Herschel*-PACS spectroscopy of IR-bright galaxies at high redshift

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ABSTRACT

We present Herschel-PACS observations of rest-frame mid-infrared and far-infrared spectral line emissions from two lensed, ultra-luminous infrared galaxies at high redshift: MIPS J142824.0+352619 (MIPS J1428), a starburst-dominated system at z = 1.3, and IRAS F10214+4724 (F10214), a source at z = 2.3 hosting both star-formation and a luminous AGN. We have detected [O I]63μm and [O III]52μm in MIPS J1428, and tentatively [O III]52μm in F10214. Together with the recent ZEUS-CSO [C II]158μm detection in MIPS J1428 we can for the first time combine [O I], [C II] and far-IR (FIR) continuum measurements for PDR modeling of an ultra-luminous (LIR ≥ 1012 L⊙) star forming galaxy at the peak epoch of cosmic star formation. We find that MIPS J1428, contrary to average local ULIRGs, does not show a deficit in [O I] relative to FIR. The combination of far-UV flux G0 and gas density n (derived from the PDR models), as well as the star formation efficiency (derived from CO and FIR) is similar to normal or starburst galaxies, despite the high infrared luminosity of this system. In contrast, F10214 has stringent upper limits on [O IV] and [S III], and an [O III]/FIR ratio at least an order of magnitude lower than local starbursts or AGN, similar to local ULIRGs.

Key words. ISM: general – galaxies: high-redshift – galaxies: evolution

1. Introduction

ISO and Spitzer observations have shown that the fraction of cosmic star formation in infrared luminous and ultra-luminous galaxies (LIRGs/ULIRGs: LIR ≥ 1011 L⊙) increases from a few percent at z ∼ 0 to more than 50% at z > 1 (Genzel & Cesarsky 2000; Soifer et al. 2008). Herschel offers the first opportunity to study the population of high-redshift infrared bright galaxies at wavelengths where they emit most strongly, both through photometry and high-resolution spectroscopy. In an attempt to probe for evolution of the ISM in the infrared galaxy population and to explore the limits of the PACS spectrometer we are investigating several tens of hours for extremely deep high-resolution FIR spectroscopy of a (small) sample of galaxies with LIR > 1012 L⊙ at redshifts ≥1. These data will be complemented by and compared to the results from our ongoing Herschel spectroscopy of nearby ULIRGs, metal-rich and metal-poor galaxies, and starburst and AGN template objects. We will thus explore a wide range of parameter space and redshift. In this letter we present the first results on two high redshift objects, demonstrating the capabilities of the PACS spectrometer in long integrations and high-z spectroscopic observations.

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imperfect offset compensation by the chop/nod observing technique, which can be important at these faint signal levels. The continuum in each of the 16 spectral pixels was scaled to the median value to correct for residual flat field effects. Finally the two nod positions were combined to completely remove the sky (telescope) background. Given that our targets are point sources to PACS we have measured line fluxes from the spectrum in the central spatial pixel of the $5 \times 5$ pixel FOV of the PACS spectrometer, applying beam size correction factors and an additional in-flight correction of the absolute response (1/1.1 in the red and 1/1.3 in the blue PACS bands) as currently recommended for PACS (Poglitsch et al. 2010). The applied beam size correction factors are listed in Table 1.

4. Results and discussion

We have detected [O I]63 $\mu$m and [O III]52 $\mu$m in MIPS J1428, and tentatively [O III]52 $\mu$m in F10214. The spectra are shown in Fig. 1 (after re-binning to approximately the spectral resolution element, which is appropriate for resolved lines). These are the first detections of these lines in galaxies at such redshifts, i.e. at the epoch of the peak of cosmic star formation. Flux values, upper limits and continuum flux densities are given in Table 1. Flux uncertainties from the calibration and from uncertainties in the continuum definition and line shapes are of the same order, and we estimate a total flux uncertainty of 40–50%.

F10214: we did not detect the targeted lines of [S III]33 $\mu$m and [O IV]26 $\mu$m, but [O III]52 $\mu$m (which is observed in the 1st order PACS band in parallel with the 2nd order [O IV] data) is serendipitously detected at a $\sim 3\sigma$-level. We resolve the tentative line and measure a FWHM of 300 ± 100 km s$^{-1}$ (corrected for the instrumental profile, which has a FWHM ~ 220 km s$^{-1}$ at 170 $\mu$m), similar to the average CO line width (246 ± 10 km s$^{-1}$.) Figure 2 shows the ratio of the limit on [O IV] to FIR$^2$ compared to a collection of local template objects from the literature (Graciá-Carpio et al., in prep.). The FIR luminosity ($L_{\text{FIR}}$) has been calculated integrating SED data from the literature (Ao et al. 2008, and references therein) and our PACS continuum measurements, with a lens magnification correction factor of 12. The upper limit on [O IV] is surprisingly low given that the source is classified as an AGN rather than the AGN, an assumption that is supported by model fits to the FIR SED, as F10214 has strong emission from the FIR and our PACS continuum measurements, with a lens magnification correction factor of 12. The upper limit on [O IV] is at least an order of magnitude lower than local starbursts or AGN.

3. Observations and data reduction

The observations were taken with the PACS spectrometer (Poglitsch et al. 2010) on board the Herschel Space Observatory (Pilbratt et al. 2010) in high resolution range spectroscopy mode. Most of the data reduction was done using the standard PACS reduction and calibration pipeline (ipipe) included in HIPE 2.0 1340$^1$, together with some additional steps to correct for

$^1$ HIPE is a joint development by the Herschel Science Ground Segment Consortium, consisting of ESA, the NASA Herschel Science Center, and the HIFI, PACS and SPIRE consortia.
We have extracted two upper limits on Arp 220 and Mrk 231, which are shown in the figure, from ISO-LWS data. Initial results from SHINING (Fischer et al. 2010) indicate a general deficiency of FIR fine-structure lines (including [O III]) in local ULIRGs, similar to the [O III] deficiency seen in F10214. With future data from SHINING we will be able to populate this diagram with many more data points for local templates covering a large parameter space, in order to put the findings reported here into context.

MIPS J1428: the [O I] and [O III] lines (Fig. 1) are detected with \( \sim 5 \sigma \) significance. They are redshifted by 220 \( \pm 100 \) km s\(^{-1} \) and 300 \( \pm 135 \) km s\(^{-1} \), respectively, with respect to \( z \approx 1.325 \) (derived from H\( \alpha \) and CO). Both lines are resolved with a FWHM of 750 \( \pm 150 \) km s\(^{-1} \) each (corrected for the instrumental profile). This is considerably broader than CO (380 \( \pm 100 \) km s\(^{-1} \), Iono et al. 2006), but comparable to H\( \alpha \) (530 \( \pm 160 \) km s\(^{-1} \), Borys et al. 2006) within the errors. The measured continuum flux densities at 120 and 150 \( \mu m \) (Table 1) are low compared to the MIPS 160 \( \mu m \) flux (430 \( \pm 90 \) mJy, Borys et al. 2006). However, preliminary processing of PACS and SPIRE photometry of the source (S. Oliver and H. Aussel, private communication) is consistent with our spectroscopic values. Using the PACS spectrum we derive \( L_{\text{FIR}}(40-500 \mu m) \approx 1.3 \times 10^{33} L_\odot / \mu \), where \( \mu \) is the magnification factor (i.e. \( L_{\text{FIR}} \geq 1.6 \times 10^{12} L_\odot \) for \( \mu \leq 8 \)).

Fig. 3. [O I]\( 63 \mu m \) and [O III]\( 52 \mu m \) line strength in F10214 and MIPS J14284 as function of star formation efficiency. Comparison data are from the literature (Graciá-Carpio et al., in prep.), except for [O I] in Mrk 231 (Fischer et al. 2010). Symbols as in Fig. 2.

Fig. 2. The [O IV]/FIR ratio in F10214 compared to template objects compiled from the literature (Graciá-Carpio et al., in prep.). Black symbols: AGN and ULIRGs known to harbour an AGN; blue: HII galaxies; green: LINERs. Open symbols and arrows are upper line flux limits.

The [O IV]/FIR ratio in MIPS J14284 is consistent with the same order as in local star forming and AGN galaxies. The [O III]/[O I] ratio is very similar to the ratio in typical starburst galaxies (like M82).

For the [O I] spectrum we cannot rule out an underlying absorption of ammonia (NH$_3$). In Fig. 1, top panel, the dotted line is a NH$_3$ model spectrum (arbitrarily scaled). The line at the bottom of panel (a) is the residual after subtracting the line (continuum) fit and the NH$_3$ model from the data. Strong FIR NH$_3$ features with high column densities have been
detected before in infrared bright galaxies, in the infrared (e.g. in Arp 220, González-Alfonso et al. 2004) and at mm wavelengths (e.g. Henkel et al. 2008). On the other hand, the corresponding NH\textsubscript{3} column density in MIPS J1428 would be quite high, and the object is not known to be heavily obscured at other wavelengths.

[O I] and [C II] are usually the brightest cooling lines of the cool ISM in galaxies. However, ISO data have shown the [C II] line in local ULIRGs to be about an order of magnitude lower relative to the FIR continuum than in normal and starburst galaxies (e.g. Malhotra et al. 2001; Luhman et al. 2003). The relative weakness of [C II] has strong implications on its potential use as a star formation tracer for high redshift ($z \geq 4$) studies (e.g. Maiolino et al. 2005, 2009). Hailey-Dunsheath et al. (2010) have observed [C II] with the ZEUS spectrometer at the CSO. They found MIPS J1428 to be a counter example, with a normal [C II]/FIR ratio. Our [O I] observation (Fig. 3) supports this, i.e. this source, a high redshift source with the high SFR and ULIRG gas, does not show a deficit in the major PDR cooling lines relative to the FIR.

We plot in Fig. 4 the position of MIPS J1428 in a [C II]/[O I] versus ([C II]+[O I])/FIR diagram. For reference, we overplot the PDR model curves from Kaufman et al. (1999), and show the location of various samples of template galaxies from the literature. This is the first time that a combined [C II] and [O I] PDR diagnostic is possible for a source at redshift $z \sim 1$. The PDR model curves are appropriate for clouds in the active regions of galaxies that are illuminated on all sides (see Contursi et al. 2002). Combined HII region and PDR modeling of normal and starbursting galaxies have demonstrated that PDRs account for more than half of the [C II] emission in these sources (e.g. Colbert et al. 1999). Strong shocks could boost the [O I] emission relative to [C II]. However, the measured [C II]/[O I] ratio of 2.5±1.2 is well above 1, suggesting we can ignore the role of shocks in this case. We conclude that local ULIRGs and AGNs are not good analogs of MIPS J1428, and that this source appears to be more like a normal/starburst galaxy.

Typical massive galaxies in the distant Universe formed stars at an order of magnitude more rapidly than in the local Universe. Either star formation was significantly more efficient or these young galaxies were much more gas rich (Tacconi et al. 2010). Figure 3 shows the [O I]/FIR ratio as a function of star formation efficiency (SFE, expressed in $L_{\text{FIR}}/M_{\text{gas}}$. $M_{\text{gas}}$ was calculated from CO measurements (Iono et al. 2006, Ao et al. 2008). For F10214 this assumes a CO conversion factor like in local ULIRGs, and that the FIR arises from star formation rather than an AGN, an assumption that is supported by the low [O IV]/FIR ratio and model fits to the FIR SED (see above). For MIPS J1428 we used a CO conversion factor for normal star forming galaxies, motivated by our findings above, which yields $M_{\text{gas}} = 5 \times 10^{11} M_\odot/\mu$. The star formation rate in MIPS J1428 of 2600 $M_\odot$/yr (i.e. SFR $\geq 300 M_\odot$/yr for $\mu \leq 8$), is quite high, comparable to local ULIRGs or to SMGs. However, given the larger gas reservoir, the star formation efficiency is well in the range of normal star forming galaxies. Even with a ULIRG-like conversion factor, $L_{\text{FIR}}/M_{\text{gas}}$ would still be lower than in most local ULIRGs. Irrespective of the conversion factor we find $L_{\text{FIR}}/L_{\text{CO}} = 115 L_\odot/(K \text{ km s}^{-1} \text{ pc}^2)$ for MIPS J1428. In a recent analysis of CO data from $z \sim 1$–3 normal star forming galaxies Genzel et al. (2010) find values of 5 to 100 for this ratio, while the average ratio for major mergers is $\sim 160$, reaching values up to 600. This is consistent with our interpretation of MIPS J1428 as a normal star forming galaxy. Our result thus adds further support to the recent results from the SINS survey (Tacconi et al. 2010) which indicate that with an increased gas reservoir

![Fig. 4.](image-url)