The Stellar Populations of Low Luminosity Active Galactic Nuclei. III: Spatially Resolved Spectral Properties

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ABSTRACT

In a recently completed survey of the stellar populations properties of LINERS and LINER/HII Transition Objects (TOs), we have identified a numerous class of galactic nuclei which stand out because of their conspicuous 10\textsuperscript{8.5}–10\textsuperscript{9} yr populations, traced by high order Balmer absorption lines and other stellar indices. These objects were called “Young-TOs”, since they all have TO-like emission line ratios. In this paper we extend this previous work, which concentrated on the nuclear properties, by investigating the radial variations of spectral properties in Low Luminosity Active Galactic Nuclei (LLAGN). Our analysis is based on high signal to noise long-slit spectra in the 3500–5500 Å interval for a sample of 47 galaxies. The data probe distances of typically up to 850 pc from the nucleus with a resolution of ~ 100 pc (~ 1”) and S/N ~ 30. Stellar population gradients are mapped by the radial profiles of absorption line equivalent widths and continuum colours along the slit. These variations are further analyzed by means of a decomposition of each spectrum in terms of template galaxies representative of very young (\leq 10\textsuperscript{7} yr), intermediate age (10\textsuperscript{8.5}–10\textsuperscript{9} yr) and old (10\textsuperscript{10} yr) stellar populations.

This study reveals that Young-TOs also differ from Old-TOs and Old-LINERs in terms of the spatial distributions of their stellar populations and dust. Specifically, our main findings are: (1) Significant stellar population gradients are found almost exclusively in Young-TOs. (2) The intermediate age population of Young-TOs, although heavily concentrated in the nucleus, reaches distances of up to a few hundred pc from the nucleus. Nevertheless, the Half Width at Half Maximum of its brightness profile is more typically 100 pc or less. (3) Objects with predominantly old stellar populations present spatially homogeneous spectra, be they LINERS or TOs. (4) Young-TOs have much more dust in their central regions than other LLAGN. (5) The B-band luminosities of the central \leq 1 Gyr population in Young-TOs are within an order of magnitude of \( M_B = -15 \), implying masses of order \( \sim 10^7 \)–10\textsuperscript{8} M\odot. This population was 10–100 times more luminous in its formation epoch, at which time young massive stars would have completely outshone any active nucleus, unless the AGN too was brighter in the past.

Key words: galaxies: active - galaxies: Seyfert - galaxies: stellar content - galaxies: nuclei - galaxies: statistics

1 INTRODUCTION

Low luminosity active galactic nuclei (LLAGN) are the most common form of activity in the nearby universe. Their proximity allows us to sample their properties on linear scales which are not accessible for farther AGN populations like
Seyferts and quasars. At optical–UV wavelengths, however, this advantage is compensated by the difficulty in isolating the light from these intrinsically weak nuclei out of a dominant stellar “background”.

In a series of papers, we have been working our own contribution to this field. In Paper I (Cid Fernandes et al. 2004a) we analyzed ground based nuclear optical spectra of a sample of 51 LINERs and TOs, while Paper II (González Delgado et al. 2004) complements this data set with archive HST/STIS spectra of 28 nearby LLAGN. These samples cover nearly half of the LLAGN in the survey of Ho, Filippenko & Sargent 1997 (hereafter HFS97). Our focus throughout this series is on the stellar populations of LLAGN, with the ultimate goal of establishing the role of stellar processes in the physics of these objects.

The main result of Papers I and II is that we have uncovered a very strong relation between the nuclear stellar population and the gas excitation, as measured by [OII]/Hβ, the most important diagnostic line ratio in LLAGN. The relation is in the sense that virtually all systems containing strong populations of ~ 1 Gyr or less have [OII]/Hβ ≤ 0.25, while nuclei dominated by older stars can reach larger values of these line ratios (Cid Fernandes et al. 2001 and references therein). It is thus tempting to interpret Young-TOs as low-luminosity analogs of starburst + Seyfert 2 composites, where the relative low excitation is explained by the starburst contribution to Hβ, which dilutes [OII]/Hβ and HeII/Hβ. Intriguingly, however, Young-TOs are substantially older than the starbursts around Seyfert 2 nuclei, many of which are just a few Myr old, as deduced by the detection of O and WR stars. While Papers I and II revealed a surprisingly large number of systems containing 10^8–10^9 yr populations, massive young stars of the type often found in Seyfert 2s seem to be rare in LLAGN. The analogy between Young-TOs and starburst + Seyfert 2 composites thus rests upon the hypothesis of the existence of a population of massive stars which remains essentially undetected at optical wavelengths. Clearly, further work is necessary to clarify the precise nature of the connection between stellar and gaseous properties in LLAGN.

One type of study which has been carried out for Seyferts is the mapping of stellar populations based on spatially resolved spectroscopy. Variations of absorption line equivalent widths (Wλ) and colours (Cλ) as a function of distance from the nucleus were mapped by means of long slit spectroscopy by Cid Fernandes, Storchi-Bergmann & Schmitt (1998), Boisson et al. (2000), González Delgado, Heckman & Leitherer (2001), Joguet et al. (2001). These variations can be transformed into stellar population profiles, as in the study by Raimann et al. (2003), who found that star-formation in starburst + Seyfert 2s composites, although concentrated in the central regions, is not confined to the nucleus, but spread over the inner ~ 1 kpc. Spatial gradients in spectral indices are also useful to detect the presence of a central continuum source, which dilutes the nuclear Wλ’s with respect to off-nuclear positions. Both a compact nuclear starburst and an AGN featureless continuum can produce this effect, but in Seyfert 2s the papers above showed that significant dilution only occurs when a starburst is present in the innermost extraction.

Spatially resolved spectroscopy of LLAGN has so far been limited to relatively few studies (eg, Cid Fernandes et al. 1998). While these previous works advanced our comprehension of individual sources, the small number of objects, differences in spectral coverage, data quality and method of analysis prevents us from drawing general conclusions about the radial distribution of stellar populations in LINERs and TOs. In this third paper we take advantage of our recently completed spectroscopic survey to extend this type of study to a large sample of LLAGN. Variations of spectral properties with distance from the nucleus are mapped with the general goal of investigating the relation between spatial gradients, emission line and nuclear stellar population properties. In particular, we aim at evaluating the spatial distribution of intermediate age populations, a distinguishing feature of Young-TOs.

In §2 we describe the data set and present examples of our spatially resolved spectra. In §3 we investigate the spatial variations of a set of spectral properties and quantify these gradients by means of suitable empirical indices. These gradients are further analyzed in §4 with the goal of producing estimates of the sizes, luminosities, masses and extinction of the intermediate stellar population in the central regions of Young-TOs. These estimates provide useful hints on the past and future history of these sources. Finally, §5 summarizes our results.

2 DATA
The data employed in this paper have been described in Paper I. Briefly, we have collected long-slit spectra in the 3500–5500 Å range for 60 galaxies selected out of the HFS97 survey. Observations were carried out at the 2.5 m Nordic Optical Telescope with a 1” slit-width and the Kitt Peak National Observatory 2.1 m telescope with a 2” slit. Our survey differs from that of our mother sample in two main aspects: wavelength coverage and spatial resolution. The information encoded in the region bluewards of 4200 Å, not covered by HFS97, has been explored in previous papers in this series. Here we concentrate on the analysis of the spatial information in this data set.

2.1 Extractions
In order to map spectral gradients, spectra were extracted in several positions along the slit. Extractions for the KPNO spectra were made at every 2.34” (3 pixels) out to at least θ = ±4.7”, but the seeing was 2–3” (FWHM). For the NOT spectra, which constitute 83% of the data analysed here, we have used 1.13” (6 pixels) long extractions out to at least θ = 4.5” from the nucleus in both directions. These narrow extractions approximately match the angular resolution of
our typical NOT observations, which were made under subarcsecond seeing. Outside this central region wider extractions were used if necessary to ensure enough signal.

The signal-to-noise ratio in each extraction was estimated from the rms fluctuation in the 4789–4839 Å interval. Galaxies with \( (S/N)_{4800} \lesssim 15 \) at angular distances \( \lesssim 4.7'' \) from the nucleus were deemed to have insufficient useful spatial coverage and discarded from the analysis. Our cleaned sample contains 47 objects, including 4 normal galaxies and 1 Starburst nucleus. In the nuclear extractions \( (S/N)_{4800} \) varies between 31 and 88 with a median of 51. Outside the nucleus, the median \( (S/N)_{4800} \) decreases from 45 at \( \theta = \pm 2.3'' \) to 31 at \( \pm 4.5'' \). The \( S/N \) in the 4010–4060 Å interval is typically 0.5 \( (S/N)_{4800} \). All 521 extractions were dereddened by Galactic extinction using the Cardelli, Clayton & Mathis (1989) law and the \( A_B \) values of Schlegel, Finkbeiner & Davis (1998). We note that the Kitt Peak the observations (7 galaxies) were taken under non-photometric conditions. This, however affects only the absolute flux scale, not the shape of the spectrum, as we verified comparing spectra of objects taken both in photometric and non-photometric nights. The single result reported in this paper which is affected by this problem is the luminosity of the central young population in NGC 404 (\( \theta 270'' \)), which is likely underestimated.

The distances to the LLAGN in this sample vary between \( d = 2.4 \) and 70.6 Mpc, with a median of 24.1 Mpc. At these distances, \( \theta = 4.5'' \) corresponds to projected radii \( r = 52-1540 \) pc, with a median of 526 pc, while our nuclear extractions correspond to 11–204 pc in radius (median = 85 pc). The spatial regions sampled by these observations are therefore smaller than the ones in our studies of Seyfert 2s (eg. Raimann et al. 2003), which sampled the inner few kpc with a resolution of \( \sim 300 \) pc.

2.2 Sample properties

Table 1 lists our sample, along with the useful spatial coverage in both angular \( (\theta_{\text{out}}) \) and linear \( (r_{\text{out}}) \) units, nuclear and off-nuclear \( S/N \), linear scale, position angle and a summary of spectral properties.

The emission line classification from HFS97 is listed in column 8 of Table 1. As in Papers I and II, we prefer to classify LLAGN as either strong-[OI] emitters (column 11), with a dividing line at \( [\text{OI}]/H\alpha = 0.25 \). These two classes differ only slightly from the LINER and TO classes of HFS97, and better represent the combined distributions of emission line and stellar population properties of LLAGN. Throughout this paper LINERs and TOs are used as synonyms of strong and weak-[OI] sources respectively.

Paper I introduced a stellar population characterization scheme defined in terms of four classes: \( \eta = Y, I, I/O \) and \( O \) (column 9). The \( Y \) class denotes objects with a dominant young starburst. The only object in our sample which fits this class is the WR-galaxy NGC 3367, which is not a LLAGN but is kept in the analysis for comparison purposes. Nuclei with strong intermediate age \( (10^8-10^9 \) yr) populations, easily identified by High Order Balmer absorption Lines (HOBLs; H8X3889 and higher) and dilute metal lines, are classed as \( \eta = I \), while nuclei dominated by old stars are attributed a \( \eta = O \) class, and \( \eta = I/O \) denotes intermediate cases. Not surprisingly, it is sometimes hard to decide where to fit a galaxy in this classification scheme. The best example of this sort of problem is NGC 772, which contains both young, intermediate age and old components (Paper I). Despite the weak HOBLs in its spectrum, we chose to tag it as \( \eta = I \).

A simpler (but still useful) classification scheme is to group \( \eta = Y \) and \( I \) objects as “Young” and \( \eta = I/O \) and \( O \) objects as “Old”. As an objective criterion for this classification we use the value of the equivalent width of the CaII K line in the nucleus: \( W_K^{\text{nuc}} \lesssim 15 \) Å for Young systems and larger for Old ones (column 10). The use of this equivalent width as an indicator of the evolutionary status of the stellar population is justified because the AGN contribution to these continuum is these sources negligible (Papers I and II). These two classes are paired with the \( [\text{OI}]/H\alpha \) class to produce our combined stellar population and emission line classification into Young/Old-TO/LINER, listed in the last column of Table 1.

Of the 42 LLAGN in our sample, 13 fit our definition of strong-[OI] sources and 29 are weak-[OI] sources, while the stellar populations types are split into 16 Young and 28 Old systems. The combined emission line and stellar population statistics are: 14 Young-TOs, 2 Young-LINERs, 11 Old-LINERs and 15 Old-TOs. Note that Young-LINER is a practically non-existent category, as the overwhelming majority of Young systems are weak-[OI] emitters.

It is worth pointing out that Young-TOs in this sample are on-average closer than other LLAGN. The distances to Young-TOs span the \( d = 2.4-35.6 \) Mpc range, with a median of 16.8 Mpc, while for other LLAGN 14.3 \( \leq d \leq 70.6 \) Mpc, with a median of 31.6 Mpc. This tendency is already present in Paper I and in the HFS97 survey, from which we culled our sample. In principle one expects that radial variations of spectral properties due to the presence of a compact central source will be harder to detect for more distant objects, due to the increasing contribution of bulge light to the nuclear extraction. This potential difficulty, coupled with the trend discussed above may lead to a bias in the sense that radial gradients would be easier to detect in Young-TOs because of their smaller distances. We do not believe this effect has a strong impact on the conclusions of this paper, given that there is still a substantial overlap in distances of Young-TOs and other LLAGN. This issue is further discussed in § 3.1 and 3.2.

2.3 Spatially resolved spectra: Examples and first impressions

Figures 1 and 2 illustrate spatially resolved spectra for a representative subset of the galaxies in our sample. Spatial gradients in spectral properties will be analyzed in detail in the remainder of this paper, but some results are evident from a simple visual inspection of these figures.

(i) First, in objects like the Old-LINER NGC 315 the off-nuclear spectra look virtually identical to the nuclear spectrum, implying a high spatial uniformity of the stellar populations. The only noticeable gradient is in the emission lines, which are concentrated in the nucleus.

(ii) Second, the strongest gradients are found in systems with conspicuous HOBLs (eg, NGC 4150, NGC 4569). As
Table 1. Col. (1): Galaxy name; Cols. (2) and (3): Useful angular and linear coverage. Col. (4): Angular scale. Cols. (5) and (6): S/N at 4800 Å at nucleus and outer extractions. Col. (7): Slit position angle. Col. (8): Spectral type according to HFS97. Col. (9): Stellar population category (Paper I). Col. (10): Equivalent width of the CaII K band at the nucleus, in Å. Col. (12): Combined emission line and stellar population class. Objects marked with a * were observed at KPNO.

(iii) Third, although HOBLs, when present, are stronger in the central extraction, they are not confined to the nucleus. This is clearly seen in the cases of NGC 4150 and NGC 4569, where HOBLs still show up in extractions more than 3″ away from the nucleus. Given that the seeing in these observations was typically better than 1″, we conclude that the “HOBLs region” is spatially extended.

(iv) As is typical of LLAGN, emission lines are generally weak. In fact, many objects show no sign of important diagnostic lines like Hβ and [OIII]λ5007 even in the nucleus. The

noted above, these are nearly all weak-[OII] sources. This combination of youngish stellar population and [OII]/Hα ≤ 0.25 fits our definition of Young-TOs.
measurement of emission lines requires careful subtraction of the starlight, which we postpone to a future communication.

3 STELLAR POPULATION GRADIENTS

A convenient way to map spatio-spectral variations is to compute profiles of absorption features and continuum colours along the slit (e.g., Cid Fernandes et al. 1998; Raimann et al. 2003). From Papers I and II we know that an AGN continuum contributes very little (if anything) to our ground based optical spectra. Any significant variation detected in these properties can thus be confidently attributed to variations in the stellar populations.

In Paper I we have measured an extensive set of stellar population indices in different systems. In this paper we will use the equivalent widths of the CaII K line ($W_K$), the G band ($W_G$), MgI ($W_{Mg}$) and $W_C$ (a “pseudo equivalent...
width” centered in the continuum just to the blue of H9) plus the $C_{3660} \equiv 3660/4020$ and $C_{5313} \equiv 5313/4020$ continuum colours, all measured in Bica’s system. The 4000 Å break index of Balogh et al. (1999), $D_n(4000)$, is also used, but only for illustrative purposes. The $W_C$ index works as a direct tracer of HOBLs: Spectra with clearly visible HOBLs all have $W_C < 3.5$ Å, while spectra dominated by old populations ($\sim 10^{10}$ yr) have larger $W_C$ due to a blend of metal lines. As shown in Paper I, $W_K$, which is a much stronger and thus more robust feature, is also a good (albeit indirect) tracer of the intermediate age populations responsible for the HOBLs.

All these indices are highly correlated (Paper I). Their radial behaviors, however, need not be the same. For instance, a compact blue source such as young or intermediate age starburst should produce a larger dilution at the nucleus of the bluer indices, like $W_K$, than of the redder ones, such
3.1 Radial Profiles of Stellar Indices

Figures 3–12 show the variations of our seven stellar population indices with angular distance from the nucleus for some illustrative cases. The top panels show $W_K$ (black, solid line), $W_G$ (magenta, thin line), $W_C$ (green, dotted line) and $W_{Mg}$ (red, dashed line). The middle panels show the $C_{3660}$ (blue, dotted line) and $C_{3313}$ (black, solid line) colours, plus the $D_n(4000)$ profile (green, dashed line). The slit brightness profile $S(r)$ at $\lambda = 4200$ Å is plotted in the bottom panel to give an idea of the light concentration. The thick line segment marks the FWHM of $S(r)$; its value is listed in the top right in both angular and linear units. A stellar profile is also plotted to illustrate the spatial resolution. Vertical dotted and dashed lines indicate projected distances of $\pm 100$ and $\pm 500$ pc from the nucleus respectively.

The examples in figures 9–12 were chosen to illustrate the variety of radial profiles found in the sample. In a first cut, the $W_\lambda$ profiles may be grouped in three categories:

(i) Flat (e.g., NGC 305 and NGC 410),
(ii) centrally peaked (e.g., NGC 7742),
(iii) “diluted” profiles (e.g., NGC 3627, NGC 4569).

Most objects studied here have either flat or diluted $W_\lambda$ profiles. In NGC 6951 and NGC 7742, the peaked appearance of $W_\lambda$ is due to circum-nuclear star-forming rings which appear in our outermost extractions (Pérez et al. 2000). Outside these rings, the absorption lines rise up again, like in NGC 1097 and other ringed galaxies studied by Cid Fernandes et al. (1998).

The main focus of our analysis throughout the rest of this paper will be on nature and properties of the source of dilution in LLAGN with diluted profiles. These profiles cannot be explained in terms of metallicity gradients, as this should produce peaked profiles. The drop in $W_\lambda$ towards the nucleus in these galaxies is thus clearly the result of dilution of the metallic features by a centrally concentrated stellar population which is younger than that a few arcseconds away from the nucleus. The most dramatic example of this effect is seen in the starburst galaxy NGC 3367, where the young starburst appears only in the three central extractions (figure 13). We note in passing that, at $d = 43.6$ Mpc, this galaxy is one of the most distant in our sample, well above the median distance of 27.9 Mpc. Yet, its $W_\lambda$ gradients are clearly mapped with our data, which shows that the worries raised in §2 about possible distance related biases and not justified in practice. Similar comments apply to NGC 5678 (figure 14 $d = 35.6$ Mpc) and NGC 772 (figure 15 $d = 32.6$ Mpc).

In LLAGN with diluted profiles, the diluting agent could in principle also be a young starburst, but, as shown in Papers I and II, in only $\sim 10\%$ of LLAGN such a young component contributes with more than 10% of the flux at 4020 Å in our ground-based nuclear spectra. For most objects, the radial dilution is caused mainly by an intermediate age population, which appears far more frequently and in much larger strengths. These populations are easily recognized by their weak metal lines and deep HOBLS, as seen, for instance, in NGC 3627 and NGC 4569 (figures 16 and 17).

Figures 18–19 show the $W_K$ profiles for all 47 galaxies in our sample, sorted in an increasing sequence of nuclear $W_K$. 

![Figure 3. Spatial variations of stellar population indices for NGC 315. Top: Radial profiles of $W_K$ (black, thick solid line), $W_G$ (magenta, thin line), $W_C$ (green, dotted line) and $W_{Mg}$ (red, dashed line). Note that $W_C$ has been multiplied by 1.5 for clarity. Middle: Radial profile of the 3660/4020 (blue, dotted line) and 5313/4020 (black, solid line) colours, and $D_n(4000)$ (green, dashed line). The 3660/4020 colour is multiplied by 2 in the plot. Bottom: Surface brightness at 4200 Å (in flux units) along the slit, normalized to $S(r = 0) = 1$. The FWHM of the slit profile is marked as a thick line segment, and listed at the top right in both arcsec and pc. The dotted line shows the instrumental profile, corresponding to a star observed in the same night. Dotted and dashed vertical lines indicate projected distances of $\pm 100$ and $\pm 500$ pc from the nucleus respectively.](image-url)
values. This ordering bears an excellent correspondence with the profile shapes: Of the first 19 galaxies (from NGC 3367 to NGC 6500), at least 16 have diluted $W_K$ profiles. The exceptions are NGC 2681, NGC 841 and possibly NGC 6500. From NGC 3166 onwards, i.e., for $W_{nuc}^K > 15$–16 Å, profiles are either centrally peaked, or, more commonly, approximately flat. This obvious link is examined in quantitative terms in the next section.

3.2 Gradients in Equivalent Widths

In order to quantify the spatial gradients seen in figures 3–15 we define a radial dilution index

$$\delta_\lambda = \frac{W_{\lambda}^{\text{off}} - W_{\lambda}^{\text{nuc}}}{W_{\lambda}^{\text{off}}}.$$  \hspace{1cm} (1)

which compares nuclear and mean off-nuclear equivalent widths. Flat $W_\lambda$ profiles should yield $\delta_\lambda \sim 0$, while $\delta_\lambda < 0$ correspond to centrally peaked profiles and $\delta_\lambda > 0$ to diluted profiles. Furthermore, if the nuclear spectrum differs from that in off-nuclear extractions only by an extra continuum source (or, more precisely, a source with negligible $W_\lambda$), then $\delta_\lambda$ measures the fractional contribution of this source to the continuum at $\lambda$ (Cid Fernandes et al. 1998).

$W_{\lambda}^{\text{off}}$ is defined as the average of $W_\lambda(\theta)$ for extractions centered at $|\theta|$ between 2.2 and 4.7" from the nucleus. Note that for the NOT observations this definition excludes extractions adjacent to the nucleus, which in some cases are contaminated by nuclear light due to seeing. The averaging is carried out weighting by the error in $W_\lambda$. The uncertainties in the dilution index were evaluated from standard error propagation. Typical one sigma uncertainties in $\delta_\lambda$ are 0.1 for $W_C$ and 0.04 for $W_K$, $W_G$ and $W_{Mg}$. We have also explored an alternative definition of $W_{\lambda}^{\text{off}}$ in terms of extractions between $r = 250$ and 750 pc from the nucleus, but this turned out to yield similar results, which further demonstrates that our conclusions are not significantly affected by potential distance-related biases.

Table 2 lists the resulting values of $\delta_\lambda$. Gradients are considered to be significant whenever $|\delta_K| > 10\%$, which corresponds to a $\sim 2.5$ sigma detection limit. According to this criterion, significantly diluted profiles ($\delta_K > 10\%$) occur in 13 of the 42 LLAGN in our sample, while only 3 have significantly peaked profiles ($\delta_K < -10\%$). Spatially homogeneous stellar populations therefore prevail among LLAGN, accounting for $\sim 60\%$ of our sample.

3.2.1 Relations between $W_\lambda$-gradients, emission line and nuclear stellar population properties

In figure 16 we investigate the relation between dilution and nuclear stellar population by plotting $\delta_\lambda$ against $W_{nuc}^K$ for $W_C$, $W_K$, $W_G$ and $W_{Mg}$. The vertical dotted lines in this plot are the same ones used in Paper I to approximately distinguish objects with significant intermediate age populations (those with $W_C \lesssim 3.5$, $W_K \lesssim 15$, $W_G \lesssim 9$ and $W_{Mg} \lesssim 9$ Å, which are classed as $\eta = I$) from those dominated by older populations (\eta = I/O and O). Figure 16 shows that these dividing lines also segregate objects with significant dilution from those without. Focusing on the $W_{nuc}^K = 15$ Å
Figure 13. Radial profiles of the equivalent width of the Ca II K line for all galaxies in the sample. Dotted vertical lines mark distances of ±100 pc from the nucleus. A horizontal dashed line is drawn at $W_K = 15 \text{ Å}$ for reference. The thick line segment in the bottom of each panel indicates the seeing, measured from the FWHM of star observed in the same night. Objects are sorted by the value of $W_K$ at the nucleus ($W_{nuc}^K$), indicated in the bottom right corner of each panel. Galaxies in this figure have $W_{nuc}^K$ between 2.5 (bottom left panel) and 14.8 Å (top right).

limit, which separates Young from Old sources in our simple classification scheme, we find that 12 out of the 13 objects with $\delta_K > 10\%$ fall into the Young category, the exception being NGC 3245, which, with $W_{nuc}^K = 15.2 \pm 0.3 \text{ Å}$, sits right at the border line between Young and Old sources. In other words, galaxies with significant radial gradients in their stellar populations contain intermediate age populations in their nuclei. The converse is also true, as at least 12 out of 16 Young-LLAGN have diluted profiles. This is the same result found in figures 14 and 15, where we see that virtually every galaxy with $W_{nuc}^K < 15 \text{ Å}$ has a diluted $W_K$ profile.

Since in Papers I and II we have shown that nearly all nuclei with weak metal absorption lines are weak-[OI] emitters, we expect that the strong relation between $\delta_\lambda$ and $W_{nuc}^K$ seen in figure 16 translates to an equally strong relation between $\delta_\lambda$ and $[\text{OIII}]/H\alpha$. This is confirmed in figure 17.
which shows that all but one object with $\delta K > 10\%$ have $\text{[O I]}/\text{H} \alpha < 0.25$. Two other weak-[OI] nuclei, NGC 404 and NGC 4150, should probably be included in the list of sources with diluted profiles. NGC 404 is so close by (2.4 Mpc) that our outer useful extractions do not reach a probable rise in $W_\lambda$'s for larger radii, if this indeed happens in this dwarf galaxy. Dust effects may also be present, as indicated by the peak in the $C_{5313}$ colour in the nucleus of NGC 404 (figure 19). In NGC 4150 the strongest dilution is seen at $\theta = +1.1''$ from the nucleus, and the rise in $W_\lambda$ seen in our last extractions has a small weight in our definition of $W_\alpha^{\text{off}}$, resulting in a small $\delta \lambda$. This asymmetry is associated with the pronounced nuclear dust lane in this galaxy (Paper II), which is responsible for its asymmetric $C_{5313}$ profile (figure 19).

The only strong-[OI] source with significant radial dilution is NGC 5005 ($\delta K = 11 \pm 3\%$, $\text{[O I]}/\text{H} \alpha = 0.65$). Given that this nucleus is classified as a L1.9 by HFS97, it is conceivable that the dilution is caused by a nuclear featureless continuum, as found in spatially resolved spectroscopy of type 1 Seyferts (Cid Fernandes et al. 1998). However, none of the other 7 type 1 LLAGN in our sample exhibits significant dilution. Furthermore, HOBLs are clearly present in the nuclear spectrum of NGC 5005, so we favor the interpretation that, as in other objects, dilution is caused mainly by a cen-

Figure 14. As Figure [13] but for galaxies with $W_\alpha^{\text{osc}}$ between 14.9 and 17.8 $\AA$.
trally concentrated intermediate age population. As noted in Paper II, and confirmed by our radial dilution analysis, the contribution of a non-stellar continuum to our ground based spectra is negligible. Clear signatures of a featureless continuum in LLAGN are only found under the much higher spatial resolution of HST, and even then they are rare.

We thus conclude that virtually all sources with radially diluted metal lines are weak-[OI] emitters. Note, however, that the converse is not true, as there are several weak-[OI] objects with either flat or, more rarely, peaked $W_\lambda$ profiles. These non-diluted weak-[OI] nuclei are dominated by old stellar populations, as deduced from their strong metal lines (figure 16, Paper I).

To summarize, combining the relations between dilution, stellar population and emission line properties we find that significant stellar populations gradients are found almost exclusively in Young-TOs, i.e., objects with weak [OI] and a conspicuous intermediate age nuclear stellar population. Old-TOs and Old-LINERs, on the other hand, tend to have spatially uniform stellar populations. These strong relations can be visualized comparing the location of different symbols in figures 16 and 17.

**Figure 15.** As Figure 13 but for galaxies with $W_K^{\text{nuc}}$ between 18 and 20 Å.
3.3.2 \( \lambda - \)gradients and the colour of the nuclear source

Another result of the \( \lambda_r \) analysis is that the spatial dilution, when significant, tends to be larger for shorter wavelength, which implies that the diluting agent is bluer than the off-nuclear population. This is illustrated in figure 18, where we plot the dilution in the K line (central \( \lambda = 3930 \) Å) against the dilution in \( W_C \) (\( \lambda = 3816 \) Å), \( W_K \) (\( \lambda = 4301 \) Å) and \( W_{Mg} \) (\( \lambda = 5176 \) Å). For LLAGN with \( \delta_K > 10\% \) the dilution follows a wavelength sequence: \( \delta_C > \delta_K > \delta_{Mg} \). (Deviations from this sequence are all within the uncertainties in \( \delta_{\lambda} \)). Some objects with clear gradients in K show little, if any, dilution in MgI (eg. NGC 3245 and NGC 6503). In NGC 772, NGC 4569 and other objects, the colour profiles confirm the existence of the blue nuclear component inferred from the behavior of \( \delta_{\lambda} \) for different lines. In others, however, \( C_{\lambda} \) shows little variation (eg, NGC 3627) or even slightly redder colours in the nucleus (NGC 3245), contrary to the inference from the absorption line gradients. As discussed below, this apparent contradiction is due to dust in the central regions of these galaxies.
Figure 16. Radial gradients in four equivalent widths, measured from the comparison of nuclear and off-nuclear spectra. Different symbols correspond to Young-TOs (filled blue circles), Young-LINERs (open blue circles), Old-TOs (filled red triangles) and Old-LINERs (open red triangles). The star indicates the starburst galaxy NGC 3367. Crosses in the top right indicate mean error bars. Vertical dotted lines divide nuclei containing only old stars (large $W_\lambda$) from those with significant intermediate age populations (small $W_\lambda$). Note that NGC 6951, which has very negative $\delta_\lambda$’s due to its star-forming ring, is outside all plot scales.

3.3 Colour gradients and extinction

Colour gradients carry information on the variations of stellar populations and extinction across a galaxy. Our $C_{3660}$ colour brackets the region containing the 4000 Å break and Balmer jump, while $C_{5313}$ is roughly equivalent to $B-V$. Because of the larger wavelength interval involved (5313 to 4020 Å) and the absence of spectral discontinuities in this range, $C_{5313}$ is the more reddening sensitive of the two indices. One must nevertheless bear in mind that a $C_{5313}(r)$ profile cannot be trivially transformed into an extinction profile without a simultaneous analysis of stellar population variations.

Figures 19–21 show the $C_{3660}$ (dotted, blue line) and $C_{5313}$ (solid, black line) colour profiles, also ordered according to $W_{nuc}^K$. Centrally peaked $C_{5313}(r)$ profiles are apparently rare among galaxies with $W_{nuc}^K \lesssim 15$ Å (figure 19), with exceptions (e.g., NGC 404, NGC 718 and NGC 3245).
Figure 19. Radial profiles of two continuum colours: $C_{3660} = 3660/4020$ (dotted, blue line) and $5313/4020$ (solid, black line). Note that the values of $C_{5313}$ have been divided by 2 for plotting purposes. Dotted vertical lines mark distances of ±100 pc from the nucleus. Objects are sorted by the value of $W_K$ at the nucleus, indicated in the bottom right corner of each panel. Galaxies in this figure have $W_K$ between 2.5 (bottom left panel) and 14.8 Å (top right).

In order to examine colour gradients in more quantitative terms we compute the ratio $C_{5313}^{\text{nuc}}/C_{5313}^{\text{off}}$ between the values of $C_{5313}$ in the nucleus and a mean off-nuclear colour, defined as the weighted average of extractions between $|\theta| = 2.2$ and $4.7''$ (as done for $W_\lambda$ in §3.2). This ratio can be transformed into the index

$$\delta_V = 5.98 \log \left( \frac{C_{5313}^{\text{nuc}}}{C_{5313}^{\text{off}}} \right)$$

which measures by how many V-band magnitudes one has to deredden the nuclear spectrum to make it match the off-nuclear $C_{5313}$ colour. The coefficient in this equation comes from assuming the Cardelli et al. (1989) extinction curve with $R_V = 3.1$, which we do throughout this paper. $\delta_V < 0$, which indicates a bluing towards the nucleus, is henceforth referred to as a “blue gradient”, while $\delta_V > 0$ is called
a “red gradient”. Colour gradients were also examined by fitting the nuclear spectrum with a combination of off-nuclear spectra plus reddening, which yields the nuclear extinction relative to that of the off-nuclear extractions. This method gives essentially identical results to those based solely on the $C_{5313}$ colour, with a mean off-set of just 0.04 mag and rms difference of 0.16 mag between the two $\delta_V$ estimates.

Figure 22 compares $\delta_V$ with $\delta_K$, $W_{K}^{\text{nuc}}$ and [OII]/H$\alpha$. The figure confirms that red gradients are more common for objects with $W_{K}^{\text{nuc}} > 15$ Å, i.e., among Old-LLAGN, which also tend to have flat $W_\lambda$ profiles. In fact, the plot shows that all objects with $W_{K}^{\text{nuc}} > 15$ Å, all strong-[OII] sources and all but one of the $\delta_K < 10\%$ objects have red gradients, the exception being NGC 4150, a Young-TO for which, as discussed above, $\delta_K$ is underestimated. On the other hand, galaxies with significantly diluted $W_\lambda$ profiles, $\sim 90\%$ of which are Young-TOs, have both blue and red gradients. Of the 13 LLAGN with $\delta_K > 10\%$, 8 have blue gradients and 5 have red gradients, but note that in several of these objects the colour gradient is negligible, with $|\delta_V| < 0.1$ mag.

Because colours per se do not disentangle intrinsic stellar population properties from extinction, these estimates of $\delta_V$ can only be interpreted as actual spatial variations in dust content in the absence of stellar population varia-

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Figure 20. As Figure [19] but for galaxies with $W_{K}^{\text{nuc}}$ between 14.9 and 17.8 Å.
This is a reasonable assumption for objects with relatively flat $W_\lambda$ profiles (and thus spatially uniform stellar populations), which, as shown above, are essentially all Old-LINERs and Old-TOs. The red-gradients observed in these objects can thus be safely attributed to extinction gradients. Note, however, that most objects with $\delta_K \sim 0$ cluster around values of $\delta_V$ of 0.1–0.4 mag, indicating that extinction gradients tend to be small.

The assumption of spatially uniform stellar populations breaks down for galaxies with diluted or peaked $W_\lambda$ profiles. In the latter case, one expects $\delta_V$ to overestimate the extinction gradient, as the reference off-nuclear extractions sample a younger population than that present in the nucleus. This is clearly the case of NGC 6951, for which we obtain $\delta_V = 1.2$ mag, the largest value in the whole sample. This effect is responsible for at least part of the trend of increasing of $\delta_V$ as $\delta_K$ becomes more negative (figure 22a). Conversely, when the nucleus contains a younger (and thus intrinsically bluer) population than off-nuclear positions, the resulting $\delta_V$ should be regarded as a lower limit to the actual variation in $A_V$.

From §3.2 and figure 18 we know that in galaxies with diluted $W_\lambda$ profiles the diluting source is intrinsically bluer than off-nuclear spectra, which should lead to blue gradients. While some of these galaxies indeed have blue gradi-
Figure 22. Colour gradients, as given by the differential extinction $\delta V$ implied by the 5313/4020 colour, plotted against (a) the dilution in the K line, (b) the nuclear equivalent width of the K line, and (c) [OI]/H$\alpha$. Nuclei which are redder (bluer) than the off-nuclear spectra have positive (negative) $\delta V$. Symbols as in figure 16.

Figure 6. As Figure 3 but for NGC 4150.

Figure 7. As Figure 3 but for NGC 5678.
ents, most (9/13) have negligible or slightly red gradients, which can only be understood in terms of a higher dust content in the nucleus. Hence, contrary to the first impression derived from the relative rarity of centrally peaked $C_{\text{5313}}$ profiles among these sources, extinction gradients seem to be a common feature of Young-TOs.

In summary, this empirical analysis shows that extinction gradients are present in LLAGN of all kinds. In Old-LINERs and Old-TOs, which have spatially uniform stellar populations, these gradients are not huge, with $\delta V$ typically smaller than 0.5 mag. Young-TOs, with their diluted $W_K$ profiles, also have extinction gradients, but a quantitative assessment of their magnitude requires a more elaborate analysis, which we present in §4.2.2.

### 3.4 Slit Profiles

The central intermediate age population which dilutes the equivalent widths of metal lines must cause an excess of flux with respect to the smooth surface brightness profile from the bulge of the host galaxy. Galaxies containing this extra central source should thus have sharper brightness profiles than those with more uniform stellar populations.

In order to verify this prediction we have measured the Half Width at Half Maximum (HWHM) of the slit profiles, denoted by $R_s$. The results are listed in the last two columns of Table 2 in angular and linear scales, and graphically illustrated in figure 23. The plot confirms that the most compact slit profiles occur among sources with diluted $W_K$ profiles. By extension of the relations between $\delta K$, $W_K^{\text{loc}}$ and $[\text{O}I]/\text{H}$, one expects these compact sources to be mostly Young-TOs, as confirmed in figures 23b and c.

The slit profiles of Young-TOs suggests characteristic sizes of 50–100 pc for their central intermediate age population. This rough estimate suffers from two caveats. First, it is based on the total flux profile, which includes the bulge light. This issue is addressed in §4 below. Second, in several cases $R_s$ corresponds to angular sizes of 1” or less (Table 2), in which case seeing starts to dominate size estimates. In fact, the comparison of galaxy and stellar profiles in the bottom panels of figures 3–12 shows that while Old LLAGN have spatially resolved profiles, in Young TOs the inner $S(r)$ profile is only marginally broader than the seeing disk, so $R_s$ should be regarded as an upper limit for these objects. A more refined study of the inner morphology of LLAGN based on high resolution imaging is underway (González Delgado et al., in preparation).

### 4 ANALYSIS AND DISCUSSION

Our spatially resolved spectra of LLAGN show that significant stellar population gradients occur almost exclusively in Young-TOs. These gradients are caused mostly by an intermediate age population (0.1–1 Gyr), although in a few cases a $< 10$ Myr nuclear starburst is also present (Papers I and II). The contribution of these stars to the total spectrum increases towards the nucleus, causing the radial dilution of metallic features. For consistence of notation, we...
Figure 23. Half Width at Half Maximum of the flux distribution along the slit plotted against (a) the dilution in the K line, (b) the nuclear equivalent width of the K line, and (c) [OI]/Hα. Symbols as in figure [11].

Figure 10. As Figure 8 but for NGC 4569.

Figure 11. As Figure 8 but for NGC 772.
hereafter denote this population the “Central Young Population” (CYP), where “young” means $\lesssim 1$ Gyr-old.

In this section we present estimates of the physical size, luminosity and extinction of the CYPs in Young-TOs. These estimates require separating the light from the CYP from that of older stars from the host’s bulge, which in turn requires a more elaborated analysis than the eminently empirical description of gradients presented in the previous section. Two methods were developed with this purpose. We close this section with a discussion on what these CYPs looked like in the past and what they might evolve to.

4.1 Fits of the Equivalent Width profiles

A rough estimate of the size of the region responsible for the radial dilution of metal lines may be obtained by evaluating at which distance from the nucleus $W_K(r)$ crosses the dividing line at $W_K = 15$ Å, which characterizes the transition from “Young” to “Old” stellar populations in our simple classification scheme. This is not always possible, either because $W_K$ sometimes does not raise above this threshold in the whole region analyzed (eg., NGC 4569, figure 10) or because of asymmetries or oscillations in the $W_K$ profile (eg., NGC 5678, figure 7). For the objects where this analysis was possible, we estimate radii between $\sim 100$ and 300 pc.

A more formal estimate may be obtained fitting the $W_\lambda$ profiles. A two-components model was build for this purpose. We assume that $W_\lambda(r)$ results from the superposition of a “background” component with a $W_\lambda(r) = W_\lambda(\infty)$ flat...
profile and a diluting component with negligible $W_\lambda$, and whose fractional contribution $f(r)$ to the total continuum at wavelength $\lambda$ and position $r$ follows a bell-shaped radial distribution. The resulting model is expressed by

$$W_\lambda(r) = W_\lambda(\infty)[1 - f(r)] = W_\lambda(\infty) \left[ 1 - \frac{\Delta_\lambda}{1 + (r/a)^2} \right]$$

where $\Delta_\lambda = [W_\lambda(\infty) - W_\lambda(0)]/W_\lambda(\infty)$ and $W_\lambda(\infty)$ are the analytical equivalents of $\delta_\lambda$ and $W_\lambda^\infty$ respectively (see equation 1). $a_W$ is the HWHM of the $f(r)$ profile, a size scale which should not be confused with the HWHM of surface brightness profile associated with the central diluting component. The latter quantity, which we denote by $R_W$, must be evaluated from the product of $S(r)$ and $f(r)$.

We have fitted this model to the $W_K$ profiles of 15 LLAGN: NGC 404, NGC 4150 plus the 13 LLAGN with $\delta_K > 10\%$ (ie, those with significant dilution). The results are reported in Table 4. The fits are generally good, as illustrated in figure 1. The dilution factors obtained from the fits are larger than the ones measured through equation 1, with $\Delta_K \sim 1.35\%$ typically. This happens because in most cases our operational definition of $W_\lambda^\infty$ includes part of the rising portion of the $W_K(r)$ curve, while equation 3 fits an asymptotic value. Interestingly, we find $\Delta_K = 23$ and 29$\%$ for NGC 404 and NGC 4150 respectively, two Young-TOSs for which $\delta_K$ fails to detect significant dilution but, according to the qualitative considerations in figure 1, should be included in the list of sources with diluted $W_\lambda$ profiles.

The values of $a_W$ range from $\sim 30$ to 400 pc, with a median of 172 pc, in agreement with the crater estimates based on the size of the $W_K < 15 \, \lambda$ region. These values are larger than the HWHM of $S(r)$, which spans the $R_S = 20 - 170$ pc range, with a median of 93 pc for this subset of galaxies (Table 4). In other words, $f(r)$ is broader than $S(r)$. Therefore, in practice the HWHM of the light distribution associated with the CYP is dictated more by the slit profile than by the $f(r)$ deduced from the $W_K(r)$ fits. The $S \times f$ profiles yield $R_W = 17$ to 120 pc (median $= 67$ pc), just slightly smaller than $R_S$. Hence, although it is clear that these CYPs often extend to more than 100 pc from the centre (as demonstrated by the detection of HOBLs well outside the nucleus; eg., figures 4 and 2), most of their light is concentrated within $r \lesssim 100$ pc. The relatively little light from the outer parts of this distribution is enough to compete with the flux from the host’s bulge, producing diluted $W_\lambda$ profiles on scales $a_W$ substantially larger than $R_W$.

It is important to emphasize that in angular units, the median $R_W$ corresponds to just 0.8$''$. Hence, although we are able to resolve the wings of the light profile of CYPs, seeing prevents us from adequately sampling their core. Our estimates of $R_W$ should thus be regarded as upper limits to the actual CYP radius. Indeed, high resolution images of a few Young-TOSs reveal structures on scales smaller than the ones we are able to trace with our $\sim 1''$ resolution. For example, NGC 4569 is known to have a very strong and compact nuclear source. Maoz et al. (1996) found, based on an HST/FOC image at 2300 $\lambda$, that the emission of this galaxy is composed of a bright unresolved nuclear point source and some faint extended emission 0.65$''$ south of the nucleus. Similar observations by Barth et al. (1998), done with HST/WFPC2 at 2200 $\lambda$, find that the nucleus is slightly resolved along PA = 20$'$, with a dimension of 0.16$'' \times 0.11''$.

4.2 Template decomposition

4.2.1 Method

An alternative and more complete way to analyze gradients in stellar populations is to model each extraction in terms of a superposition of spectra of well understood stellar populations. This can be achieved by means of the empirical starlight modeling scheme introduced in Paper I. The method consists of fitting a given spectrum with a combination of five non-active galaxies from our comparison sample, whose spectra represent stellar population classes $\eta = Y$ (NGC 3367), I (NGC 205), I/O and O (NGC 221, NGC 1023 and NGC 2950). The code outputs the fractional contribution of these components to the flux at 4020 $\lambda$, expressed as a population vector $x = (x_Y, x_I, x_O)$, where the $\eta = I/O$ and O components are grouped in $x_O$ for conciseness. The code also fits the extinction $A_\lambda$, modeled as due to an uniform dust screen with $A_V$ up to 4 mag. Regions around emission lines are masked out in the comparison of model and observed spectra. Paper I shows that this method provides excellent fits to the spectra. Unlike in Papers I and II, we have de-reddened the template galaxies by their intrinsic extinction derived by method described by Cid Fernandes et al. (2004b). Only NGC 3367 and NGC 205 are found to have significant extinction, both with $A_V = 0.9$ mag. These corrections were applied because of our interest in estimating the extinction and its radial variations in LLAGN.

We have applied this method to all nuclear and off-nuclear spectra analyzed in this paper, thereby producing stellar population and extinction profiles. The spectral fits are of similar quality to those exemplified in Paper I. The median fractional difference between model and observed spectra for all extractions is 4.5$\%$, which is acceptable considering a median noise-to-signal ratio of 6$\%$ at 4000 $\lambda$ and 3$\%$ at 4800 $\lambda$.

Examples of the resulting $x(r)$ and $A_\lambda(r)$ are illustrated in figure 25. The population vector in these plots is grouped into a predominantly old component, $x_O$, (dotted red line) and a young + intermediate age component, $x_{Y+I} = x_Y + x_I$ (solid blue line), representing the combined strengths of the NGC 3367 and NGC 205-like components. This coarse 2-components description of the stellar population matches our Young/Old classification scheme. The $x_{Y+I}(r)$ fraction, in particular, is used to map the CYP. We further plot $x_Y(r)$ as a dashed line to illustrate that $x_{Y+I} = x_Y + x_I$ is actually dominated by the intermediate age population. As found in Papers I and II, young starbursts are generally weak or absent in LLAGN, although off-nuclear star-formation occurs in a few cases, as in NGC 6951. This Old-TO provides a good example of the power of the method (figure 26). Its well known star-forming ring (Pérez et al. 2000), at $r \sim 4'' \sim 500$ pc, is nicely mapped by the $x_{Y+I}$ profile and its associated brightness distribution (bottom panel), obtained from the multiplication of $x_{Y+I}(r)$ by the slit profile $S(r)$. Notice also the rise in extinction in the ring, the presence of an intermediate age component throughout the observed region, particularly in the ring, and the prevalence of an old, bulge-like popu-
Figure 24. Top: Examples of the $W_K(r)$ fits. Bottom: Crosses show the normalized slit brightness profile. The solid blue line shows the brightness profile of the diluting component inferred from the $W_K(r)$ fits. Labels indicate the HWHM of the total brightness profile ($R_S$) and the HWHM of the diluting source ($R_W$), also indicated by the thick horizontal line-segment. Vertical dotted lines mark projected distances of ±100 pc from the nucleus.

Figure 26 shows the $\vec{x}(r)$ profiles for all 42 LLAGN in our sample. As in previous plots, galaxies are ordered from bottom-right to top-left in an increasing sequence of $W_{nuc}^\lambda$. The plot confirms that the spectral gradients identified in §3 are indeed associated with a centrally concentrated intermediate-age stellar population, plus, in a few cases, a young starburst (e.g., NGC NGC 772). This can be seen by the peaked $x_{Y+I}$ profiles from NGC 4569 to NGC 6500 in figure 26. Conversely, the old stellar component, mapped by $x_O(r)$ in these plots, bears a clear similarity in shape with the $W_\lambda$ profiles: Galaxies with diluted lines have diluted $x_O(r)$ profiles. Similarly, the spatial homogeneity of stellar populations inferred from the flat $W_\lambda(r)$ in galaxies like NGC 266 and most others in the right half of figure 26 is confirmed by equally flat $x_O$ profiles, while peaked $W_\lambda$ profiles map onto peaked $x_O$ profiles (e.g., NGC 1161).

Hence, to first order, the $x(r)$ profiles obtained from the template decomposition merely map the $W_\lambda$ variations onto the stellar population space spanned by our normal galaxy base. In fact, this relation is so strong that the equation

$$x_O = (0.068 \pm 0.001)W_K[\AA] - (0.35 \pm 0.02)$$

transforms $W_K$ into $x_O$ to within better than 0.1 rms for all 521 spectra. Plugging our $W_{nuc}^\lambda = 15$ Å dividing line in this equation we find that the transition from Young to Old stellar population occurs around $x_O \sim 2/3$, or, equivalently, $x_{Y+I} \sim 1/3$. We thus conclude that CYPs which account for $\lesssim 1/3$ of the optical light would not be recognized as such in our data. Indeed, of the 15 LLAGN with CYPs detected through the radial dilution of $W_K$ only 2 have $x_{Y+I} < 1/3$: NGC 4826 ($W_{nuc}^\lambda = 14.4$ Å and $x_{Y+I} = 0.25$) and NGC 3245 ($W_{nuc}^\lambda = 15.2$ Å and $x_{Y+I} = 0.23$).
is that there is a clear offset in the absolute values of dust
 gradi ents indicating a higher concentration of dust in the central regions.

Results of the $W_K$ fits for LLGN with diluted $W_K$ profiles.

| NGC  | $W_K(\infty)$ [Å] | $\Delta_K$ [%] | $a_{K}$ ["] | $a_W$ [pc] | $R_K$ ["] | $R_W$ [pc] |
|------|------------------|---------------|--------------|------------|-----------|-----------|
| 0404 | 12.2 ± 0.4       | 23 ± 4        | 3.7 ± 0.5    | 43 ± 6     | 1.7 ± 0.1 | 20 ± 1    |
| 0718 | 17.9 ± 1.4       | 28 ± 6        | 3.6 ± 0.6    | 374 ± 65   | 1.2 ± 0.1 | 126 ± 5   |
| 0772 | 19.9 ± 0.3       | 42 ± 3        | 1.1 ± 0.1    | 172 ± 20   | 0.5 ± 0.1 | 86 ± 3    |
| 3245 | 18.2 ± 0.3       | 17 ± 2        | 1.0 ± 0.3    | 107 ± 29   | 0.6 ± 0.1 | 67 ± 8    |
| 3627 | 15.5 ± 0.3       | 25 ± 3        | 1.4 ± 0.3    | 44 ± 9     | 0.8 ± 0.1 | 25 ± 2    |
| 3705 | 20.4 ± 0.7       | 28 ± 4        | 1.7 ± 0.5    | 139 ± 39   | 0.6 ± 0.1 | 52 ± 3    |
| 4150 | 15.0 ± 1.3       | 29 ± 7        | 4.2 ± 0.7    | 199 ± 32   | 1.8 ± 0.1 | 82 ± 3    |
| 4569 | 22.6 ± 2.4       | 78 ± 2        | 4.5 ± 0.5    | 365 ± 37   | 0.6 ± 0.1 | 52 ± 3    |
| 4736 | 15.6 ± 0.2       | 17 ± 2        | 2.3 ± 0.6    | 47 ± 12    | 0.9 ± 0.1 | 19 ± 1    |
| 4826 | 17.0 ± 0.6       | 15 ± 4        | 2.0 ± 0.7    | 39 ± 14    | 0.8 ± 0.1 | 17 ± 2    |
| 5005 | 16.5 ± 0.3       | 15 ± 3        | 1.7 ± 0.2    | 172 ± 24   | 0.8 ± 0.1 | 85 ± 4    |
| 5377 | 18.6 ± 1.0       | 52 ± 2        | 2.6 ± 0.4    | 388 ± 59   | 0.7 ± 0.1 | 106 ± 2   |
| 5678 | 13.2 ± 0.7       | 33 ± 4        | 1.1 ± 0.7    | 190 ± 115  | 0.6 ± 0.2 | 110 ± 34  |
| 5921 | 18.2 ± 1.7       | 38 ± 6        | 2.0 ± 0.5    | 244 ± 63   | 0.8 ± 0.1 | 96 ± 7    |
| 6503 | 14.4 ± 0.6       | 34 ± 4        | 1.1 ± 0.4    | 31 ± 13    | 0.6 ± 0.1 | 17 ± 3    |

4.2.2 Extinction profiles

Our empirical analysis of colour and equivalent width gradi ents in [5,3] indicates that extinction gradients are generally small in Old-LLAGN, while for Young systems we could only reach the qualitative conclusion that extinction variations must occur. A much more refined analysis is possible with the template decomposition method, which produces quantitative estimates of both gradients and absolute values of the extinction.

The $A_V(r)$ profiles derived by this method are presented in figure 27 for our 42 LLAGN. The first result which strikes the eye in this plot is the obvious asymmetry between galaxies in the left and right halves of the figure, which, given the ordering according to $W_K^{\text{pec}}$, essentially correspond to Young and Old systems respectively. The extinction profiles of Young-LLAGN are substantially more complex than those of Old-LLAGN, which are often approximately flat. In both cases, extinction gradients, when present, are generally in the sense of producing centrally peaked $A_V$ profiles, indicating a higher concentration of dust in the central regions. It is nevertheless clear that other types of dust distribution exist, as in NGC 4150 and NGC 4826, whose asymmetric $A_V(r)$ curves indicate the presence of off-nuclear dust-lanes.

A second and even more obvious result from figure 27 is that there is a clear offset in the absolute values of $A_V$ between Young and Old systems. The statistics of $A_V$ reflect this difference. Averaging $A_V(r)$ over all extractions for each galaxy, we obtain a median spatially-averaged extinction of 0.42 for our 16 Young-LLAGN, compared to 0.11 for the 26 Old-LLAGN. A similar off-set is found considering only the nuclear extractions, which have median $A_V(0) = 0.62$ and 0.21, respectively. Young-LLAGN, ~ 90% of which are Young-TOs, are therefore ~ 3 times dustier than Old-LLAGN. The clearest exception to this strong correlation is NGC 4438. The high concentration of dust inferred from $A_V$ profile of this Old-LINER is associated with the pronounced nuclear dust lane seen in HST images (Kenney & Yale 2002).

The Balmer decrement measurements of HFS97 lend further support to interpretation that Young-TOs have a higher dust content than other LLAGN. Using their tab-ulated values for objects in our sample, we find a median $H\alpha/H\beta$ of 4.6 for Young-TOs and 3.1 for other LLAGN. We can extend this analysis to the whole HFS97 sample using their measurements of the G-band equivalent width and classifying LLAGN into Young or Old adopting a $W(G\text{-band}) = 4$ dividing line, which is roughly equivalent to our Young/Old division at $W_K = 15$ Å (Paper I). The 27 Young-TOs in this larger sample have a median $H\alpha/H\beta = 4.5$, while for the other 116 LLAGN this ratio is 3.2.

We thus conclude that all evidence points towards a scenario where Young-TOs are the dustier members of the LLAGN family.

4.2.3 Sizes and luminosities of the CYPs

The population vector derived through the template decomposition analysis may be combined with the slit-profiles to produce one-dimensional surface-brightness profiles of the different stellar populations in our galaxies, as illustrated in the bottom panels of figure 28. In what follows we use this method to estimate sizes and luminosities of the CYPs, represented by the $S_{\text{CYP}}(r) = S(r) \times x_{Y+1}(r)$ profile. This method differs from the one in § 4.1 in two aspects: (1) instead of assuming a functional form for the light fraction associated to the CYP we derive this fraction empirically from the template decomposition; and (2) all the spectrum is used, as opposed to a single equivalent width.

Figure 28 shows the total slit profile $S(r)$ (thin black line), and its decomposition into Young (thick blue line) and Old (dotted red) components for our 42 LLAGN. The plot shows that the young components dominate the light in the inner ~ 100 pc from NGC 4569 up to NGC 718 ($W_K^{\text{pec}} = 13.1$ Å), becoming fainter than the inner old population as $W_K^{\text{pec}}$ increases, until it eventually “vanishes” from NGC 7177 onwards ($W_K^{\text{pec}} > 16.6$ Å). Note that, unlike all other profiles in this paper, figure 28 uses a linear scale for $r$, which emphasizes the compactness of the CYPs in Young-TOs.

We estimate the radius of the CYPs from the HWHM of the $S_{\text{CYP}}(r)$ profiles. Table 3 presents our results. As for the $W_K(r)$ fits, we obtain $x_{Y+1}$ profiles which are broader
than $S(r)$, so $R_{\text{CYP}}$ is close to $R_S$ (Table 2). The values of $R_{\text{CYP}}$ are in good agreement with $R_W$ (Table 3), which is the equivalent CYP radius in the $W_K(r)$ fits. Again, these estimates should be regarded as upper limits given that the angular sizes are limited by our spatial resolution.

The luminosity associated with the CYPs was estimated integrating $S_{\text{CYP}}(r)$ within $|r| < 5R_S$. The integration is performed in half-rings of area $\pi r dr$, i.e., extrapolating our 1D profiles to 2D. Table 4 lists both the total and CYP luminosities. Numbers in between parentheses correspond to luminosities corrected by intrinsic extinction using the modeled $A_V$ profiles. The resulting dereddened CYP luminosities.
Stellar Populations of Low Luminosity Active Galactic

Figure 26. Results of the template decomposition for all 42 LLAGN. Plots are ordered according to the value of $W_{\text{nuc}}^K$, from small values in the bottom-left to large values in the top right. Dotted, red lines correspond to $x_O$; solid blue lines correspond to $x_{Y+i}$ and dashed lines to $x_Y$.

Fluxes at 4020 Å range from $L_{\text{CY P}} \sim 10^{3.3}$ to $10^{5.5} L_\odot$/Å, with a median of $10^{4.3} L_\odot$/Å. Expressed in more conventional units, this roughly corresponds to a range in B-band absolute magnitudes\(^1\) from $\sim -12.2$ to -17.7, with a median $M_B = -14.7$. Given the uncertainties in absolute flux calibration, extinction correction and extrapolation from 1D to 2D profiles, these values should be taken as order of magnitude estimates. Yet, they are precise enough for the general considerations we present next.

\(^1\) We use a $M_B \approx -2.5 \log L_{4020} - 3.96$ conversion, for $L_{4020}$ in units of $L_\odot$/Å, derived from the Starburst99 models.
4.3 Discussion: The past and future of Young-TOs

Naturally, the intermediate age stars which typify the CYPs of Young-TOs have been younger in the past and will get older in the future. Their current age and luminosity can be used, with the aid of evolutionary synthesis models, to predict what these objects looked like in their early days and what they will eventually become.

For simplicity, let's assume that CYPs formed in instantaneous bursts $10^8$–$10^9$ yr ago. From the Starburst99 models of Leitherer et al. (1999) one infers that these CYPs were $\sim 10$ to $100$ times more luminous in the optical in their first Myrs of life. Since the old stellar population has not changed substantially over this period, the CYPs would be much easier to detect back then. The weakest CYPs recognized as such in our sample (i.e., those with $W_{39} \lesssim 15 \, \AA$) presently account for $x_{Y+I} \sim 33\%$ of the nuclear light at $\lambda 4020$. Scaling their present luminosity by factors of $10$–$100$ would raise this fraction to $83$–$98\%$, which shows that they would completely outshine the bulge light, and the optical continuum would be essentially identical to that of a starburst galaxy.
Recall, however, that Young-TOs are dusty, so these luminous infant CYPs could be substantially reddened and thus powerful far-IR sources, particularly if they had even more dust (and gas) in their early phases.

The hot, massive stars in these early phase would have a large impact in the ionizing photon field. The $\lambda$4020 flux ratio for young starbursts is of order $1000\,\AA$ (Leitherer et al. 1999). Currently, CYPs have $L_{\lambda4020} \sim 10^{43.3} L_\odot \,\AA^{-1}$ (Table 1), which scaled back to $t = 0$ yields H$\alpha$ luminosities of order $10^{42} \,\text{erg s}^{-1}$, more than two orders of magnitude larger than those currently observed in Young-TOs and LLAGN in general, which range from $10^{38}$ to $10^{40} \,\text{erg s}^{-1}$ (HFS97). In terms of $L_{H\alpha}$, they would rank among powerful starburst nuclei and Seyferts. Clearly, these objects would definitely not be classified as “Low Luminosity” in their youth. It is not clear whether they would be classified as AGN either! Unless the AGN too was much brighter in the past, these objects would surely look like starbursts.

Figure 28. Normalized slit brightness profiles (thin black line), decomposed into young (thick solid blue line) and old components (dotted red). The ordering of the galaxies is as in Fig. 26.
Table 4. CYP size and luminosities estimates from the template decomposition analysis. Columns 4 and 5 give the total and CYP monochromatic luminosities at 4020 Å integrated along the slit and extrapolated to 2D, in units of L⊙ Å⁻¹. Numbers in between parentheses are the dereddened luminosities. * = Observed under non-photometric conditions.

| NGC | R_{CYP} ["] | R_{CYP} [pc] | log L_{tot} | log L_{CYP} |
|-----|-------------|-------------|-------------|-------------|
| 0404* | 2.5 | 29 | 3.77 (4.08) | 3.54 (3.87) |
| 0718 | 1.3 | 133 | 5.14 (5.17) | 4.59 (4.64) |
| 0772 | 0.5 | 79 | 5.06 (5.21) | 4.10 (4.32) |
| 3245 | 0.7 | 74 | 5.15 (5.19) | 4.18 (4.22) |
| 3367 | 0.4 | 90 | 5.00 (5.35) | 4.91 (5.28) |
| 3627 | 0.9 | 30 | 4.31 (4.60) | 3.93 (4.26) |
| 3705 | 0.6 | 48 | 4.24 (4.44) | 3.48 (3.72) |
| 4150 | 2.1 | 98 | 4.53 (5.00) | 4.15 (4.70) |
| 4569 | 0.6 | 53 | 5.20 (5.53) | 5.19 (5.50) |
| 4736 | 1.0 | 21 | 4.64 (4.77) | 4.20 (4.34) |
| 4826 | 0.9 | 19 | 3.89 (4.05) | 3.11 (3.36) |
| 5005 | 0.9 | 98 | 5.15 (5.45) | 4.55 (4.93) |
| 5377 | 0.7 | 104 | 5.11 (5.36) | 4.85 (5.10) |
| 5678 | 0.8 | 135 | 4.89 (5.53) | 4.60 (5.27) |
| 5921 | 0.8 | 95 | 5.03 (5.21) | 4.63 (4.83) |
| 6503 | 0.7 | 19 | 3.30 (3.61) | 3.01 (3.33) |

Simple stellar populations of ages between \( t \sim 10^6 \) and \( 10^9 \) yr have mass-to-light ratios at \( \lambda 4020 \) of \(~500\) to \(~5000\) M⊙ L⊙⁻¹ Å in the solar metallicity models of Bruzual & Charlot (2003). For a median CYP luminosity of \( 10^{4.3} \) M⊙ L⊙⁻¹ Å⁻¹ (Table 4), this implies CYP masses \( M_{CYP} \sim 10^7\)–\(10^8\) M⊙. Star-formation has either ceased long ago or proceeds at a residual level in CYPs, otherwise they would look much younger. It is thus reasonable to suppose that these stars formed over a period of time whose length is a fraction of their current age. For star-formation time scales of \( 10^7\)–\(10^8\) yr, the typical star-formation rate was of order \( 1\) M⊙ yr⁻¹. These are clearly very rough estimates, but they serve to set the scale of the CYP phenomenon.

The precursors of Young-TOs thus have to be luminous nuclei with substantial amounts of star-formation and possibly a bright AGN too. Another clue is that these precursors must be found in the local-universe, since \( t \leq 10^9 \) yr corresponds to \( z < 0.1 \) for any reasonable cosmology. Two plausible contenders for the progenitors of Young-TOs are starburst nuclei and starburst + Seyfert 2 composites like Mrk 477, Mrk 1210 and others (Heckman et al. 1997; Storchi-Bergmann, Cid Fernandes & Schmitt 1998; Gonzalez Delgado, Heckman & Leitherer 2001). Given the tendency of TOs to have later Hubble types than LINERs and Seyferts (Ho, Filippenko & Sargent 2003), it seems more attractive to link Young-TOs with starburst nuclei. However, the substantial overlap in morphological properties between TOs and both starburst and AGN hosts, coupled to indications that starburst + Seyfert 2 composites have rather late type morphologies for AGN (Storchi-Bergmann et al. 2001) prevents us from drawing a firm conclusion at this stage.

Similar arguments can be used to sketch the future evolution of Young-TOs. As the CYP fades, it will eventually cross the \( x_{Y+I} = 1/3 \) threshold below which we would not identify it anymore and the system would be classified as Old (1–2). For instance, starting from a current value of \( x_{Y+I} = 2/3 \), and assuming the old populations do not change much, the CYP would cross the \( x_{Y+I} = 1/3 \) line after it fades by a factor of 4. For an assumed age of 1 Gyr, this would take \( \sim 2 \) Gyr to happen. In other words, the stellar populations of Young-TOs will become indistinguishable from those of Old-LLAGN in a few Gyrs. Though it is tempting to link Young to Old-TOs because of their identical emission line properties, as pointed out in Paper II we cannot rule out the possibility that [OII]/Hα increases as the CYP fades, which would turn a Young-TO into an Old-LINER. Note also that for either of these two evolutionary connections to work Young-TOs must somehow get rid of their excess dust (1–2) in a few Gyr, either by converting it to new stars or blowing it away.

Although much work remains to be done, these general considerations illustrate how the careful dissection of stellar populations properties can provide new and important pieces in the quest to solve the puzzle of active galactic nuclei. The evolutionary scenarios sketched above will be examined more closely in forthcoming communications.

## 5 CONCLUSIONS

In this third paper in our series dedicated to the stellar populations of LLAGN, we have investigated the radial variations of stellar populations properties in a sample of 42 LINERs and TOs plus 5 non-active galaxies. The analysis was based on high quality 3500–5500 Å long-slit spectra covering angular regions of at least \( \sim 10'' \) in diameter with a resolution of \( \sim 1'' \) (corresponding to \(~100\) pc).

The main result of Papers I and II was the identification of a class of objects which stand apart from other LLAGN in having a strong \( 10^{3–9} \) yr population. In terms of emission lines nearly all of these nuclei have weak [OI]/Hα, hence their denomination as “Young-TOs”. Here we have shown that Young-TOs are also distinct from other LLAGN in terms of the way stellar populations and dust are spatially distributed. This general conclusion was reached through two distinct and complementary ways.
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First, radial profiles of absorption line equivalent widths, continuum colours and the total flux along the slit were used to trace the spatial distribution of stellar populations. The results of this empirical analysis can be summarized as follows:

(i) We find that the $W_r$ profiles are of essentially two types: flat and diluted. Flat profiles, which indicate spatially uniform stellar populations, are more common, accounting for $\sim 60\%$ of the sample. They occur exclusively in galaxies dominated by an old, bulge-like stellar population, regardless of the LINER/TO emission line classification.

(ii) Diluted profiles, on the other hand, are produced by a central “young” population (CYP) dominated by stars of $10^{8.5}$ yr, whose relatively blue continuum dilutes the $W_r$’s of metal lines with respect to their off-nuclear values.

(iii) Although concentrated in the nucleus, these CYPs are spatially extended, reaching distances of up to 400 pc from the nucleus.

(iv) The relation between diluted profiles and nuclear stellar population is clearly expressed by the $\sim$ one-to-one relation between the radial dilution index $\delta_r$ and the nuclear $W_r$ for the CaII K line: Virtually all sources with $\delta_r > 10\%$ have $W_{rest}^{CaII} < 15 \AA$ and vice-versa. This range of $W_{rest}^{CaII}$ corresponds exactly to our definition of “Young” stellar population, meaning populations of 1 Gyr or less.

(v) Since these stars are found almost exclusively in objects with $[OII]/H\alpha \leq 0.25$ (Papers I and II), it follows that stellar population gradients are typical of Young-TOs. The fact that these stars are located in their central regions, and not spread over the whole galaxy, reinforces the suggestion that they are somehow connected to the ionization of the nuclear gas.

Second, a more detailed analysis of stellar population gradients was achieved by means of a decomposition of each spectra in terms of templates representative of very young ($\leq 10^7$ yr), intermediate age ($10^8.5 - 10^9$ yr) and old ($10^{10}$ yr) stellar populations. This analysis shows that:

(vi) The CYPs in Young-TOs account for at least $\sim 1/3$ of the total flux at 4020 Å. We confirm the finding of Papers I and II that these populations are dominated by $10^8-10^9$ yr stars. Young starbursts, even when present, make a small contribution to the optical light.

(vii) Yet another property which distinguishes Young-TOs from other members of the LLAGN family is dust content. Young-TOs are $\sim 3$ times more extincted than Old-LINERs and Old-TOs. This finding is confirmed using the HFS97 measurements of the $H\alpha/H\beta$ ratio.

(viii) Dust tends to be concentrated towards the nucleus, although asymmetric extinction profiles are also common.

(ix) The radial flux distribution of CYPs have HWHM radii of $\sim 100$ pc or less. While their core is at best partly resolved in our data, their outer regions are clearly resolved.

(x) The 4020 Å luminosities of the CYPs are within an order of magnitude of $10^{4.3} L_\odot$ Å$^{-1}$, implying B-band absolute magnitudes of $\sim -15$ and masses of order $\sim 10^7-10^8 M_\odot$. This population was $10-100$ times more luminous in their formation epoch, at which time young massive stars would have completely outshone the bulge light. The active nucleus would also be swamped by these young starbursts, unless it too was brighter in the past.

This investigation has unveiled several interesting connections between stellar population, emission line properties, spatial distribution and extinction, paving the road to a better understanding of the physics of low luminosity AGN. Future papers in this series will explore these and other connections in further detail.

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