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Carbon Nanotube Membrane Solar Sails A Challenge for Extremely Fast Space Flight

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1. Introduction

Space sailing is a concept in space propulsion technology that is based on the use of solar or other radiation for propulsion. The sunlight, or the beam of electromagnetic radiation from a laser, are reflected by the sail surface and, since photons carry momentum, their reflection changes their momentum so that a resultant force is exerted on the reflecting surface. Accordingly, spacecraft exploiting this propulsion method will carry very large, ultra-thin reflectors and will be able to transport heavy payloads both for planetary and for interstellar missions. Here the focus will be on solar sails as systems exploiting the pressure of light from the Sun for propulsion, not from a laser beamed to the sail, and their physics will be briefly analyzed from first principles involving mechanics, optics and thermodynamics. It will be then shown how the basic astrodynamical parameters and the technological and engineering requirements can be derived from first principles for interplanetary and interstellar flight purposes.

This discussion will contemplate such thumbnail sketch of the basic scientific and engineering aspects of solar sail propulsion, also known as *photonic propulsion*, just in order to allow a better understanding and appreciation of the recent technological advancements in the sail material through a proper development of carbon nanotube membranes, that has allowed the design to be realized of a solar sail featuring a cruising speed of the order of some thousandths the speed of light, i.e. a speed much higher than the speed attainable by any other propulsion methods. This is due both to the very light and reflecting sail material and to the manoeuvre of inverting the angular momentum (Vulpetti, 2002) of the sail when it has reached the perihelion according to the *Sun diving flight mode*, i.e. the mode consisting in launching the solar sail toward the Sun so that on flying by the Sun it becomes strongly accelerated to finally reach a very high cruising speed: the so-called asymptotic speed. Anyway, various other modes can be adopted, e.g. for orbiting a planet and interplanetary transportation of any payload. For detailed descriptions of solar sail structural technologies and of the astrodynamics involved in realizing some special missions, e.g. based on intra-orbit transfer of sail up to being free from planetary gravitation and ready to spacefaring, the reader is referred to the abundant specialized papers on space sailing, where also excellent treatises can be found for a systematic approach (Wright, 1993; McInnes, 1999; Vulpetti et al., 2008).

2. Solar Sails from First Principles

All the following discussion will be managing to let the reader go along the same route as I went from the basic mechanics, optics, thermodynamics and structural engineering up to the design of the latest and speediest models of solar sail whose membrane is made up of carbon nanotubes.

The problem is to design a reflector large enough to get a suitable acceleration *but* of so small a mass to be pushed and accelerated up to a significant speed by incident photons from the Sun. Accordingly, reflectance should be the highest possible with the present material technologies. But it is well known from optics that there is no such thing as a perfect reflector, some of the photons becoming absorbed by the reflector, so that the designer will have to face the problem of optimizing the combination of reflectance, density, and emittance for a correct computation of the resultant force pushing the sail, for maximizing such force as well as for keeping the sail temperature at a possible level, mainly on approaching the Sun. Indeed, thermodynamics of radiation will be thus involved. All that would not be attainable with a single material, so that at least two layers are to be planned as the sail structure: a reflecting and an emitting material. Leaving behind for the moment the problems about the nature of materials, which would also involve their structural strength, the basic approach to solar sail dynamics will be based on the following sketches depicting the mechanics, the optics and the thermodynamics of the solar sail.

In Fig. 1, I = incident light; R = reflected light; F_I = incident force; F_R = reaction force; F = the resultant; S = the sail

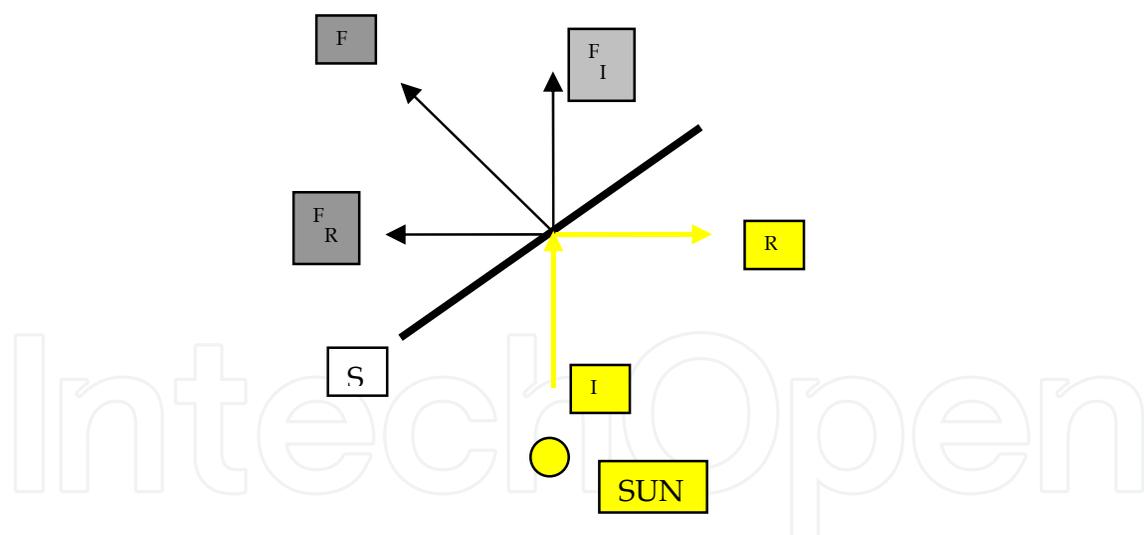


Fig. 1. Mechanics of the sail as a perfect reflector

In Fig. 2, the realistic situation for a non-ideal sail (i.e. a non perfect reflector) is depicted: the resultant will no longer be normal to the sail surface as part of incident photons will not be reflected; they will be absorbed and subsequently re-radiated as thermal radiation. The resultant will be rotated from the normal to the sail surface toward the direction of I because the force F_A from absorbed photons is quite stronger than the force F_R due to reflected photons, and the force from re-radiated photons as would be computed from thermodynamics will be normal to the surface. This will then lead to the setting forth of an optical sketch of

the physical situation (Fig. 3), the latter leading then to the application of thermodynamics of radiation for evaluating the force exerted on the sail by re-radiated photons as well as the temperature of the solar sail. The situation as in Fig. 2 would also refer to the fact that stresses on the sail surface will tend to inflect the sail, which will have a strong tendency to billow so that a proper system of tie-rods and struts is to be designed. The material of the sail surface itself should be given the property of preventing any tear in the material caused by space debris or very small asteroids from running along the whole structure and to cause them to keep confined at the place of impact. It is to be considered that sail areas up to some km squared would be planned. Of course, this represents a formidable task for designers and builders to get uniform values of the optical parameters that the sail itself would embody.

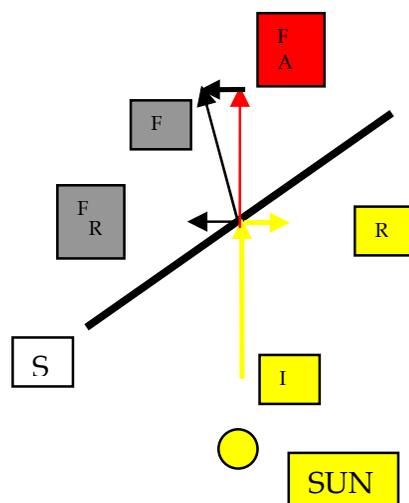


Fig. 2. Mechanics of the non-ideal sail: the resultant is shifted toward the direction of I from the normal to the surface as a result of $F_A \gg F_R$ (vectors not to scale)

In the optical force model of Fig. 3, the unit vectors and the normal to the sail surface are considered because a proper calculation of forces asks for vector representations and scalar products along the unit vector \mathbf{n} normal to the sail surface that defines the sail orientation, along the transverse unit vector \mathbf{t} normal to \mathbf{n} , along the unit vector \mathbf{u} along the direction of incident photons, and along the unit vector \mathbf{s} along the direction s of specularly reflected photons.

Now, with $F_E \equiv$ force from photon emission by re-radiation; $\alpha \equiv$ the pitch angle of solar sail relative to the Sun line; $PA \equiv$ radiation pressure \times sail area; $F_{Rs} \equiv$ force from fraction of incident photons specularly reflected; $R \equiv$ fraction reflected of the incident photons; $R_s \equiv$ fraction of reflected photons specularly reflected along \mathbf{s} ; $F_{Rn} \equiv$ force along \mathbf{n} from fraction of incident photons non-specularly reflected; $B \equiv$ coefficient describing the non-Lambertian character of the surface, i.e. a surface which doesn't appear equally bright when viewed from any aspect angle, we have (cf. Fig. 3):

$$\begin{aligned}
 \mathbf{u} &= \cos \alpha \mathbf{n} + \sin \alpha \mathbf{t} \\
 \mathbf{s} &= -\cos \alpha \mathbf{n} + \sin \alpha \mathbf{t} \\
 \mathbf{s} &= \mathbf{u} - 2 \cos \alpha \mathbf{n} \\
 F_A &= PA (\cos^2 \alpha \mathbf{n} + \cos \alpha \sin \alpha \mathbf{t}) \\
 F_{Rs} &= - (Rs) PA \cos \alpha \mathbf{s} \\
 F_{Rn} &= BR(1 - s) PA \cos \alpha \mathbf{n}
 \end{aligned}$$

and for the resultant F in terms of the normal and transverse directions

$$F = PA[(Rs \cos^2 \alpha + B(1 - s) R \cos \alpha) \mathbf{n} - Rs \cos \alpha \sin \alpha \mathbf{t}]$$

The final force component is that due to photons which have been absorbed and then re-emitted as thermal radiation from **both the front (reflecting) and back surfaces** of the sail.

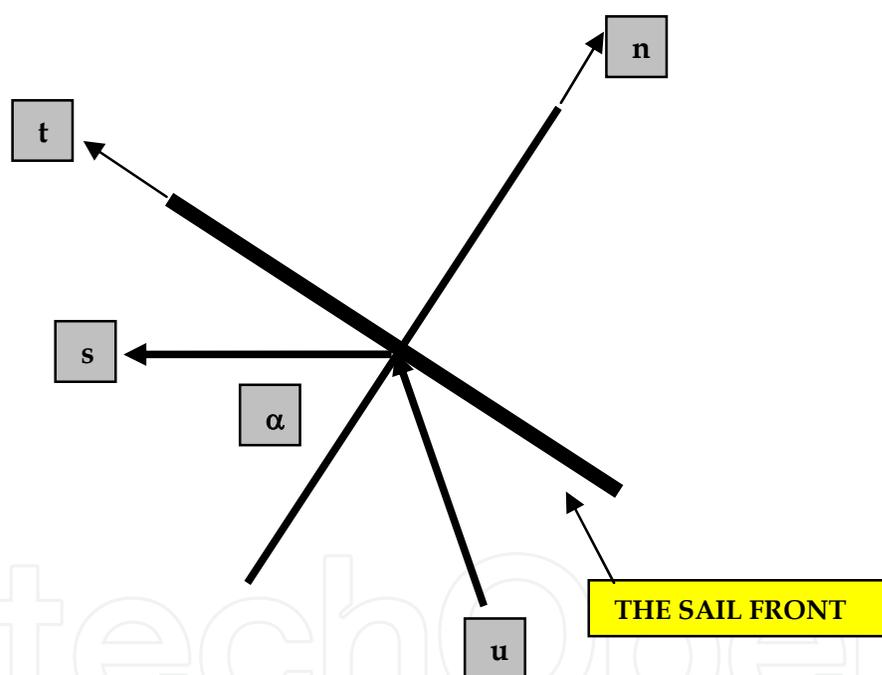


Fig. 3. Diagram of vectors for the optical model of the non-ideal solar sail

When designing the material for the solar sail film, it is important to compute the sail equilibrium temperature for two basic reasons: 1) computing the force exerted on the solar sail due to emission by re-radiation; 2) compute the sail temperature during its flight, mainly at the perihelion. Indeed, it is important to know the thermomechanical and the thermochemical behavior of the sail film during mission. For instance, in case of the so-called *light sail* made up of two-layer sails consisting of Al as the reflector and Cr as the emissive layer, as opposed to the *heavy sail* including an interposed plastic film, e.g. Kapton, it is important to estimate the whole thermal history of the double layer structure (Santoli and Scaglione, 1996) because according to the thermodynamic phase diagrams of the AlCr

system an interdiffusion process starts at a given temperature, and as a result a solid solution starts to form at the interface that goes on throughout the whole Al/Cr double layer so that all optical parameter values of the sail are changed and the whole mission fails. One of the great results stemming from the use of a carbon nanotube membrane for the sail film as a *monolayer* (Vulpetti et al.) is the perspective use of such membranes as capable of keeping all their original values of the optical parameter even after being heated up to incandescence. As to thermomechanical behavior, for instance the key point in judging about the mechanical fitness and the limitations to the performance of the Al/Cr composite double layer would be the determination of thermal stresses at the interface of that composite structure and the estimate of the possibility of occurrence of cracking, decohesion and fracture in the thin Cr film coated on the Al support (Santoli and Scaglione, 1996). *This problem would be absent from the envisaged technology of carbon nanotube monolayer films for sails that will be discussed in the following.*

The sail temperature can be calculated by the Stefan-Boltzmann law after setting forth the thermal balance of the solar sail; see Fig. 4 for the meanings of symbols and for a basic sketch stressing the vectorial nature of the problem.

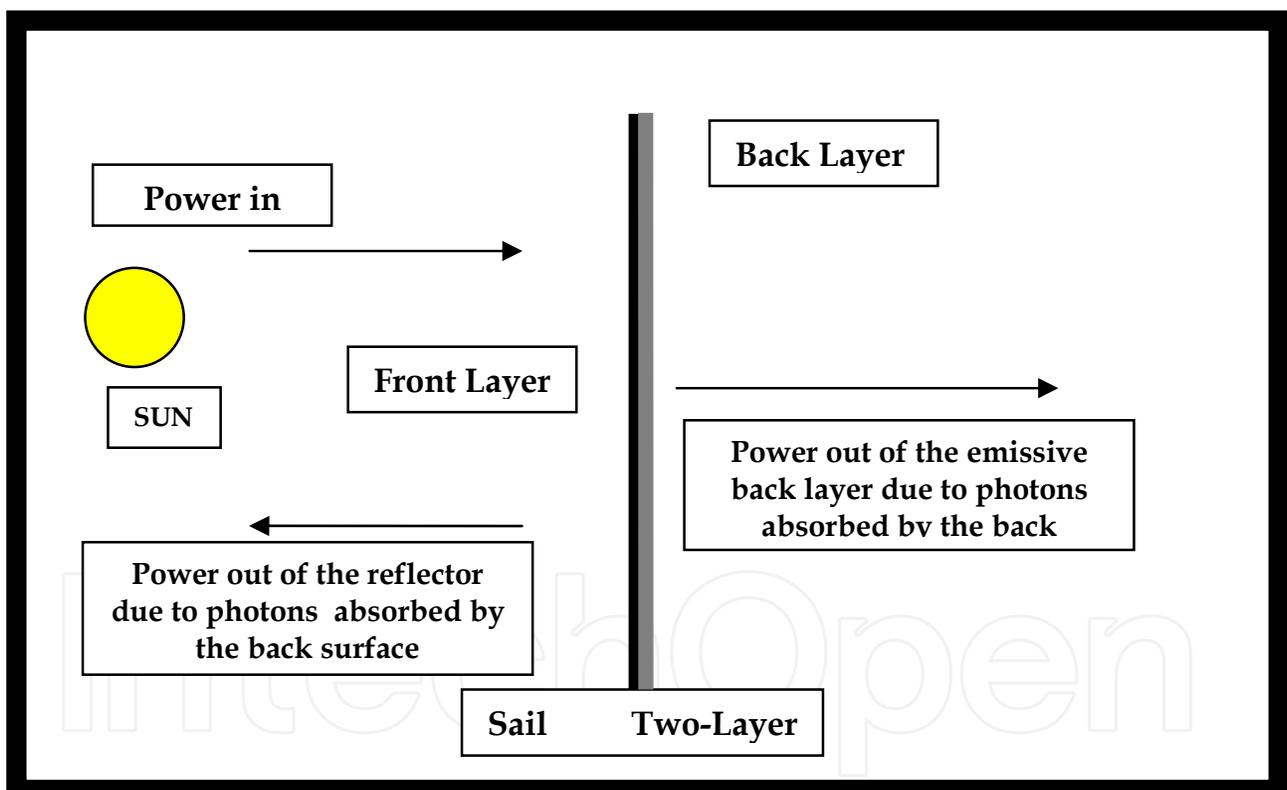


Fig. 4. The solar sail thermal balance from which the force exerted on the sail surface through emission by re-radiation and the temperature of the solar sail composite film can be calculated. This balance is of the essence for the discussion in **Section 2.1**

Now, with W as the solar flux incident on the sail, ε_f and ε_b respectively the front and back emissivities, B_b as the non-Lambertian coefficient of the back surface, σ the Stefan-Boltzmann constant, and T as the absolute temperature of the sail, we have:

Power Emitted from a Unit Area of the Sail at $T = \epsilon_f \sigma T^4$

Force due to Emission by Re-Radiation Assuming Uniform Sail $T \equiv T_e$

$$F_e = \frac{\sigma T^4}{c} (\epsilon_f B - \epsilon_b B_b) \mathbf{n}$$

and, from the balance between thermal input and thermal output (cf. Fig. 4)

$$\Delta P \equiv \text{Power in} - \text{Power out} = (1-R)W \cos \alpha - (\epsilon_f - \epsilon_b) \sigma T^4 = 0$$

so that, taking into account that $PA = W/c$, both the sail equilibrium absolute temperature T and F_e can be calculated. With the aid of the vectorial optical diagram of Fig. 3, by considering all forces mentioned above it is quite trivial to get an expression of the total force exerted on the sail in terms of its normal (\mathbf{n}) and transverse (\mathbf{t}) components. Contrarily to the ideal sail case, for the real sail as a non perfect reflector the resultant force vector will not be in the direction normal to the sail surface due to the fact that the absorbed photons force is greater than the force due to reflected photons.

This analysis of the sail physics has been carried out by means of the particle (photon) description of the electromagnetic field, but an analysis based on the wave description by application of Maxwell equations for the field could have been carried out. This way of describing solar sail motion is important for some points in **Section 2.1**. In that section some more considerations are added for a clear understanding of solar sail physics so that some misconceptions about it can be removed. Indeed, a few remarks look like being opportune because of three reasons:

- 1) the objections made to the possibility of solar sailing were published in a journal enjoying a very wide audience; anyway, the Editor was asked to remove that article
- 2) the quite widespread erroneous description of how Crookes's radiometer works, though its correct description was given about 130 years ago by two of the most renowned scientists in the history of science: J.C. Maxwell and O. Reynolds, and
- 3) thermodynamics of radiation is fundamentally involved in the astrodynamics of solar sails in general, but mainly in missions contemplating ultra-light solar sails based on the emerging technology of carbon nanotube membranes, so that a clear understanding of the co-involvement of mechanical and thermodynamical laws is of the essence in designing such kinds of missions (cf. **Sections 3.4** and **4**).

2.1 Understanding the Physics of the Solar Sail

In an article published in the journal *New Scientist* (Parsons, 2003) some observations by Thomas Gold, Cornell University, are reported, according to which a solar sail could never fly for space missions because "*the proponents of solar sailing have forgotten about thermodynamics, the branch of physics governing heat transfer*". His remarks, that caused a public debate, met with well reasoned disagreements (Diedrich, 2003), and the way they can be soundly refuted, are listed below:

Remark 1: when photons are reflected by a perfect mirror, they do not suffer a drop in temperature. Now, solar sails are governed by Carnot's rule for heat engines. According to that rule, there must be a degradation of energy in any machine that turns out free energy. A mirror doesn't have any degradation. According to this scenario, Carnot's rule says some energy can be extracted, so long as the object absorbing light remains cooler than the radiation itself.

Confutation: Carnot's rule applies to cyclic transformations of closed systems only. The solar sail in itself, i.e. excluding its environment made up of the whole Universe, doesn't work as a cyclic system; to describe the situation as a phenomenon in a closed system, the system would consist of the solar sail plus the whole Universe, into which the solar sail reflects back the light it receives from the Sun. **Remark 1 is neglecting the rest of the Universe.** Moreover, it would be very questionable to apply thermodynamics to the whole Universe, the more that the thermodynamics at the initial conditions (the "Big Bang") are not known with certainty (equilibrium? far-from-equilibrium?) (Santoli, 2009; Layzer, 1975).

Remark 2: A black sail would absorb sunlight and the momentum associated with it until it reaches thermal equilibrium, when it would stop absorbing sunlight.

Confutation: That is false. **Once an object has reached thermal equilibrium, it does not stop absorbing light!** As it has been depicted in Fig. 4, the sail would continue to absorb light after reaching thermal equilibrium, and would radiate infrared light out of the front and the back surface as a **steady state process**. Indeed, at equilibrium the temperature of the sail stops changing, and the radiated power, **as shown in the diagram**, equals the absorbed power. Should the radiated power from the front side equal the radiative power from the back side, the thrust from the radiated power would become zero, and the sail would be acted upon by the thrust from the absorbed light in this steady state. The equation for ΔP as above depicts just a steady state condition.

Remark 3: Crookes's radiometer is an example of a failed test of light pressure from reflection of photons. This device consists of four paddles attached to the arms of a rotor, inside a vacuum jar. Each paddle is silvered on one side and coated with a black absorber on the other. When placed in the sunlight, the rotor spins. If the theory of solar sailing is right, the rotor should spin with the reflecting silver surface away from the light. And it actually spins, but the other way.

Confutation: in spite of the efforts carried out about 130 years ago by J.C. Maxwell and Osborne Reynolds who were able to explain how this device, developed by the eminent physicist Sir William Crookes for measuring radiant energy of heat and light, works, very often the first erroneous explanation by Crookes himself, or other descriptions before the correct one given by J.C. Maxwell, are quoted as correct. According to Crookes's paper, light radiation pressure on the black vanes was making the rotor spin. But soon J.C. Maxwell realized that this description was wrong. Indeed, light falling on the black side should be absorbed, while light falling on the silvered side of the vanes should be reflected. As a result, there would be twice as much radiation pressure on the metal side as on the black. Accordingly, the real rotor would work the wrong way! Indeed, **the physics of Sir William Crookes's radiometer, widely known as the light mill, has nothing to do with the physics of solar sail.** It was shown (Maxwell, 1879; Reynolds, 1879) that the phenomenon is caused by the very few molecules remaining after the jar is evacuated: the radiometer work is explained by the tangential forces exerted on the **edges** of the vanes by the molecules from the warmer side of each vane which are faster than the colder molecules from the colder

side. Light pressure can be correctly measured today in laboratories with proper setups. For instance, a thin fiber with vanes attached to it twists measurably when light strikes the vanes. Lasers and microwaves are used to test light pressure. And reality of light pressure was also tested in space, e.g. when the Mariner 10 mission to Mercury and Venus used solar arrays to steer itself when it ran low on propellant. The same was for the Messenger mission to Mercury: both missions demonstrated the use of solar pressure as a method of attitude control in order to save attitude control propellant. Recent discussions of the radiometer can also be found in the scientific literature (Heckenberg, 1996; Woodruff, 1968); cf. **Section 5**.

Remark 4: light cannot exert pressure because it is a scalar quantity, while Newtonian momentum is a vector.

Confutation: again this is wrong! Light is described by Maxwell equations which are vector equations. Photons are just individual packets of light waves, and their velocity is a vector given by the photon direction multiplied by the speed of light.

Remark 5: there is no degradation of energy in the reflection process on the mirror.

Confutation: this is false. Some photons are absorbed and the sail heats up to an equilibrium temperature. Moreover, photons reflected by the reflector of a solar sail undergo a Doppler shift: their wavelengths increase and energy decreases by a factor dependent on the velocity of the sail, so that energy is transferred from the **sun - photon** system to the **solar sail** system. This change of energy can be shown to be exactly equal and opposite to the energy change of the sail.

Thus, the principles of mechanics and thermodynamics are not broken in solar sailing theory. Thermodynamics of radiation is fundamental for describing solar sail astrodynamics, together with the laws of motion of Newtonian mechanics. This will be very clear in the astrodynamic study of missions based on carbon nanotube membrane monolayer sails discussed in Section 4.

3. Engineering the Concept – From the Heavy Sail to the Ultralight Carbon Nanotube Membrane *Mono-Layer* Sail Technology

The following sections deal with the sailmaking aspects as spaceship- and mission-independent features and as the very core of the spaceship conception. While a very good systematic approach to what can now be called “*classical sails*” can be found in Wright’s book (Wright, 1993), no source of design details can be found as to the first steps from the light all-metal sail as the objective of the **Aurora Project** (Santoli & Scaglione, 1996; Scaglione & Vulpetti, 1999; Vulpetti, 1996) toward a carbon nanotube membrane sail technology other than the very recent papers concerning this approach by myself and co-workers (Vulpetti et al., 2007; Vulpetti, 2009).

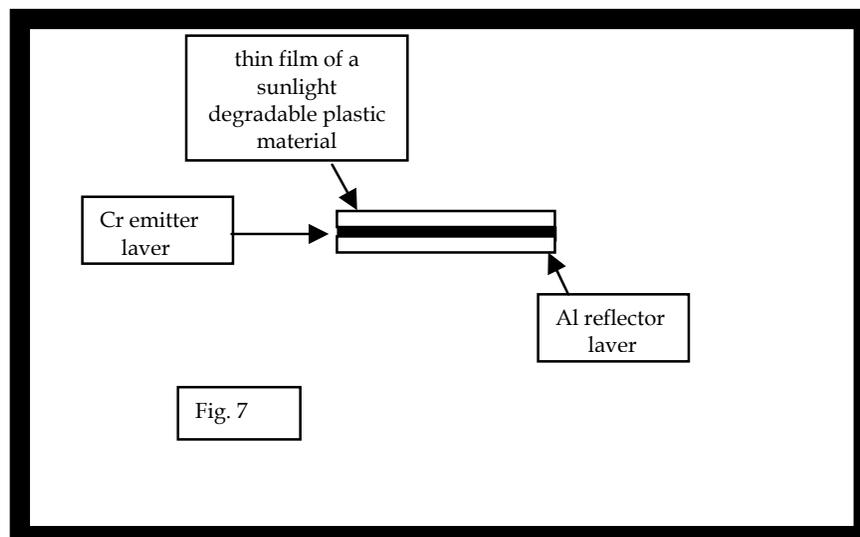
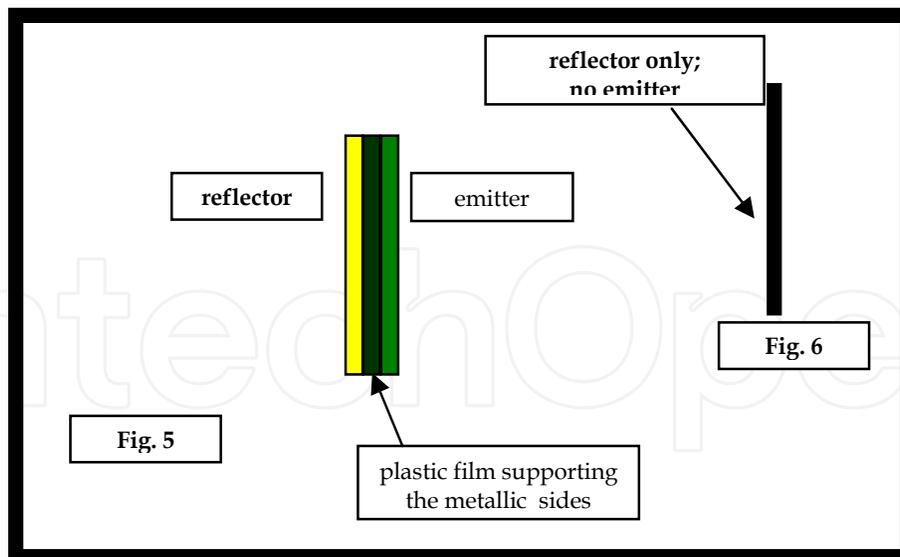
The **Aurora Project** was an Italian – British – Swiss collaboration that began in 1993 to study the general problems about an all-metal sailcraft undergoing the so-called orbital angular momentum reversal mode for fast photon solar sailing in space (Vulpetti, 1996a; 1996b). It was the very starting point and foothold for the development of the concept of the carbon nanotube membrane solar sails for even faster speeds by photonic propulsion. Accordingly, the following discussion, while illustrating some basic aspects of materials, sail shapes and support architecture engineering for a sailcraft, will reflect basically the conceptual pathway from the heavy sails contemplated in standard books to the novel concept of the ultralight

sail capable of exploiting photonic propulsion up to reaching cruise speeds whose values would be substantial fractions of the speed of light. Details concerning a design according to that novel concept are given in the case study discussed in **Section 4**.

3.1 Materials – Understanding Solar Sail Astrodynamics

In the standard design of a heavy sail, a substrate film typically provides the mechanical strength needed to carry the loads through the sail. The load will consist of the necessary structural supports for the sail not to billow too much under solar pressure – ribs, booms, masts – and of the payload – scientific instrumentation, material to be transported to other planets. Indeed, solar sails are considered as good candidates for future transportation of materials and people to other planets of the Solar System. The substrate film bears a metallic coating on each side: a reflecting and an emitter coating. An overcoating is usually put on the reflector to protect the same, e.g. aluminium, from oxidation and loss of reflectance. Elimination of the substrate film can be realized in the case of thin metallic sails, thickness about 100 nm, if the sail is manufactured in space and not subjected to folding and successive unfolding, the so-called deployment, as is the case of sails manufactured on the Earth. Deployment in Earth orbit or, better, at the first Lagrange point of the Earth – Moon system, i.e. at the point where no gravitation is experienced, is one of the biggest problems for solar sailing. A material capable of surely surviving this manoeuvre would be preferable; **the monolayer carbon nanotube membrane would support that stress better than a self-supporting all metal sail** (Santoli & Scaglione, 1996).

In the Aurora Project (Santoli & Scaglione, 1996; Scaglione & Vulpetti, 1998) the innovative concept was developed of an all-metal sail – Al as the reflector and Cr as the emitter – bearing a thin layer of plastic material on the Cr emitter layer in order to support the sail during deployment in an Earth orbit. The thin plastic film would have been removed when in orbit by the action of UV rays from the Sun, possibly with the previous addition to the plastic film of a sensitizer to make the removal complete and rapid, in order to get a much lighter sail to be launched to orbiting the sun where, at the perihelion, the manoeuvre of inversion of the angular momentum of the sail would accelerate the sail spaceship to speeds much higher than those possible for the heavy sail based on a plastic support. Fig. 5 and 6 depict the standard heavy sail and the reflector monolayer sail, whose validity depends on the thermal conditions during mission. Fig. 7 shows the Aurora Project concept design of the Al-Cr all metal sail reinforced with the plastic layer coated on the emitter side of the sail:



Very often the plastic film considered for the standard heavy sail with the film interposed between the reflector and the emitter was Kapton, a trademark of Du Pont, featuring good radiation and high temperature properties, capability of operating for years at 250°C, and availability at minimum thicknesses of 2 - 3 μm . Such thicknesses could be reduced by chemical etching or ion bombardment etching. Kapton's density is 1.42 g/cm². Mylar, a trade mark of Du Pont, showed very low resistance to UV radiation, so that it would be unsuitable for long-duration missions. The idea of a supporting plastic film to overcome problems with the deployment in an Earth orbit that was coated externally on the emitter surface, not in between the reflector and emitter layer, so giving the possibility of removing the plastic film before flying, was one of the key points of the Aurora Project, mentioned above as an innovative challenging technological and scientific objective. A possible method to get the Al/Cr bilayer free from the supporting plastic was found to be the **Plasma Chemical Vaporization Machining (PCVM)**, with removal, after deployment, by photodegradation that would not affect the quality of the underlying Cr surface. This problem of removal of the plastic support film by photolysis without damaging the Cr layer was further investigated with positive indications (Scaglione & Vulpetti, 1998).

An important parameter for understanding the astrodynamics of a solar sailship is the lightness number λ , which is defined as the characteristic acceleration, i.e. the rate at which the sailcraft would accelerate at Earth's distance from the Sun if the sailcraft were directly facing the Sun, divided by the gravitational acceleration of the Sun at Earth's distance from the Sun. Early heavy sail spacecraft were designed so as to have lightness number values substantially less than 1, but the aim of the Aurora Project was an advanced high-performance sailcraft that might reach λ 's greater than 1. Actually, lightness numbers between 0.5 and 1 could be obtained with the all-metals sail, with speeds after flybying the Sun between 60 and 80 km/s (Vulpetti, 1996; Santoli & Scaglione, 1996). But it was found (Vulpetti, 1998) that a different mathematical formalism, introducing the **lightness vector** (cf. the following section) would fully characterize the sailcraft dynamics instead of the classical equations of motion of the sail in the gravitational field; this formalism was particularly suitable to describe sailcraft motion with reversal of the orbital angular momentum and in the case of quite high lightness numbers allowing the all-metal sail to escape the solar system or to point to some distant object in the heliosphere, with velocities *somewhat* higher than the current record speed of missions beyond the planetary system, e.g. the Voyager-1 speed. This point, that leads to the astrodynamics of the extremely fast missions possible with the carbon nanotube membrane solar sails, will be discussed in a detailed way in the next section. The reader interested just in the material properties and the envisageable emerging technologies for further improvements in the performance of carbon nanotube membranes can skip this section and go directly to **Sections 3.4** and **4**.

3.2 The Astrodynamical Embodiment of the Fast Solar Sailing Concept

The introduction of very fast sailcraft technologies involves some changes in the astrodynamical mathematical formalism describing the sailcraft flight. This is of interest both for the all-metal light sail and mainly for the extremely fast carbon nanotube membrane solar sails (Vulpetti et al., 2008). For understanding the astrodynamics corresponding to any given mission and how the thermo-optical parameters of the sail membrane should be designed, the introduction of the concept of sailcraft lightness vector is to be carried out and two reference frames must be used.

3.2.1 The Reference Frames for the Solar Sail Flight Description and the Lightness Vector

DEFINITIONS:

- **Heliocentric Orbital Frame (HOF)**: the Cartesian reference frame with the origin in the sail center of gravity. In this reference frame, the x axis is the direction of the **Sun-to-sailcraft** position vector, the z axis is along the sailcraft orbital angular momentum, and the y axis forms with the x and z axis a counterclockwise reference frame
- **Heliocentric Inertial Frame (HIF)**: the inertial Cartesian reference frame centered in the Sun
- the azimuth α is the angle that the projection of the unit vector \mathbf{n} of sail orientation forms with the **HOF**
- the elevation δ is the angle that the projection of \mathbf{n} forms with the xy plane of **HOF**

Now, α and δ specify the sail orientation unit vector \mathbf{n} (already used in the description of the vector optics for the sail forces) in **HOE**, with $0 \leq \alpha < 360^\circ$ and $-90^\circ \leq \delta \leq 90^\circ$ and the following definitions can be given, irrespective of the material the sail is made up of:

$\lambda_r, \lambda_t, \lambda_n$ are the radial, the transversal, and the normal components of the **lightness vector**, $\mathbf{L} = [\lambda_r, \lambda_t, \lambda_n]$ (cf. the vectorial optics diagram of Fig.3), and any λ_r would be mathematically represented as a component of \mathbf{L} by $\lambda_r = |\mathbf{L}|$ as shown in the following.

APPLICATIONS:

The λ 's depend nonlinearly on α and δ , and linearly on the thermo-optical parameters of the sail material. They are the **key parameters** for rapidly studying, once the \mathbf{L} value of the sail (material and structure) and its components have been determined or set forth previously, the basic properties (circular orbiting; ability to escape through a hyperbolic orbit the Solar System toward a far point, acceleration and/or deceleration at given distances) of the sailcraft motion by computer programming of the equations for the motion of the sailcraft within the two reference frames defined above and, possibly, following the manoeuvre of reversing the angular momentum of the sailcraft (Vulpetti, 1999)

$$\alpha = 0, \delta = 0: [\lambda_r, 0, 0] = |\mathbf{L}| = \lambda_r$$

$$\alpha \neq 0, \delta = 0: [\lambda_r, \lambda_t, 0]$$

$$\alpha = 0, \delta \neq 0: [\lambda_r, 0, \lambda_n]$$

While these are key parameters, they are not the only quantities involved in determining the thrust acceleration of sailcraft motion, whose basic equations are made up of four basic units which are *nonlinear and not all separable*: **the effective solar pressure and gravitational acceleration, sailcraft sail loading, sail thermo-optical properties, and sail attitude**. The carbon nanotube membrane monolayer film solar sail concept stems just from a technology of merging the mechanical and thermo-optical properties of such membranes and the astrodynamics equations for any space mission, as discussed in **Sections 3.4 and 4**.

3.3 Structural Engineering – Sail Shapes and the Supporting Architectures

Generally the sail is square-shaped or round-shaped, or in the shape of a hexagon. The sail film must be kept taut under the action of the solar light pressure. Stiff structural members must hold the sail in position. A sail can carry only tension loads since the film material has no effective resistance to compression or bending. The supporting structure must provide the stiffness that the sail itself lacks. Indeed, it is not practical to have a sail that does not deflect, nor to have a design that can distribute loads completely even across the sail. The supporting structure of the sail – booms, masts, stays, tensioners etc. – will always undergo some deflection, and the sail will then experience both large scale and local deflections, respectively resulting in billowing and wrinkling. As to the sizing of the sail, its size is designed on the basis of two main factors: the mass of the payload to be carried, and the nature of the trajectory for the mission. Stated otherwise, the analysis of the trajectory from the point of departure to the destination for the designed trip time will yield the characteristic acceleration and then the lightness number or the lightness vector that is necessary for the mission.

While the general standard design principles for the shape, size and structural members can be found in the literature (Wright, 1993), the analysis of the structural engineering and materials designed for the innovative all-metal sail of the Aurora Project (Genta and Brusa, 1996; Santoli and Scaglione, 1996) will show the preliminary stress and deformations assessment for a fast sailcraft, as the immediate precursor of the extremely fast carbon nanotube solar sail, designed to escape the Solar System for sailing toward the interstellar space at very high speed. In the case of the Aurora Project, the stressing due to light pressure is well withstood by the metallic film, made up of a 0.2 μm reflective layer and 0.01 μm emissive layer, due to its high stiffness, but the film of a plastic material is needed for overcoming problems of storage and deployment. The sail, whose shape was square, was provided with a grid of thicker strips of Al foil for the back surface that would act as ripstops in case of punctures by micrometeoroids and as doublers to protect the thin zones which were in contact with the main structure. The sail is kept in position by a structure made of two booms along the diagonals and kept firm in position by a set of stay wires which were connected to two masts at the center of the square and perpendicular to the surface. The payload was located at the center of the spacecraft.

In operation, a sail is to be oriented to point the force in a useful direction. An attitude control system must be designed in order to execute a steering profile that will cause the sailcraft to follow a trajectory to its intended destination. The pressure is not uniform across a sail due to curvature in it. In addition to balancing the sailcraft, the control system must also control the pointing direction of the sailcraft by shifting the center of mass or the center of pressure on the sail. In the design for the Aurora Project, four ion thrusters were attached to the four corners to provide the attitude control.

3.4 From the Aurora Project to the Ultralight Carbon Nanotube Monolayer Film Concept

A real breakthrough in the field of carbon nanotube membranes as regards their application in a host of very different fields of practical commercial value but also of great importance for space technologies was the result of the study of a team of researchers. The paper with a detailed account of the techniques to obtain carbon nanotube sheets as multifunctional membranes appeared in the journal *Science* (Zhang et al., 2005). Macroscopic masses of individual carbon nanotubes assemblies could be produced at rates of 7 m/minute by cooperatively rotating carbon nanotubes in vertically oriented nanotube arrays – called usually “forests” in the nanotechnological community – such assemblies being in the shape of 5-cm-wide, meter-long transparent sheets. Such nanotube sheets were self-supporting and initially formed as highly anisotropic electronically conducting aerogels that could be densified into strong sheets that were so thin as 50 nanometers. It was very remarkable that the measured gravimetric strength of orthogonally oriented sheet arrays exceeds that of sheets of high-strength steel. Laboratory demonstrations for the microwave bonding of plastics and for making transparent, highly elastomeric electrodes, or planar sources of polarized broad-band radiation, flexible organic light-emitting diodes showed remarkable results for such carbon nanotube membranes.

The production process was quite different from the usual procedures for carbon nanotube sheets, that are made following the ancient art of paper-making, with a very slow filtration of carbon nanotubes dispersed in water followed by peeling the dried nanotubes as a layer from the filter; or according to some changes in this procedure as to the filtration rate by producing ultrathin nanotube sheets endowed with high transparency and high

conductivity. Sheets with partial nanotube alignment instead of isotropic sheets were produced by the application of high magnetic fields or by mechanical rubbing of those carbon nanotubes that are vertically trapped in filter pores. According to other techniques, nanotube sheets have been fabricated from nanotube aerogels, or by Langmuir-Blodgett deposition, or by casting from oleum, or by spin coating. The strong transparent and multifunctional carbon nanotube membranes by Mei Zhang and co-workers (Zhang et al., 2005) were produced by a solid-state process that for practical applications features its scalability for continuous high-rate production. Such membranes are highly oriented and they were produced by drawing them from a sidewall of multiwalled carbon nanotube (MWCNT) forests synthesized by catalytic chemical vapour deposition employing acetylene gas as the carbon source. The MWCNTs were about 10 nm in diameter, and the range of the investigated forest heights was from 70 to 300 nm. The membrane fabrication process was found to be robust, with no fundamental limitations as to the width and length of the membrane. The 5 cm membrane width obtained was equal to the forest width when the draw rate was 5 m/minute or lower. At constant draw rates above about 7 m/minute the membranes progressively narrowed, and MWCNT fibrils began to break at the intersection between the sheet sides and the forest.

The thickness of the MWCNT membrane increased with increasing forest height and was of about 18 μm in scanning electron microscopy (SEM) images of a membrane drawn from a 245 μm -high forest. From this thickness and the measured areal density of about 2.7 $\mu\text{g}/\text{cm}^2$ the volumetric density was calculated to be of 0.0015 g/cm^3 so that membranes produced were shown to be electronically conducting, highly anisotropic aerogels. These membranes were found to be very easily stackable, and they could support millimetre-sized liquid droplets that were 50,000 times more massive than the supporting membrane region in contact with the droplets. Such highly anisotropic membranes could be easily densified up to about 0.5 g/cm^3 and could be easily made into highly oriented membranes having thicknesses of about 50 nm. This 360-fold increase of density was obtained in a very simple way, i.e. by causing the membrane as it was produced to adhere to a planar substrate, e.g. glass, plastics, silicon, gold, copper, aluminium, steel, then vertically immersing the substrate bearing the attached MWCNT membrane in a liquid such as ethanol, along the nanotube alignment direction and then retracting the substrate from the liquid. The shrinking of the aerogel membrane down to thicknesses of about 50 nm was the result of surface tensions during ethanol evaporation. It is remarkable that the collapse of a membrane of about 20 μm down to about 50 nm without changes in lateral membrane dimensions means that the out-of-plane deviations in nanotube orientation become in-plane deviations that are noticeable in the SEM micrographs. The aerogel membranes can be effectively glued to a substrate by contacting selected regions with ethanol, and then allowing evaporation to densify the aerogel membrane. Adhesion increases because the collapse of aerogel thickness increases the contact area between the nanotubes and the substrate.

The membrane resistance in the draw direction was found to change by less than 10% upon densification by a factor of about 360, with an increase in the membrane transparency. The temperature dependence of the membrane resistivity was nearly the same for the forest-drawn densified nanotube membranes and for sheets made from the usual filtration method using the same forest-grown MWCNTs. The study of the electronic and optical properties of such membranes showed that the membrane resistance as measured in vacuum with the as-

drawn MWCNT membranes has a much lower temperature dependence of electrical conductivity than does an isotropic SWCNT membrane obtained by the standard filtration process. Optical transmittance as a function of wavelength was also determined for a single MWCNT membrane before and after densification, for polarized light perpendicular to the draw direction and parallel to said direction, and for unpolarized light. The densified nanotube membranes showed high values of transparency in combination with useful electrical conductivity; this is a combination that would be needed for such applications as displays, video recorders, solar cells, and solid-state lighting. The transmittance for densified MWCNT membrane was higher than 85% for perpendicular polarization, higher than 65% for parallel polarization between 400 nm and 2 μm , and higher than 85% for unpolarized radiation between 1.5 and 10 μm . These MWCNT membranes would adhere to transparencies made of poly(ethylene terephthalate) as well as to silicone rubber sheets, thereby providing transparent bilayer composites that could be bent in any direction without causing a substantial decrease in electrical conductivity, which would make them useful for a number of applications of flexible electronics.

The mechanical properties of such aerogel-like and densified MWCNT membranes showed unexpectedly high. It is remarkable to observe that the density-normalized mechanical strength could be much more accurately determined than mechanical strength, due to the fact that the membrane thickness could be less reliably measured than the ratio of the maximum force to mass-per-length in the stretch direction. Stacks of undensified membranes showed a tensile strength of between 120 and 144 MPa/(g/cm³), and a densified stack containing 18 identically oriented membrane layers had a strength of 465 MPa/(g/cm³), a value that decreased to 175 MPa/(g/cm³) when neighboring layers in the stack were orthogonally oriented to make a densified biaxial structure. Such density-normalized strengths were already comparable to or greater than the value of about 160 MPa/(g/cm³) of the strength of the Mylar and Kapton films used for ultralight spacecraft and proposed for use in solar sailing and of those for ultra-high-strength steel (about 125 MPa/(g/cm³)) and aluminium alloy (250 MPa/(g/cm³)) sheets.

As a nanotechnologist applied to space mission studies and belonging to the group for the Aurora Project, I was attracted by this paper in which the novel solid-state procedure for obtaining MWCNT membranes was described. Indeed, the details that I have selected and stressed above showed me clearly that such multifunctional membranes might be useful, with proper adaptation, to solve our problem of a solar sail even much lighter, and then much speedier, than the all-metal thin sail we had designed for the Aurora Project. My suggestion to the other members of the group was considered very carefully, and the idea of a preliminary technological study for the feasibility of a monolayer, ultra-light solar sail capable of exploiting the orbital angular momentum reversal manoeuvre fully (Vulpetti, 1996b) and reaching extrasolar system targets was conceived (Vulpetti, Santoli and Mocci, 2007). It was quite soon clear that speeds up to a substantial fraction the speed of light could have been obtained by properly adapting the multifunctional MWCNT membrane produced in the mentioned paper, where the membrane produced was mainly devoted to commercial applications where transparency was the basic requisite. The essentials of the preliminary investigation for such a kind of photon solar sail are presented in **Section 4** as a case study for the development of MWCNT membranes of such type for solar sail-propelled spacecraft.

4. A Case Study – Flying at 0.001•c and Beyond

The thrust acceleration equation of sailcraft motion consists of four basic blocks that are not all separable. They are: 1) effective solar pressure and solar gravitational acceleration; 2) sailcraft sail loading; 3) the sail thermo-optical quantities; 4) the sail attitude. The first block is outside our control; the second block is the only one that can cause the speed of sailcraft to make a jump, in the sense of the lightness number jump in a mission to extrasolar system targets designed on the basis of a MWCNT membrane whose reflectivity would have been tailored properly, according to the nanotechnological developments envisaged in our group (Vulpetti, Santoli and Mocci, 2007) and discussed here and in **Section 3**. Thermo-optical quantities and sailcraft attitude can give the thrust, whose vector control can be realized **if and only if** the total reflectance of the sail is positive. Putting all in all, for a leap forward as to speed of our sailcraft design according to the Aurora Project, we were confronted with the problem of finding a material of ultra-low density, sufficiently reflective to sunlight, structurally very strong, of low absorption and – a necessary condition for the telecommunication system with the basis on Earth – microwave transparent. Both the Aurora Project all-metal sail and any other metal sail or conventional semiconductor sailcraft had to be excluded. The only envisageable perspective was to consider the possibility of tailoring to such conditions the MWCNT membranes mentioned above. Their multifunctional capabilities with possibility of changes in their basic properties by changing their microscopic structures and/or their production procedures looked like pointing out a concrete way toward a material satisfying the following goals: 1) possibility of manufacturing monolayer sails on the ground; 2) possibility of safe deployment in space; 3) possibility of building a flat sail with such membrane; 4) possibility of realizing a big sail (it is quite normal for instance to build square sails with 250 m side); 5) possibility of increasing the insufficient reflectivity of the membranes as produced (Zhang et al., 2005) up to values about 70 – 80% reflectivity in a wide range of sunlight spectrum; and 6) possibility of obtaining very high lightness numbers. The astrodynamics equations for such sailcraft showed that cruising speeds could be reached of values higher than 300 km/s.

There were no big problems as to tailoring the original properties of the membranes to the requisites for employment as a sailcraft reflective material as the mechanical parameters and the capability of standing very high temperatures were concerned: the tensile strengths mentioned in **Section 3.4** were much higher than the tensile strengths of Kapton and other plastic materials that were considered for standard heavy sails, and temperatures up to incandescence of the MWCNT membranes could be reached without damage to the membrane properties. The real problem was to increase the electrical conductivity, i.e. the metallic character, of the MWCNTs in the membrane structures so as to have a sufficient value of reflectivity; moreover, the membrane should have been transparent or essentially transparent (zero reflectivity and zero absorbance) to microwaves in the band employed for telecommunication, in order to avoid complicated sail architectures, as for instance holes for letting communication signals pass.

It is known that MWCNTs can have a metallic character; however, procedures for synthesizing such carbon nanotubes produce generally mixtures of metallic and non-metallic MWCNTs. Mixtures of MWCNTs and SWCNTs are also produced. Recently (Dresselhaus, 2004; Burke, Rutherglen and Yu, 2006; Gregorczyk et al., 2006; Wang et al., 2004) it has been shown that metallic MWCNTs as random or regular arrays are so reflective that they can be used as optical nanoantennas. Indeed, such effect can be predicted

theoretically; however practical experimentations (Wang et al., 2004; Gregorczyk et al., 2006) have shown that complex optical responses can be obtained from periodic and nonperiodic arrays of MWCNTs as a result of controlling the geometry and spacing of the arrays, so that it is possible to create structures that respond very strongly to specific wavelengths or bands of wavelength. Finely tuned detectors that can respond to predetermined wavelength bands ranging from the ultraviolet to the infrared region.

In our further investigation, it was found that: 1) it was possible, by controlling the arrays geometry and spacing, to build membrane microscopic structures that could respond very strongly to specific wavelengths of solar light with a high efficiency of solar reception and re-radiation. This was possible because metallic MWCNTs act as molecular one-dimensional wires endowed with high conductance leading to current densities as high as 10^9 A/mm². For them, the concept of skin depth of the incoming wave of light has no practical meaning, because the wire is physically one-dimensional, i.e. electrons have no possibility of motion normal to the axis of the MWCNTs; 2) by controlling the length of the MWCNT it was possible to obtain a desirable reflectance for (useful) wavelengths of 50 nm and 20 μ m, while telecommunication microwaves could pass unabsorbed or reflected; 3) as the membranes are aerogels, it can be shown that their specific strength can be adjusted independently of the optical properties of the membrane.

Accordingly, any roadmap to MWCNT membrane solar sailcraft should start from the problem in Nanophotonics of obtaining massive amounts of pure metallic MWCNTs and of sizing their lengths properly for a controlled reflectance of the membranes obtained by the solid-state procedure discussed above.

5. Appendix – A Recent Accurate Procedure Demonstrating Light Pressure

It was in 2000 that the first experiment was carried out (Myrabo et al., 2000) devoted to measuring laser photonic thrust performance with real candidate sail materials. Such experiments show the validity of solar sailing theory against the objections reported above (**Section 2.1**). The experimental study was concerned with laser-beam pushed sails, which entail very different problems from solar sailing; it is anyway a good proof of principle. The test articles were 5-cm diameter laser sail discs fabricated from an ultralight carbon microtruss fabric that was sputter-coated with molybdenum on one side only, to improve its reflectivity to laser radiation of 10.6 μ m, and four laser sail discs with three different areal densities (6.6 g/m², 27 g/m², and 28 g/m²) were tested as magnetically supported pendulums with an overall length of 10 cm. Pendulum deflections for the heavier sails ranged from 2.4 to 11.4 degrees, as a function of a continuous wave laser power from 7.9 to 13.9 kW. The sails masses were 83.7, 87.3 and 88 mg each; their center of mass was at 11.5, 11.7, and 11.9 cm respectively below the magnetic bearing. Laser photon thrust ranged from 3.0 to 13.8 dynes. These values were calculated from the pendulum deflections. The vacuum chamber employed was 2.74 m long with a diameter of 2.13 m, which was evacuated to about 36 - 44 μ Torr. The range of 3.3 - 6.67 N/GW showed to be feasible for sailcraft propulsion by laser beam.

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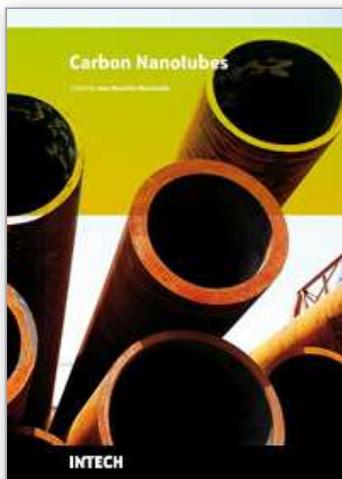
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This book has been outlined as follows: A review on the literature and increasing research interests in the field of carbon nanotubes. Fabrication techniques followed by an analysis on the physical properties of carbon nanotubes. The device physics of implemented carbon nanotubes applications along with proposed models in an effort to describe their behavior in circuits and interconnects. And ultimately, the book pursues a significant amount of work in applications of carbon nanotubes in sensors, nanoparticles and nanostructures, and biotechnology. Readers of this book should have a strong background on physical electronics and semiconductor device physics. Philanthropists and readers with strong background in quantum transport physics and semiconductors materials could definitely benefit from the results presented in the chapters of this book. Especially, those with research interests in the areas of nanoparticles and nanotechnology.

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