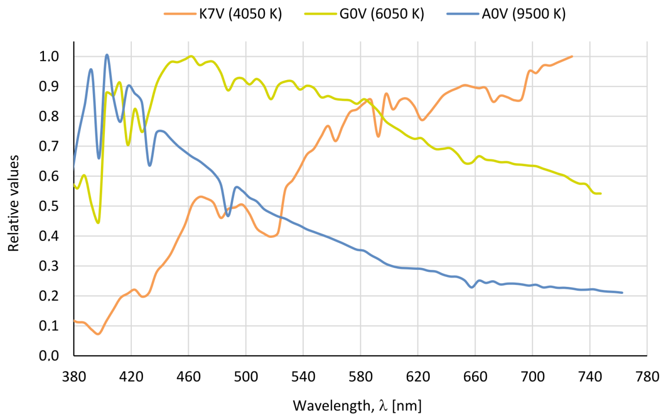

Fig. 6. Spectra of stars included in calculations of Starlight Contamination Degree index. See the text for details

3. RESULTS

First, we present results for good observing conditions, i.e. atmosphere with a low abundance of aerosols (exponent $a = 3.6$). Figure 7 presents the values of the visual SCD (vSCD) index calculated for 159 lamps. For clarity of the graph, the lamps are described with numbers instead of their CCT. The lamp with "1" is LPS (CCT = 1713 K). Lamps "2" and "3" are HPS with CCT 1865 K and 2150 K, respectively. The rest of the lamps are LED. Their numbers are assigned in the order of increasing CCT. LED number "4" has CCT = 1000 K (the warmest light color) and LED number "159" has CCT = 9753 K (the coolest light color).

For a given ground surface, the vSCD increases with CCT. For a given CCT, the index has a higher value for more reflective surfaces – it is the lowest for asphalt and the highest for snow. For the fixed lamp and fixed type of ground, the vSCD is higher for stars of lower effective temperature. However, the vSCD is significantly less sensitive to T_{eff} changes than to the CCT and ground changes. We can regard these limited variations due to T_{eff} as the range of possible vSCD values for different observed stars.

In Section 2 we assumed a situation in which existing outdoor lighting installed near the observing site will be replaced with LED sources. Thus, we will assess the vSCD index of the LED lamps regarding LPS and HPS sources as reference points. We assume that an LED lamp has a similar vSCD if the value of the index is less than 130% of the value of vSCD for LPS or HPS lamps.

Among 9 LED lamps of CCT < 2000 K, two have similar impact on visual observation as the LPS lamp. Among 38 LED

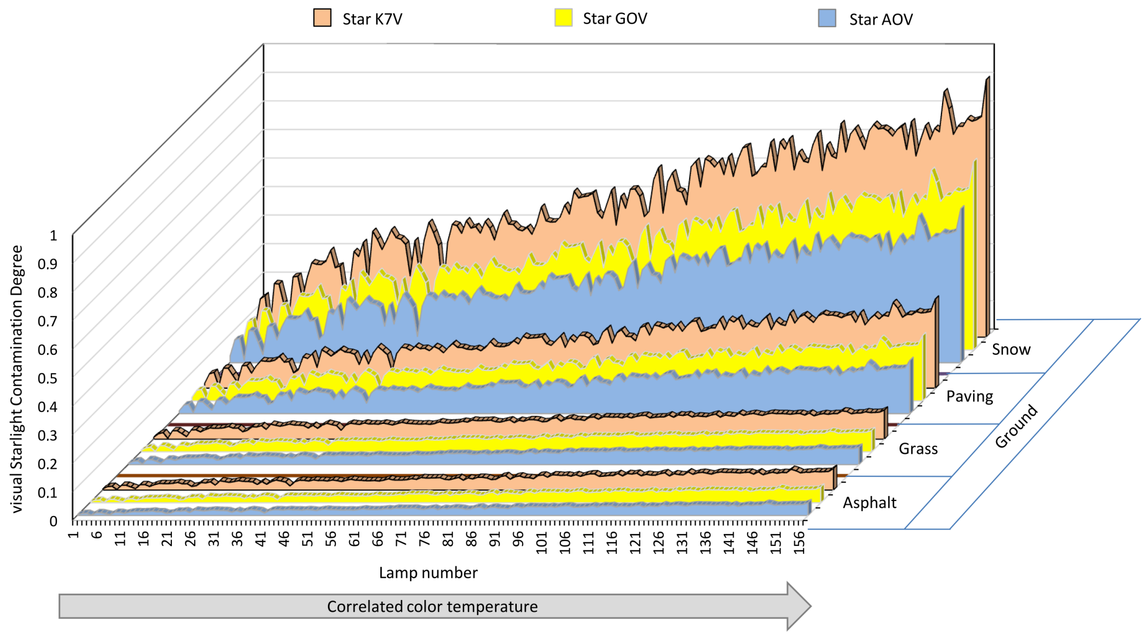

Fig. 7. Starlight Contamination Degree index calculated for visual observations. See the text for details

lamps of CCT $<$ 2900 K, eight have similar or lower impact on visual observation as the HPS lamps. The rest of the analyzed LED lamps, especially with CCT $>$ 2900 K, have higher vSCD. For example, 4000 K LED lamps (neutral white light) are 3–10 times more harmful to visual observations than LPS and HPS lamps. These white light LED lamps are commonly installed in outdoor lighting. Corresponding values for 5000 K and 9000 K LED are 4–12 and 5–15, respectively. All these results insignificantly depend on the type of ground surface.

The impact of ground reflectance on the vSCD is quite predictable – higher reflectance results in an increased disturbance of observations. The relation is linear. Asphalt has a lesser impact on observations. For grass, paving and snow the impact is about 1.5–2, 4, and 10 times higher, respectively, compared to asphalt.

Interestingly, vSCD does not increase monotonically with CCT. The increase is rugged, as can be seen in Fig. 7. Lamps of similar CCT can have a significantly different impact on visual observations. For example, there are six lamps in a short CCT range $\sim 2800-2920$ K. The lamp with the lowest vSCD has CCT $=$ 2884 K. Its vSCD is almost 1.8 smaller than for lamps located on both ends of the range. This difference is caused by the SPD, i.e. the lamp with the lowest vSCD has almost no emission below 500 nm, while the rest of the lamps of similar CCT emit in that spectral region. They significantly disturb scotopic vision. The lamp with the lowest vSCD among these six lamps is also characterized by the lowest color rendering index (CRI): 27 vs. 75–96.

Such behavior is seen for the whole set of analyzed lamps – those with lower CRI have a vSCD lower than lamps of similar CCT but higher CRI. To sum up, lamps in the sample with the lowest impact on visual observations have CCT $<$ 2900 K and low CRI (below 60).

Figure 8 presents values of the instrumental SCD (iSCD) index calculated for the same set of lamps. The number on the X-axis has the same meaning as in Fig. 8. The iSCD increases with CCT and ground reflectance. However, unlike vSCD, the instrumental index shows almost no dependence on the type of star (T_{eff} of a star).

As in the case of the vSCD, we assess the iSCD index of LED lamps with regard to LPS and HPS sources. We assume that an LED lamp has a similar iSCD if the value of the index is smaller than 110% of the value of iSCD for LPS or HPS lamps. The limit is lower (110% vs. 130%) than for visual observations. This is because instrumental observations are more sensitive to the disturbance caused by artificial light. According to the International Astronomical Union, an artificial increase in the sky brightness by only 10% may pose a significant obstacle to professional instrumental observations.

Among nine LED lamps of CCT $<$ 2000 K, two have a similar or lower impact on instrumental observation in the V_{JC} filter than the LPS lamp. Among 18 LED lamps of CCT $<$ 2400 K, ten have a similar or lower impact on instrumental observation as the HPS lamps. The most significant increase in the iSCD with CCT occurs for CCT $<$ 2600 K. Lamps with CCT $=$ 2600 K are 1.3 and 1.5 times more harmful to instrumental observations than HPS and LPS, respectively. Above $\approx$ 2600 K the increase is less pronounced. Corresponding values for 4000 K, 5000 K, and 9000 K LED are (1.4, 1.7), (1.45, 1.8), and (1.5, 1.9), respectively. These results vary by insensible degree with ground reflectance.

For a given CCT, the instrumental SCD index increases significantly with ground reflectance. The relation is similar to the case of the visual SCD index. For grass, paving, and snow the impact is about 2, 4–5, and 10 times larger, respectively, compared to asphalt.

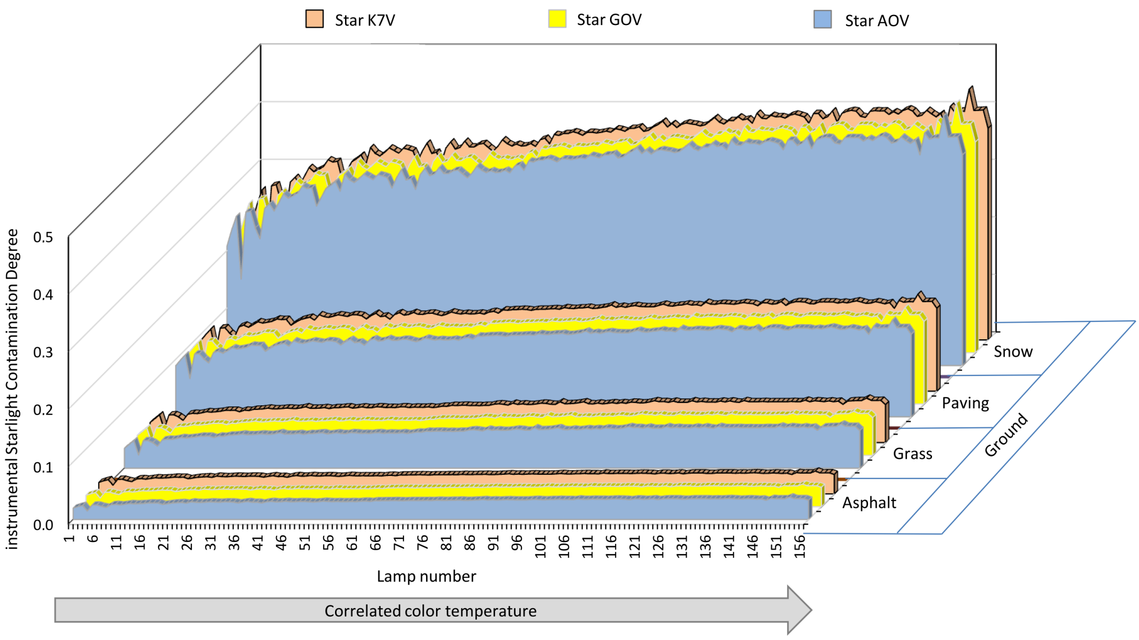

Fig. 8. Starlight Contamination Degree index calculated for instrumental observations (photometry in the V_{JC} filter). See the text for details

As in the case of the vSCD, the increase of iSCD with CCT is rugged (see Fig. 8). This is because LED lamps with similar CCT may have distinctly different spectral distributions and hence CRI. Let us consider again six lamps in the CCT range $\sim 2800-2920$ K. The lamp with the CCT $= 2884$ K has the smallest iSCD among these six lamps. It is up to 1.1 times lower than for lamps of similar temperature. The cause is the same as in the case of vSCD, i.e. amount of the light emitted below 500 nm. However, the difference is significantly lower than in the case of visual observations because the V_{JC} filter has a much lower transmission below 500 nm than the scotopic vision. In general, the spectral distribution (or CRI) of an LED lamp affects the instrumental SCD index, but this relation is weaker than for the visual SCD.

In the next step, SCD indices for less favorable observing conditions were calculated, i.e. atmosphere with a higher abundance of aerosols (exponent $a = 2.0$). The results are presented in Figs. 9 and 10 in comparison to the SCD indices calculated for clear atmosphere (exponent $a = 3.6$). For the sake of conciseness, here only plots for AV0 star and asphalt are presented. Results for other star spectra and grounds are similar.

First of all, the visual and instrumental SCD($a = 2.0$) indices show a similar trend as SCD($a = 3.6$) indices, i.e. the higher the CCT, the higher the index. Moreover, for a given lamp (given

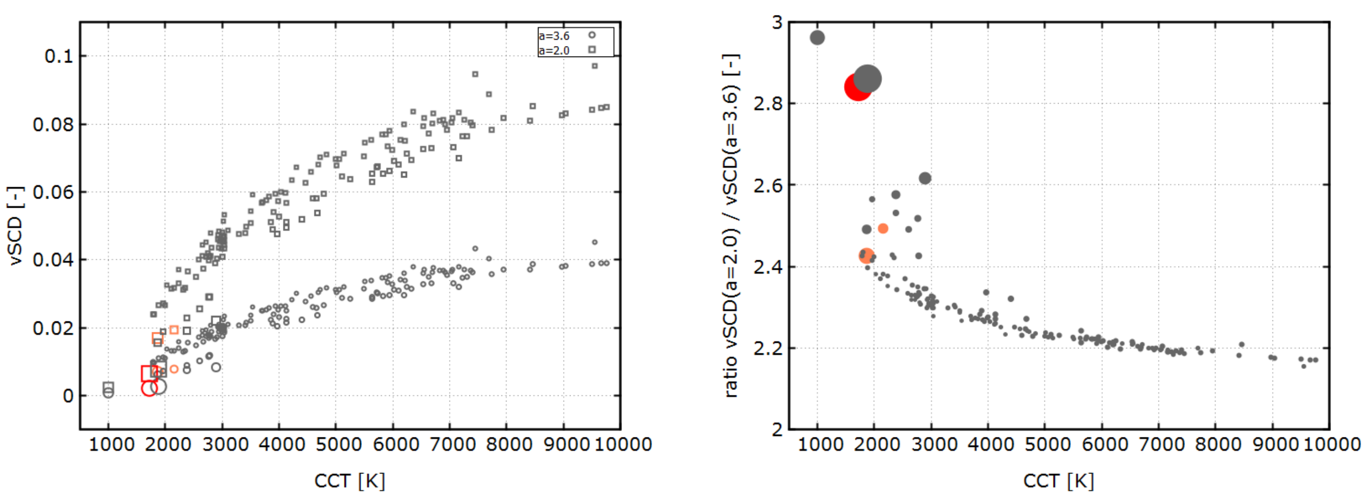

Fig. 9. Left panel: visual SCD index for clean (circles, exponent $a = 3.6$) and turbid (squares, exponent $a = 2.0$) atmosphere. Right panel: the ratio of the vSCD($a = 2.0$) index to the vSCD($a = 3.6$) index. Color code type of a lamp: LPS lamp – red, HPS lamps– orange, LDE lamps – grey. The bigger the symbol, the lower the CRI of a lamp. These are the results for AV0 star and asphalt

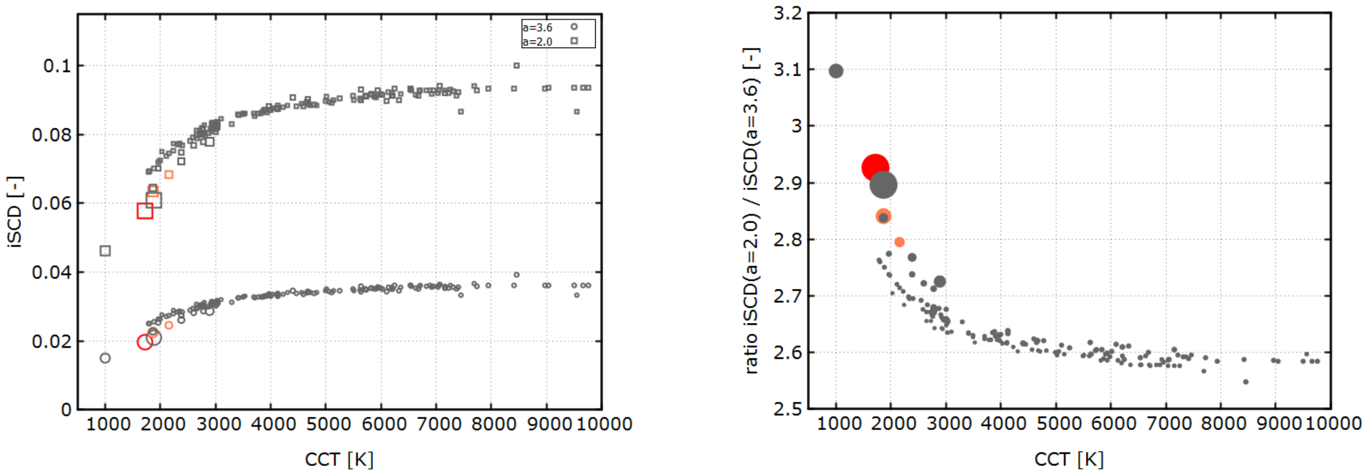

Fig. 10. Left panel: instrumental SCD index for clean (circles, exponent $a = 3.6$) and turbid (squares, exponent $a = 2.0$) atmosphere. Right panel: the ratio of the iSCD($a = 2.0$) index to the iSCD($a = 3.6$) index. Color code type of a lamp: LPS lamp – red, HPS lamps – orange, LDE lamps – grey. The bigger the symbol, the lower the CRI of a lamp. These are the results for AV0 star and asphalt

CCT), the SCD($a = 2.0$) index has a higher value than the corresponding SCD($a = 3.6$) index. This is because scattering in a turbid atmosphere is higher than in a clean atmosphere for all wavelengths in the visible radiation range. As expected, more aerosols in the atmosphere mean more scattered artificial light and, in consequence, a greater adverse impact on observations.

The main result of the calculations for the turbid atmosphere is similar to the clean one. Namely, the lamps that have a similar or lower impact on astronomical observations (with respect to the LPS and HPS lamps) are characterized by low CCT and low CRI.

The ratio SCD($a = 2.0$) to SCD($a = 3.6$) decreases with an increasing CCT because the function $\lambda^{-3.6}$ decreases more steeply with an increasing wavelength than the function $\lambda^{-2.0}$. For this reason, the ratio SCD($a = 2.0$) to SCD($a = 3.6$) is higher for lower CCT (see the upper panels in Figs. 9 and 10). Lower CCT lamps emit relatively more long-wave light. Furthermore, low CRI lamps tend to have a higher value of the ratio. Despite this, low CCT low CRI lamps are characterized by lower values of SCD indices than high CCT high CRI ones.

4. CONCLUSIONS

In this paper, we analyze the impact of more than 150 LED sources of different spectral power distributions on amateur and professional astronomical observations. This analysis considers an observing site surrounded by artificially lit areas. Such a situation is typical in regions with a high population density (e.g. Europe) where villages and towns may be located within a short distance from the site (e.g. 10–20 km). A situation that is typical of the present day is assumed, with the existing outdoor lighting installed in an area close to an observing site to be replaced with LED sources. The question we try to answer is which LED lamps have a lesser adverse impact on astronomical observations (amateur and professional). Many parameters of outdoor lighting and properties of surroundings affect the apparent condition of the sky (see Section 2). This paper focuses on one of these key parameters – the spectral power distribution of light sources. Other parameters are unchanged.

Two indices were defined to quantitatively assess the impact of artificial lighting on amateur and professional observations. The first one, visual Starlight Contamination Degree (vSCD), describes the deterioration of the night sky in the case of visual amateur observations conducted by an observer with fully dark-adapted eyes. The second one, instrumental Starlight Contamination Degree (iSCD), quantifies the disruption of professional instrumental observations conducted with the use of a CCD camera and the Johnson–Cousins V filter (photometry). The physical meaning of both *SCDs* is how much the observed part of a spectrum of a celestial object is contaminated with artificial light. Ground reflectance (four different surfaces) and the scattering of artificial light in the atmosphere were included in the calculation of the SCD indices.

The results can be summarized as follows:

- Both SCD indices increase with CCT. LED lamps with a lower value of CCT are better from the astronomical point of view; however, the relation between the SCD indices and CCT cannot be described with a monotonic function. As such, LED lamp selection cannot be based solely on CCT. Ideally, one needs to examine the spectral power distribution of the LED source. Unfortunately, producers usually do not include a spectrum of an LED lamp in the technical data sheet. Measurement of the spectral distribution by a buyer requires highly specialized and expensive equipment (spectroradiometer). In this situation, we suggest considering the CRI parameter when selecting an LED lamp. In conclusion, we recommend using LED lamps with as low as possible CCT and CRI in the zones near astronomical observing sites.
- Replacement of LPS and HPS lamps with LED lamps does not necessarily lead to a deterioration of the observation conditions. LED lamps with a very low value of CCT ($< 2000 - 2900$ K) and low CRI (< 60) can have a similar

or even smaller impact on astronomical observations. For example, the LED lamp with CCT = 1000 K has both SCD indices smaller than the LPS lamp. This LED lamp is characterized by a very narrow spectral power distribution. The most visible radiation range is not contaminated with artificial light. In general, such narrow spectral emission LED lamps are the least harmful to astronomy.

- Visual observations are very sensitive to the spectrum of LED lamps. The vSCD index increases significantly with the CCT value. Selecting the lowest CCT LED lamps for outdoor lighting in the zone near the visual observation site will make a significant difference in the perceived quality of the night sky.
- Instrumental observations with the use of the Johnson–Cousins V filter are more affected by artificial light than visual observations. This is true even for lamps with the lowest CCT. This is because the spectral transmission of the filter is located closer to the center of the visible radiation range, where the spectral emission of LED lamps is usually higher. Thus, selecting low CCT LED lamps may not be sufficient to reduce the impact on instrumental observations. In addition, reducing lumen output should be applied, if it is possible.
- Ground reflectance, which is unavoidable, plays a significant role in the artificial increase of the brightness of the night sky. The only way to reduce the impact of higher ground reflectance is to limit the luminous flux of installed lamps. This is particularly important when there is a snow cover. The SCD indices for snow are 10-fold higher than for asphalt. LED sources enable a smart control of lumen output. Thus, modern outdoor lighting can respond to changing seasonal conditions.
- Both SCD indices increase with turbidity of the atmosphere. However, this does not change the overall picture, i.e. low CCT and low CRI lamps have a lower negative impact on astronomical observations, comparable to the LPS or HPS lamps. Furthermore, instrumental observations with the use of the Johnson–Cousins V filter are slightly more affected by increased turbidity of the atmosphere than visual observations. It indicates that more strict control of artificial light is needed to lower its interference with instrumental observations.

Both indices do not facilitate a comprehensive evaluation of the impact of outdoor lighting on astronomical observations, but they are easy to compute. They can be used for quick assessment of artificial light sources from the astronomical point of view. The authors think such an assessment may be useful during the modernization of outdoor lighting in areas close to astronomical observing sites.

In the paper [34] the authors analyzed measurements of night sky brightness in selected astronomical observatories in Poland. The study shows that proper control of outdoor lighting has a significant impact on the brightness. Based on this result, the authors suggested the creation of protection zones around astronomical observatories in Poland. All outdoor lighting (public and private) within such a zone would be restrained according to certain guidelines.

Such guidelines were proposed by the International Astronomical Union [35] to protect the largest, most important astronomical observatories in the world. These are usually found in remote and sparsely populated locations. Thus, guidelines to control artificial light can be strict and cover a large area. Smaller astronomical observatories located in a highly populated region (e.g. Europe) also need protection zones, albeit less extensive. Here the guidelines cannot be so strict. The authors think that limitations on the spectra of artificial light sources should be included in these guidelines. The results of our study can help to define which LED lamps may be used, and which should be withdrawn from use in the protection zones around astronomical observatories.

This work has some limitations that should be kept in mind.

- The indices do not facilitate the calculation of the brightness of the sky or full simulation of the impact of light pollution on astronomical observations. They estimate the degree of contamination of the observed part of the spectrum of a celestial object with artificial light emitted by a given type of lamp.
- The presented results refer only to amateur observations made with fully dark-adopted eyes (scotopic vision) and to professional photometric observations made using the V filter of the Johnson–Cousins photometric system.

Regarding professional astronomical photometric observations, one should remember that there are many other filters and photometric systems [36]. It is possible to calculate the SCD index for any filter. To do so, the spectral transmission of a given filter, $F(\lambda)$ needs to be substituted into equation 3. For some filters, results may be different than for the V_{JC} filter. For example, the H-alpha filter has spectral transmission around 656 nm. Thus, its SCD index may be expected to have higher values for LED sources with spectra shifted towards the red part of the visible radiation range. The important point to be emphasized is that no single LED lamp or other artificial light source facilitates minimalizing the LP impact on photometric observations in all astronomical filters. Thus, other mitigation strategies should be considered.

It is worth mentioning that guidelines to control artificial light are not the only way to mitigate the increase in night sky brightness in observatories. It was shown that an important support for achieving this goal was the reduction of air pollution [15]. A more turbid atmosphere means more scattering of artificial light and a brighter sky. Thus, reducing air pollution (abundance of aerosols) will have a positive impact on night sky brightness. The authors of [15] showed that this solution was especially effective for areas adjacent to the observatory, so the same spatial situation as the one considered in this paper.

LED sources may pose a threat to astronomical observation, both amateur and professional. It is not just a scientific problem for the astronomical community, but also a cultural problem affecting all humanity [37]. The night sky has been our inspiration for millennia and is the cultural heritage of all mankind. Replacing discharge lamps with LED sources may make the problem of astronomical light pollution much worse if light sources with incorrect specifications are used. However, as shown in this paper, LED sources offer a possibility of light pollution control and reduction. This can be achieved, e.g. by selecting LEDs with a spectrum more friendly to the night sky. From the astronomical point of view, studies of the impact of LEDs on astronomical photometry and spectroscopy should continue. It is a task planned to be shortly undertaken.

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