Fiscal Year:	FY 2022	**Task Last Updated:**	FY 12/06/2022
PI Name:	Cornell, Eric Ph.D.		
Project Title:	Zero-G Studies of Few-Body and Many-Body Physics		
Division Name:	Physical Sciences		
Program/Discipline:			
Program/Discipline--Element/Subdiscipline:	FUNDAMENTAL PHYSICS--Fundamental physics		
Joint Agency Name:		**TechPort:**	No
Human Research Program Elements:	None		
Human Research Program Risks:	None		
Space Biology Element:	None		
Space Biology Cross-Element Discipline:	None		
Space Biology Special Category:	None		
PI Email:	Cornell@jila.colorado.edu	**Fax:**	FY
PI Organization Type:	UNIVERSITY	**Phone:**	303-492-6281
Organization Name:	University of Colorado		
PI Address 1:	JILA		
PI Address 2:	440 UCB		
PI Web Page:			
City:	Boulder	**State:**	CO
Zip Code:	80309-0440	**Congressional District:**	2
Comments:			
Project Type:	Flight	**Solicitation / Funding Source:**	2013 Fundamental Physics NNH13ZTT002N (Cold Atom Laboratory--CAL)
Start Date:	04/01/2014	**End Date:**	09/27/2024
No. of Post Docs:	1	**No. of PhD Degrees:**	1
No. of PhD Candidates:	3	**No. of Master' Degrees:**	0
No. of Master's Candidates:	0	**No. of Bachelor's Degrees:**	0
No. of Bachelor's Candidates:	0	**Monitoring Center:**	NASA JPL
Contact Monitor:	Callas, John	**Contact Phone:**	
Contact Email:	john.l.callas@jpl.nasa.gov		
Flight Program:	ISS		
Flight Assignment:	NOTE: End date changed to 9/27/2024 per U. Israelsson/JPL (Ed., 10/20/21) NOTE: End date changed to 8/31/2021 per U. Israelsson/JPL (Ed., 5/12/2020) NOTE: End date changed to 4/30/2020 per PI (Ed., 5/1/19)		
Key Personnel Changes/Previous PI:			
COI Name (Institution):	Engels, Peter Ph.D. (Washington State University, Pullman) Mossman, Maren Elizabeth Ph.D. (University of San Diego)		
Grant/Contract No.:	JPL 1502690		
Performance Goal No.:			
Performance Goal Text:			

Task Description:	Future advances in both technology and fundamental science will hinge on a better understanding of the weird effects of quantum mechanics on collections of electrons, atoms, molecules, and so on. In some cases, experiments probing this so-called "quantum few-body and many-body physics" can be more readily accomplished in the weightless environment found in an orbiting laboratory. We propose a staged series of experiments, including (1) "first science" experiment, to be performed in the Cold Atom Laboratory (CAL) flying in the International Space Station (ISS) first-generation, to answer a question in few-body quantum physics that can't be performed in a ground-based laboratory: how universal are the weakly bound clusters of three atoms known as Efimov trimers? In a weightless environment, experiments can be performed at very low densities and temperatures, the perfect conditions for these exotic but fragile quantum states to form. (2) Bose gases with "infinite" interactions. As interactions between atoms become stronger, there is a crossover between gas-phase and liquid behavior. In ultra-cold atoms, the crossover is between a quantum liquid and a quantum gas. (3) Highly rotating quantum gases. Many of the most exotic and unexplored predicted states of matter occur in the presence of very strong magnetic fields, for electrons, or high rates of rotation, for neutral particles. We will explore Quantum Hall physics in highly rotating Bose and Fermi gases. Experiments (2) and (3) will benefit significantly from the longer expansion times and weaker traps possible in weightlessness. Preliminary versions of both experiments will be done in a ground-based laboratory in order to establish the foundation for future flight-based experiments.
Rationale for HRP Directed Research:	
Research Impact/Earth Benefits:	Physics is the discipline that provides understanding of biology and chemistry at the most microscopic level, and the area within physics most relevant to chemistry and biology is "few-body physics." It is an often neglected portion of physics, because it is so difficult to do! An important way to make progress is to simplify, simplify, simplify: to come up with model systems in which we can make progress that can later be applied to human-centric disciplines like biology, and develop exotic and useful new materials. A promising way to simplify is to study matter at lower temperature, and lower densities. The Cold-Atom Lab (CAL) flying in the International Space Station (ISS) is where we will reach the lowest possible temperatures, and low densities, to do our studies of simple, yet intricate (think "snowflakes") clusters of three or four atoms. We have been doing prefatory experiments and calculations here on Earth. Not at as low temperature, but still cold enough to help us learn things we will need to know to do the space experiments. While CAL is now in flight, we have been participating in the effort to remotely tune it up for maximum performance.
Task Progress:	The goal of these investigations is the study of exotic few-body states that can form when atoms interact with each other in just the right way. Of particular interest are bound states of three atoms that are so weakly bound that the distances between atoms in the state are on the order of 1 micron or more, which is 10,000 times larger than the interatomic spacing in typical molecules. These three-body states, called Efimov states, offer a wealth of insight into fundamental physical questions, and the experimental study of these states will provide essential benchmark data for the development of new theoretical approaches involving this physics. These states are so large and fragile (or weakly bound) that their experimental realization requires ultracold and ultra-dilute atomic samples. Such conditions are difficult to obtain in Earth-based experiments but are readily provided by the NASA Cold Atom Lab (CAL). To generate Efimov states, the interaction strength between the atoms must be fine-tuned. In practice, this means the atoms need to be prepared in a specific environment with respect to the atoms' internal state and the surrounding magnetic field. During the past year of this grant, our work has focused on the preparation of these required conditions. CAL operates with two atomic species – rubidium and potassium. While rubidium can efficiently be cooled using laser cooling and evaporative cooling, only potassium offers the ability to fine-tune the interaction strength with readily available magnetic fields. Potassium is more difficult to cool directly but can be cooled via thermal contact with cooled gaseous rubidium atoms. This "sympathetic cooling" requires magnetic fields and internal atomic states different from those required to achieve Efimov states. Therefore, after the cooling stage, we must take steps to prepare the state before we can perform experiments. These steps involve short pulses and frequency sweeps of microwave and radiofrequency radiation that we are currently optimizing. After an initial phase of experimenting only with rubidium, CAL has progressed to dual species operation with rubidium and potassium in early 2022. The achievement of sympathetic cooling of potassium with rubidium by the NASA Jet Propulsion Laboratory (JPL) team has been a major success. Subsequently, we have identified the ideal microwave and radio frequencies needed for the state preparation of potassium. These resonances must be known precisely but vary depending on the local magnetic field. Therefore, they need to be found experimentally with the CAL apparatus. Our team has performed a successful series of such studies. These studies have also included commissioning a previously unused microwave generator for driving state transitions in potassium. Verifying the correct operation of this generator has been an important step not only for our experiments, but also for other investigations. Optimizing the correct state preparation for tuning interactions between atoms is now within reach and will be a major milestone towards new fundamental studies in Efimov physics. It will also be an important step for atom interferometry applications and inform the design of future experimental platforms. Our work has been performed in a collaboration between JILA / University of Colorado (Professor Cornell / Dr. D'Incao), Washington State University (Professor Engels), and the University of San Diego (Professor Mossman). Cornell, Engels, and Mossman have worked together with the CAL team at JPL to design the flight experiments and analyze the resulting data. D'Incao has focused on the development of theoretical models to interpret the anticipated Efimov results and guide the experiments by identifying the necessary parameter regimes. The work has involved a postdoctoral researcher and three graduate students. Results have been presented at the 53rd Annual Meeting of the American Physical Society (APS) Division of Atomic, Molecular, and Optical Physics (DAMOP) in a presentation titled "Few-body Physics in Microgravity", and in three invited talks at the Kavli Institute for Theoretical Physics (University of California, Santa Barbara), the Rochester Institute of Technology, and at the Congreso Nacional de Fisica de la Socieded Mexicana de Fisica (Tijuana, Mexico). All these presentations, as well as two manuscripts co-authored by D'Incao, acknowledge support by this grant. The work of our team has been a prime venue for the training of students and postdoctoral researchers at the University of Colorado, Boulder, at Washington State University, and at the University of San Diego (USD). During this reporting period, one postdoc and three graduate students have been directly involved in this research. One PhD degree has been awarded. At the University of San Diego, Prof. Mossman is establishing a ground-based ultracold atomic, molecular, and optical physics (AMO) program, and the CAL project is creating a lot of excitement amongst her students. For example, at an event held at JPL this year to celebrate four years of CAL operation, the USD group has been represented by seven undergraduate students. Two students from the Mossman group also worked at JPL as summer

	interns, one working directly with the CAL project, and Prof. Mossman has advised and mentored a third JPL CAL intern on the simulation of magnetic fields.
Bibliography Type:	Description: (Last Updated: 02/04/2025)
Articles in Other Journals or Periodicals	Haze S, D'Incao JP, Wilson J, Dorer D, Li J, Deiss M, Tiemann E, Julienne PS, and Denschlag JH. "Energy-scaling of the product state distribution for three-body recombination of ultracold atoms." arXiv preprint server. Posted Nov 7, 2022. p https://doi.org/10.48550/arXiv.2211.03834 , Nov-2022
Articles in Peer-reviewed Journals	Haze S, D'Incao JP, Dorer D, Deiss M, Tiemann E, Julienne PS, Denschlag JH "Spin-conservation propensity rule for state-to-state ultracold 85Rb three-body recombination." Phys. Rev. Lett. 2022 Apr 1;128(13):133401. https://doi.org/10.1103/PhysRevLett.128.133401 ; PMID: 35426725 , Apr-2022
Dissertations and Theses	Van de Graaff MJ. "Implosions as a probe for fluctuations in Bose-Einstein condensates." Dissertation, University of Colorado, August 2022 , Aug-2022