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Laser Cooling a Strongly Coupled Plasma

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Final Technical Report

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14. ABSTRACT
This proposal is to use the powerful techniques of laser cooling to cool ions in an ultracold neutral plasma in order to reach much stronger Coulomb coupling. Laser cooling of the plasma has been a longstanding goal for the community studying ultracold plasmas, and our recent work on the evolution of the ion temperature during the expansion of the plasma and collisions and diffusion in a strongly coupled plasma, coupled with improved simulation capabilities, has given us the basic understanding needed to achieve it. The motivation for this work is twofold. First, we are developing laser cooling as a new technique for manipulating plasmas and pushing the boundaries of plasma parameters that are accessible in the laboratory. Second, we will use laser cooled plasmas as a platform for studying strongly coupled plasma physics, with a focus on transport properties. In strongly coupled plasmas, the Coulomb interaction energy per particle exceeds the thermal energy. This occurs in high-energy-density plasmas such as inertial confinement fusion experiments and in nature in the interiors of gas giant planets and the crusts of neutron stars. Classical plasma theory breaks down in strongly coupled systems because of the non-perturbative nature of particle interactions. Improving our understanding of this regime is an important fundamental challenge and it is necessary for modelling plasmas in this regime.

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Final Technical Report for "Laser Cooling a Strongly Coupled Plasma"
AFOSR grant FA9550-17-1-0391

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Abstract

This proposal is to use the powerful techniques of laser cooling to cool ions in an ultracold neutral plasma in order to reach much stronger Coulomb coupling. Laser cooling of the plasma has been a longstanding goal for the community studying ultracold plasmas, and our recent work on the evolution of the ion temperature during the expansion of the plasma and collisions and diffusion in a strongly coupled plasma, coupled with improved simulation capabilities, has given us the basic understanding needed to achieve it.

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Summary of Main Results

(1) First demonstration of laser cooling of a neutral plasma and increase of ion Coulomb coupling to >10.
(2) Multiscale numerical simulation of laser cooling in a strongly coupled plasma; drafting of a manuscript on the topic
(3) Demonstration of magnetic trapping of an ultracold neutral plasma
(4) Development of laser-induced fluorescence at ultracold temperatures in inhomogeneous magnetic fields.

Publications

This work resulted in six publications. The highlights include a paper in Science on laser cooling a neutral plasma, a Physical Review Letter on magnetic trapping an ultracold neutral plasma that was chosen as and Editors' Suggestion and was the focus of a Physics Synopsis article, and a paper in Physics of Plasmas on plasma expansion that was chosen as an Editor's Pick.

1. "Laser Cooling of Ions in a Neutral Plasma," T. K. Langin, G. M. Gorman, and T. C. Killian, *Science* 363, 61 (2019), DOI:10.1126/science.aat3158.

2. "Exploring the Crossover Between High-energy-density Plasma and Ultracold Neutral Plasma Physics," S. D. Bergeson, Scott D. Baalrud, C. Leland Ellison, Ed Grant, Frank R. Graziani, T. C. Killian, M. S. Murillo, Jacob Roberts, and L. G. Stanton, Phys. Plasmas 26, 100501 (2019).

3. “Combined Molecular Dynamics and Quantum Trajectories Simulation of Laser-driven, Collisional Systems,” G. Gorman, T. K. Langin, M. K. Warrens, D. Vrinceanu, T. C. Killian, Phys. Rev. A 101, 012710 (2020).

4. “Magnetic Confinement of an Ultracold Neutral Plasma,” G.M. Gorman, M.K. Warrens, S.J. Bradshaw, and T.C. Killian, Phys. Rev. Lett 126, 085002 (2021). Editors' Suggestion. Physics Synopsis, "Holding on to a Cold Plasma", https://physics.aps.org/articles/v14/s27

5. “Expansion of Ultracold Neutral Plasmas with Exponentially Decaying Density Distributions,” M. K.Warrens, G. M. Gorman, S. J. Bradshaw, and T. C. Killian, Phys. Plasmas 28, 022110 (2021). Editor's Pick.

6. “Laser-induced-fluorescence imaging of a spin-polarized ultracold neutral plasma in a magnetic feld,” G. M. Gorman, M. K. Warrens, S. J. Bradshaw, and T. C. Killian, Phys. Rev. A 105, 013108 (2022).

Invited Presentations

From this work, the PI gave two invited talks at the APS Meeting of the Division of Plasma Physics (2018,2020), and invited talks at the *20th International Conference on Atomic Processes in Plasmas*, Gaithersburg, MD (4/19), International Conference on Atomic Physics, Toronto, Ontario, CA (7/22), and the 2021 Gaseous Electronics Conference, Huntsville, AL (10/21). Several colloquia were also given in the US and Europe.

1. ``Laser-driven and Magnetized Ultracold Neutral Plasmas,'' 2022 International Conference on Atomic Physics, Toronto, Ontario, CA (7/22).
2. ``Ultracold Neutral Plasmas: A Platform for Studying Strongly Coupled and Magnetized Plasmas and other Novel Systems,'' 2021 Gaseous Electronics Conference, Huntsville, AL (10/21).
3. ``Laser-Driven and Magnetized Ultracold Neutral Plasmas,'' 2020 Annual Meeting of the Division of Plasma Physics of the American Physical Society, Memphis, TN (11/20).
4. “Laser Cooled Neutral Plasmas: A Laboratory for the Study of Strongly Coupled Systems,'' Colloquium, University of Strathclyde, Department of Physics, Glasgow, United Kingdom (9/19).
5. “Experimental Measurement of Self-Diffusion in a Strongly Coupled Plasma,'' \it 20th International Conference on Atomic Processes in Plasmas, Gaithersburg, MD (4/19).
6. ``Laser Cooled Neutral Plasmas: A Laboratory for the Study of Strongly Coupled Systems,'' Colloquium, Brigham Young University Department of Physics and Astronomy, Provo, Utah (3/19).
7. ``Laser Cooled Neutral Plasmas: A Laboratory for the Study of Strongly Coupled Systems,'' \it 2018 Annual Meeting of the Division of Plasma Physics of the American Physical Society, Portland, OR, (11/18).
8. ``Laser Cooled Neutral Plasmas: A Laboratory for the Study of Strongly Coupled Systems,'' Ole Romer Colloquium, Aarhus University Department of Physics, Aarhus, Denmark (6/18).

Personnel

Thomas C. Killian – PI, typically 1 month summer salary funded by AFOSR grant FA9550-17-1-0391

Thomas Langin – PhD 2018, funded by FA9550-17-1-0391
Grant Gorman – PhD 2022, funded by FA9550-17-1-0391
MacKenzie Warrens – continuing graduate student, partially funded by FA9550-17-1-0391

Laser Cooling of Ions in an Ultracold Neutral Plasma
"Laser Cooling of Ions in a Neutral Plasma," T. K. Langin, G. M. Gorman, and T. C. Killian, **Science** 363, 61 (2019), DOI:10.1126/science.aat3158.

The publication received a great deal of attention in the popular press. For example, it was covered by Physics World: https://physicsworld.com/a/ultracold-neutral-plasma-could-simulate-the-interior-of-stars-and-planets/

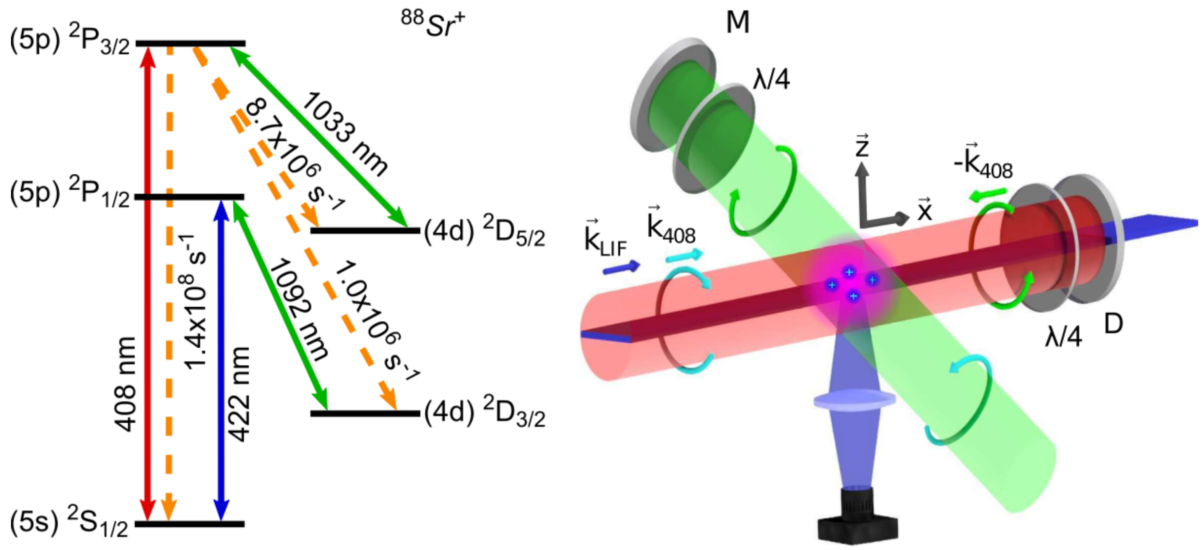

Figure 1: (A) Sr^{++} level diagram including wavelengths and decay rates for transitions relevant to cooling and imaging. (B) Experimental schematic. Cooling (408 nm) and repumping (1092 nm, 1033 nm) lasers are applied in counter-propagating configurations with indicated polarizations. Light at 422 nm for laser-induced fluorescence (LIF), shaped by a slit to illuminate a central slice of the plasma, propagates perpendicular to the imaging axis and, unless otherwise specified, along the laser-cooling axis ($\hat{x}$). Propagation directions for LIF and cooling light are indicated. LIF Images are recorded on an intensified CCD camera. A high-pass dichroic D reflects the cooling laser and transmits the LIF light. (M: mirror, and $\lambda/4$: quarter-wave plate). From **Science** 363, 61 (2019).

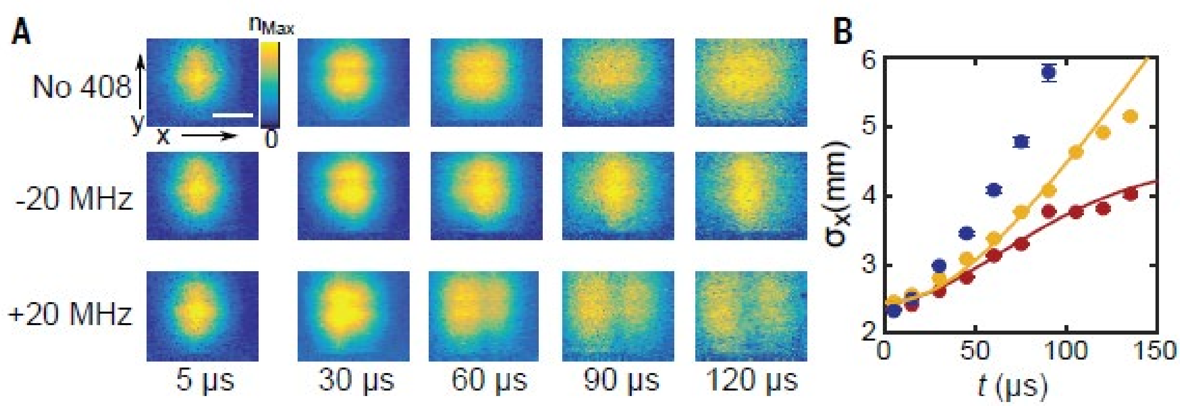

Figure 2: (A) Evolution of plasma density distribution. Red-detuned optical molasses along x retards expansion, whereas blue-detuned light accelerates it, eventually leading to bifurcation. (Laser detuning is indicated to the left of the plots.) The scale bar is 5 mm. The color bar is rescaled for each time to n_{max}=(13,8.5,4.2,2.2,1.3)x10^7 cm^{-3} for laser-cooling time t=(5,30,60,90,120)μs. (B) RMS plasma radius σ from gaussian fit to experimental data. Shown are the data for laser detuning Δ = −20 MHz [red (cooling)], Δ = 20 MHz [blue (heating)], and no 408-nm laser (yellow).

Newsweek online:
https://www.newsweek.com/laser-cooling-neutral-plasma-colder-deep-space-jupiter-white-dwarf-ultracold-
1278797
And Live Science:
https://www.livescience.com/64422-plasma-cooled-with-lasers.html
I was interviewed for a piece on Public Media's "SciTech Now" (**https://www.scitechnow.org/**) which is now available (http://bit.ly/2Xacw1w).
The original Rice Press release can be found at:
https://news.rice.edu/2019/01/03/next-up-ultracold-simulators-of-super-dense-stars-2/
and the video is https://youtu.be/kB767cjUpQs.

Numerical Simulation of Laser Cooling of Ions in an Ultracold Neutral Plasma

Laser-generated forces on atoms, ions, and molecules, such as in laser cooling, arise from coupling of external momenta and internal quantum states of the particles of interest. In most cases, optical forces can be calculated using the velocity-dependent, steady-state solutions to the optical Bloch equations (OBEs) for internal-state quantum dynamics. In a highly collisional system, however, the particle velocities and associated Doppler shifts can change significantly on the timescale required for the internal quantum states to reach steady state. These rapid changes of the velocity can cause the time averaged quantum state, and thus the calculated optical forces, to differ from the steady-state OBE solution. One such collisional system is ions in an ultracold neutral plasma.

We have developed a combined molecular dynamics (MD) and quantum trajectories (QT) code to simulate the effects of near-resonant optical fields on state-vector evolution and particle motion in a collisional system. Using MD, velocity changes due to collisions and optical forces are accurately tracked while the state-vector evolution and optical forces are determined using QT. Velocities are passed from MD to QT and optical forces are passed from QT to MD in an integrated, multi-scale architecture. We use this simulation to describe laser-cooling in a strontium ultracold neutral plasma, including the suppression of electromagnetically induced transparencies through rapid velocity changing collisions and thermalization between cooled and un-cooled dimensions for anisotropic laser cooling.

This is an important tool for improving our understanding of laser-driven ultracold plasmas and should be of significant value to the plasma community. The publication is nearing completion and will be submitted this summer.

Magnetic Trapping of an Ultracold Neutral Plasma

Ultracold neutral plasmas (UNPs) are an excellent tool for studying strongly coupled plasmas, in which the ratio of the nearest neighbor Coulomb energy to the average thermal energy, Γ_i, is greater than one. Magnetized UNPs are of current interest because of the interplay of magnetization and strong coupling, connection to plasma confinement, and modification of recombination dynamics in strong fields. We have demonstrated magnetic confinement of an UNP within the same quadrupole magnetic fields (biconic cusp) used in the laser cooling of the initial atom cloud. The plasma expansion is initially unaffected by the presence of magnetic field, but after a time that scales with $\sigma(0)/\sqrt{T_e}$, where $\sigma(0)$ is the initial plasma size and T_e is the electron temperature, the expansion essentially ceases and the density stabilizes.

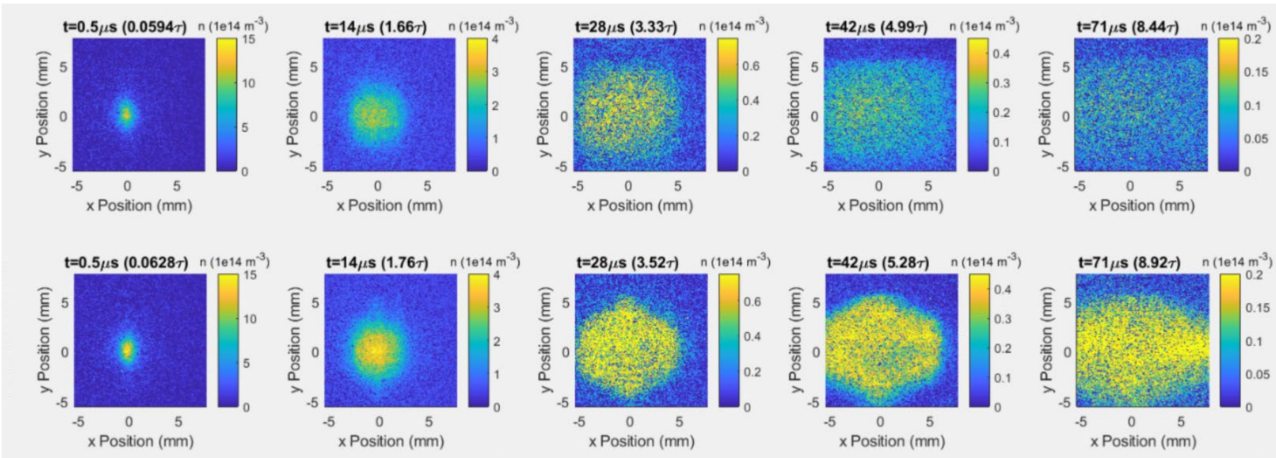

Figure 3: Laser-induced fluorescence images of ultracold neutral plasmas without (top) and with (bottom) a biconic cusp magnetic field. The electron temperature is Te=80 K. In the presence of the field, the expansion of the plasms is slowed and eventually shows trapping of the ions. We expect that electrons are constrained by the magnetic field and ions are trapped doe to Coulomb attraction to the electrons. A detailed understanding of the trapping dynamics is a focus of our current research. Magnetically trapped plasmas should provide advantages for further laser cooling and increasing Coulomb coupling.

Because the magnetic field geometry is the same as used for laser cooling the neutral atoms, it will likely provide advantages for laser cooling the ions in the neutral plasma as well.