



Universiteit
Leiden
The Netherlands

Distant star formation in the faint radio sky

Algera, H.S.B.

Citation

Algera, H. S. B. (2021, October 27). *Distant star formation in the faint radio sky*. Retrieved from <https://hdl.handle.net/1887/3221280>

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/1887/3221280>

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

Distant Star Formation in the Faint Radio Sky

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 woensdag 27 oktober 2021
klokke 11:15 uur

door

Hiddo Sunny Bouwe Algera

geboren te Sneek, Nederland
in 1995

Promotor:	Prof. dr. Huub Röttgering
Co-promotor:	Dr. Jacqueline Hodge
Promotiecommissie:	Prof. dr. Serena Viti Prof. dr. Paul van der Werf Prof. dr. Ian Smail Prof. dr. Vernes Smolčić Dr. Rychard Bouwens Dr. Dominik Riechers
	Durham University University of Zagreb Cornell University

Cover by Zehui Xu (徐泽慧)

ISBN: 978 94 6419 329 9

Printed by: Gildeprint

*Mar as de sinne no in stjer is
Like lyts as alle oaren
Dan freegje ik my ôf
Wa is de skepper fan de skepper
– Skepper fan de Skepper, Reboelje (1989)*

Contents

1	Introduction	1
1.1	The Beginning	1
1.2	The Evolution of Galaxies	2
1.2.1	Star Formation in Galaxies	5
1.2.2	Star Formation Rates	8
1.2.3	Dusty Star-forming Galaxies	10
1.2.4	The Star-forming Population	11
1.3	Radio Emission in Galaxies	13
1.3.1	Synchrotron Emission	14
1.3.2	The Far-infrared/radio Correlation	15
1.3.3	Free-free Emission	20
1.3.4	The Radio Spectrum	21
1.4	The Spectral Energy Distribution of Galaxies	23
1.4.1	An Inventory of Star formation Rate Tracers	23
1.4.2	The Cosmic Star Formation Rate Density	28
1.5	Active Galaxy Nuclei	29
1.6	The Radio Revolution	31
1.6.1	The Faint Radio Sky	32
1.6.2	The Faint Radio Population	35
1.7	This Thesis	37
1.8	The Future	39
2	The Nature of the Ultra-faint Radio Population	41
2.1	Introduction	42
2.2	Data	46
2.2.1	Radio Data	46
2.2.2	Near-UV to far-IR data	49

2.2.3	Spectroscopic Redshifts	51
2.2.4	X-ray data	52
2.3	Multi-Wavelength Cross-Matching	52
2.3.1	Radio Cross-Matching	54
2.3.2	Additional Cross-Matching	54
2.3.3	Redshifts of the Radio Sample	56
2.4	AGN Identification	60
2.4.1	HLAGN	63
2.4.2	MLAGN	67
2.4.3	AGN Identification Summary	73
2.5	Composition of the Ultra-Faint Radio Population	74
2.5.1	The Ultra-faint Radio Population	74
2.5.2	Euclidean-normalized Number Counts	76
2.5.3	Optically dark Sources	83
2.5.4	Implications for Next-Generation Radio Surveys	89
2.6	Summary & Future	91
2.A	AGN Diagnostics from SED Fitting	93
2.B	Comparison to 3 GHz VLA-COSMOS	94
2.B.1	Radio-excess AGN	95
2.B.2	SED-fitted AGN	96
2.B.3	Red, quiescent AGN	97
2.C	Incompleteness in the Multi-wavelength Photometry	98
2.C.1	X-ray AGN	98
2.C.2	MIR AGN	98
2.C.3	Radio-excess AGN	99
2.C.4	Summary	100
2.D	Final Counterpart Catalog	101
3	The Far-infrared/Radio Correlation for Dusty Star-forming Galaxies	105
3.1	Introduction	106
3.2	Observations & Methods	108
3.2.1	Submillimeter Observations	108
3.2.2	Radio Observations	109
3.2.3	Additional Multi-wavelength Data	110
3.2.4	SMG Redshifts and Physical Properties	111
3.2.5	Radio Stacking	113
3.3	Results	114
3.3.1	Radio Properties of AS2UDS	114

3.3.2	AGN in AS2UDS	119
3.3.3	(A lack of) Redshift Evolution in the FIRRC	121
3.3.4	Correlations with Physical Properties	125
3.4	Discussion	127
3.4.1	Previous Studies of the FIRRC	127
3.4.2	The FIRRC for SMGs	130
3.5	Conclusions	143
3.A	Stacking	144
3.B	Radio AGN in submm and radio-selected Samples	147
3.C	The FIRRC in Radio-selected Samples	149
4	Free-free Emission in High-redshift Star-forming Galaxies	153
4.1	Introduction	154
4.2	Observations & Data Reduction	156
4.2.1	COLD z	156
4.2.2	Ancillary Radio Observations	158
4.2.3	Ultra-violet to Submillimeter Observations	161
4.2.4	X-ray Observations	162
4.3	Continuum Sources	163
4.4	Multi-Wavelength Properties	168
4.4.1	Multi-wavelength Counterparts and Redshifts	168
4.4.2	Spectral Energy Distributions	171
4.4.3	X-ray and Mid-infrared AGN Signatures	171
4.5	34 GHz Source Counts	172
4.6	34 GHz Continuum Source Properties	177
4.6.1	Radio AGN	177
4.6.2	Radio Spectral Decomposition for Star-forming Galaxies	179
4.6.3	Line and Dust Continuum Subtraction	182
4.6.4	The Radio Spectra of High-redshift Star-forming Galaxies	183
4.6.5	Free-Free Star-Formation Rates	190
4.7	Free-free Emission with the SKA and ngVLA	193
4.8	Conclusions	195
4.A	Image Properties	197
4.A.1	Completeness	197
4.A.2	Peak versus Integrated Fluxes	198
4.A.3	Flux Boosting	199

4.B Spectral Energy Distributions	201
5 Probing Cosmic Star Formation With Radio Free-free Emission	205
5.1 Introduction	206
5.2 Data	209
5.2.1 Radio Data	209
5.2.2 Optical/FIR Data	211
5.3 Methods	212
5.3.1 Radio Stacking	212
5.3.2 Radio Spectral Decomposition	215
5.4 Results	216
5.4.1 The Typical Radio Spectrum of Radio-selected Galaxies	216
5.4.2 Free-free Emission in Optically-selected Galaxies . .	218
5.5 Discussion	223
5.5.1 Radio Star-formation Rates	223
5.5.2 A Lack of High-frequency Emission	225
5.5.3 The Cosmic Star-formation History	234
5.6 Conclusions	238
5.A Stacking	240
5.B The COSMOS $z = 5.3$ Protocluster	244
Bibliography	246
Summary	258
Samenvatting	265
Publications	272
Curriculum Vitae	275
Acknowledgements	277