# UNVEILING THE NATURE OF THE "GREEN PEA" GALAXIES: OXYGEN AND NITROGEN CHEMICAL ABUNDANCES


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**ABSTRACT:** We have investigated the oxygen and nitrogen chemical abundances in extremely compact star-forming galaxies (SFGs) with redshifts between ~ 0.11 and 0.35, popularly referred to as "green peas" (GPs). Direct and strong-line methods sensitive to the N/O ratio applied to their Sloan Digital Sky Survey (SDSS) spectra reveal that these systems are genuine metal-poor galaxies, with mean oxygen abundances ~20% solar. At a given metallicity these galaxies display systematically large N/O ratios compared to normal galaxies, which can explain the strong difference between our metallicities measurements and the previous ones. While their N/O ratios follow the relation with stellar mass of local SFGs in the SDSS, we find that the mass-metallicity relation of the GPs is offset more than 0.3 dex to lower metallicities. We argue that recent interaction-induced inflow of gas, possibly coupled with a selective metal-rich gas loss, driven by supernova winds, may explain our findings and the known galaxy properties, namely high specific star formation rates, extreme compactness, and disturbed optical morphologies. The "green pea" galaxy properties seem to be uncommon in the nearby universe, suggesting a short and extreme stage of their evolution. Therefore, these galaxies may allow us to study in great detail many processes, such as starburst activity and chemical enrichment, under physical conditions approaching those in galaxies at higher redshifts.

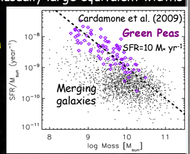

## GREEN PEAS: GENERAL PROPERTIES

This intriguing class of very compact, extremely star-forming galaxy (SFG) at low redshift (0.11 < z < 0.36) have been recently discovered by volunteers in the "Galaxy Zoo Project" an first reported and analyzed by Cardamone et al. (2009) by using SDSS-DR7. Following their work, the GPs main properties can be summarized as follows:

1) Very faint continuum emission and strong optical emission lines, namely [OIII]λ5007, with unusually large equivalent widths (up to 2000Å)
2) Extremely compact (unresolved in SDSS images): typical sizes < 5kpc
3) Large star formation rates (SFR), up to 30 $M_{sun}$ yr$^{-1}$
4) Low stellar masses, $10^8 < M_{star} < 10^{10.5}$
5) Preferably located in low-density environments
6) Rare systems, less than 2 objects per degree$^2$

(3–4) Among the largest specific SFRs seen in the local Universe !! (SSFRs up to $10^{-8}$ yr$^{-1}$)

7) Low extinction and … low metallicity…? Cardamone et al. found nearly solar values…



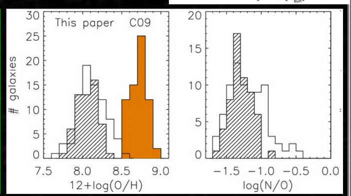

We measured the emission-line fluxes from SDSS-DR7 spectra for the 79 SF green peas, then we calculated:

Direct (lined histogram in both figures) O/H and N/O using $T_e$ [OIII] λ4363, only for 70% of the sample

Empirical O/H and N/O for the full sample (white histograms) using N2=log([NII]/Hα) and N2S2=log([NII]/[SII]), respectively, following Pérez-Montero & Contini (2009).

LOW metallicities. Mean values are 12+log(O/H)=8.05 (0.14) and log(N/O)=-1.19 (0.27)

Low extinction values, i.e., Hα/Hβ = 0.23 and C(Hβ)=3.3, in agreement with C09



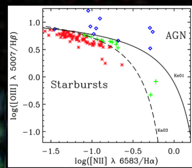

We find a systematic OFFSET of ~0.65 dex with Cardamone´s O/H values (orange hist.), which were obtained using [NII] λ6584 / [OII] λλ3726,3729 and the theoretical calibration by Kewley & Dopita (2002), without taking into account N/O

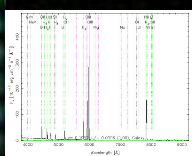
RESULT: The green peas are a genuine population of metal-poor ($Z$ ~ 0.2 $Z_{sun}$) starburst galaxies

## SAMPLES AND DATA

1- Main Sample

Star-forming green peas selected from SDSS-DR7 spectroscopic targets in the range 0.112 < z < 0.360 (strong [OIII] λ5007 emitters falling in the r-band). Using colour criteria: *ugriz* SDSS broad-bands



We used the same emission line indexes and calibrations to derive O/H and N/O for the three samples

2- Reference Sample

Local Star-Forming Galaxies (SFGs) with 0.03 < z.< 0.37

Emission-line galaxies from the MPA/JHU catalogue of SDSS/DR7

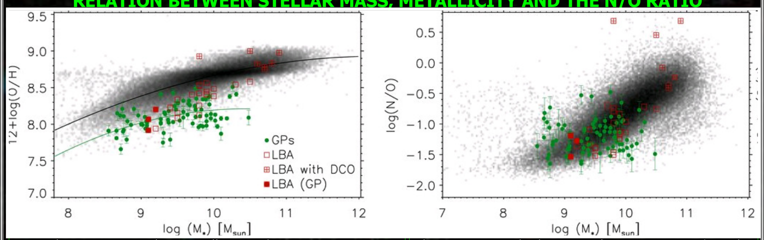
- Only spectra with high signal-to-noise ratio (S/N>5) in the relevant emission lines

3- Comparison Sample

"Lyman-break analogs" (LBAs, Overzier et al. 2008): super compact UV-selected galaxies with 0.1 < z < 0.3

- 30 galaxies. Line ratios from Overzier et al. (2009).
- Less massive LBAs include 3 galaxies also classified as green peas
- Most massive LBAs are morphologically different and host dominant (massive) central objects (DCOs)

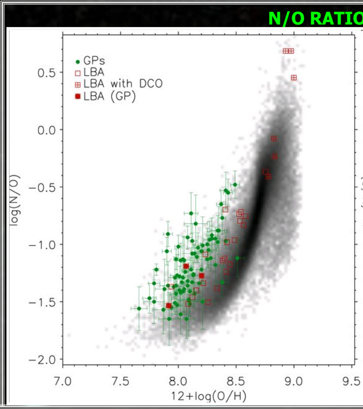
## RELATION BETWEEN STELLAR MASS, METALLICITY AND THE N/O RATIO




GPs and LBAs increase their metallicity with increasing masses. Nevertheless, GPs lie more than a factor of 2 (~0.3 dex) below the MZR of SDSS SFGs, i.e., at a fixed stellar mass GPs are systematically more metal-poor than normal SFGs. A similar shift in the MZR has been observed for the less-massive (log($M$) < $10^{10.5}$) LBAs (Hoopes et al. 2007; Overzier et al. 2010, Amorín et al. 2010). In terms of stellar mass, the observed offset (as large as 1 dex) largely exceeds the typical uncertainty quoted for the GP masses.

The SDSS SFGs display a correlation between N/O and mass, with higher N/O ratios at higher stellar masses, in agreement with Pérez-Montero & Contini (2009) for a different sample of local SFGs. The existence of this relation reflects the fact that the most massive galaxies evolve more quickly and, hence, they should have on average higher metallicities and N/O ratios. Overall, most GPs and low-mass LBAs are roughly consistent with the trend of SDSS SFGs, and no systematic offset is observed.

## N/O RATIO AND METALLICITY

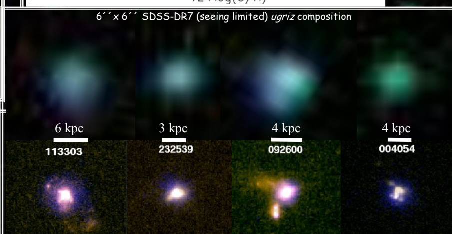



We have investigated the relation between the N/O ratio and the oxygen abundance for the sample of GPs, LBAs, and the SDSS SFGs. For the SFGs, we found a positive trend with increasing scatter toward the metal-rich regime reflecting both primary and secondary production of nitrogen in the same metallicity range. At low metallicities the trend flattens out, possibly a consequence of nitrogen being of primary origin, coming mainly from massive stars. In the low-to-intermediate metallicity range, most GPs and some LBAs display systematically larger N/O ratios for a given metallicity compared to the SDSS SFGs.

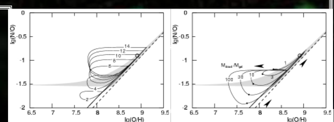
Possible reasons for this include:

a) Extra production of primary nitrogen, coming from low-metallicity intermediate-mass stars (Renzini & Voli 1981; Gavilán et al. 2006; Mollá et al. 2006)
b) Pollution by Wolf-Rayet stars (e.g., Brinchmann et al. 2008)
c) Hydrodynamical effects involving outflow and inflow of gas (van Zee et al. 1998; Köppen & Hensler 2005).

This could explain the different metallicity estimates relative to Cardamone et al.: Large N/O can enhance the N2 value (Pérez-Montero & Contini 2009). The Kewley & Dopita calibration does not take into account the dependence of [NII]/[OII] on the variation of N/O at a given O/H.




6´´x 6´´ HST (FWHM=0.1´´) blue/purple=FUV; yellow/red=optical. Overzier et al. (2009)




Above: models by Köppen & Hensler (2005). *Left*: evolutionary tracks of models with the same mass (10 galaxy masses) and duration of the accretion, but with different starting times (in Gyr). All models are evolved up to 15 Gyr age. *Right:* Tracks in the N/O-O/H-diagram of infall models with various mass ratios of the infalling gas and the galaxy. The infall event starts at the same age of 5 Gyr and lasts for 1 Gyr (marked by a dot). The shaded area indicates the region of the data.

Left: morphology of the four green peas observed in high spatial resolution with the Hubble Space Telescope. For comparison, SDSS color composite images are shown

## DISCUSSION: OUTFLOWS, INFLOWS AND STAR FORMATION

One possibility to explain the GPs´ offset position in the MZR is that these galaxies could be still converting a large amount of their cold gas reservoirs into stars. In that case, their low abundances could be due to their relatively young ages compared to normal SFGs.

Some models (e.g., Finlator & Davé 2008) show that in highly concentrated (typical sizes <3 kpc) low-mass galaxies, such as the GPs, galactic winds induced by their large SSFR are strong enough to escape from their weak potential wells, diminishing the observed global abundances. In contrast, analytical models by Dalcanton (2007) show that any subsequent star formation to the outflow will remove their effects on metallicity, unless galaxies have an inefficient star formation. SPH plus $N$-body simulations have shown that low star formation efficiencies, regulated by supernova feedback, could be primarily responsible for the lower metallicities of low-mass galaxies and their overall trend in the MZR (Brooks et al. 2007). As shown by Erb et al. (2006) for SFGs at $z$ ~ 2, the constancy in the offset of the MZR suggests the presence of selective metal-rich gas loss driven by SN winds.

Inflow of metal-poor gas, either from the outskirts of the galaxy or beyond, can dilute metals in the galaxy centers, explaining an offset to lower abundances in both the MZR and the N/O-O/H diagram. In starburst galaxies, a recent cold gas accretion can be due to interactions, which eventually increases the gas surface density and consequently the star formation. The dilution of metals due to an inflow can be restored by the effects of star formation depending on the dilution-to-dynamical timescale ratio. Since this ratio depends inversely with galaxy radius, galaxies with smaller radius, such as the GPs, may be expected to take longer time to enhance their oxygen abundances to the values expected from the MZR. In this line, the position of GPs in the $M$-N/O relation and the offset observed in the N/O-O/H plane may favor this scenario. Models by Köppen & Hensler (2005, see Figures.) have shown that the rapid decrease of the oxygen abundance during an episode of massive and rapid accretion of metal-poor gas is followed by a slower evolution which leads to the closed-box relation, thus forming a loop in the N/O-O/H diagram.The inflow hypothesis is also strongly suggested by the disturbed morphologies and close companions observed in spatially resolved *HST* Images for three GPs and most LBAs (see Figure). Recent results revealed that galaxies involved in galaxy interactions fall 0.2 dex below the MZR of normal galaxies due to tidally induced large-scale gas inflow to the galaxies' central regions (e.g., Michel-Dansac et al. 2008). Several $N$-body/SPH simulations have shown that major interactions drive starbursts and gas inflow from the outskirts of the HI progenitor disks (e.g., Rupke et al. 2010), also supporting this scenario.

We conclude arguing that recent interaction-induced inflow of gas, possibly coupled with a selective metal-rich gas loss driven by SN winds, may explain our findings and the known galaxy properties. Nevertheless, further work is needed to constrain this possible scenario. In particular, future assessment of the H i gas properties and the star formation efficiency of GPs, as well as the behavior of effective yields with mass compared with models of chemical evolution, will shed new light on the relative importance of the above processes.

Our results allow us to further constrain the evolutionary status of the GPs: their properties suggest that these galaxies are snapshots of an extreme and short phase in their evolution. GPs and the low-mass LBAs, should be compared in more detail to elucidate whether they are sharing similar evolutionary pathways. They offer the opportunity of studying in great detail the physical processes involved in the triggering and evolution of massive star formation and the chemical enrichment processes, under physical conditions approaching those in galaxies at higher redshifts.

Forthcoming analysis, based on high S/N intermediate/high-resolution spectroscopy and deep NIR imaging with the Gran Telescopio Canarias (GTC), will be used to better constrain the evolutionary status of the GPs.

## REFERENCES AND ACKNOLEDGEMENTS


Amorín, R., Pérez-Montero, E., & Vílchez, J.M., 2010, ApJ, 715L, 128A

Pérez-Montero, E. & Contini, T., 2009, MNRAS, 398, 949P

Hoopes et al. 2007, ApJS, 173, 441

Köppen & Hensler, 2005, A&A, 434, 531

Michel-Dansac et al., 2008, MNRAS, 386, L82

Erb et al., 2006, ApJ, 644, 813

Cardamone, C. et al. 2009, MNRAS, 399, 1191C

Overzier, R. et al. , 2008, ApJ, 677, 370, …and …2009, ApJ, 706, 203

Van Zee et al, 1998, ApJ, 497, L1

Finlator & Davé, 2008, MNRAS, 385, 2181

Rupke et al., 2010, ApJ, 710, L156

Dalcanton, J. J. 2007, ApJ, 658, 941

See additional references in Amorín et al. (2010) (TAKE YOUR COPY HERE !).



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