

Light pollution in Asiago: a spectroscopic perspective

Marco Codato

Master Thesis in Astrophysics and Cosmology

Abstract

Modern sky brightness monitoring techniques aim to precisely measure the total amount of radiation from the observing site but very little can be said about the various sources responsible for such radiation. In this work I will use spectroscopic data to identify the various sources in the sky of the Asiago Observatory, Italy, and study their temporal evolution.

Contents

Abstract	3
1 Introduction	7
1.1 Light pollution	7
1.2 Aim of the work	8
2 The natural sky background	9
2.1 Extraterrestrial sources	9
2.1.1 Zodiacal light	9
2.1.2 Galactic background	11
2.1.3 Diffuse galactic light	11
2.1.4 Extragalactic background	11
2.2 Terrestrial sources	11
2.2.1 Airglow	11
2.2.2 Aurorae	12
2.3 Atmospheric scattering	13
2.3.1 Scattering mechanisms	13
2.3.2 Effects on the sky brightness	14

Chapter 1

Introduction

Part I: Sky sources in theory

- Introduction
 - General introduction
 - Aim of the work
 - About the methodologies
- The natural sky
 - Main natural sources
 - And their footprint on spectra
- The light pollution
 - Definitions and aftermaths
 - Mechanism of working
 - Mention to the models in the literature
 - LP footprint in spectra

Part II: Analysis of sky background in spectra

- Software description
 - Bkg extraction
 - Bkg analysis
- Results
- Discussion and interpretation of the results
- Conclusions

1.1 Light pollution

Light pollution (LP) is the alteration of the natural light level due to artificial sources. The resulting increase of the sky brightness has many proven negative effects.

Effects on the human health. Light exposure in night time decrease the natural production melatonin. The effect is proportional to the frequency of light, with bluer radiation producing a stronger decrease of melatonin production.

Melatonin is an important hormone that regulates many biological mechanisms. It is capable of preventing some forms of cancer and is responsible for the sleep regulation. A melatonin deficiency has been proven to be correlated with higher chances of developing breast and prostate cancers and a decrease of sleep time and quality, which typically lead to further health disorders.

Melatonin decrease is proportional both to light intensity and frequency. A greater effect is given by brighter and bluer sources. In this context the spreading of LED lights, with their strong emissions in the blue side of visible spectrum, is considered a concern by many health associations.

Effects on the environment. LP affects other living beings as well as humans. Animals exposed to abnormal level of light at night change their behaviour and habits. Note this form of pollution is probably the most widespread but yet one of the least acknowledged.

Economical effects. When looking at a artificially bright sky one should consider that such photons that brighten the sky are no longer being used for the purpose they were made for, i.e. lighten streets, houses, commercial areas and so on. The energy, and thus the cost, to produce such photons is wasted.

Unluckily in the last years efficient light sources like LEDs allowed to produce powerful lighting systems at low cost making the economical argument less relevant. Since light is cheaper, it is less critical weather part of it is lost toward the sky.

Cultural effects. All the cultures around the world developed myths and legends involving the heavens; night sky inspired artists and philosophers in western cultures for centuries and in general the observation of a starry sky always belonged to the human experiences. Today due to LP FabbriXX estimates that at least the XX% of the world population lives in areas where milky way is not even visible and only a handful of bright stars can stand out of the polluted sky. In terms of traditions and human experience this is a great loss, but yet difficult, or impossible, to quantify.

Scientific effects. Of course the increase of sky brightness made astronomical observations more difficult. Observation sites moved from the town centres in the XIX century to the rural areas due to the introduction of the first lighting. With the growing urbanization, many of these sites ended up to be at the limb of the expanding urban areas, heavily limiting the possibility of relevant scientific activities. Nowadays it is likely that in a country no totally dark sites are available, forcing astronomers to build new instruments in very remote areas in poorly populated areas of the world.

A typical example of the effects in the changing of the sky condition is the Asiago observatory. It was built in 1942 in a poorly populated highland, which also offered an adequate shielding from the light of the yet small rural centres in the nearby pianura veneta. When built, the observatory also hosted the largest reflecting telescope in the Europe (Gaileo telescope, 122 m of diameter). With the economic boom in the 50s, industrial and manufacturing activities replaced agriculture in the Veneto flatland. Urban areas significantly expanded making Veneto region one of the most light polluted sites in the whole Europe. At the same time the Asiago highland become one of the most appreciated touristic destination in the surrounding area. The quality of the sky rapidly worsened also with respect to other nearby areas less touched by human activities. In such new condition the Asiago Observatory lost its central role in research activities tough preserving its nature of scientific pole.

1.2 Aim of the work

For all the issues above measuring and monitoring the LP is of crucial important.

Chapter 2

The natural sky background

Even when artificial sources are neglected, there are still several natural background sources. In this chapter each contribution will be described in detail. In the plot on the Figure 2.1 are reported, in logarithmic scale, the main background sources for a wide range of wavelengths, from UV to radio emission. In the next lines I will consider only sources relevant for optical observations.

Photons produced by several background sources interact with dusts and aerosols in the Earth atmosphere leading to extinction and diffusion (scattering) phenomena. The total sky brightness can be quantitatively expressed as

$$I_{\text{sky}} = (I_A + I_{ZL} + I_{ISL} + I_{DGL} + I_{EBL})e^{-\tau} + I_{\text{sca}} \quad (2.1)$$

where A stands for airglow, EZ is zodiacal light, ISL integrated galactic light, DGL diffuse galactic light and EBL extragalactic background light. τ is the extinction coefficients and I_{sca} gathers all the scattering terms, i.e. light scattered from previous sources and from light pollution, from [LBH⁺98].

In this chapter I will analyze in detail all the terms of the equation (2.1), their origin and the relevance and characteristic spectral features. At the end I will show and discuss some examples of sky background spectra taken from the literature.

2.1 Extraterrestrial sources

I will first consider sources of photons outside the earth atmosphere. Using space-based instrument it is possible to study these components without the interference of atmospheric emissions.

2.1.1 Zodiacal light

Zodiacal light consists on sunlight scattered by interplanetary dust particles [Lei75]. From the Earth it looks like a white glow visible during the twilight and extending from the Sun in the zodiacal region.

Angular distribution. The figure 2.3, adapted from [FHLT74], describes the angular distribution of the zodiacal light in ecliptic coordinates. Such light is maximum along the ecliptic and close to the Sun. A fainter local maximum is present in direction opposite to the Sun. It is known as *gegenschein* and is produced by back-scattered solar light. Zodiacal light brightness varies from about 10^{-6} erg/s/cm²/sr/Å on the ecliptic at 30° from the sun to about 10^{-9} erg/s/cm²/sr/Å. Gegenschein maximum brightness reaches about 10^{-7} erg/s/cm²/sr/Å. After the airglow (see §XX), this is the second brightest background source in optical bands.

The contribution of zodiacal light to the optical background is maximum during the twilight, after sunset in spring or before sunrise in autumn, from the northern hemisphere.

Spectral energy distribution. Being essentially reflected sunlight, the optical zodiacal light energy distribution has the same shape of the solar one.

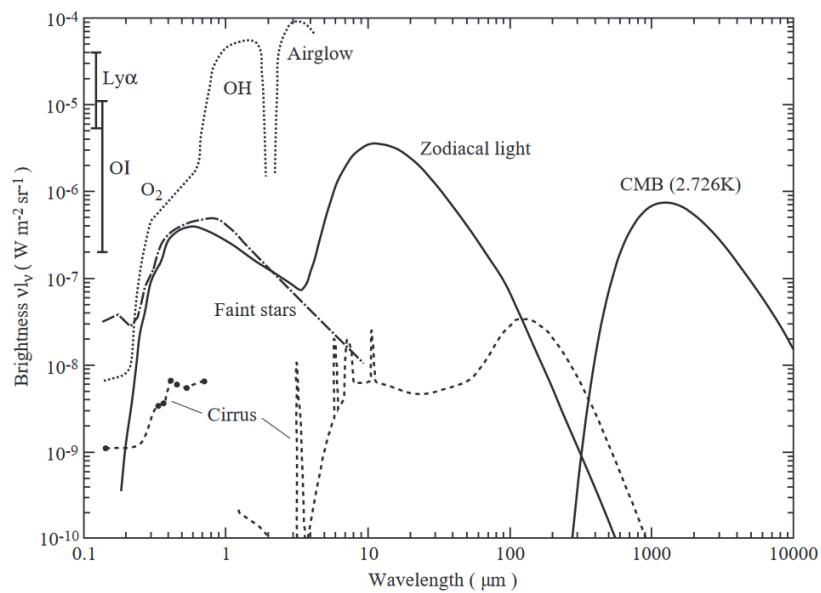


Figure 2.1: Different sky brightness contributions in different electromagnetic domains. In the optical band most relevant contribution are Airglow, zodiacal light and faint stars. From [LBH⁺98].



Figure 2.2: Zodiacal light after sunset at La Silla, Chile. Source: eso.org.

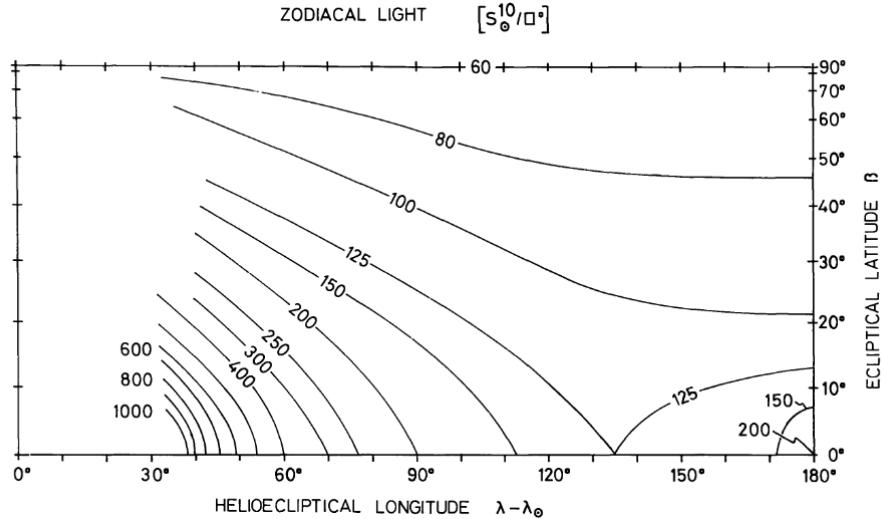


Figure 2.3: Isophotal map of the zodiacal light at 7100 Å. As a reference, according to [LBH⁺⁹⁸], $1 S_{10}^{10}/\Delta^2 = 9.21 \times 10^{-10} \text{ erg/s/cm}^2/\text{sr}/\text{\AA}$ at those wavelengths. From [FHLT74].

2.1.2 Galactic background

In optical bands a significant contribution to the background level is provided by unresolved stars in the Galaxy. The contribution of such sources depends on the ability of resolve the brightest stars [LBH⁺⁹⁸], i.e. on the limiting magnitude of the instrument.

Angular distribution. Unresolved stars background follows the morphological structure of the Milky Way. The signal is higher toward the galactic plane and the galactic center. Its spectrum follows typical optical stellar spectra with the characteristic black-body emission. It is the third most relevant contribution to the optic continuum with an emission that spans from peak values of $10^{-6} \text{ erg/s/cm}^2/\text{sr}/\text{\AA}$ in the most crowded areas to $10^{-8} \text{ erg/s/cm}^2/\text{sr}/\text{\AA}$ toward the galactic poles.

2.1.3 Diffuse galactic light

Similar to the zodiacal light, it is the result of the scattering of stellar emission with interstellar dust particles. [LBH⁺⁹⁸] estimate its contribution as between 20% and 30% of the total integrated light from the galaxy. This estimation is rather uncertain because of the faintness of the radiation and the contamination of direct stellar light. There are no comprehensive maps for the diffuse galactic light but it is very likely this emission to be concentrated along the galactic disk, analogously to the direct stellar component. Its spectral energy distribution is comparable with stellar spectra, since its nature of stellar reflected light.

2.1.4 Extragalactic background

A much smaller contribution is led by the extragalactic background, i.e. emission of faint and or unresolved galaxies. It is very difficult to quantify the resulting brightness and in many cases are available only the upper limits for extragalactic background. The main estimation difficulties are due to the faintness of the signal and with respect to the other sources. Typical values of intensity are of the order $10^{-9} \text{ erg/s/cm}^2/\text{sr}/\text{\AA}$. No reliable information about spatial distribution is available.

2.2 Terrestrial sources

Terrestrial sources are those capable of producing visible photons in the atmosphere.

2.2.1 Airglow

The airglow is the faint emission on the higher layers of the atmosphere, produced by the interaction between atoms and the particles from the solar wind or by the chemical interaction between atoms. High



Figure 2.4: Oxygen (green) and sodium (orange) airglow emission, photographed from the ISS. Source: eol.jcs.nasa.gov.

energy solar particles collide with the atmospheric atoms exciting their electrons to higher energy levels; when the electrons jump back to the initial states they release energy in form of photons, leading to the characteristic emission spectrum. Another possible emission channel is by chemical recombination: when atomic oxygen collide with nitrogen or hydrogen atoms a single molecule (NO or OH) is created and a photon is released. Atomic oxygen or nitrogen are produced by photodissociation of the respective molecules during the day by solar radiation.

Main components. We can subdivide the airglow sources as a function of the height of the emitting layer. A first layer between 85 and 100 km is provided by molecular oxygen, sodium (respectively Herzberg bands and Fraunhofer D line) and OH transitions. Going higher, up to 300 km, forbidden atomic oxygen lines are produced. The outermost layers of the atmosphere, above 1000 km, are usually referred as geocorona; in this region faint but detectable hydrogen lines are produced.

Being produced by thin and homogeneous layers, the airglow emission is relatively uniformly distributed in the sky sphere, with an increase of brightness at high zenithal distances due to the increase of geometric depth along the line of sight. Maximum brightness is achieved at about 10° above the horizon after that the overall brightness is dimmed by atmospheric extinction. Brightest lines can produce a brightness up to 10^{-5} erg/s/cm²/sr/Å

Variations in airglow emission. Airglow emission varies in time, both on short and long timescales, following the behavior of the atmosphere and the solar activity [LBH⁺98]. Emission is also related to the geomagnetic latitude: is maximal in the sub-polar region, at a latitude of about $60^\circ - 80^\circ$ after which it significantly drop. In the polar region airglow emissions are substituted with auroral emission. In the low latitude regions emissions are generally low with a slight increase toward the equator [Eat69].

2.2.2 Aurorae

Aurorae are bright light bands observable at polar latitudes. They are produced by the excitation of atoms in the high layers of the atmosphere by the solar wind. At high latitudes interplanetary high energy charged particles can penetrate the magnetosphere ad reach the atmosphere where they collide and excite atmospheric elements. Excitation energy is then released in form of a photon, responsible for the observed radiation. Auroral spectrum is constituted by emission lines. Colors ranges from green and orange (typical of oxygen transitions) to blue or purple (trace of nitrogen emission), see figure 2.5.

The occurrence and intensity of this phenomenon is strictly regulated by the solar activity, and an increase of auroral emission can be observed during solar storms or period of high activity. The



Figure 2.5: Aurora borealis in the northern Finland. Credits: Martincco.

phenomenon is observable only in polar regions, namely above 80° of latitude (see [Eat69]) and for this reason it has a limited impact on the total optical sky background only in that geographic area. Nevertheless in case of intense solar activity like solar storms, aurorae can be observed at lower latitudes. Historical sources even report the sporadic observation of aurorae up to temperate latitudes.

2.3 Atmospheric scattering

Atmospheric scattering refers to the interaction of light with aerosol particles in the atmosphere. Unlike reflection or refraction, when a light beam get scattered its photons are deflected in random directions. Note scattering is somehow the complementary of extinction: when a light beam is dimmed due to extinction it means that part of its photons has been deflected (thus scattered) away from the beam direction. Extinction occurs when looking directly at a light source, while scattering is the diffuse radiation around the source.

2.3.1 Scattering mechanisms

There are two main scattering mechanism, depending on the size of the particle with respect to the wavelength of the incident radiation: Mie and Rayleigh scattering.

Rayleigh scattering. This is due to the interaction of light with particles smaller than the wavelength: if the particle is small enough the phase difference of the beam along the particle is negligible and the it “sees” in each moment an homogeneous electromagnetic field. The particle will be forced by the beam to emit as an oscillating dipole, in phase with the beam and with the same wavelength, but in a random direction. From the dipole theory, when a light beam of intensity I_0 travels through a medium, meeting N particles of polarizability α , the scattered intensity of the beam is

$$I = I_0 \frac{8\pi^4 N \alpha}{R^2} \frac{1 + \cos^2 \varphi}{\lambda^4} \quad (2.2)$$

where λ is the wavelength of the radiation and φ the angle between the beam and the observing direction. Note that it steadily decreases at increasing wavelengths ($\propto \lambda^{-4}$), i.e. Rayleigh scattering is stronger in the blue than in the red bands. Concerning the angular distribution of scattered light, the intensity is maximum both along the original beam direction (*forward scattering*) as well as in the opposite direction, back to the source (*back scattering*). Minima are located at 90° from the maxima.

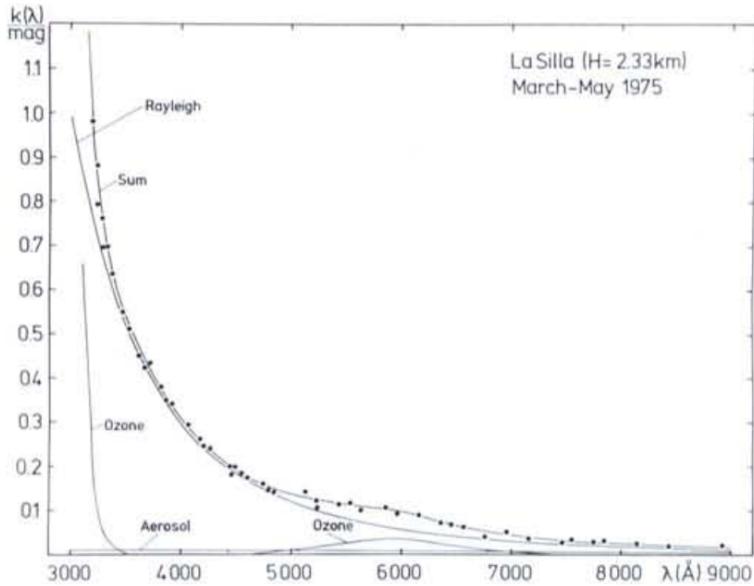


Figure 2.6: Extinction coefficients for Rayleigh and aerosol (Mie) scattering. The former component dominates over the latter at all the wavelengths, in particular for shorter ones. From [Tüg77].

In the optical regime, Rayleigh scattering is produced by the air molecules themselves. This form of scattering is responsible for the blue sky in daytime and for twilight. It is also the main responsible for atmospheric extinction, in particular at shorter wavelengths.

Mie scattering. Mie scattering occurs when light meets particles of size comparable or larger than the characteristic wavelength. In this case different parts of the particle experience different intensities of the electromagnetic field; each portion of the particle will emit as a single dipole, locally in phase with the beam, and the total emission will be the result of the interference pattern between all the portion of the particle. In this case only the wavelength of the original beam is preserved, while phase is distorted and direction is random. The numerical expression of Mie scattering is rather complex and involves the solution of Maxwell equation; several numerical or empirical relation are available in the literature. For our purposes it is relevant to say that the intensity of Mie scattering is proportional to $\propto \lambda^{-0.8}$. Moreover, most of the light is scattered along or close to the beam direction, i.e. the forward component is dominant (the larger the particle, the more relevant the forward component).

In the atmosphere Mie scattering is produced by solid particles suspended in the air (*aerosols*), such as dust grains, smoke or water drops. In the figure 2.6, from [Tüg77], are reported the extinction coefficients, a proxy the total scattered light, for Rayleigh and Mie scattering (the latter labelled as “aerosols”). It is clear that Mie scattering is negligible with respect to Rayleigh one, in particular at shorter wavelengths. This is true only in clear sky conditions, with an atmosphere locally without fog, smoke or other pollutants, that may significantly rise the impact of Mie scattering.

Note that to the Ozone extinction component in the figure 2.6 does not correspond any scattered component since it is produced by molecular absorption. In this case the radiation absorbed, instead of being re-emitted, is used to increase the kinetic energy of each ozone molecule, heating the ozone layer. This process is responsible for the temperature gradient inversion in the stratosphere.

2.3.2 Effects on the sky brightness

Every light source is responsible for a certain amount of light scattering. Depending on the site and the observation time, the effects of scattering on the total sky brightness can vary significantly.

Dark sites. In a dark site most of the scattered light is produced by airglow, zodiacal light and the galactic background, i.e. the brightest “direct” light sources. According to [LBH⁺98] scattered light from the natural sources accounts for a brightness of the order of 10^{-8} to 10^{-7} erg/s/cm²/sr/Å.

Light polluted sites. Atmospheric light scattering is the main mechanism responsible for light pollution when far from the light source. Due to Earth curvature, geographic features and atmospheric extinction the direct light contribute to pollution only when very close to the light source. As reported in the chapter XX, brightness of scattered artificial light from a city varies with the population and the distance.

Scattered sunlight and moonlight. Scattering is responsible for the twilight: even if the Sun is below the horizon some residual scattered light still brightens the sky. Conventionally astronomical twilight ends when the sun is 18° below the horizon and other light sources, such as zodiacal light, becomes more relevant.

A similar effect is provided by scattered moonlight. Such light brightness depends on the lunar phase and on the distance between the Moon and the observing position in the sky. According to [KS91] and similar sources, in optical bands scattered moonlight can lead to an increase of the sky brightness of the order of 5 mag/arcsec^2 .

Bibliography

- [Eat69] RH Eather. Latitudinal distribution of auroral and airglow emissions: The ‘soft’auroral zone. *Journal of Geophysical Research*, 74(1):153–158, 1969.
- [FHLT74] A Frey, W Hofmann, D Lemke, and C Thum. Photometry of the zodiacal light with the balloon-borne telescope thisbe. *Astronomy and Astrophysics*, 36:447–454, 1974.
- [KS91] Kevin Krisciunas and Bradley E Schaefer. A model of the brightness of moonlight. *Publications of the Astronomical Society of the Pacific*, 103(667):1033, 1991.
- [LBH⁺98] Ch Leinert, S Bowyer, LK Haikala, MS Hanner, MG Hauser, A-Ch Levasseur-Regourd, I Mann, K Mattila, WT Reach, W Schlosser, et al. The 1997 reference of diffuse night sky brightness. *Astronomy and Astrophysics Supplement Series*, 127(1):1–99, 1998.
- [Lei75] Christoph Leinert. Zodiacal light—a measure of the interplanetary environment. *Space Science Reviews*, 18(3):281–339, 1975.
- [Tüg77] H Tüg. Vertical extinction on la silla. *ESO Messenger*, 11:7–8, 1977.