# Bright beacons? ALMA non-detection of a supposedly bright [O I] 63 micrometer line in a redshift-6 dusty galaxy

Rybak, M.; Lemsom, L.; Lundgren, A.; Zavala, J.; Hodge, J.A.; de Breuck, C.; ... ; Werf, P.P. van der

Draft version September 25, 2023
Typeset using LATEX **twocolumn** style in AASTeX631



# Bright beacons? ALMA non-detection of a supposedly bright [OI] 63-$\mu$m line in a redshift-6 dusty galaxy

Matus Rybak [1,2,3] L. Lemsom,[4,1] A. Lundgren,[5,6] J. Zavala,[7] J. A. Hodge,[2] C. de Breuck,[5] C. M. Casey,[8] R. Decarli,[9] K. Torstensson,[10] J. L. Wardlow,[11] and P. P. van der Werf[2]

[1] Faculty of Electrical Engineering, Mathematics and Computer Science, Delft University of Technology, Mekelweg 4, 2628 CD Delft, The Netherlands
[2] Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands
[3] SRON - Netherlands Institute for Space Research, Niels Bohrweg 4, 2333 CA Leiden, The Netherlands
[4] Faculty of Applied Sciences, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands
[5] European Southern Observatory, Karl Schwarzschild Straße 2, 85748 Garching, Germany
[6] Aix Marseille Universitéé, CNRS, LAM, Marseille, F-13388, France
[7] National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
[8] Department of Astronomy, The University of Texas at Austin, 2515 Speedway Boulevard Stop C1400, Austin, TX 78712, USA
[9] INAF Observatory of Astrophysics and Space Science of Bologna, via Gobetti 93/3, 40129, Italy
[10] Joint ALMA Observatory, Alonso de Córdova 3107, Vitacura 763-0355, Santiago de Chile, Chile
[11] Physics Department, Lancaster University, Bailrigg, Lancaster, LA1 4YB, UK

(Received August 31, 2023)

Submitted to RN AAS

## ABSTRACT

We report a non-detection of the [O I] 63-$\mu$m emission line from the $z = 6.03$ galaxy G09.83808 using ALMA Band 9 observations, refuting the previously claimed detection with APEX by (Rybak et al. 2020); the new upper limit on the [O I] 63-$\mu$m flux is almost 20-times lower. [O I] 63-$\mu$m line could be a powerful tracer of neutral gas in the Epoch of Reionisation: yet our null result shows that detecting [O I] 63-$\mu$m from $z \geq 6$ galaxies is more challenging than previously hypothesised.

*Keywords:* High-redshift galaxies (734), Interstellar medium (847), Submillimeter astronomy (1647)

## 1. INTRODUCTION

The [O I] 63-$\mu$m line (henceforth [O I]$_{63}$, rest-frame frequency 4744.78 GHz) is often the brightest emission line of the neutral gas in star-forming galaxies, outshining the [C II]$_{158}$ line by a factor of a few (e.g. Farrah et al. 2013. With the rapidly mounting detections of galaxies at $z \geq 6$, [O I]$_{63}$ presents a potentially powerful "bright beacon" for measuring spectroscopic redshifts and studying gas content of galaxies in the Epoch of Reionisation. Although [O I]$_{63}$ has been detected in a number of $z = 1 - 3$ galaxies (e.g., Sturm et al. 2010; Coppin et al. 2012; Brisbin et al. 2015; Zhang et al. 2018; Wagg et al. 2020), to date, there has been just a single claimed [O I]$_{63}$ detection at $z \geq 3$: in Rybak et al. (2020, henceforth R20), we reported a detection of the [O I]$_{63}$ line in G09.83808, a strongly lensed, dusty star-forming galaxy at redshift $z = 6.02$ (Zavala et al. 2018), using the SEPIA660 spectrometer (Baryshev et al. 2015; Belitsky et al. 2018) on the APEX telescope.

The SEPIA660 data showed a significant ($\approx 5.2\sigma$) signal at 675.45 GHz ($z_{\rm [OI]} = 6.0246$, consistent with the systemic redshift $z = 6.0244 \pm 0.0003$, Tsujita et al. 2022). The detection was reproduced by two team members using several approaches. The measured line flux was 22±5 Jy km s$^{-1}$ which corresponds to a sky-plane (lensing-uncorrected) luminosity of $L_{\rm [OI]63} = (5.4 \pm 1.2) \times 10^{10}\ L_\odot$; almost four times brighter than the [C II] 158-$\mu$m line (Zavala et al. 2018).

## 2. OBSERVATIONS AND DATA REDUCTION

To exploit the seemingly bright [O I]$_{63}$ line in G09.83808, we re-observed it with ALMA Band 9

m.rybak@tudelft.nl

(Project #2019.1.01427.S). The observations were taken on 2019 December 5 and 9, giving a total on-source time of 99.3 min. The array consisted of 41 twelve-meter antennas with baseline lengths of 15–312 m, providing sensitivity to structure on scales of 0.2–6.0 arcsec. The December 5 observations were of poor quality and were discarded. The December 9 data were taken in outstanding weather conditions, with a precipitable water vapour of 0.3 mm.

The ALMA observations were reduced and imaged using CASA v5.6.1 (The CASA Team et al. 2022). We flagged antennas and frequency channels with elevated noise. The resulting FWHM synthesised beam size is 0.62" × 0.41" (natural weighting); the continuum imaging reaches a 1 $\sigma$ noise level of 0.53 mJy/beam.

Figure 1 (left) shows the CLEANed rest-frame 64-$\mu$m continuum image: G09.83808 is resolved into two lensed images with a peak S/N of ≈25. The total continuum flux is $S_{64\mu m} = 33.8 \pm 1.6$ mJy, consistent with the archival photometry (Tadaki et al. 2022).

We then subtracted the continuum using a first-order polynomial fit to the line-free SPWs. Fig. 1b shows a dirty-image map at the expected position of the [O I]$_{63}$ line collapsed over 260 km/s, twice the line FWHM reported in R20; Fig 1c shows the spectrum extracted from the two lensed images. We do not see any significant [O I]$_{63}$ emission: neither does $uv$-plane analysis reveal any excess emission at the expected frequency of the [O I]$_{63}$ line. The non-detection is robust with respect to calibration and imaging procedures: the tentative ($\approx 3\sigma$) emission seen in Fig 1b disappears for different bandwidths and $uv$-tapers.

Finally, we re-analyse the original APEX data from R20(2019 October 28 and November 6). After the publication of R20, additional data were taken on 2019 December 11. Compared to the other two observing blocks, the data from October 28 are affected by the higher pwv. Reducing the data from November 6 and December 11 only, does not yield a significant detection despite a lower rms (Fig. 2).

## 3. RESULTS

We set a $3\sigma$ upper limit on the [O I]$_{63}$ flux ≤6.16 Jy km s$^{-1}$, corresponding to an apparent luminosity of $L^{\rm sky}_{\rm [OI]63} \leq 2.9 \times 10^9\ L_\odot$ – almost 20× lower than the value reported in R20, $(54 \pm 12) \times 10^9\ L_\odot$. After correcting for the lensing magnification ($\mu = 9.3$, Zavala et al. 2018, we obtain a source-plane upper limit of $L_{\rm [OI]63} \leq 3.1 \times 10^8\ L_\odot$. As the [O III]$_{88}$ and CO(2–1) lines have extent similar to the dust continuum (Tadaki et al. 2022; Zavala et al. 2022): ≈2 arcsec, significantly smaller than the maximum recoverable angular scale of 6 arcseconds of our ALMA data. It is thus unlikely that the [O I])63 is so extended as to be resolved out with ALMA.

To put our non-detection in context, Fig. 1d shows the ratio between [O I] and far-infrared luminosity $L_{\rm FIR}$ as a function of $L_{\rm FIR}$ for other high-redshift (Coppin et al. 2012; Brisbin et al. 2015; Wardlow et al. 2017; Wagg et al. 2020; Litke et al. 2022) and low-redshift (Graciá-Carpio et al. 2011; Coppin et al. 2012; Díaz-Santos et al. 2017) observations. Our ALMA-derived upper limit for G09.83808 is significantly lower than previous high-redshift detections but comparable to the brightest $z \sim 0$ ultraluminous infrared galaxies (ULIRGs) and the upper limit for the $z = 5.7$ dusty galaxy SPT 0346-52 (Litke et al. 2022). Given the small magnification gradients across the source, the [O I]/FIR ratio is not significantly affected by differential magnification. The faintness of the [O I]$_{63}$ emission from G09.83808 (≥5× fainter than either [C II]$_{158}$ or [O III]$_{88}$) might be caused by large optical depth and self-absorption by the foreground cold gas, as seen in some $z \sim 0$ ULIRGs (e.g., Farrah et al. 2013; Díaz-Santos et al. 2017). The spurious $\geq 5\sigma$ APEX detection of the [O I]$_{63}$ highlights the challenges of single-dish spectroscopy in high-frequency sub-millimetre bands.

This paper makes use of the following ALMA data: ADS/JAO.ALMA#2019.1.01427.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ.

This publication is based on data acquired with the Atacama Pathfinder Experiment (APEX) under programme ID 0104.B-0551. APEX is a collaboration between the Max-Planck-Institut für Radioastronomie, the European Southern Observatory, and the Onsala Space Observatory.

The authors acknowledge assistance from Allegro, the European ALMA Regional Center node in the Netherlands.

M. R. is supported by the NWO Veni project "*Under the lens*" (VI.Veni.202.225) and the Delft Space Institute Seed Grant "*Hundred colours of galaxies*". J. L. W. acknowledges support from an STFC Ernest Rutherford Fellowship (ST/P004784/2).

*Facilities:* ALMA, APEX

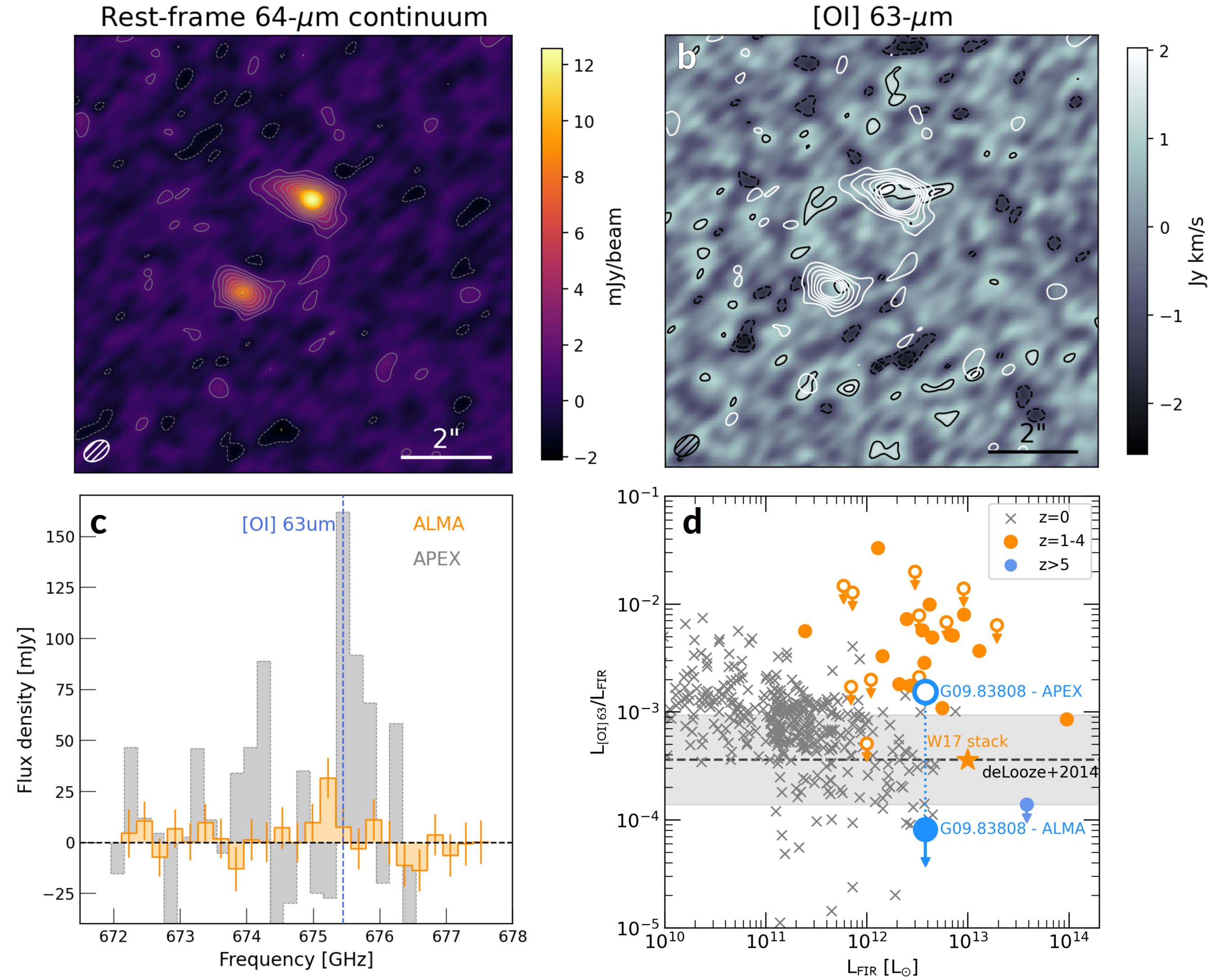


**Figure 1.** a): CLEANed image of the 64-$\mu$m rest-frame continuum, using natural weighting. The contours are drawn at ($\pm 2$, $\pm 4$, $\pm 6$, ...)$\sigma$. b) Dirty moment-0 image at the frequency of the [O I]$_{63}$; black contours drawn at ($\pm 2$, $\pm 3$, $\pm 4$, ...)$\sigma$. White contours indicate the Band 9 continuum. c) ALMA spectrum (orange) extracted from the two lensed images. We do not find any significant line emission, indicating that the claimed detection in Rybak et al. (2020) (APEX, grey) is spurious. d) [O I]$_{63}/L_{\rm FIR}$ ratio in G09.83808 (blue circles) compared to literature data and the De Looze et al. (2014) empirical relation.

## REFERENCES

Baryshev, A. M., Hesper, R., Mena, F. P., et al. 2015, A&A, 577, A129

Belitsky, V., Lapkin, I., Fredrixon, M., et al. 2018, A&A, 612, A23

Brisbin, D., Ferkinhoff, C., Nikola, T., et al. 2015, ApJ, 799, 13

Coppin, K. E. K., Danielson, A. L. R., Geach, J. E., et al. 2012, MNRAS, 427, 520

De Looze, I., Cormier, D., Lebouteiller, V., et al. 2014, A&A, 568, A62

Díaz-Santos, T., Armus, L., Charmandaris, V., et al. 2017, ApJ, 846, 32

Farrah, D., Lebouteiller, V., Spoon, H. W. W., et al. 2013, ApJ, 776, 38, doi: 10.1088/0004-637X/776/1/38

Graciá-Carpio, J., Sturm, E., Hailey-Dunsheath, S., et al. 2011, ApJ, 728, L7

Litke, K. C., Marrone, D. P., Aravena, M., et al. 2022, ApJ, 928, 179

Rybak, M., Zavala, J. A., Hodge, J. A., Casey, C. M., & Werf, P. v. d. 2020, ApJL, 889, L11

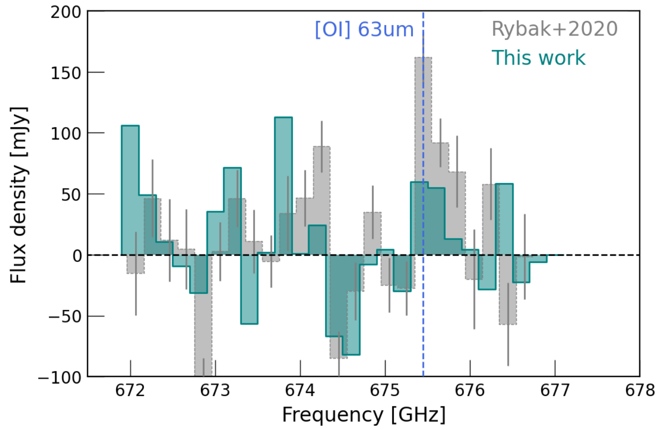


**Figure 2.** Comparison of the APEX SEPIA660 spectra from Rybak et al. (2020, grey) based on the 2019 October 28 and November 11 observations, and a new reduction of 2019 November 11 and December 11 observations (teal). Our new reduction does not confirm the claimed detection of the [O I]$_{63}$ line.

Sturm, E., Verma, A., Graciá-Carpio, J., et al. 2010, A&A, 518, L36

Tadaki, K.-i., Tsujita, A., Tamura, Y., et al. 2022, PASJ, 74, L9

The CASA Team, Bean, B., Bhatnagar, S., et al. 2022, PASP, 134, 114501

Tsujita, A., Tadaki, K.-i., Kohno, K., et al. 2022, PASJ, 74, 1429

Wagg, J., Aravena, M., Brisbin, D., et al. 2020, MNRAS, 499, 1788

Wardlow, J. L., Cooray, A., Osage, W., et al. 2017, ApJ, 837

Zavala, J. A., Montaña, A., Hughes, D. H., et al. 2018, Nature Astronomy, 2, 56

Zavala, J. A., Casey, C. M., Spilker, J., et al. 2022, ApJ, 933, 242

Zhang, Z.-Y., Ivison, R. J., George, R. D., et al. 2018, MNRAS, 481, 59