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# CHIANTI

An Astrophysical Database for Emission Line Spectroscopy

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The CHIANTI total radiative recombination rate files (rrparams)

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# 1 Overview

This document describes the format for the CHIANTI `rrparams` file, which contains the parameters used to compute the total radiative recombination coefficient for an ion.

Sect. 2 describes the format of the `rrparams` file, and Sect. 3 describes the IDL routine that reads the file and computes the recombination rate.

Note that for CHIANTI the ion name *always corresponds to the recombining ion*, so the `o_6.rrparams` file contains data for the recombination of O VI to form O V.

## 2 File format

Radiative recombination data are typically fit with a parametric fitting formula. The type of formula has varied in past publications and is discussed below.

The `rrparams` file contains only two lines of data. The first line, with a format of “i5” is an integer giving the type of the fitting formula used. The second line contains the fit parameters themselves, and these are summarized in Table 1. The second line always begins with the atomic number and spectroscopic number of the recombining ion.

Table 1: The `rrparams` file formats.

Type	Format	Parameter
All	i5	Atomic number
	i5	Spectroscopic number (e.g., 13 for “XIII”)
Type 1	i5	Unknown (!)
	e12.3	$A$
	f10.5	$B$
	e12.3	$T_0$
	e12.3	$T_1$
Type 2	i5	Unknown (!)
	e12.3	$A$
	f10.5	$B$
	e12.3	$T_0$
	e12.3	$T_1$
	f10.5	$C$
Type 3	e12.3	$A_{\text{rad}}$
	e12.3	$\eta$

Types 1 and 2 have a third column containing an unknown data parameter. It seems this is always set to 1. The code `recomb_rate.pro` (Sect. 3) does not use this parameter.

Type 1 is a 4-parameter fitting formula first introduced by Verner & Ferland (1996) and the

recombination rate is represented by

$$\alpha_{\text{RR}}(T) = A \left[ \sqrt{T/T_0} \left( 1 + \sqrt{T/T_0} \right)^{1-B} \left( 1 + \sqrt{T/T_1} \right)^{1+B} \right]^{-1} \quad (1)$$

where  $T$  is temperature and  $A$ ,  $B$ ,  $T_0$  and  $T_1$  are the four fitting parameters.

Type 2 is a modification of the Type 1 formula suggested by Gu (2003), who introduced two additional parameters  $C$  and  $T_2$  and modified  $B$  to

$$B \rightarrow B + C \exp(-T_2/T) \quad (2)$$

This is used for low-charge ions, for example, N II.

Type 3 is the simplest of the fitting formulae, first used by Aldrovandi & Pequignot (1973), and it represents the RR rate by

$$\alpha_{\text{RR}}(T) = A_{\text{rad}} \left( \frac{T}{10^4} \right)^{-\eta} \quad (3)$$

### 3 The IDL routine `recomb_rate.pro`

The routine `recomb_rate.pro` returns the *total* (dielectronic + radiative) recombination rate for the specified ion. It is called as

```
IDL> rate = recomb_rate ( ion_name, temp )
```

where `ion_name` is the name of the *recombining* ion in the CHIANTI format (e.g., ‘fe\_13’ for Fe XIII, and `temp` is an array of temperatures.

To return only the radiative recombination rate, the call is

```
IDL> rate = recomb_rate ( ion_name, temp, /radiative )
```

For clarity, if the ion is given as ‘o.6’, then the returned rate will be for O<sup>5+</sup> ions recombining to form O<sup>4+</sup>.

## 4 Data sources

In this section we describe the data sources for the RR rates in CHIANTI. The information is up-to-date with regard CHIANTI 7.1.

### 4.1 Badnell data

A consistent set of radiative recombination data for all ions of all elements up to and including zinc along all isoelectronic sequences up to sodium have been published by Badnell (2006b), and these are incorporated into CHIANTI. (This covers iron ions from Fe XXVII to Fe XVI.) Most rates were fit with the Type 1 formula, and the rest (mainly low-charge ions) with the Type 2 formula.

The data-set is available at [http://amdpp.phys.strath.ac.uk/tamoc/RR/clist\\_K](http://amdpp.phys.strath.ac.uk/tamoc/RR/clist_K), and the latest version at the time of writing is dated 12-Apr-2011.

Additional data for the Mg, Al and Ar-like sequences (Fe xv, Fe xiv and Fe ix, respectively) were taken from Altun et al. (2007), Abdel-Naby et al. (2012) and Nikolić et al. (2010), respectively. Rates only for Fe viii are from Schmidt et al. (2008). RR rates for Fe x, Fe xi, Fe xii, Fe xiii and are taken from Badnell (2006a).

All of the above rates are in CHIANTI v7.1.

## 4.2 Other ions

The Badnell data-sets cover all ions in the sequences up to and including Mg-like, as well as Al-like and Ar-like, and the few additional iron ions discussed in the previous section. Data for the remaining ions is very scarce in the literature and mostly derived through interpolation.

There is one data-set with direct calculations for a small number of ions that we use for CHIANTI. Aldrovandi & Pequignot (1974) provide RR rates for all ions of Na, Al, P, Cl and Ar in an extension of earlier work of Aldrovandi & Pequignot (1973). The rates for P ii, Cl ii–iv and Ar ii–v have been used for CHIANTI. Aldrovandi & Pequignot (1974) also give rate coefficients for Ca ii and these have been used. For CHIANTI the Aldrovandi & Pequignot (1974) rates have been fit with the 4 parameter formula of Verner & Ferland (1996) except where this fit fails to reproduce any one of the data points by less than 6 %. In this case the 6 parameter formula of Gu (2003) was used.

For all remaining ions we use the fitting parameters of D. A. Verner that are available as part of a Fortran subroutine available at <http://www.pa.uky.edu/~verner/fortran.html>. These parameters cover all ions of all isoelectronic sequences up to zinc, and were also used by Mazzotta et al. (1998) in their compilation. However, Mazzotta et al. (1998) used version 3a of the subroutine whereas the version used here is 4. The difference lies in the fit parameters for the ions Fe ii–xvi where the original Woods et al. (1981) data were re-fitted with the Verner & Ferland (1996) fitting formula to ensure correct asymptotes at low and high temperatures. The data sources used in the Verner subroutine and not superceded by the Badnell et al. datasets are discussed below.

Woods et al. (1981) provided recombination rates for all of the iron ions, thus covering recombination onto Al-like to Fe-like ions. This single data-set is responsible for the recombination rates of *all* ions of *all* sequences beyond Mg-like in the compilations of Shull & van Steenberg (1982), Arnaud & Rothenflug (1985), Arnaud & Raymond (1992) and Mazzotta et al. (1998). Shull & van Steenberg (1982) used the Woods et al. (1981) data-set to extrapolate to Ar, Ca and Ni ions, although the source of data for Ni and Ni<sup>+</sup> (for which Fe data could not be extrapolated) was not stated.

Landini & Monsignori Fossi (1990) provided extrapolations of the Shull & van Steenberg (1982) fits to Na and Al ions, and Landini & Fossi (1991) extrapolations to F, P, Cl, K, Ti, Cr, Mn and Co. We note, however, that Landini & Fossi (1991) did not publish fits for (recombination onto) Ti i–ii, Cr i–iv, Mn i–v, and Co i. Mazzotta et al. (1998) published ion fractions for all ions of all elements up to Zn and so this required new data for V, Sc, Cu and Zn. No details were given as to where these data came from, and no fits were provided.

## References

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## A Example files

This appendix gives examples of Type 1, Type 2 and Type 3 files.

Type 1 file (O VI):

```
1
8 6 1 1.7240e-10 0.65560 3.3720e+02 1.0300e+07
-1
%file: o_6.rrparams
Radiative recombination coefficients
Badnell, N. R., 2006, ApJS, 167, 334
http://adsabs.harvard.edu/abs/2006ApJS..167..334B
Radiative Recombination Data for Modeling Dynamic Finite-Density Plasmas
produced for the CHIANTI atomic database for astrophysical spectroscopy
created by Ken Dere (GMU): Wed Feb 15 11:06:18 2012
-1
```

Type 2 file (N II):

```
2
7 2 1 6.3870e-10 0.73080 9.4670e-02 2.9540e+06 0.24400 6.7390e+04
-1
%file: n_2.rrparams
Radiative recombination coefficients
Badnell, N. R., 2006, ApJS, 167, 334
http://adsabs.harvard.edu/abs/2006ApJS..167..334B
Radiative Recombination Data for Modeling Dynamic Finite-Density Plasmas
produced for the CHIANTI atomic database for astrophysical spectroscopy
created by Ken Dere (GMU): Wed Feb 15 11:06:27 2012
-1
```

Type 3 file (Ni IV):

```
3
28 4 1.4000e-12 7.0000e-01
-1
%file: ni_4.rrparams
% radiative recombination parameters, interpolated from:
Shull, J. M., Van Steenberg, M., 1982, ApJSS, 48, 95
Landini, M., Monsignori Fossi, B. C., 1990, A&ASS, 82, 229
Landini, M., Monsignori Fossi, B. C., 1991, A&ASS, 91, 183
Mazzitelli, G., Mattioli, M., 2002, ADNDT, 82, 313
produced for the CHIANTI atomic database for astrophysical spectroscopy
created by Ken Dere (GMU): Thu Feb 8 12:16:39 2007
-1
```