# 13

# Progress to Date

At this point in its development, the solar sail can be characterized as fairly late in its theoretical phase and fairly early in its developmental phase. It is probably equivalent to the chemical rocket in 1930, the automobile in 1900, and the heavier-than-air aircraft in 1910.

Already, though, enough work has been performed for us to have some understanding of the basic possible configurations that might be considered for various sail applications. Also, the work of the last decade or so has indicated the potential roles of space agencies, private foundations and space societies, and private individuals in the historical and further implementation of space photon sailing.

## PIONEERING DESIGNS

Figure 13.1 presents some suggested riggings, or configurations, for space sailcraft. These might be considered as celestial equivalents of terrestrial wind-sail riggings such as sloops and yawls.

Starting from the top left of Fig. 13.1 and moving clockwise, we first encounter the square-rigged sail configuration. Here, solar-photon radiation pressure pushes against four sail segments supported by diagonal spars. The payload is mounted at the center, on either the sunward or anti-sunward sail face. It is not necessary to construct the spars and supporting structure from solid material—inflatable spars may be considered for many applications. Although square-rigged sails may be more difficult to deploy because they don't utilize centrifugal acceleration to push an unfurling sail from the center of the structure outward, the lack of spin may result in less dynamic problems such as vibrations and oscillations.

Next we come to the parachute sail, which carries its cable-supported payload on the sunward side of the sail structure. This is a more complex rigging to deploy and may therefore be utilized in space-manufactured rather than Earth-launched solar photon sails. Equipped with high-tensile strength, low-density cables, parachute-type sails may be capable of higher accelerations than other arrangements.

The parabolic sail, or solar-photon thruster (SPT), is a two-sail variation on the parachute rigging. Here, a large sail or collector is always positioned normal to the Sun (or other photon source). The collector has a parabolic curvature (not shown in the figure) so

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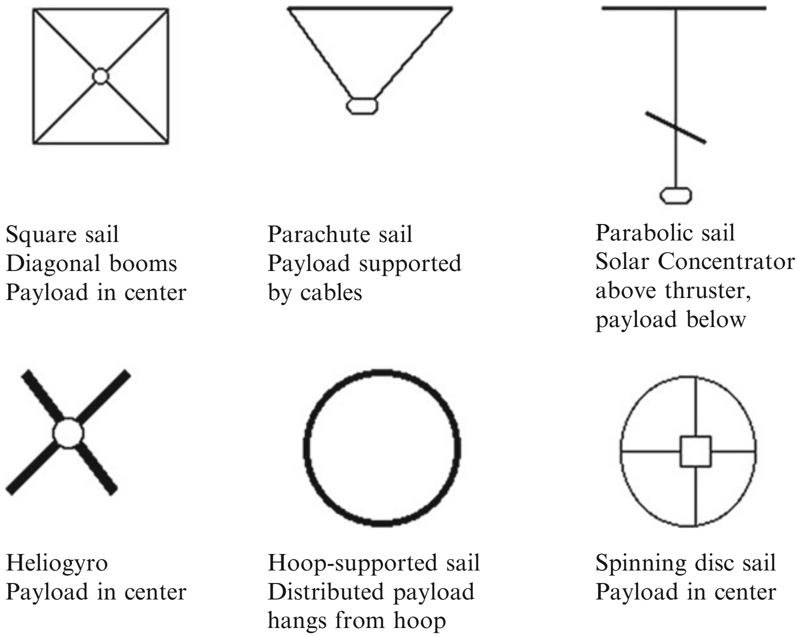



13.1 Various photon solar-sail configurations

that it can focus light on the smaller, movable thruster sail. A larger component of radiation-pressure–derived force can be tangent to the spacecraft's motion, allowing for this configuration's possible application in Earth-orbit raising. The SPT also has the potential to operate at a larger angle from the sunlight than other configurations. These advantages must be balanced against the added rigging mass and complexity.

Next is the spinning-disk sail. This rigging utilizes centrifugal acceleration as an aid in unfurling sail. The payload is mounted near the sail center.

A variation on the spinning-disk sail is the hoop sail. Here, the radial (possibly inflatable) struts are replaced by a hoop structure concentric to and containing the sail film. In this soap-bubble–like arrangement, the payload must be evenly distributed around the hoop structure, perhaps suspended from it.

The heliogyro sail rigging is inspired by the blades of a helicopter. After launch from Earth, the central core is slowly spun up and the blades are allowed to unfurl by centrifugal acceleration. Although sail deployment is relatively easy in this case, the blades must be long because of the comparatively small sail-film area-fill ratio. (There is simply not much of a sail for light to reflect from.) Payloads would likely be mounted near or at the sail's geometric center.

A final configuration is not shown in Fig. 13.1. This is the hollow-body or inflatable sail. Here, a reflective film is mounted on the Sun-facing side of a balloon-like inflatable structure that is inflated in space using a low-density fill gas. The payload is near the center on the anti-Sunward-side of this "pillow." Although easy to deploy and mathematically model, hollow-body sails are more massive and more prone to micro-meteorite damage than other riggings.

Further investigative studies and operational applications will surely produce variations on the seven solar-photon-sail rigging arrangements considered here. But these seven will likely remain the basic approaches for the foreseeable future.

Although ultimate space-manufactured sail films may be very low mass monolayers, perhaps containing perforations smaller than a wavelength of light to further reduce mass, current candidate Earth-launched sail films are tri-layered. An aluminum layer about 100 nm in thickness faces the Sun and reflects 79–93 % of the incident sunlight (mainly depending on the surface roughness). Next comes a low-mass plastic substrate perhaps a few microns thick. On the anti-sunward side of this substrate is affixed an emissive layer (often chromium) that radiates the small fraction of sunlight absorbed by the aluminized face to the space environment.

In early sails, the plastic substrate is generally selected to be heat and vacuum tolerant and immune to the effects of solar ultraviolet (UV) irradiation. But there is a very innovative, mass-reducing suggestion to use instead a plastic substrate that sublimates rapidly when exposed to solar ultraviolet. Shortly after sail unfurlment, the plastic substrate would disappear leaving only a reflective-emissive bi-layer of very low mass.

This sublimation process, if controlled and unidirectional, could even add to sail thrust during the early phase of its journey. Called "desorption," this high-velocity sublimation of sail material is a subject of current research.

Because solar-photon sails (SPSs) are large-area devices that must accelerate for long periods of time in the space environment, a method of micrometeoroid protection has been developed. Similar to "ripstops" in terrestrial wind sails, a network of thin cables could be placed in the sail film. If a micrometeoroid impact were to destroy one small segment of sail defined by intersecting cables, other sail segments would still function.

Most early sail applications will involve low accelerations—probably in the vicinity of 0.0001–0.001 Earth surface gravities. But a 1996 computer finite-element-model study by Brice Cassenti and associates demonstrated that properly configured parachute, parabolic, and hollow-body sails are stable under accelerations as high as 2.5 Earth surface gravities.

Much work has been accomplished in sail design and much still remains to be done. But as the next sections indicate, government space agencies and private organizations have done much to remove this concept from the realm of science fiction and achieve progress toward the day when this innovative mode of in-space transportation will become operational and, hopefully, of choice clearer than the performance-limited rocket-based missions.

## THE ROLE OF SPACE AGENCIES

Much photon-sail research and development has been accomplished by national and transnational space agencies such as NASA and ESA. To better understand these contributions, it's a good idea to review the environment in which the space agencies operate.

The advantage of the space agencies over small-scale entrepreneurs is essentially one of scale. Since space agencies are governmental entities, they have the ability to plan long-term research and development efforts supported by tax revenues.

For example, much has been written in recent months about the success of privately funded suborbital space flights at a fraction of the cost of similar government-funded efforts. While these comparisons make a certain amount of sense, they entirely ignore the cost of the decades-long government-sponsored space infrastructure. Space Ship 1 would not have so readily won the X-Prize for repeated flights to heights in excess of 100 km if Burt Rutan and associates had had to construct the Edwards Air Force Base and repeat the materials research leading to the technology used in their vehicle.

At least in democratic nations, however, this very advantage of space agencies to work with high annual operating budgets may work against rational space development. The space agencies must answer to the politicians, and the politicians must in turn justify expenditures to the electorate.

To get reelected, politicians must curry favor with the electorate. Sometimes high-profile stunts in space and huge projects economically supporting lots of workers with little practical output are favored over sounder approaches. The high-profile stunt results in favorable publicity and headlines; the "pork-barrel" project garners votes. To succeed, a rational space-development program must work with the politically inspired funding cycles.

With the exception of a few experimental efforts, all publicly funded space efforts utilize technologies mostly developed decades in the past. To allow new in-space propulsion technologies such as the SPS to mature to their flight application, NASA developed a step-by-step procedure called technological readiness, which works as follows: when a new space propulsion idea emerges from a theory and its basic physical principles are validated, it is assigned a technological readiness level (TRL) of 1. An example of an in-space propulsion concept now at TRL 1 is the proton-fusing interstellar ramjet. It may always remain at this level since its physics is well validated but its technology may never be defined. In some cases, such as the matter–antimatter rocket, the technological requirements can be defined, even if not achieved. Such propulsion concepts are at TRL 2.

As an in-space-propulsion concept matures, its TRL increases. Analytical or experimental proof-of-concept investigations are performed, followed by laboratory (breadboard) validation studies. Component and breadboard tests are then performed in a simulated space environment—a vacuum chamber—to achieve a TRL of 5. The next step is to successfully test a prototype of the in-space propulsion system under study in the simulated space environment. To achieve a TRL of 7, a prototype of the propulsion system must be successfully tested in space. The completed system is then qualified through demonstrations on Earth or in space. The highest level of TRL is 9, in which the propulsion system is operationally used in space missions. Examples of such "off-the-shelf" TRL-9 propulsion systems include chemical rockets, solar-electric rockets, and gravity assists.

It might be argued that the TRL system is boring and bureaucratic—just the thing that a space agency might dream up to justify its own existence. But the beauty of the approach lies in its small, clearly documented incremental steps. A space-program manager can use TRL to compensate for the politically determined, highly variable nature of space-propulsion funding. Well-documented research can advance an in-space propulsion concept one or two TRLs during any funding cycle and then be used to efficiently pick up the research effort when large-scale funding resumes. In this way, it is not necessary to endlessly reinvent the wheel.

The ESA is used to applying the technology readiness procedure to new astronautical concepts through 9 levels as well.

World space agencies have done a great deal to advance the cause of the SPS. In the late 1970s and early 1980s, NASA's Jet Propulsion Laboratory in Pasadena, California, analyzed the utility of the sail to perform a (canceled) 1986 rendezvous with Halley's Comet and propel a (canceled) extra-solar probe called TAU (thousand astronomical units). These paper studies led to the first tests of sail-like structures in space. In February 1993, a 20-m diameter thin-film reflector called Znamya was unfurled from a Progress supply craft docked to Russia's Mir space station. Znamya, designed to test the feasibility of reflecting sunlight to regions of the Russian arctic, was a modified heliogyro using centrifugal acceleration to unfurl.

In this general scenario, the NASA Interstellar Probe (ISP) mission concept deserves special attention for its high-degree of efforts in setting up many profiles of flight. Starting in the 1990s, NASA/MSFC and JPL (which is a division of Caltech, Pasadena—California) studied a large sailcraft capable of delivering 30–40 kg of scientific payload to 200 AU, passing through the three large "boundaries" of the solar system, namely, the termination shock, the heliopause, and the bow shock. A possible extension of the mission to 400 AU was also investigated. JPL's preliminary studies showed that—by means of sailcraft with sail loading of 2 g/m$^2$—it should be possible to flyby the Sun counterclockwise at 0.25 AU, and achieving 200 AU in about 15 years. In the JPL flight profile, sail was jettisoned at 5 AU from the Sun. In 2001, NASA/MSFC investigated further, and carried out mission profiles with sailcraft down to 1 g/m$^2$. They resulted in the possibility of flying by the Sun clockwise at 0.2 AU with subsequent cruise speed of about 23.5 AU/year. This would allow the sailcraft to reach 200 AU in 9 years. The mission extension to 400 AU would last about 18 instead of 30 years. An important option of this investigation was to not-jettison the sail, which might act as a very big sensor and partially as a large antenna too. MSFC and JPL mission profiles would offer *two* launch opportunities per year, *every* year! The three authors of this book participated, serving different roles, in the NASA/MSFC ISP trajectory studies.

Mission support for ISP declined for a time due to no progress being made in the preferred propulsion methods: either solar sails or nuclear electric propulsion. Both technology development projects were canceled in the mid-2000s for various reasons (NEP due to cost; solar sails due to the money being needed for the return to the Moon program). Support for ISP is now again high due to IKAROS (see below and Chap. 14). The new NASA Heliophysics Decadal Survey, mentioned in Chap. 14, could also support the Interstellar Probe.

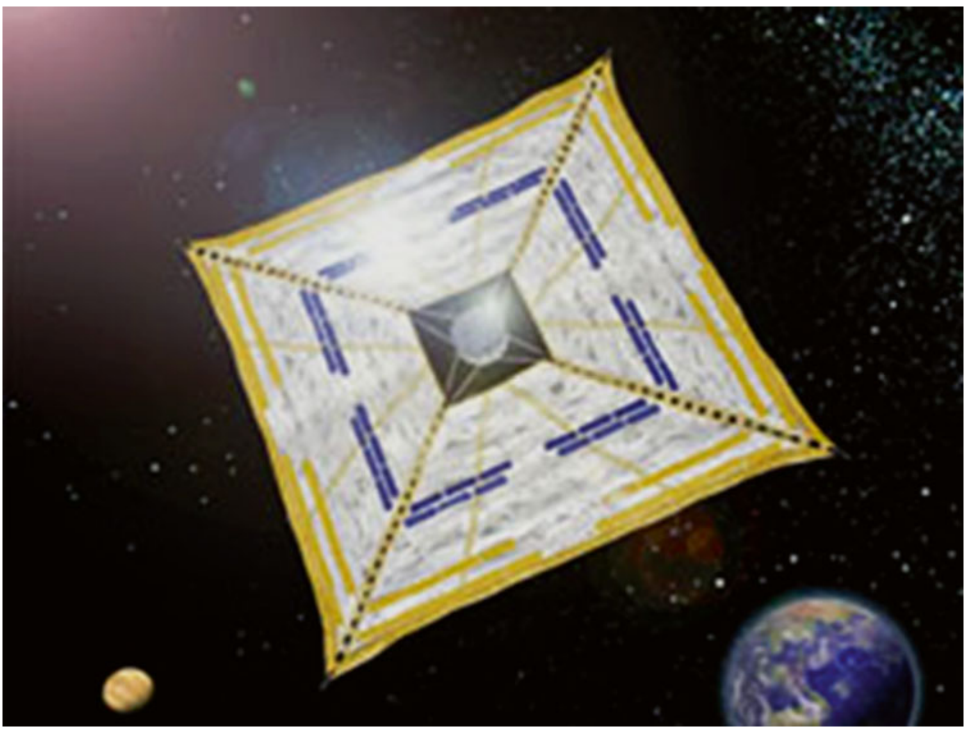
In May 1997, an American space shuttle deployed a 14-m-diameter inflatable antenna that tested the design of low-mass radiofrequency antennas and reflectors. Some of the concepts explored in this partially successful experiment are of relevance to inflatable, hollow-body solar sails.

The first test deployment of a true sail design in space came in the summer of 2004 when two small test sails were successfully unfurled from a suborbital Japanese sounding rocket. True to their country of origin, the sails were opened using the principles of origami, the Japanese art of paper folding! Capitalizing on this success, the Japanese space agency conducted an orbital solar-sail test in February 2006, when a test sail flew as a secondary payload aboard a rocket carrying the ASTRO-F (Akari) astronomical satellite. The sail unfurlment was a partial success.

Full success for the Japanese Space Agency (JAXA) occurred during 2010. On May 21 of that year, an H2A rocket was successfully launched from the Tanegashima Space Center. The primary payload was the Venus Climate Orbiter (also dubbed Akatsuki or Planet-C).

Akatsuki cannot be considered a complete success because its retrorocket failed to fire during its approach to Venus and it remains in orbit around the Sun instead of circling Venus. The secondary payload of the mission, dubbed IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) has done much better, from both a technological and an engineering point of view. IKAROS, the first solar sail to be deployed in interplanetary space, was successfully unfurled on June 9, 2010. IKAROS is a square sail, measuring about 14 m on the side and 20 m on the diagonal. The base sail material is polyimide and the sail consists of four trapezoidal petals.

The initial mass of IKAROS was 307 kg; the sail mass is 16 kg and the minimum sail thickness is 7.5 μm. During the sail deployment process, the maximum spin rate was about 25 revolutions per minute (rpm). This has since been reduced to about 1 rpm. The sail deployment process was monitored by several tiny camera that were released from the main craft (Fig. 13.2).



13.2 Artist concept showing the IKAROS unfurled (Courtesy of JAXA)

As well as demonstrating that a solar sail can be deployed in deep space, this successful mission also demonstrated that small, thin-film (25-μm) solar cells attached to the sail can produce electricity in space. As well as confirming the theory of thrust by solar radiation pressure, IKAROS demonstrated guidance and navigation of solar sail spacecraft.

One especially innovative on-board system demonstrated reflectance control of spinning solar sails. A series of on-off variable reflectance strips are attached to the sail. These multi-layered thin sheets are equipped with electrically controlled timers. If it is desired to *alter* the sail spin axis direction, then the reflectance of one side of the IKAROS sail is set to maximum (specular reflection), whereas the other side is set to the minimum (diffuse reflection). If no change is requested, then the opposite strips are kept at the same reflectance by the on-off timers.

During its first 6 months of operation, the accumulated solar-radiation pressure speed change on IKAROS was reported to be in excess of 100 m/s. On December 8, 2010, IKAROS passed Venus at a distance of 80,800 km.

Instruments aboard this sailcraft have also provided useful scientific data. As reported in 2012, a gamma-ray-burst polarimeter has observed two gamma-ray bursts at cosmological distances. The data supports a synchrotron emission model for this phenomenon.

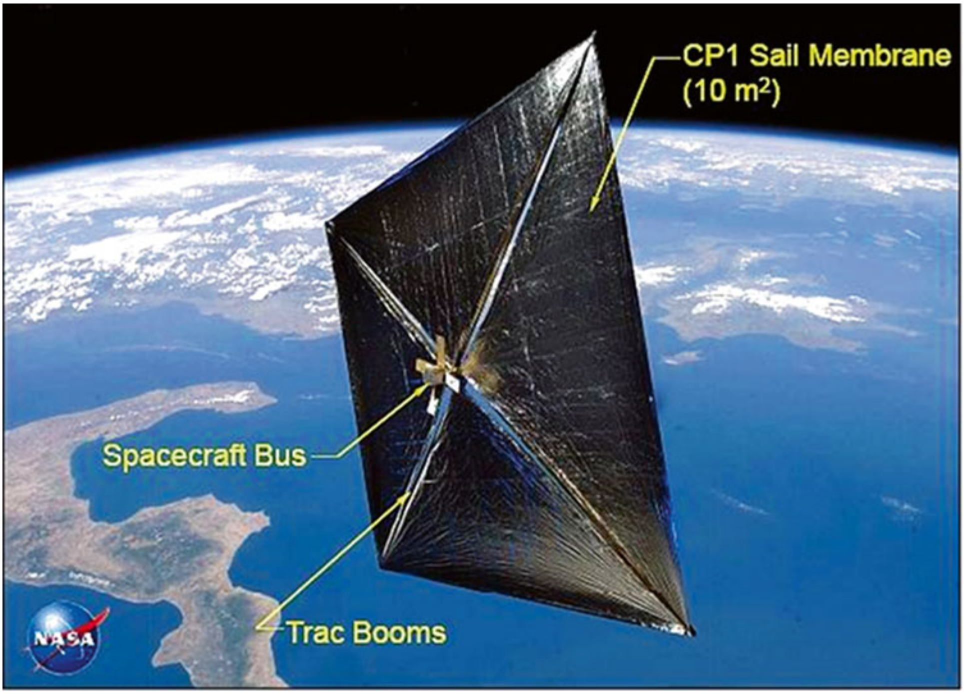
Engineers at the NASA Marshall Space Flight Center in Huntsville, Alabama, raised the solar sail's TRL using a series of unfurlment tests of subscale sails in terrestrial vacuum chambers. During 2005, a 20-m test sail was tested by NASA engineers in a terrestrial vacuum chamber (see 12.3 in Chap. 12). The pace of solar-sail development is quickening with the successful flight in Earth orbit of the NanoSail-D and with NASA's selection of L'Garde, Inc. to further mature the 20-m solar sail they developed in the mid-2000s and get it ready to fly in space later in the decade. (As of this writing, the fate of the L'Garde solar sail effort is uncertain.) Moreover, new players among government-sponsored space agencies can be expected to join the game. At present, we can safely conclude that the SPS has reached a TRL of 7 (JAXA) or 6 (NASA) and that operational applications are not many years in the future.

During 2010, NASA's successful launch and deployment of Nanosail-D2 did a lot to advance the TRL of sailcraft. Although NASA did not earn bragging rights by beating JAXA's IKAROS into space, NanoSail demonstrated sail unfoldment and operation in low Earth orbit (Fig. 13.3).

Nanosail-D2, which was launched on November 19, 2010, was the back-up craft to NanoSail-D, which failed to reach orbit due to a booster malfunction on August 8, 2008. It was initially believed that NanoSail-D2 was also a failure, since its deployment timer initially malfunctioned for some unknown reason.

Finally, on January 20, 2011, the 10-$m^2$ sail deployed perfectly. This sailcraft of mass of 4 kg was initially placed in a 623–654 km orbit and circled the Earth until its atmospheric reentry on September 17, 2011.

NanoSail was a "cubesat," unfurling in about 5 s from its 30 × 10 × 10 cm container. The purpose of this craft was to demonstrate the utility of solar sails to function as parachute-like drag sails to hasten the reentry of expended rocket stages and obsolete payloads in low Earth orbit. In collaboration with Spaceweather.com, NASA conducted a contest for amateuer astronomers attempting to photograph Nanosail in space.




13.3 Artist's rendition of Nanosail-D2 in orbit (Courtesy NASA)

Unlike the nuclear rocket, the SPS can be configured to any size. We might launch a micro-sail more properly called a solar kite that is not much larger than a living room rug with a payload of 1 or 2 kg. Our wealthier neighbor might at the same time be scaling the technology to propel an interplanetary ship with a sail diameter of 1–10 km or even a larger interstellar craft.

With such a flexible in-space propulsion system, there is plenty of room for the small-scale inventor to make contributions, whether privately or governmentally funded. The next section considers the role of private initiatives in bringing the SPS to its current stage of flight readiness.

## PRIVATE INITIATIVES

The early development of chemical rocketry was dominated by private inventors, such as Robert H. Goddard in the US, and national rocket societies in many countries. Private organizations and individuals continue to contribute to solar-sail progress.

A private individual or non-governmental organization has certain advantages and disadvantages when compared to government-sponsored space agencies. Since such groups or individuals are not beholden to taxpayers and politicians, they can tackle more visionary projects with a longer time to implementation or payoff. To implement these projects, however, private organizations must often engage in fund raising.

One contribution of private organizations has been raising public awareness of photon-sailing technology. Since 1982, three private groups—the Union pour la Promotion de la Propulsion Photonique (U3P) in France, the Solar Sail Union of Japan, and the World Space Foundation (WSF) in the US—have collaborated to publicize the concept of a solar-sail race to the Moon.

Private organizations have also planned very nontraditional solar-sail propelled space missions. One American company (Team Encounter) has raised funds to launch human-hair samples on extrasolar trajectories, advertising that perhaps ethically advanced extraterrestrials intercepting the craft might feel compelled to clone the long-deceased human "crew" from the DNA in their hair samples. Very wealthy individuals might contribute to such a mission as a very-long-duration insurance policy!

But one of the greatest advances to photon-sail technology has resulted from the very serious work of the largest nongovernmental space organization of them all, the Planetary Society in Pasadena, California. Funded by member contributions and large donors including Ann Druyan (who is Carl Sagan's widow), the Planetary Society developed Cosmos 1, the first flight-ready spacecraft in which the photon sail would be the prime method of propulsion. To conserve funds, both the suborbital and orbital Cosmos 1 launches were conducted using a Russian booster of marginal reliability. Unfortunately, the reliability of this booster must now be classified as less than marginal since both launches failed and the sails plunged to Earth before they could be unfurled. The Planetary Society's directors hope to make additional attempts with more reliable boosters. They are now developing LightSail, a cubesat derived solar sail, which, if it does make it to space, will use the pressure of sunlight to alter the craft's orbit. There are two LightSail spacecraft. LightSail-A, scheduled for launch in 2015, will be a systems test of the technology but it will not be flying in a high enough orbit to overcome atmospheric drag. LightSail-B, when and if it flies, will be a demonstration of controlled solar sail flight. Also proposed is an experiment to beam microwaves to the orbiting craft using a radio telescope in order to demonstrate collimated-energy-beam sailing. It would be nice if both solar and energy-beam sailing concepts can be validated on the same mission!

Temporary, small-scale organizations composed of visionary scientists and engineers have also contributed to the advancement of SPS technology and public awareness of this concept. During the 1990s, a group of researchers (including authors Vulpetti and Matloff) from several countries, met regularly in Italy to discuss the possibility of exploring nearby extrasolar space using sail-launched probes. It may be historically interesting to report how this team originated and worked. During the International Astronautical Congress, held in Graz, Austria, in October 1993, a group of seven solar-sail enthusiasts met to organize an in-depth study of solar sailing. After a lot of discussions, continued via mail for a couple of months, it was decided to set up a self-supporting study group. That meant that the group members would work during their free and creative time; nevertheless, some members would ask their companies to utilize some of the companies' facilities. Some companies said yes, and the group began working. The team chose the name Aurora Collaboration. (According to the ancient Greek mythology, Aurora was the younger, fair sister of Helios, the Sun god. Helios's elder sister Selene, the goddess of the Moon, was discarded for her paleness!) The active members of Aurora were author Gregory Matloff (NY University), Giancarlo Genta and his coworker Eugenio Brusa (Polytechnic

University of Turin, Italy), Salvatore Scaglione (ENEA, Rome-Italy), Gabriele Mocci (Telespazio SpA, Rome, Italy), Marco Bernasconi (Oerlikon-Contraves, Zurich-Switzerland), Salvatore Santoli (International Nanobiological Testbed, Italian Branch, Rome, Italy), Claudio Maccone (Alenia-Spazio, Turin, Italy), and author Giovanni Vulpetti (Telespazio SpA, Rome, Italy). Vulpetti was appointed as the team coordinator. Aurora committed to the following objectives: (1) considering SPS propulsion for realistic extra-solar exploration; (2) investigating mission classes and related technological implications for significantly reducing the flight time, from departure to the target(s); (3) analyzing flight profiles; and (4) sizing sailcraft's main systems for a technology demonstration mission to be proposed to the space agencies. Aurora worked from January 1994 to December 2000. Some innovations have been developed and submitted to the attention of the space communities, including NASA and ESA. For instance, the NASA Interstellar Probe (ISP) concept (for which author Johnson served as the propulsion system manager) is an evolutionary development of Aurora. In turn, the subsequent mission concept of the interstellar heliopause probe by ESA/ESTEC, is similar to a smaller-scale version of NASA ISP.

The main results of Aurora, in chronological order, are as follows:

1. The fast solar sailing theory (in either classical or full relativistic dynamics) and the related large computer code for optimizing unconventional trajectory classes
2. The bi-layer (Al-Cr) sail concept and the related preliminary experiments at ENEA for detaching plastic support in space, to have a clean all-metal sail
3. The concept of unfurling and keeping a circular sail via a small-diameter inflatable tube attached around the sail circumference; after sail deployment, the tube becomes rigid in the space environment and retains its shape without gas pressure
4. Sizing the onboard telecom system for communications from some hundreds of AU
5. The determination of the full behavior of aluminum's optical properties starting from experimental data
6. Optimization of trajectories to heliopause, near interstellar medium, and the solar gravitational lens

Aurora published 15 scientific papers, gave three presentations to European and Italian space authorities, and held a one-day workshop at Rome University. Sometimes it is not necessary to resort to newspaper, radio or television advertising to foster genuine scientific advances. Serious, unheralded, and systematic work with pure vision and scientific objectives are still the basic ingredients for stimulating the appropriate institutions to transform good ideas into reality.

## FURTHER READING

Two excellent sources considering in greater depth the material covered in this chapter are Jerome L. Wright *Space Sailing,* Gordon and Breach, 1992, and Colin McInnes *Solar Sailing*, Springer-Praxis, Chichester, UK, 1999. More information on various sail configurations can be found in the appendix of Gregory L. Matloff *Deep-Space Probes*, 2nd ed., Springer-Praxis, Chichester, UK, 2005.

An excellent review of the JAXA IKAROS sail mission is T. Tsuda, O. Mori, R. Funase, H. Sawada, T. Yamamoto, T. Saiki, T. Endo, K. Yonekura, H. Hoshino, and J. Kamaguchi, "Achievement of IKAROS-Japanese Deep Space Solar Sail Demonstration Mission," *Acta Astronautica*, **82**, 183-188 (2013). An earlier version of this manuscript is in *Proceedings of the Seventh IAA Symposium on Realistic Near-Term Advanced Scientific Space Missions—Missions to the Outer Solar System and Beyond*, ed. G. Genta, Aosta, Italy, 11-13 July, 2011.

For a description of IKAROS gamma-ray burst observations, see D. Yonetoku, T. Murakami, S. Gunji, T. Mihara, K. Toma, T. Morihara, T. Takahashi, Y. Wakashima, H. Yonemochi, T. Sakashita, N. Toukairin, H. Fujimoto, and Y. Kodama, "Gamma-Ray Burst Jets Probed by Gamma-Ray Polarization," *Astrophysical Journal Letters*, **758**, No. 1, L1 (2012).

Nanosail has been described in several sources. One useful paper is L. Johnson, M. Whorton, A. Heaton, R. Pinson, G. Laue, and C. Adams. "Nanosail-D: A Solar Sail Demonstration Mission," *Acta Astronautica*, **68**, 571-575 (2011). An earlier version of this manuscript is in *Proceedings of the Sixth IAA Symposium on Realistic Near-Term Advanced Scientific Space Missions—Missions to the Outer Solar System and Beyond*, ed. G. Genta and G. Vulpetti, Aosta, Italy, 6-9 July, 2009

For additional information regarding Nanosail, consult the project's website http://www.nasa.gov/mission_pages/smallsats/nanosaild.html