



Universiteit  
Leiden  
The Netherlands

## Hierarchical systems

Hamers, A.S.

### Citation

Hamers, A. S. (2016, June 21). *Hierarchical systems*. Retrieved from <https://hdl.handle.net/1887/41202>

Version: Not Applicable (or Unknown)

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/41202>

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

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/41202> holds various files of this Leiden University dissertation

**Author:** Hamers, Adrian Sven

**Title:** Hierarchical systems

**Issue Date:** 2016-06-21

# Hierarchical Systems

Proefschrift

ter verkrijging van  
de graad van Doctor aan de Universiteit Leiden,  
op gezag van Rector Magnificus prof. mr. C.J.J.M. Stolker,  
volgens besluit van het College voor Promoties  
te verdedigen op dinsdag 21 juni 2016  
klokke 13:45 uur

door

**Adrian Sven Hamers**  
geboren te Utrecht  
in 1988

Promotiecommissie

Promotor: Prof. dr. Simon Portegies Zwart (Universiteit Leiden)  
Co-Promotor: Prof. dr. Hagai Perets (Israel Institute of Technology)

Overige leden: Prof. dr. Pau Amaro-Seoane (Max Planck Institute for Gravitational Physics)  
Prof. dr. Rosemary Mardling (Monash University)  
Prof. dr. Alice Quillen (University of Rochester)  
Prof. dr. Huub Röttgering (Universiteit Leiden)  
Prof. dr. Scott Tremaine (Institute for Advanced Study)

ISBN: 978-94-6233-304-8  
© 2016 Adrian S. Hamers

Dit proefschrift werd financieel ondersteund door NWO, NOVA en het Leids Kerkhoven Bosscha fonds.

*Continuing in the family line of physicists*



*The endeavor to understand is the first and only basis of virtue.*  
—Baruch Spinoza



# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Gravity	1
1.2	History of the $N$ -body problem	2
1.3	Hierarchies in nature	3
1.4	Secular evolution	6
1.4.1	Principles	6
1.4.2	Implications	8
1.5	This thesis	9
1.5.1	Chapter 2 – Relativistic dynamics around an SBH	9
1.5.2	Chapter 3 – Planetesimals in the GC	12
1.5.3	Chapter 4 – Secular evolution of hierarchical quadruple systems	12
1.5.4	Chapter 5 – Explaining the lack of circumbinary planets around short-period binaries	13
1.5.5	Chapter 6 – Secular evolution of hierarchical multiple systems	13
1.5.6	Chapter 7 – Hot Jupiters in multiplanet systems	13
<b>2</b>	<b>Relativistic dynamics of stars near a supermassive black hole</b>	<b>15</b>
2.1	Introduction	16
2.2	Time-scales	17
2.3	Method	20
2.4	Orbital evolution below the SB; small- $N$ simulations	22
2.4.1	Initial conditions	22
2.4.2	Qualitative behaviour	23
2.4.3	Capture rates	24
2.4.4	Eccentricity oscillations below the SB	25
2.4.5	Diffusion in angular momentum above and below the SB	29
2.5	Dynamical evolution of the S-stars	36
2.5.1	Initial conditions	36
2.5.2	Orbital evolution	38
2.5.3	Tidally disrupted and ejected stars	42
2.5.4	Diffusion coefficients	42
2.5.5	A new criterion for the location of the barrier	50
2.6	Steady-state distribution	51

2.6.1	Analytic solutions . . . . .	54
2.6.2	Numerical solutions . . . . .	58
2.7	Discussion . . . . .	62
2.7.1	Limits on the typical S-star age from the $N$ -body simulations . . . . .	62
2.7.2	S-star relaxation times for different field-star models . . . . .	63
2.7.3	Generalizations to other galactic nuclei . . . . .	66
2.7.4	Caveats of TPI . . . . .	68
2.7.5	Location of the sign change of $\langle \Delta \ell \rangle$ at high $\ell$ . . . . .	69
2.7.6	Comparison of steady-state solutions . . . . .	69
2.8	Conclusions . . . . .	73
2.A	Simple tests of TPI . . . . .	75
2.A.1	Test stars orbiting the SBH . . . . .	75
2.A.2	Test stars orbiting a field star that orbits the SBH . . . . .	78
2.B	Dependence of the NRR diffusion coefficients on $\gamma$ . . . . .	78
2.C	Extrapolating the shape of the cumulative eccentricity distribution for the S-star simulations . . . . .	81
2.D	Dependence of derived diffusion coefficients on time lag in the simulations . . . . .	83
2.E	Steady-state solutions to the Fokker-Planck equation . . . . .	83
2.E.1	Solution of the steady-state equation . . . . .	83
2.E.2	Analytic expressions for the diffusion coefficients . . . . .	85
2.E.3	Explicit analytic steady-state solutions . . . . .	85
2.F	$N$ -body simulations with $\gamma = 1$ . . . . .	86
2.G	Equivalence of two critical radii . . . . .	88
<b>3</b>	<b>Probing the formation of planetesimals in the Galactic Centre using Sgr A* flares</b> <b>91</b>	
3.1	Introduction . . . . .	92
3.2	Setting the stage . . . . .	93
3.2.1	Models of the GC . . . . .	93
3.2.2	Disc models . . . . .	96
3.3	Stripping planetesimals from stars in the GC . . . . .	97
3.3.1	Stripping by the SBH . . . . .	97
3.3.2	Stripping by gravitational encounters with other stars . . . . .	99
3.4	Dynamics of planetesimals orbiting the SBH . . . . .	103
3.4.1	Fokker-Planck equation . . . . .	103
3.4.2	Boundary and initial conditions . . . . .	105
3.4.3	Results: distributions and disruption rates . . . . .	105
3.5	Discussion . . . . .	117
3.5.1	Comparison to observations: constraints on $N_{a/*}$ . . . . .	117
3.5.2	Internal scattering of planetesimals by planets . . . . .	117
3.5.3	Scaling of the disruption rate: tidal disruption of planets . . . . .	117
3.5.4	Changes of the stellar orbit prior to stripping . . . . .	119
3.5.5	Special case: a burst of flares? . . . . .	120
3.6	Conclusions . . . . .	124
3.A	Planetesimal stripping . . . . .	126
3.A.1	Stripping by the SBH . . . . .	126
3.A.2	Stripping by gravitational encounters . . . . .	127

3.B	Terms appearing in the Fokker-Planck equation . . . . .	128
3.B.1	Gravitational scattering flux . . . . .	128
3.B.2	Flux into the loss cone . . . . .	129
3.B.3	Collision flux . . . . .	131
3.C	Approximate semi-analytic solutions to the time-dependent Fokker-Planck equation . . . . .	133
3.D	Scaling of the disruption rate . . . . .	134
<b>4</b>	<b>Secular dynamics of hierarchical quadruple systems: the case of a triple system orbited by a fourth body</b>	<b>137</b>
4.1	Introduction . . . . .	138
4.2	Methods . . . . .	139
4.2.1	Expansion of the Hamiltonian . . . . .	139
4.2.2	Orbit averaging . . . . .	142
4.2.3	Equations of motion and numerical algorithm . . . . .	142
4.2.4	The importance of the octupole-order cross terms . . . . .	144
4.2.5	Comparisons to direct $N$ -body integrations . . . . .	150
4.3	Global evolution of highly hierarchical systems . . . . .	151
4.3.1	Examples: A and B initially coplanar . . . . .	152
4.3.2	Examples: A and B initially highly inclined . . . . .	155
4.3.3	Qualitative trends . . . . .	156
4.3.4	Quantitative dependence on $\mathcal{R}_0$ . . . . .	157
4.3.5	Behaviour near $\mathcal{R}_0 = 1$ . . . . .	161
4.3.6	General relativistic effects . . . . .	161
4.4	Discussion . . . . .	163
4.4.1	Application: planetary systems . . . . .	163
4.4.2	Application: observed stellar quadruples . . . . .	168
4.5	Conclusions . . . . .	171
4.A	The Hamiltonian for hierarchical quadruple systems . . . . .	175
4.A.1	Hierarchical triple system orbited by a fourth body . . . . .	175
4.A.2	Two binaries orbiting each other . . . . .	182
4.B	Test of the SecularQuadruple algorithm for three-body systems . . . . .	184
<b>5</b>	<b>A triple origin for the lack of tight coplanar circumbinary planets around short-period binaries</b>	<b>187</b>
5.1	Introduction . . . . .	188
5.2	Methods and assumptions . . . . .	190
5.3	The planet-shielding effect . . . . .	191
5.3.1	<i>Kepler</i> transiting circumbinary systems . . . . .	191
5.3.2	A triple with a shrinking inner binary orbit . . . . .	198
5.4	Planets in triples with short-period inner binaries . . . . .	201
5.4.1	Initial conditions . . . . .	201
5.4.2	Results . . . . .	209
5.5	Discussion . . . . .	220
5.5.1	An approximate analytic condition for planet shielding – implications for other systems . . . . .	220

5.5.2	Shielding of the planetary orbit by the inner binary . . . . .	220
5.5.3	The fate of planets with unstable orbits . . . . .	221
5.5.4	Implications for planets around blue straggler stars . . . . .	222
5.5.5	Approximations in the integrations . . . . .	222
5.5.6	Other dissipative effects . . . . .	223
5.6	Conclusions . . . . .	224
5.A	<i>Kepler</i> transiting circumbinary planets . . . . .	226
5.B	Magnetic braking in triples . . . . .	228
<b>6</b>	<b>Secular dynamics of hierarchical multiple systems composed of nested binaries, with an arbitrary number of bodies and arbitrary hierarchical structure</b>	<b>231</b>
6.1	Introduction . . . . .	232
6.2	The generalized Hamiltonian for hierarchical multiple systems . . . . .	234
6.2.1	Definition and description of the system . . . . .	234
6.2.2	The expanded Hamiltonian . . . . .	236
6.2.3	Orbit averaging . . . . .	237
6.2.4	General implications . . . . .	238
6.2.5	Numerical algorithm . . . . .	242
6.3	Tests: S-type multiplanet systems in single and multiple stellar systems . . . . .	243
6.3.1	Single-star systems . . . . .	243
6.3.2	Binary-star systems . . . . .	255
6.3.3	Triple-star systems . . . . .	268
6.4	Secular constraints in observed systems . . . . .	273
6.4.1	30 Arietis . . . . .	273
6.4.2	Mizar and Alcor . . . . .	285
6.5	Discussion . . . . .	286
6.5.1	The validity of orbit averaging . . . . .	286
6.5.2	Short-term instabilities . . . . .	288
6.6	Conclusions . . . . .	288
6.A	Derivation of the expanded and orbit-averaged hierarchical multiple Hamiltonian	291
6.A.1	Description of the system structure . . . . .	291
6.A.2	Expansion of the potential energy . . . . .	297
6.A.3	Derivation of the kinetic energy term . . . . .	301
6.A.4	Rewriting summations in the Hamiltonian . . . . .	304
6.A.5	Orbit averaging . . . . .	334
6.A.6	Estimate of the importance of non-binary terms for nested planetary systems . . . . .	344
6.A.7	Ad hoc expression for the 1PN Hamiltonian . . . . .	348
<b>7</b>	<b>Implications of secular evolution on high eccentricity migration giving rise to hot Jupiters in multiplanet systems</b>	<b>351</b>
7.1	Introduction . . . . .	352
7.2	Methods and assumptions . . . . .	354
7.2.1	Notations and overview . . . . .	354
7.2.2	Secular dynamics . . . . .	354
7.2.3	Tidal evolution . . . . .	354

7.3	Verification of the secular method with $N$ -body integrations . . . . .	356
7.3.1	Initial conditions . . . . .	356
7.3.2	Results . . . . .	357
7.3.3	Orbit crossings . . . . .	360
7.4	Conditions for producing high eccentricities due to secular evolution . . . . .	361
7.4.1	Dependence of the maximum eccentricities on the AMD with varying eccentricities and inclinations . . . . .	361
7.4.2	Dependence of the maximum eccentricities on the semimajor axes ratios	365
7.4.3	Tidal disruption versus tidal dissipation . . . . .	371
7.5	Population synthesis . . . . .	380
7.5.1	Initial conditions . . . . .	381
7.5.2	Stopping conditions . . . . .	382
7.5.3	Results . . . . .	382
7.6	Discussion . . . . .	398
7.6.1	HJ contribution and comparisons to other variants of high- $e$ migration .	398
7.7	Conclusions . . . . .	399
	<b>Samenvatting</b>	<b>403</b>
	<b>Summary</b>	<b>409</b>
	<b>Bibliography</b>	<b>414</b>
	<b>Curriculum Vitae</b>	<b>423</b>
	<b>List of publications</b>	<b>425</b>
	<b>Acknowledgements</b>	<b>427</b>

