Mon. Not. R. Astron. Soc. **322**, 201–205 (2001)

Optimizing background-limited observing during bright-Moon phases and twilight

I. K. Baldry★ and J. Bland-Hawthorn
Anglo-Australian Observatory, PO Box 296, Epping, NSW 1710, Australia

Accepted 2000 October 9. Received 2000 October 9; in original form 2000 July 28

ABSTRACT

For the majority of optical observing programmes, the sky brightness provides the fundamental limit to signal detection such that the scientific feasibility is largely dictated by the phase of the Moon. Since most observatories do not have the resources to build expensive high-resolution or infrared instruments, they are increasingly at a loss as to how to exploit bright time. We show that, with due consideration of the field and Moon position, it is possible to undertake 'dark-time' observing programmes under 'bright-time' conditions. Our recommendations are particularly appropriate to all-sky survey programmes.

In certain instances, there are gains in observing efficiency with the use of a polarizer, which can significantly reduce the moonlight (or twilight) sky-background flux relative to an extraterrestrial flux. These gains are possible in background-limited cases because the sky background can be highly polarized, caused by scattering, around 90° away from the Moon (or Sun). To take advantage of this, only minor modifications to existing instruments are needed.

Key words: instrumentation: miscellaneous – methods: observational.

1 INTRODUCTION

To make effective use of bright-time, ground-based optical telescopes are generally used to observe either sufficiently bright objects in the optical ($V \lesssim 18\,\mathrm{mag\,arcsec^{-2}}$) or to observe in the near-infrared. In the first case, this is to avoid being background-limited by the moonlit sky, and in the second case, the sky background is dominated by OH line emission[1] or thermal emission from the sky and telescope. For many telescopes, the observatory budget does not extend to expensive high-resolution optical spectrographs or infrared instruments that are suitable for bright-time observations. Some of these telescopes have formed consortia that span the globe to undertake monitoring of variable sources (e.g. pulsating stars, microlensing events, asteroids).

In this paper, we look at strategies for observing during bright time that allow background-limited objects to be observed with higher efficiency. We also look at the possibility of improving observations during twilight. In the optical, the moonlit sky is generally darker along sightlines at large angles from the Moon. Additionally, when the Moon is near 90° away, the scattered moonlight is highly polarized. By using a polarizing filter oriented at the correct angle, the sky background can then be reduced to near-dark or grey conditions.

The degree of polarization can be defined as

$$P = \frac{I_\mathrm{p}}{I_\mathrm{p} + I_\mathrm{u}} \quad \text{or} \quad \frac{I_1 - I_2}{I_1 + I_2}, \tag{1}$$

where I_p is the polarized intensity and I_u is the unpolarized intensity, or I_1 is the maximum intensity as measured in one plane of polarization and I_2 is the intensity in the orthogonal plane. Studies of the polarization of twilight (e.g. Coulson 1980; Wu & Lu 1988) have shown that scattered sunlight at 90° has a degree of polarization of about 0.85. Moonlight scattered at 90° could have a slightly higher degree of polarization since the light is partially polarized on reflection from the Moon (e.g. Dollfus 1962).

The next section quantifies observing efficiency for Poisson-noise limited observations, and determines the gain factor when using a polarizer. Sections 3 and 4 discuss observations in moonlight and twilight with and without a polarizer.

2 OBSERVING EFFICIENCY

A figure of merit (proportional to observing efficiency), for a particular instrument observing an object of a certain flux, can be defined as the signal-to-noise ratio squared (R^2) divided by the integration time (t). Ignoring read-out noise, this is given by[2]

$$f = \frac{R^2}{t} \simeq \frac{\epsilon O^2}{O + B_\mathrm{d} + B_\mathrm{m}}, \tag{2}$$

★ E-mail: baldry@aaoepp.aao.gov.au

[1] Note that if the spectral resolution is high enough to observe between the OH lines in the 1–2.2 μm wavelength range, then the background continuum becomes important and dark-time conditions may then be preferable.

[2] Equations (2) and (3) relate to observations where the background can be estimated over many more pixels than the object, otherwise the background is effectively higher (e.g. a factor of 2 in the case of beam switching with fibres).

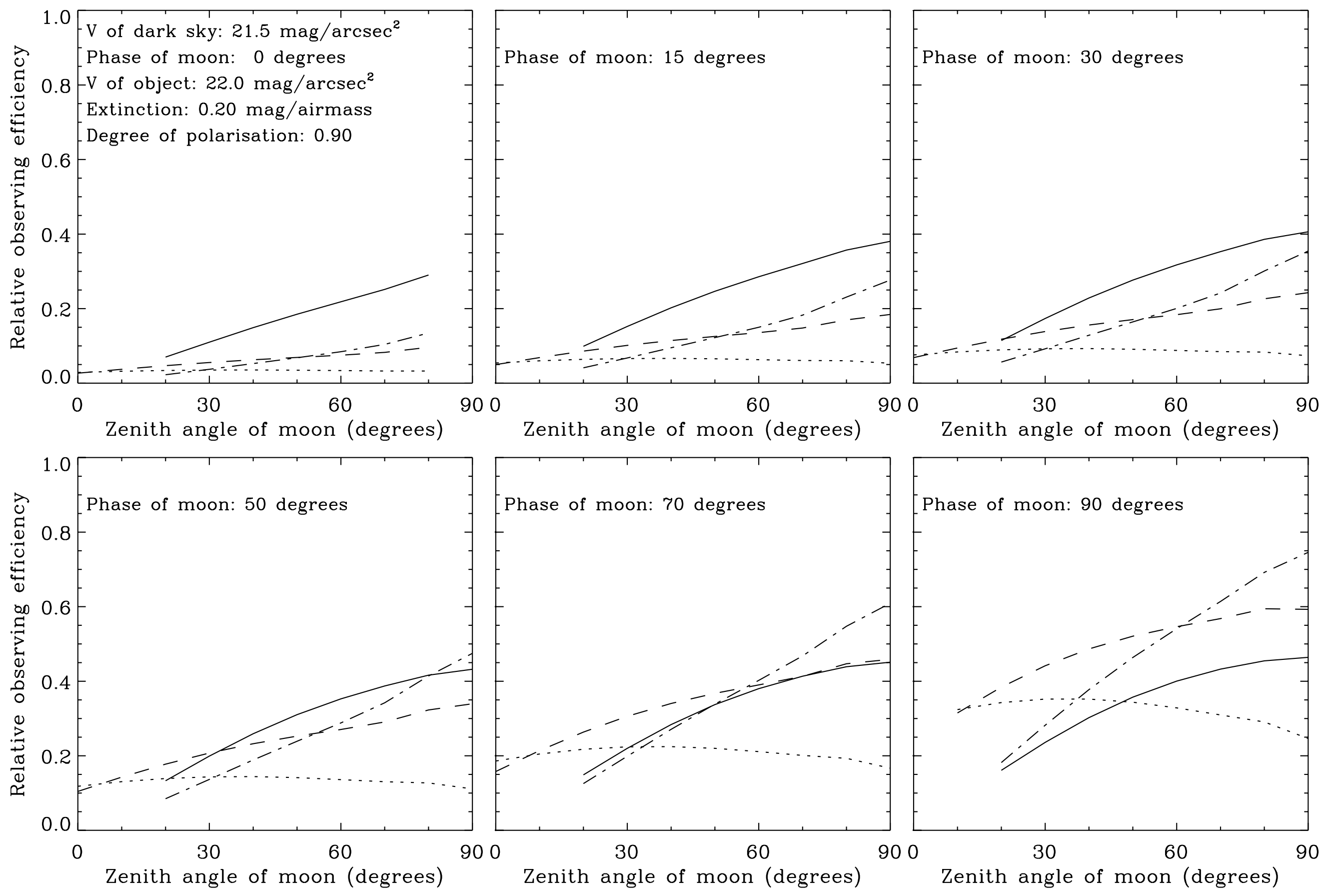

Figure 1. Calculated observing efficiencies at various Moon phases (α) from full Moon to half Moon, relative to dark-time observations at zenith. The dotted line represents observations taken 30° away from the Moon, the dashed line 60° away and the dash-and-dotted line 90° away. The solid line represents observations taken 90° away with a polarizer used to minimize the sky background, assuming the degree of polarization of the moonlight ($P_{\rm m}$) is 0.90 and the transmission of the polarizer (τ) is 0.48 with unpolarized light. The efficiencies are calculated using a model of the brightness of moonlight, described by Krisciunas & Schaefer (1991), and taking into account the extinction of object flux at the lowest possible zenith angle (for each Moon zenith angle and Moon–object separation angle).

where ϵ is the efficiency of the telescope and instrument, O is the object flux on the primary mirror, $B_{\rm d}$ is the background flux owing to the *dark* sky (could also include dark current) and $B_{\rm m}$ is the extra background flux owing to *moonlight* and/or twilight (i.e. $B_{\rm m} = 0$ for dark-time observations).

Assuming the object and dark-sky fluxes are unpolarized and a polarizer is placed in the beam to minimize the extra background flux, the figure of merit is then given by

$$f' \simeq \frac{\tau\epsilon' O^2}{O + B_{\rm d} + (1 - P_{\rm m})B_{\rm m} + 2\gamma P_{\rm m} B_{\rm m}}, \qquad (3)$$

where τ is the transmission of the polarizer with unpolarized light ($\tau \leqslant 0.50$), ϵ' is the efficiency of the telescope and instrument with polarized light, γ is the extinction[3] of the polarizer ($\gamma \ll 1$) and $P_{\rm m}$ is the degree of polarization of the extra light.

The gain in observing efficiency from using a polarizer can be written as

$$\frac{f'}{f} \simeq \tau \frac{\epsilon'}{\epsilon} \left[\frac{O + B_{\rm d} + B_{\rm m}}{O + B_{\rm d} + (1 - P_{\rm m} + 2\gamma P_{\rm m})B_{\rm m}} \right]. \qquad (4)$$

There may also be an extra gain factor owing to an improved duty cycle because the background level is lower and, therefore, integration times can be increased. In most cases, ϵ'/ϵ will be approximately unity[4] and τ will be in the range 0.35–0.48 (Section 2.1). The degree of polarization could be about 0.90 for moonlight scattered from the sky 90° away from the Moon. The extinction should not be a limiting factor with γ in the range 10^{-3}–10^{-2}.

Setting $\gamma = 0$, $\epsilon'/\epsilon = 1$ and rearranging equation (4), we obtain a condition for gains of greater than or approximately unity ($f'/f \gtrsim 1$):

$$(P_{\rm m} + \tau - 1)B_{\rm m} \gtrsim (1 - \tau)(O + B_{\rm d}). \qquad (5)$$

This condition can also be written as

$$(P + \tau - 1)B \gtrsim (1 - \tau)O, \qquad (6)$$

where P is the degree of polarization of the total background flux (B). In other words, $P > 1 - \tau$ and the background flux must be

[3] We define the extinction of a polarizer as the ratio of the minimum and maximum transmissions of polarized light, obtained by rotation.

[4] Some existing spectrographs will have a significantly higher throughput in one polarization state. We also note the possibility of designing a spectrograph to be optimized for one polarization. For example, this is possible using volume phase holographic gratings.

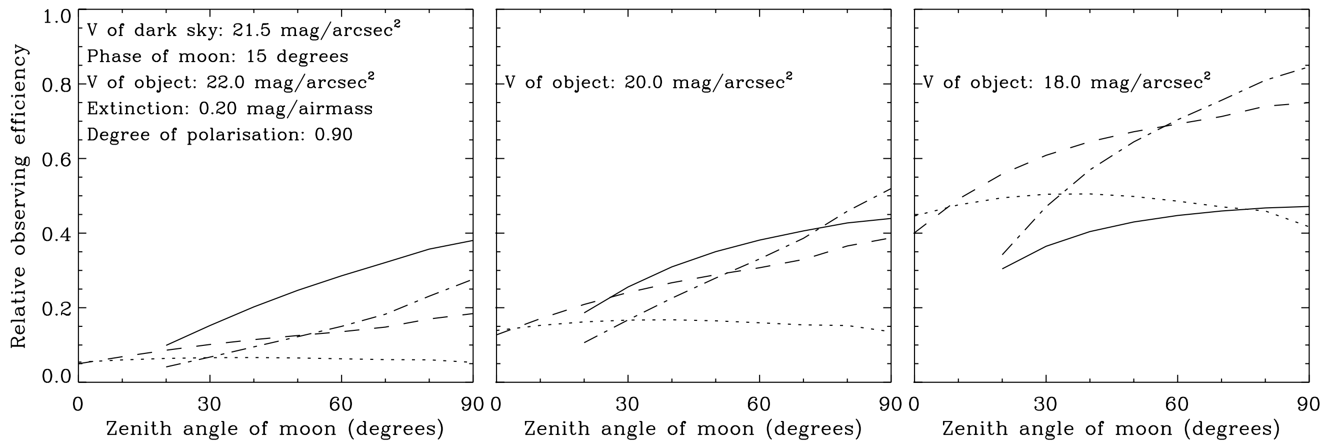

Figure 2. Calculated observing efficiencies near full Moon for objects of 22, 20 and 18 mag arcsec^{-2}, relative to dark-time observations at zenith. See Fig. 1 for details.

high enough for a polarizer to improve observing efficiency. For example, with $P = 0.78$ and $\tau = 0.48$, the background flux must be greater than or approximately twice the object flux.

2.1 Polarizing filters

Normal polarizing filters are notoriously lossy with typical transmissions of 0.70 (one polarization state). However, thin-film polarizers made by 'bleaching' can have transmissions as high as 0.96 (Gunning & Foschaar 1983). Here, a polymerizing sheet is placed in acetone to eat away most of the plastic. The polarizing film is then stretched and deposited over a substrate in a humid oven. Much of the art of bleaching resides in technical reports of the Lockheed Palar Alto Research Laboratory where it was first developed by H. E. Ramsey. When achieving the highest transmissions through bleaching, it is important that the extinction ratio be kept to about 10^{-2} or lower.

3 OBSERVING MOONLIT SKY

To consider the effect of observing objects during moonlit sky, we used the model of moonlight brightness described by Krisciunas & Schaefer (1991). For various Moon phases (α),[5] zenith angles and Moon–object separation angles, we calculated the observing efficiency [using equations (2) and (3)] relative to dark-time observations at zenith. The extinction of object flux was considered in addition to the variation in background flux. Fig. 1 shows the results of these calculations for observations of $V = 22$ mag arcsec^{-2} objects during phases from full Moon to half Moon.

During moonlit bright time ($|\alpha| < 60°$), it is generally more efficient to observe *with a polarizer* than without (on appropriate targets, i.e. background-limited and near 90° separation from the Moon). Remembering that Poisson-noise gains of less than but near unity (equation 4) can provide better observing efficiency if the duty cycle is significantly improved. Additionally, residuals associated with continuum-sky subtraction may be reduced since the relative contribution of the moonlight (solar spectrum) to the overall flux is lower.

During moonlit grey time ($60° < |\alpha| < 120°$), it is generally best to observe without a polarizer on targets that are about 40°–90° away from the Moon.

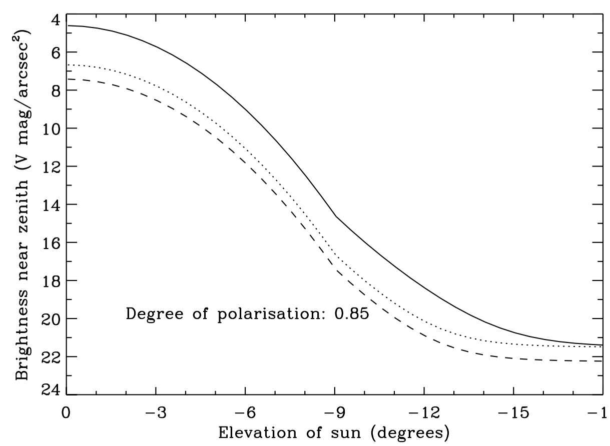

Figure 3. Model brightness of the sky during twilight (with no Moon). The solid line represents the total flux, while the dashed line represents the flux of the minimum-intensity plane of polarization, assuming the degree of polarization of the twilight is 0.85 and the dark-sky contribution is unpolarized. The dotted line is the same, magnitude adjusted by a factor of 2 in flux. The dark-sky brightness was taken as 21.5 mag arcsec^{-2} and the twilight brightness was similar to the model described by Tyson & Gal (1993).

Fig. 2 shows the observing efficiency for various object brightnesses about one day away from full Moon (relative to dark-time observations of the same object brightness). There is some improvement when using a polarizer for objects fainter than about 20 mag arcsec^{-2} at this Moon phase. The brightness for which it is useful to use a polarizer depends on the moonlight, the degree of polarization, the dark-sky contribution, transmission and instrument efficiencies (see equation 5).

4 OBSERVING TWILIGHT SKY

To consider observations during twilight, we produced a model of the twilight brightness based on the work by Tyson & Gal (1993). The sky brightness versus the elevation angle of the Sun is shown in Fig. 3. At sunset, the brightness was assumed to be about 4.5 mag arcsec^{-2} decreasing towards the dark-sky brightness at the end of astronomical twilight, where we assumed that the

[5] The phase α is defined as the angular distance between the Earth and the Sun as seen from the Moon.

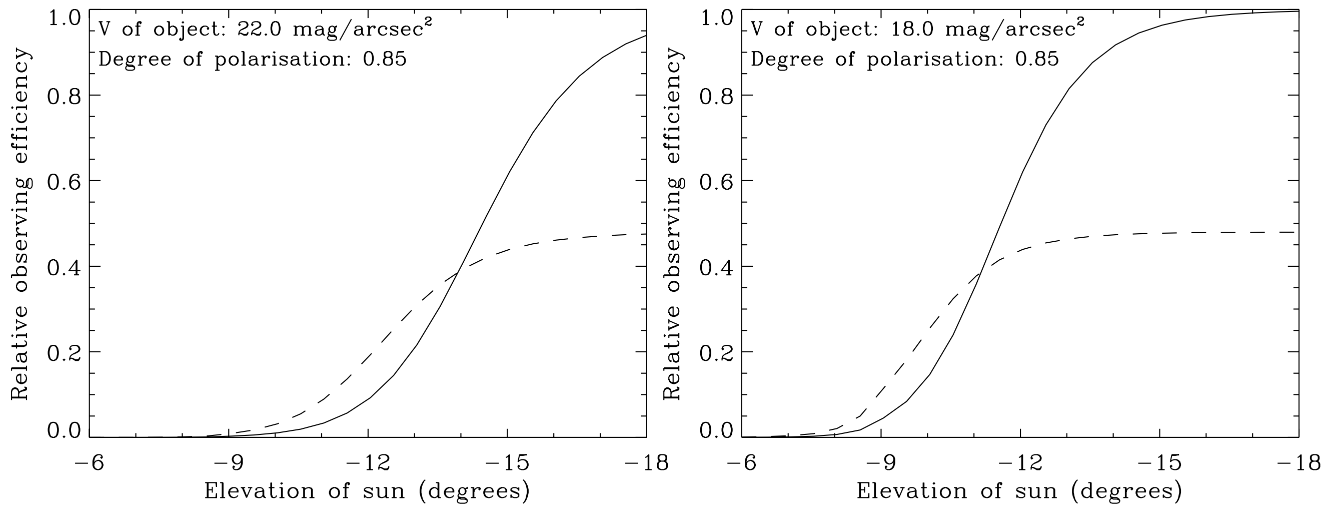

Figure 4. Calculated observing efficiencies during twilight for objects of 22 and 18 mag arcsec^{-2}, relative to dark-time observations at zenith. The solid line represents normal observations near zenith, while the dashed line represents observations taken with a polarizer used to minimize the sky background (Fig. 3).

twilight contribution was 0.1 times the dark-sky contribution. The flux for the minimum-intensity plane of polarization, observing about 90° from the Sun, is also shown.

Fig. 4 shows the Poisson-noise observing efficiencies for two different brightness objects during twilight. There is only a small range in elevation (~2°) where the efficiency is above 0.2 with a polarizer and where the gain is about or above unity (equation 4). Therefore, there is probably little use for this type of technique during twilight, with the possible exception of observing at high-latitude sites, for example, on the Antarctic continent where polarizers could allow observing in much brighter conditions that can last days or weeks. There, they could be used for site testing even if there are no specific science cases for twilight observing. By extension, a polarizer could be used for daytime observations (at any latitude) such as astrometric star or planet measurements (e.g. Rafferty & Loader 1993).

5 DISCUSSION

For effective use of a polarizer to minimize the sky background, it is necessary to be able to rotate the polarizer or the instrument in a short time relative to exposure times. A minor adaption to instruments that are in operation or under design is required, including software to calculate the required rotation angle from the Moon and object celestial coordinates. To check the validity of the setup, the sky flux can be measured at various rotation angles (of the polarizer or instrument) in order to determine the angle that transmits the minimum sky flux.

For observatories that aim to optimize the use of bright-grey time for background-limited observations, observing proposals and telescope schedules need to consider the position of the Moon.

Potentially, the most efficient use of bright-time observing with or without a polarizer will be for those instruments where ϵ'/ϵ can be significantly greater than unity. Equation (4) refers to the gain relative to the average of f over instrument rotation angles. The ability to rotate the instrument independently of the polarizer gives the option to maximize ϵ'/ϵ or, gains can be made without a polarizer just by rotating the instrument so that the background flux is minimized. The factor ϵ'/ϵ could be measured for existing spectrographs, and in the future, spectrographs could be optimized for one polarization state.

Under design at the AAO is a tunable Lyot filter that is phase free over a wide field (Bland-Hawthorn et al. 2001). The Lyot filter requires a single polarization input and therefore such an instrument has effectively $\epsilon'/\epsilon = 2$ at the appropriate polarization angle, i.e. a polarizer is used in any case. Such an instrument could be used during bright-grey time with instrument rotation used to minimize the sky background without loss of object flux.

5.1 Further work

To determine more accurately the gain in using a polarizer, it is necessary for more measurements to be made. These include measurements of the polarization of the moonlight contribution to the sky background, as a function of separation angle from the Moon and as a function of wavelength. This is not straightforward because the moonlight contribution cannot easily be distinguished from the dark-sky contribution. Important questions to answer are: over what range of the sky is it useful to use a polarizer, for example, 80°–100° from the Moon or only 85°–95°; for which broad-band filters is it useful, for example, *BVRIz* or just *V*; in the *RIzJH* bands, how is narrower-band imaging or spectroscopy between the OH emission lines affected; how does the degree of polarization vary with atmospheric conditions?

6 CONCLUSIONS

We suggest that there is a key role to play for telescopes that do not have traditional bright-time instruments. Near all-year-round dark-grey conditions can be obtained for survey work (albeit sometimes at lower efficiency), by consideration of the position of the Moon and the use of a polarizer during bright time. For any telescope, better use can be made of bright-grey conditions with or without a polarizer.

ACKNOWLEDGEMENTS

IKB thanks Tim Bedding and Hans Kjeldsen, and he hopes that this paper does not result in reduced observing time for stellar oscillation studies.

REFERENCES

Bland-Hawthorn J., van Breugel W., Gillingham P. R., Baldry I. K., Jones D. H., 2001, ApJ, submitted
Coulson K. L., 1980, Appl. Opt., 19, 3469
Dollfus A., 1962, in Kopal Z., eds, Physics and Astronomy of the Moon. Academic Press, New York, p. 131
Gunning W. J., Foschaar J., 1983, Appl. Opt., 22, 3229
Krisciunas K., Schaefer B. E., 1991, PASP, 103, 1033
Rafferty T. J., Loader B. R., 1993, A&A, 271, 727
Tyson N. D., Gal R. R., 1993, AJ, 105, 1206
Wu B., Lu D., 1988, Appl. Opt., 27, 4899

This paper has been typeset from a TEX/LATEX file prepared by the author.