Naked eye visibility of Sirius in broad daylight

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Sirius was spotted with the naked eye at broad daylight by looking along the finder of a 1 m telescope on La Palma Observatory at a 2370 m height. Sun elevation was 73°; Sirius was nearly straight under the Sun at 37° elevation. The sky radiance, although not recorded directly, could be determined from the simultaneously obtained high-precision wavelength-dependent sky polarization data near Sirius. This was done by fitting the polarization data with the doubling-adding KNMI (DAK) radiative transfer model, which provided the values of the surface albedo and of the aerosol optical thickness required for determining the absolute sky radiance. Our analysis implies that Sirius, when positioned overhead, can be a daytime naked eye object from sea level even if its culmination occurs at solar noon. It also suggests that the second-brightest star (Canopus), if positioned overhead, could be perceptible even at solar noon. © 2014 Optical Society of America

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1. Introduction

Some 30 years ago, Colin Henshaw [1] managed to see Sirius (magnitude −1.46) in daylight with the naked eye up to a solar elevation of 4.5°, thereby promoting it, after the Sun, Moon, Venus, and Jupiter [2], to the position of the fifth daytime astronomical object and the first daytime star. The Henshaw observations took place from Zimbabwe (18° S), at an altitude of 1100 m above sea level (atmospheric pressure level 890 hPa). On his selected observation days, Sirius was at 90° from the Sun, and thus for him positioned straight overhead at dawn, and located in the dark polarization band of the sky. We here augment Henshaw's observation with an unaided visual Sirius observation from an altitude of 2370 m but under less favorable circumstances: noon, high Sun, Sirius at 37° elevation and nearly straight below the Sun, with a Sun–Sirius separation of 41°.

To quantify our La Palma observations and to extrapolate them to sea level conditions requires knowledge of the absolute sky radiance. This parameter was not recorded, but instead, nearly simultaneously with the visual observation the sky polarization was instrumentally recorded, at one point in the sky. The availability of these high-precision multiwavelength sky polarization observations eliminates the need for absolute sky radiometry, as the polarization observation provides a value for the aerosol optical thickness and for the albedo of the underlying surface, from which the absolute sky radiance can be determined.

In the present paper this approach is elaborated and applied to the La Palma star observations. The extrapolation of the La Palma observations from 2370 m down to sea level indicates that Sirius may also be spotted at sea level in broad daylight.

2. Observations

The Sirius observations took place on 22 June 1988 in the dome of the 1 m Jacobus Kapteyn Telescope in Roque de los Muchachos Observatory at the Canary Island La Palma (28° 45′ 40.1″ N, 17° 52′ 41.2″ W), which is situated near the summit of the highest mountain of La Palma. The observatory's height is

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Table 1. Positions of the Sun and Sirius during the Visual Observations

	Elevation	Azimuth	Culmination Time and Elevation
Sun, 11:53-12:11 UTC	71.2°–75.0°	101.8°–107.2°	13:14 UTC (84.7°)
Sirius, 11:53-12:11 UTC	36.1°–38.3°	143.7°–148.4°	13:55 UTC (44.5°)

2370 m above sea level, and thus the telescope is at the 760 hPa atmospheric pressure level. The observations took place during a continuous 6 day polarimetric observing campaign of Venus [3–5] performed by the first and second authors of the present paper (Können and Tinbergen). The campaign required daytime operation of the telescope. Around midday of 22 June, we (Können and Tinbergen) pointed the telescope to Sirius for a daytime zero-point polarization [6] calibration of the equipment. The sky was clear, but the ocean was covered with many cumulus clouds having their tops at the subtropical inversion layer, which was, according to the 12:00 UTC Tenerife upper air sounding of that day, at pressure level 810 hPa (hence 1850 m above sea level), and therefore 500 m below the level of the observatory. Sirius was, on that day, only 10 days before its conjunction with the Sun and was therefore almost straight under the Sun (Table 1). The angular separation
between the Sun's center and Sirius was 41.2°, which is one degree above its theoretical minimum separation.

At 11:53 UTC we decided to try to spot Sirius with the naked eye by looking along the 4 m long finder of the main telescope. We knew exactly where to locate the star with respect to the finder, as we had done it many times before with Venus. With Tinbergen staying behind the controls of the telescope, Können (43 years old at the time) and the late La Palma staff member Roy Wallis (then 54 years) looked for Sirius. Both of them saw Sirius, but it was difficult; as Wallis put it during his attempt: "It comes and it goes." These visual observations took place between 11:53 and 12:11 UTC.

Immediately after these visual observations, we began the (daytime) instrumental observation on Sirius with the 12-channel multi-purpose fotometer (MPF) multiwavelength photopolarimeter [3,7] mounted behind the 1 m Jacobus Kapteyn Cassegrain Telescope (Fig. 1). The direct star observations were bracketed between two sky observations, taken at a distance of 1.5 arcmin from Sirius, at right angles to the direction of the Sun [3]. Fortunately, the raw observations are still preserved and yield the sky polarization at the location of Sirius 7 min after the visual observations (at 12:18 UTC) for eight wavelengths between 402 and 850 nm, four of them observed twice for redundancy (Table 2). The observed degrees of polarization have accuracies between 0.1% and 0.2%, depending on the channel. The plane of polarization was found within the 0.5° accuracy of the measurements to be perpendicular to the scattering plane with no perceptible wavelength dependency. The next sky observation (12:25 UTC, 14 min after the visual observation) showed stability in the degrees of polarization as a function of wavelength with a slight (0.4%) increase in the overall degree of polarization. This suggests sufficient stability of the optical properties of the atmosphere on the 14 min timescale and thus representatively of both measurements for the state of polarization during the visual Sirius observations.

The observed degree of polarization of the sky is wavelength dependent, and the values are considerably lower than expected for pure Rayleigh scattering at 41.2° from the Sun, which would be 28%. Part of the reduction in polarization occurs because of the (unpolarized) reflection from the underlying surface, but as a whole the lowering in polarization is indicative of the presence of micrometer-sized dust particles in the air—not very surprising given the proximity of La Palma to the Sahara and the meteorological situation in the days preceding the observations, with a persistent blocking depression with its center between southwestern Spain and La Palma.

Fig. 1. Multichannel photopolarimeter used for measuring the sky polarization was mounted behind the 1 m Jacobus Kapteyn Telescope at La Palma. As the primary objective of our campaign required daytime observations of Venus down to a Sun separation of 13°, we mounted baffles and screens on the east side of the telescope to shield its primary mirror from direct and singly reflected sunlight [3–5].

Table 2. Observed Sky Polarization near Sirius (41.2° from the Sun)

MPF Channel No.	Wavelength/FWHM	Degree of Polarization (%) 12:18 UTC	12:25 UTC
4	850/30	5.53	5.81
1	791/10	6.31	6.76
5	791/10	6.26	6.66
3	712/10	7.20	7.80
2	622/10	8.24	8.71
6	622/10	7.96	8.62
9	542/10	8.30	8.65
8	448/10	10.62	11.04
11	448/10	10.48	10.76
7	441/10	10.76	10.98
10	441/10	10.77	11.25
12	401/10	12.10	12.56

3. Sky Radiances Inferred from Polarization Data

We evaluated the sky polarization data with a radiative transfer model. The model used is the doubling-adding KNMI (DAK) model [8,9]. The DAK model is suited, for solar elevations $>5°$ [10], to calculate under daytime conditions the multiple scattering of polarized light in the Earth's atmosphere. It takes into account Rayleigh scattering, aerosol scattering and absorption, and reflection by the Earth's surface. A recent application of DAK to explain polarization measurements of skylight was described by Boesche *et al.* [11]. In our evaluation, we used the aerosol optical thickness (AOT) and the surface albedo (A_s) as tuning parameters. The aerosol properties in the calculations were chosen to be those of the LOWTRAN 7 tropospheric aerosol, which implies depolarizing scattering and an optical thickness that is dependent on wavelength [12].

The observed spectral dependence of the degree of polarization at the position of Sirius from 12:18 to 12:25 UTC (Table 2) could be reproduced with the model if fed with a surface albedo of 0.35 and an aerosol optical thickness (vertically over the observatory) of 0.04 at 550 nm wavelength. Figure 2 shows the fit. For comparison, two other fits are included: for AOT = 0 (no aerosols) and $A_s = 0.35$, and for AOT = 0.04 (aerosols present) and $A_s = 0.05$ (representative of a dark sea surface). These two curves demonstrate, respectively, that the spectral dependence of the polarization cannot be simulated without aerosols and, on the other hand, that an appropriate value of A_s is needed in order to get the degree of polarization correct.

The thus-obtained value of the surface albedo is consistent with the partially clouded state of the ocean. The aerosol optical thickness of 0.04 at 550 nm seems realistic for a clear atmosphere above the atmospheric boundary layer. It is consistent with the AOT value of 0.03 at 550 nm that Knap *et al.* [13] found to be typical for fine days at the Jungfraujoch Observatory (3580 m above mean sea level). This clear though not excellent condition of the atmosphere is consistent with our subjective impression during the Sirius sightings.

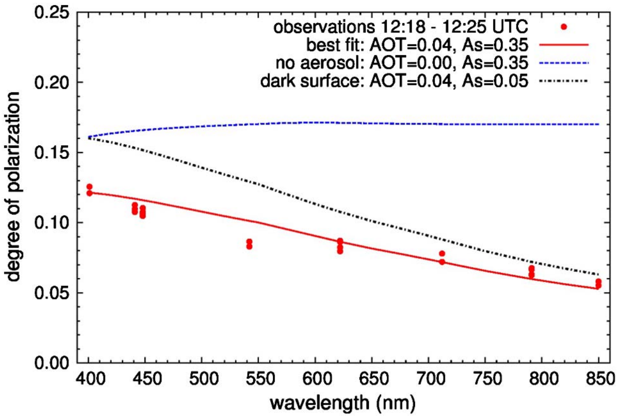

Fig. 2. Fit (solid line) of the sky polarization observations near Sirius (dots) with the radiative transfer model DAK. Fitting parameters are the aerosol optical thickness (AOT) and the surface albedo (A_s). A LOWTRAN 7 aerosol is assumed. The best fit with the data is obtained for AOT = 0.04 and $A_s = 0.35$ (values for 550 nm). The error bars in the individual data points (~0.0015) are too small to be shown in this plot. The two dashed lines demonstrate that AOT and A_s are both needed for obtaining a good fit to the observations.

From the empirically obtained values AOT = 0.04 and $A_s = 0.35$, the sky radiance as a function of wavelength can be calculated by the DAK model for any position in the sky during the La Palma observation. The result is given in Fig. 3. The sky radiance in the figure is expressed relative to the solar irradiance at the top of the atmosphere. The absolute radiance in a given wavelength interval (in $\mathrm{Wm^{-2}\,sr^{-1}}$) can be found by multiplying the values at the y axis (which are in $\mathrm{sr^{-1}}$) by the top-of-atmosphere solar irradiance (in $\mathrm{Wm^{-2}}$) in that wavelength interval.

The Rayleigh optical thickness for a 550 nm wavelength (0.0971 for unit air mass [14], so 0.0728 at the 760 hPa pressure level) indicates that the total optical thickness is 0.11. Therefore, the simulation implies that for 550 nm, 35% of the sky radiance could be attributed to scattering by aerosols and

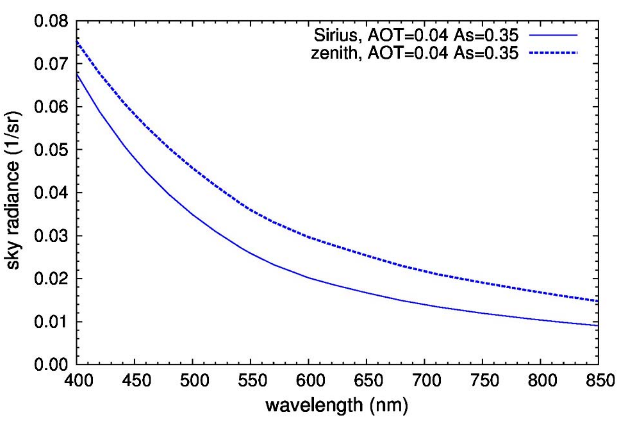

Fig. 3. Sky radiance at the La Palma site during the observation as a function of wavelength at Sirius's position (solid) and at the zenith (dashed), as calculated with DAK for AOT = 0.04 and $A_s = 0.35$ (values for 550 nm), which are values empirically obtained from the sky polarization data near Sirius (Fig. 2).

65% originates from Rayleigh scattering. This means that the sky at Sirius's location is 1.5 times brighter than it would have been for a pure Rayleigh atmosphere. DAK calculates at 550 nm the sky radiance at Sirius's position to be 0.02693 sr^{-1} per unit solar irradiance at the top of the atmosphere. Due to the uncertainty in the atmospheric input data (especially AOT), there is an uncertainty in the radiance estimations of order 10%, which corresponds to 0.1 on the stellar magnitude scale.

4. Zenith Visibility of Sirius at Sea Level

Our visual Sirius sighting applies to a Sun elevation of 73°, the star almost directly below the Sun at elevation $h_0 = 37°$, a pressure level $p_0 = 760$ hPa, and, as calculated in Section 3 for 550 nm, $\mathrm{AOT}_0 = 0.04$ and $A_{s0} = 0.35$. The subscript zero is added here to these symbols to indicate that these are the observational values, as taken in La Palma. We take the luminosity of Sirius under these observational conditions as a standard for the threshold of marginal visibility for a point source against the sky. This threshold is denoted by m_0 and is expressed here on the stellar magnitude scale.

Under daylight conditions and twilight conditions, the increase in limiting magnitude m_{Lim} of a stellar object expressed in the logarithmic stellar magnitude scale is proportional to the increase in background sky radiance $m_{\mathrm{background}}$, if the latter is also expressed on the stellar magnitude scale. The relationship is given by [15–17]

$$\Delta m_{\mathrm{Lim}} = 0.84 \Delta m_{\mathrm{backgound}}. \qquad (1)$$

In the transformations that follow below, we ignore the wavelength dependency of the response of the eye by performing the calculations for a wavelength of 550 nm. Then, with Eq. (1), the threshold for marginal visibility as a function of sky radiance R is

$$m_{\mathrm{threshold}}(R) = m_0 - 0.84 \times 2.5 \times \log_{10} \frac{R}{R_0} \qquad (2)$$

The measured apparent magnitude of a star m_{star} depends on the atmospheric attenuation, which is a function of the elevation h of the star, AOT, and the height of the observer above sea level, which we express with pressure level p ($p = 1013$ hPa at sea level). Denoting the difference in apparent stellar magnitude under equal conditions between the star under consideration and Sirius by Δm, the relation between m_{star} and m_0 becomes

$$m_{\mathrm{star}}(p, h, \mathrm{AOT}) = m_0 + \Delta m - 1.0857 \times \left[\frac{760(\mathrm{ROT} + 0.04)}{1013 \sin(37°)} - \frac{p(\mathrm{ROT} + \mathrm{AOT})}{1013 \sin(h)} \right], \qquad (3)$$

where ROT is the optical thickness for the unit air mass of an idealized Rayleigh atmosphere, which is 0.0971 for a 550 nm wavelength, and 0.04, 760 (hPa), and 37° are the values of AOT_0, p_0, and h_0, respectively, during the La Palma observation. The number 1013 is the atmospheric pressure (in hPa) at sea level. For Sirius $\Delta m = 0$; e.g., for Canopus (a −0.72 magnitude star) $\Delta m = 0.75$, as the (unattenuated) apparent stellar magnitude of Sirius is −1.47.

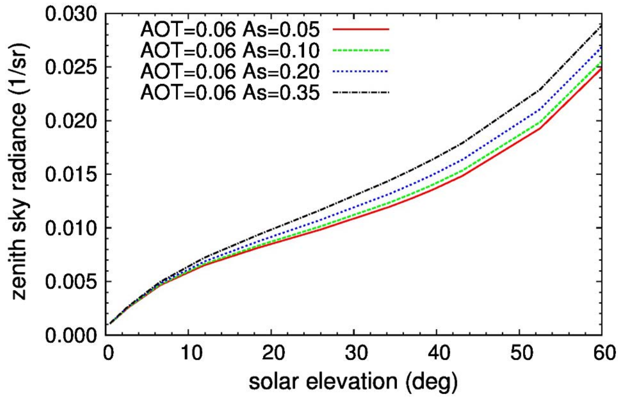

Fig. 4. Zenith radiance for aerosol optical thickness AOT = 0.06 and various values for surface albedo A_s. Values are for sea level and 550 nm wavelength.

In the calculation of the values of m_{star} and $m_{\mathrm{threshold}}(R)$ for sea level, we apply a value of AOT = 0.06 to account for the likely higher concentration of aerosols in the lower atmosphere. This value emerges from a linear extrapolation of AOT_0 from La Palma to sea level, resulting in $\mathrm{AOT} = 1013/760 \times \mathrm{AOT}_0$. An AOT value of 0.06 at sea level represents circumstances of very good visibility [14] and occurs in Europe during the advection of polar air masses. For A_s we take a value of 0.10, which is a representative value of the albedo of vegetated land at 550 nm [18]. Figure 4 shows, for fixed AOT = 0.06, the effect on the zenith radiance of a different choice of A_s; Fig. 5 shows, for $A_s = 0.10$, the effect on the zenith radiance of a different choice of AOT.

Figure 6 shows the result of the calculation of $m_{\mathrm{threshold}} - m_{\mathrm{star}}$ for a star as bright as Sirius

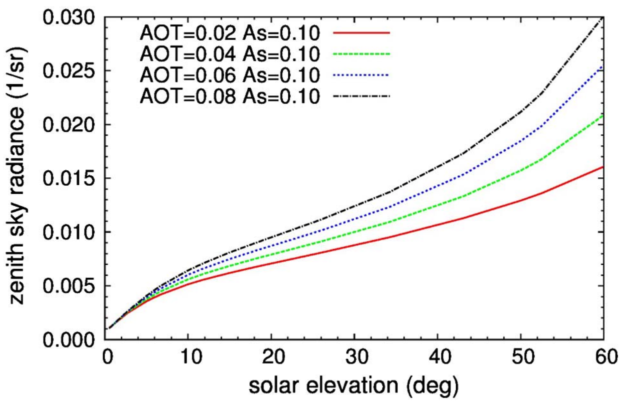

Fig. 5. Zenith radiance for surface albedo $A_s = 0.10$ and various values for aerosol optical thickness AOT. Values are for sea level and 550 nm wavelength.

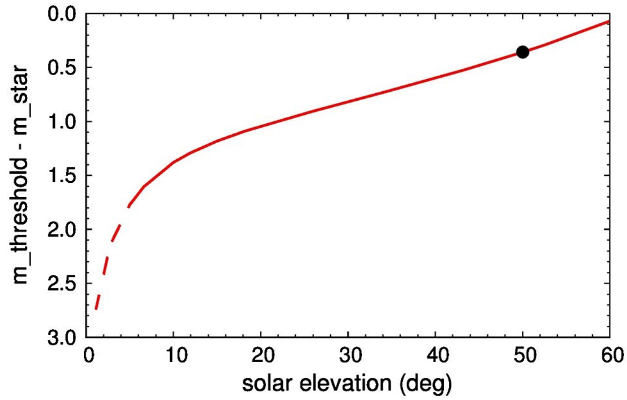

Fig. 6. Visibility from sea level of a zenith star as bright as Sirius [$\Delta m = 0$ in Eq. (3)] as a function of Sun elevation, calculated for AOT $= 0.06$ and $A_s = 0.10$. Note the inverted scale: the low values of $m_{\mathrm{threshold}} - m_{\mathrm{star}}$, on the right-hand side of the curve correspond to a bright background. A positive value of $m_{\mathrm{threshold}} - m_{\mathrm{star}}$ means that the visibility is better than for Sirius during our La Palma observation, and that a star that is by $m_{\mathrm{threshold}} - m_{\mathrm{star}}$ magnitudes less bright than Sirius would have the same visibility as Sirius had during our La Palma observation. The dashed part of the curve indicates the region where DAK tends to underestimate the sky radiance [10]. The dot is for the maximum possible sun elevation if Sirius is overhead.

($\Delta m = 0$) positioned at the zenith, as a function of solar elevation for an observer at sea level. Table 3 shows, for a solar elevation of 50°, the sensitivity of the result to variations in AOT and A_s. If $m_{\mathrm{threshold}} - m_{\mathrm{star}} > 0$, then Sirius, if located at the zenith, is more easily observable than during our visual observation at La Palma. Figure 6 shows that this is the case for the entire solar elevation range shown [0°, 60°]. Similarly, a point of value $m_{\mathrm{threshold}} - m_{\mathrm{star}}$ in Fig. 6 implies that a zenith star that is $m_{\mathrm{threshold}} - m_{\mathrm{star}}$ less bright in stellar magnitude than Sirius would have the same visibility as Sirius had during our La Palma observation.

The ecliptic latitude of Sirius is −40°. Hence, if Sirius is positioned at the zenith, the maximum elevation of the Sun is 50°. Figure 6 and Table 3 show that even in that most unfavorable case, Sirius would be more observable than during the La Palma observation. This implies that Sirius can be visible from sea level in broad daylight assuming clear skies with Sirius positioned overhead, even if the culmination of Sirius takes place at solar noon.

If we assume that the Sirius sighting at La Palma represents a star observation exactly at the limiting magnitude under optimal conditions, then Table 3 implies at sea level and Sun elevation 50° a zenith limiting magnitude of about −1.2.

Table 3. Visibility of Sirius from Sea Level during the Daytime for Various Values of AOT and A_s[a]

AOT	A_s	R/R_0	$m_{\mathrm{threshold}} - m_{\mathrm{star}}$
0.04	0.35	0.69	0.38
0.06	0.35	0.79	0.23
0.08	0.35	0.90	0.10
0.04	0.10	0.59	0.55
0.06	0.10	0.69	0.36
0.08	0.10	0.79	0.21

[a]Sirius is assumed to be at the zenith, with a solar elevation of 50° placing the Sun at its greatest elevation for a zenithal position of Sirius. R/R_0 is the sky radiance relative to that at the Sirius observation. A positive number in the last column indicates a better visibility than during our Sirius observation at La Palma.

5. Discussion

Our observation indicates that the traditional claim [16,19] that "no star may be seen from sea level during daylight hours without optical aid, except perhaps in very unusual circumstances" can be significantly relaxed: Sirius can be seen not only near sunrise [1] but even at solar noon in broad daylight. The latter conclusion is supported by an observation by Sampson and his students [20] in Willimantic, Connecticut (100 m above sea level), of Jupiter at elevation 60° and at 68° from the Sun in full daylight (solar elevation 42°). The brightness of Jupiter during Sampson's observation (magnitude −1.7) was only 0.2 magnitude greater than Sirius.

An important feature about observing stars in the daytime is the necessity to look almost exactly at the star in order to see it. One reason is that the limiting magnitude of photopic vision decreases linearly and rapidly with distance from the center of field of the human eye: at 2° from the center the limiting magnitude has worsened by 1 magnitude; at 4° by 2 magnitudes [16]. This means that for an unintentional sighting, a star should be roughly 2 magnitudes brighter than the limiting magnitude. Venus meets this requirement, but for Sirius there is little hope for an unprepared sighting. A further obstacle for daylight detection is that it is often hard to keep the eyes focused on infinity with no other objects in the air [1,16]. Neither the moon nor a bright planet can act as an orientation point for finding Sirius, as they can never be close to Sirius.

Therefore, star observations in the daytime require thorough preparation. The Jupiter observation by Sampson [20] took place when Jupiter was at less than 0.15° from the cusp of the moon (moon in waning crescent fraction illuminated $k = 0.31$ instead of 0.5 as suggested by Sampson's Fig. 1). A main factor of his observational success was the proximity to the moon, which helped to precisely locate Jupiter and to focus the eye on infinity (see also Appendix A).

Our visual observations indicate a better limiting magnitude than Henshaw's observations imply. For him, Sirius was straight overhead while he and his colleague lost sight when the Sun had risen more than 4.5° above the horizon. With the DAK model (assuming surface albedo A_s 0.10 and aerosol optical thickness AOT 0.06, and a pressure level of 890 hPa), we calculate that $m_{\mathrm{threshold}} - m_{\mathrm{star}}$ at Henshaw's altitude and a solar elevation of 4.5° is 1.5 stellar magnitudes higher than for sea level and a solar elevation of 50°.

Our calculations suggest that even Canopus (magnitude −0.71), if situated at the zenith, may be a daytime object, even at solar noon. This is partly by virtue of its high ecliptic latitude (−76°), which causes the Sun's height to be maximally 14° if Canopus is at the zenith. Then, for Canopus ($\Delta m = 0.75$) seen from sea level, $m_{\text{threshold}} - m_{\text{star}} = 0.5$ (Fig. 6), so its visibility would be comparable with that of Sirius for a Sun elevation of 50° (see Fig. 6). A practical problem is that a near-overhead passing of Canopus (declination −52°) occurs between latitude circles of, say, 40° S and 60° S, a sparsely populated region on Earth with much more sea than land. It seems therefore unlikely that an attempt will soon be undertaken to confirm its visibility during full daylight.

6. Conclusions

It appears from the preceding analysis that Sirius may be more easily visible in daytime than previously claimed. In our case two middle-aged persons (43 and 53 years old) managed to see the star in full daylight. The observation, taken from a 2370 m high mountain, indicates that Sirius, if situated at the zenith, could have been visually observed from sea level by the same people in full daylight if they knew exactly where to look. Normal age-related deterioration in visual acuity suggests that younger observers may be more successful. The analysis of the La Palma observation suggests that Canopus, when situated at the zenith, may also be a daytime naked-eye object even at solar noon.

The sky radiances used in the calculations were not recorded directly but were determined from a high-precision multiwavelength polarization measurement at one spot in the sky by fitting the polarimetric data to the DAK radiative transfer model. This method thus provides absolute values of the radiance from measurements of the degree of polarization, the latter being by definition a relative measure. A similar technique is in development to interpret the data from the iSPEX citizen science experiments [21], for which several thousand participants carry out spectropolarimetric measurements with their smartphones. The current paper demonstrates the potential of the method.

Appendix A: Regulus/Venus at Dawn

On 3 Oct 2012 around 08:00 UTC a very close Venus–Regulus conjunction (minimum separation 7′) took place. This event offered an opportunity to investigate how long Regulus (magnitude + 1.35) remains visible around sunrise. Venus (magnitude −3.6) acted as a perfect orientation point for searching for nearby Regulus. A call went out to the Chapter 't Gooi of the Royal Netherlands Association for Meteorology and Astronomy. Because of clouds, only one respondent (H. Keuning, then 60 years old) was able perform the observation. Sunrise at his position (52.29° N, 5.26° E) was at 05:44 UTC with Venus/Regulus at an elevation of 34° and at an azimuth of 23° S with respect to the Sun. The rising Sun remained hidden behind a frontal cloud deck at a 200 km distance. This front had passed the site at 00:00 UTC and, according to the De Bilt 00z radiosonde data, had its cloud tops at 8 km, hence obscuring around sunrise the first 1.5° above the observer's horizon. After the frontal passage there was a strong southwest airflow over the site (20 m/s on 06:00 UTC) advecting maritime polar air masses. Between the fast-moving clouds, the sky was clear and Venus/Regulus became visible from time to time. No instrument besides a 55 cm long cardboard cylinder of 6 cm diameter was used by the observer. At three instances Regulus (8′ from Venus) was successfully spotted with the naked eye, albeit with increasing difficulty: at 05:15 UTC (Sun elevation [astronomical refraction included, where appropriate] −5.2°), 05:25 UTC (−3.7°), and 05:50 UTC (+0.7°). Remarkably [22], the 05:25 and 05:50 UTC observations were only successful when Keuning looked through the cylinder.

These observations suggest that Regulus may be a naked-eye object until just after sunrise. However, it may have been possible only because most of the sunlight that normally illuminates the atmosphere was blocked by the extensive cloud deck of the receding front, resulting in an exceptionally dark blue sky over the site. More observations under similar conditions are needed to confirm the conclusions of this single-person observation. Narrow Venus–Regulus conjunctions recur every 8 years under almost identical circumstances; the next occasions are on 2 Oct 2020 (minimum separation 5′), 2 Oct 2028 (3′), etc.

This article is a tribute to the late Jaap Tinbergen (1934–2010), a leading expert in astronomical polarimetry [23]. The Jacobus Kapteyn Telescope is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

†Gunther P. Können is retired.
‡Jaap Tinbergen is deceased since 2010.

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