BHANU KUMAR

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Geometry + Dynamics Station
Institute for Mathematics
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RESEARCH INTERESTS

Development and adaptation of theoretical & computational tools from Hamiltonian dynamical systems, including hyperbolic, resonant, & chaotic dynamics; invariant manifold parameterization methods, and symplectic geometry, for spacecraft astrodynamics and natural celestial mechanics. Applications of these tools to dynamical analysis of real celestial systems of interest for future space missions and astronomy.

PROFESSIONAL EXPERIENCE

Department of Mathematics, University of Michigan, USA
James Van Loo Postdoctoral Fellow and Assistant Professor (fixed-term)   starting 1/2025
- Research and teaching position supported by Michigan Center for Applied & Interdisciplinary Math

Institute for Mathematics, Universität Heidelberg, Germany
Postdoctoral Researcher, Research Station Geometry + Dynamics   5/2024 - present
- Main research project on application of methods from symplectic geometry to study of periodic orbit families and bifurcations in cislunar space. Secondary work on resonances for Uranus tour design.

NASA Jet Propulsion Laboratory, California Institute of Technology, USA
NSF MSPRF Postdoctoral Research Fellow, Mission Design & Navigation   10/2022 - 4/2024
- Investigated resonant dynamics for space mission design in cislunar and Jovian systems. Discovered previously-unknown secondary resonance phenomena and developed related fast numerical methods. Supported by competitive proposal funded through NSF individual fellowship award DMS-2202994.

NASA NSTRF Student Visiting Technologist, Mission Design & Navigation   6/2018 - 7/2022
- Developed improved methods for computing quasi-periodic orbits, stable and unstable invariant manifolds, and heteroclinic connections. Preliminary research on tour design for Jupiter's moons.

Engineering Co-op Student, Radio Science Systems Group (332K)   6/2014 - 8/2017
- Worked on various technical and research tasks, including conceptual development of a novel method for interplanetary lander trajectory reconstruction using only Doppler tracking data.

EDUCATION

Ph.D. Mathematics, Georgia Institute of Technology   8/2022
  Dissertation title: *New Numerical and Computational Methods Leveraging Dynamical Systems Theory for Multi-Body Astrodynamics*
  Research Advisor: Prof. Rafael de la Llave

M.S. Aerospace Engineering, Georgia Institute of Technology   12/2021

B.S. Applied Mathematics, Georgia Institute of Technology   5/2015

B.S. Aerospace Engineering, Georgia Institute of Technology   5/2015

GRANTS, HONORS, AND AWARDS

- Top Graduate Student Award of the Georgia Tech School of Mathematics 2022
- US National Science Foundation Mathematical Sciences Postdoctoral Research 2022 - 2026
  Fellowship (accepted). Grant DMS-2202994. Total Award: $150,000.
- EU Marie Sklodowska-Curie H2020-MSCA-COFUND MathInGreaterParis postdoctoral 2022
  fellowship (declined in favor of NSF fellowship). Total Award: €111,600.
- NASA Space Technology Research Fellowship (NSTRF18). Grant 80NSSC18K1143. 2018 - 2022
  Project title: *Leveraging Dynamical Instabilities to Design Efficient Mission Trajectories*
- Georgia Tech President's Fellowship for Doctoral Studies 2015 - 2019
- Selected by NASA as a sponsored student delegate to the International Astronautical Congress 2019
- Outstanding Undergraduate Math Major Award of the Georgia Tech School of Mathematics 2015

TEACHING EXPERIENCE AND AWARDS

Thank-A-Teacher Certificate, School of Mathematics, Georgia Tech Spring 2019
MATH 3770, Statistics and Applications, for unofficial volunteer tutoring of a former student

Graduate Teaching Assistant, School of Mathematics, Georgia Tech
MATH 2552 Differential Equations Fall 2015, Spring/Fall 2016, Spring 2017, Spring 2018
MATH 1554 Linear Algebra Fall 2017

PUBLICATIONS

MANUSCRIPTS IN PREPARATION

1. B. Kumar, "A new fast multiple-shooting method for computing periodic orbits in symplectic maps leveraging simultaneous Floquet vector computation to avoid large linear systems," in preparation (orbits computed using this method, and a very brief overview of the method itself, are demonstrated in my preprint arXiv:2309.06073)

PEER-REVIEWED JOURNAL ARTICLES

1. B. Kumar, R.L. Anderson, and R. de la Llave (2024). "Rapid GPU-Assisted Search & Parameterization-Based Refinement and Continuation of Connections between Tori in Periodically Perturbed Planar Circular Restricted 3-Body Problems," to appear in *SIAM Journal on Applied Dynamical Systems*. arXiv:2109.14814v2.

2. B. Kumar, R.L. Anderson, and R. de la Llave (2023). "Transfers between Jupiter-Ganymede and Jupiter-Europa Resonant Tori In a Concentric Circular Restricted 4-Body Model," *Acta Astronautica* 211(2023): 76–87. https://doi.org/10.1016/j.actaastro.2023.05.040.

3. B. Kumar, R.L. Anderson, and R. de la Llave (2022). "Rapid and Accurate Methods for Computing Whiskered Tori and Their Manifolds in Periodically Perturbed Planar Circular Restricted 3-Body Problems," *Celest Mech Dyn Astron* 134:3. https://doi.org/10.1007/s10569-021-10057-1.

4. B. Kumar, R.L. Anderson, and R. de la Llave (2021). "High-Order Resonant Orbit Manifold Expansions For Mission Design In the Planar Circular Restricted 3-Body Problem," *Commun Nonlinear Sci Numer Simulat 97(2021): 105691*. https://doi.org/10.1016/j.cnsns.2021.105691.

CONFERENCE PROCEEDINGS

1. <u>B. Kumar</u>, A. Rawat, A.J. Rosengren, and S.D. Ross (2024). "Investigation of Interior Mean Motion Resonances and Heteroclinic Connections in the Earth-Moon System," paper presented at the 75rd International Astronautical Congress, Milan, Italy, October 2024. Paper IAC–24–C1.9.5.

2. <u>B. Kumar</u> and R.L. Anderson (2024). "A Survey of Oberon Mean Motion Resonant Unstable Orbit Properties and Connections for Uranian Tours," paper presented at the 2024 AAS/AIAA Astrodynamics Specialist Conference, Broomfield, CO, USA, August 2024. Paper AAS 24-288.

3. A. Rawat, <u>B. Kumar</u>, S.D. Ross, and A.J. Rosengren (2024). "Resonance Widths, Chaotic Zones, and Transport in Cislunar Space," paper presented at the 2024 AAS/AIAA Astrodynamics Specialist Conference, Broomfield, CO, USA, August 2024. Paper AAS 24-368.

4. <u>B. Kumar</u>, R.L. Anderson, and R. de la Llave (2023). "4th Body-Induced Secondary Resonance Overlapping Inside Unstable Resonant Orbit Families: a Jupiter-Ganymede 4:3 + Europa Case Study," paper presented at the 2023 AAS/AIAA Astrodynamics Specialist Conference, Big Sky, MT, USA, August 2023. Paper AAS 23-397. arXiv:2309.06073.

5. <u>B. Kumar</u>, R.L. Anderson, and R. de la Llave (2022). "Transfers between Jupiter-Ganymede and Jupiter-Europa Resonant Tori In a Concentric Circular Restricted 4-Body Model," paper presented at the 73rd International Astronautical Congress, Paris, France, September 2022. Paper IAC–22–C1.8.4. https://dl.iafastro.directory/event/IAC-2022/paper/73382/.

6. <u>B. Kumar</u>, R.L. Anderson, R. de la Llave, and B. Gunter (2021). "Computation and Analysis of Jupiter-Europa and Jupiter-Ganymede Resonant Orbits in the Planar Concentric Circular Restricted 4-Body Problem," paper presented at the 2021 AAS/AIAA Astrodynamics Specialist Conference, Virtual, August 2021. Paper AAS 21-651. arXiv:2109.14815.

7. <u>B. Kumar</u>, R.L. Anderson, and R. de la Llave (2021). "Using GPUs and the Parameterization Method for Rapid Search and Refinement of Connections between Tori in Periodically Perturbed Planar Circular Restricted 3-Body Problems," paper presented at the 2021 AAS/AIAA Space Flight Mechanics Meeting, Virtual, February 2021. Paper AAS 21-349. arXiv:2109.14814v1.

8. <u>B. Kumar</u>, R.L. Anderson, and R. de la Llave (2020). "Rapid and Accurate Computation of Invariant Tori, Manifolds, and Connections Near Mean Motion Resonances in Periodically Perturbed Planar Circular Restricted 3-Body Problem Models," paper presented at the 2020 AAS/AIAA Astrodynamics Specialist Conference, Virtual, August 2020. Paper AAS 20-694.

9. <u>B. Kumar</u>, R.L. Anderson, and R. de la Llave (2019). "High-Order Resonant Orbit Manifold Expansions For Mission Design In the Planar Circular Restricted 3-Body Problem," paper presented at the 70th International Astronautical Congress, Washington, D.C., USA, October 2019. Paper IAC–19–C1.4.9. https://dl.iafastro.directory/event/IAC-2019/paper/51517/.

<u>PRESENTATIONS</u>

CONFERENCE TALKS AND ABSTRACTS

1. B. Kumar, R.L. Anderson, and R. de la Llave. "4th Body-Induced Secondary Resonance Overlap Inside Unstable Resonant Orbit Families: a Jupiter-Ganymede 4:3 + Europa Case Study," 6th International Workshop on Key Topics in Orbit Propagation Applied to Space Situational Awareness (KePASSA), Arras, France, June 2024.

2. B. Kumar, R.L. Anderson, and R. de la Llave. "Europa-induced Overlapping of Secondary Resonances in the 4:3 Jupiter-Ganymede Unstable Resonant Orbit Family," Complex Planetary Systems II – Kavli-IAU Symposium 382, Namur, Belgium, July 2023.

3. B. Kumar, R.L. Anderson, and R. de la Llave. "Europa-induced Overlapping of Secondary Resonances in the 4:3 Jupiter-Ganymede Unstable Resonant Orbit Family," 13th International Conference on Nonlinear Mathematics and Physics "NoLineal", Barcelona, Spain, June 2023.

4. B. Kumar, R.L. Anderson, and R. de la Llave. "Europa-induced Overlapping of Secondary Resonances in the 4:3 Jupiter-Ganymede Unstable Resonant Orbit Family," 13th AIMS Conference on Dynamical Systems, Differential Equations and Applications, Wilmington, NC, June 2023.

5. B. Kumar, R.L. Anderson, and R. de la Llave. "Jupiter-Ganymede and Jupiter-Europa Unstable Resonant Tori In a Restricted 4-Body Model: Analysis and a Search for Transfers," SIAM Conference on Applications of Dynamical Systems (DS23), Portland, OR, May 2023.

6. B. Kumar, R.L. Anderson, and R. de la Llave. "GPU-assisted search for low-cost transfers between whiskered tori, with applications to resonance transfers in a restricted 4-body model," 5th International Workshop on Key Topics in Orbit Propagation Applied to Space Situational Awareness (KePASSA), Logroño, Spain, June 2022.

7. B. Kumar, R.L. Anderson, and R. de la Llave. "GPU-assisted search for Jupiter-Ganymede to Jupiter-Europa resonance transfers in a restricted 4-body model," Workshop on Theory, Models and Simulations in Celestial Mechanics, Pisa, Italy, June 2022.

8. B. Kumar, R.L. Anderson, and R. de la Llave. "Dynamical systems-based methods for multi-body space mission design," Midwest Dynamical Systems Early Career Conference, University of Notre Dame, South Bend, IN, May 2022.

9. B. Kumar, R.L. Anderson, R. de la Llave, and B. Gunter. "Tori and Manifolds of Jupiter-Europa and Jupiter-Ganymede Resonances in the Planar Concentric Circular Restricted 4-Body Problem," IAU Symposium 364 on Multi-scale (time and mass) Dynamics of Space Objects, October 2021.

10. B. Kumar, R.L. Anderson, and R. de la Llave. "Rapid and Accurate Computation of Invariant Tori, Manifolds, and Connections Near Mean Motion Resonances in Periodically Perturbed PCRTBP Models," SIAM Conference on Applications of Dynamical Systems (DS21), May 2021.

11. B. Kumar, R.L. Anderson, and R. de la Llave. "Using GPUs and the Parameterization Method for Rapid Search and Refinement of Connections between Tori in Periodically Perturbed Planar Circular Restricted 3-Body Problems," AMS Spring Southeastern Sectional Meeting, March 2021.

12. B. Kumar, R.L. Anderson, and R. de la Llave. "Rapid and Accurate Computation of Invariant Tori and Manifolds Near Mean Motion Resonances in Periodically Perturbed PCRTBP Models," AMS Spring Southeastern Sectional Meeting, March 2021.

13. B. Kumar, R.L. Anderson, and R. de la Llave. "Using GPUs and the Parameterization Method for Rapid Search and Refinement of Connections between Tori in Periodically Perturbed Planar Circular Restricted 3-Body Problems," Georgia Tech Exploration and Origins Colloquium, February 2021.

INVITED SEMINARS AND TALKS

1. "I Put a Resonance Inside Your Resonance So You Can Overlap While You Overlap: Why 4th-Body Effects are Important in Multi-Moon Systems," invited talk in Mission Analysis Knowledge Dissemination Seminar Series, European Space Operations Centre, June 2024.

2. "4th Body-Induced Secondary Resonance Overlap Inside Normally Hyperbolic Invariant Manifolds in Planet-Moon Systems: a Jovian Case Study," invited talk in Geometry and Dynamics Seminar, Heidelberg University, May 2024.

3. "Interior Mean Motion Resonances and Heteroclinic Connections in the Earth-Moon System," seminar in Hockney Seminar for Space Flight series, Jet Propulsion Laboratory, California Institute of Technology, April 2024.

4. "4th Body-Induced Secondary Resonance Overlap Inside Normally Hyperbolic Invariant Manifolds in Planet-Moon Systems: a Jovian Case Study," invited talk in Applied Math Seminar, University of California, Irvine, February 2024.

5. "I Put a Resonance Inside Your Resonance So You Can Overlap While You Overlap: Why 4th-Body Effects are Important in Multi-Moon Systems," seminar in Hockney Seminar for Space Flight series, Jet Propulsion Laboratory, California Institute of Technology, August 2023.

6. "Jupiter-Ganymede and Jupiter-Europa Unstable Resonant Tori In a Restricted 4-Body Model: Analysis and a Search for Transfers," invited talk in Astronomy and Dynamical Systems Seminar, Institute of Celestial Mechanics and Computation of Ephemerides, Paris Observatory, Sept. 2022.

7. "New Numerical and Computational Methods Leveraging Dynamical Systems Theory for Multi-Body Astrodynamics," invited talk in Aerospace Robotics and Control Group Special Seminar, California Institute of Technology, December 2021.

8. "Rapid and Accurate Computation of Invariant Tori, Manifolds, and Connections Near Mean Motion Resonances in Periodically Perturbed Planar Circular RTBP Models," invited talk in I-CELMECH Seminar Series, University of Milan, November 2020.

9. "Rapid and Accurate Computation of Invariant Tori, Manifolds, and Connections Near Mean Motion Resonances in Periodically Perturbed Planar Circular RTBP Models," invited talk given in CDSNS Colloquium Series, Georgia Tech, July 2020.

10. "Computation and Usage of High-Order Resonant Orbit Manifold Expansions For Mission Design In the Planar Circular Restricted 3-Body Problem," seminar at MSRI, Berkeley, CA, Dec. 2018.

POSTERS

1. "4th body-induced secondary resonance overlap inside unstable resonant orbit families: a Ganymede 4:3 + Europa case study," JPL Research Poster Conference, Pasadena, CA, November 2023.

2. "GPU-assisted search for Jupiter-Ganymede to Jupiter-Europa resonance transfers in a restricted 4-body model," Global and Local Aspects in Dynamical Systems Conference, Barcelona, Spain, July 2022.

3. "Computation and Analysis of Invariant Tori Near Resonances in the Planar Elliptic Restricted 3-body Problem," Georgia Tech Exploration and Origins Colloquium, Atlanta, GA, January 2020.

4. "Exploiting Geometric Structures at Resonances and Diffusion to Enable Rapid Tour Design," Georgia Tech Exploration and Origins Colloquium, Atlanta, GA, March 2019.

5. "Accelerating Diffusion to Enable Rapid Tour Design," JPL Research Poster Conference, Pasadena, CA, November 2018.

SERVICE AND PROFESSIONAL ACTIVITIES

- Referee work for the journals *Celestial Mechanics and Dynamical Astronomy (2 times); SIAM Journal on Applied Dynamical Systems (2 times); Journal of Guidance, Control, and Dynamics; Physica D: Nonlinear Phenomena; Nonlinearity (2 times)*
- Developed "Chaos in Space" exhibit, including outreach materials and interactive computer activity, for school children at the 2024 Pasadena Unified School District Science Fest — 3/2024
- Session Chair for the Contributed Papers Session CP9 on Many Body Problems at the May 2023 SIAM Conference on Applications of Dynamical Systems (DS23) — 5/2023
- Lead organizer of the Special Session on Celestial Mechanics and Applied Astrodynamics at the March 2021 AMS Spring Southeastern Sectional Meeting (12 invited speakers) — 3/2021
- Program Associate in the semester *Hamiltonian systems, from topology to applications through analysis* held at the Mathematical Sciences Research Institute, Berkeley, CA — Fall 2018
- Summer volunteer coach for the Georgia ARML state high school math team — 5/2012-5/2017

TECHNICAL AND LANGUAGE SKILLS

Programming: Julia (including CUDA.jl and OpenCL.jl for GPUs), MATLAB, C, Java, Bash scripting
Software: LaTeX, AGI Systems Tool Kit, Autodesk Inventor, AutoCAD, Microsoft Office
Languages spoken: English (native), French (proficient), Hindi (native speaker)