Project 1 - Emission lines

PHY669 (Astrophysics Techniques, Spring 2025)

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Please follow the links to :
1. Static notebook
2. Runnable ipynb file
3. Download the ipynb file

1. Objective

Analysing the optical spectra of the 3C 454.3 blazar and deriving various physical parameters from the emission lines.

2. Theory

2.1. Preprocessing the spectra

Before the emission lines can be processed, the spectra must be corrected for interstellar reddening. Here, we have used the reddening laws provided by P. W. A. Roming et. al. (2009). The reddening correction magnitude is given by : $E(B-V)[aR_v + b]$ where $E(B-V)$ is the color index, $R_v = 3.1$ and a, b are polynomials of the wavenumber as given in the above mentioned study.

2.2. Fitting the spectra to a powerlaw

The most prominent emission and absorbtion lines is first masked out in the spectra. The remaining section is fitted to a powerlaw.

The underlying process generating the photons is assumed to be a random process, so the number of photons detected at each pixel or wavelength (y) follows a Poisson distribution given by $P(y \mid \mu) = \mu^y e^{\mu} y!^{-1}$ where μ is the average or expected value at that particular wavelength. The value of μ follows an power law of the wavelenth x, i.e. $\mu(x) = cx^{-a}$. So the likelihood function is given by :

$$\mathcal{L}((a,c) \mid (X,Y)) = \prod_{i=1}^{N} \frac{cx_i^{-ay_i} e^{-cx_i^{-a}}}{y_i!}$$

where N is the number of data points, X is the wavelength values, and Y is the corresponding flux values in photon count. The best fit values of the parameters a and c are obtained by maximizing the log likelihood function given by :

$$\ln \mathcal{L} = \sum_{i=1}^{N} y_i \ln c - ay_i \ln x_i - cx_i^{-a} - \ln(y_i!)$$

2.3. Fitting the emission lines to gaussians

After the best fit powerlaw is obtained, the continuum is subtracted from the spectra. Next, the peaks or emission lines are selected and gaussian curves are fitted to it. Thus the central wavelength λ, peak flux excess from the continuum (A), and the width of the emission lines (standard deviation σ) can be obtained.

2.4. Thermal and doppler broadening

The emission lines are not sharp due to thermal broadening and doppler broadening.

Thermal broadening is due the relative motion of emitting atoms in plasma and the observer, the strength of which is given as a function of the temperature T of the gas (assuming a Maxwell-Boltzmann distribution) :

$$\sigma = \lambda \sqrt{\frac{kT}{E}}$$

where λ is the central wavelength of the emission line, k is the Boltzmann constant, and E is rest mass energy of the radiating particle.

Doppler broadening is due to the relative motion of the emitting atoms and the observer. The strength of the broadening is given by the average velocity v :

$$\sigma = \frac{v\lambda}{3c}$$

Both of these can be found from the standard deviation of the gaussian fit or the equivalent width. The equivalent width W is given by :

$$W = \int \left(1 - \frac{f_s}{f_c}\right) d\lambda$$

where f_s is the flux of the spectrum and f_c is the flux of the continuum. If the continuum is assumed to be locally flat and the emission line being a perfect gaussian, it can be directly calculated by

$$W = \frac{A\sigma\sqrt{2\pi}}{cx^{-a}}$$

2.5. V-band magnitude derived flux

The flux F from the source can be calculated from the V band magnitude (V) of the source (assuming the same number of photons are received for all wavelengths). It is given by :

$$F = F_{V_0} \times 10^{-\frac{V}{2.5}}$$

where F_{V_0} is the V band zero magnitude flux. It is then overplotted on the reddening corrected spectra.

3. Procedure

The function `extract_data` reads the fits file and extracts the flux and wavelengths. Then the function `reddening_correction` corrects for reddening. The `mask_emission_lines` masks the strong emission line around 5200**Å** and the atmospheric absorbtion lines beyond 6750**Å**.

The masked spectrum is then scaled by the `scale` function and passed to the `pattern_search` function which does a basic pattern search to find best fit values of the powerlaw parameters by maximizing the `log_likelihood` function. The best fit powerlaw continuum is then subtracted from the spectrum by the `subtract_baseline` function.

The `find_peaks` function finds emission line peaks and passes them to the `fit_gaussians` function to get values of the wavelength, width, and strength of the emission lines.

Thereafter, the `emission_line_stats` function calls the `thermal_broadening`, `doppler_broadening` and `equivalent_width` functions to predict the temperature, relative velocity and the equivalent width from the gaussian fit results.

The `pipe` function is used to subsequently run all these functions together. The `overlay` function is used to overplot the V-band magnitude derived flux on the reddening corrected flux. The `get_total_mag` function gives the area under the spectra and is used to select the strongest and weakest flux file. All of these are available as methods of the class `sepecat`. It takes about a minute to process all 358 files.

4. Results

If the broadening is due to temperature, the expected temperature is in the order of $\mathbf{10^5 K}$, even if the radiating particles as light as electrons. These values are impractically large as typical expected temperatures around blazars are in the order of $\mathbf{10^4 K}$. On the other hand, calculations from doppler broadening give values in the order of $\mathbf{10^3\ km/s}$, which is a plausible value for typical speeds in the accretion disk. This suggests that the broadening is due to doppler effect and not thermal broadening.

The V band magnitude derived flux is always lower than the reddening corrected flux. To the best of my guess, this is probably because the V band magnitude is corrected for background while the spectra is not.

5. Issues

1. While calculating the temperature from the broadening of the emission line, we are taking the mass of the electron. But the emission lines are of atoms. But considering the mass of atoms gives worse, physically implausible estimates of temperature.
2. Before power law fitting the flux should ideally be converted to photon count from energy. But this requires data about pixel size and exposure time. But we have been unable to get conclusive values of the same from fits files headers and the data available in the database. So we have multiplied with an arbitrary constant to aid in the fitting process.

Note :

1. The $\boldsymbol{E(B-V)}$ values were obtained from https://irsa.ipac.caltech.edu/applications/DUST/
2. Sections of the code were written and corrected with help of MS21011 (Aratrik Basu), MS21029 (Eshna Roy), MS21131 (Sravya K) and MS21213 (Rajnil Mukherjee)