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# **CRRLpy Documentation**

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## CONTENTS

<b>1</b>	<b>CRRLpy</b>	<b>3</b>
<b>2</b>	<b>crrlpy.crrls module</b>	<b>5</b>
<b>3</b>	<b>crrlpy.models.rrlmod module</b>	<b>17</b>
<b>4</b>	<b>crrlpy.crrls.frec_calc module</b>	<b>25</b>
<b>5</b>	<b>Indices and tables</b>	<b>27</b>
	<b>Python Module Index</b>	<b>29</b>
	<b>Index</b>	<b>31</b>



Contents:



## CRRLPY

Tools for processing Carbon **R**adio **R**ecombination **L**ine spectra.

The models are not shipped with the modules and scripts.

The documentation can be found in: <http://astrofle.github.io/CRRLpy/>





## CRRLPY.CRRLS MODULE

`crrlpy.crrls.alphanum_key(s)`

Turn a string into a list of string and number chunks.

**Parameters** *s* – String

**Returns** List with strings and integers.

**Return type** `list`

**Example**

```
>>> alphanum_key('z23a')
['z', 23, 'a']
```

`crrlpy.crrls.average(data, axis, n)`

Averages data along the given axis by combining n adjacent values.

**Parameters**

- **data** (*numpy array*) – Data to average along a given axis.
- **axis** (*int*) – Axis along which to average.
- **n** (*int*) – Factor by which to average.

**Returns** Data decimated by a factor n along the given axis.

**Return type** `numpy array`

`crrlpy.crrls.best_match_idx(value, array)`

Searchs for the index of the closest entry to value inside an array.

**Parameters**

- **value** (*float*) – Value to find inside the array.
- **array** (*list or numpy.array*) – List to search for the given value.

**Returns** Best match index for the value inside array.

**Return type** `float`

**Example**

```
>>> a = [1, 2, 3, 4]
>>> best_match_idx(3, a)
2
```

`crrlpy.crrls.best_match_idx_tol(value, array, tol)`

Searchs for the best match to a value inside an array given a tolerance.

**Parameters**

- **value** (*float*) – Value to find inside the array.
- **tol** (*float*) – Tolerance for match.
- **array** (*numpy.array*) – List to search for the given value.

**Returns** Best match for val inside array.

**Return type** *float*

`crrlpy.crrls.best_match_value(value, array)`  
Searchs for the closest occurrence of value in array.

**Parameters**

- **value** (*float*) – Value to find inside the array.
- **array** (*list or numpy.array*) – List to search for the given value.

**Returns** Best match for the value inside array.

**Return type** *float*.

**Example**

```
>>> a = [1,2,3,4]
>>> best_match_value(3.5, a)
3
```

`crrlpy.crrls.blank_lines(freq, tau, reffreqs, v0, dv)`  
Blanks the lines in a spectra.

**Parameters**

- **freq** (*array, MHz*) – Frequency axis of the spectra.
- **tau** (*array*) – Optical depth axis of the spectra.
- **reffreqs** (*list*) – List with the reference frequency of the lines. Should be the rest frequency.
- **v0** (*float*) – Velocity shift to apply to the lines defined by *reffreq*. (km/s)
- **dv** (*float*) – Velocity range to blank around the lines. (km/s)

`crrlpy.crrls.blank_lines2(freq, tau, reffreqs, dv)`  
Blanks the lines in a spectra.

**Parameters**

- **freq** (*array*) – Frequency axis of the spectra. (MHz)
- **tau** (*array*) – Optical depth axis of the spectra.
- **reffreqs** (*list*) – List with the reference frequency of the lines. Should be the rest frequency.
- **dv** (*float*) – Velocity range to blank around the lines. (km/s)

`crrlpy.crrls.df2dv(f0, df)`  
Convert a frequency delta to a velocity delta given a central frequency.

**Parameters**

- **f0** (*float*) – Rest frequency. (Hz)
- **df** (*float*) – Frequency delta. (Hz)

**Returns** The equivalent velocity delta for the given frequency delta.

**Return type** float in Hz

`crrlpy.crpls.dv2df(f0, dv)`

Convert a velocity delta to a frequency delta given a central frequency.

**Parameters**

- **f0** (*float*) – Rest frequency. (Hz)
- **dv** (*float*) – Velocity delta. (m/s)

**Returns** The equivalent frequency delta for the given velocity delta.

**Return type** float in  $\text{m s}^{-1}$

`crrlpy.crpls.dv_minus_doppler(dV, ddV, dD, ddD)`

Returns the Lorentzian contribution to the line width assuming that the line has a Voigt profile.

**Parameters**

- **dV** (*float*) – Total line width
- **ddV** (*float*) – Uncertainty in the total line width.
- **dD** (*float*) – Doppler contribution to the line width.
- **ddD** – Uncertainty in the Doppler contribution to the line width.

**Returns** The Lorentz contribution to the total line width.

**Return type** float

`crrlpy.crpls.dv_minus_doppler2(dV, ddV, dD, ddD)`

Returns the Lorentzian contribution to the line width assuming that the line has a Voigt profile.

**Parameters**

- **dV** (*float*) – Total line width
- **ddV** (*float*) – Uncertainty in the total line width.
- **dD** (*float*) – Doppler contribution to the line width.
- **ddD** – Uncertainty in the Doppler contribution to the line width.

**Returns** The Lorentz contribution to the total line width.

**Return type** float

`crrlpy.crpls.f2n(f, line, n_max=1500)`

Converts a given frequency to a principal quantum number  $n$  for a given line.

**Parameters**

- **f** (*array*) – Frequency to convert. (MHz)
- **line** (*string*) – The equivalent  $n$  will be referenced to this line.
- **n\_max** (*int*) – Maximum  $n$  number to include in the search. (optional, Default 1)

**Returns** Corresponding  $n$  for a given frequency and line. If the frequency is not an exact match, then it will return an empty array.

**Return type** array

`crrlpy.crpls.find_lines_sb(freq, line, z=0, verbose=False)`

Finds if there are any lines of a given type in the frequency range. The line frequencies are corrected for redshift.

**Parameters**

- **freq** (*array*) – Frequency axis in which to search for lines.
- **line** (*string*) – Line type to search for.
- **z** (*float*) – Redshift to apply to the rest frequencies.
- **verbose** (*bool*) – Verbose output?

**Returns** Lists with the principal quantum number and the reference frequency of the line. The frequencies are redshift corrected in MHz.

**Return type** array.

**Example**

```
>>> from crrlpy import crrls
>>> freq = [10, 11]
>>> ns, rf = crrls.find_lines_sb(freq, 'CIalpha')
>>> ns
array([[ 843.,  844.,  845.,  846.,  847.,  848.,  849.,  850.,  851.,
         852.,  853.,  854.,  855.,  856.,  857.,  858.,  859.,  860.,
         861.,  862.,  863.,  864.,  865.,  866.,  867.,  868.,  869.]])
```

`crrlpy.crlls.fit_continuum(x, y, degree, p0)`

Divide tb by given a model and starting parameters p0. Returns: tb/model - 1

`crrlpy.crlls.fit_model(x, y, model, p0, wy=None, mask=None)`

Fits a model to the data defined by *x* and *y*. It uses *p0* as starting values.

**Parameters**

- **x** (*array*) – Abscissa values of the data to be fit.
- **y** (*array*) – Ordinate values of the data to be fit.
- **model** (*callable*) – Model to be fit.
- **p0** (*dict*) – Dictionary with the starting values for the fit.
- **wy** (*array*) – Weights of the ordinate values. (Optional)
- **mask** (*array*) – Mask to apply to the *x* and *y* values. (Optional)

**Returns** An object containing the results of the fit.

**Return type** `lmfit.model.ModelResult`

`crrlpy.crlls.freq2vel(f0, f)`

Convert a frequency axis to a velocity axis given a central frequency. Uses the radio definition of velocity.

**Parameters**

- **f0** (*float*) – Rest frequency for the conversion. (Hz)
- **f** (*numpy array*) – Frequencies to be converted to velocity. (Hz)

**Returns** *f* converted to velocity given a rest frequency *f0*.

**Return type** numpy array

`crrlpy.crlls.fwhm2sigma(fwhm)`

Converts a FWHM to the standard deviation,  $\sigma$  of a Gaussian distribution.

**Parameters** **fwhm** (*array*) – FWHM of the Gaussian.

**Returns** Equivalent standard deviation of a Gaussian with a Full Width at Half Maximum *fwhm*.

**Return type** array

### Example

```
>>> 1/fwhm2sigma(1)
2.3548200450309493
```

`crrlpy.crrls.gauss_area(amplitude, sigma)`

Returns the area under a Gaussian of a given amplitude and sigma.

#### Parameters

- **amplitude** – Amplitude of the Gaussian,  $A$ .
- **sigma** (*array*) – Standard deviation fo the Gaussian,  $\sigma$ .

**Returns** The area under a Gaussian of a given amplitude and standard deviation.

**Return type** *array*

`crrlpy.crrls.gauss_area_err(amplitude, amplitude_err, sigma, sigma_err)`

Returns the error on the area of a Gaussian of a given *amplitude* and *sigma* with their corresponding errors. It assumes no correlation between *amplitude* and *sigma*.

#### Parameters

- **amplitude** (*array*) – Amplitude of the Gaussian.
- **amplitude\_err** (*array*) – Error on the amplitude.
- **sigma** – Standard deviation of the Gaussian.
- **sigma\_err** – Error on sigma.

**Returns** The error on the area.

**Return type** *array*

`crrlpy.crrls.gaussian(x, sigma, center, amplitude)`

Gaussian function in one dimension.

#### Parameters

- **x** (*array*) – x values for which to evaluate the Gaussian.
- **sigma** (*float*) – Standard deviation of the Gaussian.
- **center** (*float*) – Center of the Gaussian.
- **amplitude** (*float*) – Amplitude of the Gaussian.

**Returns** Gaussian function of the given amplitude and standard deviation evaluateated at x.

**Return type** *array*

`crrlpy.crrls.get_axis(header, axis)`

Constructs a cube axis.

#### Parameters

- **header** (*pyfits header*) – Fits cube header.
- **axis** (*int*) – Axis to reconstruct.

**Returns** cube axis

**Return type** numpy array

`crrlpy.crrls.get_line_mask(freq, reffreq, v0, dv)`

Return a mask with ranges where a line is expected in the given frequency range for a line with a given reference frequency at expected velocity v0 and line width dv0.

**Parameters**

- **freq** (*numpy array or list*) – Frequency axis where the line is located.
- **reffreq** (*float*) – Reference frequency for the line.
- **v0** (*float, km/s*) – Velocity of the line.
- **dv** (*float, km/s*) – Velocity range to mask.

**Returns** Mask centered at the line center and width *dv0* referenced to the input *freq*.

`crllpy.crrls.get_line_mask2(freq, reffreq, dv)`

Return a mask with ranges where a line is expected in the given frequency range for a line with a given reference frequency and line width *dv*.

**Parameters**

- **freq** (*numpy array or list*) – Frequency axis where the line is located.
- **reffreq** (*float*) – Reference frequency for the line.
- **dv** (*float, km/s*) – Velocity range to mask.

**Returns** Mask centered at the line center and width *dv0* referenced to the input *freq*.

`crllpy.crrls.get_min_sep(array)`

Get the minimum element separation in an array.

**Parameters** **array** (*array*) – Array where the minimum separation is wanted.

**Returns** The minimum separation between the elements in *array*.

**Return type** *float*

`crllpy.crrls.get_rchi2(x_obs, x_mod, y_obs, y_mod, dy_obs, dof)`

Computes the reduced  $\chi$  squared,  $\chi^2_\nu = \chi^2/dof$ .

**Parameters**

- **x\_obs** (*array*) – Abscissa values of the observations.
- **x\_mod** (*array*) – Abscissa values of the model.
- **y\_obs** (*array*) – Ordinate values of the observations.
- **y\_mod** (*array*) – Ordinate values of the model.
- **dy\_obs** (*array*) – Error on the ordinate values of the observations.
- **dof** (*float*) – Degrees of freedom.

`crllpy.crrls.get_rms(data, axis=None)`

Computes the rms of the given data.

**Parameters**

- **data** (*numpy array or list*) – Array with values where to compute the rms.
- **axis** (*int*) – Axis over which to compute the rms. Default: None

**Returns** The rms of data.

$$\text{rms} = \sqrt{\langle \text{data} \rangle^2 + V[\text{data}]}$$

where *V* is the variance of the data.

`crllpy.crrls.is_number(str)`

Checks wether a string is a number or not.

**Parameters** *str* (*string*) – String.

**Returns** True if *str* can be converted to a float.

**Return type** bool

**Example**

```
>>> is_number('10')
True
```

`crrlpy.crpls.linear(x, a, b)`  
Linear model.

**Parameters**

- **x** (*array*) – x values where to evaluate the line.
- **a** (*float*) – Slope of the line.
- **b** (*float*) – y value for x equals 0.

**Returns** A line defined by  $ax + b$ .

**Return type** array

`crrlpy.crpls.load_model(prop, specie, temp, dens, other=None)`  
Loads a model for the CRRL emission.

`crrlpy.crpls.load_ref(specie, trans)`  
Loads the reference spectrum for the specified atomic specie and transition. Available species and transitions: CI alpha CI beta CI delta CI gamma CI13 alpha HeI alpha HeI beta HI alpha HI beta SI alpha SI beta

`crrlpy.crpls.load_ref2(transition)`  
Loads the reference spectrum for the specified atomic specie and transition. Available transitions: CIalpha CIbeta CIDelta CIGamma CI13alpha HeIalpha HeIbeta HIalpha HIBeta SIalpha SIBeta

`crrlpy.crpls.lookup_freq(n, specie, trans)`  
Returns the frequency of a given transition.

`crrlpy.crpls.lorentz_width(n, ne, Te, Tr, W, dn=1)`  
Gives the Lorentzian line width due to a combination of radiation and collisional broadening. The width is the FWHM in Hz. It uses the models of Salgado et al. (2015).

**Parameters**

- **n** (*array*) – Principal quantum number for which to evaluate the Lorentz widths.
- **ne** (*float*) – Electron density to use in the collisional broadening term.
- **Te** (*float*) – Electron temperature to use in the collisional broadening term.
- **Tr** (*float*) – Radiation field temperature.
- **W** (*float*) – Cloud covering factor used in the radiation broadening term.
- **dn** (*int*) – Separation between the levels of the transition. e.g.,  $dn=1$  for CIalpha.

**Returns** The Lorentz width of a line due to radiation and collisional broadening.

**Return type** array

`crrlpy.crpls.mask_outliers(data, m=2)`  
Masks values larger than m times the data median. This is similar to sigma clipping.

**Parameters** **data** (*array*) – Data to mask.

**Returns** An array of the same shape as data with True where the data should be flagged.

**Return type** array

**Example**

```
>>> data = [1,2,3,4,5,6]
>>> mask_outliers(data, m=1)
array([ True, False, False, False, False,  True], dtype=bool)
```

`crrlpy.crrls.n2f(n, line, n_min=1, n_max=1500, unitless=True)`

Converts a given principal quantum number *n* to the frequency of a given line.

`crrlpy.crrls.natural_sort(list)`

Sort the given list in the way that humans expect. Sorting is done in place.

**Parameters** *list* (*list*) – List to sort.

**Example**

```
>>> my_list = ['spec_3', 'spec_4', 'spec_1']
>>> natural_sort(my_list)
>>> my_list
['spec_1', 'spec_3', 'spec_4']
```

`crrlpy.crrls.plot_fit(fig, x, y, fit, params, vparams, sparams, rms, x0, refs, refs_cb=None, refs_cd=None, refs_cg=None)`

`crrlpy.crrls.plot_fit_single(fig, x, y, fit, params, rms, x0, refs, refs_cb=None, refs_cd=None, refs_cg=None)`

`crrlpy.crrls.plot_model(x, y, xm, ym, out)`

`crrlpy.crrls.plot_spec_vel(out, x, y, fit, A, Aerr, x0, x0err, sx, sxerr)`

`crrlpy.crrls.pressure_broad(n, Te, ne)`

Pressure induced broadening in Hz. Shaver (1975)

`crrlpy.crrls.pressure_broad_coefs(Te)`

Defines the values of the constants *a* and  $\gamma$  that go into the collisional broadening formula of Salgado et al. (2015).

**Parameters** *Te* (*float*) – Electron temperature.

**Returns** The values of *a* and  $\gamma$ .

**Return type** list

`crrlpy.crrls.pressure_broad_salgado(n, Te, ne, dn=1)`

Pressure induced broadening in Hz. This gives the FWHM of a Lorentzian line. Salgado et al. (2015)

**Parameters**

- *n* (*float or array*) – Principal quantum number for which to compute the line broadening.
- *Te* (*float*) – Electron temperature to use when computing the collisional line width.
- *ne* (*float*) – Electron density to use when computing the collisional line width.
- *dn* (*int*) – Difference between the upper and lower level for which the line width is computed. (default 1)

**Returns** The collisional broadening FWHM in Hz using Salgado et al. (2015) formulas.

**Return type** float or array

`crrlpy.crrls.radiation_broad(n, W, Tr)`

Radiation induced broadening in Hz. Shaver (1975)



`crllpy.crlls.radiation_broad_salgado(n, W, Tr)`

Radiation induced broadening in Hz. This gives the FWHM of a Lorentzian line. Salgado et al. (2015)

`crllpy.crlls.radiation_broad_salgado_general(n, W, Tr, nu0, alpha)`

Radiation induced broadening in Hz. This gives the FWHM of a Lorentzian line. The expression is valid for power law like radiation fields. Salgado et al. (2015)

`crllpy.crlls.sigma2fwhm(sigma)`

Converts the  $\sigma$  parameter of a Gaussian distribution to its FWHM.

**Parameters** `sigma` (*float*) –  $\sigma$  value of the Gaussian distribution.

**Returns** The FWHM of a Gaussian with a standard deviation  $\sigma$ .

**Return type** *float*

`crllpy.crlls.sigma2fwhm_err(dsigma)`

Converts the error on the sigma parameter of a Gaussian distribution to the error on the FWHM.

**Parameters** `dsigma` – Error on sigma of the Gaussian distribution.

**Returns** The error on the FWHM of a Gaussian with a standard deviation  $\sigma$ .

**Return type** *float*

`crllpy.crlls.stack_interpol(spectra, vmin, vmax, dv, show=True, rmsvec=False)`

`crllpy.crlls.stack_irregular(lines, window='', **kargs)`

Stacks spectra by adding them together and then convolving with a window to reduce the noise. Available window functions: Gaussian, Savitzky-Golay and Wiener.

`crllpy.crlls.temp2tau(x, y, model, p0, wy=None, mask=None)`

Converts a temperature to optical depth. It will fit the continuum using model and then subtract it and divide by it.

**Parameters**

- `x` (*array*) – x values.
- `y` (*array*) – y values to be converted into optical depths.
- `model` (*callable*) – Model to fit to the continuum.
- `p0` – Starting values for the model to be fit to the continuum.
- `wy` (*array*) – Weights for the y values. (Optional)
- `mask` (*array*) – Mask to apply to the x and y values.

**Returns** `y/model - 1`.

**Return type** *array*

`crllpy.crlls.tryint(str)`

Returns an integer if `str` can be represented as one.

**Parameters** `str` (*string*) – String to check.

**Returns** True if `str` can be cast to an int.

**Return type** *int*

`crllpy.crlls.vel2freq(f0, vel)`

Convert a velocity axis to a frequency axis given a central frequency. Uses the radio definition,  $\nu = f_0(1 - v/c)$ .

**Parameters**

- `f0` (*float*) – Rest frequency in Hz.

- **vel** (*float or array*) – Velocity to convert in m/s.

**Returns** The frequency which is equivalent to vel.

**Return type** float or array

`crrlpy.crpls.voigt(x, sigma, gamma, center, amplitude)`

The Voigt line shape in terms of its physical parameters.

**Parameters**

- **x** – independent variable
- **sigma** – HWHM of the Gaussian
- **gamma** – HWHM of the Lorentzian
- **center** – the line center
- **amplitude** – the line area

`crrlpy.crpls.voigt_(x, y)`

`crrlpy.crpls.voigt_area(amp, fwhm, gamma, sigma)`

Returns the area under a Voigt profile. This approximation has an error of less than 0.5%

`crrlpy.crpls.voigt_area_err(area, amp, damp, fwhm, dfwhm, gamma, sigma)`

Returns the error of the area under a Voigt profile. Assumes that the parameter c has an error of 0.5%.

`crrlpy.crpls.voigt_fwhm(dD, dL)`

Computes the FWHM of a Voigt profile. [http://en.wikipedia.org/wiki/Voigt\\_profile#The\\_width\\_of\\_the\\_Voigt\\_profile](http://en.wikipedia.org/wiki/Voigt_profile#The_width_of_the_Voigt_profile)

$$FWHM_V = 0.5346dL + \sqrt{0.2166dL^2 + dD^2}$$

**Parameters**

- **dD** (*array*) – FWHM of the Gaussian core.
- **dL** (*array*) – FWHM of the Lorentz wings.

**Returns** The FWHM of a Voigt profile.

**Return type** array

`crrlpy.crpls.voigt_fwhm_err(dD, dL, ddD, ddL)`

Computes the error in the FWHM of a Voigt profile. [http://en.wikipedia.org/wiki/Voigt\\_profile#The\\_width\\_of\\_the\\_Voigt\\_profile](http://en.wikipedia.org/wiki/Voigt_profile#The_width_of_the_Voigt_profile)

**Parameters**

- **dD** (*array*) – FWHM of the Gaussian core.
- **dL** (*array*) – FWHM of the Lorentz wings.
- **ddD** (*array*) – Error on the FWHM of the Gaussian.
- **ddL** (*array*) – Error on the FWHM of the Lorentzian.

**Returns** The FWHM of a Voigt profile.

**Return type** array

`crrlpy.crpls.voigt_peak(A, alphaD, alphaL)`

Gives the peak of a Voigt profile given its Area and the Half Width at Half Maximum of the Gaussian and Lorentz profiles.

**Parameters**

- **A** (*array*) – Area of the Voigt profile.

- **alphaD** (*array*) – HWHM of the Gaussian core.
- **alphaL** (*array*) – HWHM of the Lorentz wings.

**Returns** The peak of the Voigt profile.

**Return type** *array*

`crrlpy.crrls.voigt_peak2area` (*peak, alphaD, alphaL*)

Converts the peak of a Voigt profile into the area under the profile given the Half Width at Half Maximum of the profile components.

**Parameters**

- **peak** (*array*) – Peak of the Voigt profile.
- **alphaD** (*array*) – HWHM of the Gaussian core.
- **alphaL** (*array*) – HWHM of the Lorentz wings.

**Returns** The area under the Voigt profile.

**Return type** *array*

`crrlpy.crrls.voigt_peak_err` (*peak, A, dA, alphaD, dalphaD*)

Gives the error on the peak of the Voigt profile. It assumes no correlation between the parameters and that they are normally distributed.

**Parameters**

- **peak** (*array*) – Peak of the Voigt profile.
- **A** – Area under the Voigt profile.
- **dA** (*array*) – Error on the area *A*.
- **alphaD** (*array*) – HWHM of the Gaussian core.



## CRRLPY.MODELS.RRLMOD MODULE

`crrlpy.models.rrlmod.I_Bnu(specie, Z, n, Inu_func, *args)`

Calculates the product  $B_{n+\Delta n, n} I_\nu$  to compute the line broadening due to a radiation field  $I_\nu$ .

### Parameters

- **specie** (*string*) – Atomic specie to calculate for.
- **n** (*int or list*) – Principal quantum number at which to evaluate  $\frac{2}{\pi} \sum_{\Delta n} B_{n+\Delta n, n} I_{n+\Delta n, n}(\nu)$ .
- **Inu\_func** (*function*) – Function to call and evaluate  $I_{n+\Delta n, n}(\nu)$ . It's first argument must be the frequency.
- **args** – Arguments to *Inu\_func*. The frequency must be left out. The frequency will be passed internally in units of MHz. Use the same unit when required. *Inu\_func* must take the frequency as first parameter.

**Returns** (Hz)

**Return type** `array`

### Example

```
>>> I_Bnu('CI', 1., 500, I_broken_plaw, 800, 26*u.MHz.to('Hz'), -1., -2.6)
array([ 6.65540582])
```

`crrlpy.models.rrlmod.I_CII(Te, R, NCII)`

Frequency integrated line intensity. Optically thin limit without radiative transfer.

**Returns** The frequency integrated line intensity in units of Jy Hz or g s-3

`crrlpy.models.rrlmod.I_CII_rt(wav, dnu, T158)`

Frequency integrated line intensity. Optically thin limit with radiative transfer.

**Returns** The frequency integrated line intensity in units of Jy Hz or g s-3

`crrlpy.models.rrlmod.I_broken_plaw(nu, Tr, nu0, alpha1, alpha2)`

Returns the blackbody function evaluated at nu. As temperature a broken power law is used. The power law shape has parameters: Tr, nu0, alpha1 and alpha2.

### Parameters

- **nu** ((Hz) or `astropy.units.Quantity`) – Frequency. (Hz) or `astropy.units.Quantity`
- **Tr** – Temperature at nu0. (K) or `astropy.units.Quantity`
- **nu0** – Frequency at which the spectral index changes. (Hz) or `astropy.units.Quantity`
- **alpha1** – spectral index for  $\nu < \nu_0$
- **alpha2** – spectral index for  $\nu \geq \nu_0$

**Returns** Specific intensity in  $\text{erg cm}^{-2} \text{Hz}^{-1} \text{s}^{-1} \text{sr}^{-1}$ . See `astropy.analytic_functions.blackbody.blackbody_nu`

**Return type** `astropy.units.Quantity`

`crrlpy.models.rrlmod.I_cont(nu, Te, tau, I0, unitless=False)`

Computes the specific intensity due to a blackbody at temperature  $T_e$  and optical depth  $\tau$ . It considers that there is background radiation with  $I_0$ .

**Parameters**

- **nu** ((Hz) or `astropy.units.Quantity`) – Frequency.
- **Te** – Temperature of the source function. (K) or `astropy.units.Quantity`
- **tau** – Optical depth of the medium.
- **I0** – Specific intensity of the background radiation. Must have units of  $\text{erg / (cm}^2 \text{ Hz s sr)}$  or see *unitless*.
- **unitless** – If True the return

**Returns** The specific intensity of a ray of light after traveling in an LTE medium with source function  $B_\nu(T_e)$  after crossing an optical depth  $\tau_\nu$ . The units are  $\text{erg / (cm}^2 \text{ Hz s sr)}$ . See `astropy.analytic_functions.blackbody.blackbody_nu`

`crrlpy.models.rrlmod.I_external(nu, Tbkg, Tff, tau_ff, Tr, nu0=<Quantity 100000000.0 MHz>, alpha=-2.6)`

This method is equivalent to the IDL routine

**Parameters** **nu** – Frequency. (Hz) or `astropy.units.Quantity`

`crrlpy.models.rrlmod.I_total(nu, Te, tau, I0, eta)`

`crrlpy.models.rrlmod.Mdn(dn)`

Gives the  $M(\Delta n)$  factor for a given  $\Delta n$ . ref. Menzel (1968)

**Parameters** **dn** –  $\Delta n$ .

**Returns**  $M(\Delta n)$

**Return type** `float`

**Example**

```
>>> Mdn(1)
0.1908
>>> Mdn(5)
0.001812
```

`crrlpy.models.rrlmod.R_CII(ne, nh, gamma_e, gamma_h)`

Ratio between the fine structure level population of CII, and the level population in LTE. It ignores the effect of collisions with molecular hydrogen.

`crrlpy.models.rrlmod.T_CII(Te, tau, R)`

`crrlpy.models.rrlmod.alpha_CII(Te, R)`

Computes the value of  $\alpha_{1/2}$ . Sorochenko & Tsivilev (2000).

`crrlpy.models.rrlmod.beta_CII(Te, R)`

Computes the value of  $\beta_{158}$ . Sorochenko & Tsivilev (2000).

`crrlpy.models.rrlmod.broken_plaw(nu, nu0, T0, alpha1, alpha2)`  
 Defines a broken power law.

$$T(\nu) = T_0 \left( \frac{\nu}{\nu_0} \right)^{\alpha_1} \quad \text{if } \nu < \nu_0$$

$$T(\nu) = T_0 \left( \frac{\nu}{\nu_0} \right)^{\alpha_2} \quad \text{if } \nu \geq \nu_0$$

#### Parameters

- **nu** – Frequency.
- **nu0** – Frequency at which the power law breaks.
- **T0** – Value of the power law at nu0.
- **alpha1** – Index of the power law for nu<nu0.
- **alpha2** – Index of the power law for nu>=nu0.

**Returns** Broken power law evaluated at nu.

`crrlpy.models.rrlmod.chi(n, Te, Z)`  
 Computes the  $\chi_n$  value as defined by Salgado et al. (2015).

`crrlpy.models.rrlmod.eta(freq, Te, ne, nion, Z, Tr, trans, n_max=1500)`  
 Returns the correction factor for the Planck function.

`crrlpy.models.rrlmod.gamma_e_CII(Te)`  
 Computes the de-excitation rate of the CII atom due to collisions with electrons.

**Parameters** **Te** (*float*) – Electron temperature.

**Returns** The collisional de-excitation rate in units of cm<sup>-3</sup> s<sup>-1</sup>.

**Return type** *float*

`crrlpy.models.rrlmod.gamma_h_CII(Te)`  
 Computes the de-excitation rate of the CII atom due to collisions with hydrogen atoms.

**Parameters** **Te** (*float*) – Electron temperature.

**Returns** The collisional de-excitation rate in units of cm<sup>-3</sup> s<sup>-1</sup>.

**Return type** *float*

`crrlpy.models.rrlmod.itau(temp, dens, line, n_min=5, n_max=1000, other='', verbose=False, value='itau')`

Gives the integrated optical depth for a given temperature and density. The emission measure is unity. The output units are Hz.

#### Parameters

- **temp** (*string*) – Electron temperature. Must be a string of the form ‘8d1’.
- **dens** (*float*) – Electron density.
- **line** (*string*) – Line to load models for.
- **n\_min** (*int*) – Minimum n value to include in the output. Default 1
- **n\_max** (*int*) – Maximum n value to include in the output. Default 1500, Maximum allowed value 9900
- **other** (*string*) – String to search for different radiation fields and others.
- **verbose** (*bool*) – Verbose output?

- **value** (*string*) – ['itau' | 'bbnMdn' | 'None'] Value to output. itau will output the integrated optical depth. bbnMdn will output the  $\beta_{n,n'} b_n$  times the oscillator strenght  $M(\Delta n)$ . None will output the  $\beta_{n,n'} b_n$  values.

**Returns** The principal quantum number and its asociated value.

`crrlpy.models.rrlmod.itau_h(temp, dens, trans, n_max=1000, other='', verbose=False, value='itau')`

Gives the integrated optical depth for a given temperature and density. The emission measure is unity. The output units are Hz.

`crrlpy.models.rrlmod.itau_norad(n, te, b, dn, mdn)`

Returns the optical depth with only the approximate solution to the radiative transfer problem.

`crrlpy.models.rrlmod.j_line_lte(n, ne, nion, Te, Z, trans)`

`crrlpy.models.rrlmod.kappa_cont(freq, Te, ne, nion, Z)`

Computes the absorption coefficient for the free-free process.

`crrlpy.models.rrlmod.kappa_cont_base(nu, Te, ne, nion, Z)`

`crrlpy.models.rrlmod.kappa_line(Te, ne, nion, Z, Tr, trans, n_max=1500)`

Computes the line absorption coefficient for CRRLs between levels  $n_i$  and  $n_f$ ,  $n_i > n_f$ . This can only go up to  $n_{\max}$  1500 because of the tables used for the Einstein Anm coefficients.

#### Parameters

- **Te** (*float*) – Electron temperature of the gas. (K)
- **ne** (*float*) – Electron density. ( $\text{cm}^{-3}$ )
- **nion** (*float*) – Ion density. ( $\text{cm}^{-3}$ )
- **Z** (*int*) – Electric charge of the atoms being considered.
- **Tr** (*float*) – Temperature of the radiation field felt by the gas. This specifies the temperature of the field at 100 MHz. (K)
- **trans** (*string*) – Transition for which to compute the absorption coefficient.
- **n\_max** (*int*<1500) – Maximum principal quantum number to include in the output.

#### Returns

**Return type** array

`crrlpy.models.rrlmod.kappa_line_lte(nu, Te, ne, nion, Z, Tr, line, n_min=1, n_max=1500)`

Returns the line absorption coefficient under LTE conditions.

#### Parameters

- **nu** (*array*) – Frequency. (Hz)
- **Te** (*float*) – Electron temperature of the gas. (K)
- **ne** (*float*) – Electron density. ( $\text{cm}^{-3}$ )
- **nion** (*float*) – Ion density. ( $\text{cm}^{-3}$ )
- **Z** (*int*) – Electric charge of the atoms being considered.
- **Tr** (*float*) – Temperature of the radiation field felt by the gas. This specifies the temperature of the field at 100 MHz. (K)
- **trans** (*string*) – Transition for which to compute the absorption coefficient.
- **n\_max** (*int*<1500) – Maximum principal quantum number to include in the output.



**Returns****Return type** array`crrlpy.models.rrlmod.level_pop_lte` (*n*, *ne*, *nion*, *Te*, *Z*)Returns the level population of level *n*. The return has units of  $\text{cm}^{-3}$ .`crrlpy.models.rrlmod.load_betabn` (*temp*, *dens*, *other*='', *trans*='CIalpha', *verbose*=False)

Loads a model for the CRRL emission.

`crrlpy.models.rrlmod.load_betabn_h` (*temp*, *dens*, *other*='', *trans*='alpha', *verbose*=False)

Loads a model for the HRRL emission.

`crrlpy.models.rrlmod.load_bn` (*temp*, *dens*, *other*='')Loads the *bn* values from the CRRL models.`crrlpy.models.rrlmod.load_bn2` (*Te*, *ne*, *Tr*='', *n\_min*=5, *n\_max*=1000, *verbose*=False)Loads the *bn* values from the CRRL models.**Parameters**

- **Te** (*string*) – Electron temperature of the model.
- **ne** (*string*) – Electron density of the model.
- **Tr** (*string*) – Radiation field of the model.
- **verbose** (*bool*) – Verbose output?

**Returns** The  $b_n$  value for the given model conditions.**Return type** array`crrlpy.models.rrlmod.load_bn_all` (*n\_min*=5, *n\_max*=1000, *verbose*=False)`crrlpy.models.rrlmod.load_bn_dict` (*dict*, *n\_min*=5, *n\_max*=1000, *verbose*=False)Loads the  $b_n$  values defined by dict.**Parameters**

- **dict** (*dict*) – Dictionary containing a list with values for *Te*, *ne* and *Tr*.
- **line** (*string*) – Which models should be loaded.
- **n\_min** (*int*) – Minimum *n* number to include in the output.
- **n\_max** (*int*) – Maximum *n* number to include in the output.
- **verbose** (*bool*) – Verbose output?

**Returns** List with the  $b_n$  values for the conditions defined by dict.**Return type** numpy.array**Example**

```
>>> from crrlpy.models import rrlmod
```

First define the range of parameters

```
>>> Te = np.array(['1d1', '2d1', '3d1', '4d1', '5d1'])
>>> ne = np.arange(0.01, 0.105, 0.01)
>>> Tr = np.array([800])
```

Put them in a dictionary

```
>>> models = {'Te':[t_ for t_ in Te for n_ in ne for tr_ in Tr], 'ne':[round(n_
```

Load the models

```
>>> bn = rrlmod.load_bn_dict(models, n_min=200, n_max=500, verbose=False)
```

```
crrlpy.models.rrlmod.load_itaue_all(line='CIalpha', n_min=5, n_max=1000, verbose=False,
                                     value='itaue')
```

Loads all the available models for Carbon.

#### Parameters

- **line** (*string*) – Which models should be loaded.
- **n\_min** (*int*) – Minimum n number to include in the output.
- **n\_max** (*int*) – Maximum n number to include in the output.
- **verbose** (*bool*) – Verbose output?
- **value** (*string*) – ['itaue' 'bbnMdn' None] Which value should be in the output.

```
crrlpy.models.rrlmod.load_itaue_all_hydrogen(trans='alpha', n_max=1000, verbose=False,
                                             value='itaue')
```

Loads all the available models for Hydrogen.

```
crrlpy.models.rrlmod.load_itaue_all_match(trans_out='alpha', trans_in='beta',
                                           n_max=1000, verbose=False, value='itaue')
```

Loads all trans\_out models that can be found in trans\_in. This is useful when analyzing line ratios.

```
crrlpy.models.rrlmod.load_itaue_all_norad(trans='alpha', n_max=1000)
```

Loads all the available models.

```
crrlpy.models.rrlmod.load_itaue_dict(dict, line, n_min=5, n_max=1000, verbose=False,
                                     value='itaue')
```

Loads the models defined by dict.

#### Parameters

- **dict** (*dict*) – Dictionary containing a list with values for Te, ne and Tr.
- **line** (*string*) – Which models should be loaded.
- **n\_min** (*int*) – Minimum n number to include in the output.
- **n\_max** (*int*) – Maximum n number to include in the output.
- **verbose** (*bool*) – Verbose output?
- **value** (*string*) – ['itaue' 'bbnMdn' None] Which value should be in the output.

#### Example

```
>>> from crrlpy.models import rrlmod
```

First define the range of parameters

```
>>> Te = np.array(['1d1', '2d1', '3d1', '4d1', '5d1'])
>>> ne = np.arange(0.01, 0.105, 0.01)
>>> Tr = np.array([2000])
```

Put them in a dictionary

```
>>> models = {'Te':[t_ for t_ in Te for n_ in ne for tr_ in Tr], 'ne':[round(n_
```

# Load the models

```
>>> itau_mod = rrlmod.load_itau_dict(models, 'CIalpha', n_min=250, n_max=300,
```

```
        value='itau')
```

Loads models given a temperature, radiation field and an upper limit for the electron density.

```
rrlpy.models.rrlmod.load_models(models, trans, n_max=1000, verbose=False, value='itau')
```

Loads the models in backwards compatible mode. It will sort the models by Te, ne and Tr.

```
rrlpy.models.rrlmod.make_betabn(line, temp, dens, n_min=5, n_max=1000, other='')
```

```
rrlpy.models.rrlmod.make_betabn2(line, temp, dens, n_min=5, n_max=1000, other='')
```

```
rrlpy.models.rrlmod.plaw(x, x0, y0, alpha)
```

Returns a power law.

$$y(x) = y_0 \left( \frac{x}{x_0} \right)^\alpha$$

### Parameters

- **x** (*float or array like*) – x values for which to compute the power law.
- **x0** (*float*) – x value for which the power law has amplitude y0.
- **y0** (*float*) – Amplitude of the power law at x0.
- **alpha** (*float*) – Index of the power law.

**Returns** A power law of index *alpha* evaluated at x, with amplitude y0 at x0.

**Return type** float or array

```
rrlpy.models.rrlmod.str2val(str)
```

Converts a string representing a number to a float. The string must follow the IDL convention for floats.

**Parameters** **str** (*string*) – String to convert.

**Returns** The equivalent number.

**Return type** float

### Example

```
>>> str2val('2d2')
200.0
```

```
rrlpy.models.rrlmod.tau_CII(Te, R, nc, L, dnu)
```

Computes the optical depth of the far infrared line of CII. Crawford et al. (1985).

### Parameters

- **Te** (*float*) – Electron temperature.
- **R** (*float*) – Ratio of collisional excitation to spontaneous emission.
- **nc** (*float*) – Ionized carbon number density.
- **L** (*float*) – Path length.
- **dnu** (*float*) – Line width FWHM in Hz.

**Returns**

**Return type** float

`crrlpy.models.rrlmod.val2str(val)`

Converts a float to the string format required for loading the CRRL models.

**Parameters** `val` (*float*) – Value to convert to a string.

**Returns** The value of `val` represented as a string in IDL double format.

**Return type** `string`

**Example**

```
>>> val2str(200)
'2d2'
```

`crrlpy.models.rrlmod.valid_ne(line)`

Checks all the available models and lists the available `ne` values.

## CRRLPY.CRRLS.FREC\_CALC MODULE

`crrlpy.frec_calc.line_freq(Z, R_X, n, dn)`

Uses the Rydberg formula to get the frequency of a transition to quantum number  $n$  for a given atom.

### Parameters

- **Z** (*int*) – Charge of the atom.
- **R\_X** (*float*) –
- **n** (*int*) – Principal quantum number of the transition.  $n + \Delta n \rightarrow n$ .
- **dn** (*int*) – Difference between the principal quantum number of the initial state and the final state.  $\Delta n = n_f - n_i$ .

**Returns** The frequency of the transition in MHz.

**Return type** `float`

`crrlpy.frec_calc.main()`

Main body of the program. Useful for calling as a script.

`crrlpy.frec_calc.make_line_list(line, n_min=1, n_max=1500, unitless=True)`

Creates a list of frequencies for the corresponding line. The frequencies are in MHz.

### Parameters

- **line** (*string*) – Line to compute the frequencies for.
- **n\_min** (*int*) – Minimum  $n$  number to include in the list.
- **n\_max** (*int*) – Maximum  $n$  number to include in the list.
- **unitless** (*bool*) – If True the list will have no units. If not the list will be of `astropy.units.Quantity` objects.

**Returns** 3 lists with the line name, principal quantum number and frequency of the transitions.

**Return type** `list`

`crrlpy.frec_calc.set_dn(name)`

Sets the value of Delta  $n$  depending on the transition name.

**Parameters** **name** (*string*) – Name of the transition.

**Returns**  $\Delta n$  for the given transition.

**Return type** `int`

**Example**

```
>>> set_dn('CIalpha')
1
>>> set_dn('CIDelta')
4
```

`crrlpy.frec_calc.set_specie(specie)`

Sets atomic constants based on the atomic specie.

**Parameters** `specie` (*string*) – Atomic specie.

**Returns** Array with the atomic mass in a.m.u., ionization potential, abundance relative to HI,  $V_X - V_H$  and the electric charge.

**Example**

```
>>> set_specie('CI')
[12.0, 11.4, 0.0003, 149.5, 1.0]
```

`crrlpy.frec_calc.set_trans(dn)`

Sets a name depending on the difference between atomic levels.

**Parameters** `dn` (*int*) – Separation between  $n_i$  and  $n_f$ ,  $\Delta n = n_i - n_f$ .

**Returns** alpha, beta, gamma, delta or epsilon depending on  $\Delta n$ .

**Return type** *string*

**Example**

```
>>> set_trans(5)
'epsilon'
```

## INDICES AND TABLES

- `genindex`
- `modindex`
- `search`





**C**

`crrlpy.crrls`, 5  
`crrlpy.frec_calc`, 25  
`crrlpy.models.rrlmod`, 17

**r**

`rrlmod` (*Unix*), 17



**A**

alpha\_CII() (in module `crrlpy.models.rrlmod`), 18  
 alphanum\_key() (in module `crrlpy.crrls`), 5  
 average() (in module `crrlpy.crrls`), 5

**B**

best\_match\_indx() (in module `crrlpy.crrls`), 5  
 best\_match\_indx\_tol() (in module `crrlpy.crrls`), 5  
 best\_match\_value() (in module `crrlpy.crrls`), 6  
 beta\_CII() (in module `crrlpy.models.rrlmod`), 18  
 blank\_lines() (in module `crrlpy.crrls`), 6  
 blank\_lines2() (in module `crrlpy.crrls`), 6  
 broken\_plaw() (in module `crrlpy.models.rrlmod`), 18

**C**

chi() (in module `crrlpy.models.rrlmod`), 19  
`crrlpy.crrls` (module), 5  
`crrlpy.frec_calc` (module), 25  
`crrlpy.models.rrlmod` (module), 17

**D**

df2dv() (in module `crrlpy.crrls`), 6  
 dv2df() (in module `crrlpy.crrls`), 7  
 dv\_minus\_doppler() (in module `crrlpy.crrls`), 7  
 dv\_minus\_doppler2() (in module `crrlpy.crrls`), 7

**E**

eta() (in module `crrlpy.models.rrlmod`), 19

**F**

f2n() (in module `crrlpy.crrls`), 7  
 find\_lines\_sb() (in module `crrlpy.crrls`), 7  
 fit\_continuum() (in module `crrlpy.crrls`), 8  
 fit\_model() (in module `crrlpy.crrls`), 8  
 freq2vel() (in module `crrlpy.crrls`), 8  
 fwhm2sigma() (in module `crrlpy.crrls`), 8

**G**

gamma\_e\_CII() (in module `crrlpy.models.rrlmod`), 19  
 gamma\_h\_CII() (in module `crrlpy.models.rrlmod`), 19  
 gauss\_area() (in module `crrlpy.crrls`), 9

gauss\_area\_err() (in module `crrlpy.crrls`), 9  
 gaussian() (in module `crrlpy.crrls`), 9  
 get\_axis() (in module `crrlpy.crrls`), 9  
 get\_line\_mask() (in module `crrlpy.crrls`), 9  
 get\_line\_mask2() (in module `crrlpy.crrls`), 10  
 get\_min\_sep() (in module `crrlpy.crrls`), 10  
 get\_rchi2() (in module `crrlpy.crrls`), 10  
 get\_rms() (in module `crrlpy.crrls`), 10

**I**

I\_Bnu() (in module `crrlpy.models.rrlmod`), 17  
 I\_broken\_plaw() (in module `crrlpy.models.rrlmod`), 17  
 I\_CII() (in module `crrlpy.models.rrlmod`), 17  
 I\_CII\_rt() (in module `crrlpy.models.rrlmod`), 17  
 I\_cont() (in module `crrlpy.models.rrlmod`), 18  
 I\_external() (in module `crrlpy.models.rrlmod`), 18  
 I\_total() (in module `crrlpy.models.rrlmod`), 18  
 is\_number() (in module `crrlpy.crrls`), 10  
 itau() (in module `crrlpy.models.rrlmod`), 19  
 itau\_h() (in module `crrlpy.models.rrlmod`), 20  
 itau\_norad() (in module `crrlpy.models.rrlmod`), 20

**J**

j\_line\_lte() (in module `crrlpy.models.rrlmod`), 20

**K**

kappa\_cont() (in module `crrlpy.models.rrlmod`), 20  
 kappa\_cont\_base() (in module `crrlpy.models.rrlmod`), 20  
 kappa\_line() (in module `crrlpy.models.rrlmod`), 20  
 kappa\_line\_lte() (in module `crrlpy.models.rrlmod`), 20

**L**

level\_pop\_lte() (in module `crrlpy.models.rrlmod`), 21  
 line\_freq() (in module `crrlpy.frec_calc`), 25  
 linear() (in module `crrlpy.crrls`), 11  
 load\_betabn() (in module `crrlpy.models.rrlmod`), 21  
 load\_betabn\_h() (in module `crrlpy.models.rrlmod`), 21  
 load\_bn() (in module `crrlpy.models.rrlmod`), 21  
 load\_bn2() (in module `crrlpy.models.rrlmod`), 21  
 load\_bn\_all() (in module `crrlpy.models.rrlmod`), 21  
 load\_bn\_dict() (in module `crrlpy.models.rrlmod`), 21  
 load\_itau\_all() (in module `crrlpy.models.rrlmod`), 22

load\_itaug\_all\_hydrogen() (in module cr-  
rlpy.models.rrlmod), 22  
load\_itaug\_all\_match() (in module crrlpy.models.rrlmod),  
22  
load\_itaug\_all\_norad() (in module crrlpy.models.rrlmod),  
22  
load\_itaug\_dict() (in module crrlpy.models.rrlmod), 22  
load\_itaug\_nelim() (in module crrlpy.models.rrlmod), 23  
load\_model() (in module crrlpy.crrls), 11  
load\_models() (in module crrlpy.models.rrlmod), 23  
load\_ref() (in module crrlpy.crrls), 11  
load\_ref2() (in module crrlpy.crrls), 11  
lookup\_freq() (in module crrlpy.crrls), 11  
lorentz\_width() (in module crrlpy.crrls), 11

## M

main() (in module crrlpy.freq\_calc), 25  
make\_betabn() (in module crrlpy.models.rrlmod), 23  
make\_betabn2() (in module crrlpy.models.rrlmod), 23  
make\_line\_list() (in module crrlpy.freq\_calc), 25  
mask\_outliers() (in module crrlpy.crrls), 11  
Mdn() (in module crrlpy.models.rrlmod), 18

## N

n2f() (in module crrlpy.crrls), 12  
natural\_sort() (in module crrlpy.crrls), 12

## P

plaw() (in module crrlpy.models.rrlmod), 23  
plot\_fit() (in module crrlpy.crrls), 12  
plot\_fit\_single() (in module crrlpy.crrls), 12  
plot\_model() (in module crrlpy.crrls), 12  
plot\_spec\_vel() (in module crrlpy.crrls), 12  
pressure\_broad() (in module crrlpy.crrls), 12  
pressure\_broad\_coefs() (in module crrlpy.crrls), 12  
pressure\_broad\_salgado() (in module crrlpy.crrls), 12

## R

R\_CII() (in module crrlpy.models.rrlmod), 18  
radiation\_broad() (in module crrlpy.crrls), 12  
radiation\_broad\_salgado() (in module crrlpy.crrls), 12  
radiation\_broad\_salgado\_general() (in module cr-  
rlpy.crrls), 13  
rrlmod (module), 17

## S

set\_dn() (in module crrlpy.freq\_calc), 25  
set\_specie() (in module crrlpy.freq\_calc), 26  
set\_trans() (in module crrlpy.freq\_calc), 26  
sigma2fwhm() (in module crrlpy.crrls), 13  
sigma2fwhm\_err() (in module crrlpy.crrls), 13  
stack\_interpol() (in module crrlpy.crrls), 13  
stack\_irregular() (in module crrlpy.crrls), 13

str2val() (in module crrlpy.models.rrlmod), 23

## T

T\_CII() (in module crrlpy.models.rrlmod), 18  
tau\_CII() (in module crrlpy.models.rrlmod), 23  
temp2tau() (in module crrlpy.crrls), 13  
tryint() (in module crrlpy.crrls), 13

## V

val2str() (in module crrlpy.models.rrlmod), 23  
valid\_ne() (in module crrlpy.models.rrlmod), 24  
vel2freq() (in module crrlpy.crrls), 13  
voigt() (in module crrlpy.crrls), 14  
voigt\_() (in module crrlpy.crrls), 14  
voigt\_area() (in module crrlpy.crrls), 14  
voigt\_area\_err() (in module crrlpy.crrls), 14  
voigt\_fwhm() (in module crrlpy.crrls), 14  
voigt\_fwhm\_err() (in module crrlpy.crrls), 14  
voigt\_peak() (in module crrlpy.crrls), 14  
voigt\_peak2area() (in module crrlpy.crrls), 15  
voigt\_peak\_err() (in module crrlpy.crrls), 15