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# Molecular Gas Heating in Active Galaxies: Tidal Shocks, New Stars, or Growing Black Holes

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## 1. ABSTRACT

Galaxies with growing super massive black holes appear to have warmer molecular gas than those without (Petric et al. 2018; Lambrides et al. 2019; Ogle et al. 2007; Nesvadba et al. 2011). Because some gravitational interacting galaxies have been observed to have shocked molecular gas whose emission dominates their mid-infrared (MIR) spectra (Guillard et al. 2009, 2012), we seek to understand if the warmer gas in AGN hosts observed by Lambrides et al. 2019, was heated by AGN or by tidal shocks.

To achieve this we study the morphologies of 630 galaxies at z $< 0.1$ from the Lambrides et al. (2019) sample. We use *grizy* images from the Pan-STARRS survey (Chambers et al. 2016) to classify the galaxies into mergers, non-mergers, and early-stage mergers using visual classification methods from (Nair & Abraham 2010). We look at the effect of merger status on the temperature and dust properties of the interstellar medium (ISM) as estimated by Lambrides et al. (2019) from MIR spectra. We use the ratio of the emission from rotational transitions of $H_2$ S(1) (J=3-1 at 17.035 $\mu$m) and of $H_2$ S(3) (J=5-3 at 9.665$\mu$m) to approximate the temperature of the warm molecular gas. We use the 6.2, 7.7, and 11.3 $\mu$m PAH features to study the impact of AGN and mergers on the sizes and ionization states of the dust grains. We use the strength of the 9.7 $\mu$m silicate feature as a proxy for dust obscuration. We compare the ISM properties of AGN and non-AGN hosts by performing multiple non-parametric two sample tests. Our analysis suggests that AGN have a bigger impact on the ISM but that merger AGN interactions significantly effect the state of the warm molecular gas and dust features of the ISM. We find the greatest arbiter of changes to ISM temperature and dust features to be AGNs but that merger status also has merger status also as some effect on ISM features, especially the temperature of the warm molecular $H_2$. This picture that is consistent with gas rich mergers triggering AGN and enhancing star-formation and AGN being associated with host galaxies with a warmer molecular gas component.

## 2. INTRODUCTION

The interstellar medium (ISM) fuels the growth of stars and supermassive black holes (SMBHs). The amount, phase-structure, and temperature of the ISM regulates a galaxy's evolution. The ISM is heated, ionized, and shocked by gravitational interactions, new stars, explosive stellar deaths (e.g. supernovae), and emission associated with accretting black-holes. Gravitational interactions between galaxies can cause gas in circular orbits to lose angular momentum. The gas then funnels into the central SMBH or leads to more efficient star-formation (Hopkins et al. 2016, 2008). In nearby Luminous Infrared Galaxies, observations have found that significant amounts of $H_2$ excitation coming from AGN activity but also found that the sources with the biggest warm gas kinetic energies were mergers (Stierwalt et al. 2014; Petric et al. 2018). Both the formation of young massive stars and growing SMBH - observed as active galactic nuclei (AGN), recast the physical condition of the ISM by ejecting energy back into it. However, the individual impact of both AGN and mergers on the ISM, and their connection to each other, are not simple nor are they fully understood. Our picture of galaxy evolution has been centered on the correlation between the mass of the central SMBH and that of the host galaxy's bulge (e.g. Ferrarese & Merritt 2000; Kormendy & Ho 2013). Studies of gravitational interactions and growing super-massive black holes have focused on testing the conditions and implications of their correlation. A key observational question is: do AGN heat up the molecular gas in their host galaxies?

Some AGN show ionized gas outflows that impact the ISM on galaxy-wide scales (e.g. Greene 2012; Wylezalek et al. 2017). It also appears that AGN hosts have warmer molecular gas temperatures (Rigopoulou et al. 2002; Zakamska et al. 2005; Petric et al. 2018; Lambrides et al. 2019; Ogle et al. 2007, 2010; Nesvadba et al. 2011). This may originate from simultaneous AGN and star-formation activity in AGN hosts, or it may be due to excitation of $H_2$ in tidal shocks initiated by the same processes that triggered the AGN activity: gravitational interactions. In this paper we further the study done by Lambrides et al. (2019) who showed that AGNs hosts had warm molecular gas components at higher temperatures than non-AGN hosts. We test whether or not changes in gravitational potential caused by galactic mergers heat the $H_2$ to higher temperatures than those observed in non-mergers. We classify the same galaxies used in Lambrides et al. (2019) as mergers, early mergers or non-mergers. We then compare the $H_2$ temperatures and dust features in all AGN galaxies to all pure star forming (SF) galaxies, in all mergers to all non-mergers, in all mergers to all early mergers, in all non-mergers to all early mergers, in AGN mergers to AGN non-mergers, in AGN mergers to AGN early mergers, in AGN non-mergers to AGN early mergers, in SF mergers to SF non-mergers, in SF mergers to SF early mergers, in SF non-mergers to SF early mergers, in mergers with AGN to SF mergers, in non-mergers with AGN to SF non-mergers, and in early mergers with AGN to SF early mergers.

In this paper 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 line-emission measurements from the Spitzer Infrared-spectrograph (IRS) from (Lambrides et al. 2019) using the low resolution ($R = \lambda/\Delta\lambda \sim 60$) modules.

## 3. SAMPLE

Our galaxies are chosen from the 2,015 galaxies analyzed by Lambrides et al. (2019). The spectra for these sources was taken from observations made by the *Spitzer Space Telescope's* Infrared Spectrograph. We direct the reader to Lambrides et al. (2019) for more information regarding the data acquisition, analysis, and measurements of gas and dust ISM features. To classify the morphologies of our targets we use composite, five filter, wide-field 1 arcminute, 3 arcminute, 5 acrminute sized image cutouts from the part 1 archive of the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS1 or PS1). For galaxies where a 5 arminute sized image is less than a 50 kpc radius, we adjust the cutout size accordingly to include more pixels to ensure a radius of 50kpc. The PS1 survey was conducted using a 1.8 meter telescope with a 1.4 Gigapixel camera. The redshifts of all of our galaxy sources range from $z = 0.001$ to $z = 4.27$. For our classification and further analysis, include only galaxies within a redshift of $z < 0.1$ because at our typical resolution (seeing limited 0.7 - 0.8") the visual classification becomes uncertain (Nair & Abraham 2010)While our images have higher resolution than those of(Nair & Abraham 2010) we restrict ourselves to this redshift for this initial investigation. Out of the 2,015 galaxies in the (Lambrides et al. 2019) sample, there are 728 within $z = 0.1$. Of these 728 local galaxies, 98 do not have PanSTARR image cutouts thus our analysis only includes the remaining 630 galaxies.

## 4. RESULTS

### 4.1. *Visual Classification*

Our visual classification attempts to identify all galaxies in our sample that show signs of gravitational disturbances.

To limit confusion (e.g. between galaxies at their first pass and galaxies in their second pass) we classify our targets as either non mergers ($non - mergers$), early mergers ($early - mergers$), and mergers ($mergers$). Galaxies without any visible signs of a gravitation disturbance are classified as $non - merger$s. While our visual classification techniques 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; 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 without signs of a gravitational disturbance but whose image contains at least one other object of similar brightness within a 50 kpc radius of it its galactic center. Because the PS1 image data archive does not have image cutouts that extend to a 50 kpc radius for all of the galaxies in our sample, there are 48 galaxies classified as non mergers but whose image cutouts do not extend far enough to definitively say that they are not early mergers. For this reason we believe our study may underestimate the fraction of early mergers in our sample. Future work will use the Hawaii UNIONS (Chambers 2019) survey data to remedy this issue and push our investigation at higher redshifts. 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 1).

**Figure 1.** PanSTARRs 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 mergers where objects of similar brightness within 50 kpc of galaxy that seemingly exhibit no other merger features that.

Outside merger classes, we have two other miscellaneous categories: possible mergers, and galaxies with poor image quality. We label galaxies as possible mergers for those galaxies whose morphological features are not obvious. We place galaxies in the poor quality category if the cutout images are of poor image quality, either from the reduction, or technical ccd-issues. In our sample there are 31 possible mergers and 14 poor image galaxies. Excluding these 45 uncertain galaxies, the total number of galaxies in our sample is 585. Our sample includes 248 mergers, 257 non mergers and 80 early mergers. There are a total of 207 AGN-dominated galaxies: 73 AGN-dominated mergers, 104 AGN-dominated non mergers, and 30 AGN-dominated early mergers. There are 264 SF-dominated galaxies: 139 SF-dominated mergers, 91 SF-dominated non mergers, and 34 SF-dominated early mergers.These results are summarized in Table 1.

**Table 1.** Merger Classification Summary

| | Merger | Non-Merger | Early Merger | Total |
|---|---|---|---|---|
| AGN | 73 | 104 | 30 | 207 |
| Star-forming | 139 | 91 | 34 | 264 |
| AGN/SF | 36 | 62 | 16 | 114 |
| Total | 248 | 257 | 80 | 585 |

### 4.2. *Statistical Analysis*

We use non-parametric two sample tests for censored data using the R statistical software package "survival", to investigate the relative role of mergers and AGN on the warm molecular gas and dust. To probe the impact of AGN and mergers on the warm molecular gas, we compare the relative distributions $H_2$ S(3)/S(1) luminosity ratio or $H_2$ S(3)/S(1) luminosity ratio upper limits (Table 2). In Table 3 we present our statistical investigation of the relative impact AGN and mergers have on the relative distributions of the dust grain size using the PAH 6.2$\mu$m/7.7$\mu$m luminosity ratio or its upper limits and for ionization strength we look at the PAH 11.3$\mu$m/7.7$\mu$m or its upper limits. We conduct the Logrank test and the Peto & Peto Generalized Wilcoxon Test. To quantify the differences between the amount of obscuration in mergers and non-mergers, AGN and non-AGN hosts, we also compare the strength of 9.7 $\mu$m silicate feature. For this comparison we use a Kolmogorov-Smirnov test and the Wilcoxon Rank Sum and Signed Rank Test. For the Logrank test and the Peto & Peto we omit galaxies that did not have upper limits.

#### 4.2.1. *Warm Molecular Gas*

Of the classified galaxies, all of them have $H_2$ S(3) upper limits however 80 galaxies do not have upper limits for $H_2$ S(1) and therefore are not included in the S(3)/S(1) statistical tests. Of the galaxies without upper limits, 35 are mergers: 10 AGN mergers, 19 SF mergers, 6 composite mergers. There are 36 non mergers: 15 non AGN non mergers, 16 SF non mergers, 5 composite non mergers. There are 9 early mergers: 1 AGN early mergers, 5 SF early mergers and 3 composite early mergers.

We find that the most significant differences between AGN and SF galaxies with p-values of 2e-8 and 4e-9. The second most most significant difference is between non merger AGN and non merger SF. The p-value for this comparison are 5e-6 and 2e-6. Without an AGN present, mergers seem to cause no change to the temperature of the ISM. SF mergers compared to SF non mergers have the largest p-values of 0.9. However when an AGN is present, mergers are significant. All mergers compared to all non mergers yields p-values of 2e-4 and 8e-5. These findings are consistent with a picture in which gas rich mergers trigger AGN and fuel star-formation while exciting some of the $H_2$ gas through tidal shocks. However, AGN activity appears sufficient by itself to stir up the gas, though we cannot exclude the possibility that the same mechanisms that triggered the AGN are responsible for injecting energy into the warm molecular gas.

**Table 2.** $S(3)/S(1)$

| Samples Compared | $p_{\rm log}$ | $p_{\rm peto}$ |
|---|---|---|
| All Mergers vs All Non Merger | 2e-4 | 8e-5 |
| All AGN vs All SF | 4e-8 | 4e-9 |
| | | |
| All Mergers vs All Early Mergers | 0.7 | 0.7 |
| All Non Mergers vs All Early Mergers | 0.04 | 0.03 |
| | | |
| Mergers with AGN vs Mergers SF | 0.02 | 0.01 |
| Non Mergers AGN vs Non Mergers SF | 5e-6 | 02e-6 |
| Early Mergers AGN vs Early Mergers SF | 0.1 | 0.1 |
| | | |
| AGN Mergers vs AGN Non Mergers | 0.03 | 0.03 |
| AGN Mergers vs AGN Early Mergers | 0.4 | 0.3 |
| AGN Non Mergers vs AGN Early Mergers | 0.02 | 0.01 |
| | | |
| SF Mergers vs. SF Non Mergers | 0.9 | 0.9 |
| SF Mergers vs. SF Early Mergers | 0.5 | 0.4 |
| SF Non Mergers vs. SF Early Mergers | 0.5 | 0.5 |

### 4.2.2. *Dust Features*

For the dust features there are 9 galaxies excluded from the $L[\text{PAH } 6.2\ \mu\text{m}] \big/ L[\text{PAH } 7.7\ \mu\text{m}]$ comparisons. There are 3 galaxies excluded from the $L[\text{PAH } 11.3\ \mu\text{m}] \big/ L[\text{PAH } 7.7\ \mu\text{m}]$ and the $L[\text{PAH } 11.3\ \mu\text{m}]$ comparisons. These galaxies do not have measured upper limits for their PAH luminosity. Of the galaxies excluded in the $L[\text{PAH } 6.2\ \mu\text{m}] \big/ L[\text{PAH } 7.7\ \mu\text{m}]$ comparisons: 3 are mergers, 3 are non mergers, 2 are early mergers. Of the galaxies excluded from the $L[\text{PAH } 11.3\ \mu\text{m}] \big/ L[\text{PAH } 7.7\ \mu\text{m}]$ and the $L[\text{PAH } 11.3\ \mu\text{m}]$ comparisons: 2 are mergers, 1 is a non merger, 0 are early mergers. For our comparison of $L[\text{PAH } 11.3\ \mu\text{m}] \big/ f_\nu[24\mu\text{m}]$, there are 84 galaxies without $f_\nu[24\mu\text{m}]$ measurements and 3 galaxies without $L[\text{PAH } 11.3\ \mu\text{m}]$ upper limits therefore 84 galaxies are excluded from the $L[\text{PAH } 11.3\ \mu\text{m}] \big/ f_\nu[24\mu\text{m}]$ comparisons: 35 mergers, 37 non mergers, and 9 early mergers.

In general we find similar results to that of the warm molecular gas for all but the $L[\text{PAH } 11.3\ \mu\text{m}]$. These results indicate that AGN has the largest impact on dust features. The most statistical significant differences for these dust features is all AGN to all SF galaxies. For $L[\text{PAH } 6.2\ \mu\text{m}] \big/ L[\text{PAH } 7.7\ \mu\text{m}]$ the AGN to SF p-values are 2e-4 for both tests. For the $L[\mathrm{PAH}\ 11.3\ \mu\mathrm{m}] \big/ L[\mathrm{PAH}\ 7.7\ \mu\mathrm{m}]$ the AGN to SF comparison yields p-values of $< 2\mathrm{e}{-16}$ for both test. All of our p-value test results are given in Table 3.

**Table 3.** PAH Luminosity Emission and Silicate Statistical Comparisons

| Comparison | 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 11.3$\mu$m/$f_\nu$24$\mu$m | | $\tau_{9.7}$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $p_{log}$ | $p_{peto}$ | $p_{log}$ | $p_{peto}$ | $p_{log}$ | $p_{peto}$ | $p_{log}$ | $p_{peto}$ | $p_{ks}$ | $p_{wilcox}$ |
| Merg vs. Non Merg | 0.3 | 0.3 | 4e-04 | 5e-04 | 0.1 | 0.1 | 0.02 | 0.04 | 5e-06 | 3e-06 |
| AGN vs. SF | 2e-04 | 2e-04 | <2e-16 | <2e-16 | 0.04 | 0.04 | 3e-08 | 3e-08 | <2e-16 | <2e-16 |
| Merg vs. Early | 0.9 | 0.1 | 0.007 | 0.008 | 0.6 | 0.6 | 8e-04 | 0.002 | 0.004 | 5e-04 |
| Non Merg vs. Early | 1.0 | 1.0 | 0.9 | 0.9 | 0.4 | 0.4 | 0.05 | 0.09 | 0.9 | 0.8 |
| Mergers – AGN vs. SF | 0.05 | 0.05 | 2e-12 | 2e-12 | 0.4 | 0.4 | 3e-05 | 3e-05 | 5e-06 | 7e-06 |
| Non Mergers – AGN vs SF | 0.01 | 0.01 | 1e-08 | 9e-09 | 0.1 | 0.1 | 0.004 | 0.005 | 1e-10 | 4e-10 |
| Early Mergers – AGN vs SF | 0.1 | 0.1 | 8e-06 | 8e-06 | 8e-06 | 8e-06 | 0.04 | 0.04 | 0.007 | 0.02 |
| AGN – Merg vs. Non Merg | 0.3 | 0.3 | 0.4 | 0.5 | 0.6 | 0.5 | 0.9 | 0.7 | 0.005 | 0.01 |
| AGN – Merg vs. Early | 0.3 | 0.4 | 0.3 | 0.4 | 0.7 | 0.8 | 0.1 | 0.2 | 0.4 | 0.2 |
| AGN – Non Merg vs. Early | 0.9 | 0.9 | 0.6 | 0.7 | 0.6 | 0.6 | 0.02 | 0.05 | 0.4 | 0.9 |
| SF – Merg vs. Non Merg | 0.7 | 0.8 | 0.2 | 0.2 | 0.001 | 5e-04 | 0.2 | 0.2 | 0.2 | 0.2 |
| SF – Merg vs. Early | 0.9 | 0.5 | 0.3 | 0.9 | 0.1 | 0.004 | 0.5 | 0.6 | 0.004 | 0.007 |
| SF – Non Merg vs. Early | 0.8 | 0.5 | 0.5 | 0.5 | 0.7 | 0.5 | 0.5 | 0.5 | 0.04 | 0.1 |

## 5. DISCUSSION AND CONCLUSIONS

The molecular hydrogen component of the ISM is a source of fuel for both star-formation and the growth of SMBH and is the repository for the energy coming from star-forming regions, young stars, and AGN. The warm (200-1000K) molecular gas observed in the MIR is a small (few percentage) fraction by mass of the total molecular gas reservoir. However, studies of nearby radio galaxies (e.g. Ogle et al. 2007) and mergers (Guillard et al. 2009) showed that warm molecular gas properties (mass, temperature, total luminosity relative to other coolants) provide a picture of what the total $H_2$ reservoir is doing and can be used to figure out if the total ISM is affected by an AGN or by shocks associated with gravitational interactions.

Important mechanisms responsible for exciting the $H_2$ rotational transitions are: photoionization in star- forming regions (Gautier et al. 1976; Bally & Lane 1982), AGN activity, X-ray heating, fluorescence induced by a non-thermal ultraviolet continuum, shock heating by radio jets (Moorwood & Oliva 1988; Larkin et al. 1998; Ogle et al. 2007; Guillard et al. 2012). Rotational $H_2$ 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).

Enhanced $H_2$ emission with respect to the [S(3)], PAH and IR luminosity correlations in in some galaxies (Hill & Zakamska 2014; Stierwalt et al. 2014; Petric et al. 2018; Lambrides et al. 2019) suggest that that shocks associated with supernova remnants, AGN or tidal interactions are significantly contributing to the excitation of the $H_2$ rotational transitions. We find AGN to be the dominant contributor to the changes in temperature and PAH within the ISM. We find the most significant difference in $H_2$ temperature, PAH ionization strength, PAH dust grain size, and silicate absorption in populations that harbor an AGN compared to those that do not. Our galaxy population comparisons also show that the presence of AGNs affect the ISM probed by the IRS data more than gravitational interactions change.

In sum, we find that for all but the PAH 11.3 $\mu$m luminosity comparison that AGNimpact the warm (MIR-emitting ISM). These findings are consistent with a picture in which the changing gravitational torques associated with gravitational interactions cause the gas to lose angular momentum and fall into central region triggering an AGN and feed star-formation, both of which put energy into the gas, leading to an observable warmer $H_2$ component, and a wider range of dust sizes and ionization states. As the system evolves, if the AGN turns off it no longer provides sufficient energy to shock the $H_2$ gas. If the AGN is not triggered by a major merger its host galaxy ISM can still be impacted by either radiation pressure from the AGN, or stirred up by associated outflows.

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