

## Campaign: Extending the limits of Bose Condensates in space

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## Introduction

Ultracold atoms have a promising future in space, with applications ranging from tests of fundamental physics to the development of exquisitely sensitive quantum sensors for Earth monitoring, lunar prospecting and spacecraft navigation. To realize this promise however, cold atom sources must perform at or beyond the state of the art achieved on the Earth. Fortunately, the space environment offers several distinct advantages for exploring and extending the limits of Bose condensation and ultracold atom production. These advantages include the ability to confine and manipulate atoms with exceptionally weak forces, along with the ability to observe unconfined atoms for long periods of times, both enabled by the reduced gravity. Access to the vacuum of space, which can surpass what is achievable on Earth, with an unlimited volume, offers further intriguing possibilities.

In this paper we explore some of the limits for ultra-cold gases and Bose-Einstein Condensates (BEC) that might be extended in space. These include the number of atoms in a condensate, the physical volume of a condensate, the lowest temperature achievable, the longest observation time, and the largest and most separated quantum superposition of atoms.

Improving these limits will increase the sensitivity of virtually all proposed missions involving cold atoms, and hence we believe its vitally important to explore these issues as fully as possible before investing heavily in dedicated missions aimed at addressing specific scientific questions.

## Limits to Bose Condensation

The largest BEC of alkali gases made to date have about  $10^8$  atoms [1]. Terrestrial BEC densities are typically limited to the neighborhood of  $10^{14}$  atoms/cc due to losses arising from 3-body collisions. These losses occur preferentially for the coldest atoms, resulting in an effective heating mechanism as well as a loss mechanism. High densities are essential for efficient evaporative cooling, but achieving high atom number typically requires relaxation of the trap strength in the final stages of cooling in order to reduce 3-body losses. Since these losses scale as the square of density, it is possible to find a density range with reduced losses that still supports a high level of elastic two body collisions needed for thermalization. On Earth however, one is constrained by the requirement to support the condensate against gravity, limiting how weak the trap can be made. The absence of such limits in space may make it possible to greatly increase the atom number.

Microgravity has already demonstrated its utility in achieving low effective temperatures. Here “effective temperature” is simply the temperature equivalent of the average kinetic energy of expansion, a useful metric particularly for precision measurements requiring very long interrogation times. Two microgravity experiments have achieved effective temperatures in the range of a few tens of picokelvins, and there do not appear to be fundamental limits that would prevent us from achieving sub-picokelvin temperatures, though magnetic field control will need to improve over what was utilized on the Cold Atom Lab. The best results in microgravity have employed a technique known as delta-kick cooling (DKC)[2,3] where atoms are allowed to freely expand before a harmonic potential is briefly applied to bring them to a halt. Ultimately, a limit

to achievable temperature in a given apparatus will arise from the apparatus size, which limits expansion time.

## BEC in the vacuum of space

The ultimate applications of cold atoms will involve performing experiments that aren't limited to the size of vacuum systems. While in principle there are no limits to the size of a vacuum chamber, volumes greater than a few liters will become prohibitively expensive for space applications. Accessing the vacuum of space reduces the limitations due to apparatus size, and also raises the intriguing possibility for performing experiments in an ultra-high vacuum orders-of-magnitude lower than available in a physical enclosure. Cold atom experiments may be of interest as a precise means of probing these vacuum environments: measuring the loss-rate of ultra-cold atoms from a magnetic trap depends only on the collision cross section, a fundamental atomic property. Hence cold atom vacuum sensors function as both an absolute sensor and primary vacuum standard.[4] In the following we explore several possible locations in which we could utilize the space vacuum.

### Lunar surface

The lunar surface might be the ideal place to begin experiments utilizing the vacuum of space. Here an open structure holding the required optics could be set up stably on the lunar surface with no need for an independent spacecraft. While the moon's gravity is much greater than what can be achieved in freefall, it is still weak enough for us to achieve long observation times and significantly weaker traps. An atomic fountain on the Moon would achieve free-fall observation times roughly 2.4 greater than on Earth. And, of course, in a system with no vacuum system, there is no technical limit as to how tall the fountain can be.

The lunar atmosphere is currently on average about  $2 \times 10^{-12}$  torr during the lunar night, which is significantly better than that obtained in CAL, though still not state of the art. This atmosphere may be impacted somewhat by a return of humans to the moon — the total mass of the lunar atmosphere is only about 25000 kg, while each of the Apollo lunar landers carried over 10000 kg of fuel (the measured impact of each Apollo mission on the lunar atmosphere was about 0.2 lunar atmosphere masses, which dissipated on photoionization timescales of less than a few weeks). [5] Outgassing from manmade equipment and human activities, such as construction or mining, could be additional sources. Monitoring the highly variable lunar atmosphere with cold atoms would be of considerable scientific and technical interest and could be an important secondary goal of a lunar mission.

Lacking a geodynamo, the moon has a very small magnetic field which varies widely across the surface but is typically of order a few tens of nT, roughly 1000 times weaker than the Earth's field.[6] Hence, there would be no need for magnetic shielding or compensation for a typical ultra-cold atom experiment on the lunar surface. Again, cold atoms might prove an ideal way to study such weak fields.

The effects of lunar dust, UV degradation of coatings and micrometeorite impacts on sensitive optics must be considered. As an example, the lunar reflectors deployed during the Apollo missions had their reflectivity degraded by over 90% after 44 years of operation (lunar dust is considered the most likely primary culprit). [7] These effects could be partially mitigated

by the use of sleeves and shutters over optics, perhaps along with electrostatic fields to repel dust or mechanical cleaning. The harsh thermal conditions arising from the lunar day/night cycle will also need careful consideration.

### Wake shields in LEO

A wake shield is essentially a metal plate that pushes residual gases out of the path of a rapidly moving spacecraft. As long as the velocity of the shield is substantially higher than the average velocity of thermospheric molecules, an ultra-high vacuum can be created in its wake. The Wake Shield Facility (WSF) was utilized on three Space Shuttle missions (STS-60, STS-69 and STS-80) and achieved vacuums of  $10^{-10}$  torr behind a 3.7 m diameter stainless steel shield. Such a vacuum is barely adequate for a BEC experiment. However, this vacuum was likely limited by outgassing from the shield itself, and a properly vacuum-processed shield could achieve pressures as low as  $10^{-14}$  torr, sufficient for most applications. [8]

For cold atom applications, we imagine a deployable optics assembly shielded behind a wake shield and tethered to a spacecraft or space station which would supply power and uplink/downlink capability. Active control of magnetic fields would likely be required to remove effects of the changing Earth field.

### Interplanetary space

Near ultimate vacuum can be found in interplanetary space. While the costs of a dedicated free-flying mission orbiting at, say, one of the Earth-Sun Lagrange points might be prohibitive, several of the most demanding applications of cold atoms in space may need to utilize this environment. These include missions that aim to search for gravity waves, and for dark energy or dark matter candidates. [9] In this environment, the lifetime of quantum matter can be hundreds of times longer than achievable on Earth.

### Passively cooled high temperature superconductors

Scaling up a BEC apparatus in general requires a large increase in mass and power. Making use of the vacuum of space, as we've discussed above, helps the mass budget significantly by avoiding the mass of vacuum pumps and chambers, with the mass of most other components (cameras, computers, electronics and lasers, etc.) only increasing modestly, if at all.

On the power side, the main components that require more power are lasers and magnetic field current drivers. Unfortunately, the current  $I$  required to produce a given magnetic field curvature scales as  $I/S^3$ , where  $S$  is the characteristic size of the system.[10] Hence, doubling the size of a harmonic magnetic trap will generally require a 64-fold increase in power.

We can largely eliminate this power increase by converting to superconducting magnetic coils. Here we propose to utilize another feature of the space environment, namely the ability to radiatively couple to the roughly 5K background temperature of space (at 1 AU from the sun this is somewhat above the cosmic microwave background due to zodiacal dust). Passive cooling to below 30 K is readily achievable in space [15], though care is needed to shield from Sun, Earth and Moon shine. Wires made from YBCO (92 K transition temperature) BSCCo (108 K) and REBCO ( $\text{REBa}_2\text{Cu}_3\text{O}_x$ , where RE = Y, Gd) have been utilized in high current magnet applications producing steady-state fields over 45 T [11], much larger than needed for the current application.

The cold temperatures of outer space can also be used to shield sensitive experiments from blackbody radiation, and could also be used to passively cool laser systems.

## Why explore these limits?

One of the primary reasons for studying cold atoms in space is to support the development of exquisitely sensitive quantum sensors based on atom interferometry. Such sensors may be used to test fundamental theories of physics such as general relativity, search for exotic dark energy or dark matter candidates; or serve as observatories for gravitational waves. Atom interferometry can also be used to monitor the Earth's gravitational field, aid prospecting on Mars, or help navigate spacecraft. For each of these applications, sensitivity is enhanced with larger atom numbers, colder temperatures and longer lifetimes. It is important that we fully explore and understand these limits before embarking on costly space missions focused on a specific scientific objective.

Standard theories of quantum mechanics and gravity are expected to break down as we probe nature at the Planck scale. While the Planck time, energy, and length are well beyond the reach of foreseeable experiments, the Planck mass ( $m_p = \sqrt{\hbar c/G}$ , or  $2.2 \times 10^{-8}$  kg) appears to be more accessible. The idea is that as we examine manifestly quantum objects that approach this mass, such as pure condensates, superpositions or entangled ensembles, we may see deviations from current theory that may point towards a quantum theory of gravity. Achieving the Planck mass would require a condensate of  $1.5 \times 10^{17}$  rubidium atoms, and is unlikely to be obtained even with the enhancements discussed in this paper ( $1.2 \times 10^8$  sodium atoms appears to be the current record [1]). However, a number of authors have suggested that precision measurements may be able to observe deviations at much smaller atom numbers. For example, Roger Penrose and colleagues have proposed studying a single BEC in a superposition of two locations which could test a quantum gravity proposal in which wavefunction collapse emerges from a unified theory as an objective process, resolving the longstanding measurement problem of quantum mechanics [13]. In this case, the authors considered a Cs BEC with  $4 \times 10^9$  atoms. Others have proposed looking for non-Gaussianity as a signature of quantum gravity in a sample of  $10^9$  atoms left to self-interact gravitationally for several seconds. [14]. Both experiments would likely require long duration microgravity, even if a terrestrial means of achieving the desired atom number was found.

## Technology roadmap

**Efficient, High power laser systems:** Collecting large atom numbers requires large beam diameters and high-power lasers. We will probably not be able to surpass limits achieved on Earth without developing narrow linewidth laser systems that produce greater than 10 Watts of power at NIR wavelengths.

**Deployable optical systems:** For experiments utilizing the vacuum of space, we envision a folding structure for mounting optics and magnetic coils. Rather than designing a system that can maintain stringent alignments in the external space environment, we would aim to develop active steering of optics.

**Compact very high flux cold atom sources:** In the short term, 2D MOT-derived cold atom sources appear to be the best option when one tries to optimize both flux and SWaP. Zeeman slowers incorporating superconducting magnets may be a more long-term solution.

**Space based passively cooled HTC magnets:** While HTC's have been tested in a space environment (cite), passively cooled HTC's have not been demonstrated in space. A ground program should focus on the choice of HTC materials, designs of magnets for cold atom applications, and the thermal design needed for passive cooling in different space environments.

## Costs

A program to extend the limits of Bose condensation in space will require a significant (~ \$1 million/year) ground research program for the coming decade, in conjunction with a series of space missions. An initial focus should be on achieving the current state of the art for atom numbers and lifetimes in Earth-based experiments in a space-flyable instrument. We expect a next-generation facility, such as the Quantum Explorer, described elsewhere, to largely accomplish this goal. A follow-on mission deployed on the moon might be an ideal way to develop technologies for a instrument that would utilize the vacuum of space.

The Lunar **Ultracold Neutral Atom Research (LUNAR)** facility would consist of an open support structure to hold optics, atomic sources, and magnetic coils, along with associated electronics and lasers. The complexity of the instrument would be nearly identical to the existing Cold Atom Lab (CAL), currently operating onboard the ISS, though would at least initially only incorporate a single atomic species. We expect significant additional design effort is necessary for the thermal, optomechanical and possibly electronic systems. In addition, we would likely reduce the operation time from the 3+ years demonstrated by CAL to something more like a 120-day mission duration. Beyond being an important technology demonstration, such a mission would give new insights into the Moon's dynamic atmosphere, and would also allow for a short, highly focused, research program incorporating very large condensates.

Assumptions obviously include the existence of a manned facility on the moon that would provide power and data with standard interfaces (similar to the ISS), and that costs of transporting the instrument to the surface of the moon, along with crew time are not included in the estimate.

This cost information is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

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