

A new astronomical method for determining the brightness of the night sky and its application to study long-term changes in the level of light pollution

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ABSTRACT

In this paper, I present a new method that has been developed for determining the brightness of a cloudless night sky, on the basis of widely available amateur observations of comets. The tests show the correctness of the method, which makes it possible to determine the level of light pollution, defined as the brightness of the artificial sky glow, through the use of the archival observations of comets. The use of data bases of comet observations in Poland in the period 1994–2009 has led to a positive verification of the known model map of the brightness of the night sky. Also, it has been possible to find changes in the level of light pollution in this period, at the selected observation sites.

Key words: light pollution – methods: data analysis – methods: observational – site testing – comets: general.

1 INTRODUCTION

Among the several types of light pollution, the most disturbing for astronomical observations is the artificial sky glow, which is connected to the scattering of the ground artificial light in the atmosphere. This component of light pollution mainly affects the surroundings of cities, which are the sources of light pollution. However, it is noticeable even in areas protected from the other, direct components of light pollution (Kolláth 2008, 2009).

The problem of light pollution has begun to grow rapidly in Poland since the end of the 1990s (Ścieżor 2005). At the same time, it has been possible to map the emission of light from the surface of the Earth on the basis of available satellite data (Cinzano, Falchi & Elvidge 2001a). It has also become possible to create maps of the predicted night-sky brightness, based on a model using visual observations of the faintest stars visible with the naked eye (Cinzano, Falchi & Elvidge 2001b). However, so far it has been impossible to determine the level of the artificial sky glow in the past, as well as the changes to this quantity. There is also a problem with the determination of the light pollution level in areas where there have been no such studies performed. In order to determine the night-sky brightness in such circumstances, I have developed the original method, allowing the use of astronomical observations of comets to estimate the level of light pollution. The proposed method makes it possible to quantify the level of artificial sky glow in the past, even at a time when this phenomenon had not been noticed.

2 HISTORY OF MEASUREMENTS

The measurements of the artificial sky glow can be divided into three types:

- (i) measurements of the night-sky spectrum, used to identify its artificial components;
- (ii) astronomical measurements of the quality of the night sky made at astronomical centres in order to investigate the effect of nearby settlements;
- (iii) appropriate measurements of the sky glow, especially in large urban centres or in the vicinity of these, but also in protected areas (e.g. national parks, reserves).

The oldest publications to report on the problem of artificial sky glow are related mainly to the first class of measurements. These publications, from the 1960s and 1970s, are concerned mainly with the presence of the intense spectral lines of discharge lamps in the atmospheric spectra (Walker 1973; Turnrose 1974). Such measurements continue to the present, showing that a growing share of light in the artificial sky glow comes from low-pressure sodium lamps (Massey, Gronwall & Pilachowski 1990; Osterbrock & Martel 1992; Massey & Foltz 2000). Recently, the spectral lines of rare-earth elements have been identified in the sky glow spectrum, which demonstrates that an increased participation of light in the artificial sky glow comes from metal halide lamps (Slanger et al. 2003).

The second class of measurements are less represented in the literature than the first, and are usually connected to the first. The reason is that astronomers avoid light pollution by placing astronomical centres in distant, underdeveloped areas, often high in the

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mountains, where the artificial sky glow can be seen only at a low altitude above the horizon. As a result, the contribution of the artificial sky glow to the night-sky brightness is usually estimated on the basis of other measurements (mostly spectral measurements; Benn & Ellison 1998; Massey & Foltz 2000; Patat 2003).

The third class of measurements can be divided into two types: observational methods and instrumental methods. These methods were developed simultaneously and are often used in a single research programme. The first measurements of this type were made in the early 1970s (Walker 1970, 1977; Treanor & Salpeter 1972; Berry 1976), usually using electronic photomultipliers, but also including simple visual supporting observations. For the central districts of large cities, a surface brightness of the night sky as large as $17.5 \text{ mag arcsec}^{-2}$ was obtained. These measurements were mainly made either to verify or to create an empirical model of light pollution around large urban centres. The second goal was to create maps of the light pollution in such areas (Walker 1970; Berry 1976; Cinzano et al. 2001a).

During 1987–1989, measurements of the brightness of the night sky were made at nearly 149 locations across Japan (Kosai & Isobe 1991; Isobe & Kosai 1998). The measurements were carried out using two methods: a visual method, which consisted of counting the visible stars in the selected area of the sky, and a photographic method, in which photographs were taken of the sky around the zenith for three exposure times. Similar measurements, but on a smaller scale, were carried out in 1992 (using photographs) and in 1997 (using observations) in the Netherlands (Schreuder 2001).

Another photographic method was used when night-sky brightness measurements were carried out in the vicinity of Catania, Sicily, in 1991 (Cristaldi & Foti 2000). These measurements included the use of wide-angle photography of the entire sky at 13 measuring points and the subsequent creation of contour maps of the sky brightness at a given point. A similar method, but using a more efficient record, using a CCD camera, was used at 11 protected areas (national parks and reserves) around Las Vegas, Nevada, and Flagstaff, Arizona (Duriscoe, Luginbuhl & Moore 2007), which also resulted in outline maps of the sky brightness at the measurement points.

The real breakthrough in measuring astronomical light pollution was when the United States Air Forces shared their high-resolution satellite images of the Earth, taken under the Defence Meteorological Satellite Program (DMSP; Sullivan 1991; Elvidge et al. 1997). A sophisticated analysis of the DSMP data, in conjunction with a model of the scattering of light emitted from the surface of the Earth, allowed for the creation of an atlas of light pollution. The results have been published in three versions (Cinzano et al. 2000, 2001a,b):

- (i) an atlas of the expected brightness of the faintest stars visible to the naked eye;
- (ii) an atlas of the total brightness of the night sky;
- (iii) an atlas of the expected level of light pollution (in the sense of the artificial sky glow).

Another breakthrough was the emergence of low-cost electronic light sensors, which have high sensitivity. Based on these, the Canadian company Unihedron has developed a simple device to measure the night-sky surface brightness, the Sky Quality Meter (SQM). This has enabled low-cost measurements to be carried out at many places without involving costly or cumbersome equipment. The simple handling of the SQM has made it possible for volunteers to engage in the measuring projects.

However, there still remains the problem of determining the size of the artificial sky glow for a long period in the past when no

oriented measurements of this had been carried out. There are also many areas where we have some amateur astronomical observations, but no measurements of the light pollution itself.

In order to determine the night-sky brightness in such circumstances, I have developed an innovative method, in which astronomical observations of comets can be used to evaluate the level of light pollution. The proposed method makes it possible to quantify the artificial sky glow brightness in the past, even at a time when this phenomenon had not yet been noticed (Ścieżor et al. 2010a).

The result of applying this method was the verification of the model map, showing the total sky brightness in the *V* band in Europe at the zenith (Cinzano et al. 2001b). Also, it became possible to examine changes in the brightness of the night sky in the period 1994–2009 (Ścieżor et al. 2010b).

3 UNITS USED

The surface brightness of the night sky, denoted as S_a , is given in the commonly used astronomical units of magnitudes per square arcsecond (mag arcsec^{-2}). It is a derivative of the magnitude scale (mag) defining the visual impact of the star's brightness as a point light source. Magnitude scale is a logarithmic, relative and reverse scale, in which a star of magnitude 0 is 100 times brighter than a star of magnitude 5. The mag arcsec^{-2} scale determines the surface brightness of diffuse astronomical objects, such as nebulae, galaxies, comets, or just a background sky. The derived SI unit of luminance, or perceived brightness, is the candela per square metre (cd m^{-2}), which is a measure of light emitted per unit area. It is possible to approximately convert mag arcsec^{-2} into cd m^{-2} using the following formula (Crawford 1997; Ścieżor et al. 2010b; Kyba et al. 2011):

$$[\text{cd m}^{-2}] = 10.8 \times 10^4 \times 10^{[-0.4(\text{mag arcsec}^{-2})]}. \quad (1)$$

Because of the very low surface brightness of the night sky, the commonly used unit is millicandela per square metre (mcd m^{-2}). In order to maintain compliance with other publications that deal with this problem, as well as with readings from SQMs, I mainly use the scale (mag arcsec^{-2}), also giving the appropriate values in the scale (mcd m^{-2}).

4 OUTLINES OF THE COMETARY METHOD

The new observation method for assessing the brightness of the night sky (called the cometary method) is based on measurements of the surface brightness of the faintest diffuse objects visible in the sky. On the basis of my comparative SQM measurements, as well as the literature (Blackwell 1946; Clark 1990), I believe that this surface brightness is slightly higher than that of the night sky.

However, the objects selected for analysis must have as flat a brightness distribution as possible, without any highlighted maximum, so galaxies, star clusters and nebulae are not suitable for this purpose. Comets, which are commonly observed astronomical objects, are suitable objects that meet the above condition.

From the point of view of an observer, a comet is a blurred object with a surface brightness that steadily decreases from the centre outwards, until merging with the sky background. In order to determine the amount of blur, astronomers have introduced the DC value, which describes the degree of condensation of the comet on the sky background. The value of DC is an indicator of how much the surface brightness of the coma increases towards the centre of the coma. In general, $\text{DC} = 0$ indicates totally diffuse and $\text{DC} = 9$ means stellar. As the value of DC increases, the coma

size usually decreases and becomes more sharply defined. A totally diffuse comet, with no brightening towards the centre, is rated as $DC = 0$. With $DC = 3-5$, there is a distinct brightening. By $DC = 7$, there is a steep overall gradient, and by $DC = 8$ the coma is very small, dense and intense with fairly well-defined boundaries. With $DC = 9$, the comet looks like a slightly defocused star or a planet in bad seeing.

There are many comet observers, and each reports both the DC number and the total magnitude of the comet, as well as the perceived maximum diameter of the envelope up to its merging with the sky background. Based on these two quantities, the surface brightness of the comet can be easily calculated from (Ściężor et al. 2010b)

$$S_a = m_1 + 2.5 \log A, \quad (2)$$

where S_a is the surface brightness of the object (mag arcsec^{-2}), m_1 is the total brightness of the object (mag) and A is the surface area of the object (arcsec^2).

I believe that the surface brightness of the weakest comet, which can be visible using a telescope, using binoculars or even with the naked eye, with the very low DC (0, 1 or 2), can be used as an approximate value of the surface brightness of the sky (specifically, it defines the lower limit of this value).

The main advantage of the described method is its simplicity. Globally, there are hundreds of amateur comet observers (in Poland, there are tens of amateur comet observers), and each observer tries to carry out observations as carefully as possible. This results in a large sample of reliable measurements, which can be used for further analysis. Each year, several dim comets are observed, which means that there can be virtually continuous monitoring of the night-sky brightness. There is also the possibility of using archival observations of comets from at least the early twentieth century in order to determine long-term changes in the artificial sky glow.

It should be emphasized that the estimation of the overall brightness of a comet and also the diameter of the envelope are subjective and can vary depending on the observer. An experienced observer determines the overall brightness of the comet with an accuracy of 0.2 mag, and the coma diameter to within 20 per cent. As a result, the maximum error of the obtained S_a value for such an observer is equal to about $0.36 \text{ mag arcsec}^{-2}$, which should be considered an acceptable value.

There are many factors, not related to the observer, that can affect the values of the reported comet parameters, such as changing weather conditions. All of these factors, both human and external, make the described method primarily a statistical method; as far as possible, it is necessary to take into account the many observations made by the many observers. In the case of an experienced observer, who is able to perform repeatable, reliable observations, and with the right choice of comets, even a single observation is sufficient to determine the surface brightness of the sky at a given time and place.

Of course, the cometary method is only suitable to estimate the light pollution of a cloudless sky (i.e. to determine the so-called astronomical light pollution).

5 STATISTICS

In order to analyse the artificial sky glow level using the new cometary method, I have used the observations of comets made by Polish amateur astronomers, which are stored in the archive of the Comet Observers Section (SOK) of the Polish Amateur Astronomers Society (PTMA) for the years 1994–2004, as well as

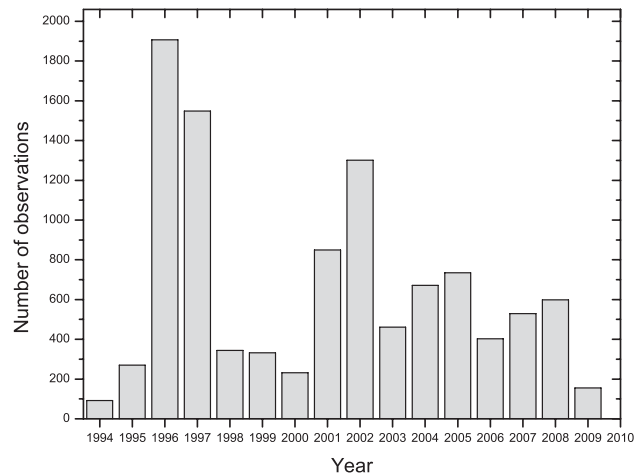


Figure 1. Numbers of amateur observations of comets in Poland during the period 1994–2009.

observations from the period 2005–2009 from the Polish Comet Observation Centre (COK). These observations have been sent regularly to the Smithsonian Astrophysical Observatory (Cambridge, MA, USA) and are stored in the data base of the International Comet Quarterly (ICQ).

During the period 1994–2009, a total of 10 428 observations of comets were recorded in the above archives with an annual average number of 652 observations (see Fig. 1). In this respect, 1996 was the richest year (with 1907 observations), and the poorest years were 1994 and 2009 (with 92 and 155 observations, respectively).

Another statistically significant value is the number of the comets observed by amateur astronomers (see Fig. 2). This weakly depends on the total number of comets observed during the year, because this number is almost constant. I think that the main factor affecting this value is the weather conditions in a given year, because the observations of comets require very good weather conditions. This becomes clear in the period considered: there were as many as 33 comets observed in 2008, whereas in 1995 and 1997 there were only five comets observed.

A very significant factor that also influences the possibility of studying the changes of light pollution in Poland is the number of regular comet observers (Fig. 3). About 20 amateur astronomers

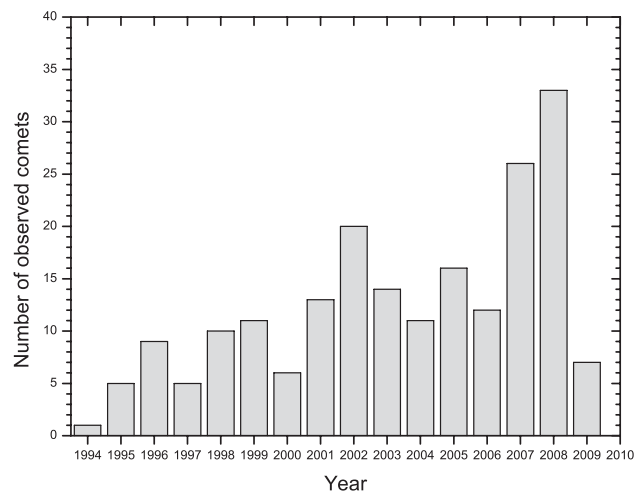


Figure 2. Numbers of comets observed by Polish amateur astronomers in the period 1994–2009.

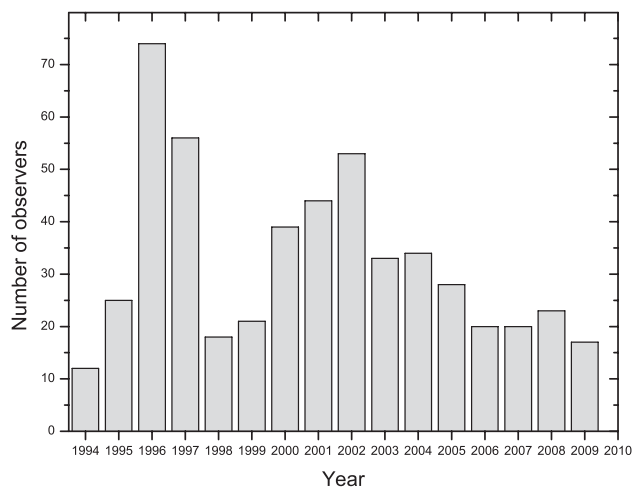


Figure 3. Numbers of Polish amateur observers of comets in the period 1994–2009.

observe comets in Poland continuously. Of course, in the case of a bright comet, this number could rise (in 1996, there were as many as 74 active comet observers), but for the purposes of my research, the most important were observations of the weak and difficult to observe comets, made by regular observers.

Because of the nature of the studied phenomenon, for further analysis I have selected only observations of comets weaker than 7 mag, and especially those with a coma brightness distribution as flat as possible (with a DC between 0 and 2). In order to avoid the effect of the lightening of the horizon, as well as the effects associated with dawn or dusk, I have selected comets observed at an elevation exceeding 45° , between 22:00 and 2:00 local time and during nights with no Moon (except for the test analysis of the dependence of the surface brightness of the night sky on the phase of the Moon).

In the period 1994–2009, there are 451 comet observations that meet the above conditions of observation. So, I have selected these observations for further analysis. In order to analyse the changes in the level of light pollution at a specified observation point, I use the observations made there by one observer. To prevent the effect of random and subjective observations, I use observations of only those comets for which such an observer made at least five brightness estimations on the same night, and I reject the two extreme magnitude estimations.

In order to analyse the problem of light pollution in Poland and its changes during the period 1994–2009, I have selected observations of comets according to the above principles. It should be noted that these observations were not dedicated to the problem discussed here, so observers certainly could not suggest any established aim. The selection criteria of comets suitable for the analysis allowed me to determine the highest recorded value of S_a , which represents the lowest surface brightness of the night sky at the measurement point.

One particular problem was the estimation of the error of such determined S_a values. Too small a number of selected observations does not allow for a reliable determination of the standard deviation, which prompted me to consider the maximum possible S_a error for an experienced observer as the measurement error (marked as error bars).

For comparison purposes, I have also used for analysis a base of comet observations, made in 1984–2009 in Germany and

1995–2004 in the United Kingdom, containing a total of over 20 000 observations.

6 VERIFICATION OF THE COMETARY METHOD

In order to determine whether the value of S_a obtained by the cometary method reflects the surface brightness of the night sky, I have analysed the available observations to determine whether any noticed periodic changes in the S_a value could be associated with such natural changes in the brightness of the night sky.

6.1 Test whether the changes in S_a are associated with the changing phases of the Moon

Sunlight reflected from the surface of the Moon illuminates the night sky. The degree of brightening is associated with the phase of the Moon; during the New Moon, there is no brightening, whereas during the Full Moon the brightening is the strongest (Walker 1987). To plot the following relationships of S_a as a function of the phase of the Moon, I have used all available observations of comets made in the area of Białystok (north-eastern Poland) in the period 1994–2004 (a subset of 49 such observations fulfilled the conditions set out in Section 4). According to the atlas of the night-sky brightness (Cinzano et al. 2001b), this is a part of Poland virtually free of light pollution.

It is clearly visible (see Fig. 4) that during the Full Moon (-1.0 and 1.0 on the horizontal axis), the surface brightness of the weakest observed comets is over $1 \text{ mag arcsec}^{-2}$ lower than at New Moon (0.0 on the horizontal axis). I think that this is in good agreement with the V -band value of $1.8 \text{ mag arcsec}^{-2}$ from the literature (Walker 1987) and also with the value of $1.5 \text{ mag arcsec}^{-2}$ obtained from my SQM measurements. Bearing in mind that the magnitude scale is logarithmic and inverse, this means that there is more than a double linear increase in the brightness of the sky during the month. In fact, the real sky brightening is even greater, because neither comet observations nor SQM measurements were carried out in the vicinity of the Moon. Furthermore, it should be noted that the Moon near its full phase is visible in the sky for almost the whole night, which might be even more important for the brightness of the sky. This effect might explain the constant value of S_a in the range of phase from -0.4 to 0.4 , because in this period the Moon sets in the evening or rises in the morning, without affecting the brightness of

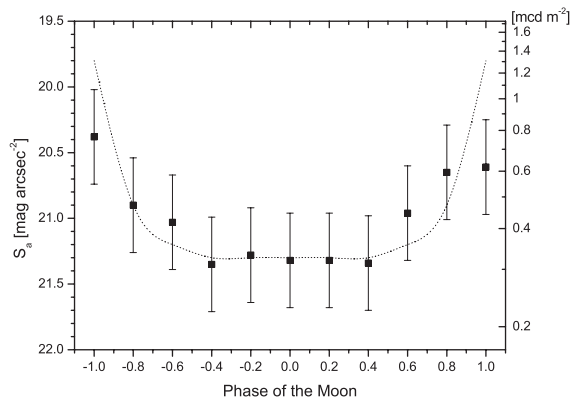


Figure 4. Surface brightness of the weakest observed comets during the lunar month. The dotted curve represents the mean S_a values obtained from the SQM measurements. Error bars show typical maximum errors for experienced observers.

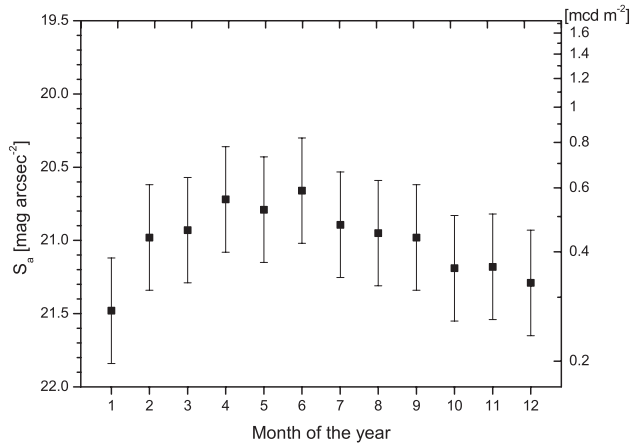


Figure 5. Surface brightness of the weakest observed comets during the year. Error bars show typical maximum errors for experienced observers.

the night sky. In subsequent instrumental research, this observation has led us to take into account only the measurements made in this range of the phases of the Moon.

6.2 Test whether changes in S_a during the year correlate to the seasonal changes of the night-sky brightness, dependent on the depth of the Sun below the horizon at midnight

Using the same subset of observations as in Section 6.1, I have plotted the S_a values of the weakest observed comets obtained on the nights with no Moon in the period 1994–2004. As is known, at night the Sun is deeper below the horizon in the winter than in the summer, and therefore the sky is darker. In the summer, the Sun at night is only a few degrees below the northern horizon, illuminating the sky to such an extent that it even leads to references to astronomical white nights. This effect should be most pronounced in north-eastern Poland, where in midsummer the Sun at midnight is only 13° below the horizon. Indeed, the plot of S_a versus the season shows the expected relationship (Fig. 5). The difference between December and June is equal to about $0.7 \text{ mag arcsec}^{-2}$, which means that there is more than a double linear increase in the surface brightness of the sky in the summer compared to the winter. I believe this is in good agreement with the value of $0.5 \text{ mag arcsec}^{-2}$, which results from my SQM measurements of the sky brightness as a function of the depth of the Sun below the horizon (Ścieżor, in preparation). The variation of sky brightness with season is slower than expected (e.g. Patat, Ugolnikov & Postlyakov 2006), which might be associated with both the selected criteria for the comet observations used and also with the other effects described, but not fully explained, in the literature (Patat 2008).

6.3 Testing the changes in S_a related to changing solar activity

In view of the 11-yr solar activity cycle, the surface brightness of the sky varies in the range from $22 \text{ mag arcsec}^{-2}$ at the minimum activity period (1994–1998 and since 2005) to $21 \text{ mag arcsec}^{-2}$ at the maximum activity period (1999–2003; Walker 1988; Osterbrock & Martel 1992). In order to determine whether this relationship is evident in the measurements of S_a , I have determined the average annual values of this value since 1995, taking into account only the subset of 167 observations made in the best conditions, by the most experienced Polish observers, between August and April in order to avoid the effect of white nights.

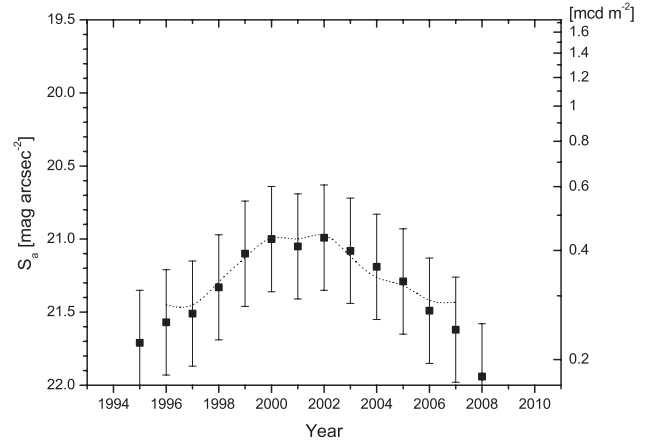


Figure 6. Surface brightness of the weakest observed comets in the period 1994–2009. Error bars show typical maximum errors for experienced observers. The dotted curve represents the expected variation of S_a with epoch.

The obtained relationship is consistent, not only qualitatively but also quantitatively, with expectations (Fig. 6). Indeed, the smallest value of S_a (the highest surface brightness) can be seen in the period 2001–2003, while the lowest surface brightness of the sky can be seen for 1995 and 2009. The S_a measurements made in the period 1985–1996 at Mauna Kea (Krisciunas 1997) show a very similar plot for the previous, 22nd, solar cycle, with the sky surface brightness amplitude equal to about $0.6 \text{ mag arcsec}^{-2}$. On the basis of widely available sunspot data, I have created the analogous, expected curve for the 23rd solar cycle. The coincidence between the S_a values and this curve is striking.

I have obtained similar results from comet observations made during the period 1984–2009 in Germany and during the period 1995–2004 in the United Kingdom, taken from the archives of the ICQ. In particular, the German data correctly show two solar cycles, the 22nd and 23rd cycles, with the maxima in 1990 and 2001, respectively (Ścieżor, in preparation).

6.4 Test to compare S_a values obtained using the cometary method with those obtained using direct SQM measurements

In order to check whether the values of S_a obtained by the cometary method are consistent with the real night-sky surface brightness, I have made simultaneous measurements using SQMs at four observational points in Poland. The results obtained are given in Table 1.

It should be noted that because of the specificity of the cometary method, the obtained value of S_a applies to the background sky between the stars, so it is always higher (i.e. the sky has a lower surface brightness) than the value measured by the SQM. In addition to the sky background, the SQM also measures the brightness of stars and other celestial objects, which increases the measured brightness (i.e. this reduces the value of S_a). Based on data from the literature (Clark 1990), I have calculated that the expected difference between these two values is equal to about $0.7 \text{ mag arcsec}^{-2}$, which is in good agreement with the values in Table 1. This difference increases with the brightness of the background sky, associated with the local light pollution. I believe that this effect is associated with the registration of the scattered light from local light sources. This means that the cometary method (at a sufficiently large statistic) gives a value that is closer to the real brightness of the sky.

Table 1. Comparison of the cometary and instrumental methods.

Locality	Coordinates	S_a (mag arcsec ⁻²)			Sample
		Cometary method	SQM	Difference	
Krakow	50°04'N 19°54'E	19.7	18.7	1.0	26 (comet.) 206 (SQM)
Lublin	51°14'N 22°33'E	19.4	18.6	0.8	28 (comet.) 4 (SQM)
Jerzmanowice near Krakow	50°12'N 19°45'E	21.4	20.6	0.8	17 (comet.) 120 (SQM)
Lubomir Mountain (Beskid Makowski)	49°45'N 20°02'E	21.5	20.9	0.6	24 (comet.) 5 (SQM)
Bieszczady Mountains	49°09'N 22°19'E	22.1	21.7	0.4	16 (comet.) 15 (SQM)

7 RESULTS

7.1 Map of light pollution in Poland

In the process of creating a set of observational data to be used for further analysis, it became clear that, based on the maximum value of S_a , four categories of light-polluted areas can be distinguished, related to the population density and the local level of industrialization (Fig. 7):

(A) large, highly industrialized cities (Krakow, Warsaw);

(B) medium and small cities, located in highly industrialized areas (Lublin, Niepołomice, Częstochowa, Szczecin and Elbląg);

(C) medium and small cities, located in average industrialized areas (Sanok, Wałbrzych) and the far suburbs of large cities, located in highly industrialized areas (Jerzmanowice near Krakow, Izabelin near Warsaw);

(D) medium and small cities, located in poorly industrialized areas (Krosno, Białystok).

The values of S_a are, of course, the sum of the artificial sky glow (the astronomical light pollution) and the natural sky glow associated with the cycle of solar activity. However, I have found that when S_a is smaller than 20.0 mag arcsec⁻², the natural component becomes smaller than the measurement accuracy (<0.2 mag arcsec⁻²) and can be omitted. In other cases ($S_a > 20.0$), I have used the observations made exclusively in the periods 1994–1998 and 2006–2009 (i.e. the periods of minimum solar activity).

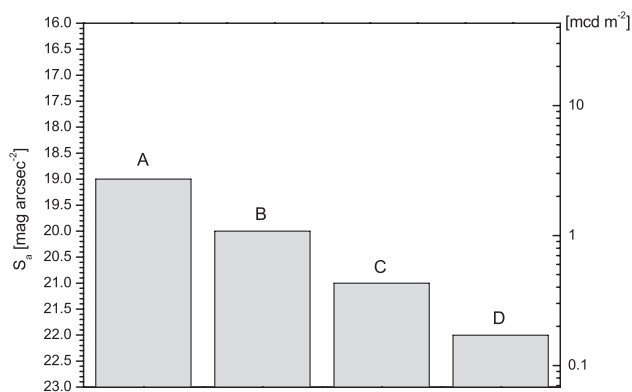


Figure 7. The values of S_a for the four categories of light-polluted areas in Poland, averaged over the period 1994–2004.

Fig. 7 clearly shows that the difference between the big cities (category A) and the areas virtually devoid of light pollution (category D) is equal to 3 mag arcsec⁻². This means that, in the absence of clouds and the Moon, in large, industrialized cities (such as Krakow and Warsaw) the sky is still about 16 times brighter than in the clean areas, located in north-eastern (Białystok) and south-eastern (Krosno) Poland.

The obtained values are fully consistent with the satellite images of the night sky over Poland and, furthermore, with the expected model of the night-sky brightness (Cinzano et al. 2001b).

These results encouraged me to map the light pollution in Poland, using the whole set of 451 observations. As a base, I used the above-mentioned model map of the night-sky brightness (Fig. 8).

The values of S_a obtained using the cometary method do not cover the entire territory of Poland (the grouping of comet observers around the big cities is clearly visible), but the comparison with the model atlas of the night-sky brightness shows, in most cases, a satisfactory convergence with the predicted values. The correlation plot (Fig. 9) clearly shows the fitting of the S_a values, obtained using the cometary method, to the S_a ranges on the model map. A few values that do not comply (e.g. the value of 20.8 south of Katowice, in the area where the atlas provides values in the range

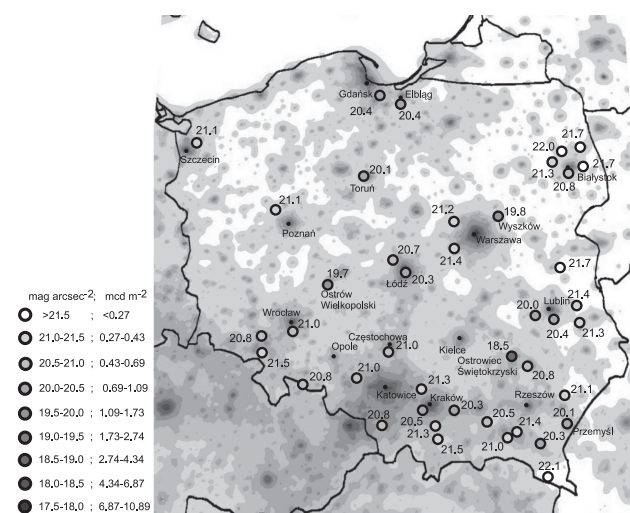


Figure 8. Fragment of a model map of light pollution in Europe (Cinzano et al. 2001b) with the marked points where I have determined the brightness of the night sky using the cometary method, with the values of S_a designated in this way.

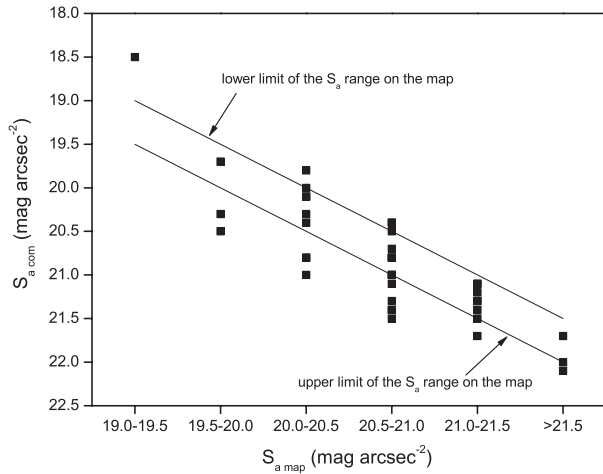


Figure 9. Correlation between the S_a values obtained using the cometary method ($S_{a,com}$) and the S_a ranges read from the model map ($S_{a,map}$).

20–20.5) can be explained by the fact that the sources of light pollution are obscured by the terrain. This phenomenon has not yet been included in the atlas, and is only now to be taken into account. Another important element that could have an impact on the difference between the measurements and the predicted local model is the fact that the model assumes only an average state of the atmosphere scattering of the light, which does not necessarily correspond to the local conditions.

7.2 Temporal changes of the light pollution in Poland

As I have mentioned earlier (Section 4), the cometary method is a statistical method and is essentially limited to a situation where we have a large number of measurements made by many observers. However, I believe that for some experienced observers, it is possible to analyse the changes in the level of light pollution, based on a small number of their observations. In this case, personal error is reduced to a minimum. There are 15 such observers in Poland.

Fig. 10 shows the changes in the brightness of the night sky in a few example places in Poland, estimated on the basis of such data.

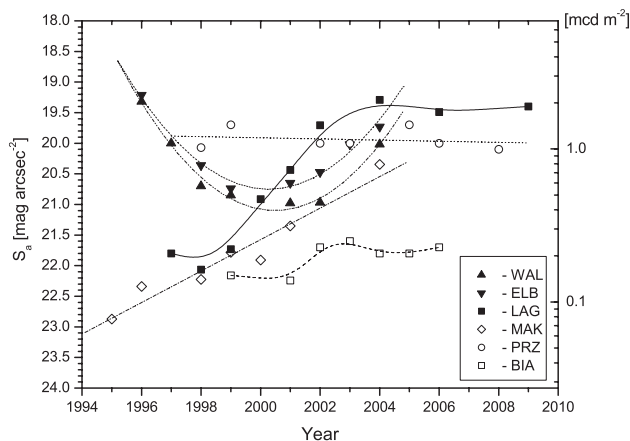


Figure 10. Temporal changes of S_a in the different environments in Poland in the period 1995–2009. The example observational points are as follows: WAL (Wałbrzych), 50°50.5′N, 16°17.5′E; ELB (Elbląg), 54°06.7′N, 19°24.4′E; LAG, (Krakow-Łagiewniki), 50°00.0′N, 19°55.4′E; MAK (Beskid Makowski Mountains), 49°46′N, 20°03.6′E; PRZ (Przemyśl), 49°45.0′N, 22°48.5′E; BIA (Białystok), 53°16.5′N, 23°18.2′E.

I have found that the change in the S_a value followed the solar activity cycle in the four tested areas: the Białystok region in north-eastern Poland (BIA in the plot), the Bieszczady Mountains in south-eastern Poland, the Beskid Niski Mountains in southern Poland and Polesie Lubelskie in eastern Poland. After reduction for this effect, the value of S_a remained almost constant at 22 mag arcsec^{−2} in the tested period. This means that these areas can be considered free from light pollution.

Similarly, I have found a constant value, but this time at 20 mag arcsec^{−2} (there is no dependence on the solar activity cycle), for the three observers who have observed comets from the peripheral districts of the large cities, as well as from the smaller cities (e.g. PRZ). I have also found no temporal changes for the Izabelin village, located on the outskirts of the Kampinos Forest, but undoubtedly the relatively small distance from Warsaw (only 16 km) affected the value of S_a , which in this case is greater than 20 mag arcsec^{−2}. This means that the factors causing the light pollution both within the cities and away from them during the described period have been not changed.

I have obtained very interesting results for the observer (assigned LAG) at a distance of 7 km south of Krakow city centre in a district that has undergone intense urbanization over the past several years (the S_a values has been reduced to take into account the changing solar activity). I have found that, in the case of the outskirts of Krakow, the value of S_a in 1997 was equal to the value determined currently for the least light-polluted parts of Poland. Since then, the value of S_a has steadily decreased (i.e. the surface brightness has increased) to saturation in 2004 at a level of about 19 mag arcsec^{−2}, which (according to my previous arrangements) is equal to the sky brightness in the centres of large, industrialized cities. It should be noted that the scale of S_a is the inverse and logarithmic scale, which means that, in this case, the surface brightness of the night sky has increased by nearly 16 times.

For the analysis, I have also used the rich archive (containing more than 300 observations) of comet observations made by the Polish Amateur Astronomers Society (PTMA) in the period 1994–2004 at the annual observation camps at the Lubomir and Lysina Range in the Beskid Makowski Mountains. After the reduction of the S_a value on the solar activity, there is an evident increasingly linear relationship (MAK in Fig. 10). During the reported period, the value of S_a has decreased there from almost 23 mag arcsec^{−2} in 1995 to about 21 mag arcsec^{−2} in 2004. This represents an increase of sky brightness of more than sixfold, which is not associated with natural phenomena.

I have obtained even more interesting results for the areas of Wałbrzych (WAL, 4 km north of the city centre, south-western Poland) and Elbląg (ELB, 6 km south from the city centre, northern Poland). The dependences have not been reduced; after taking into account the solar activity cycle, their shapes almost do not change. In both cases, the brightness of the sky was decreasing steadily (the value of S_a increased) starting from 1996 until the minimum in 2001–2002, and then rose again. I believe that this variability can be explained by changes in the concentration of the particulate matter associated with the changes in industrialization (Ścieżor et al. 2010b; Ścieżor, Kubala & Kaszowski 2012).

8 CONCLUSIONS

In this paper, I have introduced a novel method to estimate the brightness of the night sky. The method has been verified using instrumental measurements, and provisional conclusions have been presented.

The results show that the average surface brightness of the faintest observable comets can be considered as a good approximation of the surface brightness of the night sky. The main advantage of this method is its simplicity. It also allows for the use of observations, carried out over the years by the large number of widely distributed reliable amateur comet observers. These observations are not intended to measure the light pollution, so they should be completely objective in this respect.

The main advantage of the method is that it allows for an estimation of the artificial sky glow for all such locations where a proper observational data base exists. Such observations often start in the early 20th century (and, in some cases, even earlier), and so they include periods when light pollution was not studied, or even noticed.

The level of artificial sky glow depends greatly on the content of aerosols and the particulate matter in the atmosphere (Ścieżor et al. 2012). I think that it is possible to research this problem indirectly as well, especially in areas or periods where direct measurements were not carried out, or could not be performed. However, this would require the creation and verification of an appropriate model of light diffusion in the atmosphere.

From my measurements, and also according to the model (Cinzano et al. 2001b), it is clear that the level of artificial sky glow depends on the size of cities and on the industrialization of the area. In Poland, there are three areas free of light pollution: south-eastern Poland (Bieszczady Mountains), eastern Poland (Podlasie) and north-eastern Poland (Białostoczczyzna). For these areas, I have obtained a value of S_a of 22 mag arcsec⁻² for a cloudless sky with no Moon. This value is consistent with the value expected from the model for those areas. The most light-polluted areas are the large cities (Warsaw, Krakow) and the industrialized areas (Upper Silesia). Evidence of light pollution was also found in the mountain areas (Tatry Mountains; Ścieżor et al. 2012).

In the research period of 1994–2009, I have noticed practically no changes in the value of S_a for both the ecologically clean areas (S_a fixed at a high level) and for highly light-polluted areas (S_a fixed at a low level). In the same period, I have noticed a clear decrease of 2 mag arcsec⁻² in the value of S_a (i.e. a six times higher surface brightness of the night sky) for sites located on the border of heavily light-polluted and less light-polluted areas (near and far suburbs of Krakow). A preliminary data analysis suggests that there is an increase of the value of S_a (i.e. a decrease of the sky glow brightness) for Wałbrzych and Elbląg in the period 1995–2000, which might be associated with the fall in industry for these cities.

The preliminary results support the suitability of the new cometary method to determine the brightness of the night sky. Observed differences in instrumental measurements indicate the need to develop a model for the visibility of comets with a low degree of condensation, similar to the model of the limiting magnitude of the weakest observable stars.

The advantages of the new method might also include the possibility of using archive observations that were not intentionally directed at the level of light pollution, and therefore are fully objective.

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