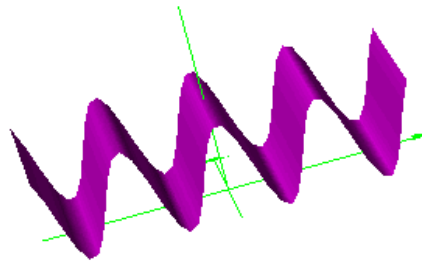


# Laser-Trapped Mirrors in Space

Phase I: Feasibility Study



Elizabeth McCormack  
Physics Department  
Bryn Mawr College

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 Maestre**, 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.

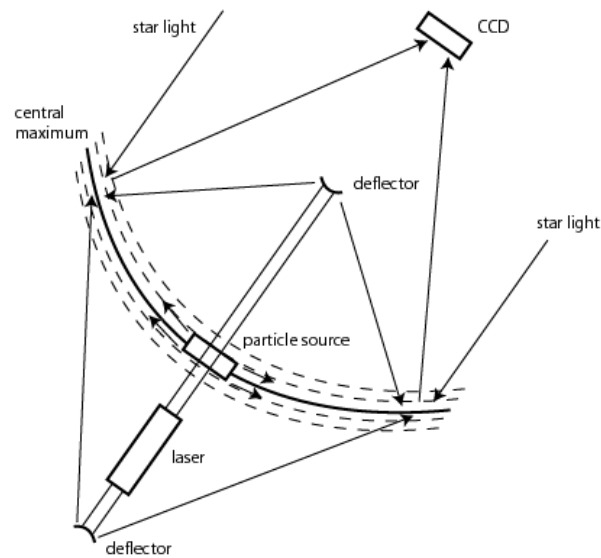
# The Project

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

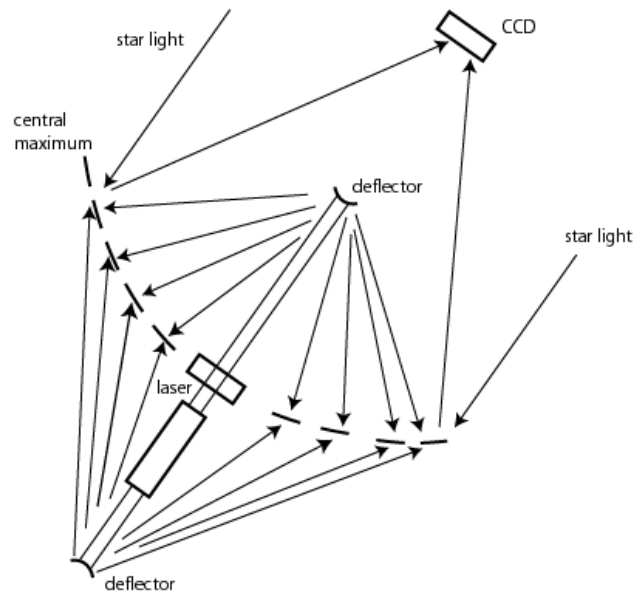
# The LTM Concept

A. Labeyrie



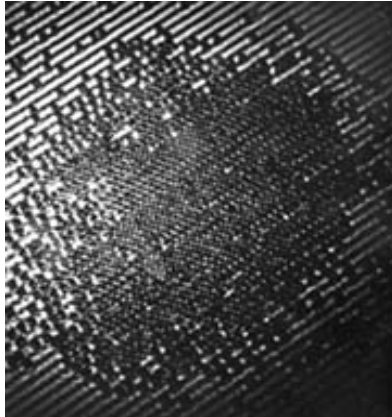
- Beams emitted in opposite directions by a laser strike two deflectors.
- Reflected light produces a series of parabolic fringe surfaces.
- Through diffractive and scattering forces, dielectric particles are attracted toward bright fringes, and metallic particles towards dark fringes.
- Ramping the 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

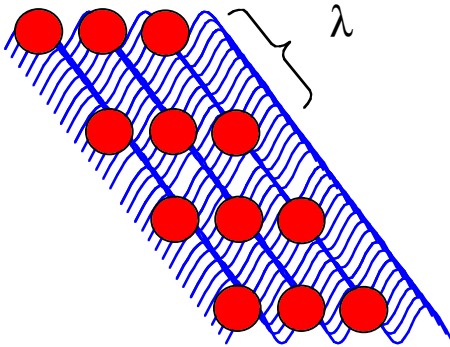


- 🌐 Potential for very large aperture mirrors with very low mass (35 m--> 100g !!) and extremely high packing efficiency (35m--> 5 cm cube).
- 🌐 Deployment without large moving parts, potential to actively alter the mirror's shape, and flexibility to change mirror "coatings" in orbit.
- 🌐 Potential for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

# Previous Work



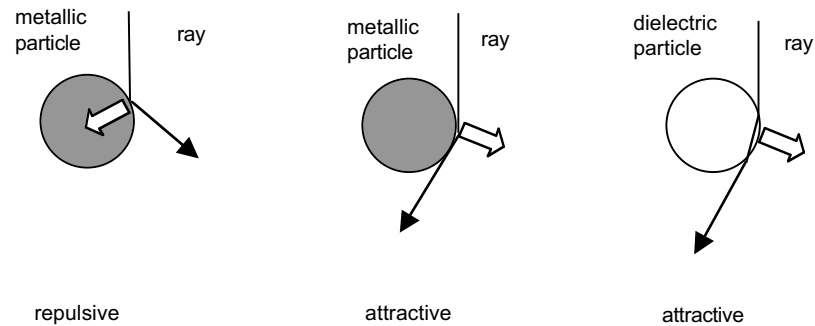
- Experiments by Fournier et al. in the early 1990's demonstrated laser trapping of arrays of macroscopic particles along interference fringes: M. Burns, J. Fournier, and J. A. Golovchenko, *Science* 249, 749 (1990).



- 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).

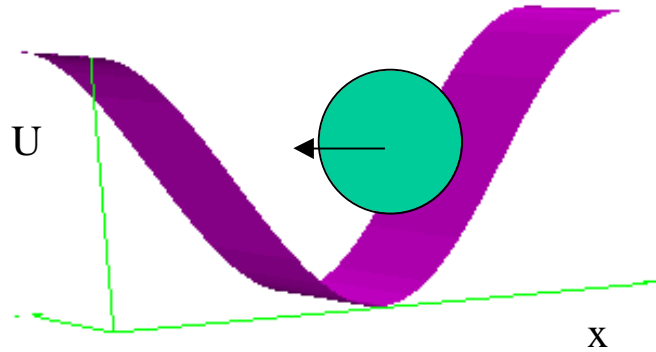
# The Forces of Light

- 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




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

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

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

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

 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<sup>2</sup>:


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

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  $T \sim 30\text{K}$

# 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:  $n_\gamma \sim 10^6 \text{ cm}^{-3}$ ,  $\lambda = 10^{-2} \text{ cm}$ .

$$\Delta E = \frac{p_\gamma^2}{2m} = \frac{(h/\lambda)^2}{2m} \quad \Delta E \sim 10^{-34} \text{ ergs/collision}$$

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:

$$\frac{dE}{dt} = \Delta E n_\gamma \sigma c \quad dE/dt \sim 10^{-26} \text{ ergs/sec}$$

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

$$\tau_{\text{evap}} = \frac{4\pi\alpha m\lambda^2}{h^2 n_\gamma \sigma c^2} I \quad \tau_{\text{evap}} \approx 1.5 \times 10^8 I \text{ sec}$$

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

where  $I$  is expressed in Watts/m<sup>2</sup>.

A respectable number: about 5 years for  $I = 1 \text{ Watt/m}^2$   
and  $\sim$  months for currently available laser intensities.

100 nm-sized particles --  $\tau_{\text{evap}} \sim$  hours, will need damping.

# Dynamical Simulations

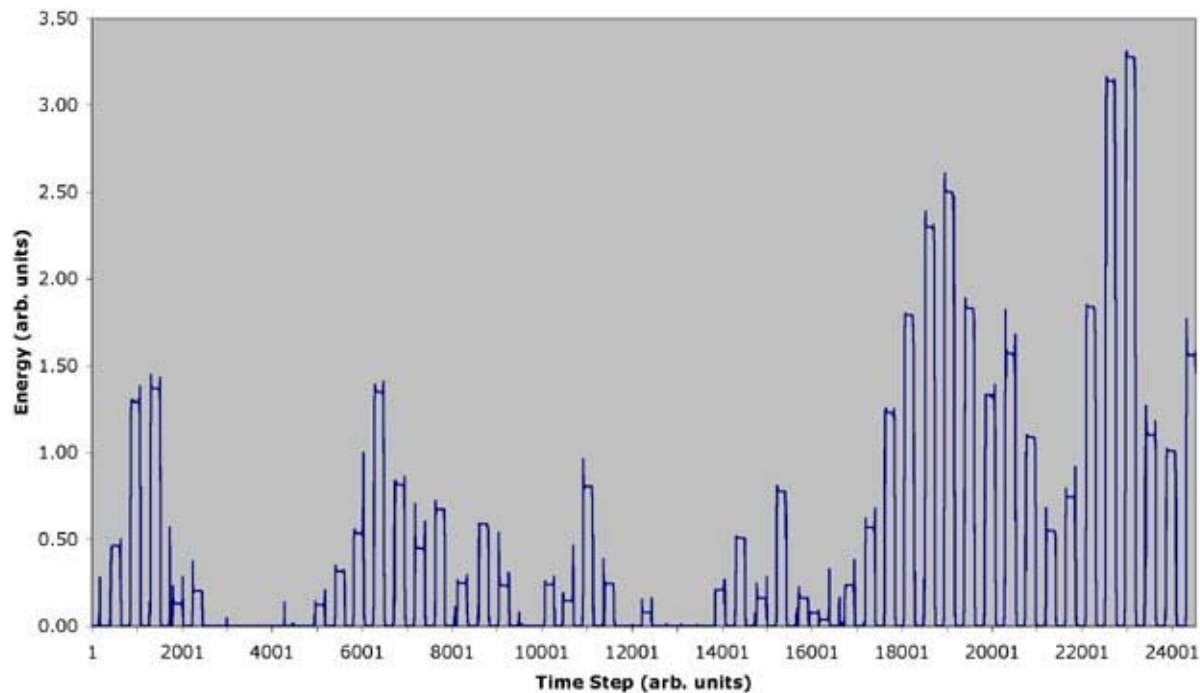


Single particle, 1-D model.

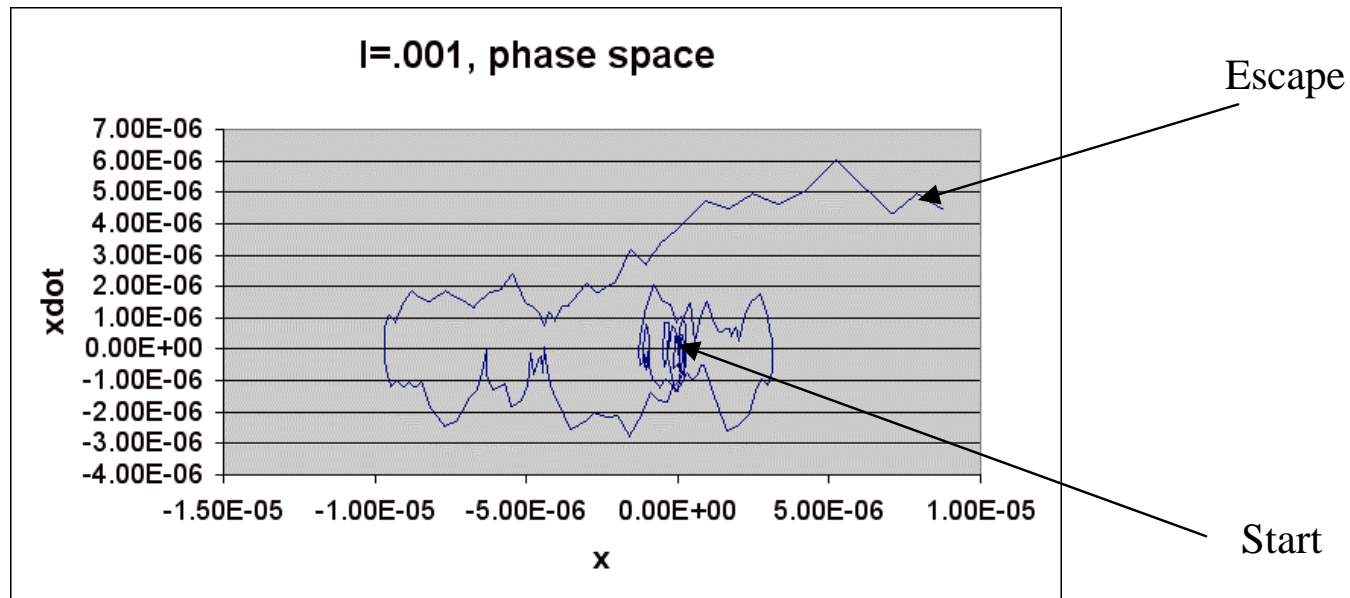
Trapped particle bombarded by background photons arriving randomly.

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



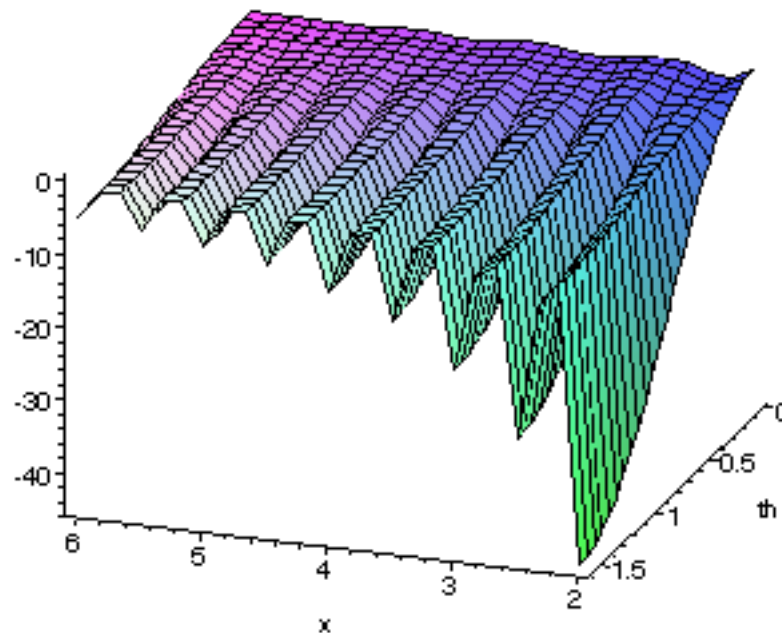
- 🌐 Although sensitive to inputs, simulations give comparable results to the estimates at low laser intensities.
- 🌐 A many particle 2-D model that includes optical binding as well as any damping mechanisms is needed and will require substantial computing power.

# 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  $\lambda$  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,  $\lambda =$  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  $th = \pi/2$  however, the binding potential is  $\sim 45$  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:  $\sim \lambda/\text{diameter}$ , 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  $\lambda=1$  micron, particles with a radius of 250 nm.  
Image at  $\lambda>1$  micron.



Reflection efficiencies will depend on the number of scatters and the ratio of  $\lambda/a$ . In the Mie regime, calculations must be done numerically. Preliminary results with  $\sim 100$  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<sub>60</sub> 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.