Highlights of Spanish Astrophysics VI, Proceedings of the IX Scientific Meeting of the Spanish Astronomical Society held on September 13 - 17, 2010, in Madrid, Spain. M. R. Zapatero Osorio et al. (eds.)

The chemical composition of ionized gas in galaxies

Jose M. Vilchez[1]

[1] Instituto de Astrofísica de Andalucía (CSIC), Glorieta de la Astronomía s/n, 18008 Granada, Spain

Abstract

Active star formation in galaxies takes place in HII regions harbouring young massive stars within an extended ionized gaseous component. Their relative structural simplicity and characteristic emission line spectrum make them ideal laboratories to study the physical properties and chemical composition of gas and stars in galaxies. Chemical abundances can be derived for Galactic and relatively nearby extragalactic HII regions, as well as for distant galaxies, applying different techniques. In this talk an overview of the derivation of chemical abundances for HII regions in galaxies is presented, with an emphasis on the different domains of spatial resolution covered by the data, from spatially resolved integral field spectra of HII regions in the Milky Way and nearby galaxies to integrated spectra of more distant galaxies. With the upcome of the new integral field spectrographs a wide coverage at good spatial sampling of galaxies and HII complexes is now possible. This new 2D spectroscopy provides us more realistic information and useful constrains to study the chemical enrichment process of the interstellar medium and some of the fundamental relations governing galaxy evolution.

1 Introduction

Massive star formation in galaxies takes place in HII regions where the youngest generations of stars are hosted. Massive stars ionize their sourrounding gas producing the observed large variety of morphologies of HII Regions, as well as their characteristic emission line spectra. Giant HII regions in spiral and irregular galaxies have been observed since many years ago, and spectroscopy of these objects has been obtained by some pioneering works during the first decades of the past century (e.g. [1]). Subsequent seminal work on spectroscopy of extragalactic HII regions was carried out by [76], Shields and coworkers (e.g. [70, 44]), [37] and notably by Pagel and collaborators (e.g. [51, 52, 50, 89, 86, 15]).

Thanks to their emission line spectrum, giant HII regions constitute a powerful tool for deriving the chemical properties of the interstellar medium (ISM) in nearby and distant galaxies. These objects are luminous enough to be observed in distant galaxies, thus allowing their chemical abundances to be derived. Since star-forming galaxies can be observed up to very large distances they can provide very useful information on the cosmic chemical evolution.

Giant HII regions populate the disks of star-forming galaxies and they can be studied at many different spatial scales, going from the nearby to the very distant universe. In this context, a spatial scale limitation has emerged in the observation of HII regions which has to be taken into account. This is imposed by the distance to the galaxies and by the typical size of the regions and can become very serious for distant star-forming galaxies, for which observed spectra typically integrate the flux of the entire galaxy. In contrast, the study of abundances in Galactic HII regions has been performed at very small spatial scales using HST. For giant extragalactic HII regions, as the ones observed in the disks of spiral galaxies, the spectroscopic information available can give us only average properties for their ionized gas and star clusters. Therefore, physical properties such as the electron temperature or the electron density of the ionized gas, which can be derived from the relevant emision line ratios, must be understood as average values and they should not be used without a reference to the corresponding spatial scales for which they were derived

In addition, for the study of the Milky Way (MW) and nearby galaxies we have access to several other sources of information of their chemical composition which are difficult or non availble for more distant objects. As an example, the oxygen abundance of the ISM of our Galaxy (MW) has been derived from measurements of the interstellar OI λ 1356Å absorption line (e.g. [77]). Planetary nebulae have been also used to derive abundances and their gradients (e.g. [79]) in our Galaxy (MW) and in external galaxies (e.g. M 33, see [10]). On the other hand, massive stars have been used to derive the abundance gradient in the MW and also in nearby galaxies (e.g. [74, 75, 85, 8] and references therein) as well as the abundance of massive clusters, near the center of our Galaxy, such as the Arches cluster (e.g. [49]).

Given the relative simplicity of the physics governing HII regions, these objects can be used to derive fundamental information on the properties of the ionized gas and massive stars. Among this information, one of the more relevant properties derived is the metal content of the gas. Metallicity is one of the fundamental parameters governing the evolution of galaxies; thus the derivation of the chemical composition of the ISM of galaxies can offer us a powerful tool to constrain their metallicity. The chemical content of the gas in HII regions can be derived from measurements of the flux of metallic lines present in their spectra. This methodology has provided precious information for our current understanding of the chemical evolution of galaxies. For example, it is well known that spiral galaxies show radial abundance gradients (see e.g. [52, 44, 89, 24, 62] and references therein). For these galaxies valuable information has been obtained from the abundance gradients of elements oxygen, nitrogen, sulfur or carbon (e.g. gradient slope and maximum metallicity value expected at their center).

Finally, with the advent of modern integral field spectroscopy units (IFU), the study of chemical abundances in galaxies has entered a new era, which we believe very promising. The opportunity to derive the 2D distribution of metallicity of an entire galaxy represents an enormous source of information which requires the application of efficient new methodologies. This approach will provide a more complete vision of the chemical evolution of galaxies. Recent work on this field (e.g. [34, 65, 68, 47, 22]) appears to go in this direction. Therefore, both galaxy structure and morphology, as well as the 2D information of the massive stellar content and chemical composition, should be analysed together in order to achieve a better understanding of the photo-chemical evolution of galaxies.

2 Derivation of the chemical abundances of the ionized gas

Thanks to their well known characteristic emission line spectrum, HII regions provide an efficient tool to determine the chemical content of the ISM in galaxies. The derivation of chemical abundances of elements like oxygen, nitrogen, carbon, sulphur, neon or argon, among others, can be perfomed using their emission lines in the spectra of HII regions. When the physical properties of the ionized gas are well known, especially electron temperature and density, ionic abundances can be derived directly from the measured line fluxes; this is the so called *direct* method. In order to derive chemical abundances using the *direct* method the physical properties of the ionized gas, electron density and temperature, have to be calculated. Within the optical range of the spectrum, useful and popular density diagnostics for HII regions include: [SII]$\lambda\lambda$ 6717/6731 and [OII]λ]λ 3726/3729; and temperature sensitive lines include: [OIII]λ 4363, [NII]λ 5755, [OII]$\lambda\lambda$ 7320,30 and [SII]$\lambda\lambda$ 4060,70. The measurement of the H Balmer decrement in the optical range can be used to derive the reddening coefficient and, once a dust model and spatial distribution are assumed, the spectra can be corrected from extinction.

The abundances of elements can be derived using either the faint recombination lines (ORL) or the -much brighter- collisionally excited lines (CEL) (or both) produced by the corresponding ions. Each selection has its pros and cons; the CEL easily observed in the optical range, though usually bright, require accurate derivation of the electron temperature. In contrast, the emissivities of infrared CEL or optical ORL do not depend much on the electron temperature, though (unfortunately) ORL are very faint and virtually no measurements exist for external galaxies yet, even with very large telescopes. Conversely, observations of infrared CEL have been performed for many object now, though they require high altitude or space observatories. Relevant work on abundances using ORL (e.g. [19, 84]) or the infrared CEL (e.g. [3] and references therein) for the derivation of chemical abundances in gaseous nebulae can be found in the recent literature. For the purpose of this work we will focus on the methodology based on the optical CEL for the derivation of abundances. Nonetheless, the results obtained using both (CEL, ORL) methodologies will be taken into account.

The derivation of gaseous chemical abundances is based on the definition of the ionization structure of the region. A valid assumption of the ionization structure is the socalled standard two-zones scheme. This simplified scheme —obviously an approximation— assumes that there are two zones of ionization, one including all high ionization ions like O^{++}, Ne^{++}, N^{++}, and another one including the lower ionzation ions, like O^{+}, N^{+}, S^{+}. The HII region is considered non isothermal and for each ionization zone an electron temperature has to be assumed; typically the electron temperature derived from the [OIII] temperature sensitive lines is assigned to the high ionization zone, whereas the electron temperature derived from the [NII] or [OII] lines is assumed for the lower ionization zone. Once the electron temperatures and densities are known, the abundance of each ion can be calculated from its corresponding equilibrium equation and line intensities measured in the spectra (see e.g. [53, 61]). The total abundance of a given element is computed adding the abundances of its different ions; for example for a typical HII region the total abundance of oxygen will be computed as O/H = $O^{++}/H^{+} + O^{+}/H^{+}$, where both ions of oxygen can be derived from emisison lines present in the optical spectrum. However, in some cases not all the ionic abundances are known and it becomes necessary to make use of an ionization correction factor (ICF) in order to calculate the total abundance from the ionic abundances derived. These ICF are very useful and can be computed using photoionization models and/or on the basis of *ab initio* simple ionization structure prescriptions (e.g. [55, 53]).

Despite the apparent simplicity of the methodology exposed above for the determination of chemical abundances in HII regions, there are still several relevant issues that have to be considered and need to be explained; among these we can highlight here the following:

i. The CEL vs ORL dichotomy and the proposed scenario of electron temperature fluctuations in nebulae [54]: ORL abundances of some ions use to be systematically larger than the corresponding ones computed using CEL (e.g. [73]).

ii. The presence of possible chemical inhomogeneities in the onized regions (e.g [83, 84]), an interesting problem intimately related to nucleosynthesis and the physics of metal dispersion and mixing in the ISM.

iii. Depletion of metals (e.g. oxygen, iron) in dust grains (e.g. [23, 71]).

iv. The effect of the complex geometry of the HII regions in the observed ionization structure, a fact nicely illustrated by recent 3D photoionization modelling [17, 18] and likely linked to the ionizing photons leakage [26].

v. Our knowledge of the ionizing spectra of hot massive stars is still plagued by many and profound uncertainties, specially in the extreme ultraviolet.

vi. The strong limitations imposed by distance on the (effective) spatial sampling and coverage of the objects observed, which can lead us to serious aperture problems. Therefore caution must be exercised when comparing e.g. spectra of (samples of) galaxies located at different distances in order to minimize aperture and sampling effects.

At present there are strong evidences that the metallicity scale derived with the *direct* method in HII regions is reliable: e.g. [8] have shown that oxygen abundances derived using this methodology for the HII regions of the nearby spiral NGC 300 agree well with the corresponding stellar abundances. Also, the interstellar oxygen abundance in the solar vicinity, derived using high resolution observations of the OIλ 1356 absorption line, agree well with the oxygen abundance of corresponding HII regions derived using the *direct* method [77]; see also [60]. In the same line, [92] have observed ultraviolet resonance absorption lines in the spectra of central stars of planetary nebulae produced by nebular gas ions which emit also CEL. They confirmed that the column densities derived for each ion both from CEL and absorption lines are in basic agreement, concluding that abundances based on forbidden lines are most reliable.

All in all, the estimated correction of the O/H abundance due to effects i, ii, and iii mentioned above could reach, on average, to values of order 0.2 dex typically (cf. [73]). This correction is important and non negligible especially for nearby HII regions, though the figure above seems comparable to the typical error in O/H provided by empirical strong-lines calibrations. It has been suggested that *direct* derivation of the O/H abundance for high-metallicity HII regions could lead to wrong values [79] on the basis of the strong electron temperature gradients predicted by photoionization models. To date no clear evidence of this effect has been reported in the literature (e.g. [6]). Perhaps one of the more relevant aspects —frequently overlooked— in physical models of HII regions is the exact geometry of the region (see [17] for the MOCASSIN 3D code). The inclusion of this factor could provide new light, for example, for the understanding of some of the discrepancies between ionic abundances derived from CEL and ORL in the optical, versus the corresponding abundances derived from CEL in the mid infrared. These improvements in HII region modeling should be accomplished after including also better models of the spectral energy distribution for the ionizing stars (points iv and v above; e.g. [72]). The last item outlined above (point vi) can introduce severe biases in the calculation of chemical abundances, especially when they are derived from integrated spectra covering different areas, from the scale of giant HII regions to several kpc or even most part of a galaxy. It seems clear that, given the huge range of spatial scales involved, before deriving chemical abundances from integrated spectra we should have a better understanding of the effects caused by the loss of spatial information (e.g. [64]).

Given the high sensitivity of the [OIII]λ 4363 line to electron temperature it is very difficult to observe it for regions with metallicity near or above solar. This seems true even for observations with the large aperture telescopes presently available. Nonetheless, other temperature sensitive lines in the optical range, such as [NII]λ 5755 and [SIII]λ 6312 could still be measured for an important fraction of the high metallicity domain with present 8m class telescopes, provided that deep enough exposures are allowed.

When no electron temperature measurement can be obtained, a *direct* derivation of the element abundances is no longer possible. Therefore in this case in order to derive abundances one has to rely on the socalled *abundance calibrations*. These calibrations provide a relation between the abundance of a given element —usually oxygen— and a combinations of the flux of bright emision lines, which can be easily measured in the spectra. These calibrations can be purely *empirical* , i.e. based on measurements of samples of selected well studied objects. [51, 2] first suggested that some emission line ratios can be calibrated in terms of the oxygen abundance. Up to date quite a few relations have been proposed to calibrate different emission line ratios into metallicity (e.g. [93, 87, 58, 59, 57, 56, 63]). Alternatively, the calibrations can be *theoretical* i.e. based on the predictions of grids of photoionization models (e.g. [16, 45, 35]). A thorough comparative analysis of the different calibrations can be found in [56, 36] or [39]. Very recently, the mid IR line ratio [NIII]/[OIII] has been proposed as a useful empirical abundance calibrator for star-forming galaxies emitting in this

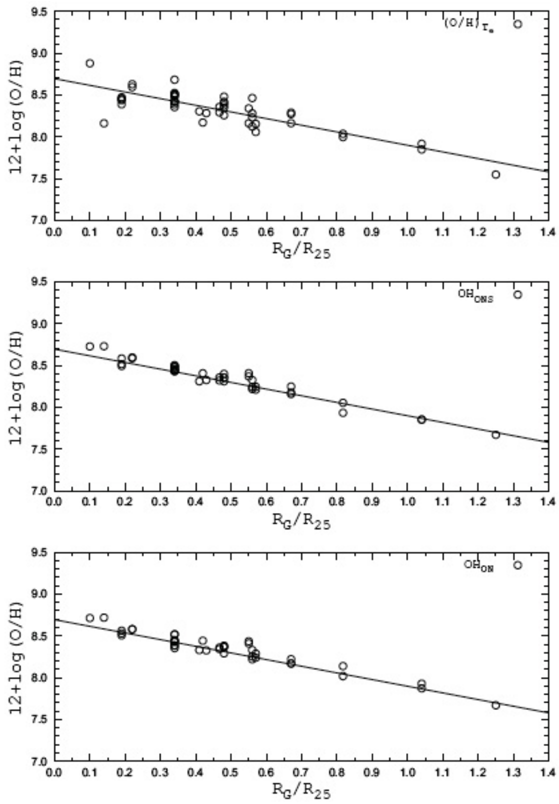

Figure 1: The oxygen abundance gradient of M 101. *Top panel*: O/H derived from the *direct* method versus galactocentric distance(in units of R_{25}) for HII regions with measured electron temperature; the linear least squares fit to the data is shown by a continuous line. *Middle and bottom panels*: O/H derived applying two versions of the improved abundance calibration of [63]; the linear fit of the top panel is shown.

wavelength range [48]; this line ratio could be a useful indicator for bright distant starburst galaxies.

In practice, errors are usually much larger for the abundances derived via calibrations (typically ~ 0.2 dex), though recent work has provided improved empirical calibrations which have reduced errors substantially. In Fig. 1 we show the O/H abundance gradient of M 101 obtained using the recent improved calibrations of [63] and also from the direct derivation of the oxygen abundance. Empirical calibrations can be very useful to derive abundances for large samples of objects and they became, in practice, the only way to estimate the metallicity of distant (star forming) galaxies. There is also an alternative way to derive the physical properties and chemical abundances of the ionized gas based on the *tailor made* model fitting of the spectra of selected objects. This method has proven to be very powerful though it has been applied only to several well observed objects.

3 Gas-phase chemical abundance gradients in galaxies

Spectroscopy of HII regions in galaxies remains and essential tool for the determination of element abundances of the ISM; the knowledge of these abundances and their variations across galaxies is a key ingredient for the study of chemical evolution. During the last years a considerable amount of work has been carried out obtaining and refining gas-phase element abundances and abundance gradients in galaxies. It is now well known that spiral galaxies present a negative radial gradient of chemical composition, with the highest abundance values localized in their centers, and typically reaching $Z_{\odot}$ to $1.5Z_{\odot}$. Besides, irregular and dwarf galaxies in general do not show measurable abundance gradients, suggesting a substantial degree of homogeneity of the chemical composition of their ISM.

The amount of work on abundance gradients of relatively nearby spiral galaxies has been increasing over the recent years; for distant galaxies, though, the derivation of abundances, gradient slope and maximum central metallicity are parameters not well known yet. These parameters are fundamental for our understanding of, for example, the process of galaxy formation and chemical evolution. Recent findings suggest that z $\sim$ 2 galaxies could have formed their disks during an inside-out process, combining important amounts of gas inflow in their very initial phases [33, 13]. For nearby galaxies, oxygen abundance gradients have been derived for a large collection of objects; also gradients of nitrogen, sulphur, neon and argon, among other elements have been derived for a handful of objects too. Abundance gradients of O/H and N/H for a representative sample of spirals presenting a good radial coverage of HII regions can be found in [62] and references therein.

Relevant examples of spiral and irregular galaxies for which derivation of high quality chemical abundances and/or gradients is available include the following: NGC 300 [8]; NGC 1365 [7]; NGC 5194 = M 51 [15, 25]; NGC 5457 = M 101 [20, 82]; NGC 6822 [31, 30]; NGC 2366 [28]; SMC [80]; NGC 598 = M 33 [89, 41, 10]; and the Milky Way [69, 87, 14]. Nonetheless, for a number of well known galaxies high quality observations are still lacking; this is the case of our neighbour M 31, for which the HII region population remains poorly studied spectroscopically.

Despite the customary assumption of radial gradients, real abundance gradients in galaxies should not necessarily follow a purely radial behaviour. Observers many times (naively) expect to derive well-behaved, smooth radial abundance gradients; however, these well behaved gradients may not exist at all, especially in those galaxies suffering substantial gas flows, as it has been illustrated by e.g. [90]. In this last work we can see the effects on abundance gradients produced by cyclonic/anticyclonic gas flows near co-rotation radius, giving rise to non-negligible departures from the radial gradient. In this line, similar effects have been reported for the slope of abundance gradients of galaxies with central bars, for which a flattening of the gradient was expected (e.g. [42, 66]); also the presence of a break in the outermost abundance gradient of some spiral galaxies has been reported [27, 9]. A flattening of the outer abundance gradient of the Milky Way has been reported from HII regions [87] and planetary nebulae [40] observations.

From the theoretical point of view, the shape of the gradient can be a key ingredient for models of galaxy formation. The inside-out scenario of galaxy formation predicts metallicity gradients that are flatter at large galactocentric distances. The disk is built up via gas infall with a time scale of formation increasing with galactocentric distance [43, 5, 12]; see also [46]. Chemodynamical models also predict a plateau of the abundance gradient at large galactocentric distance and likewise in the central region [67, 29]. Finally, the theory of viscous evolution of a star-forming disk (e.g. [38, 21]) predicts an angular momentum redistribution and gas flows, which in turns could lead to a flat abundance gradient of the ISM in the outer parts of spirals (e.g. [78, 81]). These effects are important to bear in mind since the derivation of the slope of the gradient, as well as, of the maximum and minimum metallicity values, are valuable observational clues to test the different theoretical predictions. Moreover, the existence of 2D —or 3D?— galactic structures, possibly associated to the invoked mass flows in the disks, then appear to be of extraordinary relevance for modern chemical evolution studies.

Thus a corollary of this analysis is that the next step forward in the study of chemical abundances in galaxies would require using the powerful 3D spectroscopic capabilities provided by present (and future) IFU instruments: the new observations should produce more realistic abundance maps of galaxies, rather than just radial 1D gradients. These metallicity maps will allow: i) the detection of possible spatial structures and/or asymmetries, sampling the global 2D variance in the abundance gradients at the scale of the disks (e.g. [65, 10]) and ii) the study of the chemical homogeneity of the ISM, at the scale of the giant HII complexes (e.g. [88, 83, 22, 47] and references therein), across the entire face of galaxies.

A handful of recent observations with modern IFU spectrographs will shed new light on the study of the chemical evolution of galaxies: e.g. for spirals with PPAK (e.g. [65, 68]) and VIRUS-P [4]; for irregulars and dwarfs with VIMOS (e.g. [32]), FLAMES (e.g. [47]) or PMAS-PPAK (e.g [34, 11]) and for giant HII complexes with GMOS (e.g. [91]) and PMAS-PPAK [64, 22]. More IFU panoramic observations are needed to study the metal content of galaxies and to provide critical constraints to theoretical models of their chemical evolution; also to help to derive chemical yields and to understand the fundamental relations between the metal content and macroscopic properties of galaxies (such as the mass-metallicity-luminosity relations). Finally, this new 2D information will help us to constrain galaxy formation scenarios, also taking into account the influence of the environment of galaxies, i.e. testing the effects of interactions and of dense environments (such as groups and clusters) on galaxy photo-chemical evolution.

Acknowledgments

We want to thank the organizers for this magnificent conference. Thanks are given to my collaborators of the *Estallidos* network for stimulating discussions and continuous support. This research has been funded by grants AYA2007-67965-C03-02 and CSD2006-00070 "First Science with the GTC" Consolider-Ingenio 2010 program, of the spanish MICINN.

References

[1] Aller, L.H. 1942, ApJ, 95, 52

[2] Alloin, D. et al 1979, AA, 78, 200

[3] Bernard-Salas, J. et al. 2005, in *Planetary Nebulae as Astronomical Tools*, AIP Conference Proceedings, 804, 56

[4] Blanc, G. A., Heiderman, A., Gebhardt, K., Evans, N. J., & Adams, J. 2009, ApJ, 704, 842

[5] Boissier, S., & Prantzos, N. 1999, MNRAS, 307, 857

[6] Bresolin, F. 2007, ApJ, 656, 186

[7] Bresolin, F., Schaerer, D., González Delgado, R. M., & Stasińska, G. 2005, AA, 441, 981

[8] Bresolin, F., Gieren, W., Kudritzki, R.-P., Pietrzyński, G., Urbaneja, M. A., & Carraro, G. 2009a, ApJ, 700, 309

[9] Bresolin, F., Ryan-Weber, E., Kennicutt, R. C., & Goddard, Q. 2009b, ApJ, 695, 580

[10] Bresolin, F., Stasińska, G., Vílchez, J. M., Simon, J. D., & Rosolowsky, E. 2010, MNRAS, 404, 1679

[11] Cairós, L. M., Caon, N., Zurita, C., Kehrig, C., Roth, M., & Weilbacher, P. 2010, AA, 520, A90

[12] Chiappini, C., Romano, D., & Matteucci, F. 2003, MNRAS, 339, 63

[13] Cresci, G., Mannucci, F., Maiolino, R., Marconi, A., Gnerucci, A., & Magrini, L. 2010, Nature, 467, 811

[14] Deharveng, L., Peña, M., Caplan, J., & Costero, R. 2000, MNRAS, 311, 329

[15] Diaz, A. I., Terlevich, E., Vilchez, J. M., Pagel, B. E. J., & Edmunds, M. G. 1991, MNRAS, 253, 245

[16] Dopita, M.A., & Evans, I.N. 1986, ApJ, 307, 431

[17] Ercolano, B., Bastian, N., & Stasińska, G. 2007, MNRAS, 379, 945

[18] Ercolano, B., Wesson, R., & Bastian, N. 2010, MNRAS, 401, 1375

[19] Esteban, C. 2002, RMexAA CS, 12, 56

[20] Esteban, C., Bresolin, F., Peimbert, M., García-Rojas, J., Peimbert, A., & Mesa-Delgado, A. 2009, ApJ, 700, 654

[21] Ferguson, A. M. N., & Clarke, C. J. 2001, MNRAS, 325, 781

[22] García-Benito, R., et al. 2010, MNRAS, 408, 2234

[23] García-Rojas, J., & Esteban, C. 2007, ApJ, 670, 457

[24] Garnett, D. R. 1989, ApJ, 345, 282

[25] Garnett, D. R., Kennicutt, R. C., Jr., & Bresolin, F. 2004, ApJ, 607, L21

[26] Giammanco, C., Beckman, J. E., & Cedrés, B. 2005, AA, 438, 599

[27] Gil de Paz, A., et al. 2007, ApJ, 661, 115

[28] González-Delgado, R.M., et al. 1994, ApJ, 437, 239

[29] Hensler, G., & Recchi, S. 2010, IAU Symposium 265, 325

[30] Hernández-Martínez, L., Peña, M., Carigi, L., & García-Rojas, J. 2009, AA, 505, 1027

[31] Hidalgo-Gámez, A. M., Olofsson, K., & Masegosa, J. 2001, AA, 367, 388

[32] James, B. L., Tsamis, Y. G., Barlow, M. J., Westmoquette, M. S., Walsh, J. R., Cuisinier, F., & Exter, K. M. 2009, MNRAS, 398, 2

[33] Jones, T., Ellis, R., Jullo, E., & Richard, J. 2010, ApJ, 725, L176

[34] Kehrig, C., Vílchez, J. M., Sánchez, S. F., Telles, E., Pérez-Montero, E., & Martín-Gordón, D. 2008, AA, 477, 813

[35] Kewley, L. J., & Dopita, M. A. 2002, ApJS, 142, 35

[36] Kewley, L. J., & Ellison, S. L. 2008, ApJ, 681, 1183

[37] Kwitter, K.B., & Aller, L.H. 1981, MNRAS, 195, 939

[38] Lin, D. N. C., & Pringle, J. E. 1987, ApJ, 320, L87

[39] López-Sánchez, Á. R., & Esteban, C. 2010, AA, 517, 85

[40] Maciel, W. J., & Quireza, C. 1999, AA, 345, 629

[41] Magrini, L., Vílchez, J.M., Mamapso, A., Corradi, R., & Leisy, P. 2007, AA, 470, 865

[42] Martin, P., & Roy, J.-R. 1995, ApJ, 445, 161

[43] Matteucci, F., & Francois, P. 1989, MNRAS, 239, 885

[44] McCall, M.L., Rybsky,P.M., & Shields, G.A. 1985, ApJS, 57, 1

[45] McGaugh, S. S. 1991, ApJ, 380, 140

[46] Mollá, M., & Díaz, A. I. 2005, MNRAS, 358, 521

[47] Monreal-Ibero, A., Vílchez, J. M., Walsh, J. R., & Muñoz-Tuñón, C. 2010, AA, 517, A27

[48] Nagao, T., Maiolino, R., Marconi, A., & Matsuhara, H. 2011, A&A, 526, 149

[49] Najarro, F. 2008, *The Metal Rich Universe*, Cambridge University Press

[50] Pagel, B.E.J., & Edmunds, M.G. 1981, ARAA, 19, 77

[51] Pagel, B.E.J., et al. 1979, MNRAS, 189, 95

[52] Pagel, B.E.J., Edmunds, M.G., & Smith, G. 1980, MNRAS, 193, 219

[53] Pagel, B.E.J., Simonson, E., Terlevich, R.J., & Edmunds, M.G. 1992, MNRAS, 255, 325

[54] Peimbert, M., 1967, ApJ, 150, 825

[55] Peimbert, M., & Costero, R. 1969, Bol. Obs. Tonantzintla y Tacubaya, 5, 3

[56] Pérez-Montero, E., & Díaz, A. I. 2005, MNRAS, 361, 1063

[57] Pettini, M., & Pagel, B.E.J. 2004, MNRAS, 348, L59

[58] Pilyugin, L. S. 2000, AA, 362, 325

[59] Pilyugin, L. S. 2001, AA, 374, 412

[60] Pilyugin, L. S. 2003, AA, 399, 1003

[61] Pilyugin, L. S., & Thuan, T. X. 2005, ApJ, 631, 231

[62] Pilyugin, L. S., Vílchez, J. M., & Contini, T. 2004, AA, 425, 849

[63] Pilyugin, L. S., Vílchez, J. M., & Thuan, T. X. 2010, ApJ, 720, 1738

[64] Relaño, M., Monreal-Ibero, A., Vílchez, J. M., & Kennicutt, R. C. 2010, MNRAS, 402, 1635

[65] Rosales-Ortega, F. F., Kennicutt, R. C., Sánchez, S. F., Díaz, A. I., Pasquali, A., Johnson, B. D., & Hao, C. N. 2010, MNRAS, 405, 735

[66] Roy, J.-R., & Walsh, J. R. 1997, MNRAS, 288, 715

[67] Samland, M., Hensler, G., & Theis, C. 1997, ApJ, 476, 544

[68] Sánchez, S. F., et al. 2011, MNRAS, 410, 313

[69] Shaver, P. A., McGee, R. X., Newton, L. M., Danks, A. C., & Pottasch, S. R. 1983, MNRAS, 204, 53

[70] Shields, G.A., & Searle, L. 1978, ApJ, 222, 821

[71] Simón-Díaz, S. 2010, AA, 510, 22

[72] Simón-Díaz, S., & Stasińska, G. 2008, MNRAS, 389, 1009

[73] Simón-Díaz, S., & Stasińska, G. 2011, AA, 526, 48

[74] Smartt, S., & Rolleston, W.R.J. 1997, ApJ, 481, L47

[75] Smartt, S., et al. 2001, AA, 367, 86

[76] Smith, H.E. 1975, ApJ, 199, 591

[77] Sofia, U., & Meyer, D.M. 2001, ApJ, 554, L221

[78] Sommer-Larsen, J., & Yoshii, Y. 1990, MNRAS, 243, 468

[79] Stasinska, G., 2005, AA, 434, 507

[80] Testor, G., Lemaire, J. L., & Field, D. 2003, AA, 407, 905

[81] Thon, R., & Meusinger, H. 1998, AA, 338, 413

[82] Torres-Peimbert, S., Peimbert, M., & Fierro, J. 1989, ApJ, 345, 186

[83] Tsamis, Y. G., & Pequignot, D. 2005, MNRAS, 364, 687

[84] Tsamis, Y. G., Walsh, J., Vílchez, J. M., & Pequignot, D. 2011, MNRAS, 412, 1367

[85] Urbaneja, M. A., et al. 2005, ApJ, 622, 862

[86] Vílchez, J.M., & Esteban, C. 1996, MNRAS, 280, 720

[87] Vílchez, J.M., & Iglesias-Páramo, J. 1998, ApJ, 508, 248

[88] Vílchez, J.M., Edmunds, M.G., & Pagel, B.E.J. 1988, PASP, 100 , 1428

[89] Vílchez, J.M., Pagel, B.E.J., Diaz, A.I., Terlevich, E., & Edmunds, M.G. 1988, MNRAS, 235 , 633

[90] Vorobyov, E. I., 2006, MNRAS, 370, 1046

[91] Westmoquette, M. S., Exter, K. M., Smith, L. J., & Gallagher, J. S. 2007, MNRAS, 381, 894

[92] Williams, R., Jenkins, E. B., Baldwin, J. A., Zhang, Y., Sharpee, B., Pellegrini, E., & Phillips, M. 2008, ApJ, 677, 1100

[93] Zaritsky, D., Kennicutt, R. C. Jr, & Huchra, J.P. 1994, ApJ, 420, 87