



Universiteit
Leiden

The Netherlands

Planet formation through the lens of dynamics

Huang, S.

Citation

Huang, S. (2026, June 19). *Planet formation through the lens of dynamics*.
Retrieved from <https://hdl.handle.net/1887/4306860>

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/1887/4306860>

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

Planet Formation through the Lens of Dynamics

Proefschrift

ter verkrijging van
de graad van doctor aan de Universiteit Leiden,
op gezag van rector magnificus prof. dr. S. de Rijcke,
volgens besluit van het college voor promoties
te verdedigen op vrijdag 19 juni 2026
klokke 11:30 uur

door

Shuo Huang

geboren te Hefei, China
in 1998

Promotor:

Prof. dr. S. Portegies Zwart

Co-promotor:

Prof. dr. C. Ormel

Tsinghua University

Promotiecommissie:

Prof. dr. I. A. G. Snellen

Dr. M. Kenworthy

Prof. dr. E. Kokubo

National Astronomical Observa-
tory of Japan

Dr. Y. Miguel

Prof. dr. C. Dominik

Prof. dr. A. Petit

University of Amsterdam
Côte d’Azur Observatory

ISBN: 978-94-6534-449-2

Cover: Illustration of a planetary system before and after a giant impact, generated with the assistance of ChatGPT (OpenAI), based on an input image created by Shuo Huang using PowerPoint.

We all learn at different stages and speeds, and each of us has our own strengths and areas of expertise.

– Han Yu (c. 768–824), Tang dynasty

CONTENTS

1	Introduction	1
1.1	Planet formation	2
1.1.1	Protoplanet disk	3
1.1.2	Planet migration	4
1.2	Mean motion resonance	5
1.3	Planet architecture	7
1.3.1	Exoplanet systems	7
1.3.2	The Solar System	9
1.4	This Thesis	9
1.5	Outlook: confirm and characterize broken chains	11
2	When, where, and how many exoplanets end up in orbital resonances?	15
2.1	Introduction	16
2.2	Methodology	17
2.2.1	Disc model	18
2.2.2	Type I migration	19
2.2.3	Dynamics of resonance trapping	19
2.2.4	Mass-radius relations	20
2.2.5	A statistical model of resonant and non-resonant planets	22
2.3	Resonance Trapping criterion for the restricted 3-body problem	24
2.3.1	Theoretical Derivation	24
2.3.2	Comparison with simulation	25
2.4	MCMC analysis	27
2.4.1	Sample selection	27
2.4.2	Implication on planet-disc interaction from MCMC	29
2.5	Implications for planet formation	31
2.5.1	Fraction of resonant pairs	32
2.5.2	Upper limit on the disc surface density at resonance trapping	35
2.5.3	Migration barrier reflects the disc inner rim	36
2.6	Discussion	38
2.7	Conclusions	40
	Appendices	41
2.A	Results of the General disc model	41
2.B	MCMC performance examination	42
2.B.1	Tests without assuming a disc structure	43
2.B.2	Tests assuming a disc structure	45

3 The dynamics of the special resonance chain systems and their formation:	
TRAPPIST-1	47
3.1 Introduction	48
3.2 Model	50
3.2.1 Preliminaries and Terminology	50
3.2.2 Numerical integration	52
3.2.3 Planet-disc interaction	53
3.2.4 Tidal dissipation	56
3.3 Preliminary simulations	57
3.3.1 Planet b at the cavity edge (bC)	57
3.3.2 Formation imprints for planet c and g (bCc g I)	59
3.3.3 Planet d at the cavity edge (dCc g I)	60
3.3.4 Parameter variation for Objective I (dCc g I)	62
3.4 Trapping and escape of planets in 3BRs	63
3.4.1 Crossing and trapping of the three-body resonances (dCc g I c T)	65
3.4.2 Long term tidal dissipation (dCc g I c T)	67
3.5 Early cavity infall (dCc g I c L)	68
3.5.1 Disc repulsion on planets in the cavity	69
3.5.2 Parameter study (dCc g I c L)	70
3.6 Analysis	72
3.6.1 Trapping under convergent migration in MMRs	72
3.6.2 Eccentricity-period relation in 3BRs	73
3.7 Discussion	74
3.7.1 Model Assessment	74
3.7.2 Resonances Establishing and Breaking	75
3.7.3 Application to other systems	76
3.8 Conclusions	76
Appendices	78
3.A Lindblad torque	78
4 The dynamics of the broken resonance chain systems and their formation:	
the Solar System	79
4.1 Introduction and motivation	80
4.2 Model	82
4.2.1 Initial conditions	82
4.2.2 Giant planet instability	83
4.2.3 Theia and proto-Earth mass-radius calculation	83
4.3 Comparison with Solar system	85
4.4 Implications	88
4.5 Conclusions	89
Appendices	90
4.A Formation of a resonant chain in the pebble accretion and planetesimal ac- cretion models	90
4.B Parameter sensitivity	94
4.C Venus-Mars period ratio in the late collisional growth scenario	96

5 Birth stellar cluster dynamics matters: planet population synthesis with external photo-evaporation	99
5.1 Introduction	100
5.2 Methods	101
5.2.1 Cluster evolution	101
5.2.2 Disk model	103
5.2.3 Planet growth	104
5.2.4 Planet migration	107
5.3 Initial conditions and parameter choices	107
5.4 Results	109
5.4.1 Planet formation for two example stars	109
5.4.2 Planet population: Isolated versus clustered	111
5.4.3 Co-evolution between CJ formation and the cluster	113
5.5 Analytical criteria for CJ formation in the cluster	114
5.6 Discussion	115
5.6.1 Model assessment	115
5.6.2 Cold Jupiter and Neptune in observation	117
5.7 Conclusions	118
Appendices	118
5.A Planet population in isolated stars and a star cluster	118
 6 ALMA signature of closely-spaced pebble-accreting protoplanets in Transition disks	 121
6.1 Introduction	122
6.2 Methods	123
6.2.1 Dust transport including pebble accretion	123
6.2.2 Initial conditions	124
6.3 Pebble flux reduction	124
6.3.1 Pebble accretion efficiency	124
6.3.2 Dust cavity and ring structure	126
6.4 Two groups of planet-hosting transition disks	129
6.4.1 Below pebble isolation mass: GM Aur	130
6.4.2 Above pebble isolation mass: PDS 70	131
6.4.3 A sample of transition disks	132
6.5 Discussion	135
6.5.1 Model assessment	135
6.5.2 Feasibility of the "sweet spot" on the accretion map	136
6.5.3 Emerging the planet formation story in transition disks	137
6.5.4 Consequence for planet detection	138
6.6 Conclusions	138
Appendices	139
6.A Numerical treatment of pebble flux reduction	139
6.B Evaluating dust diffusion during pebble accretion	139
6.C Simulated continuum of GM Aur with three planets	140
6.D Profile of the gap opened by planet	141
6.E Quantify the morphology of dust rings	142

Summary	163
Nederlandse samenvatting	167
List of Publications	171
Curriculum Vitæ	173
Acknowledgments	175