



Universiteit  
Leiden  
The Netherlands

## Cold gas in distant galaxies

Boogaard, L.A.

### Citation

Boogaard, L. A. (2021, February 25). *Cold gas in distant galaxies*. Retrieved from <https://hdl.handle.net/1887/3147175>

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/1887/3147175>

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

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/3147175> holds various files of this Leiden University dissertation.

**Author:** Boogaard, L.A.

**Title:** Cold gas in distant galaxies

**Issue date:** 2021-02-25

# Cold gas in distant galaxies



# Cold gas in distant galaxies

Koud gas in verre sterrenstelsels

## 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 25 februari 2021  
klokke 16.15 uur

door

Lein Adriaan Boogaard

geboren te Oegstgeest  
in 1992

Promotor: Prof. dr. P. P. van der Werf  
Co-promotor: Dr. R.J. Bouwens

Promotiecommissie: Prof. dr. H.J.A. Röttgering  
Prof. dr. J. Schaye  
Prof. dr. S. Viti  
Dr. J. A. Hodge  
Dr. J. Brinchmann Universidade do Porto (Portugal)  
Dr. F. Walter MPIA, Heidelberg (Germany)  
Prof. dr. I. R. Smail Durham University (UK)

*Voor mijn ouders*

*&*

*Voor Elisabeth*

Copyright © 2021 L. A. Boogaard

Printed by: Gildeprint

Cover design: Arjen Wiersma

Cover images: The Hubble Ultra Deep Field, *credit: NASA, ESA, and S. Beckwith (STScI) and the HUDF Team (front)*, and a 3D rendering of the ALMA Spectroscopic Survey of the HUDF 3 mm datacube (*back*).

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

ISBN 978 94 6419 120 2

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	From effect to cause . . . . .	2
1.2	The theory . . . . .	4
1.2.1	Cosmology, galaxy formation and the baryon cycle . . . . .	4
1.2.2	Star formation and the cold interstellar medium . . . . .	6
1.2.3	The light from galaxies across the electromagnetic spectrum . . . . .	11
1.3	The instruments . . . . .	12
1.3.1	Multi Unit Spectroscopic Explorer (MUSE) . . . . .	13
1.3.2	Atacama Large Millimeter Array (ALMA) . . . . .	13
1.3.3	Other facilities . . . . .	13
1.4	The state of the art . . . . .	14
1.4.1	Star formation in galaxies across cosmic time . . . . .	14
1.4.2	Molecular gas in distant galaxies . . . . .	15
1.4.3	The need for molecular deep fields . . . . .	17
1.5	The ALMA Spectroscopic Survey of the HUDF . . . . .	18
1.5.1	Motivation . . . . .	18
1.5.2	Observing strategy . . . . .	19
1.5.3	Data products: two cubes and two images . . . . .	19
1.6	The thesis . . . . .	23
1.6.1	This thesis . . . . .	23
1.6.2	Related science with ASPECS . . . . .	25
1.7	The future . . . . .	26
1.7.1	The cosmic baryon cycle . . . . .	26
1.7.2	Science and facilities . . . . .	27
<b>2</b>	<b>Constraining the low-mass end of the <math>M_*</math>–SFR relation at <math>z &lt; 1</math></b>	<b>29</b>
2.1	Introduction . . . . .	30
2.2	Observations and methods . . . . .	32
2.2.1	Observations, data reduction, and spectral line fitting . . . . .	33
2.2.2	Sample selection . . . . .	34
2.2.3	Stellar masses . . . . .	37
2.2.4	Star formation rates . . . . .	38

2.3	Consistency of SFR indicators . . . . .	39
2.4	Bayesian model . . . . .	42
2.4.1	Definition . . . . .	42
2.4.2	Execution . . . . .	44
2.4.3	Model and data limitations . . . . .	45
2.5	Star formation sequence . . . . .	45
2.5.1	Global sample . . . . .	45
2.5.2	Low-mass sample ( $\log M_*/[M_\odot] < 9.5$ ) . . . . .	49
2.5.3	The effect of redshift bins (2D) . . . . .	49
2.6	Discussion . . . . .	51
2.6.1	Comparison with the literature . . . . .	51
2.6.2	The MS slope — a quantitative comparison to models . . . . .	55
2.6.3	Implications of a shallow slope . . . . .	57
2.7	Summary and conclusions . . . . .	58
Appendix 2.A	Simulations . . . . .	60
2.A.1	Selection function and completeness . . . . .	60
2.A.2	Transformation . . . . .	61
<b>3</b>	<b>The nature and physical properties of gas-mass selected galaxies</b>	<b>65</b>
3.1	Introduction . . . . .	66
3.2	Observations . . . . .	67
3.2.1	ALMA Spectroscopic Survey . . . . .	67
3.2.2	MUSE HUDF Survey . . . . .	68
3.2.3	Multi-wavelength data (UV–radio) and MAGPHYS . . . . .	70
3.2.4	X-ray photometry . . . . .	71
3.3	The ASPECS-LP sample . . . . .	72
3.3.1	Identification of the line search sample . . . . .	72
3.3.2	Additional sources with MUSE redshift priors at $z < 2.9$ . . . . .	75
3.3.3	Full sample redshift distribution . . . . .	78
3.4	Physical properties . . . . .	79
3.4.1	Star formation rates from MAGPHYS and [O II] . . . . .	79
3.4.2	Metallicities . . . . .	81
3.4.3	Molecular gas properties . . . . .	81
3.5	Results: Global sample properties . . . . .	83
3.5.1	Stellar mass and SFR distributions . . . . .	83
3.5.2	AGN fraction . . . . .	85
3.5.3	Obscured and unobscured star formation rates . . . . .	85
3.5.4	Metallicities at $1.0 < z < 1.42$ . . . . .	86
3.6	Discussion . . . . .	87
3.6.1	Sensitivity limit to molecular gas reservoirs . . . . .	87
3.6.2	Molecular gas across the galaxy main sequence . . . . .	89
3.6.3	Evolution of molecular gas content in galaxies . . . . .	92
3.7	Summary . . . . .	93
Appendix 3.A	Source description and redshift identifications . . . . .	95

Appendix 3.B MAGPHYS fits for all CO-detected galaxies . . . . .	104
<b>4 CO excitation, [C I] and ISM conditions in galaxies at <math>z = 1 - 3</math></b>	<b>105</b>
4.1 Introduction . . . . .	106
4.2 Observations and ancillary data . . . . .	108
4.2.1 ALMA Spectroscopic Survey Data Reduction . . . . .	108
4.2.2 ASPECS Sample . . . . .	110
4.2.3 Very Large Array Observations (VLASPECS) . . . . .	111
4.2.4 Multi-wavelength data and SED fitting . . . . .	112
4.3 Methods . . . . .	112
4.3.1 Spectral line analysis . . . . .	112
4.3.2 Deriving line luminosities and molecular gas masses . . . . .	115
4.4 Results . . . . .	115
4.4.1 Observed emission lines from CO and [C I] . . . . .	115
4.5 CO excitation . . . . .	117
4.5.1 Individual sources . . . . .	117
4.5.2 Stacked line fluxes . . . . .	120
4.5.3 LVG modeling . . . . .	122
4.5.4 Dust-continuum versus low- $J$ CO . . . . .	125
4.6 Atomic carbon . . . . .	129
4.6.1 Atomic carbon abundances . . . . .	129
4.6.2 PDR modeling . . . . .	132
4.7 Discussion . . . . .	134
4.7.1 Modest excitation in mid- $J$ lines at $z = 1.0 - 1.6$ . . . . .	134
4.7.2 Increasing excitation with redshift . . . . .	136
4.7.3 The low- $J$ excitation . . . . .	138
4.7.4 Broader implications of the flux-limited survey . . . . .	140
4.7.5 Implications for the cosmic molecular gas density . . . . .	140
4.8 Summary and Conclusions . . . . .	141
Appendix 4.A Similar widths for the low- $J$ and high- $J$ CO lines . . . . .	143
Appendix 4.B Spectral line fits . . . . .	144
<b>5 Line-luminosity functions and the cosmic density of molecular gas</b>	<b>153</b>
5.1 Introduction . . . . .	154
5.2 Observations . . . . .	156
5.2.1 ALMA data . . . . .	156
5.2.2 Ancillary data . . . . .	158
5.3 Analysis and Results . . . . .	158
5.3.1 Line search at 1.2 mm . . . . .	158
5.3.2 Line fluxes . . . . .	160
5.3.3 Line identification and redshifts . . . . .	160
5.3.4 Line luminosities and molecular gas masses . . . . .	163
5.3.5 Luminosity functions and $\rho_{\text{H}_2}$ . . . . .	166
5.4 Discussion . . . . .	166

5.4.1	CO luminosity functions . . . . .	166
5.4.2	[C I] and [C II] luminosity functions . . . . .	169
5.4.3	$\rho_{\text{H}_2}$ vs redshift . . . . .	170
5.5	Conclusions . . . . .	172
Appendix 5.A	Tabulated luminosity functions . . . . .	173
Appendix 5.B	Cosmic variance . . . . .	175
Appendix 5.C	Identification of line candidates without near-infrared counterparts	178
<b>6</b>	<b>The average molecular gas content of star-forming galaxies at <math>z = 3 - 4</math></b>	<b>181</b>
6.1	Introduction . . . . .	182
6.2	Observations and sample selection . . . . .	183
6.2.1	Parent sample selection and physical properties . . . . .	183
6.2.2	Measurement of systemic redshifts . . . . .	185
6.2.3	Final systemic redshift sample . . . . .	188
6.3	Results . . . . .	190
6.3.1	Velocity offsets . . . . .	190
6.3.2	ALMA Stacking . . . . .	191
6.4	Discussion . . . . .	194
6.4.1	Molecular gas masses . . . . .	194
6.4.2	Low metallicity driving a high molecular gas mass-to-light ratio . . . . .	196
6.4.3	Contribution to the cosmic molecular gas density . . . . .	201
6.4.4	Implications for observing cold gas in low metallicity galaxies at high redshift . . . . .	201
6.5	Summary and conclusions . . . . .	203
Appendix 6.A	Table . . . . .	205
Appendix 6.B	Spectra . . . . .	208
<b>Bibliography</b>		<b>211</b>
<b>Publication list</b>		<b>221</b>
<b>Nederlandse samenvatting</b>		<b>227</b>
<b>Curriculum Vitae</b>		<b>233</b>
<b>Acknowledgements</b>		<b>235</b>