Properties of galaxies in Sloan Digital Sky Survey quasar environments at $z < 0.2$

Georgina V. Coldwell*† and Diego G. Lambas*‡

Grupo de Investigaciones en Astronomía Teórica y Experimental (IATE), Observatorio Astronómico, Universidad Nacional de Córdoba, Laprida 854, 5000 Córdoba, Argentina

Accepted 2006 June 16. Received 2006 June 8; in original form 2005 June 13

ABSTRACT

We analyse the environment of low redshift, $z < 0.2$, Sloan Digital Sky Survey (SDSS) quasars using the spectral and photometric information of galaxies from the Sloan Digital Sky Survey Third Data Release (SDSS-DR3). We compare quasar neighbourhoods with field and high-density environments through an analysis on samples of typical galaxies and groups.

We compute the surrounding surface number density of galaxies finding that quasar environments systematically avoid high-density regions. Their mean environments correspond to galaxy density enhancements similar to those of typical galaxies.

We have also explored several galaxy properties in these environments, such as spectral types, specific star formation rates (SFRs), concentration indexes, colours and active nuclei activity. We find a higher relative fraction of blue galaxies in quasar environments compared to groups and typical galaxy neighbourhoods. Consistent with this picture, the distribution of the concentration index of these galaxies also indicate a larger fraction of late-type objects. By analysing the available information of galaxy spectra we have also studied the distribution of the SFRs of these neighbour galaxies finding that quasar environments are populated by objects with an enhanced star formation activity. An analysis of the relative flux ratios of $[O\text{ III}]\lambda 5700/H\beta$ and $[N\text{ II}]\lambda 6583/H\alpha$ of emission-line galaxies shows no excess of nuclei activity in quasar neighbourhood with respect to the environment of a typical galaxy.

We conclude that low-redshift quasar neighbourhoods ($r_p < 1 h^{-1}$ Mpc, $\Delta V < 500$ km s$^{-1}$) are populated by bluer and more intense star forming galaxies of disc-type morphology than galaxies in groups and in the field. Although star formation activity is thought to be significantly triggered by interactions, we find that quasar fuelling may not require the presence of a close companion galaxy ($r_p < 100 h^{-1}$ kpc, $\Delta V < 350$ km s$^{-1}$).

As a test of the unified active galactic nucleus (AGN) model, we have performed a similar analysis to the neighbours of a sample of active galaxies. The results indicate that these neighbourhoods are comparable to those of quasars giving further support to this unified scenario.

Key words: galaxies: active – quasars: general.

1 INTRODUCTION

Important clues on galaxy formation and evolution may be obtained by characterizing statistically the properties of their neighbourhoods in the local Universe. It is well known that several properties of galaxies depend on the environment, where they formed and evolved, and where a variety of processes such as star formation, tidal stripping, merging, etc. can determine the nature of galaxies. It should also be considered the possibility of active galactic nucleus (AGN) feedback processes which could induce significant changes in the evolution of their companion galaxies (see for instance, Croton et al. 2006).

Previous works aimed to characterize the quasar neighbourhood indicate that high-redshift quasars can be used as signposts to search for rich-density regions (Djorgovski 1999; Hall & Green 1998; Fukugita et al. 2004). However, at lower redshifts ($z \lesssim 0.3$) different studies indicate that quasars could reside in environments similar to those of normal galaxies (Smith, Boyle & Maddox 1995; Sorrentino, Radovich & Rifatto 2006) or they could be located in...
groups (Fischer et al. 1996) or clusters of galaxies (McLure & Dunlop 2001). Coldwell, Martinez & Lambas (2002), analysing both the projected cross-correlation function and the colours of galaxies around a sample of quasars, and AGNs found that their typical galaxy density environment corresponds to groups of galaxies. Moreover, Coldwell & Lambas (2003, hereafter Paper I), using the spectral information of the 2dF Galaxy Redshift Survey (2dFGRS), found that the galaxies within \( r_p < 1 \, h^{-1} \) Mpc from quasars have a stronger star formation activity. These results are also supported by findings of Soecheoling, Clowes & Campusano (2002, 2004) who found that low-redshift quasars follow the large-scale structure traced by galaxy clusters but they are not placed in the central area of galaxy clusters. More likely, they are in the cluster periphery or between two, possibly merging, galaxy clusters.

The large recent spectroscopic surveys, the Sloan Digital Sky Survey (SDSS) and the 2dFGRS allow us to investigate a wide range of galaxy properties such as morphology, spectral types, colours and, also, the galaxy density using volume-limited samples. In this paper, we extend the work of Paper I by analysing the environment of Sloan quasars using the spectroscopic and photometric information available for the Sloan Digital Sky Survey Third Data Release (SDSS-DR3). We divided the sample in two range of redshift 0.03 \( < z < 0.2 \) in order to analyse different effects in these two redshift ranges populated by galaxies of different luminosities.

The layout of this paper is as follows. In Section 2, we describe the data, Section 3 shows the analysis of the local density estimates, Sections 4 and 5 describes the statistical analysis performed with the photometric and spectroscopic data, respectively, and in Section 6, we provide a brief discussion of the main results.

2 DATA

The SDSS in five optical bands will map one-quarter of the entire sky and perform a redshift survey of galaxies, quasars and stars. The DR3, from SDSS provides a data base of 374767 galaxies and 51027 quasars with measured spectra. The five filters \( u, g, r, i, z \) cover the entire wavelength range of the CCD response (Fukugita et al. 1996). The main galaxy sample is essentially a magnitude limited spectroscopic sample (with a Petrosian magnitude) \( \mu_{\text{lim}} < 17.77 \), most of galaxies span a redshift range \( 0 < z < 0.25 \) with a median redshift of 0.1 (Strauss et al. 2002).

The quasar sample is defined by quasars which have at least one emission line with a full width at half-maximum larger than 1000 km \( s^{-1} \), luminosities brighter than \( M_i = -23 \), point spread function magnitude \( i < 19.1 \) and highly reliable redshifts (Schneider et al. 2002).

The galaxy groups from SDSS were identified by Merchán & Zandivarez (2005) using the friends-of-friends algorithm developed by Huchra & Geller (1982) which was improved by implementing a procedure to avoid the artificial merging of small systems in high-density regions and applying an iterative method to recompute the group centres position. The group sample has a median velocity dispersion of 230 km \( s^{-1} \) and we restrict our target to those groups with a minimum number of eight members to obtain higher density environment.

As a way to reject the hypothesis that quasars could reside in environments such as that corresponding to galaxy groups we use three different target samples, taken from SDSS, in order to compare quasar environment with those corresponding to typical galaxies and galaxy groups, and we make appropriate comparisons of galaxy characteristics of quasar neighbourhoods with respect to those in a low-density environments corresponding to typical galaxies and denser environments as galaxy groups.

We analysed galaxy properties in the neighbourhood of different target samples in two ranges of redshifts in order to explore for luminosity dependence:

\[
0.02 < z < 0.1, \text{hereafter } Z1: 418 \text{ SDSS quasars, 1147 SDSS Galaxies and 779 SDSS Galaxy groups.}
\]

\[
0.1 < z < 0.2, \text{hereafter } Z2: 1652 \text{ SDSS quasars, 1153 SDSS Galaxies, 102 Galaxy groups.}
\]

The targets were selected to match the observed quasar redshift distribution, showed in Fig. 1, in order to have unbiased and directly comparable results and the samples have the largest number of objects (within the redshift restriction) which suffices to provide reliable statistical results. By doing so, we assume that there are not redshift-dependent systematics such as those associated to low-luminosity galaxies. A Kolmogorov–Smirnov test yields that the redshift distributions are very similar with a 90 per cent level of confidence.

Tracer galaxies consist of all objects within projected distance \( r_p < 3 \, h^{-1} \) Mpc and with radial velocity difference \( \Delta V < 500 \, \text{km s}^{-1} \) relative to the targets, so that both targets and tracers have a similar redshift distribution.

3 LOCAL DENSITY ESTIMATES

A useful characterization of the local galaxy density can be obtained by measuring the distance to the \( N \)th nearest neighbour and estimating the density within that distance. The advantage of this method is to use a systematically larger scale in lower density regions which improves sensitivity and precision at low densities. This is a two-dimensional estimate but we use the redshift information to lower the projection effects. We choose a fixed velocity interval of \( \Delta V = 1000 \, \text{km s}^{-1} \) to compute the local density which correspond to galaxies within \( \sim 3\sigma \) from the centre of a galaxy cluster (Balogh et al. 2004) and this allows inclusion of galaxies in system with large velocity dispersion. When computing projected distances we have

![Figure 1. Redshift distributions of targets in the redshift intervals Z1 and Z2. Dashed lines correspond to quasars, solid lines to typical galaxies, and dotted lines to groups of galaxies.](https://academic.oup.com/mnras/article-abstract/371/2/786/1032183)
assumed a flat cosmology ($q_0 = 0.5$, $\Omega = 0.3$, $\Omega_\Lambda = 0.7$) and a Hubble constant $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$.

We calculate surface densities, $\Sigma_1$ and $\Sigma_5$, corresponding to the projected distance $d_1$ and $d_5$ of the first and fifth neighbour brighter than $M_r = -20.5$, respectively. This absolute magnitude limit assures completeness within the redshift range explored, $z < 0.2$

$$\Sigma_n = n/(\pi d_N^2).$$  \hspace{1cm} (1)

In Fig. 2, we show the relative distribution of $\Sigma_1$ and $\Sigma_5$ where it can be appreciated that the local density of quasar environment is pretty similar to that corresponding to typical galaxies. The $\Sigma_1$ density parameter corresponds to a closest neighbour distance estimate (within the luminosity restrictions) so that the results of Fig. 2 indicate that galaxy interactions are not likely to be directly associated to quasar phenomena. The errorbar in this figure and in all figures were calculated by using bootstrap error resampling (Barrow, Bhavsar & Sonoda 1984). The results shown in Fig. 2 strongly suggest that local quasars avoid systematically high and moderately high-density regions such as groups of galaxies.

4 PHOTOMETRIC PROPERTIES

Different magnitude measurements are provided in SDSS, asinh magnitude, Petrosian magnitude, fiber magnitude, etc. where galaxies bright enough to be included in the spectroscopic sample, $r < 17.7$, have relatively high signal-to-noise ratio. Since Petrosian magnitudes are model independent and yield a large fraction of the total flux, roughly constant with redshift, they provide an adequate magnitude measurement. We have used the modified form of the Petrosian (1976) system which measures galaxy fluxes within a circular aperture whose radius is defined by the shape of the azimuthally averaged light profile in order to measure a constant fraction of the total light, independent of the position and distance of the objects.

4.1 SDSS colours

Galaxy colours can be used as estimators of the galaxy evolution. In clusters, the large fraction of red galaxies indicate an old population of galaxies with a low star formation rate (SFR). Galaxies in poor groups or in the field are bluer and with stronger SFR.

We calculate the corrected colours $u - r$ of galaxies in the neighbourhood of the targets by using K and extinction corrected absolute magnitude (Blanton et al. 2003). We analyse the relative distribution of $u - r$ colours of neighbour galaxies, within $r_p < 0.5h^{-1}$ Mpc, to Sloan quasars (dashed lines), groups of galaxies (dotted lines) and typical galaxies (solid line) in the range $0.02 < z < 0.1$, $b 0.1 < z < 0.2$.

4.2 Morphology

In SDSS are also available the apparent radii containing 50 and 90 per cent of the Petrosian flux for each band. The ratio of these fluxes, the concentration index $C$, is correlated with morphology.
and the fraction of late-type galaxies defined with $\eta$ can be used as a simple morphological classifier. In Fig. 4, galaxies with a de-Vaucouleurs profile have a value of $C \sim 3.3$ and disc galaxies have a concentration index $C \sim 2.4$ this parameter can be used as a simple morphological classifier. In Fig. 4, we can see the distribution of the concentration index parameter and the fraction of late-type galaxies defined with $C < 2.5$ as a function of $r_p$. The larger relative fraction of disc-type galaxies in quasar neighbourhoods can be clearly appreciated corresponding to ~20 per cent excess of disc-type objects.

\section{Spectral Properties}

\subsection{Spectral-type classification}

The regulation of star formation in galaxies can be strongly influenced by close companions. Besides the effects of environment, galaxies in pairs have enhanced star formation over a control sample with similar characteristics which is stronger for galaxy pairs in field that in groups of galaxies. Lambas et al. (2003) and Alonso et al. (2004) found clear evidence that star formation is enhanced over 40 per cent in close interactions. This star formation induction increases for small relative velocity and projected separation $r_p$.

On the other hand, feeding a massive black hole at the centre of galaxies may require particular conditions which could be strongly influenced by environment. Although at large redshifts quasars and radio galaxies are frequently associated to clusters, at lower redshifts a dense environment may be hostile to the presence of massive black holes (Coldwell et al. 2002; Coldwell & Lambas 2003).

In Paper I, we explored the nature of galaxies in the vicinity of the different target samples using the 2dFGRS spectral-type index $\eta$. This parameter approximately delineates the transition between early and late morphological types for $\eta \sim -1.4$. When considering $\eta > 3.5$ we are dealing with galaxies particularly active, such as starbursts with recent episodes of star formation or AGNs. SDSS galaxies are also classified by a principal component analysis, PCA (Connolly & Szalay 1999), where five eigencoefficients, $\text{ecoeff}$, are extracted. Similarly to the 2dFGRS spectral-type classification SDSS provides a spectral-type parameters with the first two eigencoefficients like $s = \arctan(-\text{ecoeff2}/\text{ecoeff1})$ which ranges from about $-0.35$ to $0.5$ for early to late galaxies. Taking in to account this and the corresponding galaxies for SDSS and 2dFGRS, we consider galaxies with $s < 0.2$ as being similar spectra than their 2dF counterparts with $(\eta < -1.4)$. Also, SDSS galaxies with $s > 0.2$ correspond to the 2dF galaxies with $\eta > 1.1$. The fraction, $F_1$, galaxies with strong star formation activity $(s > 0.2)$, and the fraction $F_2$ of early-spectral-type galaxies $(s < 0)$, are shown for the two ranges of redshifts $Z_1$ and $Z_2$ in Fig. 5. The effect is similar to that of 2dF galaxies in Fig. 1 of Paper I where it is clear that galaxies around quasars differ from that in galaxy and group environments.

\subsection{Star formation versus AGN activity}

Several important properties of galaxies have been derived for subsamples of SDSS: stellar masses, indicators of recent major starbursts, current total and specific SFRs (Brinchmann et al. 2004) and emission-line fluxes (Tremonti et al. 2004) both for the regions with spectroscopy and for the galaxies as a whole; gas-phase metallicities; AGN classifications (Kauffmann et al. 2003) based on the standard emission-line ratio diagnostic diagrams, etc.

The relation between spectral lines, $\lambda \text{[O III]}\lambda 5007, \lambda H\beta, \lambda \text{[N II]}\lambda 6583$ and $\lambda H\alpha$ luminosities, can be used to analyse possible dependence of the relative numbers of AGNs and star forming galaxies in quasar neighbourhoods compared to galaxy and group environments. We constructed the Baldwin, Phillips & Terlevich (BPT, 1981) line–ratio diagram and we used the Kauffmann et al. (2003) criteria to differentiate AGNs galaxies from other emission-line objects.
The methods for deriving the SFRs are based on models where all active galaxy classes are fundamentally the ionized gas combined and described in terms of effective metallicity, ionization parameter, dust attenuation at 5500 Å, and dust to metal ratio (Bruzual & Charlot 1993; Charlot et al. 2002). Taking into account these issues, Brinchmann et al. (2004) provide accurate total SFRs estimates free from aperture bias. Moreover, Kauffmann et al. (2003) developed a method to constrain star formation histories, dust attenuation and stellar masses of galaxies based on two stellar absorption lines indices, the 4000 Å break strength and the Balmer absorption-line index Hα. 

5.3 Star formation rates

The methods for deriving the SFRs are based on models where the contribution of the nebular emission by HII regions and diffuse ionized gas combined and described in terms of effective metallicity, ionization parameter, dust attenuation at 5500 Å, and dust to metal ratio (Bruzual & Charlot 1993; Charlot et al. 2002). Taking into account these issues, Brinchmann et al. (2004) provide accurate total SFRs estimates free from aperture bias. Moreover, Kauffmann et al. (2003) developed a method to constrain star formation histories, dust attenuation and stellar masses of galaxies based on two stellar absorption lines indices, the 4000 Å break strength and the Balmer absorption-line index Hα.

Our main interest here is to analyse the logarithmic specific SFR log SFR/M* (log yr⁻¹), where M* is the estimated mass in star, for galaxies in the different target environments. In the right-hand panels of Fig. 7, it is shown that the distribution of log SFR/M* from which it can be seen that quasar environments have a population of galaxies with a higher SFR than field galaxies (galaxy groups show a low rate of star formation as expected from the systematic decline of SFR with local density).

In order to quantify the excess of star formation activity, we calculate the fraction of galaxies with log (SFR/M*) > -10.0 and the results are shown in Fig. 7 (left-hand panels). Several theories have proposed that galaxy–galaxy interactions fuel the AGN activity by driving gas into the cores of galaxies and thus on to the black holes. We have directly explored whether quasars have companions more frequently than the control samples. Taking into account the observed thresholds in projected separation rp and relative velocity ΔV for galaxy interactions to effectively induce star formation we calculated the fraction of targets with close companions (rp < 100 h⁻¹ kpc and ΔV < 350 km s⁻¹). We find a low fraction (<15 per cent) of close companions associated to quasars, similar to that observed for galaxies in general. This result indicates that quasar fuelling may not require the presence of close companion galaxies (consistent with the distribution of Z₁ shown in Fig. 2). Moreover, we have calculated the distributions of star formation excluding these close neighbours (those within rp < 100 h⁻¹ kpc and ΔV < 350 km s⁻¹). The results are very similar to those of Fig. 7, indicating the lack of relevance of close interactions in driving these relations.

5.4 Comparison of quasar and AGN environments

The unification hypothesis for AGNs and quasars (Antonucci 1993) is a model where all active galaxy classes are fundamentally the
Galaxies in SDSS quasar environments

We have performed a statistical analysis of local quasar environments using SDSS data, our main conclusions are as follows.

(i) Nearby quasars systematically avoid high-density regions. Local surface density estimates show that SDSS quasars reside in similar density enhancements to typical galaxies, significantly less dense than cluster environments.

(ii) Star formation activity in the surrounding of quasars is higher than in the neighbourhood of typical galaxies. This important property may provide a link between star formation and the onset of quasar activity.

(iii) Quasar environment is populated by galaxies systematically bluer, and with a disc-type morphology.

(iv) In spite of the fact that galaxy interactions efficiently trigger star formation, we find no statistical evidence that the presence of close companions is associated to quasars.

(v) The presence of quasars does not affect the fraction of AGNs in neighbour galaxies.

(vi) The results mentioned are present in the two redshift ranges explored $z < 0.1$ and $0.1 < z < 0.2$ although they are stronger at lower redshifts, indicating that the brightest galaxies are not likely to be the major contributors to the effects. Also, there might be a signal for evolution in the sense that the effects are stronger locally.

(vii) AGN and quasar environment are similar regarding the galaxy characteristics explored and agree best in the highest redshift interval giving support to the unified scenario of AGNs and quasars.

Although quasar hosts tend to be red and bulge-dominated galaxies (Kauffmann et al. 2003), the indication of a relative excess of quasar neighbour galaxies with a large gas fraction could suggest either an external origin for the accretion on to the central black hole, or that quasars may affect substantially the evolution of star formation up to the Mpc scale.

ACKNOWLEDGMENTS

We thank the anonymous referee for helpful suggestions and comments. This research was partially supported by grants from CONICET, Agencia Córdoba Ciencia and the Secretaría de Ciencia y Técnica de la Universidad Nacional de Córdoba.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England.

The SDSS Web Site is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, Cambridge University, Casey Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), The Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatry, and the University of Washington.

REFERENCES

Alonso M. S., Tissera P. B., Coldwell G., Lambas D. G., 2004, MNRAS, 352, 1088
Antonucci R., 1993, ARA&A, 31, 473
Baldwin J. A., Phillips M. M., Terlevich R., 1981, PASP, 93, 5
Balogh M. et al., 2004, MNRAS, 348, 1355
Barrow J. D., Bhavsar S. P., Sonoda B. H., 1984, MNRAS, 210, 19r
Blanton M. R. et al., 2003, ApJ, 594, 186
Brinchmann J., Charlot S., White S. D. M., Tremonti C., Kauffmann G., Heckman T., Brinkmann J., 2004, MNRAS, 351, 1151
Bruzual A. G., Charlot S., 1993, ApJ, 405, 538
Charlot S., Kaufrmann G., Longhetti M., Tresse L., White S. D., Maddox S. J., Fall S. M., 2002, MNRAS, 330, 876
Coldwell G. V., Lambas D. G., 2003, MNRAS, 344, 156
Coldwell G. V., Martinez H. J., Lambas D. G., 2002, MNRAS, 336, 207
Connolly A. J., Szalay A. S., 1999, AJ, 117, 2052
Croton D. J. et al., 2006, MNRAS, 365, 11
Djorgovski S. G., 1999, in Bunker A. J., van Breugel W. J. M., eds, ASP Conf. Ser. Vol. 193 The Hy-Redshift Universe: Galaxy Formation and Evolution at High Redshift. Astron. Soc. Pac., San Francisco, p. 397
Fischer K. B., Bahcall J. N., Kirhakos S., Schneider D. P., 1996, ApJ, 468, 469
Fukugita M., Ichikawa T., Gunn J. E., Doi M., Shimasaku K., Schneider D. P., 1996, AJ, 111, 1748
Fukugita M., Yasuda N., Brinkmann J., Gunn J. E., Ivezic Z., Knapp G. R., Lupton R., Schneider D. P., 2004, ApJ, 603, 65
Hall P. B., Green R. F., 1998, ApJ, 507, 558
Huchra J. P., Geller M. J., 1982, ApJ, 257, 423

Kauffmann G. et al., 2003, MNRAS, 346, 1055
Lambas D. G., Tissera P. B., Alonso M. S., Coldwell G., 2003, MNRAS, 346, 1189
McLure R. J., Dunlop J. S., 2001, MNRAS, 321, 515M
Merchan M. E., Zandivarez A., 2005, ApJ, 630, 759
Petrosian V., 1976, ApJ, 209, 1
Schneider D. P. et al., 2003, AJ, 126, 2579
Smith R. J., Boyle B. J., Maddox S. J., 1995, MNRAS, 277, 270
Soechting I. K., Clowes R. G., Campusano L. E., 2002, MNRAS, 331, 569
Soechting I. K., Clowes R. G., Campusano L. E., 2004, MNRAS, 347, 1241
Sorrentino G., Radovich M., Rifatto A., 2006, A&A, 451, 809
Strauss M. et al., 2002, AJ, 124, 1810
Tremonti C. et al., 2004, ApJ

This paper has been typeset from a TeX/LaTeX file prepared by the author.