Gyrosynchrotron code with radiation transfer: input, output, and calling conventions

Guide for IDL users

The code is implemented as the Windows dynamic link libraries (`MWTransfer.dll`) and Linux shared objects (`MWTransfer.so`). These libraries contain two IDL-callable functions:

- `GET_MW` — the simplified function that calculates only the total intensity and circular polarization;
- `GetStokes` — the function that has more functionality and is able to calculate the full set of the Stokes parameters.

Internally, `GET_MW` is implemented as a call to `GetStokes`.

The gyrosynchrotron plasma emissivities and absorption coefficients are calculated using fast gyrosynchrotron codes (see `http://star.arm.ac.uk/~aku/GS/` for details). An user can choose between exact, continuous, and hybrid codes.

1 Function `GET_MW`

This function is called from IDL using the `call_external` function with the following syntax:

```
res=call_external(libname, 'GET_MW', Nz, Parms, RL, /f_value)
```

where `libname` is the name of the appropriate library, `Nz` is the number of volume elements along the line-of-sight (i.e., the number of points where the parameters of plasma, magnetic field, and energetic particles are specified), `Parms` is the array containing the emission source parameters (see below), and `RL` is the array receiving the computation results (see below).

1.1 Specifying the source parameters

The input parameter `Parms` is the two-dimensional ($29\times$`Nz`) single-precision floating point array. Each column of this array corresponds to a single volume element along the line-of-sight. For the volume element number `i` ($0 \le$ `i` $<$ `Nz`), the emission source parameters and the numerical code parameters are specified as follows (these parameters are the same as in the fast gyrosynchrotron codes for a homogeneous source, see `http://star.arm.ac.uk/~aku/GS/OnlineII.pdf`):

- `Parms[0, i]` is the visible source area S [cm^2].
  Only the value corresponding to the first volume element `Parms[0, 0]` *is considered.*
- `Parms[1, i]` is the length of the volume element along the line-of-sight Δz [cm].
- `Parms[2, i]` is the background plasma temperature T_0 [K].
- `Parms[3, i]` is the matching parameter ε in the thermal/nonthermal electron distributions.
- `Parms[4, i]` is the parameter $\varkappa$ in the kappa distribution.

- `Parms[5, i]` specifies the integration method and accuracy in the continuous gyrosynchrotron code.
  – If `Parms[5, i]` ≥ 1, then integration over energy is performed using the trapezoidal method with `Parms[5, i]` $+ 1$ nodes (rounded downwards to the nearest integer).
  – Otherwise, the Romberg method (with the default accuracy of 10^{-5}) is used.

- `Parms[6, i]` is the low-energy cutoff of the accelerated electrons $E_{\rm min}$ [MeV].

- `Parms[7, i]` is the high-energy cutoff of the accelerated electrons $E_{\rm max}$ [MeV].

- `Parms[8, i]` is the break energy $E_{\rm break}$ [MeV] in the double-power-law distribution.

- `Parms[9, i]` is the power-law index δ in the single-power-law distributions or the low-energy power-law index δ_1 in the double-power-law distribution.

- `Parms[10, i]` is the high-energy power-law index δ_2 in the double-power-law distribution.

- `Parms[11, i]` is the background plasma density n_0 [cm^{-3}].

- `Parms[12, i]` is the number density of fast electrons $n_{\rm b}$ [cm^{-3}].

- `Parms[13, i]` is the magnetic field B [G].

- `Parms[14, i]` is the angle between the magnetic field and the line-of-sight θ [degrees].

- `Parms[15, i]` is the starting frequency to calculate the emission spectrum f_0 [Hz].
  Only the value corresponding to the first volume element `Parms[15, 0]` *is considered.*

- `Parms[16, i]` is the logarithmic step in frequency Δ: the emission parameters are calculated at the logarithmically spaced frequency points, i.e. $f_1 = f_0 10^{\Delta}$, $f_2 = f_1 10^{\Delta}$, ...
  Only the value corresponding to the first volume element `Parms[16, 0]` *is considered.*

- `Parms[17, i]` specifies the type of the electron distribution over energy (index of the model distribution function); non-integer parameters are rounded downwards to the nearest integer.

- `Parms[18, i]` is the number of frequencies to calculate the emission spectrum N_f (non-integer parameters are rounded downwards to the nearest integer); the highest frequency equals $f_{N_f-1} = f_0 10^{(N_f-1)\Delta}$.
  Only the value corresponding to the first volume element `Parms[18, 0]` *is considered.*

- `Parms[19, i]` specifies the type of the electron distribution over pitch-angle (index of the model distribution function); non-integer parameters are rounded downwards to the nearest integer.

- `Parms[20, i]` is the loss-cone boundary $\alpha_{\rm c}$ [degrees] in the loss-cone distributions.

- `Parms[21, i]` is the beam direction α_0 [degrees] in the beam-like distributions.

- `Parms[22, i]` is the loss-cone boundary width or the beam angular width $\Delta\mu$ in the loss-cone or beam-like distributions, respectively.

- `Parms[23, i]` is the coefficient a_4 in the supergaussian pitch-angle distribution.

- `Parms[24, i]` *currently unused.*

- `Parms[25, i]` is the parameter $f_{\rm cr}^{\rm C}/f_{\rm B}$ (boundary frequency expressed in units of gyrofrequency) in the hybrid code.
  – If the emission frequency $f > f_{\rm cr}^{\rm C}$ then the emissivity and absorption coefficient are calculated using the continuous code.
  – If $f < f_{\rm cr}^{\rm C}$ then the code with summation over cyclotron harmonics is used.
  – If $f_{\rm cr}^{\rm C} = 0$ then the code becomes purely continuous.
  – If $f_{\rm cr}^{\rm C} < 0$ then the code is continuous. In addition, the continuous spectrum is renormalized using the exact parameters calculated at $f = f_{\rm cr}^{\rm WH}$ in order to improve accuracy.

- `Parms[26, i]` is the parameter $f_{\rm cr}^{\rm WH}/f_{\rm B}$ (boundary or renormalization frequency expressed in units of gyrofrequency) in the optimized hybrid code.
  – If $f_{\rm cr}^{\rm WH} < f < f_{\rm cr}^{\rm C}$ then the code with summation over cyclotron harmonics uses the approximated expressions for the Bessel functions.
  – If $f < f_{\rm cr}^{\rm C}$ and $f < f_{\rm cr}^{\rm WH}$ then the exact expressions for the Bessel functions are used.
  – If $f_{\rm cr}^{\rm C} < 0$ and $f_{\rm cr}^{\rm WH} > 0$ then the exact emission parameters calculated at $f = f_{\rm cr}^{\rm WH}$ are used to renormalize the spectrum obtained using the continuous code in order to improve accuracy.

- `Parms[27, i]` controls the behaviour of the hybrid code at the boundary frequencies:
  – If `Parms[27, i]` $\neq 0$ then the correction factors are applied to the emission spectrum to remove jumps at the frequencies $f_{\rm cr}^{\rm C}$ and (if necessary) $f_{\rm cr}^{\rm WH}$.
  – If `Parms[27, i]` $= 0$ then the spectrum is uncorrected and the jumps may appear.

- `Parms[28, i]` controls Q-optimization of the continuous code[1]:
  – If `Parms[28, i]` $\neq 0$ then the terms $(\ln Q)'$ and $(\ln Q)''$ are taking into account during calculations which improves accuracy.
  – If `Parms[28, i]` $= 0$ then the terms $(\ln Q)'$ and $(\ln Q)''$ are neglected which improves the computation speed.

The model distribution functions over energy and pitch-angle, their indices and parameters are described in `http://star.arm.ac.uk/~aku/GS/OnlineI.pdf`.

Since such parameters as the visible source area S, starting frequency f_0, frequency step Δ, and number of frequencies N_f refer to the whole emission source rather than to a single volume element, these parameters cannot vary along the line-of-sight. Actually, only the values corresponding to the first volume element are used. The values corresponding to other volume elements are ignored.

If the number of the volume elements `Nz` $= 1$ then the emission source is assumed to be homogeneous. In this case, the parameter `Parms` can be one-dimensional 29-element array with the same elements as described in `http://star.arm.ac.uk/~aku/GS/OnlineII.pdf`.

1.2 Calculation results

The results of calculation are stored in the two-dimensional single-precision floating-point array `RL` with $7 \times N_f$ elements (the number of frequencies N_f is given by `Parms[18, 0]`). This array must be created before calling `call_external`. After completion of the calculations, the array `RL` contains the following data:

- `RL[0, *]` is the N_f-element array of the emission frequencies f [GHz].

- `RL[1, *]` is the N_f-element array of the left-polarized emission intensities $I_f^{\rm (Lw)}$ [sfu] (calculated using the weak mode-coupling model).

[1] see `http://star.arm.ac.uk/~aku/GS/GS_FastCode.pdf`

- `RL[2, *]` is the N_f-element array of the right-polarized emission intensities $I_f^{(\mathrm{Rw})}$ [sfu] (calculated using the weak mode-coupling model).
- `RL[3, *]` is the N_f-element array of the left-polarized emission intensities $I_f^{(\mathrm{Ls})}$ [sfu] (calculated using the strong mode-coupling model).
- `RL[4, *]` is the N_f-element array of the right-polarized emission intensities $I_f^{(\mathrm{Rs})}$ [sfu] (calculated using the strong mode-coupling model).
- `RL[5, *]` is the N_f-element array of the left-polarized emission intensities $I_f^{(\mathrm{Le})}$ [sfu] (calculated using the exact mode-coupling model).
- `RL[6, *]` is the N_f-element array of the right-polarized emission intensities $I_f^{(\mathrm{Re})}$ [sfu] (calculated using the exact mode-coupling model).

All intensities are calculated under the assumption that the emission source is observed from the distance of one astronomical unit (e.g., it is located at the Sun and observed from the Earth).

1.3 Return value

The return value (`res`) can be one of the following:

- `res` = 0: no errors.
- `res` = 1: not enough arguments (three arguments are required).
- `res` = 2: not enough volume elements (`Nz` must be ≥ 1).
- `res` = 3: invalid parameters of the electron distribution function were encountered *(the parameter checking is not fully implemented yet, therefore some invalid parameter combinations can pass without notice).*

In case of an error (`res` $\neq 0$), the output array `RL` remains unchanged. Also note that an IDL-callable module is unable to check the type of the supplied arguments and if, e.g., the type or size of the arrays `Parms` and `RL` does not match exactly the above specifications, this can lead to an incorrect result or the system fault.

2 Function `GetStokes`

This function is called from IDL using the `call_external` function with the following syntax:

```
res=call_external(libname, 'GetStokes', Nz, Parms, RL, /f_value)
```

or

```
res=call_external(libname, 'GetStokes', Nz, Parms, RL, S, /f_value)
```

where `libname` is the name of the appropriate library, `Nz` is the number of integration nodes along the line-of-sight (i.e., the number of points where the parameters of plasma, magnetic field, and energetic particles are specified), `Parms` is the array containing the emission source parameters (see below), `RL` is the array receiving the computed intensities of the left- and right-polarized radiation, and `S` is the array receiving the computed Stokes parameters (see below).

If the parameter `S` is omitted, then the full set of the Stokes parameters is not computed and the function becomes similar to the above described function `GET_MW` (but with possibility to use open/closed intervals and vary $\Delta\eta$, see below).

2.1 Specifying the source parameters

The input parameter `Parms` is the two-dimensional ($34 \times$ `Nz`) single-precision floating point array. Each column of this array corresponds to a single point along the line-of-sight. For the point number `i` ($0 \leq$ `i` $<$ `Nz`), the emission source parameters and the numerical code parameters are specified as follows (these parameters are similar to those used by the function `GET_MW`, with only a few differences):

- `Parms[0, i]` is the visible source area S [cm^2].
  Only the value corresponding to the first point `Parms[0, 0]` *is considered.*

- `Parms[1, i]` can have two meanings:
  – If open intervals are used then `Parms[1, i]` is the length of the current volume element along the line-of-sight Δz [cm].
  – If closed intervals are used then `Parms[1, i]` is the coordinate of the current point along the line-of-sight z [cm].

- `Parms[2, i]` is the background plasma temperature T_0 [K].

- `Parms[3, i]` is the matching parameter ε in the thermal/nonthermal electron distributions.

- `Parms[4, i]` is the parameter $\varkappa$ in the kappa distribution.

- `Parms[5, i]` specifies the integration method and accuracy in the continuous gyrosynchrotron code.
  – If `Parms[5, i]` ≥ 1, then integration over energy is performed using the trapezoidal method with `Parms[5, i]` $+ 1$ nodes (rounded downwards to the nearest integer).
  – Otherwise, the Romberg method (with the default accuracy of 10^{-5}) is used.

- `Parms[6, i]` is the low-energy cutoff of the accelerated electrons $E_{\rm min}$ [MeV].

- `Parms[7, i]` is the high-energy cutoff of the accelerated electrons $E_{\rm max}$ [MeV].

- `Parms[8, i]` is the break energy $E_{\rm break}$ [MeV] in the double-power-law distribution.

- `Parms[9, i]` is the power-law index δ in the single-power-law distributions or the low-energy power-law index δ_1 in the double-power-law distribution.

- `Parms[10, i]` is the high-energy power-law index δ_2 in the double-power-law distribution.

- `Parms[11, i]` is the background plasma density n_0 [cm^{-3}].

- `Parms[12, i]` is the number density of fast electrons $n_{\rm b}$ [cm^{-3}].

- `Parms[13, i]` is the magnetic field B [G].

- `Parms[14, i]` is the angle between the magnetic field and the line-of-sight θ [degrees].

- `Parms[15, i]` is the starting frequency to calculate the emission spectrum f_0 [Hz].
  Only the value corresponding to the first point `Parms[15, 0]` *is considered.*

- `Parms[16, i]` is the logarithmic step in frequency Δ: the emission parameters are calculated at the logarithmically spaced frequency points, i.e. $f_1 = f_0 10^{\Delta}$, $f_2 = f_1 10^{\Delta}$, ...
  Only the value corresponding to the first point `Parms[16, 0]` *is considered.*

- `Parms[17, i]` specifies the type of the electron distribution over energy (index of the model distribution function); non-integer parameters are rounded downwards to the nearest integer.

- `Parms[18, i]` is the number of frequencies to calculate the emission spectrum N_f (non-integer parameters are rounded downwards to the nearest integer); the highest frequency equals $f_{N_f-1} = f_0 10^{(N_f-1)\Delta}$.
  Only the value corresponding to the first point `Parms[18, 0]` *is considered.*

- `Parms[19, i]` specifies the type of the electron distribution over pitch-angle (index of the model distribution function); non-integer parameters are rounded downwards to the nearest integer.

- `Parms[20, i]` is the loss-cone boundary α_c [degrees] in the loss-cone distributions.

- `Parms[21, i]` is the beam direction α_0 [degrees] in the beam-like distributions.

- `Parms[22, i]` is the loss-cone boundary width or the beam angular width $\Delta\mu$ in the loss-cone or beam-like distributions, respectively.

- `Parms[23, i]` is the coefficient a_4 in the supergaussian pitch-angle distribution.

- `Parms[24, i]` *currently unused.*

- `Parms[25, i]` is the parameter f_{cr}^{C}/f_B (boundary frequency expressed in units of gyrofrequency) in the hybrid code.
  – If the emission frequency $f > f_{cr}^{C}$ then the emissivity and absorption coefficient are calculated using the continuous code.
  – If $f < f_{cr}^{C}$ then the code with summation over cyclotron harmonics is used.
  – If $f_{cr}^{C} = 0$ then the code becomes purely continuous.
  – If $f_{cr}^{C} < 0$ then the code is continuous. In addition, the continuous spectrum is renormalized using the exact parameters calculated at $f = f_{cr}^{WH}$ in order to improve accuracy.

- `Parms[26, i]` is the parameter f_{cr}^{WH}/f_B (boundary or renormalization frequency expressed in units of gyrofrequency) in the optimized hybrid code.
  – If $f_{cr}^{WH} < f < f_{cr}^{C}$ then the code with summation over cyclotron harmonics uses the approximated expressions for the Bessel functions.
  – If $f < f_{cr}^{C}$ and $f < f_{cr}^{WH}$ then the exact expressions for the Bessel functions are used.
  – If $f_{cr}^{C} < 0$ and $f_{cr}^{WH} > 0$ then the exact emission parameters calculated at $f = f_{cr}^{WH}$ are used to renormalize the spectrum obtained using the continuous code in order to improve accuracy.

- `Parms[27, i]` controls the behaviour of the hybrid code at the boundary frequencies:
  – If `Parms[27, i]` $\neq 0$ then the correction factors are applied to the emission spectrum to remove jumps at the frequencies f_{cr}^{C} and (if necessary) f_{cr}^{WH}.
  – If `Parms[27, i]` $= 0$ then the spectrum is uncorrected and the jumps may appear.

- `Parms[28, i]` controls Q-optimization of the continuous code[2]:
  – If `Parms[28, i]` $\neq 0$ then the terms $(\ln Q)'$ and $(\ln Q)''$ are taking into account during calculations which improves accuracy.
  – If `Parms[28, i]` $= 0$ then the terms $(\ln Q)'$ and $(\ln Q)''$ are neglected which improves the computation speed.

[2] see `http://star.arm.ac.uk/~aku/GS/GS_FastCode.pdf`

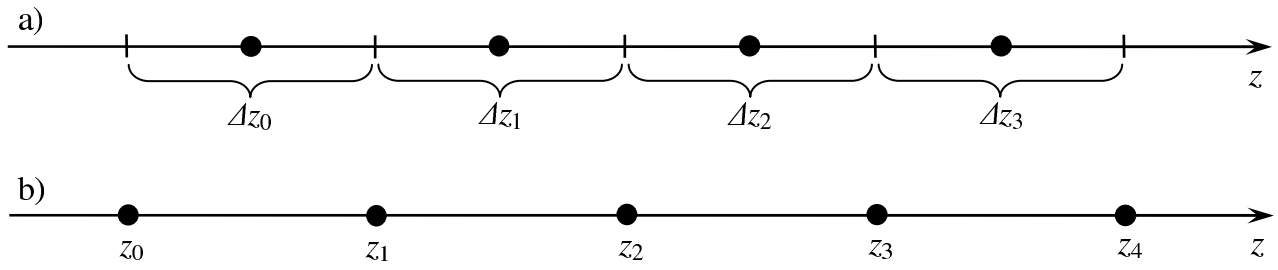

Figure 1: Two methods of describing the source stratification along the line-of-sight: open (a) and closed (b) intervals.

- `Parms[29, i]` is the azimuthal angle of the magnetic field relative to the chosen reference plane ψ [degrees].

- `Parms[30, i]` is the minimal integration step $\Delta z_{\min}$ [cm]. If the integration step along the line-of-sight during calculation of the Stokes parameters falls below $\Delta z_{\min}$ then the calculations are stopped and the Stokes parameters at the given frequency are set to zeros. *Only the value corresponding to the first point* `Parms[30, 0]` *is considered.*

- `Parms[31, i]` controls the informational messages:
  – If `Parms[31, i]` $\neq 0$ then the messages describing the current status of the computation process are displayed in the respective IDL window.
  – If `Parms[31, i]` $= 0$ then the informational messages are off.
  Only the value corresponding to the first point `Parms[31, 0]` *is considered.*

- `Parms[32, i]` switches between the open and closed intervals along the line-of-sight (see below):
  – If `Parms[32, i]` $\neq 0$ then closed intervals are used.
  – If `Parms[32, i]` $= 0$ then open intervals are used.
  Only the value corresponding to the first point `Parms[32, 0]` *is considered.*

- `Parms[33, i]` is the parameter $\Delta\eta$. If the emission propagates almost across or along the magnetic field (so that $|\cos\theta| \ll 1$ or $|\sin\theta| \ll 1$) then the viewing angle specified by `Parms[14, i]` may be corrected in order to avoid numerical errors and provide compatibility with other codes. Namely, if $|\cos\theta| < \Delta\eta$ then $\cos\theta$ is replaced by $\pm\Delta\eta$ and $\sin\theta$ is replaced by $\pm\sqrt{1-\Delta\eta^2}$ where the signs are chosen according to the original quadrant of the angle θ; similar corrections are applied if $|\sin\theta| < \Delta\eta$.
  – If `Parms[33, i]` ≤ 0 or `Parms[33, i]` ≥ 1 then the default value of $\Delta\eta = 10^{-3}$ is used.

If all the parameters `Parms[29:33, *]` equal zero and the argument `S` is omitted then the function `GetStokes` behaves exactly like `GET_MW`.

The model distribution functions over energy and pitch-angle, their indices and parameters are described in `http://star.arm.ac.uk/~aku/GS/OnlineI.pdf`.

Since such parameters as the visible source area S, starting frequency f_0, frequency step Δ, number of frequencies N_f, minimal integration step $\Delta z_{\min}$, messaging mode, and type of intervals refer to the whole emission source rather than to a single point or volume interval, these parameters cannot vary along the line-of-sight. Actually, only the values corresponding to the first point are used. The values corresponding to other points are ignored.

The parameter `Parms[32, 0]` controls how the values given by `Parms[1, *]` are interpreted (see Fig. 1). If `Parms[32, 0]` $= 0$ then open intervals are used (like in the function `GET_MW`). In this case, `Parms[1, *]` are the lengths of the intervals (volume elements) along the line-of-sight Δz_i and the parameters of plasma, magnetic field, and energetic electrons are assumed to

correspond to the centers of the respective intervals. All lengths Δz_i must be positive and the number of intervals `Nz` must be ≥ 1.

If `Parms[32, 0]` $\neq 0$ then closed intervals are used. In this case, `Parms[1, *]` are the coordinates of the points along the line-of-sight z_i and the parameters of plasma, magnetic field, and energetic electrons are specified at these points (that is, at the boundaries of the intervals). The coordinates z_i must be monotonically increasing and the number of points `Nz` must be ≥ 2.

2.2 Calculation results

The results of calculation are stored in the two-dimensional single-precision floating-point arrays `RL` with $7 \times N_f$ elements and `S` with $5 \times N_f$ elements (the number of frequencies N_f is given by `Parms[18, 0]`). These arrays must be created before calling `call_external`. The array `RL` is the same as for the function `GET_MW`; after completion of the calculations, it contains the following data:

- `RL[0, *]` is the N_f-element array of the emission frequencies f [GHz].
- `RL[1, *]` is the N_f-element array of the left-polarized emission intensities $I_f^{(\mathrm{Lw})}$ [sfu] (calculated using the weak mode-coupling model).
- `RL[2, *]` is the N_f-element array of the right-polarized emission intensities $I_f^{(\mathrm{Rw})}$ [sfu] (calculated using the weak mode-coupling model).
- `RL[3, *]` is the N_f-element array of the left-polarized emission intensities $I_f^{(\mathrm{Ls})}$ [sfu] (calculated using the strong mode-coupling model).
- `RL[4, *]` is the N_f-element array of the right-polarized emission intensities $I_f^{(\mathrm{Rs})}$ [sfu] (calculated using the strong mode-coupling model).
- `RL[5, *]` is the N_f-element array of the left-polarized emission intensities $I_f^{(\mathrm{Le})}$ [sfu] (calculated using the exact mode-coupling model).
- `RL[6, *]` is the N_f-element array of the right-polarized emission intensities $I_f^{(\mathrm{Re})}$ [sfu] (calculated using the exact mode-coupling model).

If specified, the array `S` contains the following data:

- `S[0, *]` is the N_f-element array of the emission frequencies f [GHz].
- `S[1, *]` is the N_f-element array of the values of the Stokes parameter I [sfu].
- `S[2, *]` is the N_f-element array of the values of the Stokes parameter Q [sfu].
- `S[3, *]` is the N_f-element array of the values of the Stokes parameter U [sfu].
- `S[4, *]` is the N_f-element array of the values of the Stokes parameter V [sfu].

If the integration step along the line-of-sight during calculation of the Stokes parameters falls below $\Delta z_{\min}$ then the Stokes parameters at the corresponding frequency are set to zeros. Similarly, if the emission frequency falls below the X-mode cutoff frequency somewhere along the ray trajectory then the Stokes parameters at that frequency are set to zeros.

All intensities and Stokes parameters are calculated under the assumption that the emission source is observed from the distance of one astronomical unit (e.g., it is located at the Sun and observed from the Earth).

2.3 Return value

The return value (`res`) can be one of the following:

- `res` = 0: no errors.
- `res` = 1: not enough arguments (at least three arguments are required).
- `res` = 2: not enough integration nodes (`Nz` must be ≥ 1 for the model with open intervals and ≥ 2 for the model with closed intervals).
- `res` = 3: invalid parameters of the electron distribution function were encountered *(the parameter checking is not fully implemented yet, therefore some invalid parameter combinations can pass without notice).*
- `res` = 4: integration error was encountered during calculation of the Stokes parameters (integration step below $\Delta z_{\min}$).

In case of an error ($1 \leq$ `res` ≤ 3), the output arrays remain unchanged. The value of `res` = 4 indicates that only some of the output values were calculated (intensities of the left- and right-polarized emissions at all frequencies and, possibly, the Stokes parameters at some frequencies). Also note that an IDL-callable module is unable to check the type of the supplied arguments and if, e.g., the type or size of the arrays `Parms`, `RL`, and `S` does not match exactly the above specifications, this can lead to an incorrect result or the system fault.