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Final dissertation

The evolution of the night sky spectrum in Asiago

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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 use spectra acquired in the last 15 years from the Asiago Observatory to identify the various sources in the sky and study their temporal evolution.

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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 nigh 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 mechanism. It is capable of prevent some forms of cancer and is responsible of 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 by 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

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

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/cm^2/sr/Å on the ecliptic at 30° from the sun to about 10^{-9} erg/s/cm^2/sr/Å. Gegenschein maximum brightness reaches about 10^{-7} erg/s/cm^2/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.

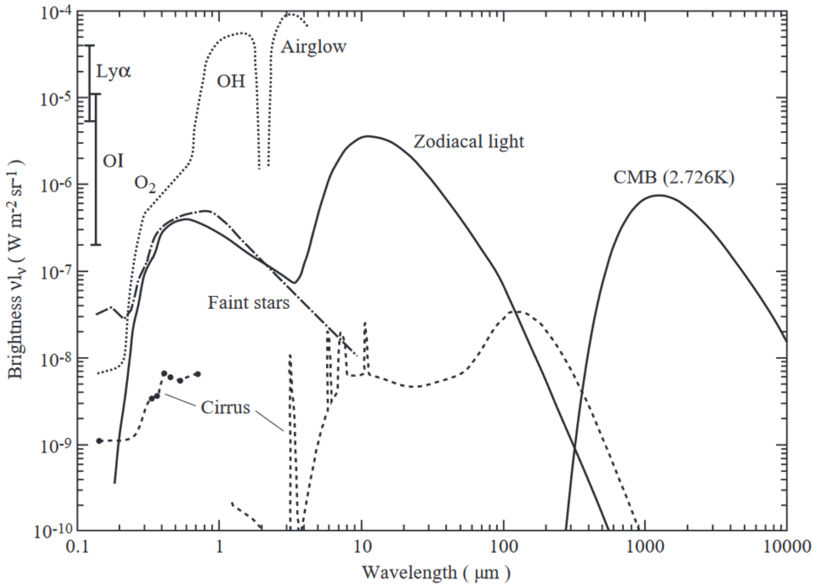

Figure 2.1: Different sky brightness contributions in different electromagnetic domains. In the optical band most relevant contribution ar Airglow, zodiacal light and faint stars. From [LBH+98].

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

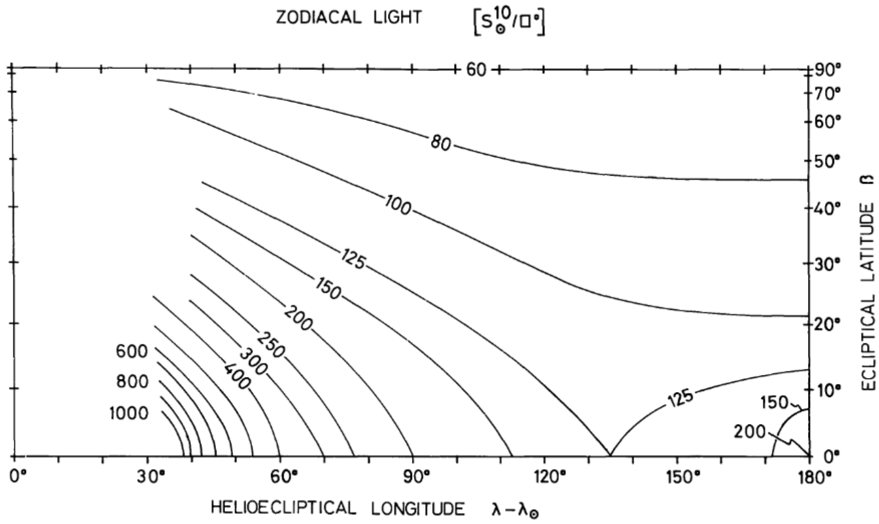

Figure 2.3: Isophotal map ot the zodiacal light as 7100 Å. As a reference, according to [LBH+98], $1\,S_{10}/\square° = 9.21 \times 10^{-10}$ erg/s/cm^2/sr/Å at those wavelengths. From [FHLT74].

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} erg/s/cm^2/sr/Å in the most crowded areas to 10^{-8} erg/s/cm^2/sr/Å 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} erg/s/cm^2/sr/Å. 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; is 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 zenital 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/cm^2/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 $60° - 80°$ 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 that 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 trough a medium, meeting N particles of polarizability α, the scattered intensity of the beam is

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

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.

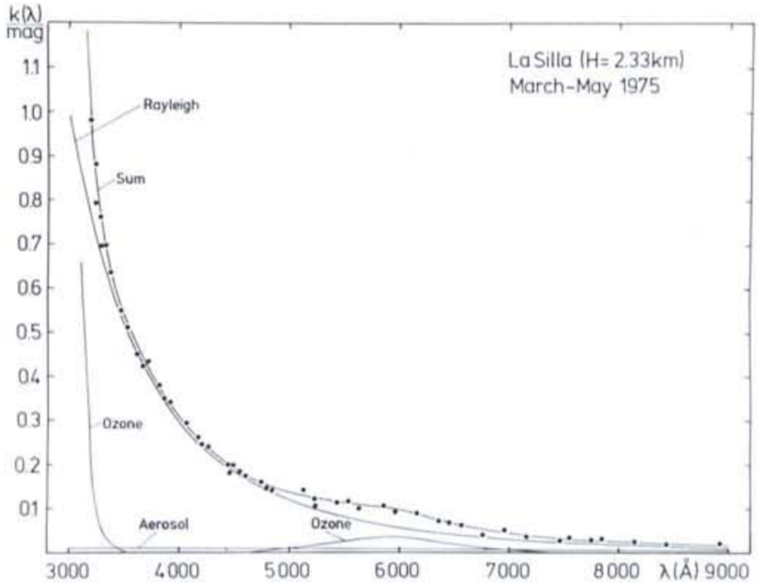

Figure 2.6: Extinction coefficients for Rayleigh and aerosol (Mie) scattering. The former component dominates over the latter at all the wavelengths, in particular for shorter ones. From [Tüg77].

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 clear 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/cm^2/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. As said before Rayleigh 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 $5\,\mathrm{mag/arcsec^2}$.

Chapter 3

Artificial sky light pollution

Chapter 4

The spectrum of the sky

Chapter 5

Sky spectra reduction

In this chapter are reported the steps in the data reduction that I designed to extract spectra of the sky from frames originally taken for scientific purposes. After a brief overview I describe accurately the data reduction process that I built. To improve the readability of this writing, I will report only the most significant pieces of code. The full source code instead is reported in the appendix A.

5.1 Introduction

5.1.1 Software management and reduction steps

In this work I developed some pieces of Python (v. 3.10) code to manage all the steps of the data reduction. Note that most of the data pre-reduction was already done and was not necessary to use old software such as IRAF or its python version PyRAF. In this work I tried to heavily automatize the script in order to be able to analyze all the frames with a single run. Many efforts were spent to build a robust code, capable of working correctly for spectra with very different features, without the necessity to fine-tune the software settings every single time a new frame is processed. All of this effort was made in order to be eventually able, in the future, to rapidly analyze new frames.

I decided to divide the source code into different independent script, each one devoted to a specific task. It follows a brief description of each step od the data reduction process.

Background extraction Starting from the original spectra I have to separate the scientific targets from the background regions. Once identified the spectra of the targets and the cosmic rays, the relative regions are masked. The remaining area contain the spectrum from the sky background only and is extracted to a new file.

Background analysis The sky spectrum is averaged along the slit direction. From the regions that do not present lines is estimated the shape of the sky continuum emission. Prominent lines or lines of interest are identified and the relative equivalent width is computed. The output of background analysis is the estimation of the continuum emission and the list of the widths of the emission lines.

Line analysis The width of the same line is compared in the different frames. Particular attention is devoted to the line intensity with the epoch of observation and the direction in the sky.

Continuum analysis Continuum intensity in different bands of the spectra is computed and correlated again with the epoch and direction of observation.

5.1.2 The dataset

This work is based on 35 spectra taken between 2006 and 2020 in the Osservatorio Astrofisico di Asiago, Asiago, northern Italy. Spectra were collected by professor Stefano Ciroi and collaborators to collect data on studied astronomical objects and were taken with the 1.22 m reflective telescope “Galileo Galilei” equipped with the grating spectrograph “Boller&Chivens”.

Each frame has been pre-reduced by Ciroi and its work group: data has been corrected for bias and flat field and calibration on both flux and wavelength was performed. Cosmic rays were not removed as well as the sky background. Before November 2011 frames have a spatial scale on the CCD of 0.63 arcsec/px while on later data the scale is 1.0 arcsec/px. For all the object has been used a grating with a line density of 300 tr/mm while the grating angle varied between 0° and 5.25° according to the type of target. Similarly slit aperture size varies from a minimum of 200 to a maximum of 400 µm while the exposure times ranged between 300 and 3600 s.

5.2 Background extraction

5.3 Background analysis

Appendix A

Source code

A.1 Background extraction

```
import numpy as np
import matplotlib.pyplot as plt
from astropy.io import fits
from scipy.signal import find_peaks, peak_widths
from datetime import datetime
import glob
import os
from wotan import flatten
from scipy.optimize import curve_fit

#######################
#OPTIONS
save_plots = True
save_FITS = False
plot_profile = True
plot_spec = True
show_ima = False

#PARAMS
peak_height = 0.05 #height abouve the bkg level
data_col_frac = .75 #minimum fraction of valid pixels in a column
width_mult = 2 # interval to exclude around a source, wrt center in FWHM units
cr_width = 2.5 # cr trace spatial width
cr_prominence = 5 #treshold height wrt average column level
cr_pad = 1 # number of px to exclude around cr, in a fixed column
LAMBDA_lim = 3500 #A, limit blue wavelength
#######################

#browse all the *.fc.fits files in a directory and its subdirectories
main_path = './Asiago_nightsky/2020/'
main_path = './'
file_ls = glob.glob(main_path+'/**/*.fc.fits', recursive= True)
names = [os.path.basename(x) for x in file_ls]

#initialize the .log file
f = open("bkg_extr.log", "w")
f.write('Running bkg_extr.py at '+
        datetime.now().strftime("%H:%M:%S, %Y-%m-%d")+'\n')
f.close()

#import table of known lines
lines = np.genfromtxt('lines.txt', usecols=0)

#append to the log
warnings_count = 0
def log_append(message):
    f = open("bkg_extr.log", "a")
    f.write(message+'\n')
    f.close()

#######################
#######################
```

```
#process all the files found
for name,file in zip(names,file_ls):

    print('processing file '+name+'\n', end='\r')

    #open a FITS file
    hdul = fits.open(file)
    hdr = hdul[0].header

    #extract wavelenght information from the header
    NAXIS1, NAXIS2 = hdr['NAXIS1'], hdr['NAXIS2']
    LAMBDA0, DELTA = hdr['CRVAL1'], hdr['CDELT1']

    #generate the lambdas array
    if hdr['CTYPE1'] != 'LINEAR':
        log_append('WARNING: no linear wavelength calibration')
    LAMBDA = np.arange(LAMBDA0, LAMBDA0+NAXIS1*DELTA, DELTA)
    if len(LAMBDA) == NAXIS1+1:
        LAMBDA = LAMBDA[:-1]

    #remove extreme blue wavelengths
    LAMBDA_start_id = len(LAMBDA)-len(LAMBDA[ LAMBDA>LAMBDA_lim])
    LAMBDA = LAMBDA[LAMBDA_start_id:]

    year = hdr['DATE-OBS'][:4]

    #aperture information from the hdr
    SLIT = hdr['SLIT'] #microns
    try:
        BINX, BINY = hdr['BINX'], hdr['BINY']
        TELSCALE = hdr['TELSCALE'] #arcsec/mm
        CCDSCALE = hdr['CCDSCALE'] #arcsec/px
    except KeyError:
        BINX, BINY = hdr['HBIN'], hdr['VBIN']

        log_append(' WARNING: no scale info in the hdr (using defauls)')

        TELSCALE = 10.70 #arcsec/mm #TO BE CHECKED!!!
        CCDSCALE = 0.63 #arcsec/px #TO BE CHECKED!!!

    SLIT_angular = SLIT/1000 * TELSCALE #slit size in arcsec
    SLIT_px = SLIT_angular / CCDSCALE / BINX #slit size in px

######################
    #bkg level estiamtion
    raw_data = hdul[0].data[:,LAMBDA_start_id:]
    raw_integr = np.sum(raw_data, axis = 1)
    x = np.arange(len(raw_integr))

    bkg_est = np.nanmedian(raw_integr)

######################
    #remove cosmic rays and UV noise
    data = np.copy(raw_data)

    cr_col_frac = np.zeros(len(LAMBDA)) #fraction of remaining px
    for cr_col,col in enumerate(data.T):
        col_avg = np.nanmean(data[:,cr_col])
        cr_line,_ = find_peaks(col,
                               prominence = cr_prominence*col_avg,
                               width = (0,cr_width))

        cr_widths = peak_widths(col, cr_line, rel_height=0.5)[0]

        #set left and right boundaries of the source region along the slit
        left_width = cr_line-cr_widths - cr_pad
        right_width = cr_line+cr_widths + cr_pad

        #scan each column and remove peaks
        cr_sel = np.zeros(np.shape(col), dtype=bool)
        for i in range(np.shape(col)[0]):
            for peak,width in zip(cr_line,cr_widths):
                if abs(i-peak) < width+cr_pad:
```

```
                    cr_sel[i] = True

        #counts how many pixels are left in a column
        saved_px = (NAXIS2 - np.sum(cr_sel))/NAXIS2
        cr_col_frac[cr_col] = saved_px
        if saved_px >= data_col_frac: #if enough, take the masked column
            data[cr_sel, cr_col] = np.nan
        else: #else discart the entire column
            data[:, cr_col] = 0.

######################
    #use noise/bkg info to find peaks
    integr = np.nansum(data, axis = 1)
    bkg_est = np.median(integr)

    #detrend: global trend (including peaks)
    _,trend_raw = flatten (x,
                            integr ,
                            method ='biweight',
                            window_length =200 ,
                            cval = 10, return_trend = True )

    #trim removing peaks, i.e. data fare above the global trend
    integr_trim = np.where(integr <= trend_raw+0.05*bkg_est,
                           integr, trend_raw)

    #detrend the trimmed data, much less sensitive to the peaks
    _,trend = flatten (x,
                       integr_trim ,
                       method ='biweight',
                       window_length =50 ,
                       cval = 10, return_trend = True )
    '''
    more plot about detrending
    plt.plot(x,integr, label='original profile')
    plt.plot(x,trend_raw, label='raw de-trend')
    plt.plot(x,integr_trim, label='trimmed profile')
    plt.plot(x,trend, label='final bkg trend estimation')
    plt.legend()
    plt.show()
    '''

    #detrend residuals: original peaks are highlighted wrt the bkg profile
    diff = integr-trend

    #find peaks
    peaks,properties = find_peaks(diff, height=0.05*bkg_est, width = cr_width)
    peak_FWHM = peak_widths(integr, peaks, rel_height=.5)[0]/2.

    if len(peak_FWHM)== 0:
        no_source = " WARNING: no sources were detected"
        log_append(no_source)

    #generate a boolean mask True outside the peaks
    bkg_sel = np.full(np.shape(x), True)
    for i,peak in enumerate(peaks):
        width = (int(peak_FWHM[i])+1)*width_mult
        for w in range(-width,width):
            bkg_sel[peak+w]=False
        w = width -1
        while integr[peak+w] >= trend[peak+w]:
            bkg_sel[peak+w] = False
            w += 1
        w = width
        while integr[peak-w] >=trend[peak-w]:
            bkg_sel[peak-w]=False
            w += 1

######################

    #plot the luminosity profile, show source and bkg regions
    if 1 == plot_profile:
        plt.title(year+'/'+name[:-8]+': wavelenght integration')
        plt.plot(raw_integr, alpha=0.2, ls='dashed', c='C1')
```

```
        plt.plot(integr, alpha=0.4) #integrated flux
        plt.scatter(x[bkg_sel],
                    integr[bkg_sel],
                    s=0.2, c='green') #select bkg

        #esimate the bkg of the filtered regions only
        bkg_est_filt = np.mean(integr[bkg_sel])

        plt.plot(x, trend_raw+0.05*bkg_est, ls='dashed', c='grey', alpha=0.5)
        ima = np.zeros(np.shape(bkg_sel))
        plt.fill_between(x, ~bkg_sel*1.1*max(integr), color='red', alpha=.1)

        #plt settings
        plt.ylim(min(integr)*0.9, max(integr)*1.1)
        plt.legend(['raw signal','cleaned signal',
                    'bkg signal only', 'detrended treshold',
                    f'peak regions ({width_mult}xFWHM)'])

        if save_plots is True:
            plt.savefig('./plots/integr/'+year+'_'+name[:-8]+'.png')
            plt.close()
        else:
            plt.show()

######################
    #integrated spectrum (along the slit)
    total = np.nanmean(data, axis = 0) #integration along the slit
    sky = np.nanmean(data[bkg_sel,:], axis = 0) #integration of bkg rows only

    total[total == 0] = np.nan

    #plot the spatially integrated spectrum of the bkg
    if 1 == plot_spec:
        plt.title(year+'/'+name[:-8]+': bkg spectrum')
        plt.plot(LAMBDA, total,  color='gray', alpha=0.3)
        plt.plot(LAMBDA, sky)
        for line in lines:
            plt.axvline(x=line, c='C1', alpha=.2)
        plt.legend(['full frame', 'sky only', 'known lines'])
        if save_plots is True:
            plt.savefig('./plots/sky_spec/'+year+'_'+name[:-8]+'.png')
            plt.close()
        else:
            plt.show()

######################
    #extract only the bkg rows

    ma_data = data #set masked data
    for i,row in enumerate(bkg_sel):
        #cancel data from the source rows
        if row == 0:
            ma_data[i,:] = np.nan

    #plot as image the bkr rows only
    if (1 == show_ima) and (save_plots ==0):
        plt.title('image (sky selection only)')
        plt.imshow(ma_data, extent = [LAMBDA[0], LAMBDA[-1], NAXIS2, 0])
        plt.show()

######################
    #save masked data in a new FITS file
    if 1 == save_FITS:
        now = datetime.now()
        now_str = now.strftime("%Y-%m-%d %H:%M:%S")

        hdr.set('BKGEXTR', now_str, 'Time of bkg extraction')
        hdr.set('UVLIM', LAMBDA_lim, 'A')
        hdr['NAXIS1']=len(data[0])
        new_hdu = fits.PrimaryHDU(ma_data)
        new_hdul = fits.HDUList([new_hdu])
        new_hdul[0].header = hdr

        file_new = file[:-5]+'.bkg.fits'
```

```
        new_hdul.writeto(file_new, overwrite=True)

f = open("bkg_extr.log", 'r')
warnings_count = len(f.readlines())-1
if warnings_count != 0:
    print(f'WARNING: {warnings_count} warnings occurred (see the log)')
```

A.2 Background analysis

```
import numpy as np
import matplotlib.pyplot as plt
from scipy.signal import find_peaks, peak_widths, savgol_filter
from scipy.interpolate import UnivariateSpline, interp1d
from astropy.io import fits
from astropy import units as u
from astropy.modeling import models
from astropy.table import Table
from datetime import datetime
import glob
import os
from wotan import flatten
from specutils.fitting import fit_lines
from specutils.spectra import Spectrum1D
#######################
#OPTIONS

plot_fits = True
save_fits = True

show_cont = False
save_cont = True

FITS_lines = True
#PARAMS
line_res = 3 #x delta lambda, min distance to consider lines as unresolved
JD0 = 2450000
line_window = 10 #DELTA units when finding lines to be masked to estimate continuum
#######################

# import lines table
lines_raw = np.genfromtxt('lines.txt', usecols=0)
ranges2 = np.genfromtxt('ranges2.txt')


line_diff = np.diff(lines_raw)

JDs = []

#browse all the *.fc.fits files in a directory and its subdirectories
main_path = './Asiago_nightsky/2009/'
main_path = './Asiago_nightsky/'
file_ls = glob.glob(main_path+'/**/*.fc.bkg.fits', recursive= True)
names = [os.path.basename(x) for x in file_ls]

#process all the files found
file_id = 0
for name,file in zip(names,file_ls):

    #load the frame
    hdul = fits.open(file)
    hdr, data = hdul[0].header, hdul[0].data

    #take wavelength info from the hdr
    NAXIS1, NAXIS2 = hdr['NAXIS1'], hdr['NAXIS2']
    LAMBDA0, DELTA = hdr['CRVAL1'], hdr['CDELT1']
    LAMBDA_lim = hdr['UVLIM']
    year = hdr['DATE-OBS'][:4]
    JDs.append(hdr['JD'])

    #the (eventually) UV-limited wavelengths array
    LAMBDA_start = max(LAMBDA_lim, LAMBDA0)
    LAMBDA = np.arange(LAMBDA_start, LAMBDA_start+NAXIS1*DELTA, DELTA)
    if len(LAMBDA) == NAXIS1+1:
```

```
        LAMBDA = LAMBDA[:-1]
    spec = np.nanmean(data, axis=0)

    #remove blended lines, i.e. to be considered as a single feature
    close_lines = np.where(line_diff < line_res*DELTA, False, True)
    close_lines = np.insert(close_lines, 0, True)
    lines = lines_raw[close_lines]

    filename = './plots/widths/'+year+'_'+name[:-13]+'.l.txt'
    f = open(filename, 'w') if FITS_lines else 0
    f.write(f"#line\t EW") if FITS_lines else 0

    ####################

    '''
    CONTINUUM ESTIMATION
    '''

    cont_sample = np.zeros(len(LAMBDA)) #samples array

    x,y=[],[]
    plt.plot(LAMBDA, spec, label='original') if show_cont else 0
    #iterate over the sampling intervals
    for Range in ranges2:

        #LAMBDAs in the sampling ranges
        in_range = (LAMBDA > Range[0]) & (LAMBDA < Range[1])
        if np.sum(in_range) == 0:
            print(f'WARNING: no data in the interval from {Range[0]}A!')

        plt.plot(LAMBDA[in_range],spec[in_range], c='C2',lw=3)

        #average the signal (small interval, linear approx.)
        LAMBDA_avg = np.mean(LAMBDA[in_range])
        spec_avg = np.mean(spec[in_range])

        x.append(LAMBDA_avg)
        y.append(spec_avg)


    #interplolate the continuum from the sampling intervals
    interp = interp1d(x, y,
                  kind = 'quadratic', fill_value="extrapolate")
    final_cont = interp(LAMBDA)

    #plot and save the results
    if show_cont is True:
        plt.plot(LAMBDA[in_range],spec[in_range], c='C2',
                  label = 'sampled regions', lw=3)

        plt.plot(LAMBDA, final_cont, label='continuum est.')
        plt.xlabel('wavelenght [A]')
        plt.ylabel('flux [erg/cm2/s/A]')
        plt.legend()
        if save_cont is True:
            plt.savefig('./plots/continuum/'+year+'_'+name[:-8]+'.png', dpi=500)
            plt.close()
        else:
            plt.show()
    else:
        plt.close()

    '''
    LINE FIT
    '''

    #LINE FIT
    u_flux = u.erg / (u.cm ** 2 * u.s * u.AA) #flux units
    A = u.AA #angstrom units
    spectrum = Spectrum1D(flux=spec*u_flux, spectral_axis=LAMBDA*A)
    EWs = []

    #model the line spectrum as sum of all the lines
    model = models.Gaussian1D(amplitude=0.5*max(spec)*u_flux,
```

```
                                    mean=lines[0]*A,
                                    stddev=5.*A)

    for line in lines[1:]:
        model = model + models.Gaussian1D(amplitude=0.5*max(spec)*u_flux,
                                          mean=line*A,
                                          stddev=5.*A)


    line_fit = fit_lines(spectrum-final_cont, model)
    y_fit = line_fit(LAMBDA*A)

    plt.plot(LAMBDA, y_fit+final_cont*u_flux,
                lw=0.4, ls = '-', c='C1') if plot_fits else 0

    EW = np.sum(y_fit/(final_cont*u_flux))
    EWs.append(EW)

    # for groups of lines the same EW is given to all the components
    EW_array = np.zeros(np.shape(lines_raw))
    EW_array[~close_lines] = np.nan #grouped lines
    EW_array[close_lines] = EWs
    for i,EW in enumerate(EW_array):
        if np.isnan(EW):
            EW_array[i] = EW_array[i-1]

        f.writelines(f"\n{lines_raw[i]}\t {EW_array[i]}") if FITS_lines else 0

    #plot the spectrum and the best fit profiles
    if plot_fits is True:
        plt.plot(LAMBDA, spec, lw=0.2, ls='-.')
        plt.xlabel('wavelenght [A]')
        plt.ylabel('flux [erg/cm2/s/A]')
    if (save_fits is True) and (plot_fits is True):
        plt.savefig('./plots/line_fit/'+year+'_'+name[:-8]+'.png', dpi=500)
    elif plot_fits is True:
        plt.show()
    plt.close()

    #plt.plot(EWs, '-o')
    f.close() if FITS_lines else 0

    #save as a new .FITS file
    if FITS_lines is True:
        #save new FIT file with with EW in a partition
        table_hdu = fits.BinTableHDU.from_columns(
            [fits.Column(name = 'line', array = lines_raw, format = 'E'),
             fits.Column(name = 'EWs', array = EW_array, format = 'E'),
             fits.Column(name = 'IsIsolated', array = close_lines, format = 'L' )])

        now = datetime.now()
        now_str = now.strftime("%Y-%m-%d %H:%M:%S")

        hdul.append(table_hdu)
        t_hdr = hdul[1].header
        t_hdr.set('UNITS', 'Angstrom')
        t_hdr.set('EWTIME', now_str, 'Time of EW computation')
        t_hdr.set('LINERES', now_str, 'Min dist btw lines, in DELTA units')

        #save the contimuum in a new partition too
        table_hdu = fits.BinTableHDU.from_columns(
            [fits.Column(name = 'LAMBDA', array = LAMBDA, format = 'E'),
             fits.Column(name = 'flux', array = final_cont, format = 'E')])
        hdul.append(table_hdu)

        #save the .FITS file
        file_new = file[:-12]+'.l.fits'
        hdul.writeto(file_new, overwrite=True)
```

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