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Analysis Tools for Nebular Emission Lines

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Abstract. The nebular analysis package in STSDAS has been substantially enhanced, and now includes several new ions and diagnostics, as well as updated atomic data for all supported ions. In addition, new tasks are being added to compute, from ratios of recombination lines, certain nebular physical parameters and the abundances of He^{+} and He^{+2} relative to H^{+}.

1. Introduction

The **nebular** analysis package is a set of applications within IRAF/STSDAS for computing physical parameters in emission line nebulae (such as electron density, N_e, and temperature, T_e), as well as ionic abundances of several elements relative to ionized hydrogen. **Nebular** also provides utilities for exploring the range of validity of the diagnostics themselves, and for employing them in the context of a very simple nebular model. Several enhancements to the package have been implemented since the original descriptive paper by Shaw & Dufour (1995) was published, and the major new features are described here.

2. New Ions and Atomic Data

Thirteen new ions of C, N, O, Ne, Na, Mg, Al, Si, S, Cl, K, and Ca have been added to the set of 21 previously supported in **nebular**. As a consequence, 15 new diagnostics for N_e and T_e are available, and they span a much greater range of density, temperature, and ionization than in the previous version. The full set of supported ions and diagnostics can be found from the **nebular** home page[1]. Several new features have also been added, including the capability to compute collisional line emissivities from up to eight (rather than the five previously supported) atomic levels, depending upon the availability of the supporting atomic data. These low-lying levels arise from the same electron configurations as the ground level. The atomic data for the various lines have been updated to the best, most recent available as of mid-1996. These data have been appearing in the literature at a rapid rate, owing to the success of the IRON project (Hummer et al. 1993), a concerted international effort to compute precise atomic data for iron-group ions of astrophysical interest. The collision strengths in particular

[1] http://ra.stsci.edu/nebular/

have been computed for most ions over a much wider range of T_e, and are more accurate by factors of 3 to 10. This improvement in the data quality permits the calculation of reliable diagnostics over a much greater range of T_e and N_e. The references to the atomic data are too numerous to include here (though they are given in the **nebular** help documentation), but in general are at least as recent as those given in the compilation by Pradhan and Peng (1995).

The T_e and N_e diagnostics of collisionally excited lines that are typically used in the literature derive from ratios of specific line intensities (or ratios of sums of intensities) which have a reasonably high emissivity, consistent with being very sensitive to the diagnostic in question. These line intensity ratios are generally the same for ions with a given ground state electron configuration. Table 1 lists the line ratios that are traditional in this sense, where the notation $I_{i \to j}$ refers to the intensity of the transition from level i to j. The correspondence of wavelength and transitions between energy levels for a given ion can be found by running the *ionic* task.

Table 1. Traditional Diagnostic Ratios

Ground Configuration	Diagnostic	Traditional Ratio
s^2	N_e	$I_{4\to1} / I_{3\to1}$
	T_e	$(I_{4\to1} + I_{3\to1}) / I_{5\to1}$
p^1	N_e	$I_{5\to2} / I_{4\to2}$
p^2	T_e	$(I_{4\to2} + I_{4\to3}) / I_{5\to4}$
p^3	N_e	$I_{3\to1} / I_{2\to1}$
	T_e	$(I_{2\to1} + I_{3\to1}) / (I_{4\to1} + I_{5\to1})$
	T_e[a]	$(I_{2\to1} + I_{3\to1}) / (I_{5\to3} + I_{5\to2} + I_{4\to3} + I_{4\to2})$
p^4	T_e	$(I_{4\to1} + I_{4\to2}) / I_{5\to4}$

[a]For N^0 and O^+.

Note that these traditional diagnostic ratios are not the only viable ratios to use: some ratios, though perhaps not as sensitive to the diagnostic in question, are useful if the spectral coverage or resolution is limited; others are simply better for some purposes, such as the T_e-sensitive [O III] ratio $I(1660+1666)/I(4363)$. Some **nebular** tasks, such as *temden* and *ntcontour*, now allow the user to specify a transition other than the traditional (default) one.

3. Recombination Lines

The **nebular** package will soon include new tasks to accommodate the analysis of recombination lines. Atomic data for H^+, He^+, and He^{+2} have been incorporated from Storey & Hummer (1995). Specifically, we adopt their tabulations of emissivities, ϵ, separately for Case A and Case B recombination. (The code interpolates in log-T_e, log-ϵ for intermediate values within their grid.) The *recomb* task will solve for the interstellar reddening and/or T_e, given a list of recombination line intensities for a single ion. The *rec_abund* task will compute the abundance of these ions with respect to H^+ from a list of recombination lines. The *abund* task, which computes abundances from collisional lines in the context of a simple model, is being enhanced to include the ionic abundance calculations from recombination lines as well.

4. Exploration of the Diagnostics

The *ntcontour* task has been substantially enhanced, and is now more useful for exploring new or traditional diagnostics from collisionally excited lines. This task computes and plots curves that show the range of T_e, N_e, and/or intensity ratios that are consistent with a specified diagnostic. A family of secondary curves may optionally be plotted, where each curve may be specified explicitly or as a set of successive, small differences from the reference ratio, giving the appearance of contours. Though for all ions there are default diagnostics for N_e and/or T_e, it is possible to customize the diagnostic to the ratio of any of the supported transitions. In addition, the diagnostics may be plotted as N_e vs. T_e, N_e vs. I_{line}, and T_e vs. I_{line}. This task may be run interactively, so that it is possible to investigate many diagnostics quickly. *Ntcontour* is particularly useful for determining the range of N_e and T_e where a particular diagnostic is sensitive, for investigating non-traditional diagnostics, and for estimating the consequences of a given level of uncertainty in an observed line ratio. Figure 1 shows an example plot of the default density-sensitive ratio for Al II.

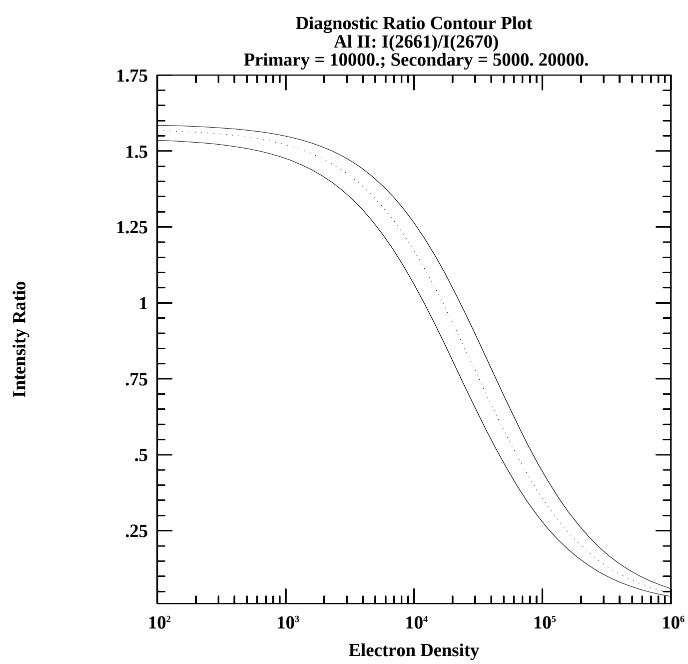

Figure 1. Ratio of [Al II] $I(2661)/I(2670)$ vs. N_e using *ntcontour*.

5. Software Features

The **nebular** package has been substantially re-designed, and is largely table-driven. For example, the atomic reference data are encapsulated in FITS binary tables, and the data pedigree (including literature references) are documented in header keywords. Fits to the collision strengths as a function of T_e are evaluated at run-time, so that the reference tables contain data in a form much as it appears in the literature. These features provide great flexibility for anyone to substitute improved atomic data, and allow for easy extensibility of the package to accommodate high-quality data for more ions as they become available.

The data and associated functional fits for one or more atoms/ions of interest are collected into persistent in-memory objects during the course of program execution. The diagnostics for N_e and T_e are stored internally as strings containing algebraic relations (in a form not unlike those given in Table 1), and are evaluated at run-time. These features allow much greater flexibility in the applications to make use of relations between ions, such as the comparison of physical diagnostics from similar ions, or the computation of relative abundances.

6. Software Availability

In their sum, the applications in the **nebular** package are a valuable set of tools for nebular analysis: the derived quantities can be used directly or as input to full photo-ionization models. Most of the enhancements described here have already been incorporated into V2.0 of the **nebular** package; the new tasks for analysis of recombination lines will be available in the next release. **Nebular** is publically available, and is included in the STSDAS external package; the new version will be found under the **analysis** package in STSDAS V2.0 and later. Users who do not have STSDAS may obtain the new version for personal installation from the **nebular** ftp[2] area. Note that **nebular** V2.0 requires that IRAF V2.10.4 (or later) and TABLES V2.0 (or later) be installed. Some of the tasks may alternatively be run via the Web from an HTML forms interface: view the **nebular** home page for details.

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[2]ftp://ra.stsci.edu/pub/nebular/