An Advanced Scattered Moonlight Model

Amy Jones[1]
Stefan Noll[1]
Wolfgang Kausch[1,2]
Cezary Szyszka[1]
Stefan Kimeswenger[3,1]

[1] Astro and Particle Physics, Leopold Franzens Universität Innsbruck, Austria
[2] Department of Astrophysics, University of Vienna, Austria
[3] Instituto de Astronomía, Universidad Católica del Norte, Antofagasta, Chile

Correcting and predicting the flux coming from the background sky is a crucial aspect of observational astronomy. We have developed a sky background model for this purpose, and it is the most complete and universal sky model that we know of to date. The largest natural source of light at night in the optical is the Moon, and it is a major contributor to the astronomical sky background. An improved spectroscopic scattered moonlight model, which is applicable from 0.3 to 2.5 μm has been developed and studied with a set of FORS1 spectra and a dedicated X-shooter dataset. To our knowledge, this is the first spectroscopic model extending into the infrared and it has been tested for many lunar phases and geometries of the Moon and target observations.

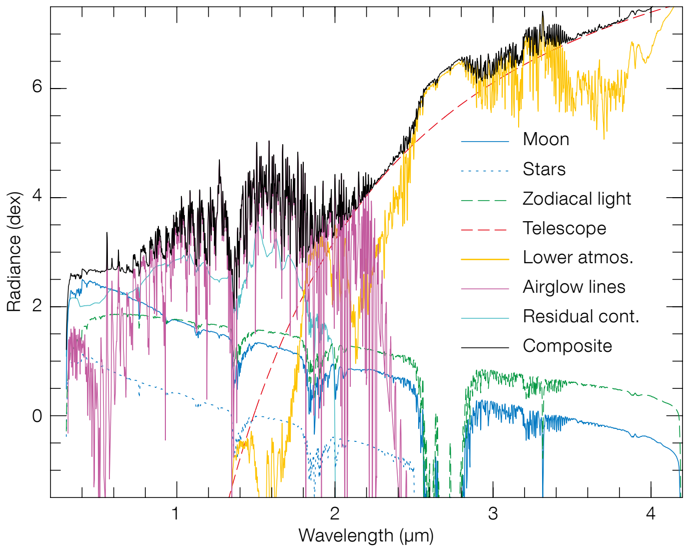

Figure 1. An example of the output from the sky background model of Noll et al. (2012). The output of the sky background model includes an emission spectrum (shown here) and a transmission spectrum. The various components of the sky background model are also shown.

Introduction

The current trend in astronomy is to build larger and larger telescopes, for example the future European Extremely Large Telescope (E-ELT). The operating costs for running these large telescopes are high and careful planning of observations is crucial since telescope time is expensive and always in demand. Thus, more accurate predictions and estimations of the noise coming from the sky background are needed to better understand how long an exposure is necessary for a given observation to reach a desired signal-to-noise ratio. The brightest natural source of light in the night sky in the optical, is the Moon (when it is above the horizon). Even in the near-infrared (NIR), there is some flux from the Moon that should be considered.

As part of the Austrian contribution to ESO, the University of Innsbruck in-kind group developed a spectroscopic sky background model from 0.3 to 30 μm for the Very Large Telescope (VLT) and the nearby future site of the E-ELT, for the ESO Exposure Time Calculator (ETC). The model is described in Noll et al. (2012). An example of an output emission spectrum from our sky background model is shown in Figure 1, and the model is available[1]. Part of this sky background model is an advanced, spectroscopic scattered moonlight model, verified from 0.3 to 2.1 μm. It provides a spectrum of the scattered moonlight, visible at the observer, depending on the atmospheric conditions, the altitude of, and the angular distance between the target and Moon, and the lunar phase and distance.

The long-standing scattered moonlight model used by ESO for the ETC was due to Walker (1987). It provides a table of the magnitudes for five photometric bands of the night sky at five different moon phases. This model is limited when it comes to producing a scattered moonlight spectrum which is accurate enough for current and future telescope operations.

Another, widely used scattered moonlight model was developed by Krisciunas & Schaefer (1991). It again only uses a photometric model based on 33 observations in the *V*-band taken at Mauna Kea (2800 metres above sea level). This empirical fit was separated into various specific functions, such as initial intensity from the Moon, Rayleigh and Mie scattering. It is simple, convenient, and easy to use with an accuracy between 8 and 23 %, when not near full Moon and for *V*-band data from Mauna Kea. In a previous paper (Noll et al., 2012), we presented a spectroscopic extension of the Krisciunas & Schaefer (1991) model, which was originally used in our sky background model. It was optimised for Cerro Paranal and covered the optical regime. Several scaling factors for the different functions were introduced to better fit data from Cerro Paranal.

We have improved the scattered moonlight model and it has evolved beyond the initial ESO ETC application. In the optical, the model was calibrated and investigated with 141 spectra and has an overall uncertainty of $\sigma \lesssim 0.2$ mag. With some dedicated X-shooter observations, we have verified the model in the optical and extended it to the NIR. It has been split into physically based modules which are given by either physical models or the best current fits. The present version is optimised for Cerro Paranal, but can be modified for any location with information about its atmospheric properties. Since our scattered moonlight model produces a spectrum, it can be used for finding spectral features and trends as well as photometric magnitudes.

We will first present the scattered moonlight model in the optical, then the model from the ultraviolet (UV) to the NIR.

Scattered moonlight model in the optical

Scattered moonlight is most influential in the optical. The scattered moonlight model was originally developed, tested, and calibrated in the optical regime with a FOcal Reducer/low dispersion Spectrograph (FORS1) dataset from Patat (2008). We used 141 spectra which had moonlight present and decent weather conditions. For a full description of the model, the data and analysis, see Jones et al. (2013).

The moonlight model is divided into several modules. The first module is the Solar spectrum from Colina et al. (1996) which is the initial source of the scattered moonlight. Then the light is reflected off the lunar surface and for this we use the empirical fit from Kieffer & Stone (2005), which depends on several lunar parameters. This fit was done using narrowband photometry, so we interpolated it as a function of wavelength. We also needed to extrapolate it to a new moon phase. Next the reflected light is scattered and absorbed in the Earth's atmosphere before reaching the telescope.

We have designed fully 3D single and double scattering calculations with an approximation to higher orders. For the scattering we use the Rayleigh approximation for the molecules and Mie scattering for the aerosols. Rayleigh scattering can be well parametrised and the molecules in the atmosphere are fairly stable. On the other hand, Mie scattering can be complicated and the aerosols can vary on timescales of hours. In the optical, an empirical fit was derived from Patat et al. (2011). We decomposed this fit into reasonable aerosol size distributions for a remote continental area, like Cerro Paranal, from Warneck & Williams (2012), by scaling the column density of the various components. Then we used the scaled distributions to produce the Mie phase function (Grainger et al. 2004; Bohren & Huffman 1983).

Altogether we had developed a scattered moonlight model, which is spectroscopic and tested from 0.4 to 0.9 μm. It depends on the altitude of, and the angular distance between the Moon and target, lunar phase and distance and the atmospheric conditions.

Results for the optical scattered moonlight model

We found that the sky background model with the new scattered moonlight model fitted the FORS1 observations well, with an uncertainty of $\lesssim$ 0.2 mag. Figure 2 shows an example of observed data with the scattered moonlight and sky background model overlaid. The model is able to reproduce the observed radiance spectra.

In Figure 3, we show the mean and uncertainty, σ, of the difference between the sky background model and the FORS1 observations. Also shown are the mean and σ for the nights with and without moonlight. The uncertainty increases towards redder wavelengths where the sky emission lines are prominent.

The scattered moonlight model performs better than the previous extrapolated version of Krisciunas & Schaefer (1991), as shown in Figure 4. For this analysis, we took the sky observations and subtracted the other background components using the sky background model. Then we compared these spectra containing only observed scattered moonlight with the scattered moonlight model. The error bars include the errors associated with the other components in the sky background model. This analysis was done for both the new advanced scattered moonlight model and the previous one based on Krisciunas & Schaefer (1991), labelled in the Figure as KS91. The error bars for the new model are consistently smaller, and the mean for all the spectra is closer to zero. For the mean of new scattered moonlight model minus the FORS1 observations to be at zero, we needed to multiply the model by 1.2. We suspect that the uncertainty in the flux calibration of the FORS1 data could significantly contribute to this global scaling factor.

Scattered moonlight model from UV to NIR

We have now extended and verified our scattered moonlight model. With dedicated observations from X-shooter (Vernet et al., 2011), we were able to test the model from 0.3 to 2.1 μm. With the data in the NIR and observations at multiple distances from the Moon, we can better investigate the aerosol scattering and constrain the Mie scattering used in the model.

We have a unique dataset taken with X-shooter for the purpose of verifying and extending our scattered moonlight model (Proposal ID: 491.L-0659) to the NIR. These data include observations of plain sky taken at three different lunar phases (runs a, b, and c) and at six different angular distances (7, 13, 20, 45, 90, 110 degrees) from the Moon. Additionally, the same standard star was observed at two different airmasses for each lunar phase run.

For the analysis we selected certain wavelength ranges, hereafter called inclusion regions. These regions are parts of the spectrum that should be free of sky emission lines and absorption features. The number of pixels per arm are 850, 850, and 653 for the UVB, VIS, and NIR X-shooter

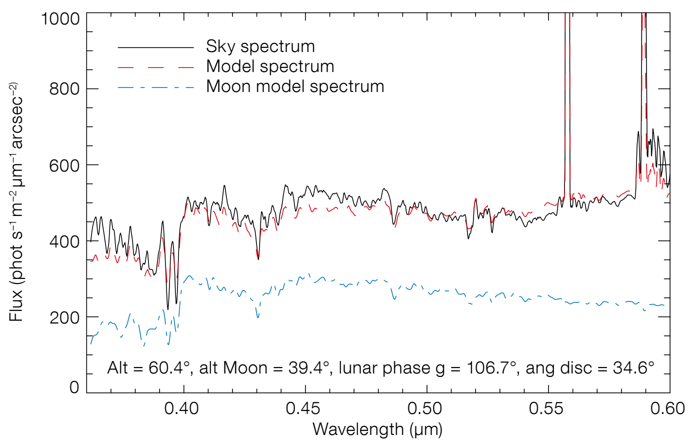

Figure 2. An example of the quality of the sky background model. The observed sky spectrum is shown in black with the full sky background model in red. The scattered moonlight portion of the model is in blue. The model fits the observed spectrum fairly well. This observation was done with moderate amount of moonlight, which comprises roughly half of the overall sky background flux.

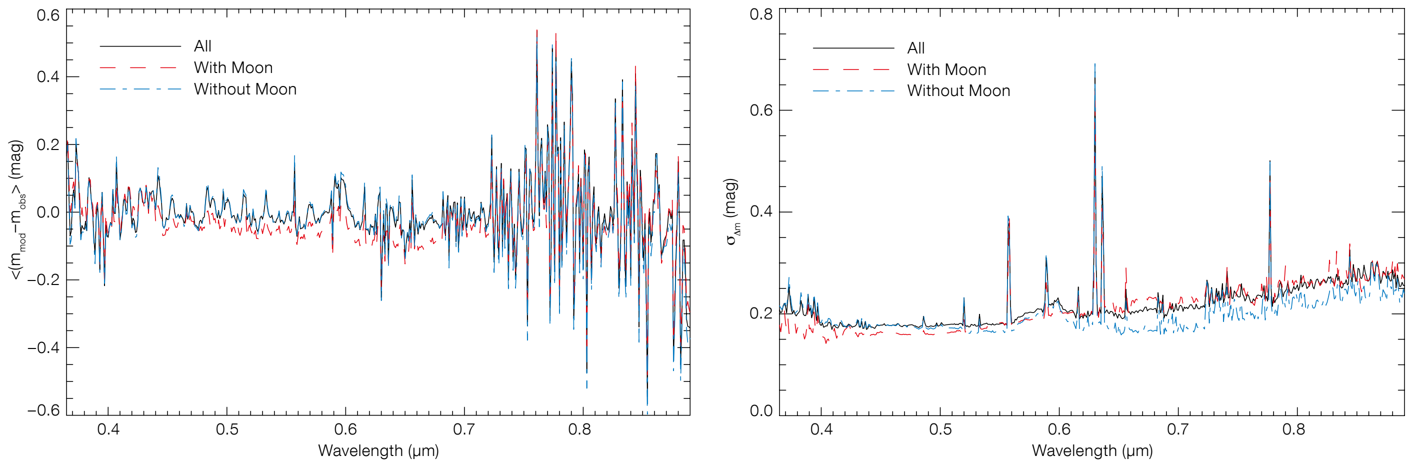

Figure 3. Mean (left) and σ (right) of the difference between the observed FORS1 and modelled spectra for the full sky background of all the spectra, those with moonlight, and only those without moonlight. See text for more details.

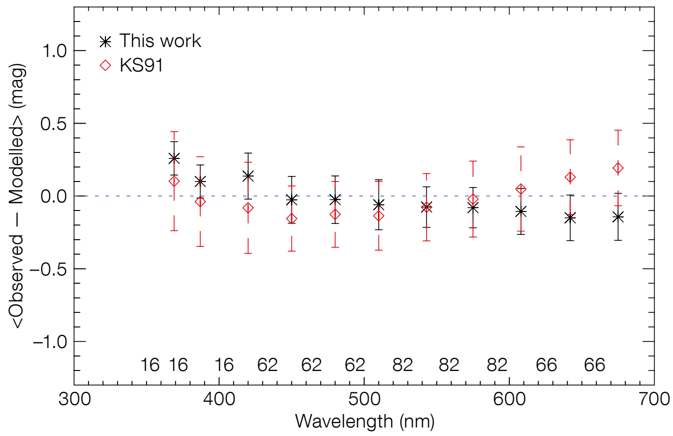

Figure 4. Means and uncertainties for the scattered moonlight model versus observed data at several 4 nm wide continuum bands. The *y*-axis is the average of the observed minus modelled fluxes for data with good weather conditions and a significant amount of moonlight. Over-plotted is the same analysis with the previous model from Noll et al. (2012), based on Krisciunas & Schaefer (1991), and labelled as KS91. The numbers below each point are the number of spectra considered. See the text for more details.

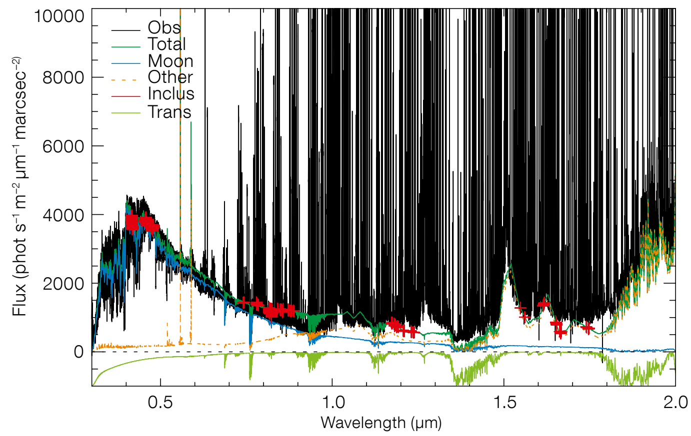

Figure 5. An example spectrum for the scattered moonlight extinction curve determination. The observed spectrum (black) is from run b with offset 45°. Overlaid is an example total sky background model (green) with the sky lines removed for clarity and the inclusion regions for the analysis (pink +). The scattered moonlight model (blue) and the other model components (orange dotted), except the sky lines, are also shown. Below the dotted black line is the transmission curve (light green).

arms, respectively and are non-consecutive. In Figure 5, we show the observed spectrum from run b at 45 degrees; overlaid are the sky background model (without sky emission lines for clarity), the scattered moonlight model, other components (except the sky emission lines) of the sky background model, the inclusion regions and the transmission spectrum.

For the aerosol extinction curve, in the optical, we used a decomposition of the empirical fit found in Patat et al. (2011). With the X-shooter data, we can take a different approach. We use the remote continental tropospheric and stratospheric aerosol size distributions (Warneck & Williams, 2012), and produce a grid of different scalings of the column density for each aerosol type. Then we used these parameters to produce the Mie phase function using an IDL code based on Bohren & Huffman (1983) and Grainger et al. (2004). Each aerosol distribution is approximated as a lognormal distribution described by *n* the number density of particles, *R* the mean radius of the particles, and a parameter *s* which determines the spread in radii of the particles. The default parameters for the various aerosols are listed in Table 1.

Type	n (cm^{-3})	R (10^{-1} µm)	log s (10^{-1})
Trop nucleation	3.20×10^{3}	0.10	1.61
Trop accumulation	2.90×10^{3}	0.58	2.17
Trop coarse	3.00×10^{-1}	9.00	3.80
Stratospheric	4.49×10^{0}	2.17	2.48
Added coarse	1.00×10^{0}	10.0	1.00

Table 1. Aerosol modes.
Note: the values used for Mie scattering of remote continental aerosols are from Warneck & Williams (2012), except for the added coarse mode (see text for details).

The grid is logarithmically spaced, varying the column density for each aerosol type, except for the tropospheric nucleation mode which is negligible and left at 100 %. The column density is directly related to the number density *n*, where we assumed a convenient effective aerosol layer width of 1 km. We also linearly varied the atmospheric refractive index, *N*.

The amount of aerosols can vary each night (e.g., Buton et al. 2013), and so far the full analysis has been done for the one night of run b (23 July 2013). We also performed a similar analysis with the aerosol grid for the spectrophotometric standard star observations taken that night. More details will be given in a future publication (Jones et al, in prep.).

When the sky observation was at close angular distances to the Moon, in particular the 7 and 13 degree offsets, we noticed a significant amount of extra observed flux compared with the modelled flux. We speculate that this could be caused either by some direct moonlight entering the detector or some additional tropospheric coarse mode which would increase the Mie forward scattering. Since we have no control over the first scenario, we explored the likelihood of the second. We added an additional aerosol size distribution for a particle with $R = 1\mu m$ and $\log s = 0.1$, which is optimal for increasing the flux at small angular distances. We also varied the column density of this new mode in the same way as the others (see Table 1).

Results of UV to NIR scattered moonlight model

After analysing the X-shooter observations with the scattered moonlight model for the various aerosol parameters, we have found the model with the highest likelihood. As shown in Figure 6 our model with the highest likelihood matches the data well. Also shown for comparison is the model which is the least likely from our grid. This model, with different amounts of aerosols, does not fit the observations, especially at smaller angular distances. The two spectra with the largest angular distances (90 and 110 degrees) are not very sensitive to the choice of aerosols. The model here reproduces the data, which leads credence to the other parts (non-aerosol scattering) of the model being accurate. By adding in the additional coarse mode, we were not able to successfully reproduce the extra flux seen at 7 degrees (not shown in Figure). Additionally, the spectrum at 13 degrees seems to behave differently than the other spectra analysed. The possibility of having extra flux coming from direct moonlight entering the dome and hitting the detector cannot be excluded. We would like to caution others about observations close to the Moon. Even in the *J*-band, some extra flux is detected.

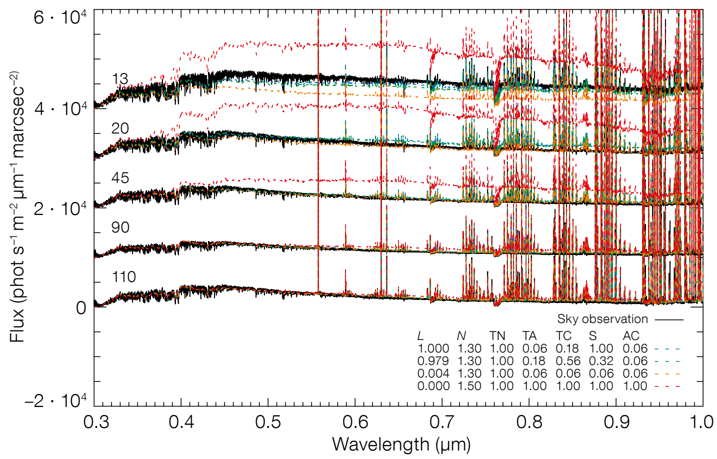

Figure 6. Four examples of how well the sky background model fits the observations. The observations at the five different angular distances to the moon (13, 20, 45, 90, and 110°) are shown, offset in flux for clarity. Overlaid for each are the most and least likely models. The overall likelihood, *L*, the refractive index *N*, and the fractions of column density (n × 1 km) for tropospheric nucleation TN, accumulation TA, coarse TC, stratospheric S, and added coarse mode AC for the different observations are shown in the legend.

Prospects

From the UV to the NIR, our scattered moonlight model seems to fit the observed data well. With the X-shooter data we can better constrain the aerosol scattering. The optical depth of aerosols τ_{aer} for the night of run b is quite a bit lower than the one empirically found by Patat et al. (2011). We deduce that the variation in the amount of aerosols can be large. We plan to extend our study of using the sky background model and archival X-shooter data to investigate the fluctuations in the amount of aerosols present at Cerro Paranal.

Overall, our improved scattered moonlight can well represent the observations. It has now been verified in the optical with FORS1 data and from the UV to NIR with X-shooter data. In addition, we have tested the model for many different lunar phases and at a range of distances between the Moon and target observation. The remaining main source of uncertainty is with the atmospheric conditions.

Acknowledgements

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Links

[1] ESO Exposure Time Calculator sky model: http://www.eso.org/observing/etc/skycalc/skycalc.htm