From star-formation to recombination: expanding our view of the radio recombination line universe

Emig, K.L.

Author: Emig, K.L.
Title: From star-formation to recombination: expanding our view of the radio recombination line universe
Issue Date: 2021-04-29

From Star-Formation to Recombination

Expanding our View of the Radio Recombination Line Universe

From Star-Formation to Recombination
Expanding our View of the Radio Recombination Line Universe

Proefschrift

ter verkrijging van
de graad van Doctor aan de Universiteit Leiden,
op gezag van Rector Magnificus Prof. dr. ir. Hester Bijl,
volgens besluit van het College voor Promoties
te verdedigen op donderdag 29 April 2021 klokke 16:15 uur

door

Kimberly Lynn Emig

geboren te
Norristown, Pennsylvania
in 1989

Promotiecommissie

Promotores:	Prof. dr. A. G. G. M. Tielens Prof. dr. H. J. A. Röttgering
Overige leden:	Prof. dr. M. Haverkorn (Radboud Universiteit) Prof. dr. H. J. van Langevelde (Universiteit Leiden) Dr. F. J. Lockman (Green Bank Observatory) Prof. dr. R. Morganti (Rijksuniversiteit Groningen) Prof. dr. P. P. van der Werf (Universiteit Leiden)

ISBN 978-94-6419-187-5

A digital copy of this thesis can be found at: https://openaccess.leidenuniv.nl

Cover design: Veronica Emig, Skylar Tibbits, and Kimberly Emig.
The front cover shows the central (170 pc) starburst of the nearby galaxy NGC 4945 in ALMA 93 GHz continuum. The emission primarily arises from free electrons in ionized gas; at 2 pc resolution, super star clusters appear as point like sources. The back cover shows diffuse ionized gas, as observed with LOFAR at 142 MHz, in an area of roughly 2° × 4° in the Cygnus X star-forming region of the Milky Way.

To women and girls everywhere

Contents

1 Introduction **1**

1.1 Phases of the Interstellar Medium 3

1.1.1 The Cold, Diffuse ISM 5

1.1.2 Warm Ionized Media 6

1.1.3 Extragalactic Tracers of the ISM 6

1.2 (Clustered) Star Forming Regions 8

1.3 Radio Recombination Lines 9

1.3.1 High frequency recombination lines 11

1.3.2 Low frequency recombinations lines from cold partially ionized gas 13

1.3.3 Hydrogen RRLs from warm low-density ionized gas 15

1.3.4 Extragalactic observations 15

1.4 Telescopes 18

1.4.1 LOFAR 18

1.4.2 ALMA 21

1.5 In this thesis 22

1.6 Future Outlook 24

2 Low-Frequency Observations of Diffuse Ionized Gas in Cygnus X **27**

2.1 Introduction 28

2.2 Data 30

2.2.1 LOFAR observations & data processing 30

2.2.2 Ancillary Data 37

2.3 Continuum Emission 37

2.4 Mapping the physical properties of ionized gas 41

2.4.1 Fitting the free-free optical depth at 142 MHz 42

2.4.2 Mapping the free-free emission measure 42

2.5 Analyzing filaments 44

2.5.1 Identifying filaments 45

2.5.2 Fitting filament profiles 45

2.5.3 Filament properties 47

2.6 Discussion 51

2.6.1 Source of ionization of the filaments 52

2.6.2 Origin of the filaments 57

2.6.3 Comparing filament properties with [N II] findings 61
2.6.4 Connection to ELD ionized gas 61
2.6.5 Future LOFAR observations 62
2.7 Conclusions 62
2.A Additional fits to filament radial profile 65
2.B Ionizing Photons from Cyg OB2 65

3 Super Star Clusters in the Central Starburst of NGC 4945 69
3.1 Introduction 70
3.2 Observations 71
3.3 Continuum Emission 72
3.3.1 Point Source Identification 76
3.3.2 Point Source Flux Extraction 77
3.3.3 Free-free Fraction at 93 GHz 80
3.4 Recombination Line Emission 84
3.4.1 Line Emission from 0.7 $''$ resolution, Intermediate configuration Observations 89
3.5 Physical Properties of the Candidate Star Clusters 93
3.5.1 Size 93
3.5.2 Age 94
3.5.3 Temperature and Metallicity 94
3.5.4 Ionized Gas: Emission Measure, Density and Mass 96
3.5.5 Ionizing Photon Production and Stellar Mass 97
3.5.6 Gas Mass from Dust 100
3.5.7 Total Mass from Gas and Stars 100
3.6 Discussion 102
3.6.1 Discussion of uncertainties 102
3.6.2 Super Star Clusters 103
3.6.3 Cluster Mass Function 104
3.6.4 Ionizing Photons and Diffuse Ionized Gas 105
3.6.5 Role of the AGN 106
3.6.6 Total Burst of Star-formation 107
3.6.7 Star Clusters and the Central Wind 107
3.6.8 Comparison with NGC 253 108
3.7 Summary 108
3.A mm Wavelength Emission from Free-free and RRLs 111
3.A.1 Recombination Line Intensity 112
3.A.2 Continuum Intensity 113
3.A.3 Physical Properties 113
3.B Recombination Line Spectra of all Sources 114
3.C Spectral Energy distribution of all Sources 114

4 The first detection of radio recombination lines at cosmological distances **119**
4.1 Introduction . . . 120
4.2 Target . . . 121
4.3 Observations and data reduction . . . 122
4.4 Spectral processing . . . 123
4.4.1 Statistical identification . . . 125
4.5 Results . . . 126
4.5.1 Further validation . . . 126
4.6 Modelling and interpretation of RRL . . . 127
4.6.1 Intervening, dwarf-like galaxy . . . 131
4.6.2 AGN-driven outflow . . . 133
4.6.3 Hydrogen RRLs from the intervening IGM . . . 135
4.7 Conclusions . . . 135
4.A RRL Modelling for high radiation temperatures . . . 136

5 Searching for the largest bound atoms in space **139**
5.1 Introduction . . . 140
5.2 Spectroscopic Data Reduction . . . 142
5.2.1 HBA Bandpass . . . 142
5.2.2 Procedure . . . 143
5.3 Searching RRLs in redshift space . . . 145
5.3.1 Stacking RRLs . . . 146
5.3.2 Spectral cross-correlation . . . 147
5.3.3 Stack cross-correlation . . . 148
5.3.4 Validation with Synthetic Spectra . . . 148
5.4 Cassiopeia A . . . 152
5.4.1 Carbon RRL Results . . . 154
5.4.2 Hydrogen RRL Results . . . 157
5.5 M 82 . . . 160
5.6 3C 190 . . . 165
5.7 Discussion of Methods . . . 167
5.8 Conclusion . . . 169
5.A Subband spectra of Cas A . . . 170
5.B Spectral properties of M 82 applying M14 criteria . . . 170

Bibliography **179**

Samenvatting **189**

Summary **197**

List of Publications **207**

Curriculum Vitae **209**

Acknowledgements **213**