



Universiteit
Leiden
The Netherlands

Neutral outflows in high-redshift dusty galaxies

Butler, K.M.

Citation

Butler, K. M. (2023, September 14). *Neutral outflows in high-redshift dusty galaxies*. Retrieved from <https://hdl.handle.net/1887/3640590>

Version: Publisher's Version

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/3640590>

Note: To cite this publication please use the final published version (if applicable).

Neutral Outflows in High-Redshift Dusty Galaxies

Proefschrift

ter verkrijging van
de graad van doctor aan de Universiteit Leiden,
op gezag van rector magnificus prof. dr. ir. H. Bijl,
volgens besluit van het college voor promoties
te verdedigen op donderdag 14 september 2023
klokke 13.45 uur

door

Kirsty May Butler

geboren te Perth, Western Australia, Australia
in 1994

Promotor: Prof. dr. P. P. van der Werf
Co-promotor: Dr. J. A. Hodge

Promotiecommissie: Prof. dr. I. A. G. Snellen
Prof. dr. J. Schaye
Prof. dr. S. Viti
Dr. P. Cox Institut d'Astrophysique de Paris
Prof. dr. K. Kraiberg Knudsen Chalmers University of Technology

Printed by: Gildeprint

ISBN: 978-94-6419-891-1

An electronic copy of this thesis can be found at <https://openaccess.leidenuniv.nl>.

© Kirsty May Butler, 2023

Cover design: A galaxy juggling its outflows. Design by Erica Emma Butler Kuser & Assistants.
Artwork by Kirsty May Butler.

To beans.

“There are many theories about how the universe began, but the truth is most of the theories are just that. Theories. All we know for certain is that in the beginning there was a bum.”
- from *Zombie Bums from Uranus* (2003) by Australian children’s author Andy Griffiths

Contents

1	Introduction	3
1.1	The Baryon Cycle	3
1.2	The Multiphase Nature of Galaxy Outflows	3
1.3	Outflows at High- z	5
1.4	This Thesis	7
	References	7
2	Resolved Neutral Outflow from a Lensed Dusty Star-Forming Galaxy at $z = 2.09$	11
2.1	Introduction	11
2.2	Observations and data reduction	14
2.2.1	ALMA Band 6 Observations and Reduction	14
2.2.2	Ancillary NIR data	16
2.2.3	Ancillary CH ⁺ data	16
2.3	Results	17
2.4	Gravitational Lens modelling and Source Plane Reconstruction	19
2.4.1	Lens modelling: VISILENS	19
2.4.2	Source Reconstruction: LENSTOOL	23
2.4.3	Comparison with Previous Lens Models	29
2.5	Outflow Geometry	29
2.5.1	Sheet	29
2.5.2	Spherical	29
2.5.3	Conical	32
2.6	Chemical Properties of the Gas	33
2.6.1	CO(9-8)	35
2.6.2	OH ⁺	35
2.6.3	CH ⁺	37
2.6.4	Comparison of OH ⁺ and CH ⁺	38
2.7	Derived Outflow Properties	39
2.7.1	Outflow Mass	41
2.7.2	Mass Outflow Rate	42
2.7.3	Outflow Energetics	46
2.7.4	Impact on the Host Galaxy and Fate of the Outflowing Neutral Gas	51
2.8	Conclusions	55
2.A	Beam Smearing Effects on Source Reconstruction of Gravitational Lenses	57
2.B	OH ⁺ ($1_0 - 1_1$) Optical Depth to Column Density	59
	References	60

3	Molecular Outflows in $z > 6$ Unobscured QSO Hosts Driven by Star Formation	67
3.1	Introduction	67
3.2	Sample, Observations and Imaging	69
3.3	Results	71
3.3.1	Spectra and Spectral Fitting	71
3.3.2	Source Sizes	76
3.3.3	Outflow Covering Fractions and Detection Rates	77
3.4	Derived Outflow Properties	78
3.4.1	Outflow Mass, Mass Outflow Rate and Depletion Times	78
3.4.2	Outflow Energetics	80
3.4.3	Escape Fractions	81
3.5	Discussion	83
3.5.1	What Drives Molecular Outflows in Unobscured QSO Hosts?	83
3.5.2	Interaction Between Central AGNs and the Surrounding ISM	84
3.5.3	The Background Dust Continuum and its Effect on the Outflow Absorption Signature	86
3.5.4	OH 119 μm Emission	89
3.6	Conclusion	90
	References	91
4	Neutral Outflows in High-z QSOs	97
4.1	Introduction	97
4.2	Sample and Observations	98
4.3	Spectra and Spectral Fitting	99
4.4	Results	99
4.4.1	Fitted Line Properties	99
4.4.2	Derived Line Properties	103
4.5	Discussion	103
4.5.1	OH ⁺ Absorption	103
4.5.2	OH ⁺ Emission	105
4.5.3	CO(9-8) Emission	106
4.6	Conclusions	107
4.A	ALMA Observation Details	108
4.B	Additional lines in WFI J2026-4536	108
	References	108
5	Neutral Outflows from $z \sim 2 - 4$ Dusty Galaxies	113
5.1	Introduction	113
5.2	Observations and data	115
5.3	Spatially Integrated Spectra and Fitting	115
5.3.1	Cycle 3 Sample Spectral Fitting	117
5.3.2	Cycle 9 Sample Spectral Fitting	120
5.4	Results	127
5.4.1	Detected Spectral Features	127
5.4.2	Derived Spectral Line Properties	128

5.5	Nature of the Sources	129
5.5.1	Cycle 3 Sample	132
5.5.2	Cycle 9 Sample	134
5.6	Tracing Fueling and Feedback with OH ⁺ Absorption	135
5.6.1	Properties of the Diffuse Neutral Gas	136
5.6.2	Detection Rates and Covering Fractions	137
5.6.3	What type of Galaxies drive Neutral Outflows in the CGM?	137
5.7	Warm Dense Molecular Gas	138
5.8	Conclusions	139
	References	141
	English Summary 🇬🇧	145
	Nederlandstalige Samenvatting 🇳🇱	149
	List of publications	153
	Curriculum vitae	155
	Acknowledgments	157