Highlights on Spanish Astrophysics IX, Proceedings of the XII Scientific Meeting of the Spanish Astronomical Society held on July 18 – 22, 2016, in Bilbao, Spain. S. Arribas, A. Alonso-Herrero, F. Figueras, C. Hernández-Monteagudo, A. Sánchez-Lavega, S. Pérez-Hoyos (eds.)

Star formation and AGN activity in the most luminous LINERs in the local universe[1]

Isabel Márquez[1], Mirjana Povic[1], Hagai Netzer[2], Josefa Masegosa[1], Raanan Nordon[2], Enrique Pérez[1] and William Schoenell[1]

[1] Instituto de Astrofísica de Andalucía (IAA-CSIC), E-18008 Granada, Spain
[2] School of Physics and Astronomy and the Wise Observatory, Tel-Aviv 69978, Israel

Abstract

This work presents the properties of 42 objects in the group of the most luminous, highest star formation rate (SFR) low-ionization nuclear emission-line regions (LINERs) at z = 0.04 0.11. We obtained long-slit spectroscopy of the nuclear regions for all sources, and FIR data (Herschel and IRAS) for 13 of them.We measured emission-line intensities, extinction, stellar populations, stellar masses, ages, active galactic nuclei (AGN) luminosities, and SFRs.We find considerable differences from other low-redshift LINERs, and general similarity to star-forming galaxies.We confirm the existence of such luminous LINERs in the local universe, after being previously detected at z $\sim$ 0.3 by Tommasin et al. The median stellar mass of these LINERs corresponds to 6 - 7 $\times$ 10^{10} $M_\odot$ which was found in previous works to correspond to the peak of relative growth rate of stellar populations and therefore for the highest SFRs. Other LINERs although showing similar AGN luminosities have lower SFR. We find that most of these sources have LAGN $\sim$ LSF suggesting co-evolution of black hole and stellarmass. In general, the fraction of local LINERs on the main sequence of star-forming galaxies is related to their AGN luminosity.

1 Introduction

LINERs are the most common active galactic nuclei (AGN), with numbers that exceed those of high-ionization' AGN ([18], and references therein) in the local universe making up to 1/3 of all galaxies and 2/3 of AGNs [23, 20]. Different mechanisms were proposed to explain their position in the diagnostic diagramas (refs. [2, 21, 33, 24]); they include shock excitation

[1]Observations were collected at CAHA (Calar Alto) and the Nordic Optical Telescope, at the Observatorio del Roque de los Muchachos, La Palma, Spain. Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

(e.g. [11, 26]), photoionization by young, hot, massive stars ([35]), photoionization by evolved post-asymptotic giant branch (pAGB) stars (e.g. [34, 1, 10, 32]), and photoionization by a central low luminosity AGN (e.g. [13, 20, 15]). Most LINERs have been shown to be powered by an AGN, especially those with stronger emission lines (e.g. EW (Hα) > 3Å, see [10]) and unresolved hard X-ray emission (e.g. [15, 16, 17, 18], and references therein).

The best studied nearby LINERs (e.g. [19, 20, 21, 25]) are found in the nuclei of galaxies with little or no evidence of active star formation (SF), usually hosted by massive early-type galaxies (rarely spirals), and with massive black holes in their centres, old stellar populations, small amounts of gas and dust, and low extinctions. At higher redshifts, Herschel/PACS observations allowed Tommasin et al. (2012) [36] (T12, hereinafter) to show that high-luminosity LINERs from the COSMOS field at z $\sim$ 0.3 have SF luminosities on average two orders of magnitude higher than that of lower AGN luminosity, nearby LINERs; these high SF rates (SFR) are much higher that those derived from the observed Hα flux. In this work, we focus on the most luminous LINERs in the local (0.04 < z <0.11) universe and study their SF and AGN activity, in order to understand the LINER phenomenon in relation to star-forming galaxies and to compare their properties with those of the LINERs at z $\sim$ 0.3. This contribution is a summary of the paper by Povic et al. (2016), [30] (hereinafter P16).

2 Sample, Data and Analysis

We initially selected all LINERs[2] with 0.04 < z <0.11 from the SDSS/DR4 catalogue in Garching MPA-JHU ([21, 4]). Among them, a statistically sufficient number (147 sources) of the most luminous LINERs (logLAGN[3] > 44.3 erg/s) were selected; we call these sourses 'LLINERs. Once the SF luminosities (LSF) were calculated[4], we chose those with LSF > 43.3 erg/s, which amounted to 47 galaxies. We obtained optical spectroscopic observations of 42 out of the 47 targets. We call these 42 objects the most luminous LINERs in terms of both AGN and SF luminosity, or 'MLLINERs'. We morphologically classify our targets by visual inspection using SDSS colour images. We separated all galaxies between early-type (E: ellipticals and lenticulars), spiral (S), and peculiar[5] (P) or unclassified.

We got optical spectroscopic data during six runs (PI Márquez) with the TWIN spectrograph attached to the 3.5m telescope in CAHA. Spectral samplings of $\sim$ 1 and 2 Å/pixel were used for the red (6700-8300Å) and blue ($\sim$ 3500-7000Å) arms, respectively. The slit width was $\sim$ 1 arcsec. Additional spectra were obtained with ALFOSC@NOT, with similar spectral sampling and slit sizes. All details concerning the sample and the observing and reduction description are provided in P16. Concerning FIR data, we obtained PACS observations for six targets (PI Netzer). We also collected IRAS FIR flux measurements available for 10 additional sources (see P16 for details).

[2]using both [NII] 6584/Hα and [OI] 6300/Hα criteria of [24], and with EW(Hα) > 2.5 Å([10])
[3]following [27]
[4]based on the Dn4000 index, see P16
[5]those showing a clear presence of interactions, additional structures (e.g. tails, rings), and/or irregular shapes

Nuclear spectra[6] were fitted[7] with STARLIGHT[8] ([8]), using templates from [5], with solar metallicity and 25 different stellar ages. We used the [6] extinction law. We obtained very good fit in $\sim 80\%$ of the cases. The best stellar population mixture are represented through three stellar ages: young ($\leq 10^8$yr), intermediate (10^8 to 10^9yr), and old ($> 10^9$yr).

Nuclear emission line spectra were obtained by subtracting from the original ones the best-fit stellar models; the flux of the strong emission lines were measured by fitting a single gaussian function. All emission lines were corrected for extinction using the ratio of HI Balmer lines, and using $H\alpha/H\beta = 3.1$ as the theoretical value for AGN ([28]). Line ratios were used to check the position of MLLINERs in the BPT diagrams ([22],[9],[24]).

The AGN luminosity of MMLINERs are based on the reddening-corrected luminosity of Hβ and [OIII]λ5007[9] (Eq. 4 in T12). We measured the SFRs both from the optical (from STARLIGHT best fits and Dn4000) and FIR. To convert SFR to LSF, we assume $\mathrm{LSF} = \mathrm{SFR} \times 10^{10}\,\mathrm{L}_\odot$. To scale the nuclear measurements to those of the entire galaxy, we assume that the specific SF rate (sSFR) is constant throughout the galaxy and therefore: $\mathrm{SFR}_{scaled} = \mathrm{SFR}_{nuclear}/\mathrm{M}_{nuclear} \times \mathrm{M}_{tot}$[10].

3 Results and discussion

Our MLLINERs are hosted by galaxies with all morphologies. We find a higher fraction ($\sim 20\%$) of E in our samples and of S in T12. Our MLLINERs show higher fractions of S in comparison to nearby LINERs in [20]. Moreover, a significant fraction ($\sim 25\%$) of MLLINERs are hosted by peculiar systems, showing unusual structures and clear signs of interactions, at both low- and higher-redshifts, which is again in contrast with the morphology of nearby LINERs.

The nuclear stellar masses of our MLLINERs cover the range 0.6 - $8.3 \times 10^{10}\,\mathrm{M}_\odot$ (average $2.1 \times 10^{10}\,\mathrm{M}_\odot$). Using the total stellar masses in SDSS MPA-JHU DR7, we estimate a median total stellar mass of $6.6 \times 10^{10}\,\mathrm{M}_\odot$. Interestingly, MLLINERs at $z \sim 0.07$ and $z \sim 0.3$ (from T12), although hosted by massive galaxies, do not cover the region of the most massive galaxies. A significant part (35%) of T12 LINERs have lower stellar masses, however the peak of the two distributions at $\log \mathrm{M}_* \sim 10.9\,\mathrm{M}_\odot$ is the same for both samples. The median total stellar mass of our MLLINERs corresponds perfectly to the critical stellar mass found both observationally ([23, 29]) and from numerical works ([31, 3]) for the growth rate of stellar populations; for most LLINERs, on the contrary, their stellar masses are already higher and correspond to lower values of the relative growth rate (lower LSF). This explains why MLLINERs having in average lower stellar masses in comparison to LLINERs, have higher LSF.

LLINERs and MLLINERs cover a similar range of extinctions, most galaxies having

[6]extracted by selecting a central region equal to 2.5 $\times$ FWHM of the seeing

[7]previously corrected for galactic extinction, K-corrected, and moved to rest-frame

[8]http://astro.ufsc.br/starlight

[9]Hα resulted to be a bad tracer for SF, since only a small, or even null, percentage of the observed Hα luminosity could be explained as coming from young stars (age $\leq 10^8$ yr) as traced by STARLIGHT

[10]nuclear stellar masses from the STARLIGHT fits, total stellares from the MPA-JHU DR7 catalogue

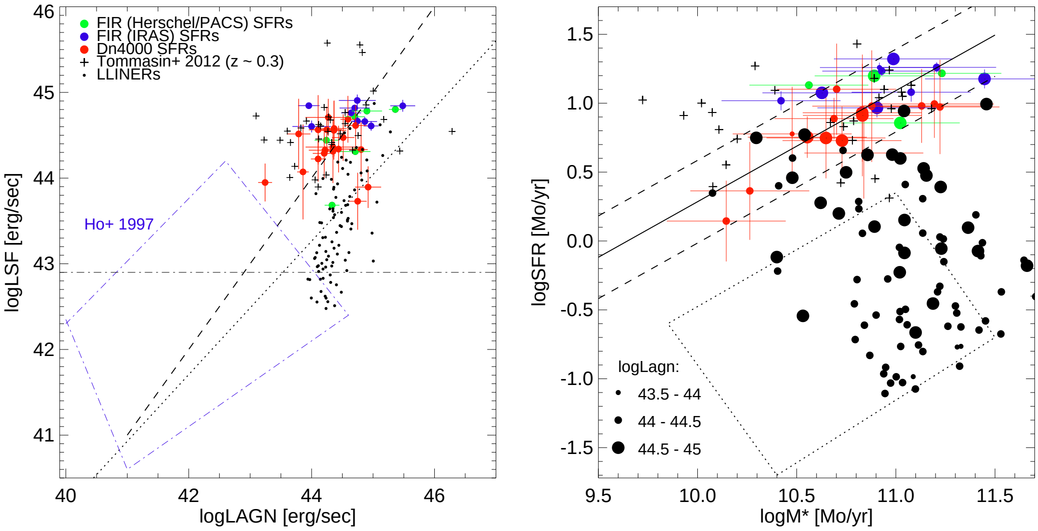

Figure 1: (Left) LSF of MMLINERs measured with Herschel/PACS FIR data (green), IRAS data (blue), and Dn4000 index (red). The entire sample of LLINERs (small black dots), and the most luminous LINERs at $z \sim 0.3$ from T12 (black crosses) are also shown, together with the location of nearby LINERs from Ho et al. (1997) (box). The dashed line shows the one-to-one LAGN-LSF relation; the dotted line shows the location of AGN-dominated sources (Netzer et al. 2009). The horizontal dashed-dot-dashed line shows the limit below which we do not trust LSF (at about $8 \times 10^{42} = 0.2\,M_\odot/yr$). (Right) SF main sequence (MS). The solid black line shows the Whitaker et al. (2012) fit for the MS, and the dashed lines its typical width. The dotted square represents the typical location of 60% of all LINERs at low redshifts in [25]. Depending on their AGN luminosity, MLLINERs and LLINERs are represented with symbols of different sizes.

$Av > 1.0$. These values are higher than the extinctions of the nearby and low-luminosity LINERs in [19], where 78% of their LINERs have $Av < 1.5$. This result agrees with the general finding that the typical extinction increases with SFR (e.g., [21]).

The nuclear regions of our MLLINERs are mainly characterised by intermediate (10^8 - 10^9 yr) and old ($> 10^9$yr) stellar populations; this is consistent with previous findings for low-luminous AGN (LINERs included) ([7, 14]). A young ($\leq 10^8$yr) population is found in the nuclear regions of 43% of MLLINERs, but for most of these galaxies it represents only $< 10\%$ of all stars. Most of SF measured in FIR is possibly related to circumnuclear regions of MLLINERs, due to high stellar masses and/or young stars, since with our nuclear spectra in average we only cover $\sim 30\%$ of the total stellar mass.

Figure 1 (left) shows that MLLINERs tend to lie on the one-to-one LSF-LAGN relation (dashed line). About 90% of all MLLINERs have values of LSF and LAGN in the range 10^{44} - 10^{45} erg/sec. Our MLLINERs are located clearly above the line of AGN-dominated galaxies from [27], and remain closer to the dashed line. On the other side, LLINERs are located below the dashed line, showing a wide range of LSF for the same LAGN. We suggest that this is again related to the stellar mass differences between MLLINERs and LLINERs. Although having the same LAGN, LLINERs with stellar masses higher than the critical one ($\sim$6,5$\times 10^{10}\,M_{\odot}$) seem to have already lower relative growth rates of stellar populations, and therefore lower LSF. In general, the location of our MLLINERs at $z \sim 0.04$ - 0.11 and those at $z \sim 0.3$ from T12 are very similar, whereas LINERs in [19] are characterised by considerably lower LAGN and LSF. We confirm the existence of LINERs in the local universe with the same SF and AGN properties as at $z \sim 0.3$, discarding therefore the pure evolutionary scenario proposed in T12.

SF galaxies show a tight and well-defined relationship called the 'main sequence' (MS) between SFR and stellar mass. This relationship depends on redshift and has been studied at different cosmic times (e.g. [4, 12, 25], and references therein). Figure 1 (right) shows the MS by [37] (solid line) for $z = 0.07$, which is the average value in our sample. For the width of the MS we used $\pm\,0.3$ dex (dashed lines). More than 90% of our MLLINERs lie along the main sequence of SF galaxies (within the dashed lines). Once again our MLLINERs at $z = 0.04$ - 0.11 show the same properties as the most luminous LINERs at $z \sim 0.3$ (black crosses in Fig. 1 (right)). At both redshifts, the most luminous LINERs represent $\sim 1/3$ of all LLINER. Most remaining 2/3 of LLINERs lie below the MS (black dots), having lower SFRs for masses typical of MLLINERs or even higher.

Recently, [25] studied the MS for different types of low-redshift galaxies from the SDSS survey, with 6.5% of the sources being LINERs (13,176 galaxies) which we consider to be representative of LINERs at low redshifts. The average stellar masses and SFRs they found are $<\log(M_*)> = 10.74$ and $<\log(\mathrm{SFR})> = -0.79$, respectively. These values are smaller than for our MLLINERs (10.82 and 0.86, respectively). This is not surprising given that our MLLINERs were selected according to both LAGN and LSF. The more important issue of the location of LINERs in the MS as a function of LAGN was not considered by [25]. To illustrate this we have estimated the fraction on the MS of all SDSS/DR7 LINERs in the redshift range 0.04 - 0.11, using different bins of LAGN. The fraction of $z = 0.04$ - 0.11 LINERs located on the MS is 2%, 3%, 11%, and 37% in the bins of logLAGN = 43 - 43.5, 43.5 - 44, 44 - 44.5, 44.5 - 45, respectively. Thus we can safely conclude that the fraction of SF galaxies among low redshift LINERs is LAGN-dependent. While studies like those of [25] are not available at higher redshifts, it seems that for the MLLINERS, this difference from the rest of the population extends at least to $z = 0.3$.

4 Main conclusions

LINERs with these kind of properties were previously studied only at $z \sim 0.3$ (T12). With our work we confirmed the existence of such LINERs also at low-redshifts ($z \sim 0.07$). They show the same properties in terms of stellar mass, SFRs, and AGN luminosity at both redshifts. We found that the median stellar mass of our most-luminous LINERs corresponds to the mass of 6 - $7 \times 10^{10}\,M_{\odot}$ measured in different works to be critical for the peak of relative growth rates of stellar populations (highest SFRs and LSF). Most of them are found on the MS of SF galaxies, with stellar masses $\gtrsim 10^{10}\,M_{\odot}$. Finally, using the entire DR7 sample, we present evidence that the fraction of LINERs on the MS depends on their AGN luminosity.

Acknowledgments

This research was supported through the projects TIC114 (Junta de Andalucía), AYA2013-42227-P (Spanish Ministry of Economy and Competitiveness) and the Israel Science Foundation grant 284/13. MP acknowledges financial support from JAE-Doc programme of the CSIC, co-funded by the European Social Fund.

References

[1] Annibali, F., et al. 2010, A&A, 519, 40
[2] Baldwin, J. A., Phillips, M. M., & Terlevich, R., 1981, PASP, 93, 5
[3] Behroozi, P. S., et al., 2012, ApJ, 770, 57
[4] Brinchmann, J., et al., 2004, MNRAS, 351, 1151
[5] Bruzual, A. G., & Charlot, S., 2003, MNRAS, 344, 1000
[6] Cardelli, J. A., et al., 1989, ApJ, 345, 245
[7] Cid-Fernandes, R. et al., 2004, ApJ 605, 105
[8] Cid-Fernandes, R. et al., 2005, MNRAS, 358, 363
[9] Cid-Fernandes, R. et al., 2010, A&A 403, 1036
[10] Cid-Fernandes, R. et al., 2011, MNRAS 413, 1687
[11] Dopita, M. et al. 1997, A&A 490, 202
[12] Elbaz, D. et al. 2007, A&A, 468, 33
[13] Ferland, G. and Netzer, H. 1983, ApJ 264, 105
[14] González Delgado, R. M., et al. 2004, ApJ 60, 6
[15] González-Martin, O., et al. 2006, A&A, 460, 45
[16] González-Martin, O., et al. 2009a, ApJ, 704, 1570
[17] González-Martin, O., et al. 2009b, A&A, 506, 1107
[18] Heckman, T. M. & Best, P. N., 2014, ARAA, 52,589
[19] Ho, L. C. 1997, ApJS 112, 315
[20] Ho, L. C. 2008, Ann.Rev.Ast.Ap., 46, 475
[21] Kauffmann, G., et al., 2003a, MNRAS, 346, 1055
[22] Kauffmann, G., et al., 2003b, MNRAS, 341,33
[23] Kauffmann, G., et al., 2003c, MNRAS, 341,54
[24] Kewley, L., et al., 2006, MNRAS, 372, 961
[25] Leslie, S. K., et al., 2016, MNRAS, 455, 82L
[26] Nagar, N. M., et al., 2005, A&A, 435, 521
[27] Netzer, H., 2009, MNRAS, 399, 1907
[28] Osterbrock, D. E. & Ferland, G. J., 2005, University Science Books
[29] Pérez, E., et al. 2013, ApJL, 764, L1
[30] Pović, M., et al. 2016, MNRAS, 462, 2878 (P16)
[31] Shankar, F., et al., 2006, ApJ, 643, 14
[32] Singh, R., et al., 2013, A&A, 558, 43
[33] Stasińska, G., 2006, MNRAS, 371, 972
[34] Stasińska, G., 2008, MNRAS, 391, L29
[35] Terlevich, R., & Melnick, J., 1985, MNRAS, 213, 841
[36] Tommasin, S., et al., 2012, ApJ 753, 155 (T12)
[37] Whitaker, K. E., et al., 2012, ApJ, 754, L29