Quantifying Star Formation Activity in the Inner 1 kpc of Local MIR Bright QSOs

M. Martínez-Paredes1,2, I. Aretxaga3, O. González-Martín1, A. Alonso-Herrero4, N. A. Levenson5, C. Ramos Almeida6,7, and E. López-Rodríguez8

1 Instituto de Radioastronomía y Astrofísica UNAM Apartado Postal 3-72, 58089 Morelia, Michoacán, Mexico
2 Korea Astronomy and Space Science Institute 776, Daejeon-dae-ro, Yuseong-gu, Daejeon, 34055, Republic of Korea
3 Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), Luis Enrique Erro 1, Sta. Ma. Tonantzintla, Puebla, Mexico; mariellauriga@kasi.re.kr, m.martinez@irya.unam.mx
4 Centro de Astrobiología, CSIC-INTA, ESAC Campus, E-28692 Villanueva de la Cañada, Madrid, Spain
5 Space Telescope Science Institute, Baltimore, MD 21218, USA
6 Instituto de Astrofísica de Canarias (IAC), E-38205 La Laguna, Tenerife, Spain
7 Departamento de Astrofísica, Universidad de La Laguna (ULL), E-38206 La Laguna, Tenerife, Spain
8 Stratospheric Observatory For Infrared Astronomy (SOFIA), NASA Ames Research Center, CA 94041, USA

Received 2018 September 7; revised 2018 November 30; accepted 2018 December 18; published 2019 January 31

Abstract

We examine star formation activity in a distant (z < 0.1) and flux-limited sample of quasars (QSOs). Midinfrared (MIR) spectral diagnostics at high spatial resolution (∼0.4 arcsec) yield star formation rates (SFRs) in the inner regions (∼300 pc–1 kpc) for 13 of 20 of the sample members. We group these objects according to the size probed by the high angular resolution spectroscopy, with characteristic scales of <0.7 and ∼0.7–1 kpc. Using the polycyclic aromatic hydrocarbon (PAH) feature at 11.3 μm, we measure SFRs around 0.2 and 1.6 M⊙ yr−1. We also measure the larger aperture PAH-derived SFRs in the individual IRS/Spitzer spectra of the sample and obtain a clear detection in ∼58% of them. We compare smaller and larger aperture measurements and find that they are similar, suggesting that star formation activity in these QSOs is more centrally concentrated, with the inner region (∼1 kpc) accounting for the majority of star formation measured on these scales, and that PAH molecules can be present in most local MIR-bright QSOs within a few hundred parsecs from the central engine. By comparison with merger simulations, we find that our estimation of the SFR and black hole (BH) accretion rates are consistent with a scenario in which the star formation activity is centrally peaked as predicted by simulations.

Key words: galaxies: star formation – infrared: galaxies – quasars: general

1. Introduction

An active galactic nucleus (AGN) harbors a supermassive black hole (SMBH, MBH ∼ 10⁶–10⁹ M⊙), which is surrounded by an accretion disk responsible for the strong radiation field that ionizes the gas around it (e.g., Magorrian et al. 1998; Peterson & Wandel 2000; Gültekin et al. 2009; Du et al. 2015). Several studies have postulated that some of the gas in the vicinity of the AGN feeds the SMBH and fuels a central starburst located in comparable scales to a dusty torus (e.g., Cid Fernandes & Terlevich 1995; González Delgado et al. 1998; Wada & Norman 2002; Thompson et al. 2005; Ballantyne 2008; Diamond-Stanic & Rieke 2010; Feruglio et al. 2010; Miller et al. 2015). Indeed, there is observational evidence of nuclear (few hundred parsec scales) starbursts in several narrow-line AGNs, such as Seyfert 2 and low-ionization nuclear emission-line regions (LINERs), which have been detected through a variety of methods and wavelengths (e.g., Terlevich et al. 1992; Oliva et al. 1995; Colina et al. 1997; Heckman et al. 1997; González Delgado et al. 1998; Pović et al. 2016), and in Seyfert 1 galaxies (e.g., Imanishi & Wada 2004; Deo et al. 2006). Despite the large effort to understand how AGN activity influences the central star formation, this is still an open issue. Some studies have found a positive correlation between the star formation rate (SFR) and AGN luminosity (e.g., Netzer 2009; Esquej et al. 2014; Delvecchio et al. 2015; Gürkan et al. 2015; Matsuoka & Woo 2015; Dong & Wu 2016) while others have found none (e.g., Rosario et al. 2012; Azadi et al. 2015; Shimizu et al. 2015; Stanley et al. 2015). One explanation for this might be the different physical scales and AGN luminosities traced by the various works, as well as finding good estimators of the SFR in AGNs.

Finding evidence of starbursts around type-1 AGNs has proven difficult, because the bright nucleus outshines classical starburst features, like the UV continuum emission and optical or near-infrared emission lines (e.g., Terlevich et al. 1990; Colina et al. 1997; Voit 1992; Cresci et al. 2004; Davies et al. 2007). Using IRS/Spitzer observations of Palomar–Green (PG) QSOs with a redshift z < 0.5, Shi et al. (2007) detected polycyclic aromatic hydrocarbons (PAHs) at 7.7 and 11.3 μm against the strong MIR AGN continuum on scales of ∼2–20 kpc. On the other hand, measuring the equivalent width (EW) of the PAH at 11.3 μm in the QUEST Spitzer survey, Schweitzer et al. (2008) found evidence for star formation in a sample of 27 PG QSOs at z < 0.3; 40% of objects showed clear PAH features, and for those that lacked individual detections the stacked spectrum revealed them, implying that starbursts are present in most QSOs at z ∼ 3.6 arcsec spatial resolution (∼3–15 kpc).

There is a large variety of methods to estimate the SFR from PAHs (Farrah et al. 2007; Pope et al. 2008; Treyer et al. 2010; Diamond-Stanic & Rieke 2012), and the results could vary up to a factor of two according to the size of the sample and method used (Shipley et al. 2016). Shi et al. (2014) found a tight correlation between the SFR derived from the PAHs at 11.3 μm and the far-IR luminosity, suggesting that the PAH emission at 11.3 μm is a good indicator of the star formation activity in QSOs (see also, Netzer et al. 2007; Shi et al. 2007). Additionally, Shipley et al. (2016) calibrated the luminosity of the PAH features at 6.2, 7.7, and 11.3 μm as a measure of the...
Table 1: Main Properties and Observational Details of the QSO Sample

| Name               | Group | z<sup>a</sup> | Angular Scale (kpc arcsec<sup>-1</sup>) | d (Mpc) | \(L_{\text{X}(2-10\text{keV})} \times 10^{43}\) (erg s<sup>-1</sup>) | Inner Physical Scale (pc) | Nuclear Spectrum<sup>b</sup> |
|--------------------|-------|----------------|------------------------------------------|---------|-----------------------------|---------------------------|-----------------------------|
| PG 1501+106/MRK 841 | 1     | 0.0364         | 0.723                                    | 160     | \(7.8 \times 10^{43}\)     | 376                       | CC/GTC                      |
| MRK 509            | 1     | 0.0344         | 0.685                                    | 151     | \(4.8 \times 10^{44}\)     | 514                       | VISIR/VLT                   |
| PG 2130+099/IIZw136 | 1     | 0.0630         | 1.213                                    | 283     | \(3.2 \times 10^{43}\)     | 631                       | CC/GTC                      |
| PG 1229+204/MRK 771 | 1     | 0.0630         | 1.213                                    | 283     | \(3.1 \times 10^{43}\)     | 631                       | CC/GTC                      |
| PG 0844+349        | 1     | 0.0640         | 1.231                                    | 287     | \(5.5 \times 10^{43}\)     | 640                       | CC/GTC                      |
| MR 2251−178        | 1     | 0.0640         | 1.231                                    | 287     | \(2.9 \times 10^{43}\)     | 640                       | CC/GTC                      |
| PG 0003+199/MRK 335 | 1     | 0.0258         | 0.519                                    | 113     | \(1.9 \times 10^{43}\)     | 670                       | CC/GTC                      |
| PG 1440+356/MRK 478 | 2     | 0.0791         | 1.494                                    | 359     | \(5.8 \times 10^{43}\)     | 777                       | CC/GTC                      |
| PG 1211+143        | 2     | 0.0809         | 1.525                                    | 368     | \(5.0 \times 10^{43}\)     | 793                       | CC/GTC                      |
| PG 1426+015/MRK 1383 | 2   | 0.0866         | 1.622                                    | 395     | \(1.3 \times 10^{43}\)     | 843                       | CC/GTC                      |
| PG 1411+442        | 2     | 0.0896         | 1.627                                    | 397     | \(2.5 \times 10^{43}\)     | 846                       | CC/GTC                      |
| PG 0050+124/IIZw1  | 2     | 0.0589         | 1.139                                    | 264     | \(7.1 \times 10^{43}\)     | 854                       | VISIR/VLT                   |
| PG 0804+761        | 2     | 0.1000         | 1.844                                    | 460     | \(2.9 \times 10^{44}\)     | 959                       | CC/GTC                      |
| PG 1448+273        | ...   | 0.0650         | 1.248                                    | 292     | \(2.0 \times 10^{43}\)     | ...                        | ...                         |
| PG 1534+580        | ...   | 0.0926         | 0.593                                    | 130     | \(1.8 \times 10^{43}\)     | ...                        | ...                         |
| PG 1535+547        | ...   | 0.0389         | 0.771                                    | 172     | \(4.0 \times 10^{42}\)     | ...                        | ...                         |
| PG 2214+139        | ...   | 0.0658         | 1.263                                    | 296     | \(6.6 \times 10^{43}\)     | ...                        | ...                         |
| PG 0923+129        | ...   | 0.0292         | 0.585                                    | 128     | \(2.6 \times 10^{43}\)     | ...                        | ...                         |
| PG 1351+640        | ...   | 0.0882         | 1.649                                    | 403     | \(1.2 \times 10^{43}\)     | ...                        | ...                         |
| PG 0007+106/MRK 1501 | ... | 0.0893         | 1.667                                    | 408     | \(1.4 \times 10^{44}\)     | ...                        | ...                         |

Notes. Columns 1 and 2 give the name and assigned number group (defined in Section 3.2), columns 3, 4, and 5 show the redshift, angular scale, and distance, column 6 lists the intrinsic hard X-ray (2–10 keV) luminosity, and columns 7 and 8 list the inner physical scale, probed by the slit-width of the high angular resolution spectrum, and the instrument and telescope used to obtain the high angular resolution spectrum.

<sup>a</sup> NED.

<sup>b</sup> Zhou & Zhang (2010).

<sup>c</sup> Martinez-Paredes et al. (2017) and references therein.

SFR, and showed that the PAH SFR method is as accurate as those based on hydrogen recombination lines (i.e., \(H_{\alpha}, P_{\alpha}\)).

High angular resolution studies of nuclear (<100 pc) star formation in AGNs in the MIR are still scarce and limited to nearby Seyfert galaxies (e.g., Roche et al. 2006; Mason et al. 2007; Watabe et al. 2008; González-Martín et al. 2013; Alonso-Herrero et al. 2014; Esquej et al. 2014; Ramos Almeida et al. 2014; Ruschel-Dutra et al. 2017; Esparza-Arredondo et al. 2018). These studies showed that PAH emission in the nuclear region (few tens of parsecs) can be explained by the ionization produced by nuclear starbursts. Nevertheless, a recent study suggests that AGN excitation could also be an important component in heating/exciting PAH molecules in the nuclear region of active galaxies (Jensen et al. 2017).

Here we use MIR high angular resolution spectra to estimate, for the first time, the star formation activity within the central several hundred parsecs in local bright MIR QSOs using the PAH at 11.3 \(\mu\)m. We compare our results with merger simulations presented by Hopkins & Quataert (2010), which predict a relationship between the SFR, on a few parsecs and several tens of kiloparsecs, and the activity of the AGN. The paper is organized as follows: Section 2 describes the sample and observations; in Section 3 we present our measurements of the PAH feature; in Sections 4 and 5 we discuss our results; and in Section 6 we present the conclusions. Throughout this paper we have assumed the following cosmology: \(H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}\), \(\Omega_m = 0.3\), and \(\Omega_{\Lambda} = 0.7\).

2. Sample and Observations

We use the sample of Martínez-Paredes et al. (2017), which was built according to the following criteria: (1) a redshift \(z < 0.1\) in order to study the inner MIR emission at scales \(<1 \text{kpc}\); (2) an \(N\)-band flux \(f_N \geq 0.02 \text{ Jy}\) in order to detect these objects from the ground; and (3) a hard X-ray luminosity \(L_{\text{X}(2-10\text{keV})} > 10^{43} \text{ erg s}^{-1}\) as an indicator of intrinsic powerful AGN activity. This sample of 20 AGNs is representative of nearby, MIR-bright quasars.

These data enable us to study the inner (few hundred parsecs) MIR emission of the PAH at 11.3 \(\mu\)m in QSOs, that is directly associated with recent star formation. Table 1 lists basic galaxy properties of the sample.

2.1. Inner (\(<1 \text{kpc}\)) N Band Spectra

We have inner (\(<1 \text{kpc}\)) spectra in the \(N\) band (~7.5–13.5 \(\mu\)m, rest-frame wavelength) of 13 QSOs. Eleven of these were obtained with the MIR instrument CC on GTC as part of the ESO-GTC program (P.I. A. Alonso-Herrero, ID program: 182.B-2005, Alonso-Herrero et al. 2016a), guaranteed time (P.I. C. Packham, Packham et al. 2005) program, and Mexican open time (P.I.: I. Aretxaga/M. Martínez-Paredes). The spectra were obtained with a slit-width of 0.52 arcsec in low resolution mode \((R = 175)\). The data were reduced using the pipeline for CanariCam developed by González-Martín et al. (2013). For more details on the observations and data reduction please refer to Martínez-Paredes et al. (2017) and Alonso-Herrero et al. (2016a, 2016b).

Two of the MIR spectra were obtained with VISIR on the VLT, MRK 509 (Hönig et al. 2010) and PG 0050+124 (Burtscher et al. 2013). These spectra were obtained in low spectral resolution mode \((R \sim 300)\), with a slit-width of 0.75 arcsec and angular resolution \(~0.3\) arcsec.
2.2. IRS/Spitzer Spectra (≤ 6 kpc)

We obtained the reduced 2D low resolution (R ~ 60−127) IRS/Spitzer spectra (Schweitzer et al. 2006; Shi et al. 2007) for all 19 QSOs available in the CASSIS database (v6., Lebouteiller et al. 2011). MR 2251 − 178 does not have a Spitzer spectrum. The spectra include the SL1 (λ ∼ 7.4−14.5 μm) and SL2 (λ ∼ 5.2−7.7 μm) modules acquired with a slit-width of 3.6 arcsec, and the LL1 (λ ∼ 19.9−39.9 μm) and LL2 (λ ∼ 13.9−21.3 μm) modules acquired with a slit-width of 10.5 arcsec (Houck et al. 2004; Werner et al. 2004). We built stitched spectra between 5−35 μm by scaling the flux of the LL and SL1 modules in the overlapping wavelengths of module SL2. The scaling factors were around 1.1 (Martínez-Paredes et al. 2017).

3. Measuring the PAH Feature at 11.3 μm

There are a variety of methods and tools to measure the PAH features (e.g., Uchida et al. 2000; Peeters et al. 2002; Smith et al. 2007; Mullaney et al. 2011; Xie et al. 2018). However, they are limited to spectra having a large spectral range and clear PAH features. Hernán-Caballero & Hatziminaoglou (2011) presented a method that implements a linear interpolation to fit a local continuum between two narrow bands on both sides of the PAH feature and integrates the area between the local continuum and spectral feature. This method allows us to measure the PAH features reliably, especially in objects with weak PAH features observed over narrow spectral ranges (Esquej et al. 2014).

3.1. The Inner and Larger Aperture Nuclear Spectra

We measure the flux and EW of the PAH at 11.3 μm (f_{11.3 μm}, EW_{11.3 μm}) for the CC and VISIR spectra of each QSO. In order to do this, we first generate fiducial mean values of each continuum band by bootstrapping on the measured fluxes (hatched pink regions in Figure 1). We generate 100 continuum values for the two continuum bands, taking into account the uncertainties of the spectrum. We randomly associate shorter and longer wavelength mean continuum values to generate linear continua below the PAH feature. Next, to measure the flux we integrate the continuum-subtracted spectrum between the continuum bands. Then, we divide the integrated flux by the flux of the local continuum at 11.3 μm to calculate the EW_{11.3 μm}. The continuum bandwidths are in the range ∆_{λ1} = 10.6−11.0 μm and ∆_{λ2} = 11.4−11.7 μm. The uncertainties are estimated repeating this process 100 times as shown in Figure 1. The values reported in Table 2 are the mean and standard deviations.

In order to determine if the PAH is clearly detected, we measure the variation of the continuum on both sidebands of the PAH feature, and use it as the level of noise. Then, comparing the flux of the PAH at 11.3 μm with the level of noise we find that for five objects the feature is clearly detected with a signal above 3σ. For PG 0804+761 and PG 1211+143, the PAH is also detected with a signal above 3σ. However, the large errors in the spectra, due to the marginal weather conditions during the observations (precipitable water vapor ~ 8 mm, Martínez-Paredes et al. 2017), do not allow us to clearly see the PAH above the continuum (see panel (c) in Figure 1), and hence we report upper limits. For the other six objects, we also report upper limits (see Table 2).

In order to make a proper comparison between the results obtained from the PAH at 11.3 μm on the CC and VISIR stacked spectra and the IRS/Spitzer spectra, we follow the same method previously described to measure the flux and EW of the PAH at 11.3 μm for the IRS/Spitzer spectra (see Table 2). An upper limit for the flux of the PAH is listed for those objects in which the feature is not clearly detected above the underlying continuum within the uncertainties. Shi et al. (2007) uses two Drude profiles centered at 11.23 and 11.33 μm, with a fixed FWHM and the slope of the underlying silicate profile as the continuum, to measure the PAH on a sample of PG QSOs that includes most of the objects in our sample. The fluxes we measure for the PAH feature at 11.3 μm are comparable to those reported by Shi et al. (2014; see the left panel of Figure 3).

3.2. The Stacked Inner and Larger Aperture Nuclear Spectrum

The limited S/N in the CC and VISIR spectra make the detection of the PAH at 11.3 μm in individual spectra difficult. We separate the 13 QSOs with CC and VISIR spectra into two groups according to the inner physical scale (<0.7 kpc and 0.7 to 1 kpc) probed by the slit-widths (see Table 1). This allows us to combine similar spatial scales and to keep track of the spatial resolution into the subsequent analysis, and stack the rest-frame high angular resolution spectra of each group in order to improve the S/N (see Table 3 and Figure 2). The stacking was done combining the normalized spectra at 10 μm of each QSO assuming an equally weighted average (see Figure 2). We multiply the final resulting stacked spectra by their corresponding average flux at 10 μm. The final error is estimated as the error propagation of the rms uncertainty. We measure the S/N using the same continuum bands as with the individual CC and VISIR spectra. For the stacked spectrum of group 2, we obtain an S/N = 6 that is nearly twice better than the average S/N of the group. For the stacked spectrum of group 1 we estimate a similar S/N than the average S/N of the group.

Note that group 1 includes a QSO that has an angular resolution corresponding to 376 pc, which is nearly two times better than the average resolution of other QSOs in the group (see Tables 1 and 3 and Figure 2). The result that we obtain without considering this object is the same within the uncertainties. We also stacked the spectra of all 13 QSOs and estimate the flux of the PAH (see Table 3 and Figure 2). However, this result should be used and interpreted carefully because we are combing different physical scales that range from ∼300 to 1 kpc.

PG 1440+356 (MRK 478) is the only QSO exhibiting strong 11.3 μm PAH emission (EW_{11.3 μm} ~ 0.04 μm) allowing a clear detection of this feature in the CC/GTC spectrum with an S/N = 8. We note that removing this object from group 2 gives a similar flux and the PAH is still detected. Errors in the spectra (see Figure 1) include only the rms uncertainty, but typical errors of nearly 10% to 15% associated with the photometric calibration at N-band should also be considered (see, Alonso-Herrero et al. 2016a; Martínez-Paredes et al. 2017).

In order to make a proper comparison between the results obtained from the PAH at 11.3 μm on the CC and VISIR stacked spectra and the IRS/Spitzer spectra, we stacked the IRS/Spitzer spectra of each group and followed the same methodology described in Section 3.2 to measure the flux and EW of the PAH at 11.3 μm (see Table 3).
Figure 1. CC spectra of PG 1440+356 (MRK 478, panel (a)), PG 1426+015 (panel (b)), and PG 1211+143 (panel (c)). The solid red lines are local continua generated through Monte Carlo simulations. The vertical dashed lines indicate the position of the PAH at 11.3 μm and of the [S IV]10.5 μm emission. The two hatched pink regions represent the bands used to measure the continua. The gray hatched region marks the approximate spectral range of low atmospheric transmission.

| Name          | $f_{11.3\,\text{μm}} \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ | EW$_{11.3\,\text{μm}}$ μm | SFR$_{\text{IR}}$ M$_{\odot}$ yr$^{-1}$ | $f_{11.3\,\text{μm}} \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ | EW$_{11.3\,\text{μm}}$ μm | SFR$_{\text{inner}}$ M$_{\odot}$ yr$^{-1}$ | $M_{\text{BH}}$ M$_{\odot}$ yr$^{-1}$ |
|---------------|-------------------------------------------------------------|-----------------------------|------------------------------------------|-------------------------------------------------------------|-----------------------------|------------------------------------------|-------------------------------|
| PG 1501+106   | <0.23                                                       | <0.057                      | <0.2                                     | <0.3                                                       | <0.007                      | <0.2                                     | 0.1                           |
| MRK 509       | 1.15 ± 0.07                                                | 0.014 ± 0.001               | 0.7 ± 0.2$^a$                            | 2.65 ± 0.01                                                | 0.0401 ± 0.0001             | 1.7 ± 0.5                                 | 1.1                           |
| PG 2130+099   | 0.38 ± 0.04                                                | 0.028 ± 0.002               | 0.8 ± 0.3                                | 0.45 ± 0.02                                                | 0.0105 ± 0.0004             | 1.0 ± 0.3                                 | 0.04                          |
| PG 1229+204   | <0.3                                                       | <0.02                       | <0.6                                     | <0.2                                                       | <0.02                       | <0.5                                     | 0.04                          |
| PG 0844+349   | <0.2                                                       | <0.01                       | <0.4                                     | <0.2                                                       | <0.02                       | <0.5                                     | 0.1                           |
| MR 2251−178   | <0.54                                                      | <0.03                       | <1.6                                     | ...                                                       | ...                         | ...                                     | 0.6                           |
| PG 0003+199   | 0.48 ± 0.05                                                | 0.022 ± 0.003               | 0.15 ± 0.05                              | 0.493 ± 0.005                                              | 0.0109 ± 0.0001             | 0.15 ± 0.05                               | 0.002                         |
| PG 1440+356   | 0.83 ± 0.07                                                | 0.035 ± 0.003               | 3 ± 1                                    | 1.607 ± 0.008                                              | 0.0739 ± 0.0004             | 6 ± 2                                     | 2.0                           |
| PG 1211+143   | <0.4                                                       | <0.02                       | <1.5                                     | <0.3                                                       | <0.008                      | <1.2                                     | 0.1                           |
| PG 1426+015   | 0.43 ± 0.06                                                | 0.0072 ± 0.0001             | 1.9 ± 0.6                                | 0.38 ± 0.02                                                | <0.03                       | <1.7                                     | 0.2                           |
| PG 1411−442   | <0.2                                                       | <0.01                       | <0.9                                     | <0.3                                                       | <0.01                       | <1.5                                     | 0.03                          |
| PG 0050−124   | <0.6                                                       | <0.006                      | <1                                       | 1.47 ± 0.05                                                | 0.0132 ± 0.0004             | 3 ± 1                                     | 1.0                           |
| PG 0804−761   | <0.2                                                       | <0.01                       | <1.2                                     | <0.2                                                       | <0.005                      | <1.1                                     | 0.6                           |
| PG 1448−273   | ...                                                        | ...                        | ...                                      | 0.480 ± 0.008                                              | 0.0400 ± 0.0007             | 1.1 ± 0.4                                 | 0.03                          |
| PG 1534+580   | ...                                                        | ...                        | ...                                      | 0.35 ± 0.01                                                | 0.0166 ± 0.0005             | 0.14 ± 0.05                               | 0.02                          |
| PG 1535−547   | ...                                                        | ...                        | ...                                      | 0.32 ± 0.05                                                | 0.023 ± 0.003               | 0.24 ± 0.08                               | 0.004                         |
| PG 2214−139   | ...                                                        | ...                        | ...                                      | <0.2                                                       | <0.01                       | <0.5                                     | 0.10                          |
| PG 0923−129   | ...                                                        | ...                        | ...                                      | 1.27 ± 0.01                                                | 0.0470 ± 0.0005             | 0.6 ± 0.2                                 | 0.03                          |
| PG 1351−640   | ...                                                        | ...                        | ...                                      | 1.47 ± 0.03                                                | 0.0321 ± 0.0006             | 7.3 ± 2.3                                 | 0.01                          |
| PG 0007+106   | ...                                                        | ...                        | ...                                      | 0.44 ± 0.02                                                | 0.0255 ± 0.001              | 2.1 ± 0.7                                 | 0.2                           |

Notes. Column 1 gives the name, columns 2, 3, and 4 give the inner aperture flux, EW, and SFR, while columns 5, 6 and 7 give the larger aperture flux, EW, and SFR. Column 8 lists the BH accretion rates.

$^a$ Similar value was reported by Esquej et al. (2014).
Table 3
Flux and EW of the PAH at 11.3 μm from the Inner (CC and VISIR) and Larger Aperture (IRS/Spitzer) Stacked Spectra

| Name | Group 1 (seven QSOs) | Group 2 (six QSOs) | All (13 QSOs) |
|------|----------------------|--------------------|---------------|
|      | kpc                  |                    |               |
| Inner Aperture | 10^{-13} f_{11.3 \mu m} \text{ erg s}^{-1} \text{ cm}^{-2} | f_{11.3 \mu m} \text{ cm}^{-2} | f_{11.3 \mu m} \text{ cm}^{-2} |
| Physical Scale | Inner Aperture | Larger Aperture | Inner Aperture | Larger Aperture |
| Group 1 (seven QSOs) | <0.7 | <0.2 | <0.006 | 3.1 | 0.56 ± 0.01 | 0.0151 ± 0.0003 |
| Group 2 (six QSOs) | 0.7−1 | 0.72 ± 0.03 | 0.015 ± 0.001 | 5.2 | 0.94 ± 0.02 | 0.0214 ± 0.0004 |
| All (13 QSOs) | <1 | <0.09 | <0.01 | 4.1 | 0.73 ± 0.01 | 0.0179 ± 0.0003 |

Note. Column 1 lists the group. Column 2 lists the average physical scale of the inner spectra. Columns 3 and 4 give the inner (CC and VISIR) flux and EW. Column 5 gives the average physical scale of the larger Spitzer aperture, while columns 6 and 7 give the larger aperture flux and EW.

Figure 2. Stacked rest-frame high angular resolution spectra. Left: stacked spectrum of group 1 (physical scale <0.7 kpc). Right: stacked spectrum of group 2 (physical scale <1 kpc). The solid red lines are the local continua generated through Monte Carlo simulations. The vertical dashed black lines indicate the position of the PAH at 11.3 μm and of the [S IV] 10.5 μm emission. The two hatched pink regions show the bands used to measure the continua. The gray hatched region marks the approximate spectral range of low atmospheric transmission.

4. Star Formation Rates
Shipley et al. (2016) calibrated the integrated luminosity of PAHs at 6.2, 7.7, and 11.3 μm as a function of the SFR using the IRS/Spitzer observations of a sample of 105 galaxies with IR luminosities between 10^{9} and 10^{12} L_{\odot}. They used the extinction-corrected H_{\alpha} to derive the SFRs. For these calculations a Kroupa initial mass function with a slope \( \alpha = 2.3 \) for stellar masses 0.5−100 M_{\odot} and a shallower slope \( \alpha = 1.3 \) for the mass range 0.1−0.5 M_{\odot} was assumed (Kroupa & Weidner 2003). We calculate the SFR using their linear relationship:

\[
\log \text{SFR}(M_{\odot} \text{ yr}^{-1}) = (-44.14 \pm 0.08) + (1.06 \pm 0.03) \times \log L_{11.3 \mu m} \text{ (erg s}^{-1})
\]  

(1)

In Table 2 we report the SFRs derived from the IRS/Spitzer spectra. Shipley et al. (2016) found that a difference of a factor of two can be obtained in the SFRs derived from PAHs, according to the method used to estimate them.

Shi et al. (2014) estimated the SFRs for most QSOs in our sample using the star-forming templates from Rieke et al. (2009). However, they point out that an issue with this method is the large intrinsic scatter between PAH fluxes and SFRs, which results from the way they anchor the continuum (Calzetti et al. 2007; Smith et al. 2007). In Figure 3 we compare the SFRs derived in this work with those derived by Shi et al. (2014). We observe that their SFRs are shifted to larger values. We find that the SFRs derived by Shi et al. (2014) are on average three times larger than the SFRs we derive from the PAH at 11.3 μm using Equation (1). However, we note that if we use the PAH measurements by the Shi et al. (2007) and the Shipley et al. (2016) relationship (Equation (1)), the SFRs are similar to those derived by us (see Table 2).

4.1. Star Formation in the Central Few Hundred Parsecs
Previous works attributed the origin of PAH features in the IRS/Spitzer spectra of local QSOs to star-forming regions in the host galaxy on scales of a few kiloparsecs (e.g., Shi et al. 2007; Schweitzer et al. 2008; Shi et al. 2014). However, high angular resolution observations of local Seyferts have shown that the PAH at 11.3 μm can be detected at scales of a few parsecs and hundreds of parsecs (Esquej et al. 2014), supporting the idea that this feature can survive the strong nuclear radiation of the AGN (Hönig et al. 2010; Diamond-Stanic & Rieke 2012; Alonso-Herrero et al. 2014). The inner (∼few hundred parsecs) MIR emission of QSOs is mostly dominated by an unresolved component associated with the dusty torus (Martínez-Paredes et al. 2017). However, the emission of PAH at 11.3 μm is clearly present in the high angular resolution spectrum of five QSOs, and in the stacked spectra of group 2 on scales of ∼1 kpc. Indeed, the emission of the PAH at 11.3 μm is strong (S/N = 8) in the high angular resolution spectrum of PG 1440+356 (MRK 478) on scales of ∼0.7 kpc.

We estimate the inner-aperture (CC and VISIR) SFR of the 13 QSOs in our sample with high angular resolution spectra (see Table 2), the SFR of the stacked spectra of groups 1 and 2, and of the stack of all QSOs (see Table 4). Note that PG 1440+356 (MRK 478) is one of the objects in group 2. Removing
this QSO from group 2 does not change our estimation of the SFR within the uncertainties.

Using the same PAH and technique, we calculate the larger aperture SFRs from the IRS/Spitzer spectrum of each QSO and from the stacked spectra of groups 1 and 2. Comparing the inner (few hundred parsec) and larger aperture (few kiloparsec) SFRs we find that they are similar (see the right panel in Figure 3). Therefore, it is likely that the star formation activity detected on larger scales is mainly concentrated within the central kiloparsec. Additionally, we find that at least half of the SFR estimated from the IRS/Spitzer spectrum of PG 1440 +356 (MRK-478) arises from an inner region of \( \sim 0.7 \, \text{kpc} \) (see Figures 1 and 4). These results suggest that the circumnuclear SFR in local MIR-bright QSOs is more centrally peaked than previously assumed, and they give evidence on the survival of the PAH at 11.3 \( \mu \text{m} \) near the strong radiation field of the AGN, on scales of few hundreds of parsecs.

### Table 4

| Name or Group | SFR\(_{\text{inner}}\) \(M_\odot/\text{yr}^{-1}\) | SFR\(_{\text{IRS}}\) \(M_\odot/\text{yr}^{-1}\) |
|---------------|--------------------------------|----------------------------|
| Group 1 (seven-QSOs) | <0.3 | 0.7 \(\pm\) 0.2\(^a\) |
| Group 2 (six-QSOs) | 1.6 \(\pm\) 0.5 | 1.6 \(\pm\) 0.5 |
| All (13-QSOs) | <0.2 | 1.8 \(\pm\) 0.5 |

**Notes.** Column 1 lists the group, columns 2 and 3 give the inner and larger aperture SFRs.

\(^a\) The SFR\(_{\text{IRS}}\) of group 1 is calculated with the stacked spectra of six objects, because MR 2251–178 does not have IRS/Spitzer spectrum.

5. The Role of AGN Activity on the Inner Star Formation

During the last decades, AGN and star formation activity have been widely studied by several authors (e.g., Nicholson et al. 1998; Best et al. 2005; Schawinski et al. 2007; Rafanelli et al. 2011; Fabian 2012; Diniz et al. 2015; Baron et al. 2017).

Despite the great effort, however, the way in which AGN activity influences the gas in the host galaxy, among the various classes, sizes, and luminosities of AGNs, is still uncertain (Beckmann & Shradler 2012).

Hopkins & Quataert (2010) presented multiscale smoothed particle hydrodynamic simulations of gravitational torques and gas inflow in AGNs from kiloparsec to subparsec scales, reaching a region where the material becomes a standard thin accretion disk. The simulations included as main ingredients: gas, stars, BHs, self-gravity, star formation, and stellar feedback. BH feedback was not included in order to isolate the physics of angular momentum transport. These simulations predict correlations between the BH accretion rate and the SFR at different physical scales from the central black hole. Their simulations suggest that nuclear star formation (<10 pc) is strongly coupled to AGN activity, following a linear relation (1:1) between BH accretion rate and SFR, while for scales <100 pc, <1 kpc, and <50 kpc scales the relationship changes by a factor of 10, 100, and 1000, respectively.

The AGN bolometric luminosity is estimated using the relation derived by Marconi et al. (2004),

\[
L_{\text{bol}} = kL(2–10 \, \text{keV}),
\]

where \( k \) is a bolometric correction factor that depends on the hard X-ray luminosity (2–10 keV) as a three-order polynomial, \( \log(L/L(2–10 \, \text{keV})) = 1.54 + 0.24L + 0.012L^2 - 0.0015L^3 \), where \( L = \log(L_{\text{bol}}/L_\odot) - 12 \). Then, we calculate the BH accretion rate using the relation obtained by Alexander & Hickox (2012),

\[
\dot{M}_{\text{BH}}(M_\odot/\text{yr}^{-1}) = 0.15 \frac{L_{\text{bol}}}{\epsilon} 10^{35} \text{ yr}^{-1},
\]

where \( \epsilon = 0.1 \) is the typical value for the mass-energy conversion efficiency in the local universe (Marconi et al. 2004). In Table 2 we list the BH accretion rates derived from Equation (3).

In Figure 4 we plot the BH accretion rate against the larger aperture SFR measured in the individual IRS/Spitzer spectra of our QSOs, on scales from 1 to 6 kpc, and the inner (CC and VISIR) SFRs measured in the stacked spectra of groups 1 and 2, on scales of <0.7 kpc and \( \sim 0.7 \) to 1 kpc, respectively. We compare our measurements with merger simulations of Hopkins & Quataert (2010), and note that \( \sim 58\% \) of the objects in our sample lies on the valid lower BH accretion rates and SFRs of the model. We note that larger aperture SFRs measured on scales of \( \sim 3 \) kpc for group 1 (stars) and \( \sim 5 \) kpc for group 2 (squares) are lower than the median SFRs predicted by simulations, on the same scales and assuming a linear...
proportionality. A similar result was found by Ho (2005) using the \[\text{O II}\]\( \lambda 3727 \) emission line to estimate the SFRs on similar scales for a sample of PG QSOs (\( z < 0.3 \)). Hopkins & Quataert (2010) argued that because QSOs are on the tail of the BH accretion rate and SFR distributions, it is plausible that the AGN feedback-dominated evolutionary stage is not well accounted for in their simulations. This is especially relevant for group 1, which has an average redshift of \( z = 0.05 \) that is 1.6 times lower than the average redshift of group 2. Therefore, we conclude that the extrapolation of the simulations is overpredicting the SFRs at the physical scales we probe for these bright nearby QSOs.

On the other hand, the low SFRs (<0.5 \( M_\odot \) yr\(^{-1} \)) measured in most QSOs of group 1 at scales of 0.7 kpc to 1 kpc (see the right panel of Figure 3), or at larger apertures ~3 kpc (as the data in the lower left corner of Figure 4), indicates that these objects are not hosted in galaxies with strong starbursts. Ho (2005) did not detect the on-going star formation in QSO hosts using his \[\text{O II}\]\( \lambda 3727 \) diagnosis on galactic scales either. Considering that many of these galaxies contain significant reservoirs of molecular gas (Ho 2005; Xia et al. 2012; Shangguan et al. 2018), the star formation efficiency in the host of QSO could be quenched. A high spatial resolution millimeter/submillimeter interferometer could confirm this scenario.

Another possibility is that PAH in QSOs is not effectively tracing the star formation within a few kiloparsecs (see, e.g., Voit 1992; Sales et al. 2010, and references therein). However, we note that for nine objects in our sample the optical SFRs (upper limits) derived by Ho (2005) are similar to the larger aperture PAHs–SFRs reported by us. While, the FIR–SFR derived by Petric et al. (2015) for a sample of 31 local (<0.5)

Figure 4. BH accretion rate as a function of the larger aperture (IRS/Spitzer) SFR of QSOs, as derived from Equation (1). The points follow the color code of the vertical bar, which indicates the central physical regions where the SFR is measured. These range from 1 to 6 kpc. The stars represent objects in group 1, while squares represent objects in group 2. The red star and square represent the inner SFR measured on the CC and VISIR stacked spectra of groups 1 and 2, respectively. The uncertainty on the BH accretion rate is assumed to be 50% due to the large hard X-ray variability of the flux in these objects (e.g., Soldi et al. 2014). The solid grey line is the 1:1 SFR: \( M_{\text{BH}} \) ratio applicable to scales \( \lesssim 10 \) pc; the dashed–dotted grey line is the 1:0.1 (\( \lesssim 100 \) pc) ratio, the dashed dark purple line is the 1:0.03 (\( \lesssim 1 \) kpc) ratio, and the dotted orange line is the 1:0.003 relation (see the text and Hopkins & Quataert 2010). The upper-right section enclosed by the dotted blue lines represents the limits above which the model is physically valid (see the text and Hopkins & Quataert 2010).

Figure 5. BH accretion rate as a function of the SFR density.

QSOs, that include the most objects in our sample, are larger. It is important to note that their FIR–SFRs are measured on even larger apertures (~20 arcsec, corresponding to several kiloparsecs) and that a fraction of the FIR emission could be heated by other sources like old stars (e.g., Symeonidis et al. 2016; Shangguan et al. 2018).

For group 2 we find that the inner SFR measured in the high angular resolution stacked spectrum on scales \( \lesssim 1 \) kpc is in agreement with the 1:0.03 SFR: \( M_{\text{BH}} \) ratio applicable to scales of \( \lesssim 1 \) kpc. These results are consistent with a scenario in which the star formation activity in these QSOs is the same within the first 5 kpc from the central engine and is more centrally concentrated on the first kiloparsec.

Finally, we use our estimates of the inner SFR between ~0.3 and 1 kpc to derive the SFR density (\( \Sigma_{\text{SFR}} \)), which is expected to be related to the nuclear molecular gas density of the host galaxy (Schmidt 1959; Kennicutt 1989, 1998; Kennicutt & Evans 2012). In Figure 5 we plot the BH accretion rate as a function of the SFR density. However, due to the large errors of the BH accretion rates and the narrow range in hard X-ray luminosity (~\( 10^{33}–10^{34} \) erg s\(^{-1} \)) covered by our sample, it is difficult to identify any reliable correlation. Therefore, future comparisons should include objects with lower and higher hard X-ray luminosities compared to those covered by our work. These comparisons will be useful for future spatially resolved studies of the Kennicutt–Schmidt law in quasar hosts.

More sensitive data, such as those that will be obtained with the Midinfrared Instrument (MIRI) on board the James Webb Space Telescope (JWST) and higher angular resolution data to be obtained with the MIR instrument on 20–40 m class telescopes, will be necessary to better constrain the location of the nuclear (few parsecs) and circumnuclear (few kiloparsecs) starbursts responsible for this emission, and consequently to test updated models. On the other hand, measurements of the molecular gas in nearby QSOs, such as those obtained with NOEMA and ALMA, would allow the investigation of the possible correlation between inner star formation and AGN activity, because the large molecular mass detected in PG 1440+356 (MRK-478) (Rodriguez-Ardila & Viegas 2003), IZw1 (Evans et al. 2001), and in most QSOs (e.g., Evans et al. 2001, 2006; Scoville et al. 2003; Bertram et al. 2007; Krips et al. 2012; Xia et al. 2012; Villar-Martín et al. 2013; Rodríguez et al. 2014) could be protecting the surviving PAH
molecules from the strong AGN radiation, as suggested by Esquej et al. (2014) and Alonso-Herrero et al. (2014) for Seyfert galaxies.

6. Summary and Conclusions

We use a sample of 20 nearby QSOs (z < 0.1) with both IRS/Spitzer (19/20) and high angular resolution (13/20) MIR spectra in order to measure the 11.3 μm PAH emission and EW on scales of a few kiloparsecs and hundreds of parsecs.

We detect clear 11.3 μm PAH emission in 58% of QSOs with IRS/Spitzer spectra, while we estimate an upper limit for the rest. We find clear emission of the PAH at 11.3 μm in five QSOs with CC and VISIR spectra, while we measure an upper limit in the other eight. Additionally, we build two groups according to their physical scale probed by the slit-width (<1 arcsec) of the high angular resolution spectra. This allows us to combine spectra obtained on similar physical scales and to improve the S/N. For group 1 we measure the PAH at 11.3 μm on the stacked spectrum within an inner region of <0.7 kpc, while for group 2 we measure the PAH on the stacked spectrum within an inner region of ~0.7–1 kpc. In order to make a consistent comparison, we also stacked the IRS/Spitzer spectra of group 1 and 2, and measured the PAHs on scales of ~3 and ~5 kpc.

Using the same technique and the luminosity of the PAH at 11.3 μm we estimate larger (few kiloparsecs) and inner (few hundred parsecs) aperture SFRs. We calculate the larger aperture SFRs for 19 QSOs with IRS/Spitzer spectra, and the inner aperture SFRs for 13 objects with high angular resolution spectra. Additionally, we calculate the larger and inner aperture SFRs for groups 1 and 2 with IRS/Spitzer as well as CC and VISIR stacked spectra.

We compare the inner and larger aperture SFRs of each group and find that they are similar. We conclude that star formation activity is present in the most nearby MIR-bright QSOs at scales of a few hundred parsecs. Finally, we calculate both the star formation and black hole accretion rate and compare them with merger simulations. We find that QSOs in group 2 show centrally concentrated star formation activity on scales ≤1 kpc in agreement with simulations. Additionally, we note that the SFRs measured on few kiloparsec scales are lower than those predicted by simulations. However, because QSOs are on the tail of the BH accretion rate and SFR distributions, it is possible that the evolutionary stage of objects in group 1, which have an average redshift 1.6 times lower than the average redshift of group 2 (z = 0.08), is not well suited to these simulations. However, it is also possible that the star formation efficiency in the host galaxy is being quenched beyond the predictions of the models, and/or that the SFR derived from PAH at 11.3 μm is not tracing the star formation activity well due to the destruction or dilution of PAH by the strong radiation of the AGN.

In any case, future higher angular resolution and more sensitive data as those expected from the MIR instruments on 20–40 m class telescopes and the MIRI on board the JWST will allow us to constrain these scenarios in a better way.

Finally, we use the inner SFR and physical scale to estimate the SFR density and compare it with the BH accretion rates. We do not find any reliable correlation. Future studies should include lower and higher hard X-ray luminosities than the ones presented here. This could help interpret future observations of the nuclear molecular gas in local QSOs.

We thank the referee for an insightful report that has improved the paper significantly. This work has been partly supported by Mexican CONACyT grants CB-2011-01-167291 and CB-2016-281948. M.M.-P. acknowledges support by UNAM-DGAPA and KASI postdoctoral fellowships. O.G.-M. acknowledges support by the PAPIIT projects IA100516 and IA103118. A.A.-H. acknowledges support from the Spanish Ministry of Economy and Competitiveness through the grant AYA2015-64346-C2-1-P, which is partially funded by the FEDER program. C.R.A. acknowledges the Ramón y Cajal Program of the Spanish Ministry of Economy and Competitiveness through project RYC-2014-15779 and the Spanish Plan Nacional de Astronomía y Astrofísica under grant AYA2016-76682-C3-2-P. This work is based on observations made with the 10.4 m GTC located in the Spanish Observatorio del Roque de Los Muchachos, in the island La Palma. It is also based partly on observations obtained with the Spitzer Space Observatory, which is operated by JPL, Caltech, under NASA contract 1407. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by JPL, Caltech, under contract with the National Aeronautics and Space Administration. CASSIS is a product of the Infrared Science Center at Cornell University, supported by NASA and JPL.
