Sam Hadden

ASTROPHYSCICIST

Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, 14th floor, Toronto, ON M5S 3H8

+1-(647) 674-9237 | hadden@cita.toronto.edu | shadden.github.io | github.com/shadden

Professional Experience

Canadian Institute for Theoretical Astrophysics — *Toronto, ON*
Postdoctoral Fellow — *Sept 2021 - Present*

Center for Astrophysics | Harvard & Smithsonian — *Cambridge, MA*
CfA Fellow — *July 2018 - August 2021*
Postdoctoral Researcher — *July 2017 - July 2018*

Education

Northwestern University — *Evanston, IL*
PhD in Physics & Astronomy — *September 2011 - Sept 2017*

- **Thesis:** "Characterizing Kepler's Multiplanet Systems with Transit Timing Variations"
- **Advisor:** Yoram Lithwick

Purdue University — *West Lafayette, IN*
BSc in Physics & Mathematics — *September 2007 - May 2011*

Awards & Fellowships

2021 **CITA Postdoctoral Fellowship**, Canadian Institute for Theoretical Astrophysics
2018 **CfA Postdoctoral Fellowship**, Center for Astrophysics | Harvard & Smithsonian
2015 **Earth & Space Science Graduate Fellowship**, NASA

Research Interests

- Exoplanet and solar system formation and evolution
- Nonlinear and chaotic dynamics of Hamiltonian systems
- Exoplanet characterization & demographics
- Numerical methods for N-body dynamics
- Bayesian inference methods

Open-source Software

CELMECH
Open-source Python code for celestial mechanics.
Extensively documented at **celmech.readthedocs.io**
Designed to interface with the `rebound` N-body code.

TTV2FAST2FURIOUS
Open-source Python code for fitting transit timing variation
Available at **github.com/shadden/TTV2Fast2Furious**

Publications

38 papers, 30 as first to third author, 6 student led

LEAD AUTHOR

1. **Hadden, S.**, "Action-Angle Variables for Axisymmetric Potentials via Birkhoff Normalization", 2024, ApJ, 972, 64
2. **Hadden, S.** & Tremaine, S., "Scattered Disc Dynamics: The Mapping Approach", 2024, MNRAS, 527, 2

3. **Hadden, S.** & Tamayo, D., "`celmech`: A Python Package for Celestial Mechanics", 2022, AJ, 164, 179
4. **Hadden, S.** & Payne, M. J., "Modeling Radial Velocity Data of Resonant Planets to Infer Migration Histories", 2020, AJ, 160, 106
5. **Hadden, S.**, "An Integrable Model for the Dynamics of Planetary Mean-motion Resonances", 2019, AJ, 158, 238
6. **Hadden, S.**, Barclay, T., Payne, M. J., Holman, M. J., "Prospects for TTV Detection and Dynamical Constraints with TESS", 2019, AJ, 158, 146
7. **Hadden, S.** & Lithwick, Y., "A Criterion for the Onset of Chaos in Systems of Two Eccentric Planets", 2018, AJ, 156, 95
8. **Hadden, S.**, Li, G., Payne, M. J., Holman, M. J., "Chaotic Dynamics of Trans-Neptunian Objects Perturbed by Planet Nine", 2018, AJ, 155, 249
9. **Hadden, S.** & Lithwick, Y., "Kepler Planet Masses and Eccentricities from TTV Analysis", 2017, AJ, 154, 5
10. **Hadden, S.** & Lithwick, Y., "Numerical and Analytical Modeling of Transit Timing Variations", 2016, ApJ, 828, 44
11. **Hadden, S.** & Lithwick, Y. "Densities and Eccentricities of 139 Kepler Planets from Transit Time Variations", 2014, ApJ, 787, 80

Student Lead Author

1. Chow, I. & **Hadden, S.**, "Influence of Modeling Assumptions on the Inferred Dynamical State of Resonant Systems: A Case Study of the HD 45364 System", 2024, submitted
2. Lammers, C., **Hadden, S.**, Murray, N., "The instability mechanism of compact multiplanet systems", 2024, ApJ, 972, 53
3. Lammers, C., **Hadden, S.**, Murray, N., "Intra-system Uniformity: A Natural Outcome of Dynamical Sculpting", 2023, MNRAS, 525, 66
4. Rath, J., **Hadden, S.**, Lithwick, Y., "The Criterion for Chaos in Three-planet Systems", 2022, ApJ, 932, 61
5. Murray, Z., **Hadden, S.**, Holman, M. J., "The Effects of Disk-induced Apsidal Precession on Planets Captured into Mean Motion Resonance", 2022, ApJ, 932, 61
6. Goldberg, M., **Hadden, S.**, Payne, M. J., Holman, M. J., "Prospects for Refining Kepler TTV Masses using TESS Observations", 2019, AJ, 157, 4

2nd & 3rd Author

1. Lin, J. ,Dudiak, I. , **Hadden, S.**, & Tamayo, D. "Creating Pileups of Eccentric Planet Pairs Wide of MMRs Through Divergent Migration", 2024, submitted
2. Wu, Y., **Hadden, S.**, Dewberry, J., et al, "Eccentricities of Close Stellar Binaries", 2024, submitted
3. Tamayo, D. & **Hadden, S.**, "A Unified, Physical Framework for Mean Motion Resonances", 2024, submitted
4. Lammers, C., ; Cranmer, M., **Hadden, S.**, et al. "Accelerating Giant Impact Simulations with Machine Learning", 2024, AJ, 975, 228
5. Abbot, D. S., Hernandez, David M., **Hadden, S.**, et al., "Simple physics and integrators accurately reproduce Mercury instability statistics", 2023, AJ, 944, 190
6. Hernandez, D. M., Zeebe, R. E., **Hadden, S.**, "Stepsize Errors in the N-body Problem: Discerning Mercury's True Possible Long-term Orbits", 2022, MNRAS, 510, 4302
7. Abbot, D. S., Webber, R. J., **Hadden, S.**, et al., "Rare Event Sampling Improves Mercury Instability Statistics", 2021, ApJ, 923, 236
8. Bhaskar, H., Li, G., **Hadden, S.**, et al., "Mildly Hierarchical Triple Dynamics and Applications to the Outer Solar System", 2021, AJ, 161, 48

9. Yee, S. W., Tamayo, D., **Hadden, S.**, Winn, J. N., "How Close are Compact Multi-Planet Systems to the Stability Limit?" , 2021, AJ, 162, 55
10. Tamayo, D., Cranmer, M., **Hadden, S.**, et al., "Predicting the Long-Term Stability of Compact Multiplanet Systems", 2020, PNAS, 117, 18194
11. Hernandez D. M., **Hadden, S.**, Makino, J., "Are Long-term N-body Simulations Reliable?", 2020, MNRAS, 493, 191
12. Li, G., **Hadden, S.**, Payne, M. J., Holman, M. J., "The Secular Dynamics of TNOs and Planet Nine Interactions", 2018, AJ, 156, 263
13. Lyutikov, M. & **Hadden, S.**, "Relativistic Magnetohydrodynamics in One Dimension", 2012, Phys. Rev. E, 85, 026401

Contributing Author

1. Abbot, D. S., Webber, R. J., et al. including **Hadden, S**, "Mercury's chaotic secular evolution as a subdiffusive process", 2024, ApJ, 967, 2
2. Cloutier, R., Greklek-McKeon, M. , et al. including **Hadden, S**, "Masses, Revised Radii, and a Third Planet Candidate in the "Inverted" Planetary System Around TOI-1266", 2024, MNRAS, 527, 3
3. Lu, T., Rein, H., et al. including **Hadden, S.**, "Self-consistent Spin, Tidal, and Dynamical Equations of Motion in the REBOUNDx Framework", 2023, AJ, 948, 41
4. Cranmer, M., Tamayo, D., Rein, Hanno., et al. including **Hadden, S**, "A Bayesian Neural Network Predicts the Dissolution of Compact Planetary Systems" 2021, PNAS, 118, 40
5. Kostov, V. B., Schlieder, J. E., Barclay, T., et al. including **Hadden, S.** "The L 98-59 System: Three Transiting, Terrestrial-size Planets Orbiting a Nearby M Dwarf" 2019, AJ, 158, 32
6. Quinn, S. N., Becker, J. C., Rodriguez, J. E., **Hadden, S.**, et al., "Near-resonance in a System of sub-Neptunes from TESS" 2019, AJ, 158, 177
7. Rodriguez, J. E., Becker, J. C., Eastman, J., **Hadden, S.**, "A Compact Multi-Planet System With A Significantly Misaligned Ultra Short Period Planet", 2018, AJ, 156, 245
8. Mann, A., Dupuy, T., Muirhead, P., et al. including **Hadden, S.**, "The Gold Standard: Accurate Stellar and Planetary Parameters for Eight Kepler M Dwarf Systems Enabled by Parallaxes", 2017, AJ, 153, 267

Student Advising & Mentoring

Summary: 10 student projects, 6 student-led papers

Gurman Sachdeva — *Univ. of Toronto*

Supervisor, AST 425 research project — *2024*

- Implementing secular equations of motion for hierarchical planetary systems in `celmech` code
- Currently a Univ. of Toronto undergraduate student

Ethan Shore — *Univ. of Toronto*

Supervisor, AST 425 research project — *2023-2024*

- Dynamical modeling of planetary system instabilities leading to free-floating planets

Audrey Burggraf — *Univ. of Toronto*

Supervisor, CITA SURF summer undergraduate research project — *2023*

- Modeling astrometric signals of multi-planet systems

Caleb Lammers — *Univ. of Toronto*

Co-supervisor with Prof. Norm Murray, undergraduate research — *2022-2023*

- Used the `celmech` code to determine the causes of dynamical instability in multi-planet systems
- Authored paper "**The instability mechanism of compact multiplanet systems**"
- Explored the role of giant impacts in producing intra-system uniformity
- Authored paper "**Intra-system uniformity: a natural outcome of dynamical sculpting**"
- Currently a Princeton University graduate student

Michael Poon — *Univ. of Toronto*

Co-supervisor with Prof. Hanno Rein, graduate research — *2021 - 2022*

- Implementing time-transformed symplectic integration method for in the `rebound` N-body code
- Currently a Univ. of Toronto graduate student

Ian Chow — *Univ. of Toronto*

Supervisor, AST 425 undergraduate research project/CITA SURF summer research — *2021 - 2024*

- Fitting radial velocity data of planets in mean motion resonance using N-body simulations
- AST 425 project awarded department's 2022 Smith Solis Research Scholarship
- Authored paper **"Influence of Modeling Assumptions on the Inferred Dynamical State of Resonant Systems"**
- Currently a Western University graduate student

Zach Murray — *CfA*

Supervisor, graduate student research project — *2020 - 2021*

- Analytical and N-body dynamical modeling of planet migration and resonance capture.
- Authored paper **"The Effects of Disk-induced Apsidal Precession on Planets Captured into Mean Motion Resonance"**

Daniel Yahalomi — *CfA*

Joint supervisor with Dr. Sam Quinn, post-baccalaureate research project — *2019*

- Joint analysis of radial velocity and transit timing data for a planetary system
- Presented at **AAS 235 Meeting**
- Currently a Columbia Unversity graduate student

Max Goldberg — *CfA*

Supervisor, undergraduate summer research project — *2019*

- Analysis of prospects for TESS observations to improve mass and orbit constrains for Kepler planets exhibiting transit timing variations.
- Authored paper **"Prospects for Refining Kepler TTV Masses using TESS Observations"**
- Currently a Caltech graduate student

Jeremy Rath — *Northwestern*

Co-supervisor with Prof. Yoram Lithwick, graduate student project — *2019-2022*

- Developed analytic theory of chaos in three-planet systems.
- Authored paper **"The Criterion for Chaos in Three-planet Systems"**
- Formerly a Northwestern University graduate student

DDA Mentoring Program — *DDA*

Division of Dynamical Astronomy program — *2021-Present*

- Virtual and in-person meetings with participating graduate students working in dynamics on approximately quarterly basis.
- Discussions focused on career guidance.

Selected Presentations

Invited Talks

Planet-Disk-Star Seminar, Tsinghua University — *December 2024*
Astro Seminar, University of Kentucky — *November 2024*
TASTY Seminar, Univ. of Toronto — *October 2024*
Rebound Conference 2024 (virtual) — *July 2024*
Astronomy Seminar, Iowa State University (virtual) — *September 2023*
Astronomy Department Colloquium, University of British Columbia — *February 2023*
Department of the Geophysical Sciences Seminar, University of Chicago — *October 2022*
Special Seminar, Northwestern University — *October 2022*
TAC Seminar, University of California Berkeley — *October 2022*
Grupo de Dinâmica Orbital e Planetologia Seminar, São Paulo State University (virtual) — *August 2022*
Exoplanets and Stars Seminar, Yale University (virtual) — *March 2022*
CITA Seminar, Canadian Institute for Theoretical Astrophysics — *October 2021*
Center for Exoplanets and Habitable Worlds Seminar, Penn State University — *February 2019*
Center for Relativistic Astrophysics Seminar, Georgia Institute of Technology — *April 2018*
SSP Seminar, Center for Astrophysics | Harvard & Smithsonian — *April 2018*
Yale Center for Astronomy and Astrophysics Seminar, Yale University — *March 2018*
Extrasolar Planets Seminar, *NASA Goddard* — *February 2018*
CITA Seminar, Canadian Institute for Theoretical Astrophysics — *June 2017*

Contributed Talks & Posters

Rogue Worlds 2024, Osaka University *December 2024*
Challenging Theory with Roman, IPAC/Caltech *July 2024*
Division of Dynamical Astronomy (DDA), 54th DDA Annual Meeting *May 2024*
Comlex Planetary Systems II, Namur, Belgium *July 2023*
Division of Dynamical Astronomy (DDA), 54th DDA Annual Meeting *May 2023*
EMAC Virtual Workshop on Open-Access Exoplanet Modeling & Analysis Tools, (virtual) *February 2023*
Division of Dynamical Astronomy (DDA), 53rd DDA Annual Meeting *April 2022*
Division of Dynamical Astronomy (DDA), 52nd DDA Annual Meeting (virtual) *May 2021*
ExoDyn2021, Virtual conference *January 2021*
Extreme Solar Systems IV (poster), Reykjavik, Icelend *August 2019*
MPIA Heidelberg, Planetary Dynamics Conference *June 2019*
Division of Dynamical Astronomy (DDA), 49th DDA Annual Meeting *April 2018*
Division of Planetary Sciences (DPS), 49th DPS Annual Meeting *October 2017*
Univ. of Toronto, Numerical Integration Methods in Planetary Science *August 2017*
Aspen Winter Conference, Formation and Dynamical Evolution of Exoplanets *April 2017*
AAS Winter Meeting, Formation and Dynamical Evolution of Exoplanets *April 2017*
Extreme Solar Systems III, Waikola Beach, HI *November 2015*
Kepler Science Conference II (poster), Mountain View, CA *November 2013*

Teaching

Courses

AST 221: Stars & Planets *Univ. of Toronto*
Guest instructor *Fall 2024*
- Computational lab exploring link between Earth's past orbital evolution and climate history

Research Computing (CTA200H) *CITA*
Guest Instructor *Summer 2023 & 2024*
- Introduction to `sympy`

General Physics/College Physics (Physics 130-1,2/Physics 135-3) *Northwestern University*
Graduate Teaching Assistant *2012-2013*
- Introductory algebra-based and calculus-based physics courses
- Designed and graded quizzes
- Led weekly recitation section

Lectures & Reading Groups

Differential Geometry Reading Group *CITA*
Lead organizer *Fall 2022*
- Reading group covering "The Geometry of Physics" by T. Frankel
- Responsibilities include organizing group discussions & informal lectures

Dynamics Discussion Group *CfA*
Lead organizer *Spring 2019*
- Discussion group comprised of CfA members focused on papers on dynamics
- Responsibilities include organizing group discussions and assigning presenters
- Website at **shadden.github.io/dynamics_group**

CITA Blackboard Lectures *CITA*
Lecturer
- "The Mapping Approach to Trans-Neptunian Dynamics", Fall 2023
- "Resonance Capture in Planetary Systems and Beyond", Winter 2022
- "A Mapping Approach to the Dynamics of Closely-spaced Planets", Fall 2021

Outreach

GK-12 Reach for the Stars Fellow *Chicago, IL*

High school introductory physics/ middle school general science *2013 - 2015*

- Designed and taught lessons in collaboration with participating teachers
- Developed formal lesson plans and recieve instruction in science pedagogy

Astronomy On Tap *Chicago, IL*

Public lecturer *2015*

- Delivered public outreach lectures based on my research

Professional Service

SOC member, Rogue Worlds 2024: Uniting Theory and Observation *December 2024*
LOC Chair, AAS Division for Dynamical Astronomy 2024 Annual Meeting *May 2024*
Lead Conference Organizer, CITA Planet Day *August 2023*
Conference SOC Member, NASA EMAC Virtual Workshop *February 2023*
Conference Co-organizer, CITA Planet Day *August 2022*
Panel Reviewer, NASA Exoplanets Research Program
Panel Reviewer, NASA Emerging Worlds Program
Panel Reviewer, C2W Postdoctoral Program
Referee, A& A, AJ, ApJ, ApJL, MNRAS, Phys. Rev. X

References

Norman Murray

Professor, Canadian Institute for Theoretical Astrophysics, Univ. of Toronto

Address: McLennan Physical Laboratories, Room 1404D, 60 St. George Street, Toronto Ontario, Canada M5S 3H8
Phone: (416) 978-1778
Email: murray@cita.utoronto.ca

Scott Tremaine

Emeritus Professor, Institute for Advanced Study

Address: Institute for Advanced Study, School of Natural Sciences, Einstein Drive, Princeton, NJ 08540
Phone: (609) 734-8191
Email: tremaine@ias.edu

Yanqin Wu

Professor, Department of Astronomy & Astrophysics, Univ. of Toronto

Address: 50 St. George Street, Toronto, Ontario, Canada M5S 3H4
Phone: (416) 946-5633
Email: yanqin.wu@utoronto.ca

Matthew Holman

Senior Astrophysicist, Center for Astrophysics | Harvard & Smithsonian

Address: 60 Garden Street, MS #51, Cambridge, MA 02138
Phone: (617) 496-7775
Email: mholman@cfa.harvard.edu

Yoram Lithwick

Associate Professor, Dept. of Physics and Astronomy, Northwestern University

Address: 1800 Sherman, 8065, Evanston, IL 14853
Phone: (847) 491-8646
Email: y-lithwick@northwestern.edu