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A deep-dive beneath the mass-metallicity relation: Unveiling chemical enrichment in galaxies through infrared emission lines

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Abstract

Future and ongoing infrared (IR) and radio observatories such as JWST, METIS, and ALMA are increasingthe amount of rest-frame IR spectroscopic data for galaxies by several orders of magnitude. The studies of the chemical composition of the interstellar medium (ISM) can be hugely improved exploiting the data obtained in these spectral ranges. Among the advantages of the IR regime, it is less affected by temperature and dust extinction, traces higher ionic species, and can also provide robust estimations of the chemical abundance ratio N/O. For instance, in (Ultra)-Luminous Infrared Galaxies ([U]LIRGs), the IR regime peers through their dusty medium and allows us to include the obscured metals in their studies. In this contribution, we describe how to take advantage of the bayesian-like code HII-CHI-Mistry-IR to analyze the chemical content in a sample of ULIRGs, reviewing our findings from the study of their IR emission, comparing them to the results from optical data, and ending up by describing the finding of deviations in a sub-sample of the analyzed ULIRGs from their expected mass-metallicity relation (MZR). We interpret this result as a consequence of the action of massive inflows of metal poor gas that produces that some galaxies experience a "deep-diving" phase in the MZR diagram, as the metals from their ISM are diluted.

1 Introduction

Heavy element accumulation and stellar mass assembly are fundamental processes in the formation and evolution of galaxies [10]. However, the key elements that govern them, such as gas accretion and outflow, are not fully understood.

The estimation of heavy elements is usually done by means of the oxygen abundance, since it is the most abundant element in mass in the gas-phase ISM and it is responsible of prominent emission lines that can be easily detected in the ultraviolet (UV), optical and infrared (IR) regimes. A variety of techniques have been proposed and used over decades to estimate the oxygen content: 1) measurements of electron temperature and density can allow us to constrain the physical properties of the gas-phase ISM and thus can be used to constrain the emissivity and later on the abundance of the desired ions [18]; 2) photoionization models can be used to modelize and reproduce the observed emission line ratios, controlling the chemical composition of the gas [6]; and, 3) empirical relations between emission line ratios and chemical abundances which are calibrated by the previous techniques.

The results obtained by means of the analysis of the oxygen abundance ($12 + \log(O/H)$) show that metals produced by stars correlate with the total stellar mass (mass-metallicity relation, MZR) [23, 1], although the mechanisms that lead to such a tight relation are not fully understood [10]. Another important caveat in this relation is the role of extreme environments, such as those found in luminous and massive galaxies, which usually suffer strong feedback as massive outflows [13] and large-scale gas accretion frequently triggered by galaxy interactions [20].

Ultra-luminous infrared galaxies (U)LIRGs are an excellent laboratory to test the effect of extreme conditions in the chemical enrichment history of galaxies, due to their high star formation rates [3] and the fact they are mostly in merger interactions [22]. In this work, we present an analysis of the chemical enrichment history of (U)LIRGs using new diagnostics based on nebular IR emission lines, which peer through their dusty medium and allows us to account for the dusty obscured metals.

2 Methodology

2.1 Sample selection

Based on previous works compiling samples of galaxies with IR spectroscopic observations [7, 8, 14] and thanks to the Infrared Database of Extragalactic Observables from Spitzer (IDEOS) [21], we compiled a sample of galaxies with mid-IR spectroscopic emission lines, whose emission is dominated by star formation (SF) activity according to the diagnostic diagram proposed by [2]: [NeV]/[NeII] ratio < 0.15 (high-ionized emission lines such as [NeV] mainly traced Active Galactic Nuclei (AGN) [14]); and from the equivalent width of the PAH feature at 6.2 μm (EQW(PAH$_{6.2\mu m}$) > 0.06 μm (which would be destroyed in the AGN environment).

We complemented this information with Brackett-α 4.05μm measurements from Akari/IRC observations (2.5–5 μm, [9]) as well as SOFIA observations of far-IR emission lines ([OIII] 52μm, [NIII] 57μm and [OIII] 88μm) from previous works [8, 14]. We ended up with a sample of 77 (U)LIRGs, and we also retrieved ancillary data for host galaxy properties such as stellar mass, star formation rate or merger stage from several sources [4, 3, 22, 12]

2.2 HII-CHI-Mistry-IR

We used IR emission lines to estimate chemical abundances in our sample of star-forming (U)LIRGs. These emission lines, in comparison with their optical counterparts, offer several advantages: 1) the IR traced high ionic species such as [OIV], [NeV], [NeVI], [ArV], [ArVI], which are fundamental to distinguish between the AGN/SF activity; 2) they are almost unaffected by electron temperature fluctuations; and, 3) they allow us to peer through dusty environments such as those characterizing (U)LIRGs. Whereas near- and mid-IR emission lines are almost unaffected by changes in the density conditions, this is an important caveat for far-IR emission lines, such as [OIII] 88μm, as their critical density drops below 500 cm^{-3}.

We relied on HII-CHI-MISTRY-IR[1] [17, 8, 14, 16]. Based on the available set of IR emission lines HI 4.05 μm, HI 7.46μm, [SIV] 10.5μm, HI 12.4μm, [NeII] 12.8μm, [NeV] 14.3μm, [NeIII] 15.6 μm, [SIII] 18μm, [NeV] 24μm, [OIV] 26μm, [SIII] 33μm, [OIII] 52μm, [NIII] 57μm and [OIII] 88μm, the code performs a bayesian-like comparison of the observed emission line ratios and those predicted by a large grid of photoionization models computed with CLOUDY v17 [6]. The grid of photoionization models was computed allowing the oxygen abundance $12 + \log(O/H)$, the nitrogen-to-oxygen abundance ratio $\log(N/O)$ and ionization parameter $\log(U)$ to be free parameters, without assumptions among them. For each galaxy (or set of emission lines), the code provides an estimation of the best values of these three parameters to reproduce the observed emission line ratios.

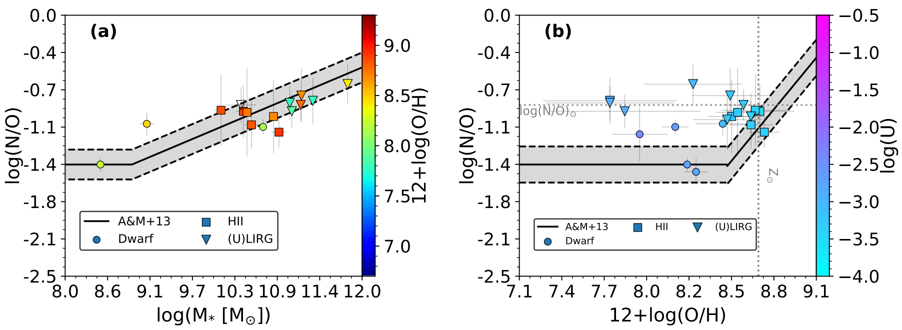

Figure 1: (a) Relation between stellar mass and nitrogen-to-oxygen ratio for our sample of galaxies. (b) Relation between the oxygen abundance and nitrogen-to-oxygen abundance ratio for our sample of galaxies. The local relations provided are those reported in [1]. Figures directly taken from [15].

[1]The code is also available in the following GitHub project.

3 Chemical abundances in (U)LIRGs

3.1 Nitrogen-to-oxygen abundance ratios and oxygen abundances

The information on log(N/O) is directly estimated from far-IR emission lines ([OIII] 52μm, [NIII] 57μm and [OIII] 88μm) [8, 14], thus the number of galaxies with a direct estimations of these quantities is lower than the total number of galaxies in the original sample (16 out of 77.)

We show in Fig. 1 the behavior of log(N/O) as function of the stellar mass (a) and the oxygen abundance $12 + \log(O/H)$ (b). We obtained that the majority of galaxies follow the reported relation for star-formating galaxies (SFGs) between log(N/O) and $\log M_*$ [1], i.e., the chemical enrichment as traced by log(N/O) follows the behavior of SFGs. However, the relation between log(N/O) and 12+log(O/H) shows that the predicted behavior (constant log(N/O) at low metallicities and increasing relation at high metallicities) is not followed for our sample of (U)LIRGs. Moreover, we observed that some galaxies (four) present extremely low oxygen abundances $(12 + \log(O/H) < 8.2)$ while their nitrogen-to-oxygen abundances points toward solar values (~ -0.86), indicative that some processes are affecting the oxygen abundance ratio.

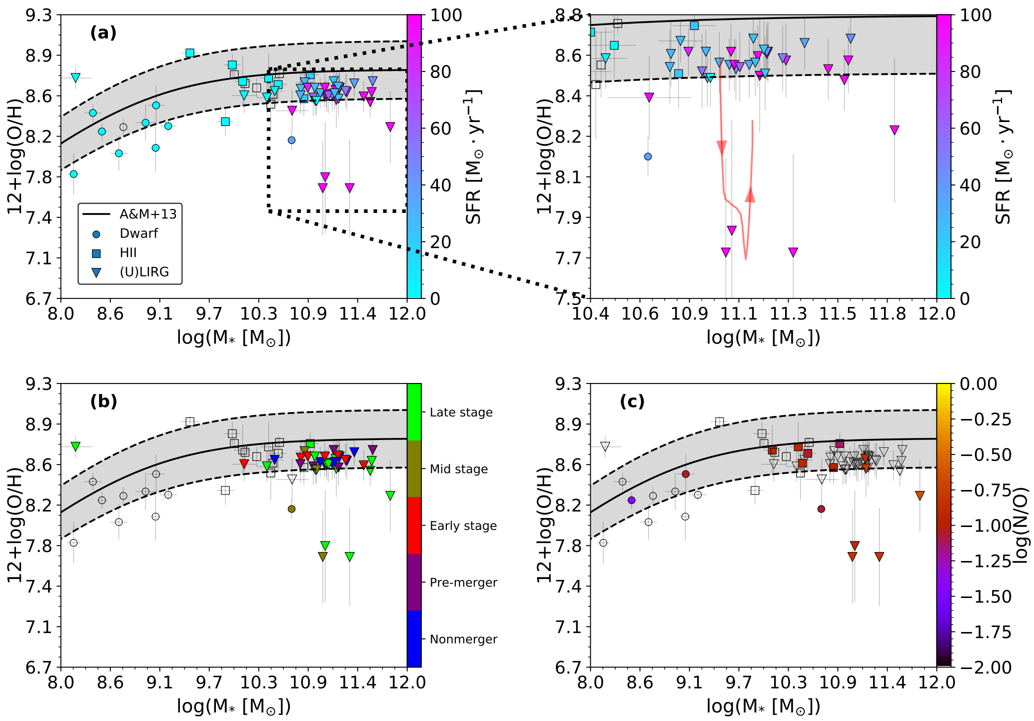

Figure 2: The mass-metallicity relation for our sample of (U)LIRGs showing different physical properties of their host galaxies: SFR (a), merger stage (b) and log(N/O) (c). Panel (a) shows a zoom in with our infall model to explain the behavior observed. Figures directly taken from [15].

3.2 Chemical enrichment as traced by the position on the MZR

We further explored the abnormalities on the $12 + \log(O/H)$ content by analyzing how they behave against other physical properties, such as the mass-metallicity relation (MZR). From Fig. 2, we observe that the previous group of galaxies that showed low $12 + \log(O/H)$ is positioned quite below the reported relation for SFGs [1]. When looking at other physical properties, we obtained that they are also characterized by high star formation rates (SFRs), solar nitrogen-to-oxygen abundances and mid-to-late stages in their merger interaction.

We conclude that this whole scenario is compatible with a merger-driven infall of metal-poor gas, that dilutes the oxygen abundance during the first Myr of interaction, followed up by an increase of star formation which explains the amounts of dust detected in these galaxies, and later on an increase on the oxygen abundance as stars pollute again the ISM as well as the pollution from outflows. This is what we call *deep-diving phase* [15], and it lasts for less than 700 Myr according to our infall models as well as simulations [11]. During this process, the nitrogen-to-oxygen abundance ratio remains almost unaffected, explaining the discrepancy between the scenarios traced by $\log(N/O)$ and $12 + \log(O/H)$ respectively.

It is important to remark that we were able to observed this scenario since we have performed an independent estimation of $12 + \log(O/H)$ and $\log(N/O)$. Previous works were not able to conclude this scenario as they were either using optical emission lines which are affected by dust attenuation [19] or they were mainly tracing the $\log(N/O)$ ratio [5] which needs to be complemented with the oxygen abundance information.

4 Conclusions

We estimated chemical abundances ($12 + \log(O/H)$ and $\log(N/O)$) from IR emission lines by means of HII-CHI-Mistry-IR, based on photoionization models, and without assuming any prior relation between oxygen and nitrogen abundances. Our methodology can be applied for both, AGN and SFG, accounting for their differences, making it a versatile tool that can be used in large samples of galaxies.

IR emission lines are key in order to properly estimate the chemical content of the gas-phase ISM in dusty objects such as (U)LIRGs, finding that they can be an indirect proof of metal-poor gas enrichment (deep-diving). We observed that some of these (U)LIRGs are undergoing a deep-diving phase, in which the oxygen abundance is diluted due to the infall of metal-poor gas, being a short (< 700 Myr) phase in the evolution of galaxies.

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