Molecular Gas and Dust Heating in Active Galaxies: Growing Black Holes or Tidal Shocks?

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Abstract

We investigate if and how growing supermassive black holes (SMBH) known as active galactic nuclei (AGN) and gravitational interactions affect the warm molecular gas and dust of galaxies. Our analysis focuses on the morphologies and warm ISM properties of 630 galaxies at z < 0.1. We use grizy images from the Pan-STARRS survey to classify the galaxies into mergers, early mergers, and non-mergers. We use MIR spectroscopic measurements of emission from rotational H2 transitions, dust, and polycyclic aromatic hydrocarbon (PAH) features, and silicate emission or absorption lines at 9.7 μm to study how gravitational interactions impact the warm ISM in AGN and non-AGN hosts. We find that in AGN-hosts, the ISM is warmer, the ratios of H2 to PAHs are larger, the PAH emission-line ratios and silicate strengths have a wider range of values than in non-AGN hosts. We find some statistical differences between the H2 emission of mergers and non-mergers, but those differences are less statistically significant than those between AGN and non-AGN hosts. Our results do not establish a relationship between the rate of BH growth and the warm ISM but point to highly statistically significant differences between AGN hosts and non-AGN hosts, differences that are not present with the same statistical significance between mergers and non-mergers. We speculate that the combination of triggering mechanisms, AGN orientations, and evolutionary stages that allow AGN to be classified as such in the MIR indicate that those AGN are energetically coupled on kiloparsec scales to their host galaxies’ warm ISM. Future optical and IR, spatially resolved spectroscopic studies are best suited to characterize this connection.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); AGN host galaxies (2017)

1. Introduction

Growing supermassive black holes (SMBH) power compact, luminous, galactic centers known as active galactic nuclei (AGN). At low redshifts, the most luminous AGN appear to be triggered by galaxy mergers (Ellison et al. 2019). The changing gravitational potential of merging galaxies may allow a fraction of the gas to lose angular momentum and fall toward the center of the galaxy where it can feed any present SMBH or get compressed and induce star formation (Hopkins et al. 2007, 2016). In this scenario some of the massive stars produced in the merger and the growing SMBH consume the surrounding ISM and inject energy into it through shocks, radiation, and turbulence. These processes increase the pressure in the gas, ionize part of it, and ultimately impede star formation and SMBH growth (Hopkins et al. 2007; Ellison et al. 2019). Several parts of this scenario have been tested but the connections between AGN and their hosts’ molecular gas on kiloparsec scales are unclear.

The ISM fuels the growth of stars and of SMBHs. The ISM is heated, ionized, and shocked by gravitational interactions, new stars, stellar deaths, and AGN winds, emission, and jets. Therefore, to understand a galaxy’s evolution we need to study the amount, phase-structure, and temperature of its ISM.

Spectroscopic observations in the MIR are a powerful way to identify and characterize AGN and a fraction of their ISM because in the MIR the AGN emission is (almost) not affected by extinction. Furthermore, the sources of MIR emission (ionized interstellar gas, nonthermal radio sources, and dust particles) can be empirically separated through a multitude of diagnostics (e.g., Genzel et al. 1998; Rigopoulou et al. 2002; Armus et al. 2007; Díaz-Santos et al. 2010; Petric et al. 2011). The warm (200–1000 K) molecular gas observed in the MIR makes up about 1%–30% of the total molecular H2 mass (Roussel et al. 2007). Studies of nearby radio galaxies (e.g., Ogle et al. 2007) and mergers (Guillard et al. 2009) showed that the warm molecular gas properties (mass, temperature, and total luminosity relative to other coolants) can be used to estimate if and how the total ISM is affected by an AGN and/or by shocks associated with gravitational interactions. Important mechanisms responsible for exciting the MIR H2 rotational transitions are photoionization in star-forming regions (Gautier et al. 1976; Bally & Lane 1982), AGN activity, X-ray heating, fluorescence induced by a nonthermal ultraviolet continuum, and shock heating by radio jets (Moorwood & Oliva 1988; Larkin et al. 1998; Ogle et al. 2007; Guillard et al. 2012). Rotational H2 emission may also be powered by shocks in dense clumps of filaments associated with interacting galaxies (Appleton et al. 2006; Ogle et al. 2007; Guillard et al. 2009). Radio galaxies, some mergers, and some IR bright galaxies have enhanced H2 emission with respect to the other MIR cooling lines (e.g., polycyclic aromatic hydrocarbon (PAH), [Si II]) which suggests that shocks associated with supernova remnants, AGN, or tidal interactions can contribute significantly to the excitation of the...
H$_{2}$ rotational transitions (Hill & Zakamska 2014; Stierwalt et al. 2014; Petric et al. 2018; Lambrides et al. 2019). Spatially resolved studies of radio jet environments in X-rays, radio, and molecular gas showed how jet-ISM interactions can propagate shocks into the ISM and affect star formation (Ogle et al. 2014; Lanz et al. 2015; Appleton et al. 2018). In nearby luminous infrared galaxies (with $L_{IR} > 10^{11} L_{\odot}$) about 20% of warm H$_{2}$ heating may come from AGN, AGN hosts have warmer molecular gas than non-AGN hosts, and the sources with the biggest warm gas kinetic energies are mergers (Stierwalt et al. 2014; Petric et al. 2018). The results of Stierwalt et al. (2014) and Petric et al. (2018) were based on relatively small numbers of AGN which made it difficult to compare AGN merger hosts to AGN non-merger hosts and SF merger hosts to SF non-merger hosts. More recently, Lambrides et al. (2019) compiled ∼2000 MIR spectra taken by the Spitzer Space Telescope’s (Werner et al. 2004) Infrared Spectrograph (IRS; Houck et al. 2004) and found a strong statistical trend for AGN hosts to have warmer (by ∼200 K) molecular gas than non-AGN hosts, based on the H$_{2}$ S(5)–S(3) transitions. While it is clear that AGN host galaxies may have a warmer molecular gas component (Rigopoulou et al. 2002; Ogle et al. 2007; Zakamska 2010; Nesvadba et al. 2011; Hill & Zakamska 2014; Stierwalt et al. 2014; Petric et al. 2018; Lambrides et al. 2019), it is unclear what physical mechanism is responsible for heating up the molecular gas in most sources. Because the data we present lack both the spatial and spectral resolution to test the details of those physical mechanisms, in this paper, we limit our investigation to one question: can the higher temperatures measured by Lambrides et al. (2019) be associated with merging hosts and not driven by the presence of an AGN? To test this we study the morphologies of the $z < 0.1$ galaxies in the Lambrides et al. (2019) and perform a complementary statistical analysis that includes nondetections. The answer to this is connected to a more physically interesting question: is it possible that the mechanisms that trigger AGN in mergers also heat up the gas, or do any AGN emissions, jets, winds, or outflows affect the temperature of the gas irrespective of the gravitational interactions of the host galaxies.

The remainder of this paper is organized as follows: in Section 2 we present our sample of galaxies, the visual merger classification and the statistical tools we used to estimate the relative effect that mergers have on the temperature of the warm molecular ISM-component compared to AGN. In Section 3 we present our results for the warm molecular gas, the PAH size distribution and ionization, and the silicate strengths. In Section 4 we discuss what our results may suggest about how galaxy interactions and growing SMBH impact the warm component of a galaxy’s ISM. We adopt cosmological parameters of $h = 0.7$, $\Omega_{m} = 0.3$, and $\Omega_{\Lambda} = 0.7$.

## 2. Sample and Analysis

We classify a $z < 0.1$ subsample of galaxies used in Lambrides et al. (2019) as mergers, early mergers, or non-mergers. We approximate the temperature of the warm molecular gas using the mid-infrared molecular emission lines of H$_{2}$ S(3) and the H$_{2}$ S(1). We use those temperatures together with the ratio of the H$_{2}$ S(3) to the 11.3 $\mu$m PAH to test if AGN and/or gravitational interactions affect the warm ISM. Roussel et al. (2007), Zakamska (2010), Petric et al. (2018), and Lambrides et al. (2019) find that the molecular emission-line ratios H$_{2}$ S(3) to H$_{2}$ S(1) are not affected by extinction.

### 2.1. Targets

The 2015 galaxies analyzed by Lambrides et al. (2019) have redshifts between $z = 0.001$ and $z = 4.27$ and were selected from the Spitzer archive\(^{7}\) based on proposal topics related to active galaxies. The reduced spectra were provided by the Combined Atlas of Sources with Spitzer IRS Spectra (Lebouteiller et al. 2011), but further processed as described in Lambrides et al. (2019). Our morphology analysis (see Section 2.3) is based on visual classification using Pan-STARRS images, and therefore our sample only includes the galaxies at $z < 0.1$; given the typical spatial resolution of Pan-STARRS (0.7–0.8′) the visual classification becomes uncertain at higher redshifts (Nair & Abraham 2010).

While Lambrides et al. (2019) found no obvious, systematic effects on the dust/gas analysis associated with the heterogeneous nature of the sample, a significant number of radio-loud AGN would skew our analysis because radio-loud AGN are mostly hosted by mergers (Chiaberge et al. 2015). We use the FIRST survey catalog (Becker et al. 1995) to compute rest-frame 1.4 GHz luminosities, using a spectral index of $–0.7$ as in Lacy et al. (1993) and the radio-loud definition of Ivezić et al. (2002) to determine that only 10 galaxies in our sample are radio-loud AGN. We did the analysis with and without the 10 RL galaxies and found that they had a minimal impact on the statistical tests. A future paper on the entire sample of Lambrides et al. (2019) will employ higher image quality optical data to expand the analysis to the higher redshift sources in the sample and will also benefit from on-going radio surveys with which to investigate the connection between radio selected AGN and the warm molecular gas.

### 2.2. MIR Measurements

Here we briefly present the MIR spectroscopic features used in our analysis. A more comprehensive description of those measurements is provided in Lambrides et al. (2019). We first assume that the temperature of the warm molecular gas is proportional to the ratio of two emission lines from rotational transitions of H$_{2}$ S(3) ($J = 5–3$ at 9.665 $\mu$m) to S(1) ($J = 3–1$ at 17.035 $\mu$m). We then use the 6.2, 7.7, and 11.3 $\mu$m PAH features to study the impact AGN and mergers may have on the sizes and ionization states of the dust grains. The relative strength of the 6.2 to the 7.7 PAH bands changes with grain-size distribution while the ratio of the 11.3 to the 7.7 PAH complexes are a function of their ionization states (Li & Draine 2001; Draine & Li 2007). We use the strength of the 9.7 $\mu$m silicate feature as a proxy for dust obscuration. However, we note that differences in dust geometry relative to the sources of MIR emission may complicate the analysis (Zakamska 2010).

We use the intensity of the 11.3 $\mu$m PAH and its ratio to the 24 $\mu$m flux as an estimate of the importance of star formation in the studied galaxies. We acknowledge the debate around the validity of using 11.3 $\mu$m PAH as a robust tracer of star formation rate in AGN hosts (Smith et al. 2007; Díaz-Santos et al. 2010; Diamond-Stanic & Rieke 2012).

The most direct methods employed to estimate the AGN contribution to the MIR emission in individual galaxies are the ratios of high to low ionization fine-structure emission lines. However, those lines require higher spectral resolution than

\(^{7}\)https://sha.ipac.caltech.edu/applications/Spitzer/SHA/
that available to Lambrides et al. (2019). Diagnostics from the low-resolution data are based on the dust properties (e.g., PAH features and dust continuum emission). For large samples of sources, diagnostics based on the PAH ratios or the MIR continuum slope match those from high to low ionization line ratios (Petric et al. 2011).

In Figure 1 we present the cumulative distributions of the H$_2$ S(3)/S(1) ratios, H$_2$ S(3)/11.3 μm PAH flux ratios, the 11.3–7.7 μm PAHs emission ratios, and the silicate strengths.

### 2.3. Visual Classification

Our visual classification attempts to identify all galaxies in our sample that show signs of gravitational disturbances. We classify our targets as either non-mergers, early mergers, or mergers. While our visual classification technique was based on that of Nair & Abraham (2010), we also referred to Larson et al. (2016), Stierwalt et al. (2013), Bridge et al. (2010), Zheng et al. (1997), and Petric et al. (2011) for their investigations of morphologies of nearby galaxies. We define non-mergers as galaxies without any visible signs of a gravitation disturbance. We categorize early mergers as galaxies that have an apparent neighbor galaxy within ~50 kpc radius of its center.

Blumenthal et al. (2020) point out the difficulties in identifying early mergers: tidal features are more evident in high stellar mass objects, with a high-gas fraction, and are also dependent on the geometry of the merger and the viewing geometry. Therefore while we present some of the possible statistical differences between early mergers, mergers, and non-mergers, we focus on statistical differences between mergers and non-mergers. We postpone a more focused discussion about early mergers to an investigation using multiple classification techniques. We use the term merger to describe galaxies that show at least one of the following signatures of a gravitational disturbance: morphological asymmetries, tidal tails, shells, or multiple nuclei (see Figure 2).

We were unable to classify 45 galaxies due to either defects in the stacked multfilter images or uncertainty in the morphological features indicating either a disturbance due to gravitational interactions or an intricate dust geometry. Excluding these 45 galaxies, the total number of galaxies in our sample is 585:248 mergers, 257 non-mergers and 80 early mergers. These results are summarized in Table 1 along with median values of the aforementioned MIR measurements. Three of the authors on this paper classified a subsample of 20 galaxies and were in excellent agreement: only two galaxies were assigned different classifications by one of the classifiers.

### 3. Results

#### 3.1. Statistical Analysis

We use the nonparametric, two sample tests, Logrank test and the Peto & Peto Generalized Wilcoxon test for censored data...
using the R statistical software package survival (Feigelson & Nelson 1985), to investigate the relative role of mergers and AGN on the warm molecular gas and dust. Those tests look at differences between reconstructed distributions of values derived from measurements of detected features and upper limits and a maximum-likelihood formalism developed by Kaplan & Meier (1958). This method was tested exhaustively by Iseobe et al. (1986) using Monte-Carlo simulations.

In Table 2 we present the p-values from the Logrank, Peto, and Kolmogorov–Smirnov (KS) tests which represent the likelihood that each of the two compared samples were drawn from a common population. The smaller the p-value the less alike the samples are. Values below 0.01 are significant, those between 0.01 and 0.1 are marginal and we only interpret them as possible hints for future analysis, values above 0.1 indicate no statistical differences between the samples compared, essentially telling us that the two populations are indistinguishable.

### 3.2. Effects of a Growing SMBH on the Warm Molecular Gas and Dust

We find that AGN hosts have higher H$_2$ S(3) to S(1) emission-line ratios than non-AGN hosts suggesting higher molecular gas temperatures in AGN hosts. The median H$_2$ S(3) to H$_2$ (S1) ratio for all the AGN hosts is two times higher than that for SF hosts. We also find that AGN hosts have higher H$_2$ S(3)/11.3 $\mu$m PAH ratios than galaxies without an AGN, which suggests that the observed warmer may be related to the AGN emission. The largest and most statistically significant differences in terms of H$_2$ temperatures and H$_2$ S(3)/11.3 $\mu$m PAH ratios are those between non-merger AGN hosts and non-merger SF hosts.

The MIR-emitting dust appears to also be affected by the presence of an AGN. We find statistically significant differences between the 11.3 and 7.7 $\mu$m PAH emission ratios of AGN and non-AGN hosts with higher medians and a wider range of values for AGN hosts compared to non-AGN hosts. This result confirms, with a larger sample, the findings of Smith et al. (2007). Smith et al. (2007) suggest that this may be due to differences in the ionization states of the PAHs: the 11.3 $\mu$m feature is thought to be produced by neutral PAHs, while the 7.7 $\mu$m feature arises primarily from PAH cations (e.g., Allamandola et al. 1999; Draine & Li 2007). As discussed in Smith et al. (2007) harder radiation fields destroy PAH grains; therefore, if the grain or molecular carriers of the 7.7 $\mu$m PAH feature are not the same as those of the 11.3 $\mu$m PAH feature they will be ionized and/or dissociated at different rates. The 7.7 $\mu$m PAH feature originates from smaller grains that may be destroyed easier than the bigger grains that emit the 11.3 $\mu$m PAH feature.

We suggest the same explanation here although we think the location of silicates, PAHs, and H$_2$ relative to the AGN/SF regions may also play a role. As pointed out by Zakamska (2010) and Lambrides et al. (2019), the ratio of the 11.3 to 7.7 $\mu$m PAH features is inversely proportional to the silicate strengths at 9.7 $\mu$m but not at all correlated with any of the H$_2$ properties (temperature, intensity, and H$_2$/PAH). Zakamska (2010) suggest that the connection between the silicate strengths and the PAHs emission-line ratios can be explained if the PAHs are located behind silicates and water ices in AGN dominated galaxies. A wider range of 11.3–7.7 $\mu$m PAH

### Table 1

**Data Summary**

|         | Merger | Non-merger | Early Merger | Total |
|---------|--------|------------|--------------|-------|
| Morphology classifications |        |            |              |       |
| AGN     | 73     | 104        | 30           | 207   |
| Star-forming | 139    | 91         | 34           | 264   |
| AGN/SF  | 36     | 62         | 16           | 114   |
| Total   | 248    | 257        | 80           | 585   |
| Medians of H$_2$ S(3) to S(1) ratios |        |            |              |       |
| AGN     | 0.5    | 0.7        | 0.3          | 0.6   |
| Star-forming | 0.3    | 0.3        | 0.3          | 0.3   |
| For all above | 0.4    | 0.5        | 0.3          | 0.4   |
| Medians of H$_2$ S(3)/11.3 $\mu$m PAH ratios |        |            |              |       |
| AGN     | 0.10   | 0.11       | 0.13         | 0.11  |
| Star-forming | 0.01   | 0.01       | 0.01         | 0.01  |
| For all above | 0.02   | 0.05       | 0.03         | 0.02  |
| Medians of 11.3 $\mu$m PAH/7.7 $\mu$m PAH ratios |        |            |              |       |
| AGN     | 0.4    | 0.5        | 0.4          | 0.5   |
| Star-forming | 0.3    | 0.3        | 0.3          | 0.3   |
| For all above | 0.3    | 0.4        | 0.3          | 0.3   |
| Medians of $\tau$ 9.7 $\mu$m |        |            |              |       |
| AGN     | 0.3    | 0.2        | 0.1          | 0.2   |
| Star-forming | 0.7    | 0.6        | 0.5          | 0.6   |
| For all above | 0.6    | 0.3        | 0.3          | 0.5   |

**Figure 2.** Pan-STARRS images of NGC 4088, NGC 0520, NGC 5218, NGC 4922 NED02, and UGC 07064 illustrating the different merger features we use for our classification: galaxy asymmetry, tidal tails, galactic shells, multiple nuclei, and early/possible mergers for galaxies of similar brightness within 50 kpc of each other.
| Comparison                          | H$_2$ S(3)/S(1)       | H$_2$ S(3)/PAH | PAH 6.2 $\mu$m/PAH 7.7$\mu$m | PAH 11.3 $\mu$m/PAH 7.7$\mu$m | PAH 11.3$\mu$m/PAH 24$\mu$m |
|------------------------------------|-----------------------|---------------|-------------------------------|--------------------------------|----------------------------|
| Mergers versus Non-mergers         | 2e–4 8e–5            | 7e–5 2e–5     | 0.3 0.3                       | 4e–4 5e–4                      | 0.1 0.1                     |
| AGN versus SF                      | 4e–08 4e–09          | <2e–16 <2e–16 | <2e–16 2e–04                  | <2e–16 <2e–16                  | 0.04 0.04                   |
| Mergers versus Early Mergers       | 0.7 0.7              | 0.7 0.6       | 0.09 0.1                      | 0.007 0.008                    | 0.6 0.6                     |
| Non-mergers versus Early Mergers   | 0.04 0.03            | 0.03 0.02     | 1.0 1.0                       | 0.9 0.9                        | 0.4 0.4                     |
| Mergers—AGN versus SF              | 0.02 0.01            | 6e–08 2e–08   | 0.05 0.05                     | 2.01 12 2e–12                  | 0.4 0.4                     |
| Non-mergers—AGN versus SF          | 5e–06 4e–06          | 8e–09 7e–09   | 0.01 0.01                     | 1.0–08 9e–09                   | 0.1 0.1                     |
| Early Mergers—AGN versus SF        | 0.1 0.1              | 0.01 0.008    | 0.1 0.1                       | 8e–06 8e–06                    | 0.4e–04                     |
| AGN—Mergers versus Non-mergers     | 0.3 0.3              | 0.07 0.06     | 0.3 0.3                       | 0.4 0.5                        | 0.6 0.5                     |
| AGN—Mergers versus Early Mergers   | 0.4 0.3              | 0.7 0.7       | 0.3 0.4                       | 0.3 0.4                        | 0.7 0.8                     |
| AGN—Non-mergers versus Early Mergers| 0.02 0.01           | 0.1 0.1       | 0.9 0.9                       | 0.6 0.7                        | 0.6 0.6                     |
| SF—Mergers versus Non-mergers      | 0.9 0.9              | 0.9 0.9       | 0.7 0.8                       | 0.2 0.2                        | 0.001 5e–04                  |
| SF—Mergers versus Early Mergers    | 0.5 0.4              | 0.5 0.5       | 0.9 0.5                       | 0.3 0.9                        | 0.1 0.004                   |
| SF—Non-mergers versus Early Mergers| 0.5 0.5              | 0.5 0.5       | 0.8 0.5                       | 0.5 0.5                        | 0.7 0.5                     |
| AGN/SF—Mergers versus Non-mergers  | 0.02 0.01            | 0.01 0.02     | 0.08 0.1                      | 0.03 0.04                      | 0.4 0.4                     |
| AGN/SF—Mergers versus Early Merger | 0.01 0.009           | 0.09 0.1      | 0.04 0.06                     | 0.2 0.1                        | 0.8 0.7                     |
| AGN/SF—Non versus Early Merger     | 0.6 0.6              | 0.5 0.6       | 0.4 0.4                       | 0.6 0.7                        | 0.6 0.6                     |
| AGN/SF—Non versus Early Merger     | 0.6 0.6              | 0.5 0.6       | 0.4 0.4                       | 0.6 0.7                        | 0.6 0.6                     |

Note. The cited $p$-values from the logrank, peto, and KS tests give the likelihood that the two samples were drawn from a common population. As such, the smaller the $p$-value the less alike the samples are. Values below 0.01 are highly significant, those between 0.01 but below 0.1 are marginal and we only interpret them as possible hints for future analysis, values above 0.1 indicate the samples are drawn from the same population.
features ratios measured in AGN hosts may suggest that AGN hosts have more complex and diverse dust geometries than galaxies that do not host AGN.

In Figure 3 we compare the distributions of silicate strengths measurements in AGN and non-AGN hosts. We also compare the distributions of silicate strengths measurements in mergers and non-mergers. We find that the silicate strengths of non-AGN hosts differ significantly from those of AGN hosts. The median silicate strengths of AGN are about 3 times lower than those of non-AGN hosts and also span a wider range of values. This matches the finding of Lambrides et al. (2019) for a sample spanning a larger redshift range. The heterogeneous nature of the targets in this study and the preponderance of mergers and non-mergers among AGN or that in the nearby universe (z < 1) the fraction of highly obscured AGN is low (Lacy et al. 2007).

We also find statistically significant (p < 2E − 4) differences between grain-size distributions, as estimated by the $L_{6.2}/L_{7.7}$ between AGN and non-AGN hosts.

### 3.3. Effects of Gravitational Interactions on the Warm Molecular Gas and Dust

We compare the warm molecular gas temperatures of all the mergers in our sample to those of all the non-mergers and find that their median $H_2$ S(3) to S(1) ratios are similar, but their distributions are different (the p-value for this comparison are 5E−6 and 2E−6). However, the differences in terms of the warm molecular gas temperatures among AGN only (AGN mergers versus AGN non-mergers) are not highly significant (p-values ~0.03) and they are nonexistent among non-AGN hosts (p-values ~0.9). Among AGN+SF composites we do find slightly more statistically significant differences between mergers and non-mergers (p values ~0.01).

We also find that the distribution of PAH emission features flux ratios seems to differ significantly between mergers and non-mergers but the statistical strength of those differences decreases sharply when we compare subsamples: AGN mergers versus AGN non-mergers or SF-mergers versus SF non-mergers. The mergers in our sample have deeper absorption features than non-mergers or early mergers for both AGN and non-AGN hosts. In a future paper we will analyze the morphologies of the complete sample from Lambrides et al. (2019) to increase the number of galaxies available for analysis, and assess if/how stellar versus ISM mass may affect our findings.

### 4. Discussion

In this work we analyze the morphologies and warm ISM properties, as estimated from $griz$ imaging with Pan-STARRS and MIR spectroscopic features, of 630 galaxies at $z < 0.1$. We use nonparametric two sample tests for censored data as implemented in the R statistical software package *asurv* to compare galaxies that host AGN to those that appear not to host AGN. We use the same tests to compare galaxies whose morphological features suggest they are interacting with other galaxies (mergers) to galaxies that do not seem to have been gravitationally disturbed (non-mergers). The detailed results of these statistical tests are provided in Table 2. Here we provide a qualitative summary of our findings and we speculate about their meaning.

1. Galaxies that can be identified as AGN on the basis of their MIR properties are statistically different from those that cannot be identified as AGN. In particular, galaxies that host AGN have higher $H_2 / 11.3 \mu m$ PAH ratios and higher $H_2$ temperature as estimated from the $H_2 S(3)/S(1)$ emission-line ratios.

2. The MIR-emitting dust also appears affected by the presence of an AGN. We find statistically significant differences between the 11.3 $\mu m$ PAH/7.7 $\mu m$ PAH feature ratios of AGN and non-AGN hosts.

3. We find statistically significant differences between grain-size distributions, as estimated by the 6.2−7.7 $\mu m$ PAH feature ratios between AGN and non-AGN hosts.

4. We find statistically significant differences between the distributions of silicate strengths in AGN and non-AGN hosts: non-AGN hosts appear to have deeper absorption than AGN-hosts.

5. We find some statistical suggestive differences between the $H_2 / 11.3 \mu m$ PAH ratios and $H_2$ temperature estimated from the $H_2 S(3)/S(1)$ emission-line ratios of mergers and non-mergers. However, those differences are less statistically significant than those between AGN and non-AGN hosts.

Our results likely reflect the heterogeneous nature of our sample and we may miss the most obscured AGN because in the nearby universe (z < 1) the fraction of highly obscured AGN is low (Lacy et al. 2007). Our results do not establish a relation between the rate of BH growth and the warm ISM. However, we do find highly statistically significant differences between AGN hosts and non-AGN hosts. We do not find differences...
with the same high statistical significance between mergers and non-mergers.

AGN affect the ISM we measure in the IRS spectra more than gravitational interactions. This is puzzling because there is significant evidence in the literature that mergers trigger AGN and enhance star formation (e.g., Ellison et al. 2019). Yet, while we do find statistical differences between the warm H$_2$ temperatures of mergers and non-mergers, those differences are less significant when we compare AGN merger hosts and AGN non-merger hosts as well as AGN/SF composites.

One speculative explanation is that AGN in mergers were triggered by the merger, and AGN in non-mergers were triggered by secular processes. This would simply mean that the mechanisms that fuel the AGN do not fundamentally alter the ISM on kiloparsec scales. Instead, if an AGN is present it might be possible that warm ISM occurs on the same timescale as the AGN but that it is irrelevant of its triggering mechanism, or merger-history.

One alternative possibility to AGN impacting the host galaxy, is that the shock heating we see in the AGN hosts’ warm ISM occurs on the same timescale as the AGN but that it is not directly linked to the AGN itself. It may be possible that the mechanisms that move gas from kiloparsec to subparsec scales (e.g., supernovae, star formation, and galactic bars) also heat up the ISM. Such processes do not lead to the fast shocks measured in some mergers (Appleton et al. 2006; e.g.,) but slower shocks and turbulence can enhance the temperature of the warm molecular gas and the ratio of H$_2$ emission relative to other coolants (e.g., $11.3 \mu$m PAH emission). We note also that AGN timescales are on the order of 10$^5$ yr (e.g., Schwabinski et al. 2015) while our ability to identify mergers is on the order of 10$^5$ (e.g., Ellison et al. 2019), so if the timescales for shocked H$_2$ gas are similar to those of AGN then the statistics of shocked H$_2$ gas should change with AGN triggering mechanism because different AGN triggering could lead to different gas motions and properties.

Riffel et al. (2020) use Sloan Digital Sky Survey optical spectra for a subsample of the Lambrieds et al. (2019) galaxies to suggest that the excess of MIR H$_2$ emission seen in AGN is produced by shocks due to AGN driven outflows in the same clouds that produce [O I] emission. Spatially resolved kinematics would be required to confirm this hypothesis. Spatially resolved studies of AGN environments in X-rays, radio, and molecular gas such as those performed by Lanz et al. (2015), Ogle et al. (2014), and Appleton et al. (2018) with planned and future IR facilities will help us push beyond phenomenological findings to a better physical understanding of the processes that connect AGN and ISM.

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