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Particulate matter as an amplifier for astronomical light pollution

T. Ściężor[⋆] and M. Kubala

Cracow University of Technology, Faculty of the Environmental Engineering, Warszawska 24, P-31-155 Kraków, Poland

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ABSTRACT

In this paper, we state that the main factor that influences seasonal changes in the brightness of the cloudless, moonless, light-polluted night sky is primarily particulate matter, emitted mainly from low-emission sources, especially in winter. This effect is particularly noticeable in Cracow and its surroundings, one of the places in Europe that is most polluted by particulate matter. Measurements taken over a period of one year have allowed us to show a linear relationship between the concentration of particulate matter and the brightness of the clear, cloudless night sky. We have also found similar correlations in other, industrialized areas of Poland, as well as at the Mount Suhora Astronomical Observatory. We believe that the factor described here should be taken into account when planning the construction of new astronomical observatories, especially those located near large urban areas.

Key words: atmospheric effects – light pollution – methods: data analysis – site testing.

1 INTRODUCTION

According to the literature on this subject, the main reason for an increase in the brightness of the light-polluted night sky is the cloud coverage, which reflects ground lights (Ściężor et al. 2010; Kyba et al. 2011). However, in the case of astronomical observations, the factors that are important are those that increase the brightness of the clear and cloudless sky. One of these factors that is widely known, especially in the infrared range of the spectrum, is the water vapour contained in the lower layers of the atmosphere, which even condenses to a fog. Indeed, this is one of the reasons why astronomical observatories are located on the mountain tops, in areas with low humidity (Kerber et al. 2014). The strong brightening effect of fog has also been described (Ściężor et al. 2010).

2 HISTORY OF MEASUREMENTS

Measurements of the light pollution of astronomical observations began in the 1960s and 1970s, mainly in the framework of studies of the spectrum of the night sky (Walker 1973; Turnrose 1974; Osterbrock, Walker & Koski 1976; Massey, Gronwall & Pilachowski 1990; Osterbrock & Martel 1992; Massey & Foltz 2000; Slanger et al. 2003). Another group of studies consisted of estimations of the night-sky quality at astronomical centres (Benn & Ellison 1998; Massey & Foltz 2000; Patat 2003). There were also measurements of light pollution in large urban centres or in their vicinity, as well as in protected areas, such as national parks or nature reserves (Walker 1970, 1977; Treanor & Salpeter 1972; Bertiau, de Graeve & Treanor 1973; Berry 1976). However, all these studies were carried out using either expensive and cumbersome instruments or visual, approximate methods (Kosai & Isobe 1991; Isobe & Kosai 1998; Schreuder 2001). Some studies were also carried out using photographs (Kosai & Isobe 1991; Isobe & Kosai 1998; Cristaldi & Foti 2000) or CCD images of the night sky (Duriscoe, Luginbuhl & Moore 2007). A more detailed overview of the history of all these measurements, together with its characteristics, has been described earlier by one of the authors of this paper (Ściężor 2013).

The emergence of low-cost electronic light sensors with high sensitivity enabled low-cost field measurements of light pollution, without involving costly or cumbersome equipment. On this basis, the Canadian company Unihedron produced a simple-to-use meter of the surface brightness of the night sky, the Sky Quality Meter (SQM). This made it possible to involve volunteers in measurements.

One of the first large-scale research projects using SQMs consisted of measurements of the brightness of the night sky in the Zselic Landscape Protection Area, south of Kaposvar in Hungary (Kolláth 2008). The aim of this research project was to check the usefulness of SQMs for such measurements, and also to measure the quality of the night sky at the newly established night-sky protected area. These measurements are still ongoing (Kolláth 2010).

Another research project using the SQM consisted of field measurements of light pollution in Hong Kong and the surrounding area, conducted by the Department of Physics of the local university. These measurements were carried out by a group of volunteers (between 2008 March and 2009 May), not only in clear-sky conditions, but also in partial and total cloud cover or haze. In addition, light-pollution measurements were compared with air-quality data. The result was a map of light pollution in Hong Kong and the surrounding areas, as well as the publication of a report. However, the authors of the report, Pun & So (2012), failed to show any

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[⋆] E-mail: sciezor@vistula.pk.edu.pl

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clear correlation. These measurements have been continued at 18 selected fixed measurement points during the period 2010–2013 (Pun et al. 2014).

At the same time (between 2008 November and 2010 January), similar SQM measurements were carried out in the area of the Cracow agglomeration by a team whose members are the authors of this paper. A measurement report has been published in Polish (Ściężor et al. 2010), and preliminary conclusions based on these measurements have also been published in English (Kubala et al. 2009). These measurements have shown, among other things, that there are correlations between the brightness of the light-polluted night sky and the snow cover, the cloudiness and the concentration of particulate matter. The same team carried out similar measurements in the mountain areas of southern Poland (Ściężor, Kubala & Kaszowski 2012).

Recently, more advanced SQM measurements have been carried out in Berlin, Germany (Kyba et al. 2012). The aim of these measurements was to research the changes in the spectrum of the artificial sky glow, for different wavelengths, and their dependence on cloud cover. Other SQM measurements have been carried out at the Vienna University Observatory in order to research the influence of different environmental conditions on the brightness of the night sky and to study the implications for human vision (Puschnig, Posch & Uttenthaler 2014a). Another SQM study, focusing on the influence of clouds and of the moon on the brightness of the night sky, has been carried out at the Leibniz Institute for Astrophysics in Potsdam-Babelsberg (Puschnig et al. 2014b).

3 OUTLINE OF THE MEASUREMENT METHOD

We have performed measurements of the brightness of the night sky using the aforementioned SQM, which is a microprocessor-based transmitter of a frequency signal from the brightness sensor TSL237, produced by Texas Advanced Optoelectronic Solutions (TAOS) Inc.[1] The microprocessor of the SQM is programmed in such a way that the reading from the sensor is converted into a commonly used unit of the surface brightness of the night sky (i.e. mag arcsec^{-2}).

The high sensitivity and accuracy of TSL237 over the entire operating range mean that this sensor can be used for measurements of a very small stream of light. Because the spectral sensitivity of the sensor has a maximum at a wavelength of 700 nm and its characteristic ranges from 300 to 1100 nm, so far in the infrared, the SQM is equipped additionally with a filter HOYA CM-500 for the additional cut-off of infrared parts of the spectrum. The sensor, compensated in such a way, has maximum sensitivity at a wavelength of 540 nm, which roughly corresponds to the maximum of colour vision (photopic; 555 nm), with a slight shift towards the maximum night vision (scotopic; 507 nm). This maximum perfectly agrees with the maximum of the bandwidth of the Johnson–Cousins *V* system, used in astronomy for photometric measurements, corresponding to the sensitivity of the human eye. The full spectral sensitivity curve of the SQM ranges from 300 to 740 nm, and the relative sensitivity, greater than 10 per cent, ranges from 340 to 680 nm. It is a much broader characteristic than in all three above-mentioned standards. For this reason, after thorough research, the Laboratory of Photometry and Radiometry of Light Pollution (LPLAB), which supports the Light Pollution Science and Technology Institute (ISTIL) in Thiene, Italy, has recommended that the spectral sensitivity of the SQM is considered to be another of the many photometric standards used in astronomy (Cinzano 2005).

According to the LPLAB research, the difference between the SQM standard and the *V* standard (SQM-*V*) depends on the type of light source and, for the application area of the SQM, ranges from 0.00 to 0.25 mag arcsec^{-2}. For natural and medium light-polluted skies, the accepted correction is equal to 0.17 ± 0.07 mag arcsec^{-2} (Cinzano 2005). It should be noted that in this paper we give the SQM readings without this correction.

The SQM is produced in several versions. We have mainly used the manually triggered SQM-L (10 devices). The SQM-L is more useful in an urban environment than the regular SQM, because it used a simple optical system for collecting light in a solid angle of only 40° (Cinzano 2007). This makes it easier to use in such an environment, characterized by a large number of ground-based light sources, which might directly affect the results of measurements when using a standard SQM.

We have performed the measurements, as far as possible, every day, in all weather conditions, between 22 and 2 of the local time, if it was possible at the local midnight, which minimized the effects of natural seasonal changes in the brightness of the sky. Each observer noted their comments on the measurement conditions and the state of the atmosphere at the time of measurement. For further analysis, we have chosen only measurements made during cloudless (0 oktas cloud cover) and moonless (the moon at the time of measurement is below the horizon, in a phase of less than 30 per cent; Ściężor 2013) nights, and in the absence of any visible haze, assessed on the basis of the horizontal visibility of distant objects (horizontal visibility over 10 km).

We have carried out each measurement with the SQM directed towards the zenith, in a place not illuminated by any local ground light source, with no light source visible within the zenithal angle of 60°, and where the measured part of the sky (the solid angle 40°) was not obscured by any obstructions (trees, buildings, etc.).

We have found that with these requirements, in stable weather conditions, differences between the successive measurements do not exceed 0.02 mag arcsec^{-2}, with the exception of windy nights when the accuracy decreases to 0.05 mag arcsec^{-2}. Therefore, for control purposes, each time we have made a series of five measurements and we have recorded the mean value, rounded to 0.1 mag arcsec^{-2}. We consider such an accuracy to be sufficient for the intended purposes.

4 UNITS USED

Usually, the TSL237 sensor has a frequency output proportional to the irradiance with responsivity 2.3 kHz (μW cm^{-2})$^{-1}$. Unfortunately, the producer of the SQM does not reveal what algorithm is used for the conversion of the scale of the sensor (μW cm^{-2}) to the scale of the meter (mag arcsec^{-2}). Only the relationship between a surface magnitude and a luminance scale is known. This relationship is not straightforward. However, by assuming a linear correlation between the perceived surface brightness (luminance) and the physical surface brightness, it can be shown that

$$(\mathrm{mag\ arcsec^{-2}}) = -2.5 \log[(\mathrm{cd\ m^{-2}})] + \mathrm{const.} \qquad (1)$$

The constant can be determined by giving the reference point of these two scales. Following the reference of 3.2×10^{-6} cd m^{-2} for 26.33 mag arcsec^{-2} for the *V*-band (Crawford 1997), we can obtain

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[1] TSL237, high-sensitivity light-to-frequency converter, TAOS Inc., TAOS052G, September 2007.

the relation

$$(\text{mag arcsec}^{-2}) = 12.59 - 2.5\log[(\text{cd m}^{-2})], \tag{2}$$

or vice versa,

$$(\text{cd m}^{-2}) = 108\,930 \times 10^{(\text{mag arcsec}^{-2})}. \tag{3}$$

Because of the very low surface brightness of the night sky, the commonly used unit is millicandela per square metre (mcd m^{-2}). In this paper, we use the scale, mag arcsec^{-2}, but for illustrative purposes we have also added an auxiliary mcd m^{-2} axis to the plots.

5 STATISTICS

We have measured the brightness of the night sky, denoted as S_a, from 2008 mid-November to 2010 early January, at 10 fixed measurement points located both within the administrative boundaries of Cracow and in suburban areas (Fig. 1). The measurement point closest to the city centre (less than a kilometre) was located on the boulevards in the bend of the Vistula River near the Wawel Hill (KCE); see Table 1. Three measurement points were located on large housing estates: the Podwawelskie Housing Estate, 2.6 km south of the city centre (KPO); the Prądnik Czerwony Housing Estate, 3.5 km north of the city centre (KPC); the Bieżanów Nowy Housing Estate on the eastern edge of Cracow, 8 km east of the city centre (KBI). The other points within the city boundaries were located in allotments near the Bronowice Nowe Housing Estate, 4 km north-west from the city centre (KBR) and in the heavily industrialized district Cracow-Łagiewniki, 6 km south of the city centre (KLA). Two measurement points were located outside the administrative boundaries of Cracow, in single-family housing in Wieliczka, 13 km south-east from Cracow (WIE) and in Mogilany, 14 km south of Cracow (MOG). The last two measurement points, the farthest points, were located in Łuczyce, 15 km north-east of Cracow (LUC) and in Jerzmanowice, 22 km north-west of Cracow (JER). During this period, we have made a total of 2985 measurements, 363 of which meet the required conditions (moonless, cloudless and fogless nights, with visibility exceeding 10 km).

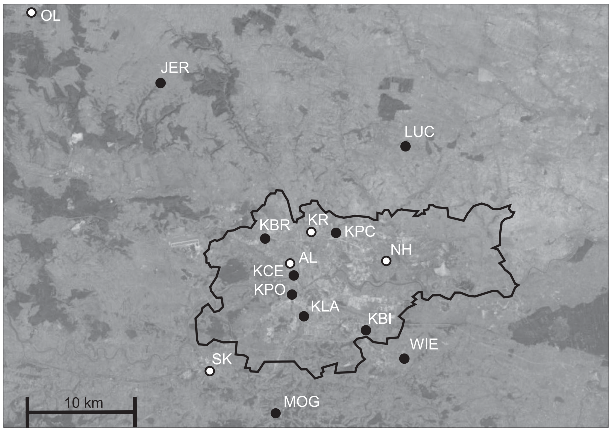

Figure 1. The map of Cracow and its surroundings (©2014 Google, ©2014 MGGP Aero, ©2014 Digital Globe) with marked measuring points of both S_a (black circles; see Table 1) and PM10 (white circles; see Table 2).

Table 1. Measuring points of S_a (N is the number of measurements used).

Locality	Code	Coordinates			N
		Latitude	Longitude	Altitude	
Cracow	KBI	50°00′49″N	20°01′36″E	219 m	38
	KBR	50°04′44″N	19°53′47″E	215 m	32
	KCE	50°03′17″N	19°55′49″E	199 m	29
	KLA	50°01′17″N	19°56′41″E	242 m	29
	KPC	50°05′32″N	19°58′37″E	221 m	70
	KPO	50°02′23″N	19°55′38″E	205 m	50
Wieliczka	WIE	49°59′16″N	20°04′51″E	255 m	39
Mogilany	MOG	49°56′17″N	19°54′38″E	315 m	44
Łuczyce	LUC	50°09′31″N	20°04′39″E	276 m	22
Jerzmanowice	JER	50°12′40″N	19°44′54″E	441 m	14
Mt Suhora	SUH	49°34′11″N	20°04′05″E	986 m	58
Wałbrzych	WAL	50°48′39″N	16°16′55″E	417 m	54

From 2012 April 6 until now, analogous measurements have been made at the Mount Suhora Astronomical Observatory (SUH), located at an altitude of 986 m above sea level, 55 km south of Cracow (Table 1). During this period, there have been 242 measurements, 58 of which meet the conditions described above.

In this paper, we also use the long-term data of annual averaged brightness of the night sky on the outskirts of the city of Wałbrzych in Lower Silesia (WAL; see Table 1), obtained using the cometary method, which was developed earlier by one of the authors of this paper (Ścieżor 2013). Of the total of 164 observations of comets made at this position in the period 1996–2004, 54 observations were suitable for this purpose.

6 SEASONAL CHANGES IN THE CONCENTRATIONS OF PARTICULATE MATTER

The concentrations of particulate matter, denoted as PM10, are measured every hour, 2 m above ground level, at several dedicated monitoring stations in and around Cracow (see Table 2). Monthly averaged results of these measurements are published in the monthly bulletin of the Voivodeship Inspectorate for Environmental Protection (VIEP), available at the web site, http://www.krakow.pios.gov.pl/biuletyn.php. A sonic detection and ranging (SODAR) study carried out in this area shows that, at night, dust accumulates in the near ground layer to a height of about 200 m above ground level. As a result of the turbulent movements, it distributes evenly (Walczewski 1994), which makes it a potential light-diffusing agent. Unfortunately, the positions of the particulate matter measuring stations do not coincide with the positions of the previously described light pollution measurement points (Fig. 1). The question arises whether the PM10 values, published for the VIEP stations, can also refer to these measurement points.

Table 2. Monitoring stations of PM10 (AL, NH, KR, OL, SK) or TSP (WL).

Locality	Code	Coordinates		
		Latitude	Longitude	Altitude
Cracow	AL	50°03′17″N	19°55′50″E	208 m
	NH	50°04′03″N	20°02′59″E	206 m
	KR	50°05′14″N	19°56′23″E	222 m
Olkusz	OL	50°16′39″N	19°34′10″E	370 m
Skawina	SK	49°58′16″N	19°49′50″E	230 m
Wałbrzych	WL	50°50′32″N	16°17′34″E	389 m

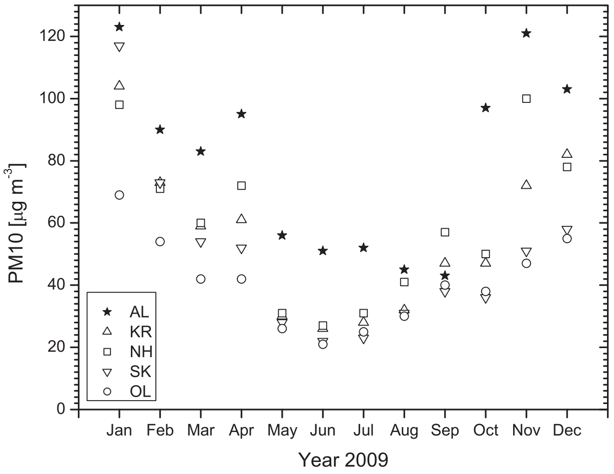

Figure 2. Temporal changes of PM10 in the subsequent months of 2009 for all VIEP monitoring stations in Cracow and its surroundings.

Therefore, it is necessary to make a mutual comparison of the seasonal changes of PM10 for the considered VIEP stations in order to answer the following two questions.

(i) Qualitative: do the seasonal changes of PM10 have similar characteristics at all monitoring stations?

(ii) Quantitative: are PM10 values similar at all monitoring stations?

For the analysis, we have used the monthly averaged values of PM10, measured at the VIEP stations closest to the light pollution measurement points (Table 2).[2] Based on the plot of the PM10 changes in the year, we have concluded that not only do these changes have the same characteristics, but also their absolute values are similar (Fig. 2). The exception is the PM10 monitoring station Aleje (AL), located in the green belt between the two bands of the inner ring road of Cracow, where the predominant pollutant is that of transport, for which the values of PM10 are different from those measured at the other monitoring stations. For further analysis, we have used the values of PM10 measured at all monitoring stations, except for station AL.

Fig. 2 shows that the concentration of particulate matter in the winter months (December and January) for four selected monitoring stations is about five times higher than in the summer months. We believe that this is related to the increased emission of particulate matter in the winter, mainly from coal-fired home heating systems (so-called low emission). It should be noted that Cracow is one of the few European cities with the highest concentration of particulate matter (Bielec-Bąkowska et al. 2011; European Environment Agency 2013). In the summer months, the PM10 value is almost identical for all monitoring stations and is approximately equal to 25 µg m^{-3} (the maximum deviation from the average is equal to 5 µg m^{-3}). In the winter months, the mutual differences increase, depending on the location of the measuring station. We have distinguished two groups of VIEP stations: the M group and the W group. The first group (M), located within the city, consists of the Nowa Huta (NH) and Krowodrza (KR) stations. The second group (W), located in non-urban areas beyond the Cracow Trough, consists of the Olkusz (OL) and Skawina (SK) stations. Within these two groups, the maximum deviation from the mean value in the winter is also equal to 5 µg m^{-3}. However, despite the differences between the values of PM10 for groups M and W, we have noticed that the character of the seasonal changes in all analysed PM10 monitoring stations is very similar and, as one of us has noted previously (Ścieżor et al. 2010), resembles the seasonal changes in the monthly averaged brightness of the clear, cloudless sky.

For further analysis of the changes in the brightness of the night sky, we have selected the M group as the source of data on PM10 concentrations for measuring points KPO, KBR, KLA, KPC, KBI and KCE, and the W group as the source of data on PM10 concentrations for measuring points WIE, MOG, JER and LUC.

However, there is no PM10 measurement station in the vicinity of the SUH measuring point. Therefore, we have used the monthly averaged PM10 calculated for this point in the period 2012–2013 by the model, Forecasting of Air Pollution Propagation System (FAPPS), with a spatial resolution of 1 km and a precision of 0.01 µg m^{-3}. FAPPS is a set of models: the ALADIN numerical weather prediction, the MM5 non-hydrostatic mesoscale model, the CALMET meteorological preprocessor and the CALPUFF puff dispersion model. The basic products of FAPPS system are diagnostic and prognostic maps of air pollution concentrations, maps of the ventilation index, information about the expected health risks and the module supporting severe accident management. For the prediction of pollutants, it uses only the specified emission, the type of source (point, volume, surface) and the forecast of meteorological conditions (Godłowska et al. 2012; Hajto et al. 2012).[3]

For the WAL measuring point, we have used the average annual concentrations of the total suspended particulate matter (TSP), measured during the period 1996–2004 at the VIEP measurement station (WL) located just 2 km from this point[4] (Table 2). We believe that, in this case, the relationship between S_a and TSP can be compared with the relationship between S_a and PM10 determined at the rest of the measuring points, according to the known linear correlation between PM10 and TSP (Kermani et al. 2003). Usually, the conversion ratio of PM10 to TSP is estimated to be around 0.5 (Thrall & Hudiszevskyj 1984; Ho & Nielsen 2007).

7 RESULTS

The common plot of the seasonal changes in the monthly averaged brightness of the clear and cloudless sky (S_a) and the seasonal changes in the monthly averaged concentration of particulate matter (PM10) shows a distinct qualitative similarity of these changes during the year (Fig. 3).

In order to verify the validity of this observation, we have plotted the monthly averaged values of S_a for cloudless and moonless nights, measured at the individual measuring points, against the monthly averaged concentrations of the particulate matter (PM10), measured at the monitoring stations from groups M and W (Table 2). We have also added values of S_a obtained at the SUH measurement point, in this case against the monthly averaged PM10 values obtained from the model FAPPS (see Fig. 4; for clarity, only data for selected measuring points are plotted).

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[2] http://www.krakow.pios.gov.pl/biuletyn.php

[3] See http://www.smog.imgw.pl. Precise data for the SUH measuring point are provided by Wiesław Kaszowski and Jolanta Godłowska from the Cracow branch of the Institute of Meteorology and Water Management.

[4] See http://www.wroclaw.pios.gov.pl/index.php/monitoring-srodowiska/powietrze/wyniki-pomiarow/. Precise data are provided by Agnieszka Mikołajczyk from VIEP Wrocław.

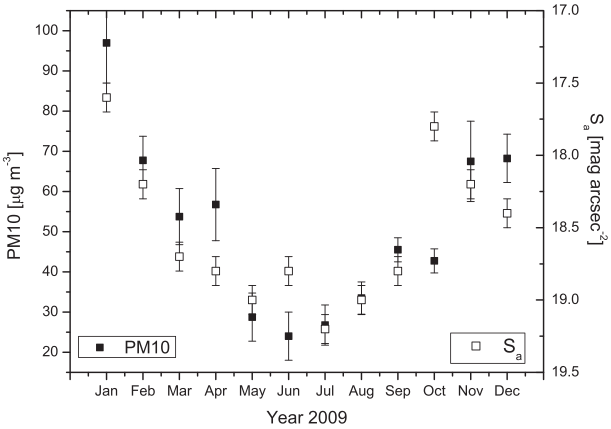

Figure 3. Comparison of the temporal changes of the monthly averaged S_a and the monthly averaged PM10 in the subsequent months of 2009 in Cracow and its surroundings. Error bars represent the standard error of the mean of PM10 at all monitoring stations (except AL) as well as of S_a at all measuring points.

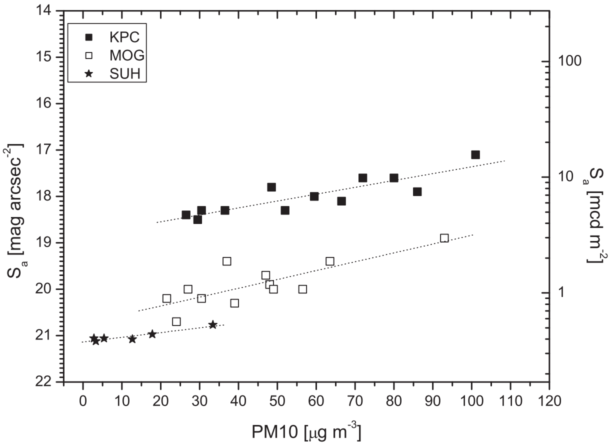

Figure 4. Monthly averaged S_a against the monthly averaged PM10 for selected measuring points in Cracow (KPC, group M) and its surroundings (MOG, group W), and also for the Mount Suhora Astronomical Observatory (SUH). The dotted lines represent the linear regression fitting for each measuring point.

The plot shows a clear linear relationship for the representatives of both group A and group B. We have observed similar relationships for all measuring points of these groups. It is worth noting that with the increase of the concentration of particulate matter in the atmosphere from zero to the maximum value (approximately 100 µg m^{-3}), the value of S_a might decrease by more than 1 mag arcsec^{-2}.

The relationship seen between S_a (expressed in terms of mag arcsec^{-2}) and PM10 (expressed in terms of µg m^{-3}) seems to be linear and we propose to describe it by

$$S_a = \mathrm{PMS} \cdot \mathrm{PM10} + S_b. \tag{4}$$

Here, the value of the intercept term S_b is equal to the largest possible value of S_a at the selected measuring point, which corresponds to the darkest possible sky at this point. We think that the slope gradient PMS is a parameter related to the grain type and size of particulate matter (Table 3).

For the SUH measuring point, the difference between the S_a value measured in the winter months and the same value measured in the summer months is equal to only 0.3 mag arcsec^{-2}. It is significantly lower than in the city and its surroundings. We also associate this effect with the light scattering on the particulate matter, coming from low-emission heating systems in the surrounding settlements; the nearest village is located just 3 km from the observatory, and cities, such as Rabka and especially Nowy Targ, are located only 10 km from it. It is known that the location of the Mount Suhora Astronomical Observatory is characterized by the influx of pollutants from neighbouring areas (Cieśla & Bryja 2010). We have noticed that the value of PMS is close to that obtained in the measuring points of urban groups M and W (Table 3). However, this relationship requires thorough research, which we plan to do in the near future, after installing the measurement station of PM10 in the aforementioned cities.

Table 3. Linear regression coefficients of S_a on PM10, together with its standard deviations obtained by the ordinary least-squares method.

Locality	Code	PMS	S_b
Cracow	KBI	-0.010 ± 0.003	19.1 ± 0.2
	KBR	-0.023 ± 0.008	18.4 ± 0.5
	KCE	-0.018 ± 0.004	18.7 ± 0.3
	KLA	-0.016 ± 0.003	19.0 ± 0.2
	KPC	-0.013 ± 0.003	18.8 ± 0.2
	KPO	-0.017 ± 0.005	18.5 ± 0.3
Wieliczka	WIE	-0.021 ± 0.008	19.5 ± 0.5
Mogilany	MOG	-0.015 ± 0.003	20.6 ± 0.2
Łuczyce	LUC	-0.016 ± 0.015	20.6 ± 0.6
Jerzmanowice	JER	-0.029 ± 0.011	21.0 ± 0.5
Mt Suhora	SUH	-0.010 ± 0.002	21.1 ± 0.0
Wałbrzych[a]	WAL	-0.107 ± 0.007	24.0 ± 0.2

Note: [a]Linear regression coefficients of S_a on TSP.

For the WAL measuring point, in Fig. 5, we have plotted the annual averaged value of S_a against the annual averaged value of the TSP. This plot also shows a clear linear relationship between S_a and TSP. With the increase in the concentration of the particulate matter in the atmosphere from 30 to 43 µg m^{-3}, the value of S_a decreases by 1.43 mag arcsec^{-2}, which means an almost fourfold linear increase in surface brightness of the clear and cloudless sky. In this case, the value of PMS is significantly higher than in the case of all previously described measurements, which is probably connected with the use

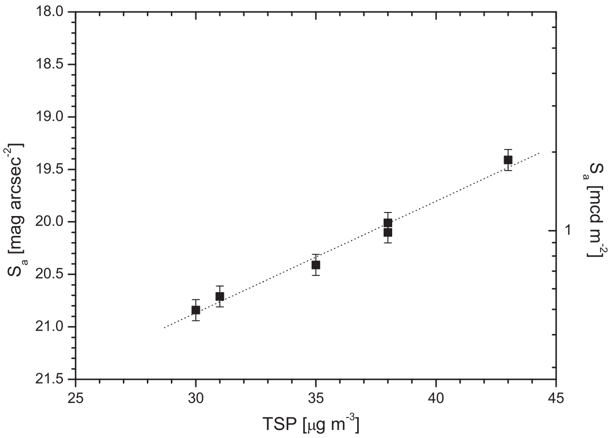

Figure 5. Annual averaged S_a against the annual averaged TSP for the measuring point in Wałbrzych. The dotted line represents the linear regression fitting.

of the other quantity describing the particulate matter concentration in Wałbrzych (TSP). In turn, the value of S_b is significantly higher than in the previous cases, which results from using the cometary method for determining the value of S_a (Ścieżor 2013).

8 STATISTICAL ANALYSIS OF RESULTS

In order to check how strong the correlations are between the changes in the values of S_a and PM10 (or TSP), for each measuring point we have calculated the linear correlation coefficient between the monthly averaged value of S_a for cloudless and moonless nights, measured at the measuring points listed in Table 1, and the monthly averaged concentration of particulate matter, measured at the monitoring stations listed in Table 2. In addition, for each measuring point, we have performed the *F*-test of the hypothesis of lack of correlation. This test consisted of calculating the value of the *F*-test statistic according to

$$F = SS_{\mathrm{reg}} \cdot (N-2)/SS_{\mathrm{res}}, \tag{5}$$

where SS_{reg} is the regression sum of squares (SSR), SS_{res} is the error sum of squares (SSE) and N is the number of correlated pairs of monthly averaged values of S_a and PM10. For WAL, we have considered the annual averaged values of S_a and TSP.

This quantity meets the F distribution with $(1, N-2)$ degrees of freedom. If the calculated probability of F is small, then the hypothesis of lack of correlation can be rejected. The results of this analysis are presented in Table 4.

We believe that the results for the measuring points within the Cracow agglomeration are consistent, except for the LUC measuring point, where we cannot reject the hypothesis of lack of correlation. The reasons for this discrepancy are not known. These measurements were possibly affected by the local strong source of low emission of variable intensity (smoking chimneys), as an observer reported. Similarly, a nearby source of particulate matter was also reported at the measuring points JER and WIE. In other cases, the probability of obtaining the value of F does not exceed 3 per cent and, in four cases, even 1 per cent, so the resulting correlations are highly significant.

We have obtained a similar statistical significance of correlation for the SUH measuring point, but it must be noted that, in this case, we have taken into account the modelled values of PM10.

Table 4. Correlations between values of S_a and concentrations of particulate matter for each measuring point, where LPMP denotes the code of the light pollution measuring point, PMMS denotes the code of the particulate matter measurement station, N is the number of correlated months, r is the correlation coefficient, F is the F-test statistic and $P(F)$ is the probability of F (in per cent).

LPMP	PMMS	N	r	F	$P(F)$
KBI	NH	12	−0.72	10.83	0.81
KBR	KR	12	−0.66	7.82	1.89
KCE	KR	11	−0.81	17.10	0.25
KLA	KR	12	−0.87	31.35	0.02
KPC	NH	12	−0.77	14.33	0.36
KPO	KR	10	−0.75	10.02	1.32
WIE	NH	12	−0.65	7.15	2.33
MOG	SK	12	−0.81	18.90	0.14
JER	OL	11	−0.67	7.43	2.34
LUC	OL	10	−0.36	1.21	30.31
SUH	FAPPS model	6	−0.93	27.53	0.63
WAL	WL	6	−0.99	251.29	0.01

The parameters of the mean annual correlations of the S_a and TSP changes, determined in the period 1996–2004 for the WAL measuring point, indicate an even clearer linear correlation of these values. This is probably the result of the long time of averaging.

It should be noted that the Fort Skala Astronomical Observatory in Cracow is also located in an area with an increased concentration of PM10.[5] Measurements for this position have been ongoing since 2013 October, but because of the very short measurement time, it is not yet possible to carry out a full statistical analysis of this case.

9 CONCLUSIONS

We have found a clear linear relationship between the concentration of particulate matter (PM10 or TSP) and the brightness of the clear and cloudless night sky (S_a). The established linear correlation might be one of the auxiliary factors allowing the prediction of the quality of the night sky at the place of observation, depending on the dust level in the atmosphere, measured at nearby meteorological stations. In particular, the established dependence can be used to determine the expected sky brightness at a given observation point under ideal conditions, as given by the value of S_b.

The problem of correlation of S_a and concentration of the particulate matter (PM10 or TSP) requires the creation and use of an appropriate data base for various environments, which will be the subject of further research. It should be emphasized that we only state the linear relationship between the brightness of the clear, moonless night sky and the concentration of the particulate matter measured at 2 m above ground level, while in fact the light scattering takes place in the upper layers of the atmosphere. As we have mentioned in Section 6, at night, dust accumulates in the near-ground layer to a height of about 200 m, and as a result of turbulent movements, it distributes evenly. However, the problem of the vertical distribution of dust is complex. In the case of the atmosphere radiance measurements, it is not possible to specify the vertical distribution of dust. In this way, it is only possible to estimate the mean dust concentration in the direction of probing. We believe that the correlated measurements of brightness of the clear, moonless night sky and dust distribution in the nocturnal boundary layer will allow us to explain the phenomenon we have observed.

We believe that where there are few particulate matter measuring stations in the vicinity of the observing place, on the basis of the determined correlation it should be possible to identify the main direction of the inflow of contaminants. We intend to carry out such an experiment in the near future at the SUH measuring point, after establishing at least two stations measuring the particulate matter concentration in the surrounding settlements.

Unfortunately, there are no analogous seasonal measurements of S_a for other places in Poland, where the concentration of particulate matter is measured. However, in some cases, it would be possible to use the rich archive of observations of comets, as shown for the example of the measuring point WAL. This would enable us to study the changes in the average annual value of S_a by using the cometary method to determine the brightness of the clear and cloudless sky (Ścieżor 2013). For confirmation of the universality of the presented relationship at a given location, it could allow us to estimate the concentration of particulate matter for places and periods in the past, for which there are no such data, but for which archival observations of comets are available.

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[5] See http://www.smog.imgw.pl.

We have also found that, for astronomical observatories on mountains, there is an evident effect of local settlements on the brightness of the clear and cloudless sky, which are sources of light scattering particulate matter; this is important especially in winter. This means that this effect should also be taken into account when planning the construction of new astronomical observatories. This applies in particular, but not only, to school observatories, often built on the outskirts of large cities.

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