Lunar Skylight Polarization Signal Polluted by Urban Lighting

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Abstract. An edited version of this paper was published by AGU. Copyright (2011) American Geophysical Union. Citation: Kyba, C. C. M., T. Ruhtz, J. Fischer, and F. Hölker (2011), Lunar skylight polarization signal polluted by urban lighting, J. Geophys. Res., 116, D24106, doi:10.1029/2011JD016698. On clear moonlit nights, a band of highly polarized light stretches across the sky at a 90 degree angle from the moon, and it was recently demonstrated that nocturnal organisms are able to navigate based on it. Urban skyglow is believed to be almost unpolarized, and is therefore expected to dilute this unique partially linearly polarized signal. We found that urban skyglow has a greater than expected degree of linear polarization ($p = 8.6 \pm 0.3\%$), and confirmed that its presence diminishes the natural lunar polarization signal. We also observed that the degree of linear polarization can be reduced as the moon rises, due to the misalignment between the polarization angles of the skyglow and scattered moonlight. Under near ideal observing conditions, we found that the lunar polarization signal was clearly visible ($p = 29.2 \pm 0.8\%$) at a site with minimal light pollution 28 km from Berlin's center, but was reduced ($p = 11.3 \pm 0.3\%$) within the city itself. Daytime measurements indicate that without skyglow p would likely be in excess of 50%. These results indicate that nocturnal animal navigation systems based on perceiving polarized scattered moonlight likely fail to operate properly in highly light-polluted areas, and that future light pollution models must take polarization into account.

1. Introduction

The extreme distance to the Sun and Moon ensures that when their light enters Earth's atmosphere it is highly collimated. When this light is scattered by atmospheric molecules (Rayleigh scattering), the scattered light becomes linearly polarized, with the degree of linear polarization (p) depending upon the scattering angle. The value of p is maximal at angles 90° from the source, so on clear days at sunset and sunrise a compass-like band of highly polarized light extends across the sky through the zenith along an approximately North-South axis. Advances in digital imaging have allowed quantitative measurements of this pattern during the day [*North and Duggin*, 1997], twilight [*Cronin et al.*, 2006], and on moonlit nights [*Gál et al.*, 2001]. Digital imaging has also been used to study light pollution [*Duriscoe et al.*, 2007], but although light pollution is expected to corrupt the natural pattern of celestial polarization [*Cronin and Marshall*, 2011], until now the lunar polarization signal for urban skies has not been reported.

It has long been known that many diurnal animals are able to perceive linearly polarized light [*Verkhovskaya*, 1940], and exploit the solar polarization signal as a navigational aid [*von Frisch*, 1949; *Horváth and Varjú*, 2004]. Songbirds, for example, calibrate their magnetic compass using polarization cues during twilight [*Cochran et al.*, 2004; *Muheim et al.*, 2006]. While the lunar polarization signal exhibits almost the same degree of linear polarization and pattern as the solar one [*Gál et al.*, 2001], the intensity of moonlight is up to seven orders of magnitude lower than sunlight, making its detection far more challenging [*Warrant*, 2004]. Despite this difficulty, it has been shown that a species of dung beetle (Coleoptera: Scarabaeinae) navigates using the lunar polarization signal even at the time of the crescent moon [*Dacke et al.*, 2003, 2011], and it is suspected that other nocturnal organisms (e. g. moths [*Nowinszky*, 2004; *Nowinszky and Puskás*, 2011], bees, crickets, and spiders [*Warrant and Dacke*, 2010; *Dacke et al.*, 2011]) make use of this same signal.

Although understanding of the extent to which nocturnal animals use the lunar polarization signal is in its infancy, the land area over which it is viewable in pristine form is relentlessly shrinking due to human activity. Both the lit area of the Earth and the brightness of urban lighting have increased dramatically over the last century, and it is possible that the navigation systems of moths in brightly lit Europe have been affected through screening of polarized moonlight [*Nowinszky and Puskás*, 2011]. Worldwide, the annual rate of lighting increase is estimated to be 3-6%, with large local variations [*Narisada and Schreuder*, 2004; *Hölker et al.*, 2010a]. The past two decades have seen increasing recognition of the ecological impacts that both direct [*Rydell*, 1992; *Salmon et al.*, 1995] and indirect [*Moore et al.*, 2000] night lighting have on organisms, food webs, and ecosystems [*Rich and Longcore*, 2006; *Navara and Nelson*, 2007; *Hölker et al.*, 2010b].

While the light produced by typical street lamps is normally not strongly polarized, light pollution in urban areas can become polarized both through the scattering of light by the atmosphere [*Kerola*, 2006], and through reflections from natural or artificial planar surfaces [*Können*, 1985; *Horváth et al.*, 2009] (e.g. lake water, asphalt, and glass windows). The skyglow seen by an urban observer is not expected to be highly polarized [*Kerola*, 2006], because the sources of light are distributed around the observer (i.e. the light is uncollimated). An important exception to this generalization is light scattered from the collimated beam of a searchlight, which can be strongly polarized in a clean atmosphere [*Können*, 1985]. When unpolarized light is added to polarized light, the value of p is decreased. Therefore, the brighter a city's skyglow, the greater we expect the lunar polarization pattern to be polluted.

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0148-0227/11/2011JD016698$9.00

2. Methods

2.1. Measurement locations and dates

Berlin is an ideal site to perform light pollution research, as the surrounding area in the state of Brandenburg has comparatively little lighting. This can be seen in Panel A of Figure 1, which shows the view of Berlin from space. We took data at the two locations marked by the black and white x's in the figure. The urban location is our measurement tower at the Freie Universität (52.4577°N, 13.3107°E), and the rural location is an unlit parking lot (52.5296°N, 12.9978°E) adjacent to the "Sielmanns Naturlandschaft Döberitzer Heide" *Naturschutzgebiet* (wildlife sanctuary). Panels B and C show the sky brightness at these two locations. As a test of our method, we also took images of the daylit sky from the urban location, and of a highly polarized LCD screen in the laboratory.

The data for the urban-rural comparison were taken on the night of February 21-22, 2011. To ensure an adequate polarization signal, we required a night with extremely clear skies and as full a moon as possible. Perfectly clear skies were critical, as clouds strongly amplify urban light pollution [*Kyba et al.*, 2011; *Lolkema et al.*, 2011] (increasing the background), and reduce p [*Pomozi et al.*, 2001] (decreasing the signal). Such optimal observation nights occur only a few times per year, so the typical urban polarization signal is expected to be considerably smaller than that reported. The urban moonlit images were taken from 00:30-00:45, when the moon was approximately 14 degrees above the horizon, 81.5% illuminated, and the angle between the Moon and Polaris (the North Star) was 105.5°. The rural images were taken from 2:02-2:19, when the moon was 21 degrees above the horizon, 80.9% illuminated, and with 105.4° between the moon and Polaris. For comparison, moonrise images were taken from 23:06-23:14, and moonless images were taken the following evening, which was also clear, from 22:13-22:40.

2.2. Image acquisition

All data were taken using a Finger Lakes Instrument (FLI) Microline camera (Kodak KAI-4022 chip, cooled to -15 C), Sigma 24mm F1.8 DG lens, and Hama pro class 77mm linearly polarizing filter. Night (day) images were taken with the aperture set to F2.8 (F22), and with an integration time of 5 seconds (10 ms). Wavelength ranges were restricted using an FLI CFW-1-8 filter wheel with FLI 28mm color filters. The approximate wavelength ranges are shown later with the results, and detailed transmission curves are available online (www.flicamera.com/filters/index.html). It should be noted that the red filter does not have strong transmission at the 589 nm line produced by low pressure sodium lamps [*Elvidge et al.*, 2010]. This is not expected to have an impact on the interpretation of our results, both because the light from this line is transmitted by the luminous filter, and because Berlin uses an extremely wide range of lighting technologies. Dark current measurements were taken concurrently with the color images. An opaque filter was used to block the light for the dark current measurement, and when the images were analyzed it was discovered that this filter blocked only 99.3% of the incoming light. Measured polarization values were multiplied by 1.014 to compensate for this light leakage.

2.3. Image processing

Images were acquired using the Astroart 4 data acquisition program, and analysis was performed using the Interactive Data Language (IDL). The images were centered on the North Star, ensuring that the angle between the moon and the center of the image (105.5°) remained the same at each location. Image data were background corrected pixel-by-pixel, and re-binned from 2048x2048 pixels to 256x256 pixels, to improve individual pixel statistics. The field of view was 33.9° along each axis.

The degree of linear polarization can be obtained with measurements at three angles of the transmission direction of the linear polarizer [*Gál et al.*, 2001; *Cronin et al.*, 2006], but we made use of a fourth measurement to allow a check of the filter alignment [*North and Duggin*, 1997]. We define the Stoke's vector S as

$$S = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} \frac{1}{2}\left(I_{0^\circ} + I_{45^\circ} + I_{90^\circ} + I_{135^\circ}\right) \\ I_{0^\circ} - I_{90^\circ} \\ I_{45^\circ} - I_{135^\circ} \\ \equiv 0 \end{pmatrix} \quad (1)$$

where I_{45° is the intensity measured with the filter turned to the 45° position. We have assumed that circular polarization is absent. The degree of linear polarization is then

$$p = \frac{\sqrt{S_1^2 + S_2^2}}{S_0} \quad (2)$$

For a perfect measurement, the sum of measurements taken with polarizations at right angles should be independent of the angles. We define a test variable for the filter alignment:

$$\delta_p = [(I_{0^\circ} + I_{90^\circ}) - (I_{45^\circ} + I_{135^\circ})]/S_0 \quad (3)$$

which should be zero for perfectly aligned filters (assuming a stable light field and no CCD noise). Finally, we define an angle of polarization relative to the filter position at 0°:

$$\phi = 0.5 \arccos \frac{S_1}{\sqrt{S_1^2 + S_2^2}} \qquad S_2 < 0 \quad (4)$$

$$\phi = \pi - 0.5 \arccos \frac{S_1}{\sqrt{S_1^2 + S_2^2}} \qquad S_2 > 0 \quad (5)$$

To ensure the urban-rural comparison was based on exactly the same patch of the sky, we identified all star-free pixels within 64 re-binned pixels of Polaris. Stars were removed by flagging all pixels for which the multi-image variance of S_0 was at least three times that for the average pixel. The four intensity values, I_0, I_{45}, I_{90}, and I_{135}, are the mean value of the remaining star-free pixels.

For each observation we took 4-6 sets of images, and in all cases we report the polarization measurement from the third set. We refrained from combining the data from multiple acquisitions because the polarization angle of scattered moonlight is not constant, and because Berlin's skyglow becomes dimmer as the night progresses [*Kyba et al.*, 2011].

2.4. Estimation of uncertainties

The two largest sources of uncertainty for p and the polarization angle arose from filter mis-alignment and CCD dark current fluctuations. To estimate the standard error from these statistical variations, we wrote a Monte Carlo simulation in FORTRAN. For each observed p and polarization angle, we simulated 10,000 observations with normally distributed filter position errors and dark current fluctuations. The standard error was defined as the root mean square spread of this distribution.

This code was used with the daytime measurements to estimate our 1σ filter positioning uncertainty as $\sim 1^\circ$. The resulting simulated standard errors agreed well with the statistical variation observed in multiple measurements (the one exception was for the case of the LCD screen, where the assigned uncertainties were larger than the observed variation. We attributed this to the far more comfortable working conditions in the laboratory, where we were able to position the filter more accurately.). We found that the test

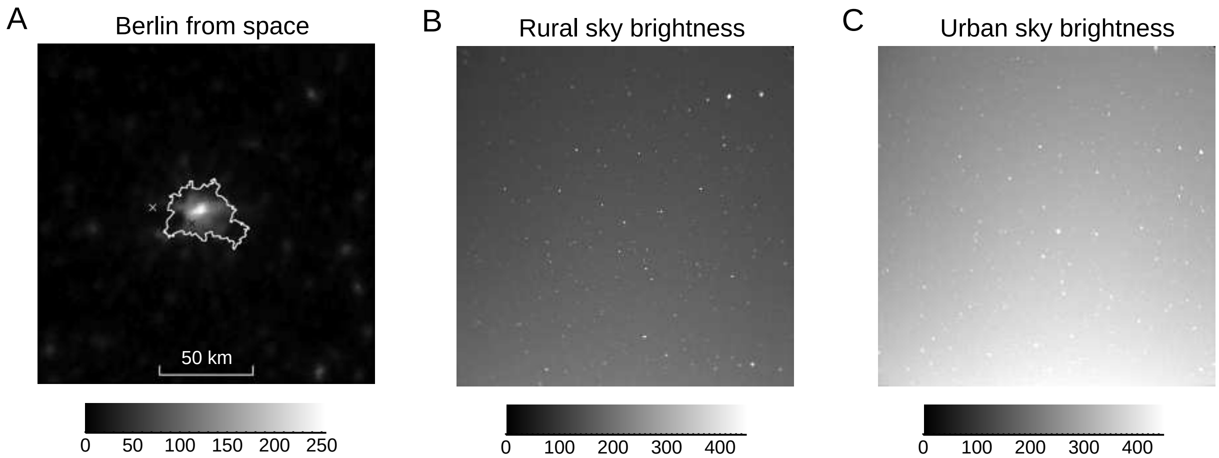

Figure 1. Spatial distribution of light pollution. Panel A shows the upward directed radiance measured over Berlin by the Defense Meteorological Satellite Program in 2006 (Image is oriented so that North is upward). The x's mark the rural and urban locations we compared on February 21-22, 2011. Panels B and C compare the brightness of the sky observed at the rural and urban locations. The images are centered on the North Star, and pixel brightnesses are the measured intensity component of the Stokes matrix (S_0), where a maximum value of 450 was set to preserve contrast. In both images East (towards Berlin's center) is in the right hand direction and upwards (downwards) is towards the zenith (horizon). Image and data processing by NOAA's National Geophysical Data Center. DMSP data collected by US Air Force Weather Agency. Outline of Berlin added by Helga Kuechly.

statistic δ_p was non-zero, indicating a systematic offset of $\sim 2.5°$ in at least one of the filter positions. We estimate that this results in a systematic deviation of the degree of linear polarization measurements of $\pm3\%$ of the measured value. This systematic offset should apply approximately equally to all measurements, and is therefore irrelevant for the urban/rural comparison. It is negligible compared to the intrinsic variation due to changes in the moon's illuminated fraction and elevation.

3. Results

Figure 1 demonstrates that the intensity of light escaping and reflected by the atmosphere depends upon proximity to urban areas. The degree of linear polarization from skyglow and moonlight at the urban and rural sites are compared to each other and to reference situations in Table 1. The observed rural degree of linear polarization ($p = 29.2 \pm 0.8\%$) was clearly observable, but only about half of what we observed for a sunlit sky ($p = 56.6\pm1\%$). In contrast, the lunar polarization signal was very weak when observed within the city ($p = 11.3 \pm 0.3\%$). Given that we performed these measurements in almost ideal conditions (cloud free, and with the moon 81% illuminated), it is to be expected that on most nights the lunar polarization signal is no longer discernible in many urban locations by the organisms capable of perceiving it in un-lit environments.

The polarization of urban skyglow in the absence of the moon (8.6±0.3%) was larger than we expected, and considerably larger than the ∼2% predicted by a recent light pollution model that takes polarization into account [*Kerola*, 2006]. We speculate on the possible origin of this polarization in the conclusion, and simply note here that this level of urban skyglow polarization could have biological implications for clear moonless nights, as crickets are able to perceive the polarization signal of the sky if p exceeds 5% [*Horváth and Varjú*, 2004].

The weakest polarization values we observed were, somewhat surprisingly, for the case of the rising moon. We believed this to be due to a mismatch between the angle of polarization of skyglow and scattered moonlight, and performed a dedicated moonrise experiment at the urban location on the night of May 21-22, 2011 to test this. We found that when the polarization angle of moonlight differs from that of skyglow, the introduction of moonlight initially reduces the degree of linear polarization, as is shown in Panel A of Figure 2. Provided the moon is bright enough, as it rises the strongly polarized scattered moonlight will begin to dominate over the weakly polarized skyglow, and p will increase, as can be seen after 1:30. (The increased spread in the data at this time was probably due to the visually observed passage of thin cirrus clouds over the field of view). The dip in p shown in panel A and the rotation of the angle of polarization shown in panel B were most pronounced for blue light, and least pronounced for red (this is not shown to preserve clarity).

Outside of the tropics, the full moon rises to much lower elevations in summer than in winter. Since the moon provides less light at lower elevations, in general we expect the washing out of the lunar polarization signal be greatest in summer, and during moonrise and moonset. We found that for the exceptionally high elevation winter moon on the night of January 16-17, 2011 (52° elevation, 89% illuminated), the scattered moonlight was bright enough to dominate over the mostly unpolarized urban skyglow. This allowed us to observe the gradient of the natural polarization pattern, shown in Figure 3. Panels A and C compare the sky brightness near Polaris and at the horizon, and panels B and D show the degree of linear polarization for the same scenes. The sky gradient in panel B is mainly due to changes in the Rayleigh scattering angle, whereas towards the horizon (panel D) p decreases due to the increasing fraction of (mostly unpolarized) skyglow. Even under these extraordinarily favorable observing conditions the degree of linear polarization was not comparable to that observed for scattered sunlight at the same urban location (cf. Table 1).

4. Discussion and Conclusion

This study demonstrates that in Berlin, and presumably urban areas in general, urban skyglow pollutes the lunar skylight polarization signal to such a degree that on most nights polarization-based animal navigation is no longer expected to be possible. This occurs because skyglow has a

Table 1. Degree of linear polarization results

Location	Situation	Luminous (370-700 nm)	Red (590-690 nm)	Green (490-580 nm)	Blue (370-510 nm)
Urban	No Moon	8.6±0.3%	8.5±1.4%	9.4±0.7%	10.1±0.5%
Urban	Moonrise	3.9±0.2%	-	-	-
Urban	Moon	11.3±0.3%	8±2%	12.7±0.8%	16.7±1.1%
Rural	Moon	29.2±0.8%	21±5%	31±2%	36±2%
Urban	Daytime	56.6±1.0%	56±1.1%	57.7±1.1%	57.2±1.1%
Laboratory	LCD screen	98.1±1.2%	99.2±1.2%	98.4±1.2%	98.3±1.2%

The degree of linear polarization observed for each location and situation is shown, along with 1σ statistical standard error. The reduction in polarization caused by urban light pollution is worse at longer wavelengths, which we presume to be due to both the stronger scattering of moonlight at short wavelengths, and the comparatively low color temperature of Berlin's street lights. An additional systematic uncertainty of $\sim$3% of the measured value (due to systematic filter mis-alignment) applies equally to all measurements. Note that the uncertainty in the measured values is much smaller than the intrinsic variability caused by gross changes in urban illumination and moon elevation [*Kyba et al.*, 2011]. All night sky data were taken February 21 and 22, 2011.

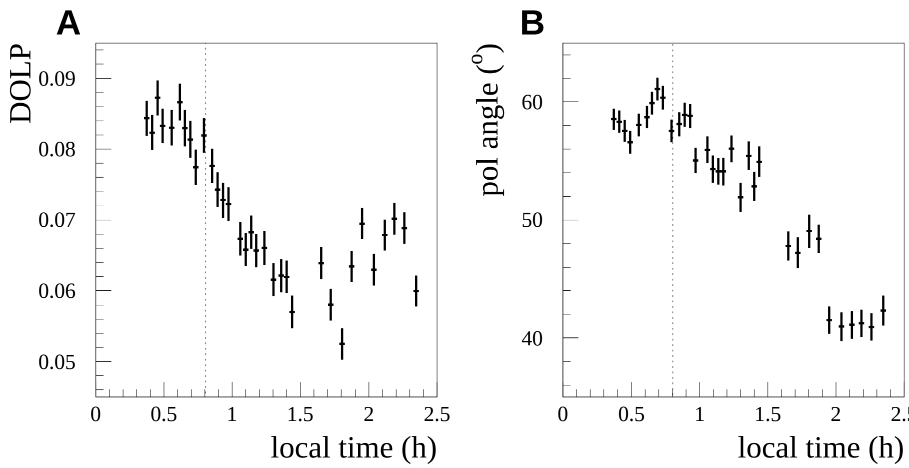

Figure 2. Changes in urban sky polarization during moonrise. Panel A shows the measured degree of linear polarization decreasing immediately after moonrise (dashed line), and gradually increasing again as moonlight began to dominate over skyglow. Panel B shows the rotation of the angle of polarization as the scattered moonlight is added. All data are for the luminous filter, with 1σ standard errors shown. These data were taken on May 21-22, 2011, when the moon was not as full or as high in the sky as in the other measurements (i.e. the transition from skyglow to moonlight dominance was far more rapid on February 21-22). The onset of sunrise prevented further measurements. The pattern of polarization in pristine moonlit skies is discussed in detail by *Gál et al.* [2001].

low value of polarization compared to scattered moonlight, and when unpolarized light is mixed with polarized light the total degree of linear polarization (p) is reduced.

Many nocturnal organisms are believed to orient their movements using the polarization of the moonlit sky. Unfortunately, it is very difficult to experimentally verify this, particularly for the case of flying insects, and further research into this area is warranted. Since skyglow can propagate great distances from an urban core, the ecological impact of light pollution may extend over vast swaths of the Earths surface, including places where the sky already appears "dark" to humans. If it is the case that the loss of navigational ability greatly reduces the fitness of some nocturnal organisms, then the depolarizing effect of skyglow is a remarkably under-appreciated form of global pollution.

In addition to our main finding, that skyglow reduces the polarization of moonlit skies, we also found that skyglow itself can have a non-negligible degree of linear polarization ($p = 8.6 \pm 0.3\%$ for our location in Berlin observing in the direction of the North Star), which is large enough to be perceived by crickets. This surprising result indicates that it is important that future simulations of skyglow take polarization into account. One possible explanation for the polarization of skyglow in the absence of the moon could be the tendency for the artificial canyons created by city streets to partially collimate the emitted light. If this is the cause, one would expect the skyglow polarization of North American cities (with streets laid out on a North-South/East-West grid) to be even larger than that observed in Berlin, as the directions of collimation would be more consistent throughout the whole city. Another possibility is that the observed polarization is generated by inhomogeneities in the positions of lights on the ground.

We found that in the case of a rising moon, p decreased compared to its value before moonrise, and then increased as the moon rose higher. We attribute this to a mis-match between the polarization angle of skyglow and scattered moonlight, and this explanation agrees with our observation that the angle of polarization rapidly changed as the moon rose. In most cases one should expect that the two angles of polarization, which depend on the position of the moon, the position of the observer in the city, and the viewing direction, will not be aligned. In these cases we expect that a reduction in polarization will always occur during moonrise. If a researcher could find a location where the polarization angle of skyglow matched that expected to occur due to the rising moon, then we would expect p to begin increasing immediately, rather than dipping as in Panel A of Figure 2. Further investigation of these effects will require a polarimeter capable of automatic measurements and scanning different regions of the sky.

Given the human near-blindness to polarized light, it is natural for researchers to first focus on light intensity and color when studying the impact of light pollution on animal behavior. But perhaps it could be the case that for some organisms the polarization of light (or lack thereof) is as

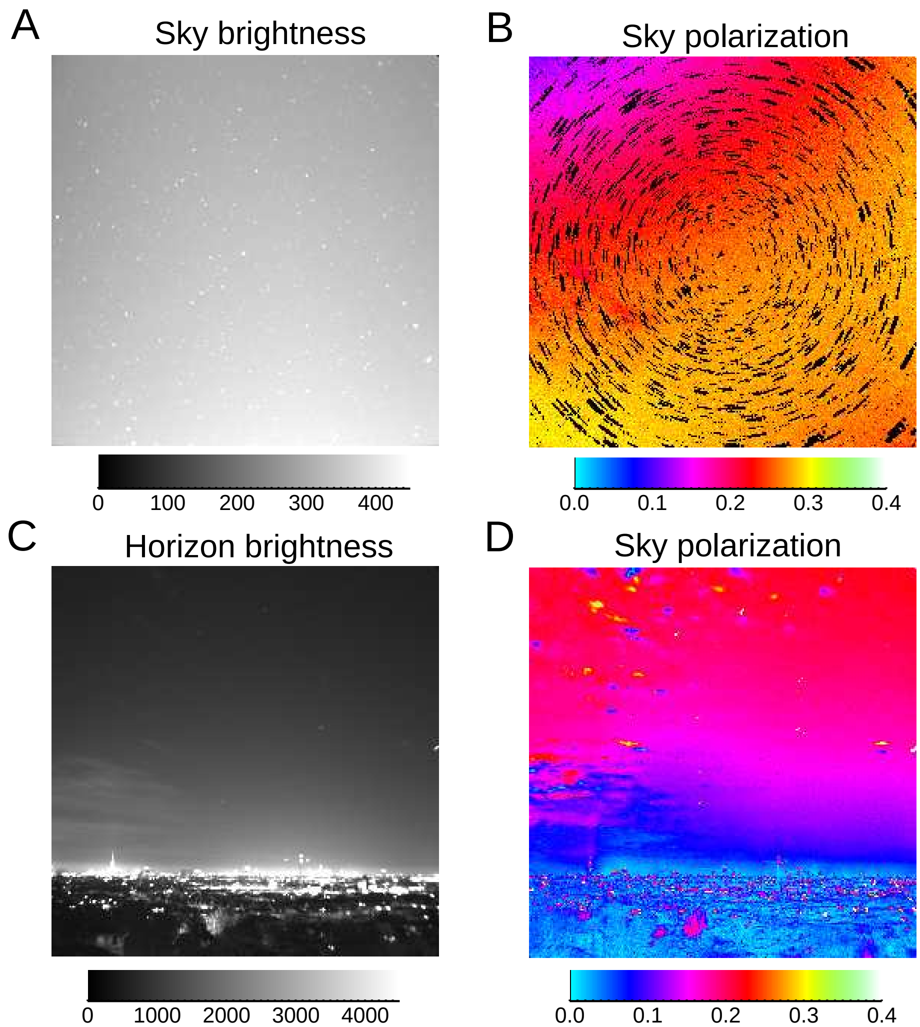

Figure 3. The dependence of sky brightness and degree of linear polarization on viewing direction. This figure shows data acquired with the luminous filter at the urban location on the night of January 16-17, 2011. Panels A and C show the sky and horizon brightness (note factor of 10 difference in scale, the darkest sky pixels in C have a value of ∼550). Panels B and D show the degree of linear polarization calculated for each pixel (stars are masked out in panel B). The gradient in panel B arises from changes in the Rayleigh scattering angle (the moon is far away from the image, in the upward and left direction). The gradient in panel D is due to unpolarized light pollution blocking the moon's signal (the moon is even further away in this image, behind the observer). The sky polarization is larger than in Table 1 because the moon was higher and fuller.

or more important than the light itself. As an example, migrating birds are known to be attracted to searchlights most strongly on nights with a low cloud layer [*Rich and Longcore*, 2006]. Since birds are not able to set their magnetic compass using the twilight polarization pattern on cloudy nights, could it be that they are attracted to the polarization signal, rather than to the light itself? Answering this, and other as yet unasked questions, will require further study of both the polarization of urban nightscapes and nocturnal polarization-based navigation.

Acknowledgments. This work was supported by the project *Verlust der Nacht* (funded by the Federal Ministry of Education and Research, Germany, BMBF-033L038A) and by focal area MILIEU (FU Berlin). CK and TR thank their families for understanding their repeated absence around the time of full moon.

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