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Gas Phase Metallicities of Local Ultra-Luminous Infrared Galaxies Follow Normal Star-Forming Galaxies

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Despite advances in observational data, theoretical models, and computational techniques to simulate key physical processes in the formation and evolution of galaxies, the stellar mass assembly of galaxies still remains an unsolved problem today. Optical spectroscopic measurements appears to show that the gas-phase metallicities of local ultra-luminous infrared galaxies (ULIRGs) are significantly lower than those of normal star-forming galaxies^{1–3}. This difference has resulted in the claim that ULIRGs are fueled by metal-poor gas accretion from the outskirts⁴. Here we report on a new set of gas-phase metallicity measurements making use of the far-infrared spectral lines of [OIII]52 μm , [OIII]88 μm , and [NIII]57 μm instead of the usual optical lines. Photoionization models have resulted in a metallicity diagnostic based on these three lines that break the electron density degeneracy and reduces the scatter of the correlation significantly⁵. Using new data from SOFIA and archival data from Herschel Space Observatory, we find that local ULIRGs lie on the mass-metallicity relation of star-forming galaxies and have metallicities comparable to other galaxies with similar stellar masses and star formation rates. The lack of a departure suggests that ULIRGs follow the same mass assembly mechanism as luminous star-forming galaxies and ~ 0.3 dex under-abundance in metallicities derived from optical lines is a result of heavily obscured metal-rich gas which has a negligible effect when using the FIR line diagnostics.

Galaxy mass assembly is intricately connected to how galaxies form and grow their metal content. Elemental abundances of galaxies, as determined through nebular recombination lines from the HII regions of the interstellar medium, are used to capture insights into the history of star formation, stellar nucleosynthesis, and baryon recycling processes within

galaxies⁴⁴. The mass assembly of galaxies, and thus the metal abundance, is regulated by a diverse set of phenomena, from those associated with the external environment^{6,7} with gas inflow and mergers, to internal processes such as feedback from the central super-massive black hole appearing as an active galactic nucleus (AGN). Accurate measurement of elemental abundances of different galaxy populations throughout the cosmic history remains one of the key observational goals of modern-day astrophysics.

Ultra-luminous infrared galaxies (ULIRGs) are a cosmologically important galaxy population whose nature changes substantially with redshift. At $z < 0.3$, ULIRGs are rare, with less than one per \sim hundred square degrees, and are invariably mergers between approximately equal-mass galaxies^{8–11}. Evidence suggests that the infrared emission that dominates the spectral energy distribution (SED) arises from the dust heated by UV photons, mostly emitted by massive stars associated with the starburst^{12,13}, with some role for AGNs^{14–16}. The number of ULIRGs rises rapidly and reaches a density of several hundred per square degree at $z \geq 1$. High-redshift ULIRGs have a lower merger fraction, wider range in dust temperatures and thus SED shapes, and a greater star-formation efficiency compared to local ULIRGs that are dominated by nuclear starbursts^{17–20}. Understanding the physical processes in low-redshift ULIRGs then becomes crucial since they connect to the stellar history and super-massive black hole mass assembly in $\geq L_\star$ galaxies, establishing galaxy evolution over cosmic time for massive galaxies in the Universe.

The gas-phase metal abundances of local ULIRGs, with oxygen abundance used as a proxy for metallicity, inferred from optical emission lines^{2,21,22} appear to lie below the now well-established stellar mass-metallicity relation for star-forming galaxies, when the two populations are compared at the same stellar mass. These measurements make use of the same nebular emission lines as used for metallicity measurements of other star-forming galaxies²³. This observed abundance offset from the mass-metallicity relation has at least two explanations²⁴. First, as shown by theoretical models and numerical simulations^{25–27}, tidal forces acting in merging/interacting galaxies primarily funnel low-metallicity gas from the outskirts toward the central active star-forming regions, explaining not only the observed nuclear metallicity under-abundances, but also the shallower metallicity gradients^{2,22,28}. If this explanation is correct then it implies ULIRGs undergo different mass assembly history than those of normal star-forming galaxies. The other explanation is that low gas-phase metal abundances inferred from the optical nebular lines may not be representative of the metallicity of the heavily obscured bulk of the star-forming gas in ULIRGs, due to the presence of a large dust mass in ULIRGs associated with the starburst. While the metallicity based on oxygen-to-hydrogen ratio is found to be low, ULIRGs also show a $\sim 3\times$ over-abundance in neon relative to solar²⁹, suggesting the presence of uncertainties and complexities in measurements and their interpretation. Given the overall implications to understand mass assembly of galaxies, it becomes necessary to conduct independent, reliable, and extinction-insensitive determinations of gas-phase metallicities to further understand if ULIRGs are in fact metal poor relative to other star-forming galaxies.

The far-infrared (FIR) fine-structure lines of nitrogen, and oxygen offer a powerful tool to characterize the interstellar medium of local and high- z galaxies, including radiation fields, gas densities, temperatures, and metal abundances that are much less susceptible to extinction than UV and optical transitions^{30,31}. While UV/optical line diagnostics have been established and used for decades, the use of FIR diagnostics is still in their infancy^{32,33}. As the FIR part of the electromagnetic spectrum is not accessible from the ground, a major limitation associated with FIR diagnostics is the lack of observational facilities with instruments having the necessary sensitivity to conduct sensitive spectroscopic measurements. The Herschel Space Observatory⁴¹ with PACS⁴² and SPIRE⁴³ instruments offered significantly improved sensitivity and resolution over previous space-based facilities, but observations still lacked the full coverage in the far-infrared band missing some of the key diagnostic lines for ULIRGs at low redshifts. This gap at wavelengths below $55\mu\text{m}$ is now filled by the Stratospheric Observatory for Infrared Astronomy (SOFIA) with its FIFI-LS instrument providing sensitivity to detect key spectral lines missed by Herschel.

Using SOFIA/FIFI-LS, we observed a sample of five local ULIRGs with $S_{60\mu\text{m}} \geq 7$ Jy at $0.01 < z < 0.13$, with key spectral emission lines appearing in windows uncontaminated by the atmospheric emission even at altitude. The observations in the SOFIA/FIFI-LS blue channel cover the [OIII]52 μm and [NIII]57 μm lines missing from archival Herschel/PACS observations (Table 1; see Methods for measurement details). These spectral lines complete the line observations needed to measure the robust FIR metallicity tracer⁵ using the ratio $(2.2 \times [\text{OIII}]88 + [\text{OIII}]52) / [\text{NIII}]57$. Attempts to estimate abundances with FIR fine-structure emission line diagnostics similar to this ratio using all three spectral lines have been subject to large uncertainties due to the lack of [OIII]52 data⁴⁵. Therefore, previous attempts to measure metal abundances with FIR emission lines have involved the ratio of [OIII]88/[NIII]57. Photoionization models, however, show that such a ratio is subject to large uncertainties in the electron density of the ISM and the ionization parameter⁵. Similarly, [OIII]52/[NIII]57 can be used as a diagnostic to measure gas-phase metal abundance but again this ratio is impacted by uncertainties in the electron density and ionization parameter. The dependence here, however, is opposite to that of the [OIII]88/[NIII]57 ratio such that an optimal combination involving both [OIII]52 μm and [OIII]88 μm emission lines is mostly independent of the density. The ratio is capable of providing a metallicity mostly independent of the ionizing source and ionization parameter with an intrinsic scatter of 0.2 dex at a given value of the line ratio⁵. This FIR metallicity estimator is also not significantly affected by either the age of the ionizing stellar population or the presence of an AGN, allowing a clear observational approach to draw definite conclusions on whether the optical-based metallicities are underestimated. We convert the line ratio, $2.2 \times [\text{OIII}]88 + [\text{OIII}]52 / [\text{NIII}]57$, to gas-phase metallicity, adopting the ionization parameter value of $U = 10^{-3}$. For our sample with $\Sigma_{\text{FIR}} \sim 10^{11} - 10^{12} L_{\odot}/\text{Kpc}^2$ an ionization parameter of $U \sim 10^{-2.7} - 10^{-3.5}$ is estimated from observations²⁴. The existing photoionization models⁵ show that this range of ionization parameter has a minimal effect, < 0.05 dex, in our metallicity measurements.

The metallicity of our ULIRG sample is also measured from optical fine-structure lines using the R23 ratio given by $([\text{OII}]3726 + [\text{OIII}]4959, 5007)/\text{H}\beta$ ratio or O3N2 given by $([\text{OIII}]5007/\text{H}\beta)/([\text{NII}]6584/\text{H}\alpha)$, and adopting a theoretical calibration to convert these line ratios using optical nebular recombination lines to an estimate of the oxygen abundance³⁴. The calibration used to derive optical metallicities³⁴ assumes a different N/O abundance³⁵ at a given metallicity compared to the FIR metallicity calibration⁵ based on the observed N/O abundances in nearby galaxies³⁶. In order to maintain comparable results on the oxygen abundance that can be directly compared to existing results from optical measurements on the mass-metallicity relation of star-forming galaxies, we convert the FIR oxygen abundance to the same metallicity calibration as optical measurements (see Figure 1 in the Methods Section). In the Methods Section we show that our results are also valid even when the original FIR metallicities are retained and compared with optical metallicities derived from a calibration with the consistent assumption of a N/O – O/H relation as FIR metallicity.

As shown in Figure 1, for the same five ULIRGs, optical recombination line ratio results in metallicity measurements that are at least 0.3 dex lower than the mass-metallicity relation of star forming galaxies as found with SDSS³⁴. We also include previously published²⁴ FIR metal abundance measurements based on $[\text{OIII}]88/[\text{NIII}]57$ ratio where available. They lead to metal abundances that are larger than optical lines estimates but still fall below the mass-metallicity relation of star-forming galaxies²⁴. Finally, using $[\text{OIII}]52, 88 \mu\text{m}$ and $[\text{NIII}]57 \mu\text{m}$ lines we perform metallicity measurements utilizing the above diagnostic, rescaled to the same oxygen abundance calibration as that used for the mass-metallicity relation with optical line ratios in Figure 1. These FIR-based, extinction-insensitive metallicity measurements indicate that ULIRGs lie on the mass-metallicity relation of star-forming galaxies. They also do not indicate unusual metal deficiencies in ULIRGs, as one would conclude with optical line ratios alone.

Figure 1 also shows that ULIRGs are found primarily towards the bottom of the mass-metallicity relation. We find that this is also consistent with expectations for normal star-forming galaxies with similar star-formation rates as the ULIRG sample. We estimate the average star-formation rate of our ULIRG sample, $\text{SFR} \sim 10^{2.5} \text{ M}_{\odot}/\text{year}$, using a calibration between FIR luminosity and star-formation rate³⁸. We use the MPA/JHU Value-Added Galaxy Catalog from SDSS-DR7^{34,39,40} to build a subsample of SDSS galaxies with similar star-formation rates and negligible amount of dust. We select galaxies at $0.07 < z < 0.3$ with $\text{SFR} > 10^2 \text{ M}_{\odot}/\text{year}$ and $E(B - V) < 0.06$. We further exclude AGNs for the sample as it is known that optical-based metallicities can be contaminated by the ionizing spectrum of an AGN, while FIR metallicity indicator used in this work is robust even in the presence of an AGN⁵. These criteria leave us with 35 star-forming galaxies. Figure 2 shows the comparison between the gas phase metallicity of these galaxies derived from optical diagnostic lines and that of ULIRGs from FIR-based calibration⁵. We find that the gas-phase metallicity of ULIRGs are consistent with star-forming galaxies with similar star-formation rates. ULIRGs do not show a sign of significant metal deficiency.

According to our result, ULIRGs are metal-rich or at least have oxygen abundances comparable to normal star-forming galaxies, but remain heavily dust-obscured. The dust obscuration is an important consideration since the attenuation of optical recombination lines from the HII regions of the ISM could lead to gas-phase metallicity results that are likely to be biased to lower values. The FIR-based metallicity tracer used in this work with all three emission lines has the potential to offer unbiased studies of gas-phase oxygen abundance of the ISM of ULIRGs. While our measurements are for a sample of local ULIRGs, we expect this implication to hold true for all dusty galaxies, including those that are found at high redshifts. Given that the abundance of ULIRG-like dust-rich galaxies increase rapidly at $z > 1$, and even dominating the cosmic star-formation rate density at $z \sim 2 - 3$, gas-phase metal abundances at the peak epoch of galaxy formation could be impacted at some level if metal abundances are only estimate with rest-frame optical lines. In the future, Origins Space Telescope³⁷ has the ability carry out metal abundance measurements and other diagnostic studies on the ISM and AGN activity in galaxies using a suite of far-infrared emission lines. Further development of metallicity diagnostics such as the ratio used here to properly understand ways to reduce the existing degeneracies will also be useful for interpretation of results from future infrared facilities.

Source ID	[O III]52 μm $\times 10^{-16} \text{W.m}^{-2}$	[N III]57 μm $\times 10^{-16} \text{W.m}^{-2}$	[O III]88 μm $\times 10^{-16} \text{W.m}^{-2}$
IRAS 12112+0305	3.06 ± 0.69	0.56 ± 0.17	1.06 ± 0.14
Mrk 273	2.49 ± 0.42	1.50 ± 0.20	4.33 ± 0.33
IRAS 15250+3609	6.99 ± 0.72	0.83 ± 0.09	0.41 ± 0.04
IRAS 17208-0014	5.06 ± 0.47	1.18 ± 0.13	2.56 ± 0.20
IRAS F08572+3915	1.31 ± 0.01	0.24 ± 0.04	0.51 ± 0.03

Table 1 – FIR line flux densities for the sample of ULIRGs used in this work. All of [OIII]52 μm line observations are with SOFIA/FIFI-LS (Methods Section) while all of [OIII]88 μm measurements are from the Herschel/PACS archive of SHINING survey of bright ULIRGs²⁴. For [NIII]57 μm we also make use of the Herschel/PACS archive of SHINING survey, except for IRAS 15250+3609 which is a new measurements with SOFIA/FIFI-LS.

Source ID	z	$S_{60\mu m}$ (Jy)	$\log(L_{IR}/L_{\odot})$	$\log M_*/M_{\odot}$	$12 + \log(\text{O}/\text{H})_{\text{FIR}}$	$12 + \log(\text{O}/\text{H})_{\text{Optical}}$
IRAS 12112+0305	0.0730	8.18	12.48	11.05	$9.02^{+0.22}_{-0.16}$	8.75
Mrk 273	0.0378	22.51	12.10	10.84	$9.13^{+0.09}_{-0.08}$	8.77
IRAS 15250+3609	0.0552	7.10	12.00	10.67	$9.03^{+0.09}_{-0.07}$	8.65
IRAS 17208-0014	0.0430	34.79	12.68	11.30	$9.06^{+0.07}_{-0.06}$	8.94
IRAS F08572+3915	0.0584	7.30	12.04	10.51	$8.99^{+0.09}_{-0.08}$	8.74

Table 2 – The properties of the ULIRG sample used in this work. z : redshift, $S_{60\mu m}$: IRAS 60 μm flux density, L_{IR} : total 8-1000 μm IR luminosity, M_* : stellar mass, $12 + \log(\text{O}/\text{H})_{\text{FIR}}$: Oxygen abundance using [OIII]52, 88 and [NIII]57, $12 + \log(\text{O}/\text{H})_{\text{Optical}}$: Oxygen abundance using rest-frame recombination optical lines using the $R23$ or $O3N2$ estimators described in the Methods Section. The oxygen abundance measurements have a typical uncertainty of 0.1 dex.

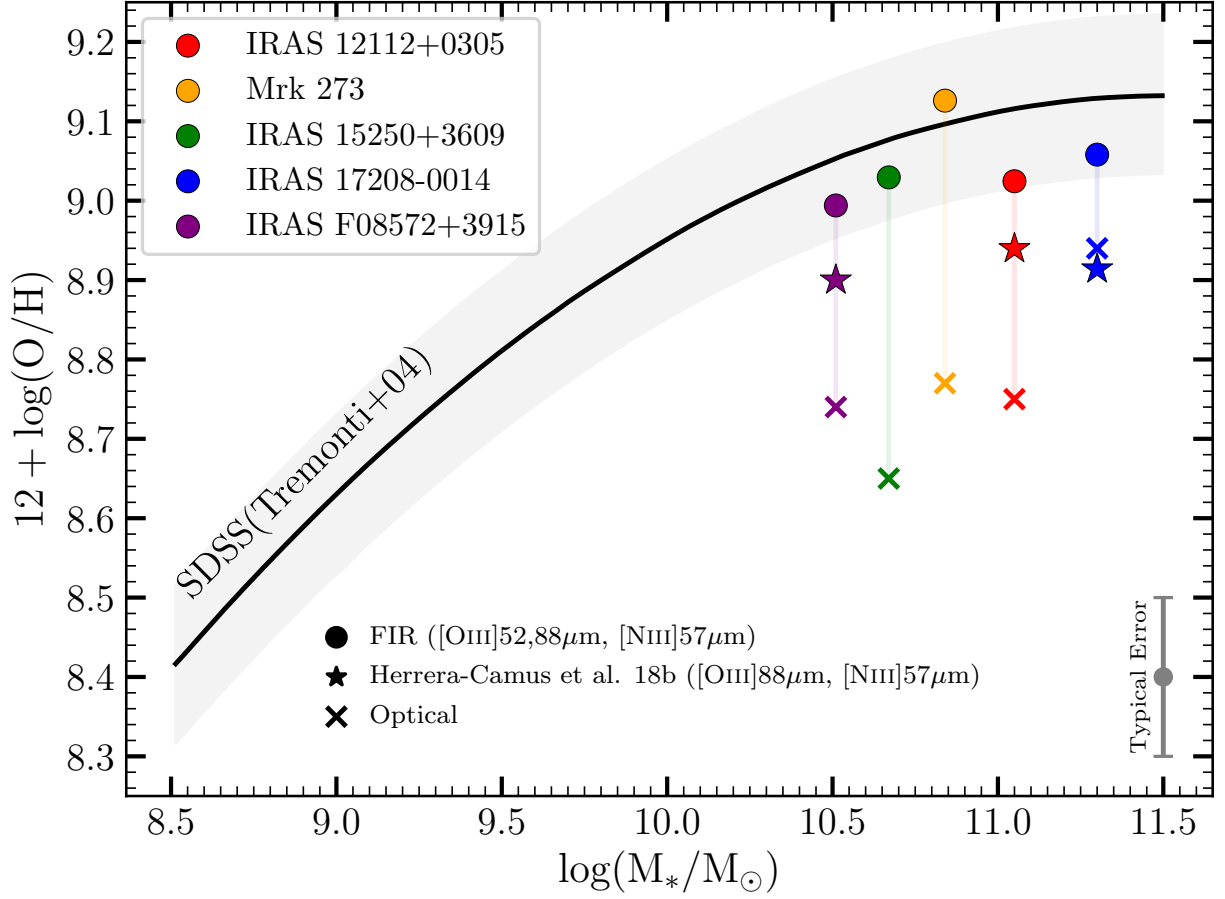


Figure 1 – Mass-metallicity relation observed in local galaxies³⁴ and ULIRGs whose metallicities are measured using optical-based (crosses) and IR-based (circles; this work) methods. All metallicity measurements are shown in the same scale³⁴. The FIR metallicity measurements from literature²⁴ based on $[\text{OIII}]88/[\text{NIII}]57$ ratio are also included where they are available (stars).

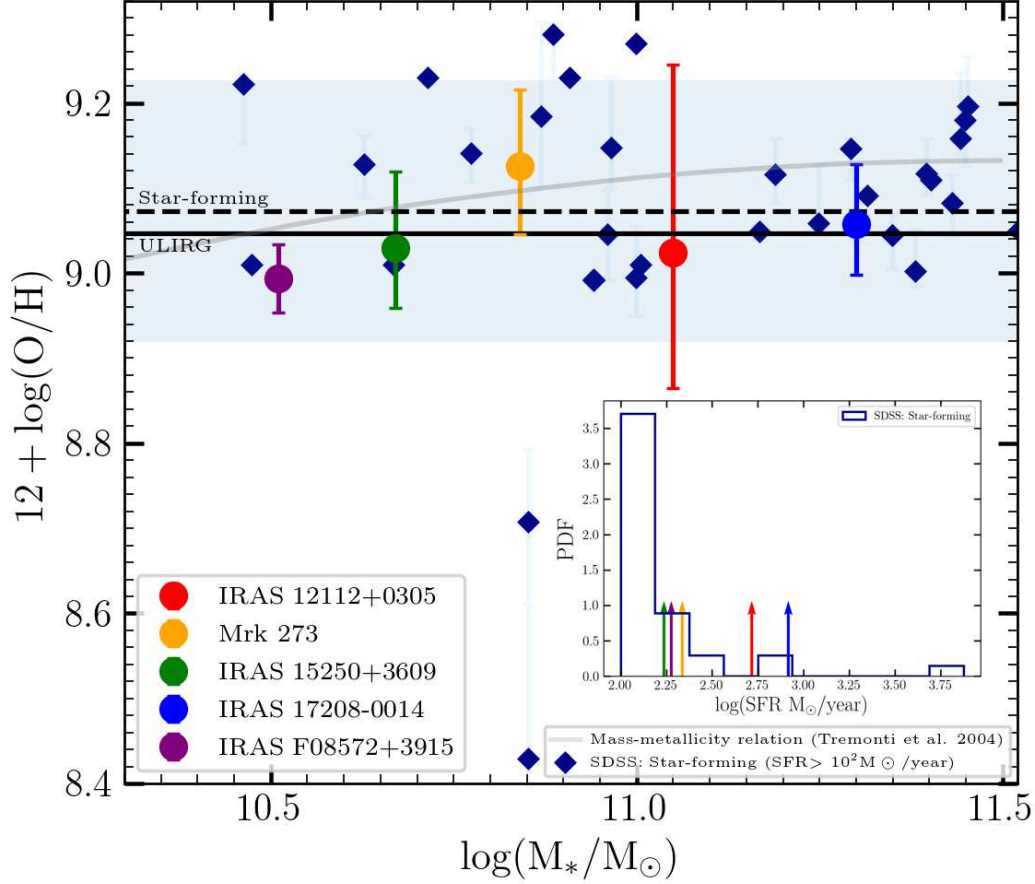


Figure 2 – A comparison between the gas-phase metallicity measurements of ULIRGs derived from FIR diagnostic lines and star-forming galaxies with similar star formation rates, which do not suffer the dust extinction ($E(B - V) < 0.06$), derived from optical diagnostic lines. The sub-panel shows the star formation rate distribution of the sample used in this figure. We find that the average FIR-based gas-phase metallicities of ULIRGs (horizontal black line) are consistent with star-forming galaxies (horizontal dashed line). The shaded region shows the 1σ scatter in the gas-phase metallicity of the star-forming sample.

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