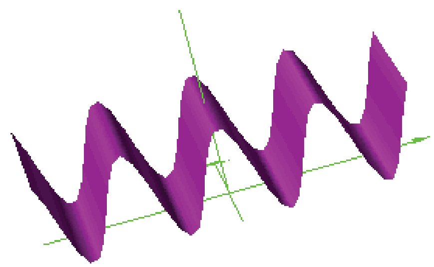
Laser-Trapped Mirrors in Space

Phase I: Feasibility Study



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NIAC Fellows Meeting 2002

The Collaboration

Dr. Tony Rothman, Research Associate at Bryn Mawr College.

Dr. Jean-Marc Fournier,Scientist at the Rowland Institute for Science.

Professor Antoine Labeyrie, Chair of Observational Astrophysics and Director of the Laboratoire d'Interferometrie Stellaire et Exoplanetaire, College de France.

Dr. Daniel Maystre, Director of Research at the Centre National de la Recherche Scientifique and Director of the Laboratoire d'Optique. Electromagnetique at the University of Aix-Marseille and the University of Provence, France.

Dr. Robin Kaiser, Director of the Laboratoire Ondes et Desordre à Institut Non-Lineaire de Nice in Sophia-Antipolis, France.

Dr. Robert Stachnik, Director of the Christina River Institute and member of the NASA Headquarters Astrophysics Working Group and the Terrestrial Planet Finder Science Working Group.

Professor Naomi Halas, Stanley C. Moore Professor in Electrical and Computer Engineering at Rice University.

Dr. Ed Friedman, Senior Scientist in the NASA Programs component of Boeing/SVS, Albuquerque, New Mexico.

Dr. Daniel Ou-Yang, Physicist at Lehigh University.

Peter Anninos, Scientist at Lawrence Livermore National Laboratory.

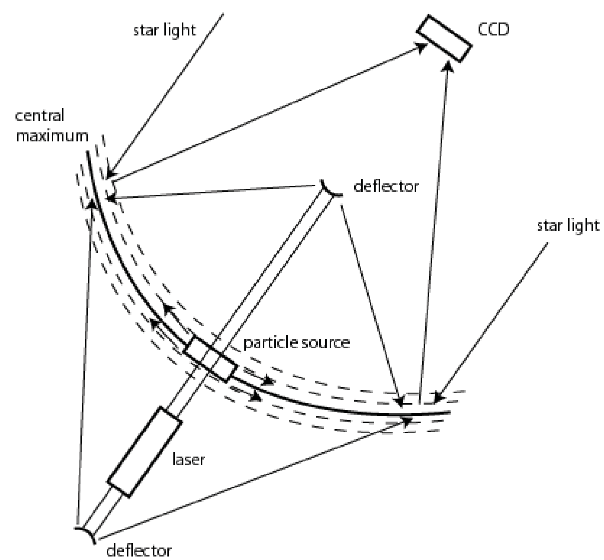
The Project

Can Laser Trapped Mirrors be a practical solution to the problem of building large, low-mass, optical systems in Space?

- The Laser-Trapped Mirror (LTM) Concept
- Mirror Evaporation Time
- Dynamical Simulations
- Optical Binding Potential
- Image Quality and Particle Size
- Damping Mechanisms
- Trap Loading
- Findings and Next Steps

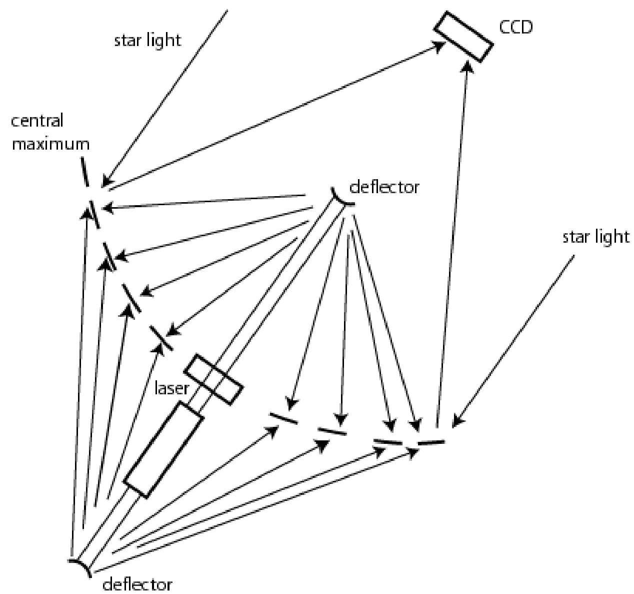
The LTM Concept

A. Labeyrie



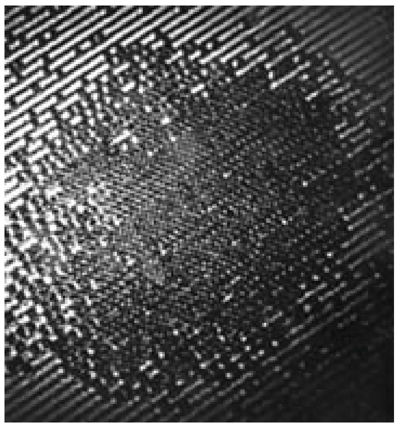
- Beams emitted in opposite directions by a laser strike two deflectors.
- Reflected light produces a series of parabolic fringe surfaces.
- Through diffractive and scattering forces, dielectric particles are attracted toward bright fringes, and metallic particles towards dark fringes.
- Ramping the laser wavelength permits sweeping of particles to the central fringe.
- Result is a reflective surface in the shape of a mirror of almost arbitrary size.

Impact

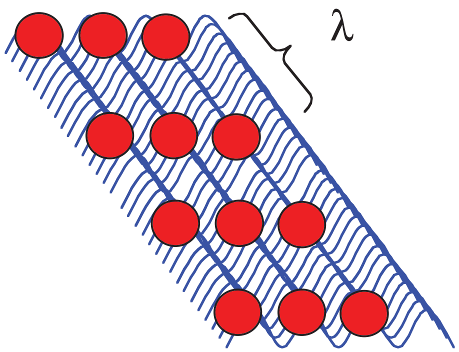


- Potential for very large aperture mirrors with very low mass (35 m--> 100g !!) and extremely high packing efficiency (35m--> 5 cm cube).
- Deployment without large moving parts, potential to actively alter the mirror's shape, and flexibility to change mirror "coatings" in orbit.
- Potential for fabricating "naturally" co-phased arrays as shown at left.
- Resilience against meteoroid damage.
- Applications in the NASA Terrestial Planet Finder (TPF) program.

Previous Work



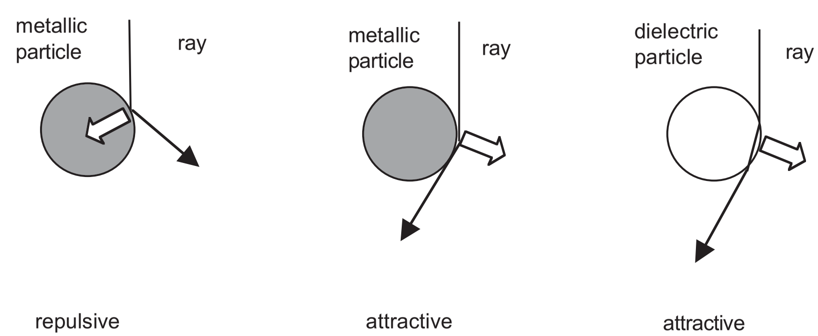
- Experiments by Fournier et al. in the early 1990's demonstrated laser trapping of arrays of macroscopic particles along interference fringes: M. Burns, J. Fournier, and J. A. Golovchenko, Science 249, 749 (1990).



- Fournier et al. also observed that laser trapped particles can self-organize along a fringe due to photon re-scattering among the trapped particles resulting in "optical matter" (analogous to regular matter, which is self-organized by electronic interactions): M. Burns, J. Fournier, and J. A. Golovchenko, Phys. Rev. Lett. 63, 1233 (1989).

The Forces of Light

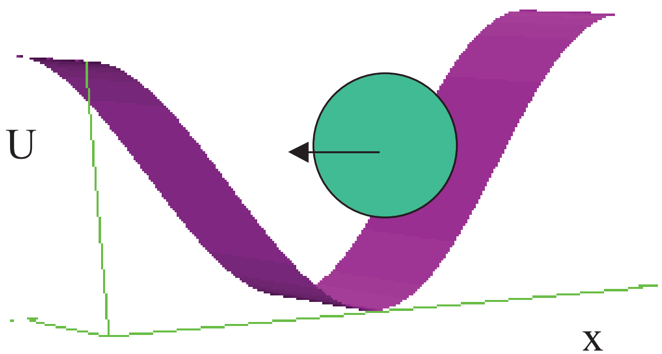
- Optical Trapping: overlapped light fields create positions of stable equilibrium. Any displacement results in a restoring force on the particle.



- Light reflection results in repulsion (scattering force). Light refraction results in attraction (induced dipole and field gradient forces). Strongly wavelength-dependent processes.

- Particles will remain trapped for a length of time limited by collisions with background particles and photons.

Trap Dynamics



$$F = -\frac{\partial U}{\partial x}$$

$$k_{eff} = \frac{16\pi^3 \alpha I}{c\lambda^2}$$

$$\omega^2 = \frac{k_{eff}}{m}$$

$\omega \approx 10\sqrt{I}$, where I is in Watts/m^2.

- Dynamical time scale is on the order of 1 second.

Trap Strength

- Dipole interaction traps dielectric particles in regions of high field intensity.

$$U = P \cdot E \cong \frac{1}{2}\alpha E \cdot E$$

$$\alpha = \frac{n^2 - 1}{n^2 + 1} a^3$$

- For two counter-propagating plane waves, the trap strength is:

$$U_{trap} = \frac{2\pi\alpha}{c} I$$

- For 1 micron-sized particles with a reasonable index of refraction, n=1.6 and *I* expressed in Watts/m^2:

$$U_{trap} = 6 \times 10^{-20} I \ \text{ergs}$$

This is the difficulty;
this number is extremely small.

- Equivalent to a temperature of milliKelvins and an escape velocity of 10^{-4} cm/s.
  Compare to infrared background at T ~ 30K

The Questions

- Can a Laser Trapped Mirror be constructed?

- If so, can it be maintained?

  - What are the laser power requirements for sustaining a laser-trapped mirror in space?

  - What strategies are available to limit particle heating in order to increase trapping times? (shape, materials, damping structures)

  - What particle size and density are needed to achieve quality imaging?

Estimate of Evaporation Time

- At 30 K, background photons: $n_\gamma \sim 10^6\ \text{cm}^{-3}$, $\lambda = 10^{-2}$ cm.

$$\Delta E = \frac{p_\gamma^2}{2m} = \frac{(h/\lambda)^2}{2m}$$

$\Delta E \sim 10^{-34}$ ergs/collision

- Given a cross-section, $\sigma = 10^{-2}\ \sigma_{\text{geometric}}$, for the interaction of silica with these photons, the rate of increase of the kinetic energy of a trapped particle is:

$$\frac{dE}{dt} = \Delta E n_\gamma \sigma c$$

$dE/dt \sim 10^{-26}$ ergs/sec

- Integrating and evaluating for a 1 micron-sized particle, we get:

$$\tau_{evap} = \frac{4\pi\alpha m\lambda^2}{h^2 n_\gamma \sigma c^2} I$$

$$\tau_{evap} \approx 1.5 \times 10^8\, I\ \text{sec}$$

Scales with radius $\sim a^4$:
Particle size is critical.

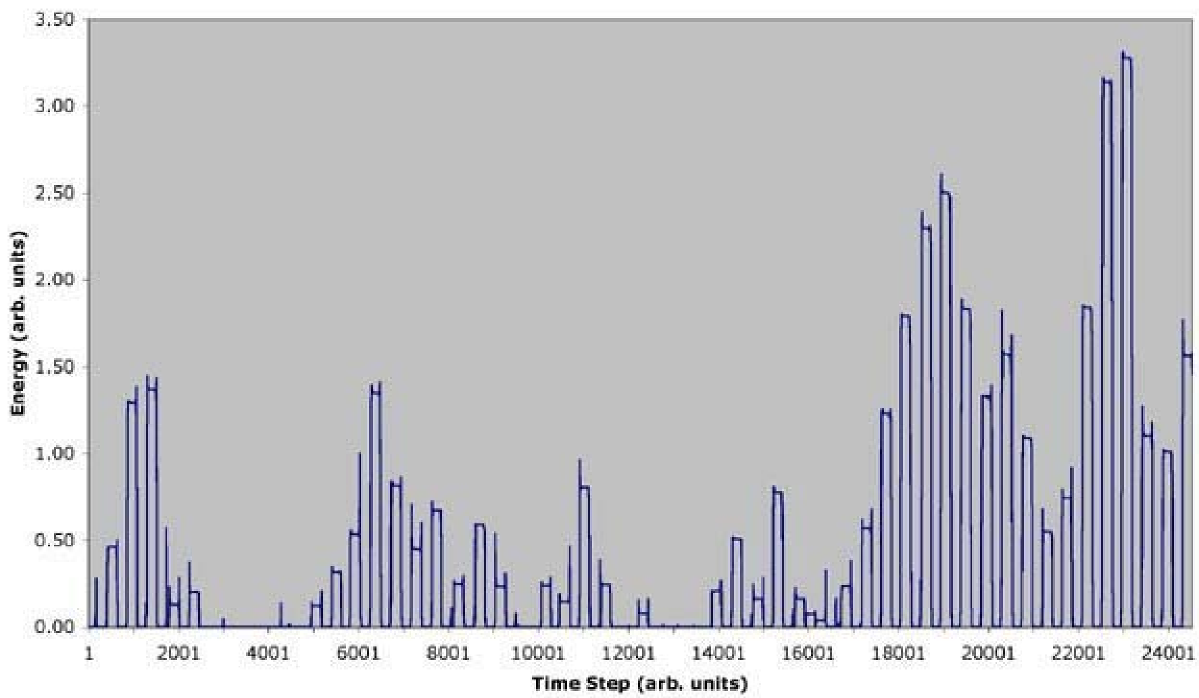
where I is expressed in Watts/m^2.

- A respectable number: about 5 years for $I = 1$ Watt/m^2 and ~ months for currently available laser intensities.
  100 nm-sized particles --τ_{evap} ~ hours, will need damping.

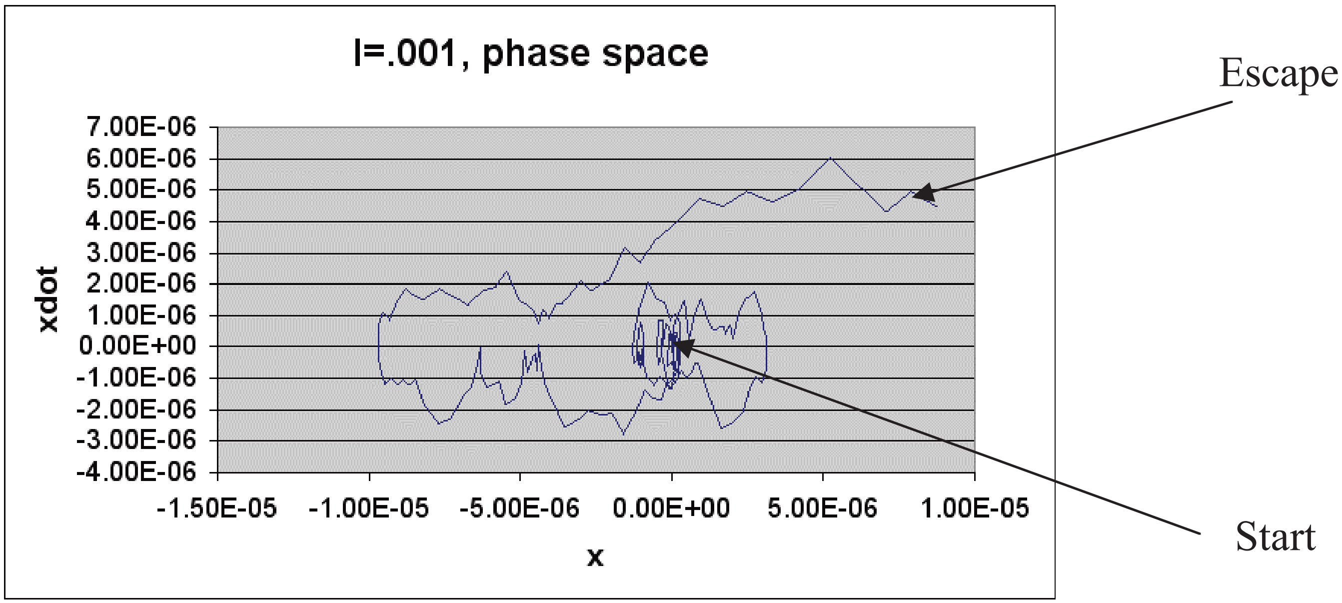
Dynamical Simulations

- Single particle, 1-D model.
  Trapped particle bombarded by background photons arriving randomly.
  Nonlinear forcing term leads to chaotic dynamics.

Output from Tony's numerical code, zeroth order version: Kinetic energy of a particle in a one dimensional harmonic trap (with no damping) experiencing momentum kicks from background photons randomized in direction.



Chaotic Dynamics



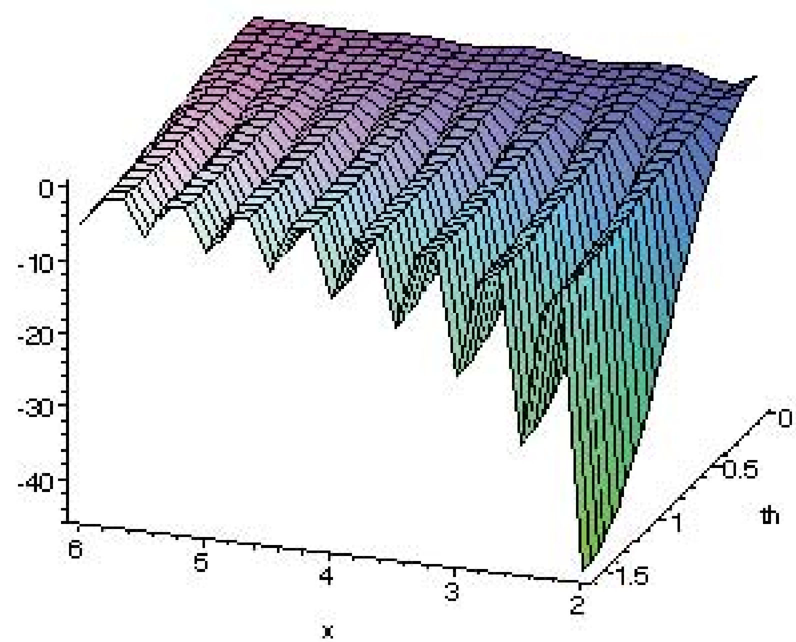
- Although sensitive to inputs, simulations give comparable results to the estimates at low laser intensities.
- A many particle 2-D model that includes optical binding as well as any damping mechanisms is needed and will require substantial computing power.

Optical Binding Potential

- Induced dipole moments in adjacent spheres will give rise to electromagnetic forces between the spheres.
- Burns, et al. give an approximation for this interaction energy: long-range interaction which oscillates in sign at λ and falls off as $1/r$.
- Calculations of this two-particle binding potential look encouraging. However, results are based on approximations not necessarily valid in the regime where particle radius $\sim \lambda$.
- Need to explore this effect with no approximations, i.e., in the Mie scattering regime. We are currently developing numerical codes with Peter Anninos at LLNL.

Two-Particle Binding Potential

- Here, λ = particle radius = 500 nm and the light is linearly polarized.
  The *x* coordinate is in units of particle radius; x=2 corresponds to adjacent particles.
  The *th* coordinate is the angle between the line connecting the two particles and the polarization vector.
  The *z* coordinate is in units of the optical trap depth.



- For *th*=0 the enhancement in potential is modest, for *th* =π/2 however, the binding potential is ~45 times the trapping potential. For 20 particles, enhancement is 300.

- Will this enhancement persist in numerical calculations made with no approximations?

Image Quality and Particle Size

- Consensus is that resolving power will be the same as an ordinary mirror: $\sim \lambda$/diameter, as long as $\lambda > a$, where a is the particle radius. However, this competes with the advantages of larger particles for a more stable trap.

    - Trap at λ=1 micron, particles with a radius of 250 nm.
      Image at λ>1 micron.

- Reflection efficiencies will depend on the number of scatters and the ratio of λ/a.
  In the Mie regime, calculations must be done numerically.
  Preliminary results with ~100 particles yield results ranging from 10^{-2} to 10^{-4}.

Damping Mechanisms

- Doppler Cooling--Atoms vs. Micron-sized particles

$$\tau_{cool} \sim m/Q$$
$$Q = \frac{\lambda}{\Delta\lambda}$$

Need uniform particle samples.

- Collisional Damping

  •Kinetic energy converted into internal modes: must radiate away, but we know this coupling to the infrared is small.

- Evaporative Cooling--3-body collisions--how many particles are lost? How much cooling can be gained?

- Stochastic Cooling--any collective motion could be used to cool by removing center-of-mass motion adaptively by manipulating the location of the trap--requires sampling of the system at a rate faster than the dynamics.

- Atoms in fullerene cages--atoms retain sharp absorption features, but the C_{60} cage can have wideband reflection properties.

Trap Loading

- Frozen particles on a Mylar sheet--rate of particle evaporation from the sheet would be key.

- “Edge rover”--optical tweezer trap used to load cold particles in a spiral pattern--at what rate could the mirror be constructed in this manner?

Findings and Next Steps

- Formidable technical obstacles do exist and much of the physics involved is not currently well understood.

  However, we have not found any physical impossibilities or so-called "show-stoppers" to prevent the construction of an LTM.

- Investigations in several key areas are needed:

  • Nano and micro-fabrication of designer particles--low absorption at background and trapping wavelengths and high reflectivity at observing wavelengths.

  • Collective behavior of micron-sized particles in light fields--numerical work in the Mie scattering regime to explore optical binding effects.

  • Zero-gravity and vacuum environment experiments to explore possible trap loading schemes.