Prospectus

Cooling Rubidium-87 Atoms using Adiabatic Expansion in Microgravity
(Technical Topic)

Actor Network Theory and Orbital Debris Mitigation
(STS Topic)

By

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

The modern world depends greatly on the continuous operation of countless spacecraft currently in orbit about the Earth. GPS satellites for navigation and timing, earth-observing satellites for weather forecasting and climate research, and countless communications satellites are all integral components of our society (CSA, 2018). However, in order for these satellites to operate, they must safely navigate the crowded orbital environment. Furthermore, the space around the Earth is packed with orbital debris, objects in space that no longer serve any purpose. Currently, most spacecraft navigate using a combination of GPS signals and onboard inertial navigation units, which use continuous measurements of the acceleration a spacecraft has been subjected to in order to determine position and velocity. The technical solution to the hazardous space environment is to develop more precise and robust navigation systems that can be used to avoid other spacecraft and the growing number of debris objects orbiting the Earth. To address this problem, we are creating a new technique for cooling atoms that can be used to create extremely precise inertial measurement units.

However, it is obvious that just developing better navigation systems will not be enough to keep satellites safe and operating. It is necessary to consider how a network of users determines the orbital environment that satellites will encounter. Even if better navigation systems were created, there would still be more debris from the ever increasing number of satellites being put into orbit and eventually failing. The international network of spacefaring nations and how they deal with debris from a policy and technical perspective must be better understood.

To effectively mitigate orbital debris and to have satellites avoid debris and collisions, it is necessary to understand both the social and technical factors. In the following section, I outline a new technique for creating cold atom samples that can be used in inertial measurement units for better navigation. In the section after that, I outline how the STS framework Actor Network Theory is relevant for analyzing how a network of spacefaring nations was created to impose a set of guidelines on how all countries would work to mitigate the creation of orbital debris.

Technical Problem

Since the first creation of a Bose-Einstein Condensate (BEC) in 1995 the field of ultracold physics has undergone a number of developments. In a BEC, thousands of atoms all occupy the same quantum-mechanical state, which allows previously inaccessible quantum effects to be observed and controlled on a macroscopic scale (Reichel, 2005). However, even though BECs are simple to observe, they can be very difficult to create. In order to transition from a classical atomic vapor into a condensate, the atoms must be cooled to about a millionth of a degree above zero. Current practices involve using a combination of laser and evaporative cooling. Both of these techniques rely on the use of magnetic trapping to control the location of atoms in free space. In magnetic trapping, the magnetic properties of atoms can be used to contain them in a magnetic potential that can be created and controlled by running current through various wire configurations (Perez-Rios et al., 2013).

Although BECs are difficult to make, they have many possible applications, perhaps the most important being in the field of precision measurements. In one especially useful application, interferometry can be performed on BECs to make inertial measurements (measurements of accelerations). In classical interferometry electromagnetic waves are split then superimposed, and their interference measured to determine the forces the waves were subjected to. In atomic interferometry, the wavelike nature of atoms is exploited to do the same thing. However, unlike photons (light), atoms have mass, and can be used to measure gravity as well as accelerations and rotations. And since the wavelength of atoms can be smaller than that of light, atomic interferometry has the potential to be much more precise than classical interferometry (Cronin et al., 2009).

In order to study BECs and atomic interferometry free from the force of gravity, NASA JPL developed the Cold Atom Laboratory (CAL). Located on the International Space Station, CAL offers a unique opportunity to study cold atoms in microgravity, where they are free from confinement forces (Elliot et al., 2018). Previous experiments in this area have used drop towers or sounding rockets to achieve microgravity conditions, but CAL has the obvious advantage of continuous microgravity. The CAL apparatus creates BECs of Rubidium-87 atoms in a tightly confining magnetic trap using a laser and evaporative cooling. However, in order for the atom sample to be useful for interferometry, the BEC must be nearly stationary with respect to the apparatus and as cold as possible. A tightly-confining trap near the chip is required in order to perform evaporative cooling, but if the trap were abruptly turned off, the sample would expand very quickly. In order to avoid this, the trap must be slowly relaxed using a technique called adiabatic expansion.

The goal of the technical project is to use the new technique of adiabatic expansion to create an ultracold and stationary sample of Rubidium-87 atoms using the CAL apparatus. This involves carefully turning down the currents in the wires that control the magnetic trap in order to weaken it and be left with only the coldest atoms. The manner in which the currents are decreased will affect the final motion of the condensate, so how to weaken the trap in order to make the sample stationary must be determined. The main challenge with the adiabatic expansion technique is that as the magnetic trap is weakened, it can be affected by stray background magnetic fields and magnetic gradients (Sackett et al., 2018). In order to prove the feasibility of adiabatic expansion, methods of dealing with these fields and gradients must be developed. At the end of the experiment, a cold atom sample that is usable in atomic interferometry should be able to be reliably created.

STS Problem

Since the beginning of the space age over 60 years ago, humans have been continuously launching objects into space. Although many of those objects re-enter the atmosphere where they either burn up or land on the surface of the Earth, many others remain in orbit. Orbital debris is defined as any human made object in orbit about the earth that no longer serves any purpose (May, 2015). This includes spacecraft that are no longer functioning, used upper stages of rockets, debris from explosions or failures of spacecraft, and even flecks of paint or material releases by thermal stress or particle impact with other objects. The U.S. Space Surveillance Network routinely tracks orbital debris, and today there are more than 23,000 pieces of orbital debris larger than 10 cm known to be orbiting the Earth (ARES, 2019). Orbital debris poses a large risk to spacecraft in Earth orbit, and as the population of debris continues to grow there is an increasing risk of collisions that will lead to damage and possibly more debris.

Since 1988, it has been the policy of the United States government to minimize the creation of new orbital debris, and in 2001 an official set of U.S. Government Orbital Debris Mitigation Standard Practices was adopted. Additionally, NASA and the Department of Defense conduct research on the development of technologies and techniques to limit or remove orbital debris, as well as model the current orbital debris environment (NASA, 2017). However, the United States is not the only space faring nation. Countries such as Russia, Japan, China, France, other members of the European Union, and Australia all have active space programs and create their own debris. Prior to 2007, there was no internationally agreed on set of guidelines for mitigating and dealing with orbital debris. This ignored the reality that all space going nations are contributing to orbital debris in some manner. It is obvious that just focusing on research and modeling for orbital debris or the individual orbital debris mitigation of various countries is inadequate to completely understand the problem of orbital debris. Instead of viewing technical and policy solutions to orbital debris separately, I believe it is necessary to view them as two parts of one network that must be built. By considering both the technical and policy efforts as part of the same network, we may better understand how a complete effort to mitigate orbital debris can be made.

To analyze this problem, I will use Callon's Actor Network Theory, which is an approach to understanding the technology-society relationship that examines power dynamics in heterogeneous networks. Heterogenous networks are networks comprised of different kinds of actors, such as human and non-human actors. They are often created by a network builder, which is a person, group, or organization responsible for forming an actor-network to solve a problem or accomplish a goal (Callon, 1987). Specifically, I will use Callon's Actor Network Theory to analyze the creation and adoption of the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space by the United Nations in 2007 (United Nations, 2010). I will also use Callon's theory to analyze why this network may be at risk from rogue actors of both human and technical nature. The problem of orbital debris provides an opportunity to analyze a large and complicated actor network composed of many parts.

Conclusion

The technical report will explain how adiabatic expansion can be used to create an ultracold and stationary sample of Rubidium-87 atoms in microgravity. This BEC will be viable for use in atomic interferometry for making inertial measurements for spacecraft navigation. The STS research paper will use Actor Network Theory to analyze the creation of an international network of spacefaring nations to deal with debris from a policy and technical perspective.

The results of the technical project will help to alleviate the need for more accurate navigation devices on satellites in an increasingly treacherous orbital environment. The results of the STS paper will use actor network theory to analyze a more unified approach to orbital debris mitigation and how the network may be at risk.

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