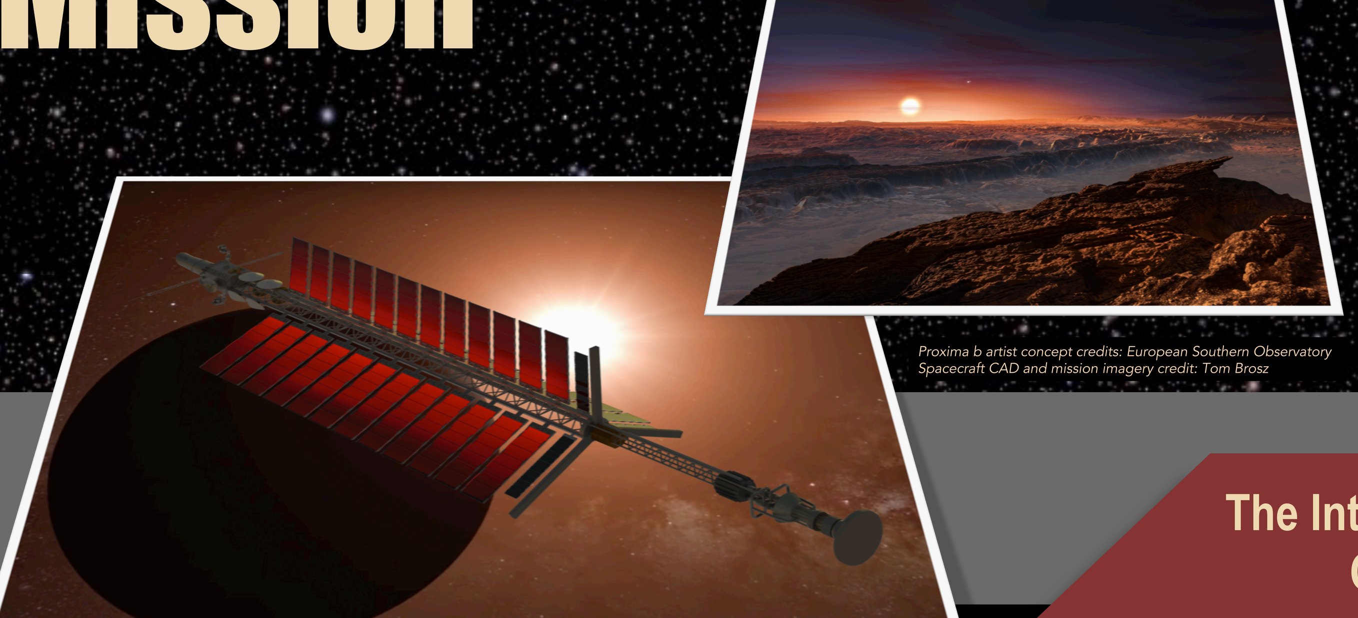
NASA Innovative Advanced Concepts
2017 NIAC Symposium, September 25-27, 2017 Denver, Colorado

Mach Effects for In-Space Propulsion: An Interstellar Mission

Dr. Heidi Fearn, Dr. José Rodal, Marshall Eubanks, Dr. Bruce Long, Dr. James F. Woodward, Paul March and Gary C Hudson
The Space Studies Institute in collaboration with California State University Fullerton, Department of Physics
Nolan van Rossum, Graduate Student Collaborator, University of Wisconsin



Proxima b artist concept credits: European Southern Observatory
Spacecraft CAD and mission imagery credit: Tom Brosz

The MEGA Drive

"Inertia here arises from mass out there" [1]

The Mach Effect Gravity Assist (MEGA) drive utilizes precisely synchronized oscillations in the total energy of the device to produce a steady gravitational force resulting from General Relativity's equivalence principle and conservation of momentum. This device consists of:

- A stack of 8, 2 mm thick PZT (lead-zirconate-titanate) discs, 19 mm diameter and 17.5 mm length overall;
- Two 0.3mm thick discs that are unpowered and used as a strain gauge within the stack; and,
- A brass reaction mass 19.05 mm long and weighing 93 g and an aluminum end mass weighing 7.3 grams and 4.5mm in length.

The resonant frequency of the current demo device is ~36 kHz.

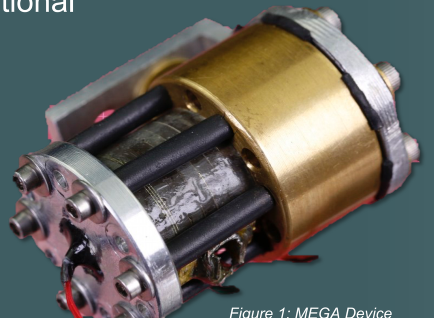


Figure 1: MEGA Device

The Propulsion Challenge

Propellant-less propulsion is a prerequisite for interstellar travel

The vast amounts of propellant needed for conventional rockets eliminates them as realistic options for long-distance missions. **We must do better.**

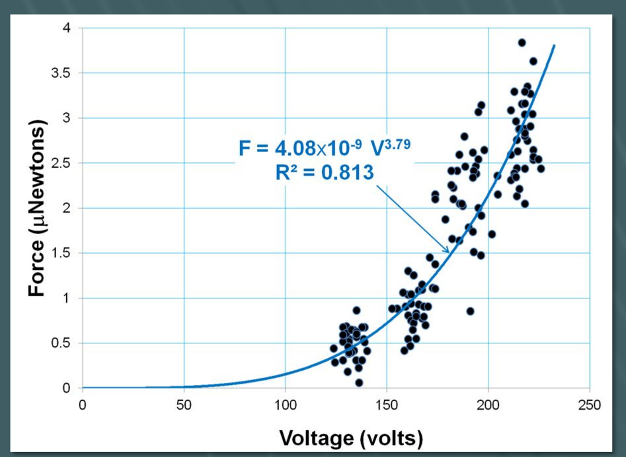


Figure 2: Thrust vs. Voltage. Theoretical analysis of the (thrust) force shows that it should be a function of voltage to the 4th power. A least squares power regression of force (F) vs. voltage (V) data is shown as $F = c V^n$, where $c = 4.08 \times 10^{-9}$ and $n = 3.79$ are the regressed parameters, and the coefficient of determination is $R^2 = 0.813$. The force is (approximately) a function of voltage to the 4th power, consistent with theory.

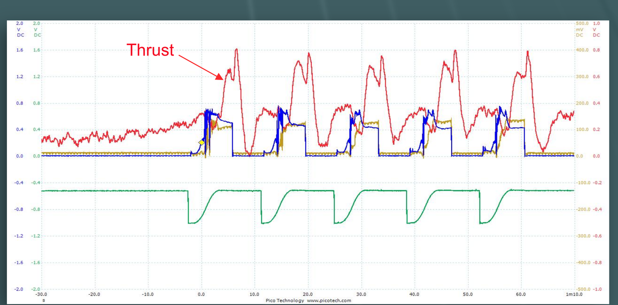


*Figure 3: Chirped pulses. Frequency starts high then drops down to the resonant frequency of the device. Chirp is shown inverted in **green**. The **blue** trace is the voltage pulse amplitude. The **red** trace is the thrust of the device. The **brown** trace is the voltage output from the strain gauge. See Ref [3].*

The MEGA drive does not eject propellant.

- Thrust is due to the interaction between the gravitational potential of the universe and the second time derivative of the total energy in the device.
- Inertial mass fluctuations are then generated in the device.
- This fluctuation can be utilized to produce forward or reverse motion at an appropriate frequency.

How does this work?

- A gravitational mass fluctuation is produced.
- A time-averaged net force is then acting on the center-of-mass. (See Q&A below.)
- The input power is expended to entropy (dissipation by damping into heat).

Energy and Momentum

- The kinetic energy of the spacecraft comes from the gravitational field.
- No input power is used to create the kinetic energy of the device.
- Momentum of the open system is conserved since the energy gained by the spacecraft is potential energy lost by the gravitational field of the universe.

References

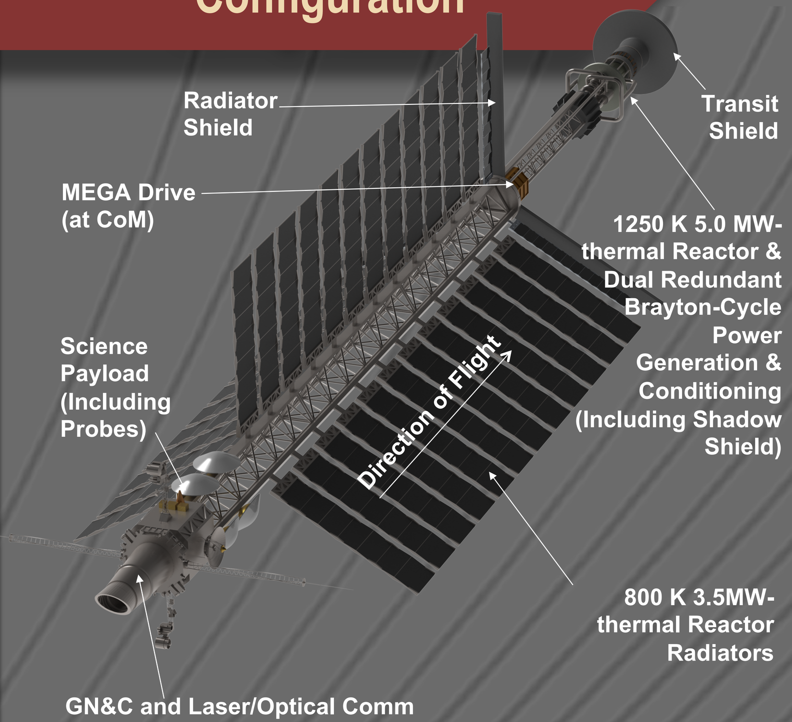
[1] I. Ciufolini and J. A. Wheeler, ***Gravitation and Inertia***, Princeton Series in Physics, Princeton Univ. Press. Preface to Chapter 1. (1995).
[2] James F. Woodward, ***Making Starships and Stargates; The Science Of Interstellar Transport And Absurdly Benign Wormholes***, Springer Press (2013). See page 73, Eq. (3.5).
[3] H. Fearn and L. L. Williams eds., ***Proceedings of the Estes Park Advanced Propulsion Workshop***, Sept 19-22 (2016). ISBN 978-0-578-19003-7. See chapter 3, p 186-189.
[4] ibid [3] J.J.A. Rodal, pp. 151-159 & Appendix D.
[5] H. Fearn, N. van Rossum, K. Wanser and J. Woodward, "Theory of a Mach Effect Thruster II," Journal of Modern Physics, Issue 6, pp. 1868-1880, 2015.

NIAC Study Approach

Three primary tasks:

1. Improve current laboratory-scale devices to provide long duration thrust for practical propulsion (e.g. chirped pulsed AC).
2. Design and develop power supply and electrical systems to provide feedback and control of the input AC voltage and frequency to improve the efficiency of the MEGA drive.
3. Using the data from steps 1 and 2 above, design a probe to carry a 400 kg or greater payload to a rendezvous with Proxima Centauri b within 20 years with data to be recorded and transmitted back over 5 additional years.

The Interstellar Spacecraft Configuration

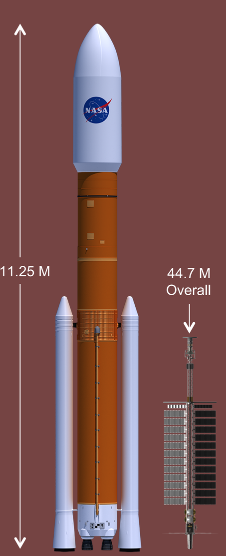


The Interstellar Spacecraft Design, Components & Mission

Interstellar Mach Effect Spacecraft – 1 (IMES-1)

After the challenge of creating a MEGA drive which can propel an interstellar spacecraft to a rendezvous with Proxima b, the more conventional question of the spacecraft's technical feasibility remains. We have chosen a basic configuration that is derived from predecessor concepts such as the *Prometheus* Jupiter Icy Moons Orbiter and other nuclear-powered, long-mission-life designs, such as Cassini, Voyager and Galileo. With the expected thrust to mass ratlos, mission durations and lifetimes will need to be at least 30 years for voyages to the nominal target, Proxima Centauri, and the other nearest stars. IMES-1 will be assembled and checked out in the Earth-Moon L1 point.

Configuration. IMES-1 is configured as a "lambda" structure (resembling the Greek letter λ) with a central composite truss. The forward portion of the spacecraft is reserved for the carbon-carbon transit shield, reactor, main reactor shield, power generation and power conditioning elements. The aft section contains the Science Module, the GN&C (Guidance, Navigation and Control) module and the Laser Communications system that provides connectivity with Mission Control on Earth. (However, necessarily, the IMES-1 will be fully autonomous during flight and while on station in the Proxima b system.)



MEGA Drive Spacecraft Size Comparison to SLS Block II

MEGA Drive Module. The MEGA drive module is located near the spacecraft Center of Mass (CoM). It consists of 1500 individual thrusters that each produce 4.5 Newtons of reversible thrust. Each MEGA drive thrust unit will consume 1.5 kW-electric power. The MEGA drive module will also provide electrical power distribution, control and thermal management for each of the thruster units.

Main Reactor. The IMES-1 Main Reactor will be a fast-fission 5 MW-thermal reactor rated at 1.5 MW-electrical output, employing liquid sodium metal coolant operated at 1250 K. It is not brought critical until the spacecraft assembly is completed in L1.

Electrical Power Generation, Distribution and Control : This system will use a Carnot cycle based dual-redundant closed Brayton-cycle power conversion system. This system employs 1,250 K high side temp liquid sodium from the reactor and then expands it through the Brayton turbines and finally dissipates the waste heat through the 800 K radiators to deep space via infrared radiation. Overall primary generation power conversion efficiency is ~25%. The 1.25 MW-electrical Power Management Unit (PPU) will convert the dual Brayton turbo-alternator wild-frequency ac outputs to two regulated 120 VDC (at 2.5kW-electric each) power buses and two 600 VDC (at 600 kW-electric each) power buses that will supply hotel loads and the MEGA drive module, respectively.

Thermal Control. A number of high-temperature radiators which reject reactor waste heat are located in three 120°-spaced planes around the central truss. These reject 3.5 MW of heat while operating at 800 K. A smaller lower-temperature radiator is positioned just aft of the Radiator Shields to reject waste heat from the MEGA drive thrusters. Conventional passive and heat pipe thermal control approaches are used as required in the Science, GN&C and Comm modules.

GN&C and Laser Comm. It is not enough to send a probe to another star system. Data will also have to be sent back and the spacecraft will have to navigate in an autonomous fashion. The communications goal is a minimum of 1 Gigabyte per year at 4.24 light years, a download capability comparable to that achieved by *New Horizons* after its (much closer) Pluto flyby. Free-space optical Pulse Position Modulation (PPM) communications using a 1 kW solid state Nd:YAG laser operating at 1064 nanometers and a 1 meter^2 optical / near-IR receive/transmit telescope can meet these goals, with 100 meter^2 communications telescopes for reception at Earth.

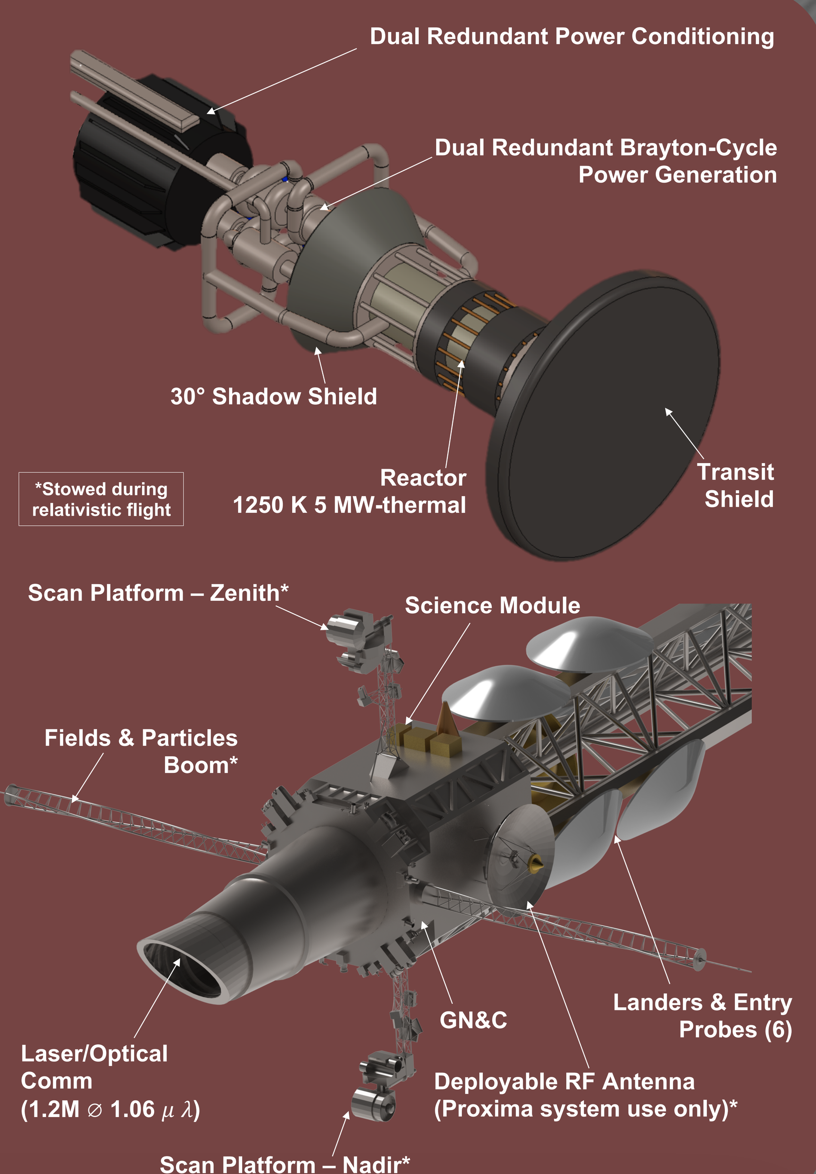
Mission autonomous navigation requirements differ between the cruise phase (when it is not possible to observe in the forward direction due to degradation from the interstellar medium at velocities up to 0.4 c), the far-approach phase (when the speed has dropped sufficiently to allow the deployment of a forward observation platform but the target is still directly in front of the spacecraft) and the operational period (the planetary orbit insertion and subsequent operations). Navigation will be supported with two optical/IR telescopes, the 1.26 meter rear-facing communications telescope, and the movable optical navigation / science camera (ONSC), a 20.8 cm telescope based on the *New Horizons* LORRI instrument. During the cruise phase the ONSC's boom will be flush with the spacecraft and behind the protection of the forward transit shield, and the ONSC will face roughly orthogonal to the spacecraft velocity vector while the vehicle undergoes a slow rotation, enabling the ONSC to repeatedly observe a swath of the sky. At the Far Approach transition, the ONSC boom will rotate outwards and the ONSC will observe in the forward direction, so that it can begin a search for small bodies orbiting Proxima and conduct approach optical navigation.

Science Module. The IMES-1 spacecraft Science Module payload includes dual redundant zenith and nadir scan platforms employing multi-spectral imaging, a fields & particles sensor suite and a complement of deployable probes for both atmospheric sounding and surface analysis. RF comm would be used in-system to communicate with the deployable probes.

Preliminary Solar Gravity Lens Mission*

It might be prudent to attempt a shorter preliminary voyage to assess the atmospheric properties of Proxima b before actually embarking on the full journey. It has been suggested that a prototype probe sent to the focal point of Sol's gravity lens might carefully observe at the light in the Einstein ring from Proxima b and determine whether the atmosphere is transparent or not. We could also obtain valuable information about the atmospheric composition. This data would tell us if we can use only visible and near-visible spectrum cameras to map the surface from orbit or if IMES-1 would need side-looking radar.

*A similar solar lens mission has been suggested by 2017 NIAC Fellow Slava Turyshev in "*Direct Multipixel Imaging And Spectroscopy Of An Exoplanet With A Solar Gravity Lens Mission*".



Questions & Answers

(1) Does the device during operation change mass, and if so, how?

In our experiments using a device with an initial mass of 0.2 kg, the mass is calculated to fluctuate (sinusoidally at a frequency exceeding 30 kHz) with a zero to peak amplitude on the order of a Planck mass (the mass of a hypothetical black hole whose Schwarzschild radius equals the Planck length). This is a mass fluctuation per unit mass on the order of $\Delta m/m = 10^{-8}$.

The theoretical mass fluctuation is $\Delta m(t) = (1/(4 \pi G \rho c^2)) \, \partial^2 E/\partial t^2$ where:

G = gravitational constant= 6.67408×10^{-11} m^3 /(kg s^2)
ρ = mass density (kg/m^3)
c = speed of light in vacuum = 2.99792458×10^8 m/s

A mass fluctuation per unit mass on the order of 10^{-8} with a period of microseconds is a small variation in mass per unit time. It deserves further experimental and theoretical study. For comparison, here are some more commonly known mass changes:

(1) Combustion: decrease in mass due to combustion of methane in the gas burner of a kitchen stove: $\Delta m/m = -10^{-10}$.

(2) Change of phase: increase in mass due to melting of ice: $\Delta m/m = 3.7 \times 10^{-12}$

(3) Temperature change: increase in mass due to temperature increase of a flat iron by 200 K: $\Delta m/m = 10^{-12}$.

(4) Emission of solar power from our Sun: the rate at which the Sun emits energy from its surface (its luminosity), is around 3.8×10^{26} Watts, therefore the rate at which solar mass disappears is=4.2×10^9 kilograms per second. Since the total mass of the Sun is 2×10^{30} kilograms, the change in mass of our Sun per 100 years is $\Delta m/m = 6.5 \times 10^{-12}$.

(5) Strong nuclear force: due to the strong nuclear force, energy is required to separate a stable nucleus into its constituent protons and neutrons. The more stable the nucleus is, the greater is the amount of energy needed to break it apart (called the binding energy of the nucleus). For example, for deuterium (a stable isotope of hydrogen: the bound state of a proton and a neutron), the binding energy and hence the defect of mass is 2.2 MeV, so that $\Delta m/m = 10^{-3}$.

(2) How does the MEGA drive move?

The minimum model of complexity to illustrate the rate of change of the center of momentum due to variable mass is a system of two masses m_1 and m_2 coupled by a spring k.

$$p_{COM} = \frac{\frac{m_1 \dot{x}_1}{\sqrt{1-\dot{x}_1^2/c^2}} + \frac{m_2 \dot{x}_2}{\sqrt{1-\dot{x}_2^2/c^2}}}{\frac{m_1}{\sqrt{1-\dot{x}_1^2/c^2}} + \frac{m_2}{\sqrt{1-\dot{x}_2^2/c^2}}}$$

A dashpot is also necessary for realistic modeling of the amplitude of vibration, but for simplicity, the rate of change of (COM) momentum can be demonstrated without a damper. For this illustrative purposes the following assumptions are made:

1. no damping
2. very weak gravitational field
3. uniform gravitational field with respect to the dimensions of the drive
4. small spin and spin rates
5. small strain

The positions of the masses from an arbitrary reference point are x_1 and x_2. Time differentiation is shown by an overdot. Then, it can be shown that the rate of change of the **center of momentum** (COM) is given by the first time derivative of the variable masses as follows:

$$\dot{p}_{COM} = \frac{\frac{\dot{m}_1 \dot{x}_1}{\sqrt{1-\dot{x}_1^2/c^2}} + \frac{\dot{m}_2 \dot{x}_2}{\sqrt{1-\dot{x}_2^2/c^2}}}{\frac{m_1}{\sqrt{1-\dot{x}_1^2/c^2}} + \frac{m_2}{\sqrt{1-\dot{x}_2^2/c^2}}} + \text{higher order terms}$$

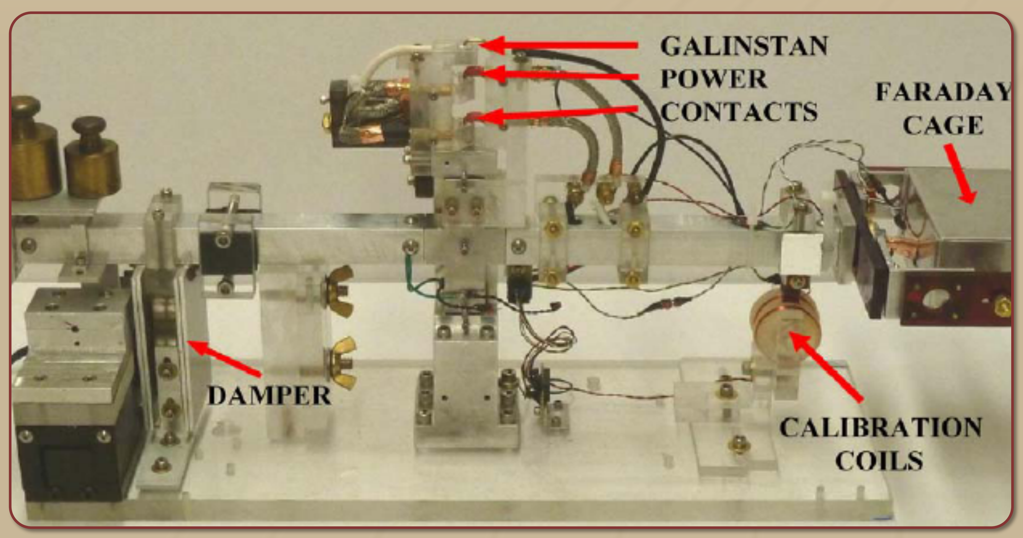
Note that:

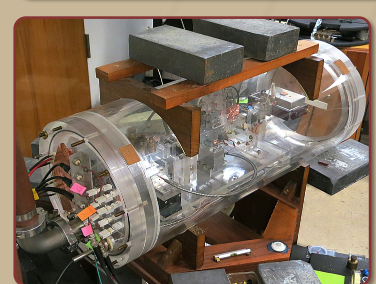
(1) if the masses are constant, then the rate of change of momentum of the COM is zero; and,

(2) if the masses are variable but equal, such that $m_1=m_2$, then the displacements, velocities and accelerations due to oscillation of the masses at the natural frequency (in reality, the first eigenmode) are equal in magnitude but opposite in sign, and therefore the rate of change of momentum is zero for the COM;

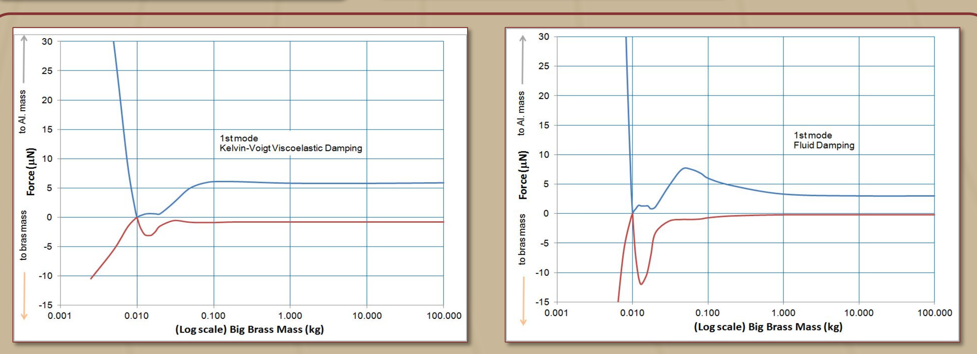
(3) To change the COM it is needed to excite oscillations of unequal variable masses, their rates of change and their displacements and velocities, at two frequencies ω_1 and ω_2, with $\omega_2 = 2\,\omega_1$.

Multiplication of harmonic terms (the first time derivative of the mass times the velocity all being harmonic functions of time) results in even terms having a non-zero time cycle average, for example: $\cos^2(\omega t) = \frac{1}{2} + \cos(2\omega t)/2$. Conservation of momentum for a system of unequal masses with such a fluctuation in mass, demands that the center of momentum must change with time.





Test Setup At CalState University Fullerton (CSUF). The torsional pendulum used in these experiments is shown above. A more complete description can be found in Ref [2]. The vacuum chamber used is shown in the photo to the far left. Scale can be determined from the near left image of Prof. Woodward reversing force direction of the device.



Force vs. Brass Mass. Analytical calculation model of the force (on the center of mass) vs. the initial mass of the brass end, keeping all other variables constant. The PZT stack is modeled as a continuum with partial differential equations, where internal damping is modeled either as material damping (Kelvin-Voigt viscoelastic model) or as fluid damping. The left panel shows the calculation for material damping, which is the expected behavior of the device in space. The right panel shows the calculation for fluid damping, which may be more representative of the behavior in experiments where one end is supported by a compliant support. Both calculations show no force when the brass mass equals the aluminum mass (0.01 kg), which is consistent with experiments. The fluid damping model shows a slightly optimal mass for brass below 0.1 kg which is also consistent with experiments. Due to damping, the force (magnitude and direction) depends on how close the excitation is to mechanical resonance. The blue and red curves show the maximum force in each direction. The behavior is frequency dependent: the smaller the brass mass the higher the natural frequency.

(3) Why hasn't this force been seen in experiments before?

The force measured by experiment is due to both the piezoelectric and electrostriction effects. Piezoelectricity is only found in certain crystals in nature and is represented by a 3rd order tensor which is uncommon. There are two excitations involved the lowest 30kHz and the second at twice that frequency, which is not a common occurrence. The force measured in the current experiments is very small, microNewtons, and would be unlikely to be observed in work that was not focused on anomalous accelerations and anomalous forces.

One possible explanation, left to explore, is that the force maybe hidden by a chameleon field. A chameleon field is a massive scalar field (a "fifth force") following a Klein-Gordon equation with a field mass (and thus a group velocity and Compton wavelength) that depends on the local matter density. The chameleon field would have a Compton wavelength of order 0.1 mm or less in high density regions (such as within the Earth's atmosphere), enabling the theory to survive fifth force tests, but a much lower mass (and larger Compton wavelength) in the vacuum of space. In this theory, the chameleon field in a high-density region surrounded by a vacuum is confined to a thin screen, of order 1 micrometer in depth and thus with a high field gradient, on the surface of the massive body. The group velocity of the field in the various proposed theories would be 100's of meters per second on the surface of a massive body, and very close to the speed of light in deep space.

The test units in our experimental work, in the near vacuum of a test chamber, would have a thin screen and would be vibrating that screen at roughly the frequency ($\sim v_{group}/R$) of the first normal mode of chameleon radiation for the drive stack. These units should thus be efficient radiators of chameleon field radiation, converting acoustic oscillations to chameleon waves in a fashion analogous to how magnetoelectric antennas convert acoustic waves to electromagnetic waves. This chameleon radiation, with its low group velocity at the surface of the body, would carry away substantially more momentum per unit energy than would a photon rocket. (The wave frequency would substantially increase outside of the drive unit, but that does not change the momentum loss at the drive surface). This momentum change will cause a thrust, which should be even larger in deep space than in a vacuum chamber. In a confined vacuum chamber, it would be reasonable to expect standing chameleon waves to be set up inside the chamber, which may be detectable experimentally.

A literature search does not reveal any other search for fifth force or analogous effects at frequencies much larger than diurnal, roughly 9 orders of magnitude smaller than the 35 kHz used in our experimental work.

There is both theoretical basis as well as proposed experiments in this area (one of them is a 2017 Phase I NIAC grant by Dr. Nan Yu at JPL, "A direct probe of dark energy interactions with a solar system laboratory").

(4) Doesn't the explanation of Mach's Principle require information to propagate at greater than the speed of light if there is connection between local mass and the distant stars?

If the energy of stars 10^8 light years away were being fluctuated at consistent uniform frequencies ω and $2\,\omega$, then the only way fluctuating stars billions of light years away would be able to affect immediately the mass of the device here, would be through a superposition of advanced and retarded waves. But what is being fluctuated in CSUF experiments is the self-energy of the device here, **at the same location as the mass of the device,** rather than 10^8 light years away. What fluctuates is the device's self-energy – it is a **self-interaction effect**. Therefore there is no need for propagation of information faster than the speed of light.

(5) Why doesn't the MEGA drive result in free energy, and therefore used for energy generation?

The MEGA drive does not violate energy conservation. The kinetic energy comes from the gravitational field, not from the electrical power applied to the device. There is a large nonzero gravitational potential in the universe we are tapping into to gain kinetic energy of the device. If we take a small amount of energy, practically no loss will be noticed by the whole universe. There are far more efficient ways of extracting energy, for example, from nuclear or solar power. Trying to extract energy from gravitation *via* the Mach effect is very inefficient.

The benefit of Mach effect propulsion is to avoid carrying propellant for long space missions, particularly for interstellar missions.

(6) Does the MEGA drive violate General Relativity?

No the MEGA drive does not violate Einstein's general relativity.

The theory is based on Einstein's theory of gravitation. The mass change result can be obtained from general relativity.

The theory is Machian and fully consistent with Einstein's general relativity.

(7) What natural systems might exhibit MEGA drive effects? Could these be observed, and how?

We have examined astronomical observations to see if they exhibited MEGA effects, which require two excitations (at frequencies f and 2f), but we haven't found anything yet. Such excitations do naturally occur in elliptical orbits (as one can ascertain from harmonic expansion). However, the naturally occurring frequencies (harmonics of the orbital periods) are not high enough to produce an observable effect. For example, the well-known binary pulsar PSR B1913+16 (also called the Hulse–Taylor binary after its discoverers) has an orbital period of 7.75 hours, and an eccentric orbit, resulting in totally unobservable orbital perturbations on the order of one part in 10^{30}.