



Universiteit  
Leiden  
The Netherlands

## From intracluster medium dynamics to particle acceleration

Zhang, X.

### Citation

Zhang, X. (2022, June 29). *From intracluster medium dynamics to particle acceleration*. Retrieved from <https://hdl.handle.net/1887/3421512>

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/1887/3421512>

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

# From intracluster medium dynamics to particle acceleration

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 29 juni 2022  
klokke 11.15 uur

door

**Xiaoyuan Zhang**

张啸远

geboren te Ningbo, China  
in 1992

**Promotor:** Prof.dr. J.S. Kaastra  
**Co-promotor:** Dr. A. Simionescu

**Promotiecommissie:** Prof.dr. H.J.A. Röttgering  
Prof.dr. H. Hoekstra  
Prof.dr. K.H. Kuijken  
Prof.dr. M.W. Wise (Universiteit van Amsterdam)  
Dr. N. Ota (Nara Women's University)

ISBN: 978-94-6423-861-7

©2022 Xiaoyuan Zhang

The cover is designed by Xiaoyuan Zhang. It is an image simulated from a power spectrum of a  $-11/3$  slope power law. Python modules used: TurbuStat and matplotlib.

*To my wife*



---

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Galaxy clusters and the intracluster medium . . . . .	1
1.1.1	X-ray instruments and observations . . . . .	3
1.2	Gas motions in the ICM . . . . .	4
1.2.1	Shocks and cold fronts as evidence of ICM dynamics	5
1.2.2	Quantifying ICM gas motions . . . . .	7
1.3	Nonthermal views of galaxy clusters . . . . .	11
1.3.1	Radio relics . . . . .	12
1.3.2	Radio halos . . . . .	12
1.4	Connecting the nonthermal to the thermal properties . . . .	13
1.4.1	X-ray - radio associations . . . . .	13
1.4.2	Accelerations mechanisms by gas motions . . . . .	16
1.5	This thesis . . . . .	17
1.6	Future prospects . . . . .	19
<b>2</b>	<b>X-ray study of the merging galaxy cluster Abell 3411-3412 with <i>XMM-Newton</i> and <i>Suzaku</i></b>	<b>21</b>
2.1	Introduction . . . . .	23
2.2	Data reduction . . . . .	25
2.2.1	XMM-Newton . . . . .	25
2.2.2	Suzaku . . . . .	27
2.2.3	Chandra . . . . .	27
2.3	Imaging analysis . . . . .	29
2.4	Spectral analysis . . . . .	30
2.4.1	XMM-Newton . . . . .	31
2.4.2	Suzaku . . . . .	34

2.4.3	XMM-Newton-Suzaku cross-calibration . . . . .	36
2.5	Results . . . . .	36
2.5.1	Properties of surface brightness discontinuities . . . . .	36
2.5.2	Global temperature . . . . .	40
2.5.3	Temperature profiles to the outskirts . . . . .	41
2.6	Discussion . . . . .	42
2.6.1	$T_{500}$ discrepancy . . . . .	42
2.6.2	Shock properties . . . . .	44
2.6.3	The mystery of the southern edge . . . . .	47
2.6.4	The location of the bow shock . . . . .	48
2.7	Conclusion . . . . .	50
2.A	Light curves of EPIC CCDs . . . . .	52
2.B	Soft proton modelling . . . . .	52
2.B.1	Spectral analysis . . . . .	53
2.B.2	Vignetting function . . . . .	55
2.B.3	Self-calibration . . . . .	56
2.C	Cosmic X-ray background . . . . .	59
2.C.1	Point-source flux and the $\log N - \log S$ relation . . . . .	60
2.C.2	Detection limit and CXB flux . . . . .	62
<b>3</b>	<b>Deep <i>Chandra</i> observations of merging galaxy cluster</b>	
	<b>ZwCl 2341+0000</b>	<b>67</b>
3.1	Introduction . . . . .	69
3.2	Observations and data analysis . . . . .	71
3.2.1	<i>Chandra</i> X-ray data . . . . .	71
3.2.2	GMRT and JVLA radio data . . . . .	78
3.3	Results . . . . .	81
3.3.1	General X-ray properties . . . . .	81
3.3.2	SE edge . . . . .	84
3.3.3	SW bays . . . . .	85
3.3.4	NE and western wings . . . . .	86
3.3.5	NW cone . . . . .	87
3.3.6	Bridge and northern outskirts . . . . .	89
3.4	Discussion . . . . .	90
3.4.1	Shock fronts and radio relics . . . . .	90
3.4.2	Conic subcluster . . . . .	92
3.4.3	The origin of the NE wing . . . . .	96
3.5	Conclusion . . . . .	97

3.A	JVLA B-configuration radio map . . . . .	99
3.B	Radio spectral index uncertainty map . . . . .	99
3.C	Temperature uncertainty map . . . . .	99
3.D	Projected surface brightness profile for a cone-shaped cold front . . . . .	101
<b>4</b>	<b>CIG 0217+70: A massive merging galaxy cluster with a large radio halo and relics</b>	<b>103</b>
4.1	Introduction . . . . .	104
4.2	Observations and data reduction . . . . .	105
4.3	Data analysis and results . . . . .	105
4.3.1	Spectral properties and X-ray redshift . . . . .	107
4.3.2	X-ray morphology and surface brightness discontinuities . . . . .	109
4.4	Discussion . . . . .	111
4.4.1	Radio halo scaling relations . . . . .	111
4.4.2	The western X-ray "channel" . . . . .	111
4.4.3	Possible merging scenario . . . . .	113
4.5	Conclusion . . . . .	113
<b>5</b>	<b>The <i>Planck</i> clusters in the LOFAR sky: Dynamic states and density fluctuations of the intracluster medium</b>	<b>115</b>
5.1	Introduction . . . . .	116
5.2	X-ray sample . . . . .	117
5.2.1	Sample for morphological analysis . . . . .	119
5.2.2	Sample for power spectral analysis . . . . .	119
5.3	Data reduction and spectral analysis . . . . .	120
5.3.1	XMM-Newton EPIC spectral analysis . . . . .	120
5.3.2	pn background scaling . . . . .	122
5.4	Morphological parameters . . . . .	123
5.4.1	Individual measurements . . . . .	124
5.4.2	Discrepancy in concentration parameter . . . . .	124
5.4.3	Discrepancy in centroid shift . . . . .	127
5.4.4	Relaxation score . . . . .	128
5.5	ICM density fluctuations on large scales . . . . .	128
5.5.1	Calculation of 2D surface brightness fluctuations . . . . .	128
5.5.2	$A_{2D}$ spectra and correlations with other parameters . . . . .	131
5.5.3	Turbulent velocity dispersion . . . . .	131



## Contents

---

5.6	Relation between radio halo power and ICM thermodynamic properties . . . . .	133
5.7	Discussion . . . . .	136
5.8	Conclusion . . . . .	137
5.A	Temperature measurements of the sample . . . . .	148
	<b>Bibliography</b>	<b>149</b>
	<b>Nederlandse Samenvatting</b>	<b>159</b>
	<b>English Summary</b>	<b>163</b>
	<b>List of publications</b>	<b>167</b>
	<b>Curriculum Vitae</b>	<b>171</b>
	<b>Acknowledgments</b>	<b>173</b>