HIGH-LYING OH ABSORPTION, [C II] DEFICITS, AND EXTREME L_{FIR}/M_{H2} RATIOS IN GALAXIES

E. González-Alfonso1, J. Fischer2, E. Sturm3, J. Graciá-Carpio3, S. Veilleux4, M. Meléndez4, D. Lutz5, A. Poglitsch6, S. Aalto7, N. Talia8, H. W. W. Spoon6, D. Farrah9, A. Blasco10, C. Henkel11, A. Contursi12, A. Verma13, M. Spaans14, H. A. Smith12, M. L. N. Ashby12, S. Hailey-Dunsheath13, S. García-Burillo14, J. Martín-Pintado15, P. van der Werf16, R. Meijerink16, R. Genzel3

1Universidad de Alcalá, Departamento de Física y Matemáticas, Campus Universitario, E-28871 Alcalá de Henares, Madrid, Spain
2Naval Research Laboratory, Remote Sensing Division, 4555 Overlook Ave SW, Washington, DC 20375, USA
3Max-Planck-Institut für Extraterrestrische Physik (MPE), Giessenbachstraße 1, 85748 Garching, Germany
4Department of Astronomy, University of Maryland, College Park, MD 20742, USA
5Department of Earth and Space Sciences, Chalmers University of Technology, Onsala Space Observatory, Onsala, Sweden
6Cornell University, Astronomy Department, Ithaca, NY 14853, USA
7Department of Physics, Virginia Tech, Blacksburg, VA 24061, USA
8Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121, Bonn, Germany
9Astronomy Department, Kind Abdulaziz University, P.O. Box 80203, Jeddah 21589, Saudi Arabia
10University of Oxford, Oxford Astrophysics, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK
11Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands
12Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
13California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125, USA
14Observatorio Astronómico Nacional (OAN)-Observatorio de Madrid, Alfonso XII 3, 28014, Madrid, Spain
15CSIC/INTA, Ctra de Torrejón a Aljavir, km 4, 28850, Torrejón de Ardoz, Madrid, Spain and Sterrewacht Leiden, Leiden University, PO Box 9513, 2300 RA, Leiden, The Netherlands

Draft version December 16, 2014

ABSTRACT

Herschel/PACS observations of 29 local (Ultra-)Luminous Infrared Galaxies, including both starburst and AGN-dominated sources as diagnosed in the mid-infrared/optical, show that the equivalent width of the absorbing OH 65 μm Π3/2 J = 9/2 − 7/2 line (W_{eq}(OH65)) with lower level energy E_{low} ≈ 300 K, is anticorrelated with the [C ii]158 μm line to far-infrared luminosity ratio, and correlated with the far-infrared luminosity per unit gas mass and with the 60-to-100 μm far-infrared color. While all sources are in the active L_{IR}/M_{H2} > 50 L☉/M☉ mode as derived from previous CO line studies, the OH65 absorption shows a bimodal distribution with a discontinuity at L_{FIR}/M_{H2} ≈ 100 L☉/M☉. In the most buried sources, OH65 probes material partially responsible for the silicate 9.7 μm absorption. Combined with observations of the OH 71 μm Π1/2 J = 7/2 − 5/2 doublet (E_{low} ≈ 415 K), radiative transfer models characterized by the equivalent dust temperature, T_{dust}, and the continuum optical depth at 100 μm, τ_{100}, indicate that strong [C ii]158 μm deficits are associated with far-IR thick (τ_{100} > 0.7, N_{H} ≈ 10^{24} cm^{-2}), warm (T_{dust} ≳ 60 K) structures where the OH 65 μm absorption is produced, most likely in circumnuclear disks/tori/cocoons. With their high L_{FIR}/M_{H2} ratios and columns, the presence of these structures is expected to give rise to strong [C ii] deficits. W_{eq}(OH65) probes the fraction of infrared luminosity arising from these compact/warm environments, which is ≳ 30−50% in sources with high W_{eq}(OH65). Sources with high W_{eq}(OH65) have surface densities of both L_{IR} and M_{H2} higher than inferred from the half-light (CO or UV/optical) radius, tracing coherent structures that represent the most buried/active stage of (circum)nuclear starburst-AGN co-evolution.

Subject headings: galaxies: ISM — galaxies: evolution — infrared: galaxies — line: formation

1. INTRODUCTION

From the first spectroscopic observations of (ultra)luminous infrared galaxies ((U)LIRGs) in the far-infrared (far-IR) domain with the Infrared Space Observatory (ISO), evidence was found that the strength of fine-structure lines (from both ions and atoms) in emission are generally anticorrelated with the depth and excitation of the molecular lines observed in absorption (Fischer et al. 1999). The most commonly observed line, the fine-structure [C ii]157.7 μm transition (hereafter [C ii]), tends to exhibit a strong deficit with respect to the far-IR luminosity in ULIRGs relative to less luminous systems (Luhman et al. 1998, 2003). In normal galaxies, the [C ii]/FIR luminosity ratio remains nearly constant (0.1 − 1%), while it decreases in galaxies with warmer far-IR colors (Malhotra et al. 2001, Díaz-Santos et al. 2013). On the other hand, studies of individual templates (Arp 220 and Mrk 231) indicated that high far-IR radiation densities associated with the nuclear regions of galaxies with [C ii] deficits, are required to account for the observed high-lying molecular absorption (González-Alfonso et al. 2004, 2008; hereafter G-A08).

The launch of the Herschel Space Observatory (Pilbratt et al. 2010) has dramatically improved the sensitivity of these measurements. Observations with the PACS spectrometer (Poglitsch et al. 2010) soon revealed that the observed deficit of [C ii] relative to the far-IR emission applies to all far-IR fine-structure lines (Fischer et al. 2010, Farrah et al. 2013, Graciá-Carpio et al. 2011, hereafter G-C11). G-C11 also showed that the deficits are better correlated with L_{FIR}/M_{gas}, than with L_{IR}, while PACS observations of three (U)LIRGs with strong line deficits, NGC 4418, Arp 220, and Mrk 231, showed deep absorption in high-lying molecular lines (González-Alfonso et al. 2012, 2014a; hereafter G-A12 and G-A14). NGC 4418 is a case in point, as it shows the highest [C ii] deficit, a moderate L_{IR} ∼ 1.5 × 10^{11} L☉ but a high L_{FIR}/M_{gas} ≈ 400
Fig. 1. — a) Infrared luminosities as a function of the H$_2$ masses for our sample of local (U)LIRGs. Symbol colors indicate values of $W_{eq}$(OH65) in four bins. The solid and dotted lines are fits to ULIRG-SMG-QSO mergers and spiral-BzK-normal galaxies, respectively, given by Daddi et al. (2010) (black) and Genzel et al. (2010) (blue). b) Histogram of $W_{eq}$(OH65) calculated between $-200$ and $+200$ km s$^{-1}$ in bins of 5 km s$^{-1}$, showing an apparent bimodal distribution with a long tail extending up to 85 km s$^{-1}$. c) Histogram of $W_{eq}$(OH65) calculated between $-300$ and $+1200$ km s$^{-1}$ (covering essentially the whole doublet), with bins of 10 km s$^{-1}$.

L$_{⊙}$/M$_{⊙}$ (G-C11), and the highest-lying H$_2$O absorption among all galaxies with full FIR spectra (G-A12).

To explore the connection between intense far-IR fields and both the highly excited molecular gas and the [C ii] deficit, we investigate the relationship between the OH $^{2}\Pi_{3/2}/^{2}\Pi_{1/2}$ transition at 65.2 µm (hereafter OH65) with $E_{low}$ ≈ 300 K, and the [C ii] line, L$_{FIR}$/M$_{gas}$, the 9.7 µm silicate absorption, and the far-IR colors, also using measurements of the OH $^{2}\Pi_{1/2}/^{2}\Pi_{1/2}$ transition at 71.2 µm (hereafter OH71, $E_{low}$ ≈ 415 K) in galaxies for which it is available. OH is a versatile molecule with high abundances in active regions including photodissociated regions (PDRs), cosmic-ray dominated regions (CRDRs), and X-ray dominated regions (XDRs) (e.g. Goicoechea & Cernicharo 2002; Goicoechea et al. 2011; Meijerink et al. 2011; González-Alfonso et al. 2013), and traces powerful galactic-scale molecular outflows in some sources (Fischer et al. 2010; Sturm et al. 2011; Spoon et al. 2013; Veilleux et al. 2013, hereafter V13; G-A14) mostly associated with large AGN luminosity fractions and luminosities. In extragalactic sources, the OH65 doublet (when detected) is absorption-dominated, indicating that the excitation of the lower $^{2}\Pi_{3/2}/^{2}\Pi_{1/2}$ level is governed by radiative (rather than collisional) processes. The OH65 pumping thus involves successive absorptions in the 119, 84, and finally in the 65 µm doublet with high A–Einstein coefficients (0.14, 0.51, and 1.2 s$^{-1}$, see the energy level diagram of OH in G-A14), thus ensuring an excellent probe of strong far-IR fields.

2. OBSERVATIONS

We have used Herschel/PACS observations of the OH65 transition in local ($z < 0.1$) galaxies, included in the Herschel guaranteed time key program SHING (PI: E. Sturm) and in three OT programs (PIs:

Collisional excitation of $^{2}\Pi_{1/2}/^{2}\Pi_{3/2}$ J = 7/2 followed by OH65 absorption is not dominant owing to the high A–Einstein coefficient of the 84 µm ($^{2}\Pi_{3/2}/^{2}\Pi_{1/2}$ 7/2–5/2) transition; efficient OH65 absorption involves a high radiation density such that it will also dominate the excitation of $^{2}\Pi_{3/2}/^{2}\Pi_{1/2}$ J = 7/2 under reasonable physical conditions.

Fig. 2. — The OH $^{2}\Pi_{3/2}/^{2}\Pi_{1/2}$ 65 µm J = 9/2 – 7/2 continuum-normalized spectra in all galaxies in the sample, with the velocity plotted relative to the rest-frame wavelength of the blue component of the doublet ($J = 9/2 – 7/2$ line at 65.1316 µm). The spectra are grouped according to the values of the equivalent width measured between −200 and +200 km s$^{-1}$ around the blue component (indicated by the solid vertical lines and listed in Table 2). The dotted vertical lines indicate the positions of the two components of the doublet. The green, red, and blue spectra are vertically shifted for clarity.
High-lying OH absorption, [C II] deficits, and extreme $L_{\text{FIR}}/M_{\text{H}_2}$ ratios in galaxies

![Graph](image)

Fig. 3.—The OH $^2\text{H}_1/\alpha$ 71 $\mu m$ $J = \frac{9}{2}-\frac{7}{2}$ continuum-normalized spectra in all 15 galaxies for which it is available, with the velocity plotted relative to the rest-frame wavelength of the blue component of the doublet at 71.171 $\mu m$. The dotted vertical lines indicate the positions of the two $\lambda$-components of the doublet, which are blended into a single spectral feature. The spectra are grouped according to the values of the equivalent width measured between $-200$ and $+600$ $\text{km s}^{-1}$ (indicated by the vertical solid lines and listed in Table 2). The red and blue spectra are vertically shifted for clarity. The position of the H$_2$O 524 – 413 line ($E_{\text{low}} \approx 400$ K) is indicated.

E. González-Alfonso; J. Fischer, S. Hailey-Dunsheath.

Table 1 lists the sample galaxies and their properties. With a total of 29 galaxies, the sample is biased towards ULIRGs (including 17 out of the 18 most luminous sources in the IRAS Revised Bright Galaxy Sample; Sanders et al. 2003), but also contains less luminous systems including Seyferts and HII galaxies. The OH71 doublet was observed in a subsample of 15 sources. The locations of the targets in the $L_{\text{IR}} - M_{\text{H}_2}$ plane, shown in Fig. 1, indicate that all except NGC 4945 (with $L_{\text{IR}} = 2.3 \times 10^{10}$ $L_\odot$) belong to the high $L_{\text{IR}}/M_{\text{H}_2}$ mode ($> 50$ $L_\odot$/M$_\odot$) as compared with normal/disk galaxies (Daddi et al. 2010, Genzel et al. 2011).

The data were reduced using the standard PACS reduction and calibration pipeline included in HIPE 6.0 and 10.0, recalibrating the data with a reference telescope spectrum obtained from observations of Neptune (G-C11). A few spectra were also reduced using HIPE 12.0. There are moderate calibration differences (typically $\approx 10\%$ and in a few sources up to $\approx 20\%$) in both line and continuum flux densities between HIPE 6.0 and 10.0 – 12.0, but the continuum-normalized spectra used to measure the OH equivalent widths were found essentially identical in the different versions. Likewise, the PACS-based ratios presented below ([C II]/FIR and f60/f100) are not sensitive to global calibration issues.

The OH71 spectra, displayed in Fig. 2, are dominated by absorption at central velocities, but some sources show detection of blue wings (e.g. Mrk 231, G-A14). Redshifted reemission by the blue component of the doublet from outflowing gas on the far side of the nucleus has the effect of decreasing the relative strength of the red component of the doublet (see asymmetrical doublets in Fig. 2). We measured the equivalent width ($W_{\text{eq}}$) of the OH $^3\Pi_2/1 J = \frac{9}{2}-\frac{7}{2}$ doublet between $-200$ and $+200$ $\text{km s}^{-1}$ around the blue component of the doublet, and between $-300$ and $+1200$ $\text{km s}^{-1}$, covering essentially the whole doublet (Table 2 and Fig. 2). This work is focussed on the structures traced by the excited OH at central velocities, so hereafter we primarily study $W_{\text{eq}}$ (OH65) in the $-200$ and $+200$ $\text{km s}^{-1}$ velocity range while the outflowing gas component will be treated in a separate study. The OH71 spectra, shown in Fig. 3, also indicate peak absorption at central velocities.

Most sources in the sample are unresolved with the PACS $9'' \times 9''$ spatial resolution, and thus $W_{\text{eq}}$(OH65) measured from the central PACS spaxel applies to the whole galaxy. For resolved sources (M82, Arp 299a, NGC 1068, NGC 253, and NGC 4945), $W_{\text{eq}}$(OH65) was measured from the 25-spaxel combined spectra, covering a field of view (FoV) of $47'' \times 47''$. Likewise, $W_{\text{eq}}$(OH71), the flux of the [C II] line, the FIR, and the flux densities at 60 and 100 $\mu m$ (f60 and f100) were all integrated over the total PACS FoV. Even for the extended sources, the PACS f60 and f100 agree to within 20% with the 60 and 100 $\mu m$ IRAS flux densities (Sanders et al. 2003, Surace et al. 2004), indicating that PACS recovers the bulk of the galaxy far-IR continuum emission and the $W_{\text{eq}}$(OH) represent global values. The IRAS 25 $\mu m$ flux densities (f25) are then also used in our analysis. All PACS-measured [C II] line fluxes agree with the ISO-LWS values or upper limits (Brauher et al. 2008) within 40%, and most of them within 25%. Most values of $M_{\text{H}_2}$ were estimated from the spatially-integrated CO(1-0) luminosities from previous studies (Table 1) by using a conversion factor $\alpha_{\text{CO}}$ decreasing with $f60$ and $f100$ (G-C11). Since the sources in our sample are warm, $\alpha_{\text{CO}} = 0.8$ was mostly applied (Table 1); only UGC 5101, NGC 7469, and especially NGC 4945 have significantly higher $\alpha_{\text{CO}} > 1.2$.

3. RESULTS

$W_{\text{eq}}$(OH65) shows a bimodal distribution (Fig. 1) with peaks at $< 5$ and $20 – 30$ $\text{km s}^{-1}$ and a long tail extending up to 85 $\text{km s}^{-1}$. A Pearson $\chi^2$-test comparing the observed distribution for central velocities in Fig. 1 with a flat distribution gives a $P$-value $\approx 0.01$, which remains low (0.03) when the full doublet is considered (Fig. 1). While most ULIRGs are strong in OH65, some of them (IRAS 9022-3615, UGC 5101, IRAS F10565+2448) are weak and, conversely, there are three sources with moderate luminosities that are strong in OH65 (NGC 4418, Zw 049.057, and IRAS F11506-3851). Nevertheless, sources with high OH65 absorption have, on average, higher infrared luminosities for fixed $M_{\text{H}_2}$ (Fig. 1). Among galaxies with low $W_{\text{eq}}$(OH65) $< 10$ $\text{km s}^{-1}$, some still have clear detections of OH65 (IRAS F10565+2448, UGC 5101, IRAS 9022-3615, NGC 4945, NGC 253), but no trace of OH65 absorption is found in others (M 82, NGC 1068, NGC 7469). OH71 is detected in the 10 sources with $W_{\text{eq}}$(OH65) $> 20$ $\text{km s}^{-1}$ (Fig. 2), Table 2 and is undetected in the remaining five sources where OH65 is weak or undetected.

Figure 4 shows that $W_{\text{eq}}$(OH65) and [C II]/FIR are anticorrelated, with data points mainly concentrated in the upper-left and lower-right quadrants. The [C II]/FIR value that separates the two regimes, $\approx 10^{-3}$, is sim-
Fig. 4.— Equivalent width of the OH $\Pi$ $3/2$ $J = \frac{3}{2} - \frac{1}{2}$ line at 65.132 $\mu$m (the blue component of the 65 $\mu$m doublet) between $-200$ and $+200$ km s$^{-1}$ as a function of (a) the [C II] 158 $\mu$m line to FIR ratio, (b) the far-IR luminosity per unit gas mass, (c) the apparent optical depth of the silicate absorption at 9.7 $\mu$m (from Spoon et al. 2007), (d) the 25-to-60 $\mu$m color, and (e) the 60-to-100 $\mu$m color. Abbreviated source names are indicated. Red, green, blue, light-blue, and black colors indicate H II, LINER, Seyfert-1, Seyfert-2, and unclassified optical spectral types, respectively (from Veilleux et al. 1995, 1999; Vérón-Cetty & Vérón 2006; Rupke et al. 2005; García-Marín et al. 2006; Kim et al. 1998, V09, or NED/SIMBAD). Circles and squares indicate sources with fractional AGN contribution to the bolometric luminosity of $\alpha_{\text{AGN}} \geq 50\%$ and $<50\%$, respectively, as derived from $f_{15}/f_{30}$ (V09). Pearson $\chi^2$ independence-tests give chance probabilities $P = 0.012 - 0.0 - 0.043 - 0.74 - 0.025$ for panels a-b-c-d-e, respectively.

Fig. 4b. A discontinuity in OH65 absorption is found at $L_{\text{FIR}}/M_{\text{H}_2} \sim 100 \, L_{\odot}/M_{\odot}$, similar to the one that separates mergers from normal galaxies in the [C II]/FIR-$L_{\text{FIR}}/M_{\text{gas}}$ plane (G-C11). It is worth noting that $M_{\text{H}_2}$ is the most uncertain value in Fig. 4; however, Fig. 5 shows that the correlation remains when using the CO (1-0) luminosity directly, and that [C II]/FIR shows a marked anticorrelation with $L_{\text{FIR}}/L_{\text{CO}}$. Figure 4c relates $W_{\text{eq}}$(OH65) and the apparent optical depth of the 9.7 $\mu$m silicate feature (Spoon et al. 2007). With the exception of the nearly edge-on galaxy NGC 4945, sources with weak $W_{\text{eq}}$(OH65) $<10$ km s$^{-1}$ have moderate $\tau_{9.7} \lesssim 1.7$, suggesting that a significant fraction of the silicate absorption in the most obscured ($\tau_{9.7} \gtrsim 2$) objects is produced by the material responsible for the OH65 absorption. This is consistent with the

\[
\text{Fig. 4.} \quad \text{Equivalent width of the OH $\Pi$ $3/2$ $J = \frac{3}{2} - \frac{1}{2}$ line at 65.132 $\mu$m (the blue component of the 65 $\mu$m doublet) between $-200$ and $+200$ km s$^{-1}$ as a function of (a) the [C II] 158 $\mu$m line to FIR ratio, (b) the far-IR luminosity per unit gas mass, (c) the apparent optical depth of the silicate absorption at 9.7 $\mu$m (from Spoon et al. 2007), (d) the 25-to-60 $\mu$m color, and (e) the 60-to-100 $\mu$m color. Abbreviated source names are indicated. Red, green, blue, light-blue, and black colors indicate H II, LINER, Seyfert-1, Seyfert-2, and unclassified optical spectral types, respectively (from Veilleux et al. 1995, 1999; Vérón-Cetty & Vérón 2006; Rupke et al. 2005; García-Marín et al. 2006; Kim et al. 1998, V09, or NED/SIMBAD). Circles and squares indicate sources with fractional AGN contribution to the bolometric luminosity of $\alpha_{\text{AGN}} \geq 50\%$ and $<50\%$, respectively, as derived from $f_{15}/f_{30}$ (V09). Pearson $\chi^2$ independence-tests give chance probabilities $P = 0.012 - 0.0 - 0.043 - 0.74 - 0.025$ for panels a-b-c-d-e, respectively.

Fig. 4b. A discontinuity in OH65 absorption is found at $L_{\text{FIR}}/M_{\text{H}_2} \sim 100 \, L_{\odot}/M_{\odot}$, similar to the one that separates mergers from normal galaxies in the [C II]/FIR-$L_{\text{FIR}}/M_{\text{gas}}$ plane (G-C11). It is worth noting that $M_{\text{H}_2}$ is the most uncertain value in Fig. 4; however, Fig. 5 shows that the correlation remains when using the CO (1-0) luminosity directly, and that [C II]/FIR shows a marked anticorrelation with $L_{\text{FIR}}/L_{\text{CO}}$. Figure 4c relates $W_{\text{eq}}$(OH65) and the apparent optical depth of the 9.7 $\mu$m silicate feature (Spoon et al. 2007). With the exception of the nearly edge-on galaxy NGC 4945, sources with weak $W_{\text{eq}}$(OH65) $<10$ km s$^{-1}$ have moderate $\tau_{9.7} \lesssim 1.7$, suggesting that a significant fraction of the silicate absorption in the most obscured ($\tau_{9.7} \gtrsim 2$) objects is produced by the material responsible for the OH65 absorption. This is consistent with the

\[
\text{We note that M 82, with a global $L_{\text{FIR}}/M_{\text{H}_2} \sim 80 \, L_{\odot}/M_{\odot}$, has a CO(1-0) luminosity of half the total value within the PACS FoV (Weiß et al. 2007; see also Table 1), and hence $L_{\text{FIR}}/M_{\text{H}_2} \sim 160 \, L_{\odot}/M_{\odot}$ in this region. Nevertheless, inhomogeneities are also expected in unresolved sources (§4.2 below), and thus we use the global values of $M_{\text{H}_2}$ in Fig. 4b.}

\[
\text{The FoV was centered in the Arp 299 A1 nucleus (IC 694, Aalto et al. 1997) where the peak OH65 absorption is found, but includes extended [C II] and CO emitting regions.}
\]
High-lying OH absorption, [C II] deficits, and extreme $L_{\text{FIR}}/M_{\text{H}_2}$ ratios in galaxies

| Galaxy name | $D$ (Mpc) | $L_{\text{FIR}}$ (10$^{11}$ $L_{\odot}$) | $L_{\text{CO}}$ (10$^{9}$ $L_{\odot}$) | $\alpha_{\text{CO}}$ | $M_{\text{H}_2}$ (10$^8$ $M_{\odot}$) | $L_{\text{FIR}}/M_{\text{H}_2}$ (10$^2$ $L_{\odot}/M_{\odot}$) | $r_{9.7}$ (f/250) | f/600 | f/1000 | R$_{\text{CO}}$ |
|-------------|-----------|--------------------------------------|---------------------------------|-----------------|-------------------------------|---------------------------------|-----------------|-------|--------|--------|
| IRAS 07251-0248 | 398.0 | 22.00 | 5.35 | 0.803 | 4.30 | 4.82 | 0.20 | 0.12 | Sp |
| IRAS 09022-3615 | 268.0 | 19.20 | 26.56 | 0.803 | 21.33 | 0.70 | 0.11 | 0.11 | GC |
| M 82 | 3.9 | 0.68 | 0.75 | 0.803 | 0.60 | 0.79 | 0.10 | 0.22 | 0.94 | Wb05a |
| IRAS 13120-5453 | 136.0 | 18.60 | | | | | | | |
| NGC 253 | 3.3 | 0.31 | 0.66 | 0.929 | 0.61 | 0.38 | 0.10 | 0.15 | 0.80 | He97b |
| NGC 1068 | 18.0 | 3.18 | 4.06 | 0.896 | 3.64 | 0.36 | 0.50 | 0.27 | 0.66 | Sc83c |
| IRAS 05189-2524 | 186.0 | 13.80 | 3.90 | 0.803 | 3.13 | 3.20 | 0.43 | 0.24 | 1.23 | Pa12 |
| IRAS F08572+3915 | 261.0 | 13.20 | 1.56 | 0.803 | 1.25 | 10.06 | 3.99 | 0.24 | 1.74 | So97d |
| UGC 5101 | 173.0 | 9.91 | 5.44 | 1.650 | 8.97 | 0.86 | 1.68 | 0.08 | 1.72 | So97d |
| IRAS F16056+2448 | 193.0 | 11.40 | 6.79 | 0.803 | 5.45 | 1.87 | 0.85 | 0.09 | 0.91 | So97d |
| Arp 299a | 46.5 | 7.41 | 3.30 | 0.803 | 2.65 | 1.99 | 0.20 | 0.18 | Ca99 |
| IRAS F11506-3851 | 39.0 | 3.29 | 3.50 | 0.954 | 1.32 | 1.45 | 0.06 | 0.16 | 0.76 | Mi90e |
| IRAS F12112+0305 | 333.0 | 20.40 | 16.25 | 0.803 | 13.06 | 1.19 | 1.14 | 0.09 | 0.88 | Ch90 |
| NGC 4418 | 35.9 | 1.50 | 0.41 | 0.803 | 0.33 | 3.65 | 0.40 | 0.22 | 1.38 | Pa12 |
| Mkr 231 | 186.0 | 33.70 | 8.84 | 0.803 | 7.10 | 3.46 | 0.65 | 0.25 | 1.25 | So97d |
| NGC 4945 | 3.4 | 0.23 | 0.48 | 2.754 | 1.32 | 0.14 | 2.79 | 0.07 | 0.50 | He94f |
| Mrk 273 | 156.0 | 14.50 | 6.11 | 0.803 | 4.91 | 2.71 | 1.90 | 0.10 | 0.22 | Sc83c |
| IRAS F14344-1476 | 376.0 | 20.90 | 15.23 | 0.803 | 12.24 | 1.72 | 2.10 | 0.07 | 0.24 | Sc83c |
| IRAS F14378-3651 | 304.0 | 14.60 | 5.18 | 0.803 | 4.16 | 2.98 | 1.47 | 0.10 | 0.18 | Mio9e |
| Zw 049.057 | 58.0 | 1.76 | 0.97 | 1.116 | 1.09 | 1.24 | 0.10 | 0.10 | 0.87 | Sc83c |
| IRAS F15250+3609 | 245.0 | 10.60 | 1.88 | 0.803 | 1.51 | 5.97 | 3.30 | 0.18 | 1.34 | Ch90 |
| Arp 220 | 79.4 | 15.20 | 8.17 | 0.803 | 6.56 | 2.56 | 2.83 | 0.06 | 0.99 | Sc83c |
| NGC 0240 | 106.0 | 6.98 | 9.16 | 0.803 | 7.36 | 0.73 | 1.52 | 0.15 | 0.89 | So97d |
| IRAS F17207-0014 | 187.0 | 25.00 | 13.12 | 0.803 | 10.54 | 2.53 | 1.68 | 0.04 | 1.01 | Pa12 |
| IRAS F19297-0406 | 383.0 | 24.60 | 11.13 | 0.803 | 8.94 | 2.44 | 1.43 | 0.09 | 0.98 | So97d |
| IRAS F20551-4250 | 185.0 | 10.20 | 6.10 | 0.803 | 4.90 | 1.84 | 2.69 | 0.14 | 1.28 | Mio9e |
| IRAS F22491-1808 | 343.0 | 13.20 | 3.12 | 0.803 | 2.51 | 5.22 | 1.23 | 0.10 | 1.28 | Ch90 |
| NGC 7469 | 64.5 | 3.52 | 2.98 | 1.697 | 5.06 | 4.38 | 0.37 | 0.21 | 0.74 | Pa12 |
| IRAS F23463+3604 | 281.0 | 14.30 | 9.61 | 0.803 | 7.72 | 1.59 | 1.69 | 0.12 | 1.01 | So97d |

Note: (1) Galaxy name; (2) Distance to the galaxy; (3) Dust located in the host galaxy; (4) $\alpha_{\text{CO}}$ luminosity from previous studies (col 12); $L_{\text{CO}}$ (1-0) fluxes corrected for extinction; (5) Conversion factor; $L_{\text{H}_2} = \alpha_{\text{CO}} \times L_{\text{CO}}$. $\alpha_{\text{CO}}$ increases with decreasing $L_{\text{FIR}}/M_{\text{H}_2}$; (6) Far-IR luminosity (40–500 $\mu$m) to $H_2$ mass ratio; (7) Optical depth of the silicate absorption at 9.7 $\mu$m; (8) Continuum 25- to 60- $\mu$m flux density; (9) 60- to 100- $\mu$m flux density ratio; (10) 60- to 100- $\mu$m flux density ratio; (11) Reference for $L_{\text{CO}}$ and $\alpha_{\text{CO}}$; (12) Unpublished CO data taken with APEX, and assuming $L_{\text{CO,2CO}}/L_{\text{CO,1CO}} = 0.7$; (13) Apparent optical depth of the silicate absorption at 9.7 $\mu$m; (14) Far-IR (40–500 $\mu$m) to $H_2$ mass ratio; (15) Far-IR (40–500 $\mu$m) to $H_2$ mass ratio.

Finding by [Goulding et al. (2012)] that the high-lying OH65 doublet. High OH65 absorption, however, does not guarantee that there is also accompanied by high OH excitation as measured by the high-lying OH65 doublet.
4. RADIATIVE TRANSFER MODELS

To characterize the overall physical conditions derived from the present observations, and to interpret the trends shown in Fig. 4, phenomenological radiative transfer models have been generated (G-A14 and references therein). The model sources are spherical and assume uniform physical conditions, parameterized by the dust temperature ($T_{\text{dust}}$), the continuum optical depth at 100 $\mu$m ($\tau_{100}$), the gas temperature and density ($T_{\text{gas}}$ and $n_{\text{H}}$), the OH and C$^+$ column densities ($N_{\text{OH}}$ and $N_{\text{C}^+}$), and the velocity dispersion ($\Delta V$).

4.1. Single-component models

Initially, we naively assume that the OH65 absorption and [C II] emission arise from the same region and that the covering factor of the continuum by the excited OH is unity; these assumptions represent only a first approach to the interpretation of the observations but still enable us to extract some general conclusions. To decrease the number of free parameters, we approximate some of them according to previous chemical or radiative transfer models: (i) The gas column density ($N_{\text{H}}$) is directly related to $\tau_{100}$ by adopting a standard gas-to-dust ratio by mass of 100 and a dust mass opacity coefficient at 100 $\mu$m of $\kappa_{100} = 44.5$ cm$^2$/g$^{-1}$; $N_{\text{H}} = 1.3 \times 10^4 \tau_{100}$ cm$^{-2}$ (González-Alfonso et al. 2014). (ii) $N_{\text{OH}}$ is fixed by assuming an OH abundance relative to H of $2.5 \times 10^{-6}$ (G-A12, G-A14). (iii) We assume that the [C II] emission is dominated by PDRs (Farrah et al. 2013) and $N_{\text{C}^+}$ is estimated on the basis of previous models (e.g. Abel et al. 2009, Kaufman et al. 1999, G-C11). For a single PDR, $N_{\text{C}^+} \sim 10^{18}$ cm$^{-2}$ is typically inferred for high incident far-UV radiation intensity $G_0$, and $T_{\text{dust}} \sim 10 \times G_0^{0.2}$ K characterizes the warm dust in PDRs (Hollenbach et al. 1991). We set $X_{\text{C}^+} = (2 - 6) \times 10^{-5}$ for $T_{\text{dust}} = 30 - 90$ K to approximately account for these results and calculate $N_{\text{C}^+}$ based on $N_{\text{H}}(\tau_{100})$. (iv) We adopt $n_{\text{H}} = 5 \times 10^4$ cm$^{-3}$ and $T_{\text{gas}} = 150$ K, i.e., high density conditions appropriate for the circumnuclear regions of (U)LIRGs, ensuring that the [C II] transition is thermalized and emits at nearly the maximum emission per C$^+$ ion (Tielens & Hollenbach 1985). The OH65 transition is pumped through absorption of far-IR photons and it is thus not sensitive to $n_{\text{H}}$ and $T_{\text{gas}}$ (G-A08). (v) $\Delta V = 100$ km s$^{-1}$ in all models, describing the velocity dispersion along a characteristic line of sight. This has no effect in case of optically thin lines. As we show below, however, high columns and thus many overlapping (shadowing) regions characterize the environments where the OH65 absorption is
The deficit in [C II] is produced because the cooling line cannot track the increase of $T_{\text{dust}}(G_0)$ (e.g. Kaufman et al. 1999). The region where carbon is ionized, and thus the total number of emitting C$^+$ ions, is restricted to $\tau_{\text{FUV}} \sim 1$ regardless of $G_0$, but the increase of $G_0$ increases the FIR continuum -thus lowering [C II]/FIR. Nevertheless, the presence of a [C II] deficit is not critically sensitive to the physical details of the PDRs and can be mostly understood in terms of the global $L_{\text{FIR}}/M_{\text{H}_2}$: a strong upper limit on the [C II] emission is given by (G-A08)

$$ \frac{L_{\text{[C II]}}}{L_{\text{FIR}}} < 8.3 \times 10^{-4} \times \left( \frac{X_{\text{C}^+}}{4 \times 10^{-5}} \right) \times \left( \frac{300 L_{\odot}/M_{\odot}}{L_{\text{FIR}}/M_{\text{H}_2}} \right), $$

which assumes optically thin [C II] emission with $T_{\text{ex}} >> E_{\text{upper}} = 91$ K and up to 1/3 of all carbon ionized (for solar metallicities), which is high for molecular regions. In the optically thick regime, line saturation and extinction effects maintain a low [C II]/FIR even in case of high $M_{\text{H}_2}$. Equation (1) directly links the [C II]/FIR ratio with $L_{\text{FIR}}/M_{\text{H}_2}$, and shows that strong [C II] deficits are unavoidable in galaxies with high $L_{\text{FIR}}/M_{\text{H}_2}$, i.e. those that are also strong in OH65 (Figs. 5a-b).

The single component models, however, cannot account for the observed $f_{25}/f_{60}$ with the $T_{\text{dust}}$ and $\tau_{100}$ inferred from the other panels of Fig. 4. Indeed, the main consequence of assuming coexistent OH65 absorption and [C II] emission, i.e. modeling only one OH transition with a fixed covering factor of unity, is the underestimation of $T_{\text{dust}}$ and $\tau_{100}$ (e.g. see multitransition, composite models for NGC 4418, Arp 220, and Mrk 231 in G-A12 and G-A14). Extended and optically thin regions of (U)LIRGs are emitters of both [C II] and 65 $\mu$m continuum (Diaz-Santos et al. 2014), and will dilute both the circumnuclear OH65 absorption and the [C II] deficit.

4.2. The OH71/OH65 ratio and Composite models

The ratio of the OH71 to the OH65 doublet absorption enables a better estimate of $T_{\text{dust}}$ and $\tau_{100}$, inde-

---

**Figure 5.** a) Equivalent width of the OH65 transition between $-200$ and $+200$ km s$^{-1}$ around the blue component of the doublet, and (b) the [C II]158 $\mu$m line to FIR ratio, as a function of the the far-IR to CO (1-0) luminosity ratio in our galaxy sample. Symbol colors and shapes have the same meaning as in Fig. 4.
Fig. 6.— Same as Fig. 4 with results from single-component (§4.1, grey symbols and lines) and composite (§4.2, blue and green) radiative transfer models overlaid. The single-component models are characterized by the dust temperature, $T_{\text{dust}}$, and the continuum optical depth at 100 $\mu$m, $\tau_{100}$. Solid grey lines connect results with constant $\tau_{100}$ (indicated in magenta in panel b), and dashed grey lines connect results with constant $T_{\text{dust}}$ (indicated with grey numbers, in K). The composite models have three components: two optically thin components with $T_{\text{dust}} = 65$ and 30 K, generating the bulk of the [C ii] 158 $\mu$m emission but negligible OH 65 $\mu$m absorption, and one optically thick ($\tau_{100} = 1$) and very warm ($T_{\text{dust}} = 95$ K for model $M_1$, blue symbols, and $T_{\text{dust}} = 60$ K for model $M_2$, green symbols) component, responsible for the OH 65 $\mu$m absorption. The mix of components is described by the parameters $\beta_{65-30} = L_{65}/(L_{65} + L_{30})$ and $\beta_{\text{thick}} = L_{\text{thick}}/L_{\text{total}}$ (see §4.2). $\beta_{65-30} = 0.75$ and 0.25 for models $M_1$ and $M_2$, respectively. Along the sequence for both blue and green lines, $\beta_{\text{thick}}$ is varied from 0 to 1 by intervals of 0.1, with $\beta_{\text{thick}} = 1$ indicated with a red circle.

Fig. 7.— a) Modeled $W_{\text{eq}}$(OH71)/$W_{\text{eq}}$(OH65) as a function of $T_{\text{dust}}$ for $\tau_{100} \geq 0.4$, together with the ratios measured for the 10 sources where OH71 is detected, indicating $T_{\text{dust}} \geq 60$ K. b) Model-derived $L_{\text{IR}}$ versus $H_2$ mass in the surface density plane. The grey parallelogram identifies the region favored by the composite models ($C_{\text{thick}}$, §4.2) with $\tau_{100} = 0.5 - 5$ and $T_{\text{dust}} \geq 60$ K. Solid, dashed, and dotted lines show the fits to (U)LIRGs/mergers/SMGs given in [Daddi et al. 2010], [García-Burillo et al. 2012], and [Genzel et al. 2010], respectively.
High-lying OH absorption, [C II] deficits, and extreme \( L_{\text{FIR}}/M_{\text{H}_2} \) ratios in galaxies

...dependent of the covering factor of the continuum by the excited OH. The modeled ratio of the total doublet equivalent widths, \( W_{\text{eq}}(\text{OH}71)/W_{\text{eq}}(\text{OH}65) \), is plotted as a function of \( T_{\text{dust}} \) (for \( \tau_{100} \geq 0.4 \)) in Fig. 4, and compared with the measured ratios. The observed minimum \( W_{\text{eq}}(\text{OH}71)/W_{\text{eq}}(\text{OH}65) \) \( \approx 0.2 \) ratio indicates \( T_{\text{dust}} \) \( \geq 60 \) K, significantly higher than inferred in [3,4]. This lower limit is still very conservative for hot subcomponents in some sources, where higher-lying transitions of OH (at 53.0 and 56 \( \mu \)m) and \( H_2 \)O indicate \( T_{\text{dust}} \) \( \geq 90 \) K (G-A12; G-A14; Falstad et al., in preparation). In addition, unless the dust is very warm, the measured ratios in Fig. 7 favor \( \tau_{100} \leq 0.7 \), equivalent to \( N_\text{H} \leq 10^{22} \) cm\(^{-2}\).

To account for the trends in Fig. 4 together with the high \( T_{\text{dust}} \) inferred from \( W_{\text{eq}}(\text{OH}71)/W_{\text{eq}}(\text{OH}65) \) in many of the sources, we relax the assumptions in [3,4], and use composite models. It is assumed here that the bulk of the sources can be described by an optically thick very warm component (\( C_{\text{thick}} \)) that accounts for the OH65 absorption, and a colder, optically thin (presumably more extended) component (\( C_{\text{thin}} \)) that accounts for the bulk of the [C II] emission but gives negligible OH65 absorption. The physical conditions are: (i) \( C_{\text{thick}} \): two models with \( T_{\text{dust}} = 95 \) and 60 K are considered (hereafter \( M_1 \) and \( M_2 \), respectively); in both, a nominal \( \tau_{100} = 1 \) is used. (ii) \( C_{\text{thin}} \): this is itself a model composed of two optically thin dust components with \( T_{\text{dust}} = 65 \) and 30 K, consistent with the \( G_0 \)-range derived by Farrah et al. (2013) and with results independent of \( \tau_{100} \) for values \( \leq 0.1 \). The mix of these two components is governed by \( \beta_{65-30} = L_{\text{IR}}^{65}/(L_{\text{IR}}^{30} + L_{\text{IR}}^{65}) \), i.e., the fraction of the optically thin IR luminosity arising from the warm 65 K component, which is fixed to 0.75 and 0.25 for \( M_1 \) and \( M_2 \), respectively. The values of \( T_{\text{dust}} \) and \( \beta_{65-30} \) for \( C_{\text{thin}} \) are chosen to bracket the observed \( f25/f60 \) and \( f60/f100 \) colors for sources that have weak—but measurable—OH65 absorption. We adopt here a typical \( N_\text{H} \leq 10^{23} \) cm\(^{-2}\) to simulate the [C II] emission (e.g., Malhotra et al. 2001; Parkin et al. 2013). The mix of \( C_{\text{thick}} \) and \( C_{\text{thin}} \) is described by the only free parameter \( \beta_{\text{thick}} = T_{\text{dust}}^\text{thick} / T_{\text{dust}}^\text{total} \), the fraction of the total IR luminosity arising from the \( C_{\text{thick}} \) component.

Results for these models are shown in Fig. 9 blue/green curves and circles correspond to models \( M_1/M_2 \), respectively. The circles on these curves represent a sequence of models where \( \beta_{\text{thick}} \) is varied from 0 to 1 in intervals of 0.1, with \( \beta_{\text{thick}} = 1 \) indicated with a red circle. According to this approach, the source position within the different observational planes is interpreted in terms of the overall energetic relevance of the optically thick, very warm structure (\( \beta_{\text{thick}} \)). For sources with \( W_{\text{eq}}(\text{OH}65) \leq 6 \) km s\(^{-1}\), \( \beta_{\text{thick}} \leq 10\% \), while sources with \( W_{\text{eq}}(\text{OH}65) \geq 20 \) km s\(^{-1}\) are characterized by \( \beta_{\text{thick}} \geq 30 - 50\% \) for \( M_1/M_2 \), respectively. In the latter objects, a fraction of the optically thick emission is expected to be reemission by dust heated by the optically thick component [Soifer et al. 1999; González-Alfonso et al. 2004], and thus \( C_{\text{thick}} \) most likely dominates the output of these galaxies. The modeled curves are consistent with the steep increase of \( W_{\text{eq}}(\text{OH}65) \) with decreasing [C II]/FIR below \( \sim 10^{-3} \), and with increasing \( L_{\text{FIR}}/M_{\text{H}_2} \) above \( \approx 100 \text{ L}_\odot/\text{M}_\odot \). The [C II] emission is still underpredicted in some sources, which may suggest significant contributions by (diffuse) ionized gas.

5. CONCLUSIONS

Absorption in high-lying transitions of molecules with high dipolar moment and level spacing (i.e., mostly light hydrides), represented by OH65 and OH71, has been shown here to be strong in most local ULIRGs (70%) and in several LIRGs. Despite the high columns inferred in galaxies with high \( W_{\text{eq}}(\text{OH}) \), their low [C II]/FIR and low \( L_{\text{CO}}/L_{\text{FIR}} \) suggest that both are associated with a “deficit” in \( M_{\text{H}_2} \) relative to the far-IR continuum emission, accompanied by additional effects such as significant optical depth in the [C II] line and high excitation of CO. High columns and \( T_{\text{dust}} \) but low \( M_{\text{H}_2}/L_{\text{FIR}} \) are indicative of high radiation densities and small volumes, with the high columns of gas and dust confined to small regions around the bright, buried illuminating source(s) (nearly) dominating the galaxy output. The relationship between the model parameterization used here and that in terms of the dominant exciting source (AGN or starburst), volume and column densities, and ionization parameter (Abel et al. 2009; Fischer et al. 2014, G-C11), as well as the origin of the deficit in fine-structure lines other than [C II], will be explored in future work.

The inferred column densities associated with \( W_{\text{eq}}(\text{OH}65) \geq 20 \) km s\(^{-1}\), \( N_\text{H} \geq 10^{23} \) cm\(^{-2}\), are higher than those derived from the silicate strength at 9.7 \( \mu \)m. Models by Sirocky et al. (2008) indicate that the observed \( \tau_{\nu, \text{7}} \leq 4 \) can be explained with \( \tau_{\nu, \text{7}} \leq 300 \) (\( N_\text{H} \leq 5 \times 10^{23} \) cm\(^{-2}\)). Since the OH65 regions/structure will block all the inner mid-IR emission passing through it, the observed mid-IR emission and associated silicate absorption are biased toward relatively unabsorbed mid-IR emitting regions. Likewise, several sources in the sample show mid-IR AGN signatures as [Ne v] emission (IRAS 05189-2524 and Mrk 273; Armus et al. 2007; V09) or an optical Broad Line Region (e.g., Mrk 231), and our direct view of this emission indicates tiny absorbing columns in comparison with those inferred from OH65. If the OH65 absorption is generated in a circumnuclear disk/torus/cocoon, either the combination of scale height/inclination, and/or clumpiness are required to account for the apparent decrease of extinction with decreasing wavelength. In sources with high contrast in mid-to-far infrared extinction, either extreme clumpiness or important inclination effects are necessarily involved. In other sources, extinction of the mid-IR emission by the OH65 structure is consistent with their low \( f25/f60 \) ratio. Though these structures are variably clumpy, the OH65 bimodality (Fig. 11) suggests that they are coherent and quickly formed, and provide an effective way to obscure the signposts of AGNs at shorter wavelengths in some sources.

In the direction of the warm, optically thick re-
gions/structure where the OH$65$ absorption is produced, the surface density of both $L_{\text{IR}}$ and H$_{2}$ mass are significantly higher than the average values previously estimated for the areas within the half-light radius (from CO or optical/UV). The grey parallelogram in Fig. (7) indicates the location of the $C_{\text{thick}}$ component for the ten sources where both OH$65$ and OH$71$ are detected: $\Sigma_{\text{H}_2} \sim 10^{3.8} - 10^{4.7} M_{\odot} \text{pc}^{-2}$ ($\tau_{1000} \sim 0.5 - 5$) and $\Sigma_{\text{IR}} \gtrsim 10^{12.8} L_{\odot} \text{kpc}^{-2}$ ($T_{\text{dust}} \geq 60$ K). The latter high fluxes are consistent with previous estimates using sizes derived from radio emission and strengthen the role of radiation pressure support (Scoville 2004, Thompson et al. 2003, see their Fig. 3). For starburst-dominated sources and using a $\text{Chabrier (2003)}$ IMF, the corresponding SFRs are $\Sigma_{\text{SFR}} \gtrsim 10^{2.8} M_{\odot} \text{yr}^{-1} \text{kpc}^{-2}$. For hot subcomponents in some sources like the $C_{\text{core}}$ component of NGC 4418, $\Sigma_{\text{IR}} \gtrsim 10^{14} L_{\odot} \text{kpc}^{-2}$ and $\tau_{1000} \gtrsim 8$ ($N_{\text{H}_2} \gtrsim 10^{25} \text{cm}^{-2}$) on spatial scales of $\sim 20$ pc (G-A12, Sakamoto et al. 2013, Costagliola et al. 2013, Varenius et al. 2014).

The solid, dashed, and dotted black lines in Fig. (7) are extrapolations of the fits found in previous studies for subsamples of (U)LIRGs/mergers/SMGs. A pure SF scenario involves the shadowing of $\gtrsim 70$ (for $\tau_{1000} \gtrsim 1$) star-forming regions, each with $A_V \sim 10$ mag and $G_0 \gtrsim 10^4$, on spatial scales of a few $\times (10 - 100)$ pc; on spatial scales of a few parsecs, there is apparently no analog star-forming region close to the Galactic center.8 The implied gas consumption timescales are $\tau_{\text{gas}} = (25 - 3.5) \times \tau_{1000}$ Myr for $T_{\text{dust}} = 60 - 95$ K, comparable to those estimated for extreme sources exhibiting powerful OH outflows driven by buried AGNs (Sturm et al. 2011). On the other hand, 21 sources in our sample were analyzed in the OH $119$ $\mu$m transition by V13, and 12 (with $W_{\text{eq}}(\text{OH}65) > 10$ km s$^{-1}$) were found to have $|v_{\text{LSR}}| > 500$ km s$^{-1}$ (the velocity below which 84% of the absorption takes place), most likely indicative of significant AGN feedback. The OH$65$-(U)LIRG phase may thus represent the starburst-AGN co-evolution phase in its shortlived most buried/active stage.

PACS has been developed by a consortium of institutes led by MPE (Germany) and including UVIE (Austria); KU Leuven, CSL, IMEC (Belgium); CEA, LAM (France); MPIA (Germany); INAF/FASI/OAA/OAP/OAT, LENS, SISSA (Italy); IAC (Spain). This development has been supported by the funding agencies BMVIT (Austria), ESA-PRODEX (Belgium), CEA/CNES (France), DLR (Germany), ASI/INAF (Italy), and CICYT/MCYT (Spain). E.G-A is a Research Associate at the Harvard-Smithsonian CfA, and thanks the Spanish Ministerio de Economía y Competitividad for support under projects AYA2010-21697-C05-01 and FIS2012-39162-C06-01. E.G-A and H.A.S acknowledge partial support from NASA grants NNX14AJ61G, Basic research in IR astronomy at NRL is funded by the US-ONR; J.F. acknowledges support from NSFC/JPL subcontracts 138907 and 1456609. S.V. and M.M. acknowledge support from the programs of NSFC (JPL 1455432; H.A.S acknowledges NASA grant NNX14AJ61G). This research has made use of NASA’s Astrophysics Data System and of GILDAS (http://www.iram.fr/IRAMFR/GILDAS).

Facilities: Herschel Space Observatory (PACS).

REFERENCES

Aalto, S., Radford, S. J. E., Scoville, N. Z., & Sargent, A. I. 1997, ApJ, 475, L107
Abel, N. P., Dudley, C., Fischer, J., Satyapal, S., & van Hoof, P. A. M. 2009, ApJ, 701, 1147
Armus, L., Charmandaris, V., Bernard-Salas, J., et al. 2007, ApJ, 656, 148
Brauher, J. R., Dale, D. A., & Helou, G. 2008, ApJS, 178, 280
Burlon, D., Ajello, M., Greiner, J., Comastri, A., Merloni, A., & Gehrels, N. ApJ, 728, 58
Casoli, F., Willaime, M.-C., Viallefond, F., & Gerin, M. 1999, A&A, 346, 663
Chabrier, G. 2003, ApJ, 586, L133
Chung, A., Narayanan, G., Yun, M. S., Heyer, M., & Erickson, N. R. 2009, AJ, 138, 858
Costagliola, F., Aalto, S., Sakamoto, K., Martin, S., Beswick, R., Muller, S., & Klockner, H.-R. 2013, A&A, 556, A60
Daddi, E., Elbaz, D., Walter, F., et al. 2010, ApJ, 714, L118
Díaz-Santos, T., Armus, L., Charmandaris, V., et al. 2013, ApJ, 774, 68
Díaz-Santos, T., Armus, L., Charmandaris, V., et al. 2014, ApJ, in press (arXiv:1405.3983)
Downes, D., Solomon, P. M., & Radford, S. J. E. 1993, ApJ, 414, L13

8 In Sgr B2(M), the peak of one of the most active and optically thick molecular cloud complexes in the Milky Way, $W_{\text{eq}}(\text{OH}65) \sim 2$ km s$^{-1}$ as measured with ISO/FP (Polehampton et al. 2004), consistent with its moderate effective $T_{\text{dust}} \sim 34$ K, $\Sigma_{\text{IR}} \sim 10^{11.8} L_{\odot} \text{kpc}^{-2}$, and $L_{\text{IR}}/M_{\text{dust}} \sim 22 L_{\odot}/M_{\odot}$ for a gas-to-dust ratio by mass of 100 (Etzalzue et al. 2013). OH$65$ is not detected towards Sgr A* and its circumnuclear disk (Goicoechea et al. 2013), and is detected in emission towards the Orion bar PDR indicating collisional excitation in warm and dense gas (Goicoechea et al. 2011).

Etzalzue, M., Goicoechea, J. R., Cernicharo, J., Polehampton, E. T., Noriega-Crespo, A., Molinari, S., Swinyard, B. M., Wu, R., & Bally, J. 2013, A&A, 556, A137
Farrah, D.; Lebouteiller, V.; Spoon, H. W. W., et al. 2013, ApJ, 776, 38
Fischer, J., Linkman, M. L., Satyapal, S., et al. 1999, Ap&SS, 266, 91
Fischer, J., Sturm, E., Goicoechea-Alfonso, et al. 2010, A&A, 518, L41
Fischer, J., Abel, N. P., Goicoechea-Alfonso, E., Dudley, C. C., Satyapal, S., & van Hoof, P. A. M. 2014, ApJ, in press (arXiv:1409.2521)
García-Marín, M., Colina, L., Arribas, S., Alonso-Herrero, A., & Mediavilla, E. 2006, ApJ, 650, 850
García-Burillo, S., Usero, A., Alonso-Herrero, A., Graciá-Carpio, J., Pereira-Santaella, M., Colina, L., Planesas, P., & Arribas, S. 2012, A&A, 539, A8
Genzel, R., Tacconi, L. J., Graciá-Carpio, J. et al. 2010, MNRAS, 407, 2901
Goicoechea, J. R. & Cernicharo, J. 2002, ApJ, 576, L77
Goicoechea, J. R., Joblin, C., Contursi, A., Berné, O., Cernicharo, J., Gerin, M., Le Bourlot, J., Bergin, E. A., Bell, T. A., & Röllig, M. 2011, A&A, 530, L16
Goicoechea, J. R., Etzalzue, M., Cernicharo, J., et al. 2013, ApJ, 769, L13
González-Alfonso, E., Smith, H. A., Fischer, J., & Cernicharo, J. 2004, ApJ, 613, 247
González-Alfonso, E., Smith, H. A., Asby, M. L. N., Fischer, J., Spinoglio, L., & Grundy, T. W. 2008, ApJ, 675, 303 (G-A08)
González-Alfonso, E., Fischer, J., Graciá-Carpio, J., et al. 2012, A&A, 541, A4 (G-A12)
González-Alfonso, E., Fischer, J., Bruderer, S., et al. 2013, A&A, 550, A25
High-lying OH absorption, [C II] deficits, and extreme $L_{\text{FIR}}/M_{\text{H}_2}$ ratios in galaxies

González-Alfonso, E., Fischer, J., Graciá-Carpio, J., et al. 2014, A&A, 561, A27 (G-A14)
González-Alfonso, E., Fischer, J., Aalto, S., & Falstad, N. 2014, A&A, 567, A91
Goulding, A. D., Alexander, M. D., Bauer, F. E., Forman, W. R., Hickox, R. C., Jones, C., Mullaney, J. R., & Trichas, M. 2012, ApJ, 755, 5
Graciá-Carpio, J., Sturm, E., Hailey-Dunsheath, S., et al. 2011, ApJ, 728, L7 (G-C11)
Helou, G., Khan, I. R., Malek, L., & Boehmer, L. 1988, ApJS, 68, 151
Henkel, C., Whiteoak, J. B., & Mauersberger, R. 1994, A&A, 284, 17
Hollenbach, D. J., Takahashi, T., & Tielens, A. G. G. M. 1991, ApJ, 377, 192
Houghton, S., Whiteoak, J. B., Koribalski, B., Booth, R., Wiklind, T., & Wielebinski, R. 1997, A&A, 335, 923
Kaufman, M. J., Wolfire, M. G., Hollenbach, D. J., & Luhman, M. L. 1999, ApJ, 527, 795
Kim, D.-C., Veilleux, S., & Sanders, D. B. 1998, ApJ, 508, 627
Luhman, M. L., Satyapal, S., Fischer, J., Wolfe, M. G., Cox, P., Lord, S. D., Smith, H. A., Stacey, G. J., & Ungere, S. J. 1998, ApJ, 504, L11
Luhman, M. L., Satyapal, S., Fischer, J., Wolfe, M. G., Sturm, E., Dudley, C. C., Lutz, D., & Genzel, R. 2003, ApJ, 594, 758
Malhotra, S., Kaufman, M. J., Hollenbach, D., et al. 2001, ApJ, 561, 766
Meijerink, R., Spaans, M., Loenen, A. F., & van der Werf, P. P. 2011, A&A, 525, A119
Mirabel, I. F., Booth, R. S., Johansson, L. E. B., Garay, G., & Sanders, D. B. 1990, A&A, 236, 327
Narayanan, D., Groppi, C. E., Kulesa, C. A., & Walker, C. K. 2005, ApJ, 630, 269
Papadopoulos, P. P., van der Werf, P. P., Xilouris, E. M., Isaak, K. G., Gao, Y., & Mühle, S. 2012, MNRAS, 426, 2601
Parkin, T. J., Wilson, C. D., Schirm, M. R. F., et al. 2013, ApJ, 776, 65
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
Polehampton, E. T., Baluteau, J.-P., Swinyard, B. M., Goicoechea, J. R., Brown, J. M., White, G. J., Cornicharo, J., & Grundy, T. W. 2007, MNRAS, 377, 1122
Rupke, D. S., Veilleux, S., & Sanders, D. B. 2005, ApJS, 160, 87
Sakamoto, K., Aalto, S., Costagliola, F., Martín, S., Ohyama, Y., Wiedner, M. C.; Wilner, D. J. 2013, ApJ, 764, 42
Sanders, D. B., Mazzarella, J. M., Kim, D.-C., Surace, J. A., & Soifer, B. T. 2003, AJ, 126, 1607
Scoville, N. Z., Young, J. S., & Lucy, L. B. 1983, ApJ, 270, 443
Scoville, N. Z. 2004, in The Neutral ISM in Starburst Galaxies, ed. S. Aalto, S. Hüttemeister, & A. Pedlar, ASP Conf. Ser., 320, 253
Sirocky, M. M., Levenson, N. A., Elitzur, M., Spoon, H. W. W., & Armus, L. 2008, ApJ, 678, 729
Soifer, B. T., Neugebauer, G., Matthews, K., Becklin, E. E., Ressler, M., Werner, M. W., Weinberger, A. J., & Egan, E. 1999, ApJ, 513, 207
Solomon, P. M., Downes, D., Radford, S. J. E., & Barrett, J. W. 1997, ApJ, 478, 144
Spoon, H. W. W., Koornneef, J., Moorwood, A. F. M., Lutz, D., & Tielens, A. G. G. M. 2000, A&A, 357, 898
Spoon, H. W. W., Marshall, J. A., Houck, J. R., Elitzur, M., Hao, L., Armus, L., Brandl, B. R., & Charmandaris, V. 2007, ApJ, 654, L49
Spoon, H. W. W., Farrah, D., Lebouteiller, V., et al. 2013, ApJ, 775, 127
Sturm, E., González-Alfonso, E., Veilleux, S., et al. 2011, ApJ, 733, L16
Surace, J. A., Sanders, D. B., & Mazzarella, J. M. 2004, AJ, 127, 3235
Thompson, T. A., Quataert, E., & Murray, N. 2005, ApJ, 630, 1677
Tielens, A. G. G. M. & Hollenbach, D. 1985, ApJ, 291, 722
Varenius, E., Conway, J. E., Martí-Vidal, I., Aalto, S., Beswick, R., Costagliola, F., & Klöckner, H.-R. 2014, A&A, 566, A15
Veilleux, S., Kim, D.-C., Sanders, D. B., Mazzarella, J. M., & Soifer, B. T. 1995, ApJS, 98, 171
Veilleux, S., Kim, D.-C., & Sanders, D. B. 1999, ApJ, 522, 113
Veilleux, S., Rupke, D. S. N., Kim, D.-C., et al. 2009, ApJS, 182, 628 (V09)
Veilleux, S., Meléndez, M.; Sturm, E., et al. 2013, ApJ, 776, 27 (V13)
Véron-Cetty, M.-P. & Véron, P. 2006, A&A, 455, 773
Weiß, A., Walter, F., & Scoville, N. Z. 2005, A&A, 438, 533