

Red Galaxies at High Redshift

Red Galaxies at High Redshift

Proefschrift

ter verkrijging van
de graad van Doctor aan de Universiteit Leiden,
op gezag van de Rector Magnificus prof. mr. P.F. van der Heijden,
volgens besluit van het College voor Promoties
te verdedigen op donderdag 27 september 2007
klokke 16.15 uur

door

Stijn Elisabeth Raphaël Wuyts

geboren te Mortsel
in 1980

Promotiecommissie

Promotores: Prof. dr. M. Franx
Prof. dr. P. G. van Dokkum (Yale University)

Referent: Dr. S. C. Trager (Rijksuniversiteit Groningen)

Overige leden: Prof. dr. P. T. de Zeeuw
Prof. dr. K. H. Kuijken
Dr. P. van der Werf
Dr. J. Schaye

Aan mijn ouders

Cover: Acryl on canvas by Imelda Wuyts

Table of contents

	Page
Chapter 1. Introduction	1
1.1 Large-scale structure formation	1
1.2 Galaxy formation	1
1.3 This thesis	3
Chapter 2. The detailed fundamental plane of two high-redshift clusters: MS 2053–04 at $z = 0.58$ and MS 1054–03 at $z = 0.83$	7
2.1 Introduction	8
2.2 Spectroscopy	9
2.2.1 Sample selection and observations	9
2.2.2 Basic reduction	9
2.2.3 Velocity dispersions	10
2.3 Imaging	11
2.3.1 Structural parameters	11
2.3.2 Error in the structural parameters	12
2.3.3 Visual and quantitative classifications	14
2.3.4 Transformation to rest-frame magnitude	14
2.4 The fundamental plane	16
2.4.1 Zero point and scatter	16
2.5 Correlations with other parameters	18
2.5.1 The color-magnitude relation	18
2.5.2 $H\beta$ linestrength	18
2.5.3 Location in the cluster	20
2.5.4 Galaxy mass and selection effects	20
2.5.5 Summary of correlations	21
2.6 Evolution of M/L ratio	21
2.7 Summary	23
Chapter 3. B-to-24 μm photometry of the GOODS-CDFS: multi-wavelength catalog and total IR properties of distant K_s-selected galaxies	27
3.1 Introduction	28
3.2 Observations	29
3.2.1 The GOODS Chandra Deep Field South	29
3.2.2 The ACS $BViz$ data	29
3.2.3 The ISAAC JHK_s data	29
3.2.4 The IRAC 3.6-8.0 μm data	29
3.2.5 The MIPS 24 μm data	30
3.3 Final images	30

3.3.1	Pixel scales and large scale backgrounds	30
3.3.2	Image quality and PSF matching	31
3.3.3	Zero points	33
3.3.4	Mosaicing and astrometry	34
3.3.5	Signal to noise and limiting depths	35
3.4	Source detection and photometry	36
3.4.1	K_s -band detection	36
3.4.2	Photometry	37
3.5	Redshifts	40
3.5.1	Spectroscopic redshifts	40
3.5.2	Photometric redshifts	41
3.6	Catalog parameters	42
3.7	Comparison to the GOODS-MUSIC catalog	43
3.7.1	Differences in data and strategy	43
3.7.2	Comparing photometry	45
3.7.3	Comparing photometric redshifts	45
3.8	Total IR properties of distant K_s -selected galaxies	46
3.8.1	Observed $24\ \mu\text{m}$ flux as function of observed colors	46
3.8.2	Total IR luminosity as function of rest-frame colors	48
3.9	Summary	52
Chapter 4. Optical spectroscopy of Distant Red Galaxies		55
4.1	Introduction	56
4.2	Sample selection	57
4.2.1	Pure $J - K$ selected sample	57
4.2.2	DRGs from other surveys	57
4.3	Observations	58
4.4	Data reduction	59
4.5	Results from optical spectroscopy of DRGs	60
4.5.1	Redshift determination, success rate, and bias	60
4.5.2	Optical spectra	60
4.5.3	Redshift distribution	63
4.6	Photometric redshifts	64
4.6.1	Method and template sets	64
4.6.2	Quality of photometric redshifts	65
4.7	The nature of low-redshift DRGs	66
4.8	Summary	69
Chapter 5. What do we learn from IRAC observations of galaxies at $2 < z <$		
3.5?		77
5.1	Introduction	78
5.2	Data, photometry and sample selection	79
5.2.1	Data	79
5.2.2	Photometry	80
5.2.3	Sample selection	81

5.3	SED modeling	81
5.4	Rest-frame optical to near-infrared color distribution	84
5.5	Constraints on stellar population properties at $2 < z < 3.5$: age, dust and mass	89
5.5.1	Predictions from stellar population synthesis models	89
5.5.2	Constraints on mass, dust and age from modeling our observed galaxies	93
5.6	Stellar mass - optical color relation	98
5.7	Summary	101
Chapter 6. Recovering stellar population properties and redshifts from broadband photometry of simulated galaxies: lessons for SED modeling		105
6.1	Introduction	106
6.2	The simulations	107
6.2.1	Main characteristics	107
6.2.2	Extracting photometry from the simulation output	110
6.2.3	The colors and SEDs of simulated and observed galaxies	111
6.3	SED modeling: methodology	113
6.4	Results from SED modeling at fixed redshift	114
6.4.1	Impact of mismatch between true and template SFH	114
6.4.2	Impact of attenuation	116
6.4.3	Impact of stellar metallicity	121
6.4.4	Impact of AGN contribution	122
6.4.5	Overall performance	123
6.4.6	Lessons for SED modeling	126
6.5	Results from SED modeling with free redshift	127
6.5.1	The photometric redshift code EAZY	128
6.5.2	Recovering redshifts and stellar population properties from broadband photometry	128
6.6	Summary	130
Chapter 7. Color distributions, number and mass densities of massive galaxies at $1.5 < z < 3$: comparing observations with merger simulations		135
7.1	Introduction	136
7.2	Overview of the observations	137
7.2.1	Fields, coverage, and depth	137
7.2.2	Redshifts and rest-frame photometry	138
7.2.3	Stellar masses	138
7.2.4	Star formation rates	139
7.3	Overview of the simulations	139
7.4	Sample selection	140
7.5	Methodology for cosmological context	141
7.6	The number density, mass density and mass function of galaxies with $\log M > 10.6$ at $1.5 < z < 3$	144
7.7	The color distribution of galaxies with $\log M > 10.6$ at $1.5 < z < 3$	146

7.7.1	The $U - V$ color distribution	146
7.7.2	The $V - J$ color distribution	148
7.7.3	$U - V$ versus $V - J$ color-color distribution	149
7.8	Specific star formation rate as a function of stellar mass	151
7.9	The abundance of massive galaxies at $1.5 < z < 3$: analysis by type	154
7.9.1	The number and mass density of massive ($\log M > 10.6$) quiescent red galaxies	154
7.9.2	The number and mass density of massive ($\log M > 10.6$) star-forming galaxies	157
7.9.3	The number and mass density of massive ($\log M > 10.6$) galaxies with $SFR/M > 1 \text{ Gyr}^{-1}$	158
7.9.4	The number and mass density of galaxies with $M > 10^{11} M_{\odot}$ and $U - V > 1.3$	158
7.10	Comments and caveats	159
7.10.1	Pair statistics	159
7.10.2	Dependence on stellar population synthesis code	161
7.10.3	Reproducing dusty red starbursts	161
7.10.4	Cosmic variance	163
7.11	Summary	163
	Nederlandse samenvatting	167
	Curriculum vitae	175
	Nawoord	177