Fiscal Year:	FY 2021	**Task Last Updated:**	FY 04/01/2021
PI Name:	Lundblad, Nathan Ph.D.		
Project Title:	Microgravity Dynamics of Bubble-Geometry Bose-Einstein Condensates		
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:	nlundbla@bates.edu	**Fax:**	FY
PI Organization Type:	UNIVERSITY	**Phone:**	207-786-6321
Organization Name:	Bates College		
PI Address 1:	Department of Physics and Astronomy		
PI Address 2:	44 Campus Ave		
PI Web Page:			
City:	Lewiston	**State:**	ME
Zip Code:	04240-6018	**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:	2	**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:	ISS NOTE: End date changed to 9/27/2024 per U. Israelsson/JPL (Ed., 10/20/21) NOTE: End date changed to 3/31/2022 per B. Carpenter/NASA HQ (Ed., 1/4/2021) NOTE: New end date is 10/30/2020 per JPL (Ed., 5/21/19)		
Key Personnel Changes/Previous PI:	April 2021 report: Postdoctoral associate Ryan Carollo departed October 2019; new postdoctoral associate Joseph Murphree started July 2020.		
COI Name (Institution):	Aveline, David Ph.D. (Jet Propulsion Laboratory) Lannert, Courtney Ph.D. (Smith College) Vishveshwara, Smitha Ph.D. (University of Illinois at Urbana-Champaign)		
Grant/Contract No.:	JPL 1502172		
Performance Goal No.:			
Performance Goal Text:			

Task Description:	Notions of geometry, topology, and dimensionality have directed the historical development of quantum-gas physics. With a toolbox of forces used to confine, guide, and excite Bose-Einstein condensates (BEC) or degenerate Fermi gases (DFG), physicists have used quantum gases to test fundamental ideas in quantum theory, statistical mechanics, and in recent years notions of strongly-correlated many-body physics from the condensed-matter world. We propose a specific program to explore a trapping geometry for quantum gases that is both tantalizing theoretically and prohibitively difficult to attain terrestrially: a quantum gas in a bubble geometry, i.e., a trap formed by a spherical or ellipsoidal shell structure, confining a 2D quantum gas to the surface of an experimentally-controlled topologically-connected “bubble.” The physics of a quantum gas confined to such a surface has not been explored terrestrially due to the limitations of gravitational sag; interesting work has certainly been done with gases confined to the lower regions of bubble potentials, but the fully symmetric situation has yet to be explored. The low-energy excitations of such a system are unexplored, and notions of vortex creation and behavior as well as Kosterlitz-Thouless physics are tantalizing aims as well. The solid-state modeling goals of the optical-lattice physics community are also fundamentally connected to the system, as the canonical Mott-insulator/superfluid transition features superfluid shells isolated between insulating regions. The central method to reach the sought-after bubble-geometry BEC or DFG is that of rf or microwave dressing of the bare trapping potentials provided by the Cold Atom Laboratory (CAL) “chip trap.” Radiofrequency dressing has been used conceptually through "rf-knife" evaporative cooling, but more recently through explicit construction of adiabatic potentials for interferometry, and shell-trap construction for both thermal and quantum gases. The proposed work is a window into a physical regime that is quite difficult to achieve terrestrially due to trap distortion; given the advantages of a microgravity environment, NASA CAL is uniquely positioned to realize the physics goals of this proposal.
Rationale for HRP Directed Research:	
Research Impact/Earth Benefits:	This work, while focused on the fundamental physics of ultracold atoms and not directly connected to human life, has a similar impact to life on Earth as that of all fundamental physics; it broadens our understanding of the physical world and helps us further cement our collective picture of quantum mechanics as "the way the world works." It explores the limits of how large Bose-Einstein condensates can be made, and to what extent the gravity-well of terrestrial labs render certain investigations difficult or impossible. The observations made aboard CAL through this project are a clear demonstration that physical insight can sometimes require microgravity facilities to be fully developed, and that spaceborne atomic physics experiments can be valuable contributions to our collective scientific efforts.
Task Progress:	The FY2020 and FY2021 periods of this work were centrally focused on data collection from the CAL instrument, which began collection of ultracold-shell data in December 2018 and throughout 2019. Lundblad and postdoctoral associates Ryan Carollo and Joseph Murphree were central drivers of this work in this period, together with our partner at Jet Propulsion Laboratory (JPL), David Aveline, who in addition to service as co-investigator was our primary liaison to experimental operations. Theory co-investigators Smitha Vishveshwara and Courtney Lannert provided helpful insight and critical support, especially in regard to computational modeling of observed phenomena. Phase 1 ("SM2") of the operation continued until the end of calendar 2019. Our datasets from this period focus on the generation of ultracold shell systems, confirming theoretical predictions that microgravity would enable their occurrence. We performed thermometry on the resulting shells as a function of size, and also explored the wide variety of shell sizes that could be created with this protocol. Reduction and analysis of this data is in process. A key conclusion of this work appears to be that while ultracold shells are possible in microgravity, maintaining the BEC state across the inflation process is difficult, due to nonadiabiaticity and low initial condensate fraction. Nevertheless, these observations represent physics impossible (or prohibitively difficult) to observe in a terrestrial setting, and have opened a new pathway in ultracold atomic physics research enabled by CAL and the International Space Station (ISS). Phase 2 ("SM3") of the CAL operation commenced soon after and is ongoing. With a new atom chip geometry, SM3 permits us to explore shells with more spherical aspect ratios and possessing reduced inhomogeneity due to a larger rf coil. We have explored the parameter space of shell geometry and temperature with several different trap configurations, and we have also initiated an effort to use CAL's atom-interferometer Bragg beam to probe the nature of these ultracold shells. Looking ahead to upcoming upgrades, we hope to apply a second rf/microwave field in order to evaporatively cool the samples in the shell, thereby avoiding the heating associated with shell inflation; we also hope to use an additional signal associated with an upcoming upgrade to perform rf/microwave spectroscopy of the shell state in order to better understand the nature of Bose–Einstein condensation in a shell geometry. Continued theoretical development occurred within the shell collaboration, leading to published work from Padavic et al. focusing on potential vortex physics in ultracold shells. Lundblad also continued collaborative discussions with Dr. Barry Garraway of Sussex regarding the potential to use microwave fields aboard CAL to enhance bubble quality. Many years of modeling effort from students and postdocs culminated in a paper presenting the idea of the shell project and realistic modeling of its experimental sequences (https:// ; see also Bibliography section). This paper is proving to be a useful resource for theorists around the world seeking to obtain a sense of the capabilities of CAL in the shell-physics context. Results of our research activities were presented at several conferences, including the 2019 and 2020 American Physical Society (APS) Meetings of the Division of Atomic, Molecular, and Optical Physics (DAMOP). Additionally, Lundblad traveled to the December 2019 workshop in Ulm, Germany, focusing on the development of a successor instrument to CAL (Bose-Einstein Condensate and Cold Atom Laboratory (BECCAL)), and presented preliminary data.
Bibliography Type:	Description: (Last Updated: 02/04/2025)
Abstracts for Journals and Proceedings	Lundblad N, Carollo RA, Aveline DC, Lannert C, Padavic K, Rhyno B, Vishveshwara S. "Observations of ultracold atoms in microgravity shell potentials." 51st Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, Portland, Oregon, June 1–5, 2020. Bulletin of the American Physical Society. 2020;65(4):Abstract: E01.00106. https://meetings.aps.org/Meeting/DAMOP20/Session/E01.106 , Jun-2020

Abstracts for Journals and Proceedings	Rhyno B, Padavic K, Sun K, Lannert C, Lundblad N, Vishveshwara S. "Thermodynamics and vortex physics in shell-shaped Bose-Einstein condensates." 51st Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, Portland, Oregon, June 1–5, 2020. Bulletin of the American Physical Society. 2020 Jun;65(4):Abstract: Q01.00167. https://meetings.aps.org/Meeting/DAMOP20/Session/Q01.167 , Jun-2020
Abstracts for Journals and Proceedings	Padavic K, Sun K, Lannert C, Vishveshwara S. "Vortex Physics in Hollow Bose-Einstein Condensates." 50th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, Milwaukee, Wisconsin, May 27–31, 2019. Bulletin of the American Physical Society. 2019 May;64(4):Abstract: E01.00121. http://meetings.aps.org/Meeting/DAMOP19/Session/E01.121 , May-2019
Abstracts for Journals and Proceedings	Carollo RA, Gold M, Jiang X, Padavic K, Vishveshwara S, Lannert C, Aveline D, Lundblad N. "Shell-Geometry Bose-Einstein Condensates in Microgravity." 50th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, Milwaukee, Wisconsin, May 27–31, 2019. Bulletin of the American Physical Society. 2019 May;64(4):Abstract: E01.00131. http://meetings.aps.org/Meeting/DAMOP19/Session/E01.131 , May-2019
Articles in Peer-reviewed Journals	Lundblad N, Carollo RA, Lannert C, Gold MJ, Jiang X, Paseltiner D, Sergay N, Aveline DC. "Shell potentials for microgravity Bose-Einstein condensates." npj Microgravity. 2019 Dec 4;5:30. https://doi.org/10.1038/s41526-019-0087-y ; PMID: 31815180; PMCID: PMC6892894 , Dec-2019
Articles in Peer-reviewed Journals	Padavic K., Sun K, Lannert C, Vishveshwara S. "Vortex-antivortex physics in shell-shaped Bose-Einstein condensates." Physical Review A - Atomic, Molecular, and Optical Physics. 2020 Oct;102(4):043305. https://doi.org/10.1103/PhysRevA.102.043305 , Oct-2020
Dissertations and Theses	Padavic-Callaghan K. (Karmela Padavic-Callaghan) "Hollow condensates, topological ladders and quasiperiodic chains." Dissertation, University of Illinois, Urbana-Champaign, July 2020. , Jul-2020