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The CALIFA connection between outer-disk reddening and gas-phase metallicities

R. A. Marino[1,2], A. Gil de Paz[2], S. F. Sánchez[3], P. Sánchez-Blázquez[4,5], A. Castillo-Morales[2], N. Cardiel[2], S. Pascual[2], J. Vílchez[6], and the CALIFA Team[7]

[1] Institute for Astronomy, Department of Physics, ETH Zürich, Switzerland
[2] Departamento de Astrofísica y CC. de la Atmósfera, Facultad de CC. Físicas, Universidad Complutense de Madrid, Spain
[3] Instituto de Astronomía, Universidad Nacional Autonóma de México, México, D. F
[4] Departamento de Física Teórica, Universidad Autónoma de Madrid, 28049 Madrid, Spain
[5] Instituto de Astrofísica , Universidad Pontifica Católica de Chile, Av. Vicuña Mackenna 4860, Santiago, Chile
[6] Instituto de Astrofísica de Andalucía (IAA/CSIC), Granada, Spain
[7] Centro Astronómico Hispano Alemán, Calar Alto, (CSIC-MPG), Almeria, Spain

Abstract

In Marino et al. 2016 we investigate, for the first time in a statistically significant and well-defined sample, the behavior of the colors and of the oxygen abundance from H II regions located within and beyond the break radius in the surface brightness profiles. We perform a detailed light-profile classification using Sloan Digital Sky Survey (SDSS) *g'*- and *r'*-band surface brightness, *(g'- r')* color, as well we characterize the ionized-gas oxygen abundance profiles for 350 galaxies within Calar Alto Legacy Integral Field Area (CALIFA) Survey. Our main results are: (i) We find that about 84% of our disks show clear *down*- or *up-bending* profiles (Type ii and Type iii, respectively) while the remaining 16% are well fitted by one single exponential law (Type i); (ii) The analysis of the color gradients reveals a *U-shape* profile for the Type ii galaxies with a minimum *(g'- r')* color of ∼0.5 mag; (iii) We find a statistically significant signal of flattening in the outer ionized-gas metallicities, associated with the difference in the outer-to-inner disk gradient distribution. We discuss the relation between the outer-disk ionized-gas metallicity gradients and the presence of breaks in the surface brightness profiles of disk galaxies in the context of the evolution of galaxy disks and we propose different mechanism(s) that could have driven the formation and evolution of the galaxies' outskirts and, in particular, the reddening of the stellar colors found in these peripherical regions.

1 Introduction

Most of the detailed structural studies of nearby disk galaxies carried out to date have been focused on the (most easily accessible) inner parts of galaxies. However, the faintest regions of galactic disks, that are intimately linked to the mechanisms involved in their growing and shaping, are still poorly understood. Since the pioneering work on surface photometry of nearby galaxies by [15] we know that galaxy disks follow an exponential light profile according to the inside-out scenario of galaxy formation ([10] [11]) but this decline does not continue to the last measured point. Consequently, not all the disk galaxies are well described with a single exponential fitting function as shown in several studies ([3], [12], [4] among others), and it became accepted the existence of three basic classes of surface brightness profiles depending on an apparent break in surface brightness (SB): (i) Type i (TI) profiles that do follow a single exponential law beyond the bulge area all along the optical extension of the galaxies, (ii) Type ii (TII) profiles that present a double exponential law with a *down-bending* beyond the break radius, and (iii) Type iii (TIII) profiles that exhibit an *up-bending* in the outer part (for a detailed explanation see the classification schema presented in Fig.4 of [12]). In addition, [1] have also found for TII disks a characteristic minimum color at break radius associated with a *U*-shape color profiles that posed another challenge to the inside-out scenario. Different mechanisms have been invoked to explain the origin of the breaks detected in spiral galaxies and we refer the reader to [9] for a detailed discussion.

Another important departure from the somewhat *naive* prediction of the inside-out scenario comes from the study of the H II regions observed in the outskirts of disks that are of crucial importance because we presume that they have experienced only a small degree of alteration in their abundances due to star formation activity. Contrary to the theoretical prediction of an universal radial abundance/metallicity gradient in disk galaxies, several investigations both in our Milky Way ([16]) and in nearby galaxies ([2]; [7]; [14]) have reported a shallower oxygen abundance gradient (or flattening) in the outskirts.

All these observables have provided a fundamental piece of evidence to the actual scenario for the formation of galaxy disks. A fundamental question therefore arises from these results: are the breaks observed in the SB profiles and the flattening in the oxygen abundance gradients connected? In order to address this aspect, in [9] we present the combined analysis of the metallicity gradients obtained from CALIFA (based on the tools and calibrations presented in [7] and [8]) with their SDSS SB and color profiles. The SDSS *g'* and *r'* SB and (*g'*−*r'*) color profiles were derived using the DR10 data products,

2 Data and Analysis

This work is based on 350 galaxies observed by the CALIFA survey [13] at CAHA 3.5m telescope with PMAS (Potsdam Multi Aperture Spectrograph) in the PPak mode. CALIFA is an IFS survey, whose main aim is to acquire spatially resolved spectroscopic information of ∼600 galaxies in the Local Universe ($0.005 < z < 0.03$), sampling their optical extension up to ∼2.5 R_{eff} along the major axis with a spatial resolution of 1"/spaxel, and covering the wavelength range 3700 Å-7500 Å. By construction, our sample includes galaxies of any

Table 1: Statistics of our sample according to the SB profiles classification. Errors represent the standard deviations.

Sample statistics					
Quantities	TII			TIII	
	TII-CT	TII.o-CT	TII.o-OLR	TIII-d	TIII-s
Number TOT=131	37	18	43	30	3
Frequency [%]	30.3	13.8	29.6	23.7	2.6
R_{break} [R_{eff}]	1.45±0.33	1.44±0.32	1.50±0.38	1.53±0.45	1.20±0.09
μ_{break} [mag/"^{2}]	22.32±0.67	22.18±0.64	22.56±0.63	22.83±0.59	21.76±0.60
$(g'-r')_{break}$ [mag]	0.51±0.14	0.48±0.14	0.48±0.12	0.51±0.14	0.71±0.07
$(12+\log(O/H)_{break, N2}$ [dex/kpc]	8.51±0.08	8.47±0.07	8.53±0.06	8.51±0.11	8.60±0.09

morphological type, being representative of all local galaxies between $-23 < M_{abs,z} < -18$. Details on the data reduction are given in [6] and in [5]. Global properties for the galaxies in our sample, such as morphological type, stellar mass, distance, etc., were taken from [17]. For the ∼ 15000 H II regions extracted from the CALIFA datacubes, the radial oxygen gradients normalized at R_{eff} were computed using the *M13–N2* calibration ([8]). The SDSS g' and r' SB and $(g'-r')$ color profiles are based on the DR10 data. After excluding the bulge component, we have derived the broken exponential and the position of the break radius that best fits our SB profile via bootstrapping and the results of our disks classification are presented in Table 1, including the detailed frequencies and the SB, color and oxygen abundance measurements at break radius for each subtype. We find that in the r'-band only 16% of the CALIFA galaxies are well described by a simple power law (TI profiles) while the remaining 84% of galaxies are better described by a broken exponential law. In order to ensure a good statistical sampling we impose that our final sample must include only spiral galaxies that have a minimum 5 H II regions beyond the break radius and also present a broken exponential light profile (i.e. elliptical galaxies and TI are excluded from the following analysis). The final sample comprises a total of 131 galaxies (98 TII + 33TIII). Moreover, we find a flattening or inverted an inverted oxygen abundance trend beyond the break radius for 69 galaxies, which are the ones showing positive differences, $\Delta\,\alpha_{(O/H)} > 0$ (difference outer-inner). Negatives values of $\Delta\,\alpha_{(O/H)}$ indicate a relative drop in the external part of the oxygen radial profile (as most profiles show a negative internal metallicity gradient). The difference between the outer and the inner slopes of our (O/H) fits is plotted in Fig.1.

3 The interplay between stellar light and abundance profile

In order to interpret the nature of SB breaks in nearby galaxies, we have investigated the relation between the outer-disk ionized-gas metallicity gradients and the presence of breaks in their surface brightness profiles and the changes in color across these breaks. SDSS g'- and

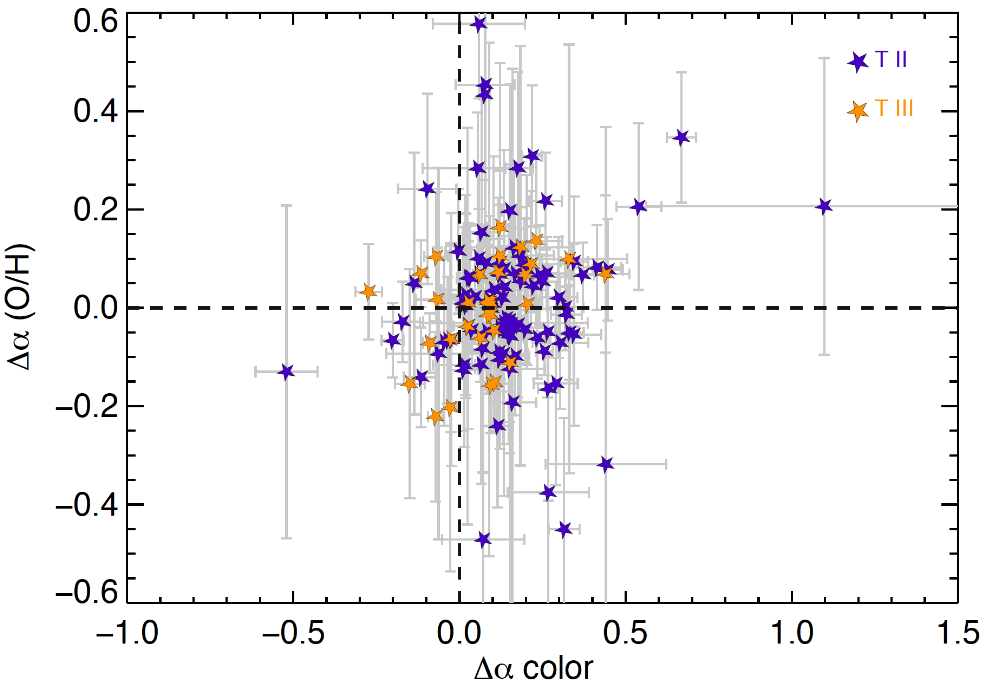

Figure 1: Distribution of the oxygen metallicity slopes (outer-inner) difference, $\Delta\,\alpha_{(\mathrm{O/H})}$, versus the *(g'- r')* color slopes one, $\Delta\,\alpha_{\mathrm{color}}$. We plot our TII galaxies with purple diamonds while the TIII are in orange.

r'-band surface brightness, *(g'- r')* color, and CALIFA survey ionized-gas oxygen abundance profiles for 350 galaxies are used for this purpose. We perform a detailed light-profile classification of the CALIFA galaxies and from the analysis of the color gradients at both sides of this break we also found a *U*-shaped profile for our TYPE II galaxies with a minimum (bluest) *(g'- r')* color of ~ 0.5 mag that is in agreement with previous findings. Using the results from this analysis we compute, for the first time in a statistically significant and well-defined sample, the behavior of the oxygen abundance in H II regions located at both sides of the break radius. The results presented in [9] are a step forward in revealing which are the possible mechanism(s) that drive the formation and evolution of the galaxies outskirts and, in particular, the reddening of the stellar colors found in these regions. The main results from this work are:

- (I) The percentage of SB profiles and mean break colors found confirm those reported by previous works, this time using the well-defined and large sample of nearby galaxies from the CALIFA IFS survey.
- (II) Most of the CALIFA TII and TIII disk galaxies show a flattening and even a reversal in their color gradients.
- (III) The distribution of differences in the outer−inner (gas) metallicity gradient shows no correlation with the difference in color gradient in the case of the TII disks, while there is a positive correlation between them (i.e. a metallicity flattening) in the case of the TIII disks. Such flattening in the oxygen abundance could be due to the presence of a polluted intergalactic medium (IGM) gas in the outskirts of these disks that was enriched by galactic winds and/or outflows during an early phase of galaxy evolution.
- (IV) For more massive TIII disks, the outer color reddening associated with a flattening in their oxygen gradients can be explained as due to a past inside-out growth that has now decreased in frequency and/or strength. Our results indicate that the outer regions of spiral disks also suffer from mass down−sizing effects.

The complete atlas of the 324 CALIFA galaxies is presented in Appendix B along with the disk classification table and the derived properties at break radius obtained [9].

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References

[1] Bakos, J., Trujillo, I., & Pohlen, M. 2008, ApJ, 683, L103

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

[3] Erwin, P., Pohlen, M., & Beckman, J. E. 2008, AJ, 135, 20

[4] Florido, E., Battaner, E., Zurita, A., Guijarro, A. 2007, A&A, 472, 39

[5] García-Benito, R., Zibetti, S., Sánchez, S. F., et al. 2015, A&A, 576, A135

[6] Husemann, B., Jahnke, K., Sánchez, S. F., et al. 2013, A&A, 549, A87

[7] Marino, R. A., Gil de Paz, A., Castillo-Morales, A. et al. 2012, ApJ, 754, 61

[8] Marino, R. A., Rosales-Ortega, F. F., Sánchez, S. F. et al. 2013, A&A, 559, 114

[9] Marino, R. A., Gil de Paz, A., Sánchez, S. F. et al. 2016, A&A, 585, 47

[10] White, S. D. M., & Frenk, C. S. 1991, ApJ, 379, 52

[11] Mo, H. J., Mao, S., & White, S. D. M. 1998, MNRAS, 295, 319

[12] Pohlen, M., & Trujillo, I. 2006, A&A, 454, 759

[13] Sánchez, S. F., Kennicutt, R. C., Gil de Paz, A., et al. 2012a, A&A, 538, A8

[14] Sánchez, S. F., Rosales-Ortega, F. F., Marino, R. A. et al. 2012b, A&A, 546, A2

[15] van der Kruit, P. C. 1979, A&AS, 38, 15

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

[17] Walcher, C. J., Wisotzki, L., Bekeraité, S., et al. 2014, A&A, 569, A1