17

New Projects in Progress

As these words are composed in 2014, we are in the initial phase of solar-photon-sail operational application. Probably, a good historical analog is the status of the chemical rocket in late 1957. As was then the case with Sputnik 1 and 2 in their relation to the chemical rocket, the utility of small solar sails has been demonstrated by the successful operation of NASA NanoSail-D2 in low Earth orbit, and JAXA IKAROS in interplanetary space.

We can unfurl small sails in the space environment, control their attitude relative to the Sun, and demonstrate their utility for purposes of in-space propulsion. With the gamma-ray-burst detector mounted on IKAROS, the application of the sail as a platform for science has been demonstrated; besides, other packages on IKAROS are related to applied research.

However, we still have a long way to go to establish the solar-photon sail as an off-the-shelf device useful to perform or enable missions in the solar system and beyond. One thing that must be accomplished is development and application of sails scaled up from the ~20-m size range to those useful for propelling larger payloads at velocities comparable to or higher than those routinely achieved with solar electric propulsion.

A number of possible missions are possible in the near future, say before around 2020, which could improve the sail's utility and provide additional confidence to advanced mission planners. This chapter discusses a few of these.

MISSION TO JUPITER AND THE TROJAN ASTEROIDS

As follow-on to IKAROS, the Japanese space agency JAXA is considering a probe to Jupiter and the Trojan asteroids to be launched in ~2020. The Trojan asteroids are a class of small celestial bodies that follow or lead Jupiter by 60° in the planet's solar orbit. They are located near the gravitationally stable Lagrange points (L4 and L5) and are named after mythological heroes of the Trojan War (Fig. 17.1).

This Jupiter Magnetosphere Orbiter (JMO) would first be injected into an orbit with perihelion near Venus and aphelion near Earth. A sail would be used near perihelion to increase orbital energy so that the aphelion would be raised. After one or more solar passes, with possible application of planetary gravity assists, the aphelion of the space-vehicle would be about 5.2 AU, the solar orbit of Jupiter. Using solar-electric propulsion

G. Vulpetti et al., *Solar Sails*, Springer Praxis Books,
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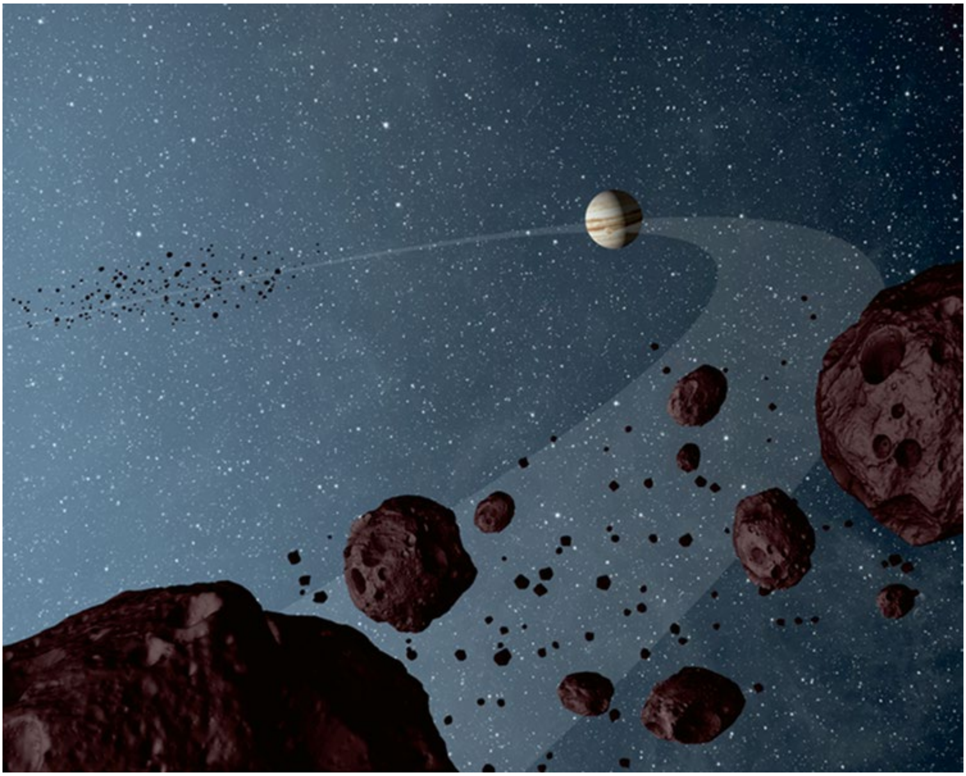

17.1 Artist rendering of the Trojan asteroids and Jupiter (Courtesy of NASA)

far from the Sun, this *hybrid-propulsion*[1] space-vehicle would be maneuvered to explore Jupiter's magnetosphere and encounter at least one Trojan asteroid. The total duration of the mission would approximate 11 years.

Following a paper on the concept by Sasaki et al., we can evaluate some stages of this mission. First, we assume a square sail somewhat larger than IKAROS: about 100-m on a side, with an area of 10,000 m^2. We next assume that, like IKAROS, the sail film is 7.5-μm polyimide. Structure including inflatable booms may raise the mass of the sail system by 30 %; as a result, the mass of the sail and structure is about 150 kg. We next assume that the payload amounts to an additional 100 kg, so the total vehicle mass is 250 kg. Dividing by the unfurled sail area, the vehicle sail loading is 0.025 kg/m^2.[2]

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[1] In a long and detailed paper presented at the 1st World Space Congress, Washington D.C. (1992), author Vulpetti first introduced and analyzed a space-vehicle driven by nuclear ion propulsion *and* solar-photon sail (see *Further Reading*). He proposed the designation of *staged-propulsion spacecraft* in order to highlight the opportunity for utilizing different-kind propulsive systems in different ranges of Sun-vehicle distance in a same complex mission.

[2] or 25 g/m^2; we shall use such units in the subsequent chapters for a more direct visualization.

The next step is to calculate the value of the Lightness Number L, which (in a way equivalent to what we did in Chap. 15) may be defined as the ratio of the solar-radiation-pressure force on the *sail* to the solar gravitational force on the *sailcraft*, when the sail is fully unfurled and directly facing the Sun.[3] Assuming a 90 % sail reflectance, Eq. (4.19) of author Matloff's *Deep Space Probes* can be applied to estimate the value of L for this sail as 0.06. At the Earth's solar orbit, the gravitational acceleration on the sail is about 0.00593 m/s^2; near Venus the value of this parameter is about 0.0113 m/s^2. Multiplying these numbers by the calculated value of L, we find that the sail's solar-radiation-pressure acceleration near Earth and Venus respectively is about 0.00035 and 0.00067 m/s^2. Approximately, near Venus, solar radiation pressure on the sail can increase the sailcraft's velocity by about 58 m/s (at most) each day. Near Earth, the solar sail can increase the vehicle's solar orbital velocity by about 30 m/s (at most) per day.

We next assume that this sailcraft, like IKAROS, is initially injected into a Hohmann minimum energy trajectory, with the perihelion of its solar orbit near Venus and the aphelion near Earth. The time required to traverse one-half of the sailcraft's initial solar circuit is 146 days. The sailcraft's solar-orbital velocity will increase if the sail is tilted towards the Sun during the post-perihelion phase of the trajectory. By the time it crosses Earth's orbit, its solar-orbital velocity may increase by about 6 km/s, depending upon the sail axis angle relative to the Sun. The effect of this increased orbital velocity will be an increase in the sailcraft's aphelion.

The sailcraft can also make use of gravity assists as it passes Earth, Moon, and Venus to increase its aphelion further. However, it is easy to estimate how many Venus passes are required to inject it into a Jupiter-bound trajectory.

The specific energy (energy per unit mass) of a Hohmann trajectory can be written:

$$\varepsilon = \frac{-GM_{sun}}{\left(r_a + r_p\right)} = \frac{1}{2}V_{s/c}^2 - \frac{GM_{sun}}{r} \quad (m/s^2) \tag{17.1}$$

where G is the Universal Gravitational Constant, M_{sun} is the Sun's mass, r_a and r_p are respectively craft aphelion and perihelion distances, and $V_{s/c}$ is the sailcraft's velocity at distance r from the Sun's center.

Next, we substitute numerical values for various parameters in Eq. (17.1). In the International System of units, $G = 6.67 \times 10^{-11}$ Nm^2/kg^2 and $M_{sun} = 1.99 \times 10^{30}$ kg. The average solar distances for Venus, Earth and Jupiter are respectively 108.2, 149.6, and 777.9 million km.

The specific energy of the initial Earth-Venus Hohmann trajectory is calculated as $-5.15 \times 10^8\,(m/s)^2$. When the sailcraft is in its final Venus-Jupiter trajectory, the orbital specific energy is $-1.50 \times 10^8\,(m/s)^2$.

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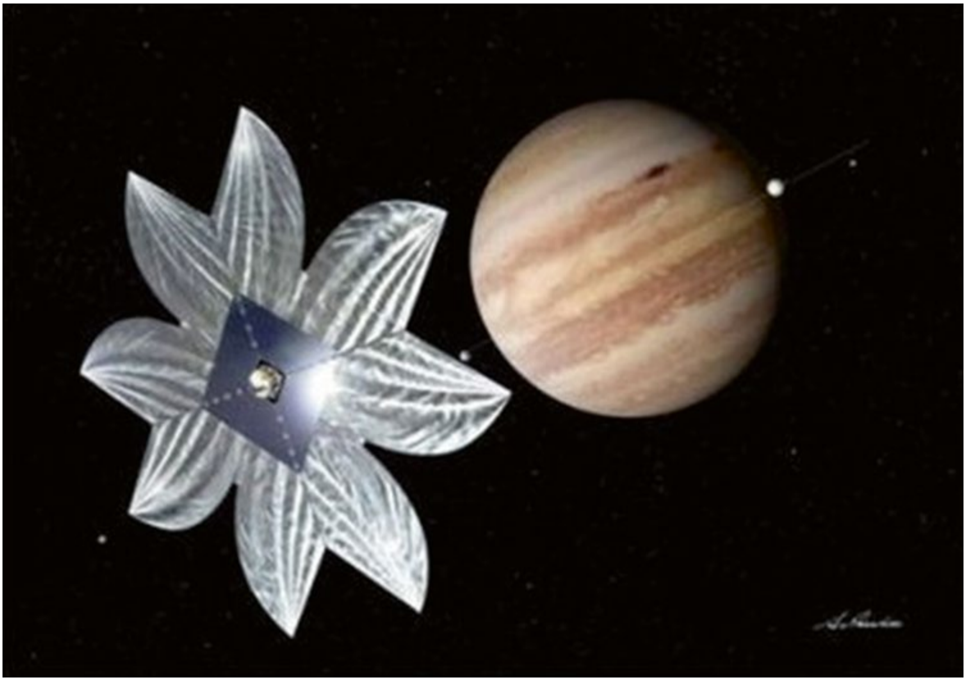
[3] This is the classical definition of the lightness number. In Part-V, we will introduce the reader to a new mathematical formalism for the Astrodynamics of solar-photon sailing, which is more versatile for a better comprehension of the potentialities of the solar-photon propulsion. In addition, this formalism opens fruitful ways to sophisticated sailcraft trajectories and missions. The following four chapters are devoted to the graduate student, chiefly.



17.2 Artist rendering about a sailcraft approaching Jupiter (Courtesy of NASA)

At perihelion (near Venus), the sailcraft's initial solar velocity is 37.7 km/s. In its final Jupiter-bound orbit, the sailcraft's solar velocity near Venus is 46.4 km/s. To alter the initial Earth-Venus orbit into a Venus-Jupiter orbit, about a velocity increment of 9.1 km/s must be provided. The solar sail alone can provide this if it is operated during two solar passes. Figure 17.2 is an artist rendering of the sail near Jupiter.

This is a very surprising result for a first-generation solar sail. It may be thought that using the solar photon sail in the very near term to launch outer-planet probes will give us experience with the "sun-diver" maneuver necessary to drive sails that are more advanced to destinations beyond the solar system.[4]

It is also of interest to estimate the fraction of the sail's area that must be covered by solar cells to supply electricity to the solar electric rocket for maneuvers near Jupiter and the Trojan asteroids. It is assumed here that the maximum power level to this thruster is 1.5 kW, similar to that of previous solar-electric propelled missions such as the NASA Deep Space 1.

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[4] However, to restrain easy enthusiasm, we have to say that very distant space targets require so high energies that future very deep-space sailcraft have to be designed with much higher lightness number. This appears possible if sail system is designed via nanotechnology.

Since Jupiter is about 5.2 AU from the Sun, the solar flux of light (or the solar irradiance) near this planet is about 51 W/m^2. Assuming a 10 % solar-cell efficiency, about 5 W of electricity can be provided to the thruster from each square meter of solar cell mounted on the sail. About 300 m^2 are required, which is 3 % of the solar-photon-sail area.

ASTEROID DIVERSION

Planetary astronomers have learned a great deal recently about that class of asteroids and extinct comets called Near Earth Objects (NEOs). These rocky, metallic and icy objects range in size between a boulder and a large mountain. Sometimes they impact the Earth with devastating consequences. The impact that contributed heavily to the demise of the dinosaurs about 65 million years ago was very likely a NEO. Much more recently, in 1908, ~50–100 m celestial visitor entered the atmosphere exploded above Tunguska, Siberia releasing the energy equivalent to a thermonuclear weapon. More recently, a meteor entered the Earth's atmosphere over Russia in February 2013 and exploded. Scientists estimate that it deposited as much energy into the atmosphere as 30 Hiroshima-scale atomic bombs.

There are thousands of these objects large enough to cause significant damage if they impact our planet. Several private organizations are planning to mine them for resources valuable both on Earth and in space. For these reasons, President Obama has directed NASA to plan for a human mission to a close NEO to be conducted around 2020.

Various techniques of altering NEO solar orbits have been suggested and some may be experimented with during early explorations. Although Hollywood special effects experts prefer the dramatic nuclear-explosion option, experiments with such devices are forbidden by international treaty. Since certain NEO varieties are flimsy and tenuous, explosives may result in fragmentation rather than diversion. If we accurately know the trajectory of an offending NEO decades before its predicted impact, there are several non-explosive diversion techniques employing the solar photon sail.

Two of these might be experimented with by early expeditions to nearby NEOs. These are the gravity tractor and kinetic deflection.

THE GRAVITY TRACTOR

Initially conceived by Apollo 9 astronaut Rusty Schweickart, the Gravity Tractor is very simple in concept. A solar sail flies in formation with the Earth-threatening NEO, using solar-radiation pressure to maintain its separation from the object. Over a period of many years or decades, the mutual gravitational attraction of the sail and NEO slightly alters the solar trajectory of the NEO, converting an Earth impact into a near miss.

As an illustration, consider a 500-kg solar photon sail maintaining a 100-m separation from a 30-m radius NEO with a mass density of 2 g/cm^3. The NEO's approximate mass is calculated to be 2×10^8 kg. The mutual gravitational force between the two objects can be written as:

$$F_{grav} = \frac{GM_{sail}M_{neo}}{R^2} = M_{neo}a_{neo} \quad [\mathrm{N}], \tag{17.2}$$

where G once again is the Universal Gravitational Constant, M_{sail} is the sail mass, M_{neo} is NEO mass, R is the constant separation between the sail and the NEO center of mass, and a_{neo} is the NEO's acceleration caused by the sail's gravitational attraction.

Note that NEO mass cancels when acceleration is calculated. But stand-off distance R, of course, increases as NEO radius increases. For the NEO, sail, and separation considered, the gravitational force is calculated as 0.000667 N. The gravitational acceleration of the NEO towards the sail is 3.33×10^{-12} m/s^2.

After 60 years, the NEO's velocity towards the sail will have increased to 0.0062 m/s. Since the average NEO velocity towards the sail during a six-decades operation will be half this value, the NEO's solar orbit will be deflected by about 6,000 km or one Earth radius.

The advantages of the gravity tractor as a NEO deflection scheme are that it can be used for any variety of NEO and no direct contact with the NEO is required. But to be effective, the NEO's solar orbit must be known to extreme precision and the solar sail must remain on station for decades.

KINETIC NEO DEFLECTION USING THE SOLAR SAIL

In early 2005, NASA launched the Deep Impact probe towards Comet 9P/Tempel. Approaching the comet's nucleus in July 2005, Deep Impact split into two components. The main probe observed the impact of the 370-kg sub-probe upon the comet's nucleus at a relative velocity of more than 10 km/s. Although an energized plume of debris and a crater equivalent in size to a football field were produced, the comet nucleus did not fragment (Fig. 17.3).

Because the solar-photon sail does not require fuel, it can perform a "cranking" maneuver to modify its solar inclination. From Colin McInnes monograph, the orbital inclination can change by 0.2° per week if the sailcraft's lightness number is 0.1 and its solar distance is 1 AU. This amounts to an inclination change of about 10° per year. Thus, less than two decades are required to maneuver such a sailcraft into a retrograde solar orbit at 1 AU. If the aim is very precise, the sailcraft could smash into an Earth-threatening asteroid at a relative velocity of at least 60 km/s. This amounts to a specific energy of 1.8×10^9 J/kg.[5]

If this tremendous specific energy (about 36× that of the Deep Impact sub-probe) does not fragment the NEO, it is possible that the linear momentum change of the NEO due to the head-on collision could alter a predicted Earth-impact into a near miss. Linear momentum of an object is defined as the product of mass M and velocity V. In any collision, the total linear momentum of the system is conserved.

Consider, for example, a 1,600 kg sailcraft that slams head-on into a 10^{10} kg NEO at a relative velocity of 60 km/s. Note that before the collision, the linear momentum of the sailcraft is about 10^8 kg m/s.

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[5] When lightness number values in the range 0.5–0.7 are achieved (via nanotechnology), higher-speed impacts will be got in about 1 year too by using sailcraft trajectories very different from orbital cranking. However, the explanation of such performance is beyond of the aims of this chapter.

17.3 The Deep-Impact sub-probe striking the nucleus of Comet 9P/Tempel (Courtesy of NASA)

If we assume that there is no fragmentation during the collision, all of the sailcraft linear momentum is transferred to the NEO. The NEO's velocity in its solar orbit is reduced by about 0.01 m/s. This might not seem like a lot, but after thirty years, the NEO's position in its solar orbit will be about 10,000 km displaced from where it would be if no collision had occurred. Given decades warning time and extremely accurate trajectory control, kinetic impact could convert an Earth-impact into a near miss.

SOME OTHER SOLAR-SAIL RELATED APPROACHES TO NEO DIVERSION

Several other approaches to NEO diversion do not directly utilize the solar photon sail, but do apply related technologies. These may be tried as well during early human visits to near NEOs.

The simplest of these is to bombard the offending NEO with reflective paint balls. Solar radiation pressure on the NEO would be increased by the increased reflectivity.

Over a period of many years or decades, the NEO's heliocentric orbit might be slightly altered. Another approach is the solar collector, in which a parabolic reflector stationed near the NEO concentrates sunlight on that asteroid. If the NEO is rich in volatiles such as water ice, a jet of energized material would be raised by the concentrated sunlight and the NEO's solar orbit would be altered.

FURTHER READING

A nice online review of JAXA plans for a hybrid sail/ion-drive mission to Jupiter and the Trojan asteroids can be found in S. Sasaki et al., *Japanese mission plan for Jupiter system: the Jupiter magnetospheric orbiter and the Trojan asteroid explorer*, presented at EPSC-DPS Joint Meeting 2011. This is its web-address: http://yly-mac.gps.caltech.edu/A_DPS/dps%202011%20/a_dps%202011%20program%20+%20abstracts/pdf/EPSC-DPS2011-1091.pdf, checked successfully on May 20, 2014.

Many texts consider the kinematics of Hohmann transfer orbits. We used R. R. Bate, D. D. Mueller and J. E. White, *Fundamentals of Astrodynamics*, Dover, NY (1971). A nice source for the numerical values of astronomical and physical constants is K. Lodders and B. Fegley Jr., *The Planetary Scientist's Companion*, Oxford University Press, NY (1998).

Our reference for the ion-thruster power level of the NASA Deep Space 1 probe is M. J. L. Turner, *Rocket and Spacecraft Propulsion*, 2nd ed., Springer-Praxis, Chichester, UK (2005).

The gravity tractor as a NEO deflection scheme has received a fair amount of attention in recent years. One reference is B. Wie, "Deflection and Control of Gravity Tractor Spacecraft for Asteroid Deflection," *Journal of Guidance, Control, and Dynamics*, **31**, 1413-1423 (2008).

Orbit cranking by solar radiation pressure, as a method of altering orbital inclination without the expenditure of fuel, is considered by C. McInnes on pp. 143-146 of *Solar Sailing: Technology, Dynamics, and Mission Applications*, Springer-Praxis, Chichester, UK (1999). However, this method was first considered by JPL in the 1970s.

A review of the paintball NEO-diversion suggestion is available on-line as J. Chu, "Paintballs may Deflect an Incoming Asteroid," *MIT News*, http://web.mit.edu/newsoffice/2012/deflecting-an-asteroid-with-paintballs-1026.html (accessed February 14, 2013).

The application of the solar collector in NEO deflection is discussed in the paper G. L. Matloff, *Deflecting Earth-Threatening Asteroids Using the Solar Collector*, Acta Astronautica, **82**, 209-214 (2013).

Using both nuclear ion propulsion and solar-photon sailing for very high energy missions was first proposed and analyzed in detail by author Vulpetti in his paper *Missions to the Heliopause and Beyond by Staged Propulsion Spacecraft*, paper IAA-92-0240, The World Space Congress, Aug. 28 – Sept. 5, Washington D.C. (1992)