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AtomNeb: IDL Library for Atomic Data of Ionized Nebulae

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Software

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Summary

Ionized gaseous nebulae are interstellar clouds of hydrogen-rich materials, which are photo-ionized by ultraviolet radiation from stars, making them visible in multi-wavelength bands. Ionized nebulae can be used as an astrophysical tool to trace the chemical composition of the interstellar medium in our Galaxy and other galaxies, and to study mixing processes in stellar evolution. Spectra emitted from ionized nebulae generally contain collisionally excited and recombination lines. Electron temperatures, electron densities, and ionic abundances can be determined from *collisionally excited lines* (CEL) by solving statistical equilibrium equations using collision strengths (Ω_{ij}) and transition probabilities (A_{ij}) of ions. Moreover, physical conditions and chemical abundances can be calculated from *recombination lines* (RL) using effective recombination coefficients ($\alpha_{\rm eff}$) of ions. The atomic data, i.e. Ω_{ij}, A_{ij}, and $\alpha_{\rm eff}$, are used to calculate line emissivities in nebular spectral analysis tools (e.g. Howarth & Adams (1981); Shaw & Dufour (1994); Shaw, de La Pena, Katsanis, & Williams (1998); Luridiana, Morisset, & Shaw (2015); Howarth et al. (2016); Danehkar (2018a)), and photoionization codes (e.g. Ferland et al. (1998); Kallman & Bautista (2001); Ercolano, Barlow, Storey, & Liu (2003); Ercolano, Barlow, & Storey (2005); Ercolano, Young, Drake, & Raymond (2008)). Hence, the atomic data for collisional excitation and recombination process are essential to determine physical conditions and elemental abundances of ionized nebulae from collisionally excited and recombination lines (see e.g. Danehkar, Parker, & Ercolano (2013); Danehkar, Todt, Ercolano, & Kniazev (2014); Danehkar (2014); Danehkar, Parker, & Steffen (2016); Danehkar (2018b)).

`AtomNeb` is a database containing atomic data stored in the Flexible Image Transport System (FITS) file format (Wells, Greisen, & Harten (1981); Hanisch et al. (2001); Pence, Chiappetti, Page, Shaw, & Stobie (2010)) produced for nebular spectral analysis. FITS tables provide easy access to atomic data for spectral analysis tools. Especially, `AtomNeb` includes the atomic data for both the *collisional excitation* and *recombination* process of ions usually observed in nebular astrophysics. The `AtomNeb` interface library is equipped with several application programming interface (API) functions written in the Interactive Data Language (IDL) for reading the atomic data from the `AtomNeb` FITS files. Furthermore, the `AtomNeb` IDL library can be employed in the GNU Data Language (GDL) (Arabas, Schellens, Coulais, Gales, & Messmer (2010); Coulais et al. (2010)), an open-source free compiler for IDL codes.

- The API functions for the *CEL atomic data* developed in the IDL programming language were designed to easily read *collision strengths* (Ω_{ij}) and *transition probabilities* (A_{ij}) of given ions, which can be used to derive electron temperatures,

electron densities, and ionic abundances from measured fluxes of collisionally excited lines. The CEL data include energy levels (E_j), collision strengths (Ω_{ij}), and transition probabilities (A_{ij}) from the CHIANTI database version 5.2 (Landi et al. (2006)), version 6.0 (Dere et al. (2009)), and version 7.0 (Landi, Del Zanna, Young, Dere, & Mason (2012)), which were compiled according to the atomic data used in the FORTRAN program `MOCASSIN` (Ercolano et al. (2003); Ercolano et al. (2005); Ercolano et al. (2008)). The CEL data also include a collection compiled based on the atomic data used in the Python package `pyNeb` for spectral analysis (Luridiana et al. (2015)).

- The API functions for the *RL atomic data* developed in IDL were designed to provide easy access to *effective recombination coefficients* ($\alpha_{\rm eff}$) and *branching ratios* (Br) of recombination lines of given ions. The RL data include effective recombination coefficients for C II (Davey, Storey, & Kisielius (2000)), N II (Escalante & Victor (1990)), O II (Storey (1994); Liu, Storey, Barlow, & Clegg (1995)), and Ne II (Kisielius, Storey, Davey, & Neale (1998)), which were compiled based on the atomic data in `MOCASSIN`. The RL data also include hydrogenic ions for Z=1 to 8 (Storey & Hummer (1995)), effective recombination coefficients for H, He, C, N, O, and Ne ions (Pequignot, Petitjean, & Boisson (1991)), effective recombination coefficients for He I (Porter, Ferland, Storey, & Detisch (2012); Porter, Ferland, Storey, & Detisch (2013)), effective recombination coefficients for N II (Fang, Storey, & Liu (2011); Fang, Storey, & Liu (2013)), and effective recombination coefficients for O II (Storey, Sochi, & Bastin (2017)).

The `AtomNeb` IDL/GDL package uses the FITS file related IDL procedures from the IDL Astronomy User's library (Landsman (1993); Landsman (1995)) to read the atomic data from the `AtomNeb` FITS files. The API functions of the `AtomNeb` IDL library, together with the `proEQUIB` IDL library (Danehkar (2018a)), can be used to perform plasma diagnostics and abundance analysis of nebular spectra emitted from ionized gaseous nebulae.

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