WATER VAPOR IN NEARBY INFRARED GALAXIES AS PROBED BY HERSCHEL

Chentao Yang (杨辰涛)1,2,3, Yu Gao (高瀚)2,4, Omont4,5, Daizhong Liu (刘岱钟)2,3, K. G. Isaak6, D. Downes7, P. P. van der Werf8, and Nanyao Lu9

1 Department of Astronomy, Beijing Normal University, Beijing 100875, China
2 Purple Mountain Observatory/Key Lab of Radio Astronomy, Chinese Academy of Sciences, Nanjing 210089, China
3 University of Chinese Academy of Sciences, Beijing, China
4 Institut d’Astrophysique de Paris, UPMC Université Paris 06, UMR7095, F-75014 Paris, France
5 CNRS, UMR7095, Institut d’Astrophysique de Paris, F-75014 Paris, France
6 ESA Astrophysics Missions Division, ESTEC, P.O. Box 299, 2200 AG Noordwijk, The Netherlands
7 Institut de Radioastronomie Millimétrique (IRAM), 300 rue de la Piscine, F-38406 Saint-Martin d’Hères, France
8 Leiden Observatory, Leiden University, Post Office Box 9513, NL-2300 RA Leiden, The Netherlands
9 Infrared Processing and Analysis Center, California Institute of Technology, MS 100-22, Pasadena, CA 91125, USA

Received 2013 April 19; accepted 2013 May 27; published 2013 June 21

ABSTRACT

We report the first systematic study of the submillimeter water vapor rotational emission lines in infrared (IR) galaxies based on the Fourier Transform Spectrometer (FTS) data of Herschel SPIRE. Among the 176 galaxies with publicly available FTS data, 45 have at least one H2O emission line detected. The H2O line luminosities range from ~1 × 10^5 L⊙ to ~5 × 10^7 L⊙ while the total IR luminosities (LIR) have a similar spread (~1–300 × 10^10 L⊙). In addition, emission lines of H2O+ and H3O+ are also detected. H2O is found, for most galaxies, to be the strongest molecular emitter after CO in FTS spectra. The luminosity of the five most important H2O lines is near-linearly correlated with LIR, regardless of whether or not strong active galactic nucleus signature is present. However, the luminosity of H2O(211–202) and H2O(220–211) appears to increase slightly faster than linear with LIR. Although the slope turns out to be slightly steeper when LIR decreases with increasing f_{25}/f_{100}, but see no dependence on f_{25}/f_{100}, possibly indicating that very warm dust contributes little to the excitation of the submillimeter H2O lines. The average spectral line energy distribution (SLED) of the entire sample is consistent with individual SLEDs and the IR pumping plus collisional excitation model, showing that the strongest lines are H2O(202–111) and H2O(321–312).

Key words: galaxies: ISM – galaxies: starburst – infrared: ISM – ISM: molecules

Online-only material: color figures

1. INTRODUCTION

H2O can be one of the most abundant oxygen molecular carriers besides CO in the warm interstellar gas (but it is mostly locked in icy interstellar dust grains in cold regions of the Galaxy; e.g., Melnick & Bergin 2005; van Dishoeck et al. 2011). Nevertheless, the study of the rotational H2O line is always far more challenging than CO at low redshift. The main difficulty is from the contamination of the H2O in the Earth’s atmosphere. However, some pioneering research with the Infrared Space Observatory (covering ~2–200 μm; Kessler et al. 1996) of both star-forming regions within our Galaxy, such as Orion (Harwit et al. 1998), and nearby galaxies, such as Arp220 (González-Alfonso et al. 2004), NGC 253 and NGC 1068 (Goicoechea et al. 2005), and Mrk231 (González-Alfonso et al. 2008), revealed that H2O lines likely trace the local infrared radiation field (IRF) directly, and thus provide a unique diagnostic probing the physical and chemical processes, unlike other gas tracers such as CO. The Herschel Space Observatory (Pilbratt et al. 2010), with great improvement of sensitivity, angular resolution, and band coverage, offers an unprecedented opportunity to study the submillimeter regime of galaxies without atmospheric contamination, and thus provides unique chances to observe the H2O lines within the SPIRE band (194–672 μm; Griffin et al. 2010).

Herschel has revealed a wealth of submillimeter H2O lines in, e.g., Mrk231 (van der Werf et al. 2010; González-Alfonso et al. 2010, G-A10 hereafter), Arp220 (Rangwala et al. 2011; González-Alfonso et al. 2012, 2013), NGC 4418 (González-Alfonso et al. 2012), NGC 1068 (Spinoglio et al. 2012), NGC 6240 (Meijerink et al. 2013), and M82 (Kamenetzky et al. 2012), from the energy level E_{up}/k = 53 K up to E_{up}/k = 642 K. Moreover, some detections from the ground in high-z ultra-luminous IR galaxies (ULIRGs) were also reported (e.g., Omont et al. 2011, 2013; van der Werf et al. 2011; Combes et al. 2012; Riechers et al. 2013). H2O line strength is found to be comparable with neighboring high-J CO lines (J = 8–7 to J = 13–12) in these studies.

By modeling the H2O excitation and dust continuum in Mrk231, G-A10 interpreted that collisional excitation from a cool extended region (610 pc, 41 K) is responsible for part of the low-laying line excitation, while IR pumping through far-IR photons by compact warm dense gas (120 pc, 95 K) excites high-lying lines and part of low-lying lines. The high abundance of H2O can be explained as a consequence of shocks/cosmic rays and X-ray Dominated Regions (XDR) chemistry (Meijerink & Spaans 2005), and/or an undepleted chemistry (G-A10). Therefore, H2O excitation is naturally linked to the local IRF, probing, e.g., the size and strength of the IR power source; tracing a different regime of gas than that of CO. Hence, it is important to have a systematic study of the H2O lines in galaxies to better understand the gas excitation and physical processes within.

2. THE SAMPLE AND DATA REDUCTION

We used the Herschel Science Archive (HSA), containing both the SPIRE/Fourier Transform Spectrometer (FTS; Naylor et al. 2010) spectra at 450–1550 GHz, and the PACS (Poglitsch...
et al. 2010) images at 70, 100, and 160 \( \mu m \). Our sample consists of 45 sources with at least 1 rotational \( H_2O \) transition detected among 176 nearby galaxies available. The data are from 10 projects including HerCULES (PI: P. van der Werf) with an \( H_2O \) detection rate \( \sim 80\% \) and GOALS (PI: N. L. Lu., a full list can be found here: http://stfarg.pmo.ac.cn/~yangcht/h2oSample.txt). The typical SPIRE/FTS integration time is about several hours.

The data were reduced with HIPE v9 (Ott 2010). Basic steps of spectral data reduction contain background removal using off-axis detector subtraction and flux calibration with Neptune and Uranus, when available. Deglitch, flat field calibration through HIPE and brightness drift subtraction with Scanamorphos (Roussel 2012) have been used to reduce PACS images. All \( H_2O \) emission line detections are above the 3\( \sigma \) level. The instrumental sinc function has been adopted for the line fit using customized HIPE scripts, since the intrinsic line width is smaller than the instrumental resolution in most cases. However, although the flux could be underestimated by \( \sim 20\% \) for a few sources with very broad line widths such as Arp220, it is still insignificant when we consider the line fitting error \( (\sim 20\%) \), the main source of the errors. Then we use the formula in Solomon et al. (1992) to convert line intensity \( (J(1,0)) \) to \( L_{H_2O} \), taking the luminosity distance \( D_L \) in Sanders et al. (2003) \( (H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.3, \text{ and } \Omega_L = 0.7; \text{Mould et al. 2000}) \).

After convolving Spitzer/MIPS 24 \( \mu m \), PACS 70, 100, and 160 \( \mu m \) images to match with the SPIRE beams (Swinyard et al. 2010) following Aniano et al. (2011), we determine whether or not the source is extended based on its radial profile as compared with that of the corresponding Gaussian point-spread functions (PSFs). We use the total IR luminosities \( (8-1000 \mu m) \) from Sanders et al. (2003) as the \( L_{IR} \) for point sources. For extended galaxies, in-beam \( L_{IR} \) is calculated to ensure that \( L_{H_2O} \) and \( L_{IR} \) are spatially matched. First, we take the weighting coefficients of Galametz et al. (2013) to combine MIPS 24, PACS 70, 100, and 160 \( \mu m \) images into composite maps. Then the in-beam flux ratio between in-aperture and that of the entire source is derived with aperture photometries (FWHM of the Gaussian PSFs). It should be noted that the practically measured area by SPIRE/FTS is not limited in the FWHM beam, and we require an additional correction factor to account for this (D. Liu et al., in preparation). Applying this factor, we can then obtain the corrected in-beam fraction of the \( L_{IR} \) for extended sources. \( L_{IR} \) matched with the SPIRE beam can thus be obtained by applying this factor and the in-beam fraction to the global \( L_{IR} \) in Sanders et al. (2003). The full data set containing \( L_{IR} \) and \( L_{H_2O} \) will be described in D. Liu et al. (in preparation). Since we take the global flux density ratios of 25–60 \( \mu m \), applying this factor and the in-beam fraction to the global \( L \) in Sanders et al. (2003), the full data set containing \( L_{H_2O} \) are spatially matched. First, we take the weighting coefficients of the errors. Then we use the formula in Solomon et al. (1992) when we consider the line fitting error \( (\sim 20\%) \), the main source of the errors. Then we use the formula in Solomon et al. (1992) when we consider the line fitting error \( (\sim 20\%) \), the main source of the errors.

### 3. RESULTS AND DISCUSSION

In our sample we find that \( H_2O \) is the strongest molecular emitter after high-\( J \) CO \( (J = 8-7 \text{ to } J = 13-12) \) in the SPIRE band. In some cases \( (\sim 13\%) \), e.g., ESO320-G030, the strength of \( H_2O(321-312) \) is even stronger. Besides the \( H_2O \) emission lines, \( H_2O(1_1-0_0) \) is detected in absorption in three sources, including Arp220 as reported by Rangwala et al. (2011). \( H_2O^+ \) absorption lines were also detected in a few sources (D. Liu et al. in preparation). In addition, emission lines of \( H_2O^+ \) and \( H_2O^2+ \) are detected (Section 3.3). Those ionic molecules are the intermediate species for the main route of gas-phase \( H_2O \) formation.

#### 3.1. Relation between \( H_2O \) and IR Luminosities

The correlation between \( L_{H_2O} \) for different transitions and \( L_{IR} \) was analyzed by two different methods: a Bayesian approach, and the nonlinear \( x^2 \) fitting routine, MPFIT (Markwardt 2009). In Figure 1, we plot the luminosities of \( H_2O(1_{11}-0_{00}), H_2O(2_{02}-1_{11}), H_2O(2_{12}-2_{02}), H_2O(2_{22}-2_{11}), H_2O(3_{12}-3_{03}), H_2O(3_{21}-3_{12}), H_2O(4_{22}-4_{13}), \) and \( H_2O(5_{23}-5_{14}) \) (lines 1 to 8 hereafter) against the corresponding \( L_{IR} \). In addition to our sample, we also include five high-\( z \) ULIRGs (Omont et al. 2013, see online Table 4) and HLSJ30918+5144 (Combes et al. 2012) in our fit for lines 2 and 3 (Figure 1). The QSO APM08279+5255 at \( z = 3.9 \) (van der Werf et al. 2011) is also added for comparison.

The two fitting methods yield similar results in log–log space over four orders of magnitude of the luminosity range. The fit can be described as

\[
\log L_{H_2O} = \alpha \log L_{IR} + \beta
\]

The derived parameters are listed in Table 1. All values of \( \alpha \) are close to 1, i.e., a linear relation, though the \( \alpha \) given by the Bayesian approach are closer to linear. However, the \( \alpha \) of lines 3 and 4 are a bit higher than that of the other lines. This is weakly significant when we consider the errors. The \( \alpha \) of lines 2 and 3 are consistent with Omont et al. (2013). As the slopes are close to linear, we perform an additional linear fit by fixing \( \alpha = 1 \), and use \( x^2 \) fitting to determine the constant ratios between \( L_{H_2O} \) and \( L_{IR} \). These ratios vary from \( 3.3 \times 10^{-6} \) for \( H_2O(1_{11}-0_{00}) \) to \( 1.1 \times 10^{-5} \) for \( H_2O(3_{21}-3_{12}) \) (see the gray dashed lines and text in Figure 1 and Table 1). Because the detections of lines 1, 7, and 8 are not statistically significant, more data are needed to solidify the fits. In Figure 1, we find most of the \( H_2O(2_{12}-2_{02}) \) and \( H_2O(3_{21}-3_{12}) \) upper limits for the non-detections are consistent with the correlation. All the (U)LIRGs have a strong \( H_2O \) emission compatible with the correlation pointing out to a rather large \( H_2O \) abundance as known in shocked regions (e.g., G-A10; Harwit et al. 1998). Unlike the case in the Orion Bar, the protootypical photodissociation region (PDR), where CO lines are a factor \( \gtrsim 50 \) stronger than the \( H_2O \) lines, the high \( H_2O/CO \) ratio of most sources in our sample makes it unlikely that those strong \( H_2O \) emission originate in classical PDRs (e.g., G-A10). The high \( CO/H_2O \) ratio in M82 (\( \sim 40 \); Weiß et al. 2010) indicates that it is dominated by classical PDRs, and thus has much weaker \( H_2O \) lines. As in Weiß et al. (2010), the \( H_2O \) lines in M82 are found to be very weak, nearly an order of magnitude below the correlation. It would be important to analyze the weak \( H_2O \) emission in other galaxies such as M82, but it is beyond the scope of this work. Therefore, we excluded M82 from our fit. Additionally, when we fit the correlations for \( L_{H_2O,O-2} \) and \( L_{H_2O,O-3} \) without high-\( z \) ULIRGs, we get slightly lower slopes. This means that high-\( z \) ULIRGs at the high \( L_{IR} \) end have slightly higher \( L_{H_2O}/L_{IR} \).

The line correlation could be the result of the very intense far-IR radiation via IR pumping. After the absorption of far-IR
photon, the upper level H$_2$O molecules cascade toward the lines we observed in an approximately constant fraction. Thus, the H$_2$O luminosity should be linearly correlated with the IR emission. Though detailed excitation modeling is required, this linear correlation already shows the importance of IR pumping.

Using the NASA/IPAC Extragalactic Database (NED), we have separated our sample into two groups: optically identified, strong, active-galactic-nucleus-(AGN)-dominated (Seyfert types 1 and 2) and star-forming-dominated galaxies possibly with mild AGNs (classes H$_{\text{II}}$, composite and LINER of Kewley et al. 2006, hereafter “H$_{\text{II}}$+mild-AGN”), as red and blue points in Figure 1, respectively. There is no obvious difference between these two groups and they both exhibit similar correlations. This implies that both strong-AGN and H$_{\text{II}}$+mild-AGN sources behave similarly in H$_2$O emission, and a strong AGN may have little impact on the H$_2$O excitation. Although the

---

**Figure 1**. Correlation between $L_{H_2O}$ and the corresponding $L_{IR}$ of our sample. The fitted lines by MPFIT and LINMIX_ERR are shown in black and brown lines, respectively, while the gray lines are the linear fitting with a fixed slope ($\alpha = 1$). The red, blue, green, and black dots represent strong-AGN, H$_{\text{II}}$ with mild AGNs (classes H$_{\text{II}}$+mild-AGN-dominated, high-$z$ ULIRGs, and the upper limits for non-detections, respectively. The solid triangles are the mapping mode data of NGC 1068. Mrk231 is marked in red squares. M82 and APM08279+5255, marked with dashed error bars, are excluded from the fitting.

(A color version of this figure is available in the online journal.)

---

**Table 1**

| H$_2$O Line | $\nu_{\text{rest}}$(GHz) | $\alpha_{\chi^2}$ | $\alpha_{\text{Bayes}}$ | $\beta_{\chi^2}$ | $\beta_{\text{Bayes}}$ | $[L_{H_2O}/L_{IR}]$ |
|-------------|--------------------------|-------------------|-------------------------|-------------------|-------------------------|-----------------------|
| 1, 1$_{11}$–0$_{00}$ | 1113.343 | 0.89 ± 0.09 | 0.86 ± 0.17 | -4.24 ± 1.06 | -3.76 ± 1.94 | 3.29 × 10$^{-6}$ |
| 2, 2$_{02}$–1$_{11}$ | 987.927 | 1.12 ± 0.04 | 1.08 ± 0.05 | -6.52 ± 0.47 | -6.07 ± 0.59 | 7.58 × 10$^{-6}$ |
| 3, 3$_{11}$–2$_{02}$ | 752.033 | 1.21 ± 0.04 | 1.18 ± 0.06 | -7.72 ± 0.49 | -7.34 ± 0.67 | 5.53 × 10$^{-6}$ |
| 4, 2$_{22}$–3$_{11}$ | 1228.789 | 1.19 ± 0.06 | 1.10 ± 0.08 | -7.30 ± 0.69 | -6.33 ± 0.97 | 7.49 × 10$^{-6}$ |
| 5, 3$_{12}$–2$_{03}$ | 1097.365 | 1.03 ± 0.04 | 0.98 ± 0.06 | -5.45 ± 0.51 | -4.88 ± 0.65 | 7.10 × 10$^{-6}$ |
| 6, 3$_{21}$–3$_{12}$ | 1162.912 | 1.11 ± 0.05 | 1.07 ± 0.09 | -6.22 ± 0.57 | -5.88 ± 1.05 | 1.07 × 10$^{-5}$ |
| 7, 4$_{32}$–5$_{21}$ | 1207.639 | 0.94 ± 0.12 | 0.84 ± 0.22 | -2.91 ± 1.12 | -3.43 ± 2.51 | 5.71 × 10$^{-6}$ |
| 8, 5$_{23}$–6$_{12}$ | 1410.618 | 0.78 ± 0.10 | 0.99 ± 0.19 | -4.56 ± 1.37 | -4.93 ± 2.30 | 3.66 × 10$^{-6}$ |

**Notes.** $^a$ The resulting parameters of 1$_{11}$–0$_{00}$, 3$_{21}$–3$_{12}$, and 5$_{23}$–5$_{12}$ contain large uncertainties due to the small sample size. $\alpha_{\chi^2}$ and $\beta_{\chi^2}$ are the slope and intercept from $\chi^2$ fitting, while $\alpha_{\text{Bayes}}$ and $\beta_{\text{Bayes}}$ are from the Bayesian method.
number of statistics is small, the detection rate of H\textsc{ii}+mild-AGN (∼3.2%) is lower than strong AGN (∼12.4%) for H\textsubscript{2}O(111–000). The remaining H\textsubscript{2}O lines have comparable detection rates of both kinds, and lines 2 and 3 have the highest detection rate of about 30%. The absence of an apparent significant AGN contribution indicates that an AGN may not be the main power source of the H\textsubscript{2}O excitation. The origin of such abundant H\textsubscript{2}O reservoir might thus favor an undepleted chemistry or shocks/cosmic rays rather than XDR chemistry (G-A10).

We then analyzed the correlation between \(L_{\text{H}_2\text{O}}/L_{\text{IR}}\) and the IR colors, along with the \(L_{\text{IR}}\) (Figure 2 and Table 2). We dismiss lines 1, 7, and 8 here for their insignificant statistics because hardly any correlation has been found between \(L_{\text{H}_2\text{O}}/L_{\text{IR}}\) and \(f_{25}/f_{60}\) (Table 2). We find, however, that \(L_{\text{H}_2\text{O}}/L_{\text{IR}}\) ratios decrease with the increasing \(f_{25}/f_{60}\), with significant correlation coefficients (\(R \sim -0.5\)). A similar correlation has also been found in lines 7 and 8, though with low statistics. This correlation may be explained by a smaller contribution to the submillimeter H\textsubscript{2}O line excitation from very warm dust radiation (dust temperature \(T_d \sim 110\) K) than from warm dust (\(T_d \sim 50\) K). We also find that line 6 has the largest \(R \sim -0.7\), possibly indicating that this transition is more sensitive to \(T_d\) than others. There is no significant correlation between \(L_{\text{H}_2\text{O}}/L_{\text{IR}}\) and \(L_{\text{IR}}\) except for line 3 (\(R \sim 0.4\), as shown in the second column of Figure 2 and in Table 2). This seems to be consistent with the slightly super-linear relation found for \(L_{\text{H}_2\text{O}}/L_{\text{IR}}\) with \(L_{\text{IR}}\) (Figure 1). The non-variation of \(L_{\text{H}_2\text{O}}/L_{\text{IR}}\) with \(L_{\text{IR}}\) for most lines confirms the validity of the near-linear relations in Figure 1.

Again, here we separate the sources into strong-AGN and H\textsc{ii}+mild-AGN as in Figure 1. It appears that strong AGNs, on average, have higher \(f_{25}/f_{60}\) compared with the others. This is a well-known property of AGN sources that have more very warm dust than starburst sources (e.g., Younger et al. 2009). However, both strong-AGN and H\textsc{ii}+mild-AGN species show a similar trend for the variation of \(L_{\text{H}_2\text{O}}/L_{\text{IR}}\) with \(f_{25}/f_{60}\). Their different IR colors might cause the average value of \(L_{\text{H}_2\text{O}}/L_{\text{IR}}\) in strong AGNs to be slightly lower, by about 40%, than in H\textsc{ii}+mild-AGN sources for all lines (Figure 2 and Table 2), but the difference is hardly significant.
squares represent the lensed QSO APM08279+5255 (van der Werf et al. 2011). The color version of this figure is available in the online journal.

Mrk231 (G-A10) and Arp220 (Rangwala et al. 2011), respectively. The purple dominated galaxies, respectively. The green and light blue symbols represent the FTs beam sizes.

Figure 3. Upper panel shows the H2O energy level diagram. Among the red lines that indicate the main possible IR pumping paths, the solid lines show the observed absorption lines in Mrk231, Arp220 and NGC 4418 (G-A10; González-Alfonso et al. 2012). The blue lines are the transitions we detected. The lower panel shows the H2O(202-111) normalized H2O intensities (in Jy km s^-1). The black dashed line represents the average values of the whole sample, while red and blue points and lines are those of the strong-AGN- and H II+mild-AGN-dominated galaxies, respectively. The green and light blue symbols represent Mrk231 (G-A10) and Arp220 (Rangwala et al. 2011), respectively. The purple squares represent the lensed QSO APM08279+5255 (van der Werf et al. 2011).

(A color version of this figure is available in the online journal.)

3.2. H2O Line Ratios and the Average Spectral Line Energy Distribution (SLED)

Line ratios between different transitions could help us understand the excitation of H2O and the physical condition of the warm dense gas. Thus, we compare the H2O line ratios with IR colors and luminosities. As discussed in Section 2, different transitions have various beam sizes. In order to compare different H2O transitions, we have to remove this beam size dependence. We simply do this by dividing L_H2O/L_IR by a b/10 hereafter) could represent the true luminosity ratio between two H2O lines, a and b. Table 2 lists the results. In Figure 2, (L_H2O/L_IR)b has the steepest dependence on f_25/f_60 compared with other lines. Thus, the ratio between L_H2O/L_IR of any other line and (L_H2O/L_IR)b should have a correlation with f_25/f_60. Indeed, as we can see in the table, where the R for line ratios 2/6, 3/6, and 5/6 versus f_25/f_60 is >-0.5. Also the line ratio 2/3 decreases with increasing f_60/f_100 (R ~ -0.5). Although there are some R close to ±0.5 for the correlation between L_H2O/L_IR and L_IR, these trends may not be real for they are within the error. The low line ratio 2/6 in Table 2 might indicate that IR pumping is important since collisional excitation alone cannot explain the high intensities of the high-lying lines compared with low-lying lines (e.g., G-A10).

In order to have a general view of the H2O excitation, we calculate the error-weighted average line intensity ratios with respect to H2O(202-111). In Figure 3, the upper panel shows the H2O energy level diagram. The lower panel of Figure 3 shows an average H2O SLED together with SLEDs taken from previous case studies (G-A10; van der Werf et al. 2011; Rangwala et al. 2011). The individual studies agree well with our averaged SLED. All SLEDs show two peaks at H2O(202-111) and H2O(312-312), and the latter is slightly stronger. The explanation for the strong high-lying peak could be that the IR spectral energy distribution (SED) peaks are close to 75 μm which could result in higher IR pumping efficiency considering the possibility of IR pumping at 75 μm (Figure 3, upper panel) which is the main power source of H2O(312-312) and H2O(312-312) (G-A10). However, we should be cautious in this interpretation because the H2O line intensities depend not only on the excitation conditions, but also on the intrinsic line strengths of the H2O molecule. Detailed excitation modeling is therefore needed. The high-lying lines to H2O(202-111) ratios in H II+mild-AGNs appear a bit stronger than strong AGNs (Figure 3 and Table 2). In Section 3.1, we find that the high-lying lines have steeper correlation on f_25/f_60, thus strong AGNs, with higher f_25/f_60, are expected to show lower high-lying lines to H2O(202-111) ratios.

3.3. Emission Lines of H2O-related Ionic and Isotope Molecules

Besides H2O, the related ionic and 18O isotope molecular emission lines are also found. H2O* forms via ionization of H and H2, after the combination of H2, it forms H2O*, and the recombinatiion with electrons leads to OH and H2O (Hollenbach et al. 2012). Among 45 H2O-detected sources, 5 have H2O*(111-000,J/3,1/2) (1115.204 GHz), another 5 have H2O*(111-000,J/2,1/2) (1139.561 GHz), 12 have H2O*(202-111,J/3,2) (746.194 GHz), 7 sources have H2O*(202-111,J/3,2) (742.033 GHz), and 3 have H2O* (312-312) (1136.704 GHz) detected. Both strong-AGN- and H II+mild-AGN-dominated galaxies are among these detections. We find their luminosities to be tightly correlated with those of the related H2O transitions. Taking H2O*(202-111,J/3,2), which has the largest number of detections as an example, the luminosities of H2O*(202-111,J/3,2) and H2O(202-111) perfectly fit a linear correlation. H2O*(202-111) lines are about 4.5 times weaker than H2O(202-111) and 2.5 times weaker than H2O(211-202), while the strength of H2O*(111-000) is almost the same as that of H2O(111-000). These preliminary results are important for further observations of those ionic diagnostic lines in high-z galaxies, although the number of the sources (≤10) is not sufficient to draw any concrete conclusion at this stage.

4. CONCLUSIONS

H2O is found to be the second strongest molecular emitter in our sample of 45 nearby IR galaxies after high-J CO lines within the SPIRE/FTS band. Near-linear correlations have been found between various H2O rotational transitions and corresponding
whereas H$_2$O(211–202) and H$_2$O(220–211) may have slightly steeper slopes. The ratios of $L_{\text{H}_2\text{O}}/L_{\text{IR}}$ vary with $f_{25}/f_{60}$, while nearly no trend with $f_{60}/f_{100}$ and $L_{\text{IR}}$ has been found, indicating that very warm dust contributes little to the H$_2$O excitation. The near constant $L_{\text{H}_2\text{O}}/L_{\text{IR}}$ ratios reveal an intrinsic linear correlation, regardless of whether or not a strong AGN is present. We find no significant difference in the correlation between strong-AGN- and star-forming-dominated galaxies, although strong AGNs might have slightly smaller average ratios $L_{\text{H}_2\text{O}}/L_{\text{IR}}$. In less than one-third of both kinds of galaxies, related ionic H$_2$O$^+$ emission lines have been detected, while their strength tightly correlates with that of the corresponding H$_2$O lines. H$_{18}$O isotope line emission is also detected in three sources. It seems that the IR pumping at 75 μm, the IR SED peak, is most important in excitation of high-lying H$_2$O lines in these IR galaxies. Nevertheless, detailed modeling is needed, e.g., Large Velocity Gradient or XDR models, in order to derive some physical parameters of the H$_2$O excitation and to provide a quantitative diagnostic tool of the IR radiation field and warm dense gas in galaxies other than CO lines.

This research is based on the data from HSA and is partially supported by the NSF of China (No. 11173059).

Facility: Herschel

REFERENCES

Aniano, G., Draine, B. T., Gordon, K. D., & Sandstrom, K. 2011, PASP, 123, 1218

Combes, F., Rex, M., Rawle, T. D., et al. 2012, A&A, 538, L4

Galametz, M., Kennicutt, R. C., Calzetti, D., et al. 2013, MNRAS, 431, 1956

Goicoechea, J. R., Martín-Pintado, J., & Cernicharo, J. 2005, ApJ, 619, 291

González-Alfonso, E., Smith, H. A., Ashby, M. L. N., et al. 2008, ApJ, 675, 303

González-Alfonso, E., Smith, H. A., Fischer, J., & Cernicharo, J. 2004, ApJ, 613, 247

Griffin, M. J., Abergel, A., Abreu, A., et al. 2010, A&A, 518, L3

Harwit, M., Neufeld, D. A., Melnick, G. J., & Kaufman, M. J. 1998, ApJL, 497, L105

Hollenbach, D., Kaufman, M. J., Neufeld, D., et al. 2012, ApJ, 754, 105

Kamenetzky, J., Glenn, J., Rangwala, N., et al. 2012, ApJ, 753, 70

Kelly, B. C. 2007, ApJ, 665, 1489

Kessler, M. F., Anderegg, M. E., et al. 1996, A&A, 315, L27

Kewley, L. J., Groves, B., Kauffmann, G., & Heckman, T. 2006, MNRAS, 372, 961

Markwardt, C. B. 2009, in ASP Conf. Ser. 411, Astronomical Data Analysis Software and Systems XVIII, ed. D. A. Bohleender, D. Durand, & P. Dowler (San Francisco, CA: ASP), 251

Meijerink, R., Kristensen, L. E., Weiß, A., et al. 2013, ApJL, 762, L16

Meijerink, R., & Spaans, M. 2005, A&A, 436, 397

Melnick, G. J., & Bergin, E. A. 2005, AdSpR, 36, 1027

Mould, J. R., Huchra, J. P., Freedman, W. L., et al. 2000, ApJ, 529, 786

Naylor, D. A., Baluteau, J.-P., Barlow, M. J., et al. 2010, Proc. SPIE, 7731, 773116

Omont, A., Neri, R., Cox, P., et al. 2011, A&A, 530, L3

Omont, A., Yang, C., Cox, P., et al. 2013, A&A, 551, A115

Ott, S. 2010, in ASP Conf. Ser. 434, Astronomical Data Analysis Software and Systems XIX, ed. Y. Mizumoto, K.-I. Morita, & M. Ohsishi (San Francisco, CA: ASP), 139

Pilbratt, G. L., Riedinger, J. R., Passvogel, T., et al. 2010, A&A, 518, L1

Poglitsch, A., Waelkens, C., Geis, N., et al. 2010, A&A, 518, L2

Rangwala, N., Maloney, P. R., Glenn, J., et al. 2011, ApJ, 743, 94

Riechers, D. A., Bradford, C. M., Clements, D. L., et al. 2013, Natur, 496, 329

Roussel, H. 2012, arXiv:1205.2576

Sanders, D. B., Mazzarella, J. M., Kim, D.-C., Surace, J. A., & Soifer, B. T. 2003, AJ, 126, 1067

Solomon, P. M., Downes, D., & Radford, S. 1992, ApJL, 398, L29

Spinoglio, L., Pereira-Santaella, M., Busquet, G., et al. 2012, ApJ, 758, 108

Swinyard, B. M., Ade, P., Baluteau, J.-P., et al. 2010, A&A, 518, L4

van der Werf, P. P., Herczeg, A., Spaans, M., et al. 2011, ApJL, 741, L38

van der Werf, P. P., Isaak, K. G., Meijerink, R., et al. 2010, A&A, 518, L42

van Dishoeck, E. F., Kristensen, L. E., Benz, A. O., et al. 2011, PASP, 123, 138

Weiß, A., Requena-Torres, M. A., & Güsten, R. 2010, A&A, 521, L1

Younger, J. D., Hayward, C. C., Narayanan, D., et al. 2009, MNRAS, 396, L66