

Contents

1	Introduction	1
1.1	The Galaxy	1
1.2	Dark Matter	2
1.3	Galactic Surveys	4
1.4	Dynamics	5
1.4.1	Angle-Action Coordinates	6
1.4.2	Angle-Action Coordinates in Galactic Dynamics	6
1.5	Dynamical Modelling of the Galaxy	7
1.6	Tidal Streams	9
1.6.1	Constraining the Galactic Potential with Tidal Streams	10
1.7	Overview of Thesis	11
1.7.1	Angle-Action Estimation in a General Axisymmetric Potential	12
1.7.2	Actions, Angles and Frequencies from Numerically Integrated Orbits	12
1.7.3	Action Estimation Using a Triaxial Stäckel Approximation	13
1.7.4	Stream-Orbit Misalignment	13
1.7.5	Stream Modelling in Angle-Frequency Space	14
1.7.6	Determining the Velocity Dispersion of the Thick Disc	14
1.7.7	Extended Distribution Functions for the Galactic Disc	14
	References	15
2	Angle-Action Estimation in a General Axisymmetric Potential	19
2.1	Introduction	19
2.1.1	Angle-Action Variables	20
2.2	Actions and Angles in a Stäckel Potential	21

2.3	Estimating Actions in a Fitted Stäckel Potential	24
2.3.1	Procedure	26
2.3.2	Discussion.	27
2.3.3	Application	28
2.3.4	Geneva-Copenhagen Survey	36
2.3.5	Prolate Axisymmetric Potentials	40
2.4	Polar Adiabatic Approximation	43
2.5	Ellipsoidal Adiabatic Approximation.	44
2.6	Axisymmetric Stäckel Fudge	46
2.7	Iterative Torus Machine	47
2.8	Method Comparison	49
2.8.1	Total Angular Momentum	49
2.8.2	Single Torus	50
2.8.3	Multiple Tori	50
2.8.4	Computational Cost	53
2.9	Conclusions.	53
2.9.1	Future Work	55
	References	55
3	Actions, Angles and Frequencies from Numerically	
	Integrated Orbits	57
3.1	Introduction.	57
3.2	Formalism.	58
3.2.1	Toy Potentials	59
3.2.2	Generating Function	60
3.2.3	Choice of N_T , N_{max} and T	63
3.3	Example	66
3.3.1	Accuracy of the Method	69
3.3.2	Near-Resonant Orbit	71
3.4	Application	72
3.4.1	An Example Orbit	72
3.4.2	A Typical Constant Energy Surface	74
3.5	Discussion.	75
3.5.1	Relation to Previous Work	75
3.5.2	Possibility of Using Stäckel Tori	76
3.5.3	Resonances and Chaos	77
3.6	Conclusions.	80
3.6.1	Future Work	81
	References	82

4	Action Estimation Using a Triaxial Stäckel Approximation	85
4.1	Introduction	85
4.2	Triaxial Stäckel Potentials	86
4.2.1	Ellipsoidal Coordinates	86
4.2.2	Stäckel Potentials	88
4.3	Triaxial Stäckel Fudge	89
4.3.1	Relation to Axisymmetric Case	91
4.4	Tests	93
4.4.1	Selection of Coordinate System	93
4.5	Accuracy	96
4.5.1	Surfaces of Section	100
4.6	A Triaxial Model with Specified DF	101
4.6.1	Normalization	102
4.6.2	The Jeans Equation	103
4.7	Conclusions	105
4.7.1	Future Work	106
	References	107
5	Stream-Orbit Misalignment	109
5.1	Introduction	109
5.2	Known Streams	110
5.2.1	GD-1	111
5.2.2	Orphan	111
5.2.3	Anticenter	111
5.2.4	NGC 5466	112
5.2.5	Palomar 5	112
5.2.6	Sagittarius	112
5.2.7	Acheron, Cocytos, Lethe and Styx	113
5.2.8	Aquarius	113
5.2.9	Cetus, Virgo and Triangulum	113
5.3	Tidal Streams in Angle-Action Coordinates	114
5.4	The Problem with Orbit-Fitting	116
5.4.1	Known Streams	120
5.5	Mass Dependence	121
5.6	Anisotropies in the Action Distribution	126
5.7	Errors in Potential Parameters	128
5.8	Conclusions	131
5.8.1	Future Work	132
	References	133
6	Stream Modelling in Angle-Frequency Space	135
6.1	Streams in Angle-Action Space	137
6.1.1	A Simulation	137

6.2	Algorithm	141
6.3	Test	142
6.3.1	Error Estimation.	144
6.4	Errors in Stream Data	145
6.5	Data Averaging in Observable Space	150
6.6	A Probabilistic Approach	152
6.7	Model.	157
6.7.1	MCMC.	158
6.8	Tests of Probabilistic Approach	159
6.8.1	No Contaminants	162
6.8.2	Inclusion of Outliers	162
6.9	Discussion.	165
6.10	Conclusions.	166
6.10.1	Future Work	168
	References	168
7	Determining the Velocity Dispersion of the Thick Disc.	171
7.1	Introduction.	171
7.2	Probability Plot Method	172
7.3	Dynamical Galaxy Models.	174
7.4	MB Method.	178
7.5	Errors	179
7.5.1	Observational Errors.	179
7.5.2	Poisson Noise and Systematics.	180
7.6	Comparison with Other Work	182
7.7	Conclusions.	184
	References	185
8	Extended Distribution Functions for the Galactic Disc	187
8.1	Introduction.	187
8.2	Model.	189
8.2.1	ISM Metallicity	189
8.2.2	Extended Distribution Function	190
8.2.3	Full $\mathcal{D}_F$ Evolution with a 3D Action-Space Kernel	192
8.2.4	Performing the Integrals	193
8.2.5	Halo $\mathcal{E}_{DF}$	194
8.3	Data	195
8.3.1	Geneva-Copenhagen Survey	195
8.3.2	SEGUE G dwarfs.	196
8.3.3	Gilmore-Reid Density Curve	197

8.4	Selection Functions.	197
8.4.1	GCS Selection Function	199
8.4.2	SEGUE Selection Function	199
8.4.3	Using Minimal Knowledge of the Selection Function	200
8.5	Choice of Parameters	202
8.6	Results	204
8.6.1	Sampling Mock Catalogues	205
8.6.2	Apparent Magnitude Cut	205
8.6.3	GCS	207
8.6.4	SEGUE G dwarfs	212
8.7	Conclusions	216
8.7.1	Future Work	217
	References	218
9	Conclusions	221
9.1	Overview	221
9.1.1	Angle-Action Estimation in a General Axisymmetric Potential	221
9.1.2	Actions, Angles and Frequencies from Numerically Integrated Orbits	222
9.1.3	Action Estimation Using a Triaxial Stäckel Approximation	222
9.1.4	Stream-Orbit Misalignment	223
9.1.5	Stream Modelling in Angle-Frequency Space	223
9.1.6	Determining the Velocity Dispersion of the Thick Disc	224
9.1.7	Extended Distribution Functions for the Galactic Disc	224
9.2	Context	225
9.2.1	Galactic Structure	225
9.2.2	Galactic History	226
9.3	Future Work	227
	References	228
	Appendix A: Computing the Angle-Action Variables in a Axisymmetric Stäckel Potential	229
	Appendix B: Derivation of Best-Fitting Stäckel Potential Functions	233
	Appendix C: Angle-Actions in the Isochrone Potential	235
	Appendix D: Symmetries	237

Appendix E: Angles and Frequencies from Stäckel Fudge	241
Appendix F: A Family of Two-Parameter Potentials	245
Appendix G: Finding Angles and Frequencies for Stream Particles . . .	251
Appendix H: EDF Normalization	255
Appendix I: Markov Chain Monte Carlo EDF Parameter Search	257
Curriculum Vitae	261

Dynamics of the Milky Way

Tidal Streams and Extended Distribution Functions for
the Galactic Disc

Sanders, J.

2015, XXII, 264 p. 85 illus., 35 illus. in color., Hardcover

ISBN: 978-3-319-18771-6