The impact of nitrogen-to-oxygen ratio on photoionization model-based abundances

Enrique Pérez Montero
Instituto de Astrofísica de Andalucía - CSIC
Granada, Spain

Understanding nebular emission in high-z galaxies. Pasadena. July 13-17 2015
Nitrogen in gas phase of galaxies

N is one of the most abundant coolants in gas-phase of galaxies.

Its trace can be easily seen in the optical spectrum of HII regions thanks to the emission lines at 6548 and 6584 Å, close to Hα.
Origin of nitrogen and relation with oxygen

N is mainly produced via the CNO cycle in low and intermediate mass stars as a secondary product (i.e. it depends on O abundance). The O/H vs. N/O relation at $12+\log(O/H) > 8.0$ is monotonically increasing for many objects evolving as a closed box, but it presents in fact a large dispersion ...

Pérez-Montero & Contini (2009)

The impact of N/O on photoionization model abundances. E. Pérez Montero
The dispersion of the O/H vs. N/O relation

In closed-box chemical evolution models, N/O can significantly vary as a function of star formation efficiency.

For scenarios of outflows of enriched gas or inflows of metal-poor gas, N/O remains unaffected, while metallicity deviates from the expected closed-box yield.

The impact of N/O on photoionization model abundances. E. Pérez Montero
Since many diagnostic based on [NII] assume a typical SFE in a CB model, deviations from this scenario cannot be properly identified (e.g. AGN selection in BPT diagrams).

Pérez-Montero & Contini (2009)
Strong-line calibrators to derive O/H based on [NII] lines are widely used (e.g. N2, O3N2, N2O2) but they all based on the same assumptions, but these have only statistical value … and they are not alway valid for the family of objects we want to study.

The impact of N/O on photoionization model abundances. E. Pérez Montero
How to calculate N/O

N2O2 is the best way way to calculate N/O in absence of an auroral line. It has the advantage that it does not depend on U, and this is why it is widely used as a proxy of O/H, assuming a fixed O/H vs. N/O law.

$$N2O2 = \log \left[ \frac{I([N\,\Pi]6584 \text{ Å})}{I([O\,\Pi]3727 \text{ Å})} \right]$$
and an alternative for high-z galaxies

N2S2 is the best option for objects with a limited wavelength coverage and it reduces the dependence on reddening or flux calibration.

\[ N2S2 = \log \left( \frac{I([N\text{II}]6584\text{Å})}{I([S\text{II}]6717, 6731\text{Å})} \right) \]

The impact of N/O on photoionization model abundances. E. Pérez Montero
The strange case of green pea galaxies

GPs are very compact (2-3 kpc diameter) dominated by their prominent emission lines (EW([OIII]) > 100). They are UV luminous and with low reddening. Are they analogs to the high-z building blocks?

Cardamone et al. (2009) used N2O2 to conclude they are metal-rich, what it is unexpected. They show prominent [OIII] 4363 and [NII] 6584 fluxes.

They are metal-poor objects with a very high N/O (Amorín et al. 2010, 2012).

The impact of N/O on photoionization model abundances. E. Pérez Montero
Wolf-Rayet stars can produce local N pollution but integral field spectroscopy of metal-poor SF galaxies with oversolar N shows chemical homogenous patterns of several kpc.

Then interactions with metal-poor clouds that trigger SF, decrease Z, but keeps N/O high look natural.
A combined inspection of the MZR and the MNOR gives a detailed diagnostics of the chemical evolution of star-forming galaxies as it is the case of green peas.

Amorín et al. 2010

The impact of N/O on photoionization model abundances. E. Pérez Montero
Relations with the total stellar mass

For the rest of star-forming galaxies this situation translates in that the MNOR does not depend on SFR.


The impact of N/O on photoionization model abundances. E. Pérez Montero
The situation of high-z galaxies

At high redshift, this could be the situation of most of the sampled star-forming galaxies.

At $z = 1.5$ all the star-forming galaxies detected using Subaru imaging + follow up IR observations of emission lines point to an overabundance of N/O, but consistent with their stellar mass.
A new method should work for all metallicity regimes, using different sets of emission lines and deliver both O/H and N/O. This can only be achieved using models.

Ideally, it should be also consistent with the direct method if no additional physical assumptions are taken in the models (e.g. shocks, kappa distribution, t fluctuations, same atomic coefficients, etc ...)

The impact of N/O on photoionization model abundances. E. Pérez Montero
The grid of models was calculated using:

- **Cloudy v. 13.03** (Ferland et al. 2013)
- **POPSTAR** (Mollá et al. 2010) model stellar atmospheres (same Z as the gas, age = 1 Myr, Chabrier IMF)
- Constant density
- Radiation-bounded geometry
- All elements scaled to O, except N
- Standard MW dust-to-gas ratio
- Variation of input parameter:
  - $12+\log(O/H)$: [7.1, 9.1] 0.1bin
  - $\log(N/O)$: [-2.0, 0.0] 0.125bin
  - $\log U$: [-4.00, -1.50] 0.25bins

This gives a total of 3,927 models

The impact of N/O on photoionization model abundances. E. Pérez Montero
HII-CHI-mistry (Pérez-Montero 2014, http://www.iaa.es/~epm/HII-CHI-mistry.html) is a code to derive O/H, N/O and log U using a $\chi^2$ weighted mean of the differences with the reddening corrected [OII], [OIII] (4363 and 5007), [NII] and [SII] optical emission lines.

**STEP 1**

N/O is calculated using as observables adequate emission-line ratios (e.g. N2O2, N2S2) insensitive to O/H and U

$$\log(N/O)_f = \frac{\sum_i \log(N/O)_i / \chi_i}{\sum_i 1 / \chi_i},$$

Errors are calculated as the standard deviation of the weighted distribution

$$\Delta \log(N/O))^2 = \frac{\sum_i \log((N/O)_f - \log(N/O)_i)^2 / \chi_i}{\sum_i 1 / \chi_i}.$$

**STEP 2**

The grid of models is constrained for the closest values of N/O and [NII] can be used in a new iteration to derive O/H and log U in a similar way.

$$12 + \log(O/H)_f = \frac{\sum_k (12 + \log(O/H))_k / \chi_k}{\sum_k 1 / \chi_k}$$

$$\log U_f = \frac{\sum_k \log U_k / \chi_k}{\sum_k 1 / \chi_k}.$$
HII-CHI-mistry was evaluated using chemical abundances re-calculated following the direct method (PyNeb; Luridiana+ 2012) for the sample of objects presented by Marino+ (2013).

The agreement both for O/H and N/O when all emission lines are considered, including [OIII] 4363, is excellent.

Observables: RO3, [OIII], [OIII], [NII], [SII]
Models: complete grid

Observables: RO3, N2O2, N2S2
Models: complete grid

The impact of N/O on photoionization model abundances. E. Pérez Montero
In absence of the \([\text{OIII}]\) auroral line, it is not possible to recover the abundances derived from the direct method except if a constrained grid of models is assumed in the calculations.

An empirical constraint in the plane \(\text{O/H} \text{ vs. log } U\) is found for the local objects that can be also applied to the objects with no estimate of the electron temperature.
Strategies when N/O cannot be derived

In case no emission-line ratio sensitive to N/O can be measured (e.g. N2O2, N2S2), the script cannot constrain the input space of parameters and the constrain is assumed following an empirical average.

However, it must be kept in mind that deviations of this law can lead to wrong metallicity derivations (e.g. green peas)

The impact of N/O on photoionization model abundances. E. Pérez Montero
HII-CHI-mistry is especially useful for sets of data with different available emission lines and/or covering a wide range of metallicity variation (e.g. MZR, spiral gradients ...).

In the case of M101, HCM enables to determine O/H both in the inner metal-rich regions with no auroral lines (Kennicutt+1996) and the outer metal-poor HII regions (Kennicutt+2003) and taking N/O variations into account.

The impact of N/O on photoionization model abundances. E. Pérez Montero
Similar results are found for N/O between N/O from different strong-line methods (e.g. N2O2 and N2S2) and HII-CHI-mistry.

By inspecting N/O we can see that the nature of SDH323 (at 1.2 times the effective radius) is metal-poor with high N/O.
Florido+ (2015) have analyzed the centres of close spiral galaxies with and without a bar. They conclude that the higher N2 observed in barred objects is owing to a higher N/O and not to a higher O/H, contrary to the results obtained by Ellison+ (2011).

This N/O difference can be possibly due to a different SFE influenced by the gas flows driven by the bar.

The impact of N/O on photoionization model abundances. E. Pérez Montero
The application of HCM to more than 10,000 pure HII regions detected in a sample of more than 300 spiral galaxies in CALIFA allows us to study the spatial variation both for O/H and N/O (Pérez-Montero+ in prep.)

The dispersion in the O/H vs. N/O diagram for individual HII regions is much higher than the values at the effective radius once the gradients are calculated for non-interacting galaxies (rho changes from 0.35 to 0.77).
Relation between slopes and stellar mass

Both the slopes for O/H and N/O do not depend on galaxy size, once they are normalized with the effective radius, but both the MZR and the MNOR are recovered with very low dispersion using the characteristic values.
Extremely metal-poor galaxies (XMPs; 12+ log(O/H) < 7.69) can be key objects to understand the epoch of the formation of the first galaxies. Are they young/little evolved objects or old systems undergoing violent SF?

A search for XMPs with a cometary aspect (tadpoles) and very deep OSIRIS-GTC observations of both their bright knot of SF and weak low surface brightness tail gives us the possibility to measure chemical variations across these objects (Sanchez Almeida+ submitted)

The impact of N/O on photoionization model abundances. E. Pérez Montero
XMP cometary galaxies observed with GTC

We have used GTC+WHT optical spectroscopy to study metallicity profiles in cometary XMP. HCM allows its consistent derivation in the bright knots and in the faint tails that confirm the interchange with metal-poor gas from the cosmic web.
Similar strategies for the ultraviolet

Carbon has a quite similar behavior than nitrogen, and their lines dominate the spectrum in the UV. Model-based abundances using UV lines have to acquaint for C/O. HII-CHI-mistry is coming soon ... (Pérez-Montero in prep.).
Don’t use [NII] to derive O/H if you don’t know N/O. The dispersion in the O/H vs. N/O relation is large and gives important clues on the evolution of galaxies.

Deriving N/O is possible with N2O2 and N2S2, but the best way is using HII-CHI-mistry, consistent with the direct method even in the absence of auroral lines and valid with different sets of available emission-lines.

So far, HCM helped us to see an overabundance of N/O in the centers of barred galaxies (Florido+), to calculate gradients in CALIFA galaxies (Pérez-Montero+) and to dissect abundance profiles in extremely metal poor galaxies (Sánchez Almeida+).