Upgrading Diagnostic Diagrams

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Abstract:

Diagnostic diagrams of forbidden lines have been a useful tool for observers to obtain information on the basic physical properties of thin gaseous nebulae in astrophysics for many decades now. Moreover they are also the initial tool to derive thermodynamic properties of the plasma from observations to get ionization correction factors and thus proper abundances of the nebulae. Some are in wavelength domains which were difficult to take either due to missing wavelength coverage or due to low resolution of older spectrographs. Furthermore, most of them are calculated using just the species involved as a single atom gas, although some of them are affected by well-known fluorescence mechanisms as well. Also atomic data improves with time. The new diagnostic diagrams were calculated by using large grids of parameter space in the photoionization code CLOUDY. For a given basic parameter the input radiation field was varied to find those solutions with cooling heating equilibrium. Empirical numerical functions were fitted to provide formulas usable in e.g. data reduction pipelines. The resulting diagrams differ significantly from those used up to now.

Our setup:

To derive the electron temperature T_e, at least two metastable levels above the ground level with different energies are required. In contrast to the determination of the electron densities described below, the collisional de-excitation must not play a role here. This boundary condition is often overlooked by observers when using the classical diagnostic diagrams in dense environments as well. Typical representatives are [OIII] (4959Å+5007Å)/4363Å using the exponential approximation in Osterbrock & Ferland (2006, thereafter OF06) and [ArIII] (7135Å+7751Å)/5192Å, published in Keenan et al. (1988). As shown by Izotov et al. (2006) and Nicholls et al. (2012), especially the widely used exponential law of [OIII] suffers from the approximations of temperature independent collision strengths.

To derive the electron density n_e, a pair of lines with nearly the same excitation state is chosen. When density increases, the lines with longer lifetimes are affected by collisional de-excitation first. The major representatives for these diagrams are [SII] 6716Å/6732Å in the calibration of OF06 and [OII] 3726Å/3729Å by Pradhan et al. (2006). The latter pair is difficult to observe due to the small distance between the lines. Both ions have ionization energies (from the lower state) close to that of hydrogen. The line pair of [ArIV] 4711Å/4740Å, calibrated by Stanghellini & Kaler (1989, hereinafter SK89), is sparsely used. The blue line of the pair is very near to a He I emission. On the other hand this ionization state fits much better to the often used temperature determination using [OIII].

The three latest versions of the photoionization code CLOUDY, namely C08, C10 and C13, are used for our calculations (Ferland et al. 2013). CLOUDY gives a very sophisticated framework, containing a large set of physical interactions in plasmas with mixed chemistry. Therefore the stellar temperature or the luminosity is varied until this equilibrium is found. We find no major variations, except for [OIII] we find differences worth to be included properly. We attribute this to the effects of the Bowen fluorescence. The whole parameter space is scanned. Up to about 100 models are calculated for every data point along the curve and thus a few thousand models per curve. A dedicated C program is written as a wrapper around the whole setup for the selection of the appropriate equilibrium results. The final curves were fitted by empirical functions to give the observers a directly applicable formula.

As a next step we want to examine more closely the [NII] lines (6548Å+6584Å)/5755Å. Those lines are fairly strong and therefore often included by observers in their spectral investigations. The diagrams are more difficult to calculate than those shown here, and require a different setup.

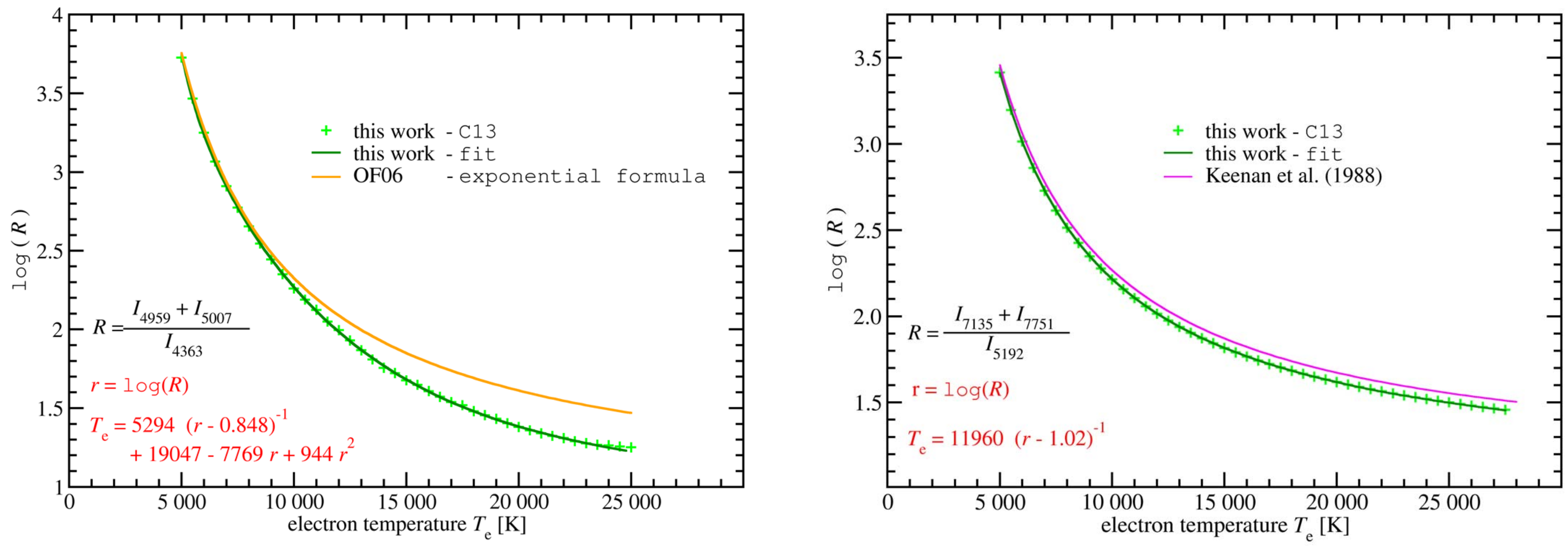

Fig.1: The diagnostic diagrams for determining the electron temperature T_e. Especially the widely used exponential formula given in OF06 significantly deviates from our new CLOUDY result. For [OIII] we were unable to find heating-cooling equilibria with photoionized plasma above 24000 K by illuminating the model nebula with a stellar radiation field.

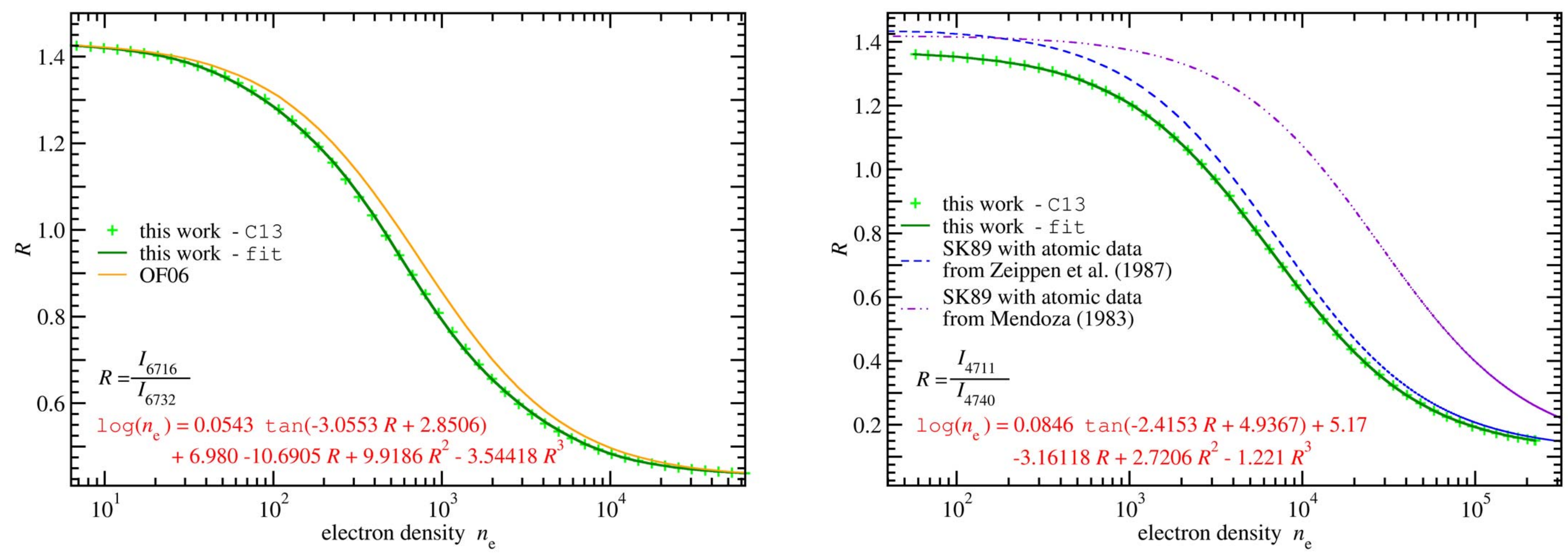

Fig.2: The diagnostic diagrams for determining the electron density n_e (for T_e = 10000K). The OF06 result for [SII] is identical with our result, using our setup with C08. The older [ArIV] calibration should no longer at all be used.

Results:

Although diagnostic diagrams are not a replacement for a full model (e.g. using CLOUDY), they are widely used by observers for initial interpretation of the data. The presentation of straight applicable formulas to go from the observables to the physical property is an additional add-on for the users. The full investigation, including the temperature dependency of the diagrams for n_e, will be subject of a forthcoming paper.

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