Low-Metallicity Star Formation:
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Ionized gas in dwarf galaxies: Abundance indicators

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Abstract. We discuss the four basic methods to derive HII region abundances in metal-poor galaxies by presenting a few recent results obtained with these methods. We end up by commenting on the yet unsolved problem of temperature fluctuations in HII regions, which may plague abundance determinations, as well as the discrepancy between abundances derived from recombination lines and collisionally excited lines, to which inhomogeneous chemical composition might be the explanation.

Keywords. (ISM:) HII regions, galaxies: abundances, galaxies: dwarf

1. Introduction

The ionized gas provides the best way to determine elemental abundances in dwarf galaxies. We present and discuss the four basic methods to derive abundances from HII regions, using examples drawn from the recent literature.

2. Te-based methods

When the data allow the determination of the electron temperature (Te) *directly* from the spectra (generally using the [O III] λ4363/[O III] λ5007 ratio), ionic abundances are readily obtained from observed emission line intensities, since these are proportional to the abundances and to the Te-dependent line emissivities. Generally, the lines that are used for abundance determinations are the strongest ones in the spectrum, which are collisionally excited forbidden lines for the heavy elements, and recombination lines for H and He. The abundances of the elements are then obtained by applying ionization correction factors, derived from simple considerations or from photoionization model grids. Izotov *et al.* (2006) have provided a series of analytical formulae to derive abundances with such methods, based on photoionization models for giant HII regions using the stellar energy distributions computed using Starburst 99 (Leitherer *et al.* 1999) with the updated model atmospheres by Smith *et al.* (2002).

In Figure 1, we show an example of a result obtained with Te-based abundance determinations in HII regions and planetary nebulae belonging to two Magellanic irregular galaxies: NGC 3109 and the Small Magellanic Clouds (Peña *et al.* 2007). The figure shows that the oxygen abundances are remarkably similar in all of the HII regions of each galaxy. The scatter is 0.07 dex and 0.09 dex, respectively. This implies that mixing has been very strong in the interstellar medium of these galaxies. Such a result is obtained due to the quality of the observations and the accuracy of the method. One can also see that the range in oxygen abundances for the planetary nebulae is significantly larger. This is due to a combination of nucleosynthesis processes in the planetary nebula progenitors and to chemical evolution of the galaxies.

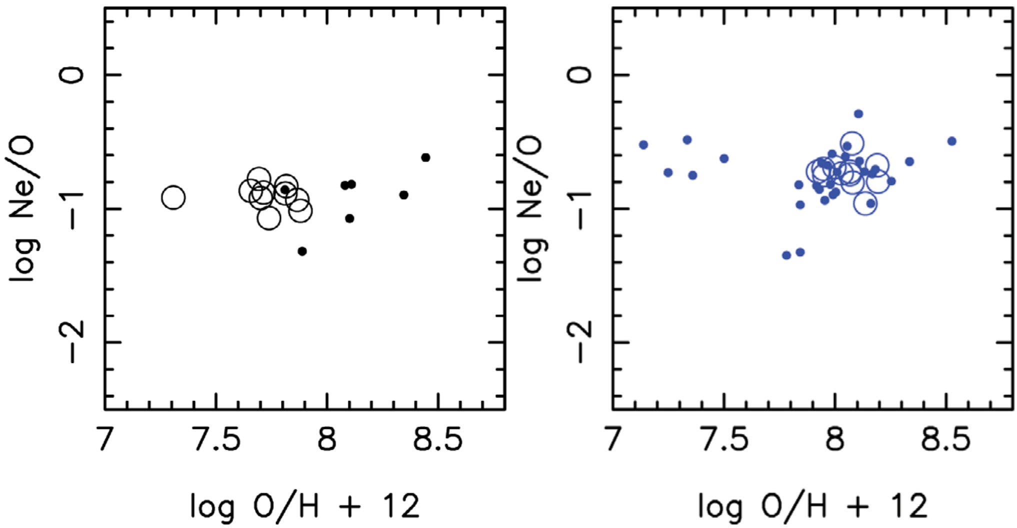

Figure 1. HII regions (large circles) and planetary nebulae (small points) in two Magellanic irregular galaxies: NGC 3109 (left) and the Small Magellanic Cloud (right).

3. Strong line methods

When the [O III] λ4363 line is not observed, the metallicity can still be estimated using *statistical* methods, based on strong lines only. These methods take advantage of the fact that the metallicity appears to be strongly linked to the mean effective temperature of the stellar radiation field and to the ionization parameter, U, of the nebula. As a result, in first approximation, one can consider that the strong line spectrum of a giant HII region is essentially determined by the metallicity.

Strong line methods have to be calibrated. In the low metallicity regime, which is the one of interest for dwarf galaxies, calibration is relatively easy, since one can use giant HII regions in which the weak [O III] λ4363 line has been measured (in the high metallicity regime, the calibration is more difficult, and less reliable).

Strong line methods are expected to be less accurate than Te-methods. Moreover, they can be biased, if applied to a category of objects that do not share the same structural properties as the sample which was used to calibrate the method.

The various panels of Fig. 2 show the values of different line ratios used as metallicity indicators as a function of 12 + log O/H. These are: [Ne III] λ3869/[O III] λ5007, proposed by Nagao *et al.* (2006), ([O II] λ3727 + [O III] λ5007)/Hβ, introduced by Pagel *et al.* (1979), [O III] λ5007/[N II] λ6584, first proposed by Alloin *et al.* (1979), [S III] λ9069/[O III] λ5007, proposed by Stasińska (2006), [O III] λ5007/[O II] λ3727, considered by Nagao *et al.* (2006), and [N II] λ6584/Hα, first used by Storchi Bergmann *et al.* (1994). The curves drawn with symbols correspond to sequences of photoionization models ionized by blackbody radiation (for simplicity) with varying metallicities (i.e. the abundances of all the heavy elements vary in step with that of oxygen, except nitrogen whose abundance increases more rapidly with O/H to mimic secondary nitrogen production). The curves drawn with circles correspond to models of different ionization parameters, with larger symbols representing larger ionization parameters. The curves drawn with triangles correspond to an effective temperature, $T_{\rm eff}$ of 60,000 K, the curves drawn with circles correspond to $T_{\rm eff}$ = 50,000 K and the curves drawn with squares to 40,000 K. Clearly, some of the indicators vary very little – if at all – with O/H. Rather, they depend on $T_{\rm eff}$ and on U. The thick curves correspond to the calibrations of these abundance indicators as given by Nagao *et al.* (2006) (except for [S III] λ9069/[O III] λ5007 which is given by Stasińska 2006). Figure 2 shows that the metallicity dependence of these metallicity indicators is largely due to the variation of effective temperature and ionization parameter with metallicity. If then such metallicity indicators are used to compare the abundances of two samples that are expected to be characterized by systematically different values of effective temperature and/or ionization parameter, the interpretation in terms of abundances may be wrong.

This is likely the case in a recent study by Sanchez *et al.* (2008) aiming at the characterization of two groups of galaxies: blue compact dwarf (BCD) galaxies selected from the Sloan Digital Sky Survey (SDSS), and quiescent blue compact dwarf (QBCD) galaxies, also selected from the SDSS on the basis of photometric criteria mainly. Using the [N II] λ6584/Hα index, these authors find that QBCDs have larger HII region-based oxygen abundances than BCDs, a property difficult to explain in terms of galactic chemical evolution. However, by definition, QBCDs are expected to have cooler exciting stars than BCDs, since the most massive stars have already disappeared. It is also likely that the ionization parameter in QBCD HII regions is smaller than those in BCDs. Indeed, the total number of ionizing photons from an ageing star burst decreases in time and, in addition, the HII region is expected to be more extended at larger ages due to expansion. Both factors increase the value of [N II] λ6584/Hα at a given metallicity: thus the O/H abundance derived using the same calibration line as for BCDs will result in overestimated abundances, as seen in Fig. 2.

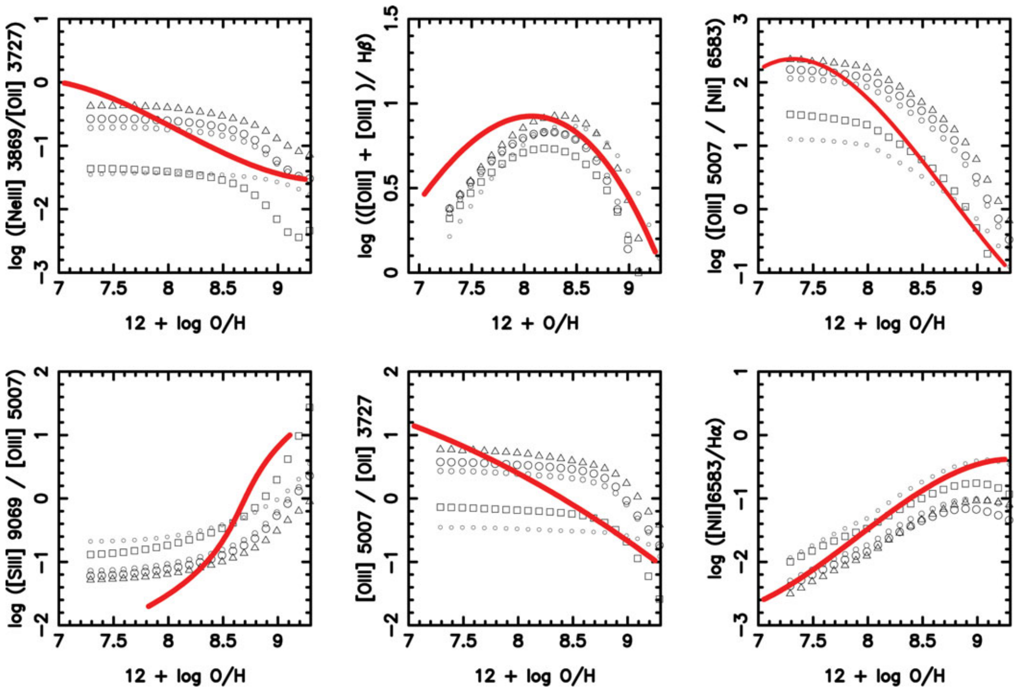

Figure 2. The values of different line ratios used as metallicity indicators as a function of 12 + log O/H for sequences of photoionization models. Triangles: $T_{\rm eff}$ =60,000 K; circles: $T_{\rm eff}$ = 50,000 K; squares $T_{\rm eff}$ = 40,000 K. The symbol sizes indicate the ionization parameters, with larger symbols representing larger ionization parameters. The thick curves correspond to the calibrations of these abundance indicators as given by Nagao *et al.* (2006).

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4. Comparison to grids of photoionization models

It is often considered that, in the cases where the electron temperature cannot be obtained directly from the spectra, abundances derived by comparison with grids of photoionization models are more reliable than abundances obtained by strong line methods. The idea behind such an opinion is that photoionization models take into account the physics of interaction of the photons with nebular matter and predict trustworthy emission line intensities.

There are, however, a number of conditions to be fulfilled before abundances derived in such a way can be considered reliable.

First of all, as is obvious, the grid must be built by varying all the important independent parameters that determine the spectrum of an HII region. Second, the grid must be adequately meshed. It is preferable that the grid contains the entire range of observed line ratios, so that extrapolations are not needed. The possibility of multiple solutions must be clearly identified and conveniently dealt with.

Another important aspect is the criteria chosen for fitting a given object. The common procedure is to use a χ^2 method on (a subset of) line ratios. This is potentially dangerous and may lead to important biases in the derived abundances. A good example of such biases is the determination of oxygen abundances in emission line galaxies from the Sloan Digital Sky Survey by Tremonti *et al.* (2004). These authors compared the intensities of the strongest emission lines in these objects (Hα, Hβ, [O II] λ3727, [O III] λ5007, [N II] λ6584, [S II] λ6716, λ6731) with a grid of 2×10^5 photoionization models computed by Charlot & Longhetti (2001) and corresponding to different assumptions about the effective gas parameters (metallicity, ionization parameter, dust-to-gas ratio, star formation histories etc...). Yin *et al.* (2007) showed the presence of an important offset between the values of O/H derived by Tremonti *et al.* (2004) and those derived directly with the classical Te-based method. In addition, they found that the offset strongly correlated with N/O. This led them to point out that, since in Tremonti *et al.* (2004), all the lines are used simultaneously, any difference in an abundance ratio with the ratio used in the Charlot & Longhetti (2001) models has the potential of causing offsets. They attribute the difference between the O/H values determined by Tremonti *et al.* (2004) and those obtained with the Te-method to the crude way in which secondary nitrogen enrichment is treated in the Charlot & Longhetti (2001) grid.

5. Tailored model-fitting

Tailored-model fitting is a better way to obtain abundances, but it is obviously a more complicated process. As explained in Stasińska (2007), however, here also a number of conditions must be fulfilled. One is that the model must reproduce *all* of the emission lines that bear information on the physical conditions in the ionized gas, and not only the strongest lines. The other is that the observed lines must allow a full abundance diagnostic (which is not always the case): very different solutions are possible if there is no diagnostic of the electron temperature.

It is sometimes difficult to fit detailed observations with a photoionization model. Then the abundances are not obtained with the required accuracy. One such example is the case of the extremely metal-poor blue compact galaxy, I Zw 18. Stasińska & Schaerer (1999) found it impossible to reproduce the observed [O III] λ4363/5007 ratio with a model that had a geometry reflecting the gross features in the Hα image, and that was powered by a radiation obtained from stellar population synthesis models fitting the observed stellar data. The best models yielded a [O III] λ4363/5007 ratio too low by about 30%, leading

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to an uncertainty in the O/H ratio by about 20% in this case. In view of uncertainties generally quoted for abundance determinations, this may seem unimportant. However, I Zw 18 is an exemplary test case, where one should be able to fit the data perfectly. Péquignot (2008) reconsidered the problem, and introduced the presence of diffuse matter between ionized filaments, in a way similar to the model adopted by Jamet *et al.* (2005). It turns out that such a model can explain the observed spectrum in most of its details. A propitious circumstance is that, in the meantime, collisional strengths for the excitation of Lyman lines of hydrogen have been recomputed and turn out to be lower than the ones used by Stasińska & Schaerer, making cooling less efficient. It is however not clear whether the model by Péquignot (2008) can reproduce the high electron temperatures observed even at large distances from the exciting cluster by Vílchez & Iglesias-Páramo (1998). The comparison of the works by Stasińska & Schaerer (1999) and Péquignot (2008) leads to an interesting remark: prior to modelling, the observational data must be analyzed critically; this is a difficult task, and the views adopted by several authors may differ in details that turn out to be important to constrain the models.

6. Old, unsolved problems in ionized nebulae affecting abundance determinations

It has long been known that nebular temperatures derived from various indicators are different. While nebulae are not expected to be exactly isothermal, the observed differences are larger than expected from photoionization models. Peimbert (1967) postulated the existence of temperature fluctuations to account for these differences, and developed a formalism to estimate the magnitude of these fluctuations from observations using his famous parameter t^2. Peimbert & Costero (1969) showed that ignoring t^2 in abundance derivations led to an underestimate of the abundances and proposed a formalism to account for this t^2. Since then, the nebular astronomical community is divided as to the reality of temperature fluctuations in HII regions. While numerous studies point towards a value of t^2 typically of 0.03-0.04, little direct evidence is seen. Perhaps the most convincing direct observational argument is provided by the high spatial resolution imaging of the Orion nebula by O'Dell *et al.* (2003).

Recently, the derivation of the electron temperatures from recombination lines of O^{++} allowed an independent determination of t^2, by comparison with the temperature derived from [O III] λ4363/5007 (see García-Rojas & Esteban 2007 and references therein). However, it has been argued that the different temperatures derived for O^{++} could in fact be due to an inhomogeneous chemical composition, with oxygen-rich clumps embedded in a medium of "normal" chemical composition (Tsamis *et al.* 2003, Tsamis & Péquignot 2005). Such clumps could be produced by the scenario of Tenorio-Tagle (1996) for the enrichment of the interstellar medium by supernova ejecta. One may ask what is the meaning of the derived abundances in this case. Stasińska *et al.* (2007) have examined this question and found that, at least in the cases they considered, optical recombination lines strongly overestimate the average oxygen abundance, while collisionally excited lines overestimate them only slightly. Peimbert *et al.* (2007) do not share this point of view, and argue that the correct oxygen abundances in HII regions are those derived from recombination lines which, in the case of metal-rich objects, lead to values about twice as large than when derived from collisionally excited lines.

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