SPAMM – Spectral Properties of AGN Modeled through MCMC

Spectral Components

Nuclear Continuum

$$F_{\lambda,\mathrm{PL}} = F_{\mathrm{PL},0}\,\left(\frac{\lambda}{\lambda_0}\right)^{\alpha} \tag{1}$$

where $F_{\mathrm{PL},0}$ is the power-law normalization, α is the power-law slope and λ_0 is the median wavelength of the observed wavelength range.

Code Parameters

- `param1`: power-law slope (α_λ)
- `param2`: power-law normalization ($F_{\mathrm{PL},0}$)

Priors

- α_λ: flat prior in range [-3,3]
- $F_{\mathrm{PL},0}$: flat prior between 0 and the maximum of the spectral flux after computing running median *(to be discussed)*

Balmer Continuum

If we assume gas clouds with uniform temperature $\mathrm{T_e}$, that are partially optically thick, for wavelengths bluer than the Balmer edge ($\lambda_{\mathrm{BE}} = 3646$ Å, rest frame), the Balmer spectrum can be parametrized as (Grandi et al., 1982):

$$F_{\lambda,\mathrm{BC}} = F_{\mathrm{BE}}\;B_\lambda\left(\mathrm{T_e}\right)\;\left(1 - \mathrm{e}^{-\tau_{\mathrm{BE}}\left(\frac{\lambda}{\lambda_{\mathrm{BE}}}\right)^3}\right),\;\lambda < \lambda_{\mathrm{BE}} \tag{2}$$

where $\mathrm{B}_\lambda(\mathrm{T_e})$ is the Planck function at the electron temperature $\mathrm{T_e}$, τ_{BE} is the optical depth at the Balmer edge, and $\mathrm{F_{BE}}$ is the normalized flux density at the Balmer edge. At wavelengths $\lambda > 3646$ Å high order Balmer lines are merging into a pseudo continuum, yielding a smooth rise to the Balmer edge.

Discussion: there is the possibility of supplementing the functional form for $\lambda >3646$ Å with high-order Balmer emission lines (up to n=50), that might be computed using the relative line strengths as given by Storey 1995, case B. Possibly not needed if we are modeling continuum and emission lines (including high-order Balmer lines) at the same time.

Code Parameters

- `param1`: electron temperature ($\mathrm{T_e}$)
- `param2`: optical depth at the Balmer edge (τ_{BE})
- `param3`: normalized flux density at the Balmer edge ($\mathrm{F_{BE}}$)

Priors

- T_e: flat prior in the [5,000-20,000] Kelvin range.
- τ_{BE}: flat prior in the [0.1-2.0] range.
- F_{BE}:
  - Option 1: if the Balmer edge is included in the spectral range, flat prior between 0 and the observed spectral flux at the Balmer edge after computing running median *(to be discussed)*
  - Option 2: if the Balmer edge is not included in the spectral range, flat prior between 0 and the maximum flux after computing running median *(super conservative, to be discussed)*

FeII & FeIII

Linear combination of N broadened and scaled iron templates:

$$F_{\lambda,\mathrm{Fe}} = \sum_{\mathrm{i=1,..N}} F_{\mathrm{Fe,0,i}}\ \mathrm{FeTempl}_{\lambda,\mathrm{i}}(\sigma_i) \tag{3}$$

where $\mathrm{FeTempl}_{\lambda,\mathrm{i}}$ is the iron template, $F_{\mathrm{Fe,0,i}}$ is the template normalization, and σ_i is the width of the broadening kernel.

Code Parameters

- `param1`: iron templates ($\mathrm{FeTempl}_{\lambda,\mathrm{i}}$)
  - `UV template`: Vestergaard & Wilkes (2001), (1250-3090) Å
  - `Optical template`: Véron-Cetty et al. (2004), (3535-7530) Å
  - `Gap between UV and Optical template`: Beverly Wills, (3090-3534.4) Å *(In Marianne's hands)*
  - *Discussion: more options?*
- `param2`: width of the broadening Lorentzian kernel (σ_i)
- `param3`: template normalization ($F_{\mathrm{Fe,0,i}}$)

Priors

- σ_i: flat prior in the [500-20,000] km/s range. The other possibility is to have a Gaussian prior centered on the line width of Hβ.
- $F_{\mathrm{Fe,0,i}}$: flat prior between 0 and the maximum flux after computing running median *(super conservative, to be discussed)*

Host Galaxy

Linear combination of N galaxy templates:

$$F_{\lambda,\mathrm{Host}} = \sum_{\mathrm{i=1,..N}} F_{\mathrm{Host,0,i}}\ \mathrm{HostTempl}_{\lambda,\mathrm{i}} \tag{4}$$

where $\mathrm{HostTempl}_{\lambda,\mathrm{i}}$ is the host galaxy template, and $F_{\mathrm{Host,0,i}}$ is the template normalization.

Possible useful codes for inspection:

Code	Paper	Comments
STARLIGHT	Cid Fernandes, R. et al. 2005, MNRAS, 358, 363	One spectrum at a time
GANDALF	Sarzi et al. 2006, MNRAS, 366, 1151	Deals with 2D data

Code Parameters

- `param1`: Synthesis model: Choice of templates to combine
  - `Option 1`: Observed Template Galaxies (e.g., Kinney et al. 1996)
  - `Option 2`: Observed Template Stars
  - `Option 3`: PÉGASE
  - `Option 4`: Starburst99
  - `Option 5`: Bruzal & Charlot 2003
- `param2`: How many models/templates to include
- `param3`: Kinematics – fit or fix?
- `param4`: Wavelength Range
- `param5`: Mask – block certain wavelength ranges e.g., Hα

Priors

1. Age range of interest?
2. Metallicity range?
3. redshift

Host Galaxy Reddening

Code Parameters

- `param1`: Possible reddening laws:
  - `Option 1`: Milky Way
  - `Option 2`: Large Magellanic Cloud, LMC

– `Option 3`: Small Magellanic Cloud, SMC
– `Option 4`: Fit for R_v?

- `param2`: Dust_geometry: foreground screen or mixed media.

Priors

- τ_ν: flat between zero and 1.0 *Discussion: do we need higher τ values?*

Nuclear Reddening

Code Parameters

- `param1`: Possible reddening laws:
  – `Option 1`: Small Magellanic Cloud, SMC
  – `Option 2`: Fit for R_v?
- `param2`: Dust_geometry: foreground screen or mixed media.

Priors

- τ_ν: flat between zero and 1.0 *Discussion: do we need higher τ values?*

Emission lines

Functional fitting to broad and narrow emission-line components.

- **Broad Emission Line List, $\boldsymbol{\lambda_{0,b}}$**
  – Lyα λ1215 (actual $\lambda = 1215.670$Å)
  – N V λ1240 (doublet at $\lambda\lambda$1238.808, 1242.796Å)
  – "1400 Feature": Si IV (doublet at $\lambda\lambda$1393.755, 1402.770Å) plus O IV] blend ($\lambda\lambda$1397.210, 1399.780, 1404.790, 1407.390Å)
  – N IV] λ1486 (actual $\lambda = 1486.500$Å)
  – C IV λ1549 (unresolved doublet at $\lambda\lambda$1548.188, 1550.762Å)
  – He II λ1640 (actual $\lambda = 1640.720$Å)
  – O III] λ1663 (doublet at $\lambda\lambda$1660.800, 1666.140Å)
  – C III] λ1909: actually a blend of Al III $\lambda\lambda$1854.720, 1862.780Å, Si III] $\lambda = 1892.030$Å, and C III] $\lambda = 1908.734$Å.
  – Mg II λ2798 (doublet at $\lambda\lambda$2796.350, 2803.530Å)
  – Hδ $\lambda = 4101.735$Å
  – Hγ $\lambda = 4340.450$Å
  – He II λ4686 (actual $\lambda = 4685.650$Å)
  – Hβ $\lambda = 4861.320$Å
  – He I λ4922 (actual $\lambda = 4921.9$Å)
  – He I $\lambda = 5016$Å
  – He I λ5876 (actual $\lambda = 5875.680$Å)

- He I $\lambda 6678$ (actual $\lambda = 6678.000$Å)
- He I $\lambda 7065$ (actual $\lambda = 7065.300$Å)
- Hα $\lambda = 6562.780$Å

Comment: MV has a long list of Helium and Balmer lines in the optical and UV from Hα to the Balmer Jump that goes to high order (#50 in Balmer line series). The list also has relative line ratios and relative amplitude of BaC jump.

- **Narrow Emission Line List, $\boldsymbol{\lambda_{0,n}}$**
  - [Ne V] $\lambda 3425.900$Å
  - [O II] $\lambda\lambda 3726.000$, 3728.800Å
  - [Ne III] $\lambda 3868.800$Å
  - He II (actual $\lambda = 4685.650$Å)
  - Hβ $\lambda = 4861.320$Å
  - [O III] $\lambda\lambda 4958.920$, 5006.850Å
  - [N II] $\lambda\lambda 6548.060$, 6583.39Å
  - Hα $\lambda = 6562.780$Å
  - [Si II] $\lambda\lambda 6716.420$, 6730.780Å

Fitting Function Possibilities

- Narrow Lines
  - Single Gaussian with Prior (1)
  - Double Gaussian with Prior (1)
  - Option (automatically test) for additional (broader) Gaussian to [O III] $\lambda\lambda 4959, 5007$ base.
- Broad Lines
  - Multiple Gaussians
  - Multiple Gauss-Hermite polynomials
  - Gaussian (very broad) plus Gauss-Hermite (broad)
  - Multiple Lorentzians
  - Mix of Gaussian and Lorentzian(s) (i.e., Voigt profile)
  - Powerlaw profiles + 1-2 Gaussians

Functional Forms

- Gaussian:

$$F_\lambda = \frac{f_{\rm peak}}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\lambda-\mu}{\sigma}\right)^2}, \tag{5}$$

  where the Gaussian FWHM$= 2\sqrt{2\ln 2}\sigma$ and $\mu = \lambda_0$(broad, narrow).
  Free parameters: $f_{\rm peak}$ (peak flux), μ, σ. For multiple Gaussian components, the

amplitudes can be tied relative to one another (i.e. to the amplitude of the first component).

Discussion: MV suggests to use relative velocity shift rather than wavelengths shift, since it is more physical

- 6th Order Gauss-Hermite Polynomial:

$$F_\lambda = [f_{\rm peak}\alpha(w)/\sigma]\left(1 + \sum_{j=3}^{6} h_j H_j(w)\right), \tag{6}$$

$$w \equiv (\lambda - \mu)/\sigma, \tag{7}$$

$$\alpha(w) = \frac{1}{2\sqrt{\pi}} e^{-\frac{1}{2}w^2}. \tag{8}$$

where this follows the normalization of van der Marel & Franx (1993, ApJ, 407, 525; first equation). The H_j coefficients can be found in Cappellari et al. (2002, ApJ, 578, 787):

$$H_3(w) = \frac{w(2w^2-3)}{\sqrt{3}}, \tag{9}$$

$$H_4(w) = \frac{w^2(4w^2-12)+3}{2\sqrt{6}}, \tag{10}$$

$$H_5(w) = \frac{w[w^2(4w^2-20)+15]}{2\sqrt{15}}, \tag{11}$$

$$H_6(w) = \frac{w^2[w^2(8w^2-60)+90]-15}{12\sqrt{5}}. \tag{12}$$

Free parameters: $f_{\rm peak}$, μ, σ, h_3, h_4, h_5, h_6.

- Lorentzian

$$F_\lambda = \frac{f_{\rm peak}}{\pi}\frac{\frac{1}{2}\sigma}{(\lambda-\mu)^2 + (\frac{1}{2}\sigma)^2}, \tag{13}$$

where $\mu = \lambda_0$(b,n) and the Lorentzian FWHM $= \sigma = 2f_{\rm peak}/(\pi F(\mu))$.

- Powerlaw profile:

Priors

1. Limit all component positions (i.e., velocity offset from laboratory wavelengths) to within a given wavelength (or velocity) range to prevent the components to wander.

2. Width and velocity shifts of each of the Gaussian components of narrow forbidden lines tied together and FWHM <1200 km s^{-1}

3. Ranges of widths and velocity shifts to be included. I.e., profile limits to be specified - either one for each emission line, or for each type of line (broad, narrow, weak, strong, etc.) *Comment: MV has a separate long list - don't want to list here in case it needs to be coded differently.*

4. Narrow emission line redshift solution, i.e., $\mu = \lambda_{0,n}(1+z) \pm \Delta\mu$ is constant.
5. Narrow line doublet ratios fixed:
    - [O II] $\lambda\lambda$3726.000, 3728.800Å; ??:?? (This is density dependent)
    - [O III] $\lambda\lambda$4958.920, 5006.850Å; 1:3
    - [Si II] $\lambda\lambda$6716.420, 6730.780Å; ??:??
    - [N II] $\lambda\lambda$6548.060, 6583.39Å; ??:??
6. Fix relative line ratios of all Balmer lines
7. Fluxes must be non-negative (BLR and NLR emission)
8. Tie together the widths and velocity shifts of broad line components of identical species, e.g., He II λ1640 and He II λ4686? *(To be discussed).*
9. assumptions about CIV redshelf?? Additional HeII component? He II, Fe II, Al III, O II].
10. Suggested Parameter Space to search *(to be discussed)*
    - $f_{\rm peak}/f_{\rm cont}$ = [0, 1.d4, 1.d-3]
    - $\mu = \lambda_{0,n}(1+z) \pm 1000\,{\rm km\,s^{-1}}$; $\Delta\mu \sim f$(pixscale)
    - σ = [100, 3.d4]; $\Delta\sigma \sim f$(pixscale)
    - h_j = [-0.3, 0.3, 1.d-3]

Code Parameters

- `param1`: description of parameter 1 here

Discussion: Do we want to measure line dispersion on functional fit to the data or to the residual data (after eliminating the modeled blending line emission from other emission contributions)?