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

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.

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.
- $\tau_{\rm BE}$: flat prior in the [0.1-2.0] range.
- $F_{\rm BE}$: flat prior between 0 and the flux measured at $\lambda_{\rm BC,max}$, where $\lambda_{\rm BC,max}$ is the wavelength corresponding to the maximum of the Balmer Continuum in the observed spectral range.

High order Balmer lines

At wavelengths λ >3646 Å high order Balmer lines are merging into a pseudo continuum, yielding a smooth rise to the Balmer edge. Therefore, together with the continuum components, we also model high-order Balmer emission lines (up to n=50). Each high order emission line is modeled with a single Gaussian *(Discussion: is it enough? Should we go for a Lorentzian profile?)*:

$$F_\lambda = \frac{f_{\rm peak}}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\lambda-\mu}{\sigma}\right)^2}, \tag{3}$$

Code Parameters

$\forall$ Gaussian component:

- `param1` central wavelength (μ)
- `param2` width (σ)
- `param3` amplitude ($f_{\rm peak}$)

Priors

- `Global priors for emission lines`
- Fixed emission line ratios: either from Marianne's list *(under which assumptions are they computed?)*, or they can be computed using prescription by Storey & Hummer (1995), case B ($n_e = 10^8 - 10^9\ cm^{-3}$)

FeII & FeIII

Linear combination of N broadened and scaled iron templates:

$$F_{\lambda,\rm Fe} = \sum_{\rm i=1,..N} F_{\rm Fe,0,i}\ {\rm FeTempl}_{\lambda,\rm i}(\sigma_i) \tag{4}$$

where ${\rm FeTempl}_{\lambda,\rm i}$ is the iron template, $F_{\rm Fe,0,i}$ 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
  - `Optical template`: Kovacevic et al. (2010), (4000-5400) Å – 5 separate templates (4 templates for F,G,S and P groups, 1 template for I ZW1 lines)
- `param2`: broadening kernel (Gaussian, Lorentzian)
- `param3`: width of the broadening kernel (σ_i)
- `param4`: template normalization ($F_{\mathrm{Fe,0,i}}$)

Priors

- σ_i: log-normal 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 flux measured at $\lambda_{\mathrm{Fe,i,max}}$, where $\lambda_{\mathrm{Fe,i,max}}$ is the wavelength corresponding to the maximum of the i-th iron template in the observed spectral range.

Host Galaxy

Linear combination of N smoothed galaxy templates:

$$F_{\lambda,\mathrm{Host}} = \sum_{\mathrm{i}=1,..\mathrm{N}} F_{\mathrm{Host,0,i}}\ \mathrm{HostTempl}_{\lambda,\mathrm{i}}(\sigma_*) \tag{5}$$

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

Code Parameters

- `param1`: Host galaxy templates ($\mathrm{HostTempl}_{\lambda,\mathrm{i}}$) *The template choice might depend on the observed wavelength range, how do we prefer to implement this? (switch – prior)*
  - `Option 1`: Empirical Templates of Galaxies (e.g. Kinney et al. 1996, ??)
  - `Option 2`: *FUTURE DEVELOPMENT* Evolutionary stellar population synthesis models e.g. Bruzal & Charlot 2003, PÉGASE (starbursts and evolved galaxies), Starburst99 (star-forming galaxies)
- `param3`: stellar dispersion (σ_*), corresponding to the width of the smoothing kernel (Gaussian?)

Priors

1. $F_{\mathrm{Host,0,i}}$: flat prior between 0 and the maximum of the spectral flux after computing running median

2. σ_*: flat prior in the [30-600] km/s range.

3. `Age`: *FUTURE DEVELOPMENT, only in case of evolutionary stellar population synthesis models*

4. `Metallicity`: *FUTURE DEVELOPMENT, only in case of evolutionary stellar population synthesis models*

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

Host Galaxy Reddening

Simple parameterization of reddening law between 0.12 – 2.2 μm (Calzetti et al. 2000):

$$F_o(\lambda) = F_i(\lambda)10^{-0.4A'(\lambda)} = F_i(\lambda)10^{-0.4E_s(B-V)k'(\lambda)}, \tag{6}$$

$$E_s(B-V) = (0.44 \pm 0.03)E_g(B-V), \tag{7}$$

$$k' = \begin{cases} 2.659(-1.857 + 1.040/\lambda) + 4.05 & : \ 0.63\mu m \leq \lambda \leq 2.2\mu m \\ 2.659(-2.156 + 1.509/\lambda - 0.198/\lambda^2 + 0.011/\lambda^3) + 4.05 & : \ 0.12\mu m \leq \lambda \leq 0.63\mu m, \end{cases}$$

$F_o(\lambda)$ and $F_i(\lambda)$ are the dust-obscured and intrinsic continuum flux densities, respectivly; $A'(\lambda)$ is the dust obscuration, $E_s(B-V)$ and $E_g(B-V)$ are the color excess of the stellar continuum and of the nebular emission lines.

$$\beta = 1.9E_g(B-V) + \beta_o. \tag{8}$$

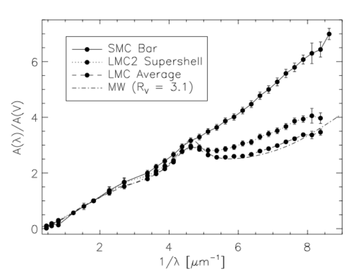

Fig. 10.—Sample average extinction curves plotted along with the "average" Milky Way curve (CCM with $R_V = 3.1$).

Figure 1: Gordon 2003 Plot

TABLE 4

SAMPLE AVERAGE CURVES

λ (μm)	x (μm^{-1})	$A(\lambda)/A(V)$		
		SMC Bar	LMC2 Supershell	LMC Average
2.198	0.455	0.016 ± 0.003	0.101 ± 0.003	0.030 ± 0.003
1.650	0.606	0.169 ± 0.020	0.097 ± 0.020	0.186 ± 0.020
1.250	0.800	0.131 ± 0.013	0.299 ± 0.013	0.257 ± 0.013
0.810	1.235	0.567 ± 0.048	...	...
0.650	1.538	0.801 ± 0.113	...	...
0.550	1.818	1.000 ± 0.046	1.000 ± 0.048	1.000 ± 0.048
0.440	2.273	1.374 ± 0.127	1.349 ± 0.113	1.293 ± 0.113
0.370	2.703	1.672 ± 0.123	1.665 ± 0.046	1.518 ± 0.046
0.296	3.375	2.000 ± 0.095	1.899 ± 0.127	1.786 ± 0.127
0.276	3.625	2.220 ± 0.093	2.067 ± 0.123	1.969 ± 0.123
0.258	3.875	2.428 ± 0.093	2.249 ± 0.095	2.149 ± 0.095
0.242	4.125	2.661 ± 0.095	2.447 ± 0.093	2.391 ± 0.093
0.229	4.375	2.947 ± 0.099	2.777 ± 0.093	2.771 ± 0.093
0.216	4.625	3.161 ± 0.102	2.922 ± 0.095	2.967 ± 0.095
0.205	4.875	3.293 ± 0.104	2.921 ± 0.099	2.846 ± 0.099
0.195	5.125	3.489 ± 0.105	2.812 ± 0.102	2.646 ± 0.102
0.186	5.375	3.637 ± 0.107	2.805 ± 0.104	2.565 ± 0.104
0.178	5.625	3.866 ± 0.112	2.863 ± 0.105	2.566 ± 0.105
0.170	5.875	4.013 ± 0.115	2.932 ± 0.107	2.598 ± 0.107
0.163	6.125	4.243 ± 0.119	3.060 ± 0.112	2.607 ± 0.112
0.157	6.375	4.472 ± 0.124	3.110 ± 0.115	2.668 ± 0.115
0.151	6.625	4.776 ± 0.131	3.299 ± 0.119	2.787 ± 0.119
0.145	6.875	5.000 ± 0.135	3.408 ± 0.124	2.874 ± 0.124
0.140	7.125	5.272 ± 0.142	3.515 ± 0.131	2.983 ± 0.131
0.136	7.375	5.575 ± 0.148	3.670 ± 0.135	3.118 ± 0.135
0.131	7.625	5.795 ± 0.153	3.862 ± 0.142	3.231 ± 0.142
0.127	7.875	6.074 ± 0.160	3.937 ± 0.148	3.374 ± 0.148
0.123	8.125	6.297 ± 0.368	4.055 ± 0.153	3.366 ± 0.153
0.119	8.375	6.436 ± 0.271	3.969 ± 0.160	3.467 ± 0.160
0.116	8.625	6.992 ± 0.201	...	...

Figure 2: Gordon 2003 Table

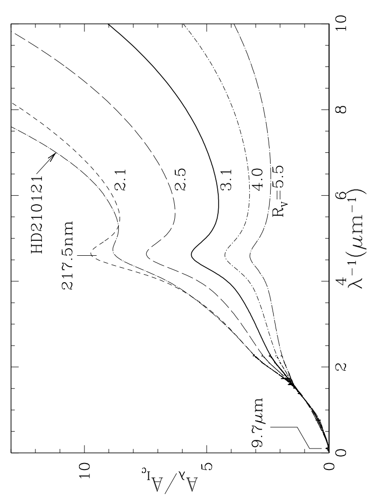

Figure 3: Draine 2011 Plot

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 λ6678 (actual $\lambda = 6678.000$Å)
- He I λ7065 (actual $\lambda = 7065.300$Å)
- Hα $\lambda = 6562.780$Å

- **Narrow Emission Line List, $\boldsymbol{\lambda_{0,n}}$**
  - [Ne V] λ3425.900Å
  - [O II] $\lambda\lambda$3726.000, 3728.800Å
  - [Ne III] λ3868.800Å
  - 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:

$$F_\lambda = \frac{f_{\rm peak}}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\lambda-\mu}{\sigma}\right)^2}, \tag{9}$$

  where the Gaussian FWHM$= 2\sqrt{2\ln 2}\sigma$ and $\mu = \lambda_0$(broad, narrow).

- 6th Order Gauss-Hermite Polynomial:

$$F_\lambda = [f_{\rm peak}\alpha(w)/\sigma]\left(1+\sum_{j=3}^{6} h_j H_j(w)\right), \tag{10}$$

$$w \equiv (\lambda-\mu)/\sigma, \tag{11}$$

$$\alpha(w) = \frac{1}{2\sqrt{\pi}}e^{-\frac{1}{2}w^2}. \tag{12}$$

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):

$$H_3(w) = \frac{w(2w^2-3)}{\sqrt{3}}, \tag{13}$$

$$H_4(w) = \frac{w^2(4w^2-12)+3}{2\sqrt{6}}, \tag{14}$$

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

$$H_6(w) = \frac{w^2[w^2(8w^2-60)+90]-15}{12\sqrt{5}}. \tag{16}$$

- Lorentzian

$$F_\lambda = \frac{f_{\rm peak}}{\pi}\frac{\frac{1}{2}\sigma}{(\lambda-\mu)^2+(\frac{1}{2}\sigma)^2}, \tag{17}$$

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

- Powerlaw profile:

Code Parameters

- ∀ Gaussian component:
  - `param1` central wavelength (μ)
  - `param2` width (σ)
  - `param3` amplitude ($f_{\rm peak}$)
- ∀ 6th Order Gauss-Hermite Polynomial:
  - `param1` central wavelength (μ)
  - `param2` width of the Gaussian component(σ)
  - `param3` amplitude of the Gauss-Hermite series ($f_{\rm peak}$)
  - `param4-7` Gauss-Hermite moments h_3, h_4, h_5, h_6
- ∀ Lorentzian component:

- `param1` central wavelength (μ)
- `param2` width (σ)
- `param3` amplitude (f_{peak})

- ∀ Power-law profile:
  - `param1`

Priors

1. Limit all component positions (i.e., velocity offset from laboratory wavelengths) to within a given velocity range to prevent the components to wander.
2. For multiple Gaussian components, the amplitudes can be tied relative to one another (i.e. to the amplitude of the first component).
3. Width and velocity shifts of each of the Gaussian components of narrow forbidden lines tied together and FWHM <1200 km s^{-1}
4. 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.*
5. Narrow emission line redshift solution, i.e., $\mu = \lambda_{0,n}(1+z) \pm \Delta\mu$ is constant.
6. 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; ??:??
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 tested).*
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)*
    - $f_{\text{peak}}/f_{\text{cont}}$ = [0, 1.d4, 1.d-3]
    - $\mu = \lambda_{0,n}(1+z) \pm 1000\,\text{km}\,\text{s}^{-1}; \Delta\mu \sim f(\text{pixscale})$
    - σ = [100, 3.d4]; $\Delta\sigma \sim f(\text{pixscale})$
    - h_j = [-0.3, 0.3, 1.d-3]