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GRAPHENE: THE ULTIMATE INTERSTELLAR SOLAR SAIL MATERIAL?

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Graphene (a carbon molecular monolayer) is a wonder material of great interest to materials researchers. Its molecular-layer thickness, finite fractional absorption, high melting point, and impermeability to gases coupled with the fact that doped materials, additives and multiple layers increase both fractional absorption and reflectivity indicates that it may be a superior material for application in solar-photon sailing. This paper first reviews relevant graphene physical and optical properties and then investigates the kinematics of interstellar solar sails constructed using this material. Two sail configurations are considered: thin-film probes and hollow-bodies sails. It is shown that graphene sail performance may be superior to that of beryllium sails. Less intense perihelion passes and accelerations may allow transit times to Alpha Centauri approximating a millennium. Future research should consider the interaction of graphene sails with the space environment and large-scale fabrication techniques.

Keywords: Solar sailing, graphene, interstellar travel

1. INTRODUCTION: SOLAR-PHOTON SAILING AS A STAR TRAVEL OPTION

The solar-photon sail (more commonly referred to as the solar sail) is pushed through space by the pressure of solar photons and has emerged as a possible option for the propulsion of long-duration extrasolar and interstellar exploration and colonization missions. For such an application, the sail must be as thin, highly reflective, temperature tolerant and space-environment resistant as possible. To achieve solar-system exit velocities allowing 1,000-2,000 year transit times to the nearest stars (Alpha Centauri A/B and Proxima Centauri at 4.3 light years), sails must be unfurled as close to the Sun as possible [1].

Four sail configurations might be considered for such ventures: flat sails with instrumentation deposited on the anti-Sun-facing side like Robert Forward's "Starwisp" might be suitable for robotic probes [2]; parachute sails, hollow-body (or "pillow") sails or hoop sails have been suggested for more elaborate inhabited ventures [3-6].

Two advantages of the solar sail for interstellar propulsion are that the sail can be used for both acceleration and deceleration if the destination is a Sun-like star and the sail and associated structure can be wound around the habitat en route to serve as additional shielding against galactic cosmic radiation [7].

To date, the most studied material for interstellar solar sailing is beryllium [8]. A hollow-body beryllium sail with a ~40-nm thickness deployed from a solar parabolic orbit with a perihelion of around 0.07 AU seems capable of projecting large payloads on interstellar transits of about 0.002c, which implies a ~2,000 year transit time for a voyage to Alpha Centauri. Space-environment interactions might preclude tighter perihelion passes and thinner sails [9].

But it is unlikely that beryllium represents the ultimate solar sail material. Graphene, a mono-molecular lattice of carbon atoms, has received a great deal of recent attention from materials experts and condensed matter physicists. This paper investigates the possible utility of this material for application to both thin-film probes and hollow-body sails propelling inhabited starships.

2. GRAPHENE PHYSICAL AND OPTICAL CHARACTERISTICS

It has been reported that the thickness of a pure graphene monolayer is about 0.335 nm [10]. The theoretical areal mass thickness of a graphene monolayer is 7.4×10^{-7} kg/m^2 [10].

Investigations have been performed of gas diffusion through graphene membrane monolayers. Surprisingly, these membranes are impermeable to many gases, including helium [10]. Low diffusion of gases through graphene monolayer membranes is of special interest to designers of hollow body solar sails, which require fill gases [5,8]. Fill gases absorbed by the graphene may increase graphene monolayer areal mass thickness by ~30% [10].

Another advantage of graphene for solar sail applications is the extraordinary strength of this material. Changgu Lee and colleagues have measured the intrinsic strength of monolayer graphene as 130 GPa [11]. A graphene monolayer's tensile strength is about 200× that of steel [12].

The fractional reflectance of a graphene monolayer across the visible spectrum is about 0.05 if alkali metal atoms are intercalated with the graphene [13]. Pure graphene monolayers have essentially invisible (zero reflectivity), unless deposited on an appropriate substrate [14]. Fractional absorption of a graphene monolayer has also been determined to be about 0.023 in the visible spectral range [15].

In a recent paper, Arturo Grappone pointed out that the fractional absorption of graphene can be greatly improved by constructing a two-layer structure consisting of graphene and molybdenite. Fractional absorptions of 0.37 seem to be possible using this approach [16]. A paper by S.P. Apell, G.W. Hanson and C. Hagglund suggests that sandwiching graphene between two appropriate layers can raise fractional absorption of graphene above 50% [15].

3. SAIL KINEMATICS

Although equations have been derived for the case of interstellar sail deployment at the perihelion of an elliptical or hyperbolic solar orbit [17, 3, 4], we here consider the simpler case of sail deployment from a parabolic solar orbit. Since graphene is a non-opaque thin film, we replace the factor (1+R) with (A+ 2R) in the sail kinematics equations, where A and R respectively represent fractional absorption and reflectivity, as discussed on p.93 of Ref. [1].

The spacecraft could be maneuvered into its initial parabolic solar orbit with the aid of a Jupiter gravity assist [3, 4]. Alternatively the sail could be unfurled early in the mission and solar radiation pressure could be applied to achieve this trajectory [18].

To simplify calculations, it is assumed that the sail is always oriented normal to the Sun in the post-perihelion acceleration phase. However, altering and optimizing this solar aspect angle may have kinematical advantages [1, 19].

One significant parameter in the evaluation of solar sail performance is the lightness factor η, which is the ratio of solar radiation pressure force on the sail to solar gravitational force [1, 17]. We modify Eq. (4.19) of Ref. 1 to correct for the fact that the Solar Constant is close to 1,366 W/m^2 [19] rather than 1,400 W/m^2 and replace (1+R) by (A+2R) to obtain:

$$\eta = 7.68X10^{-4}\left(\frac{A+2R}{\sigma_{s/c}}\right) \tag{1}$$

In Eq. (1), $\sigma_{s/c}$ is the areal mass thickness of the spacecraft.

For the case of a sail oriented normal to the Sun that is unfurled at the perihelion of a parabolic solar orbit, we apply Eq. (4.27) of Ref. 1. This result allows us to estimate interstellar cruise velocity relative to the Sun, V_{fin}:

$$V_{fin} \approx \eta^{1/2} V_{pp} \tag{2}$$

where V_{pp} is the solar escape or parabolic velocity at perihelion. The Earth orbits the Sun in a nearly circular orbit at a mean velocity of 29.79 km/s [20]. The solar escape velocity at 1 AU from the Sun is therefore 42.1 km/s. If we substitute Eq. (1) into Eq. (2) and apply the definition of escape velocity, we obtain:

$$V_{fin} \approx 1.167\sqrt{\frac{(A+2R)}{D_{au}\sigma_{s/c}}}\ \text{km/s} \tag{3}$$

where D_{au} is the perihelion distance from the Sun's center in astronomical units and $\sigma_{s/c}$ is the areal mass thickness of the spacecraft in kilograms per square meter.

It is easy to show that solar gravitational acceleration at 1 AU is 6.04 × 10^{-4} g. Peak solar-radiation-pressure acceleration on the spacecraft at perihelion will therefore be:

$$ACC_{peri} = 6.04X10^{-4}\frac{\eta}{D_{au}^2}\ \text{g} \tag{4}$$

4. THERMAL AND STRESS APPROXIMATION

Graphene is a partially transparent substance. As such consideration of its thermal properties requires special attention. We here follow a similar analytical strategy to that applied in Ref. [21].

First, we recall that for any substance,

$$A + R + T = 1 \tag{5}$$

where A, R, and T are respectively fractional optical absorption, reflectance and transmission of the substance. For any partially transparent substance, emissivity can be defined [1, 21, 22]:

$$\varepsilon = \frac{(1-T)(1-R)}{1-TR} \tag{6}$$

In Ref. [21], T and R in Eq. (5) were wavelength-averaged with the blackbody curve approximating the radiation temperature of beryllium and aluminum solar sails thinner than 30 nm. Because graphene is a very new designer substance and is still a subject of intense research, we here treat A, R, and T as wavelength independent.

Recalling that the Solar Constant is close to 1366 W/m^2 and that the sail is fully unfurled at perihelion and is always oriented normal to the Sun, Eq. (4.21) of Ref. [1] is modified to obtain perihelion sail temperature:

$$T_{peri} \approx 331\left(\frac{A}{\varepsilon D_{au}^2}\right)^{1/4}\ \text{K} \tag{7}$$

Stress will be handled in a conservative fashion. Even though pure graphene appears to be the strongest known substance, experiments must ultimately demonstrate how absorbed infill gas and intercalated alkali metal atoms will affect the tensile strength of a graphene monolayer. Accordingly, stress on the sail during acceleration will be orders of magnitude below the maximum tensile strength of graphene. Therefore,

$$STRESS = \sigma_{pay} ACC_{peri} << 1.30 \times 10^{11}\ \text{Pa} \tag{8}$$

where acceleration is expressed in MKS units and σ_{pay} is payload (and non-sail structure) areal mass thickness. As will be discussed, stress should pose no difficulty for the scenarios considered.

5. MISSION SCENARIOS

We consider several alternative graphene sail concepts. The first is a pure graphene monolayer facing the Sun with a thin-film payload deposited on the anti-Sunward face.

5.1 Scenario 1: A Starwisp Variant

Initially proposed by Forward [2] following an unpublished suggestion by Freeman Dyson and further investigated by Landis [23], Starwisp-type interstellar probes would consist of a thin film payload deposited on one side of a photon sail. If accelerated by a Sun-pumped maser [2] or laser [23], the craft might be capable of high acceleration and interstellar cruise velocities. Here we consider a Starwisp-variant accelerated by solar electromagnetic radiation pressure.

As shown in Fig. 1(A), the graphene sail pushes against the thin-film payload deposited upon it (possibly as a mesh or ribbon arrangement). We consider an arbitrary disc sail radius of 2 km and a payload structure mass of 5 kg. The sail mass is 9.3 kg and the spacecraft areal mass thickness is 1.14×10^{-6} kg/m^2.

Since the reflectivity of pure graphene is assumed to be nil and the fractional absorption is 0.023, Eq. (1) is applied to calculate the lightness factor to be 15.5. Using Eq. (3), the interstellar cruise velocity is 524 km/s, starting from a 0.1-AU-perihelion solar parabolic orbit and 627 km/s starting from a 0.07-AU-perihelion solar parabolic orbit.

From Eq. (4), the peak acceleration for the 0.1-AU perihelion case is 0.94 g. The maximum acceleration for the 0.07-AU perihelion case is 1.91 g.

Sail emissivity is 0.023 from Eq. (6). From Eq. (7), the perihelion temperatures for the 0.1-AU perihelion and 0.07-AU perihelion cases are 1047 K and 1251 K. Peak stress during the solar acceleration phase is many orders of magnitude less than graphene's enormous tensile strength.

These results and those of the following scenarios are summarized in Table 1.

5.2 Scenario 2: A Hollow-Body Interstellar Probe

Figure 1(B) presents the configuration of the next two scenarios. This is a hollow-body or pillow sail with the hydrogen fill gas of Refs. [5 & 8] replaced by helium. The anti-Sun sail face is a graphene monolayer with its areal mass thickness increased to 10^{-6} kg/m^2 by absorbed fill gas. The Sun-facing sail face is composed of graphene superimposed between two appropriate monolayers to increase fractional absorption of sunlight to 0.4. Alkali atoms are intercalated with the outer monolayer on the Sun-facing sail face to increase sail fractional reflectivity to 0.05. The areal mass thickness of the Sun-facing sail face is assumed to be 4×10^{-6} kg/m^2. The sail therefore has a total areal mass thickness of 5×10^{-6} kg/m^2.

The factor (A+2R) is 0.5 and the fractional transmission of sunlight is 0.55. We assume a sail radius of 1 km, which implies a sail mass of 15.7 kg. The assumed payload (and non-sail structure) mass is 9.3 kg, the total spacecraft mass is 25 kg and the areal mass thickness of the spacecraft is 8.0×10^{-6} kg/m^2.

From Eq. (1), we calculate the lightness factor to be an enormous 48! If deployed at the perihelion of a 0.2-AU-perihelion parabolic solar orbit, the sail exits the solar system at 652 km/s. If the sail is deployed at the perihelion of a 0.1-AU-perihelion parabolic solar orbit, it departs at 922 km/s.

Applying Eq. (4), peak acceleration at the 0.2 AU perihelion is 0.73 g. Peak acceleration at the 0.1 AU perihelion is 2.9 g.

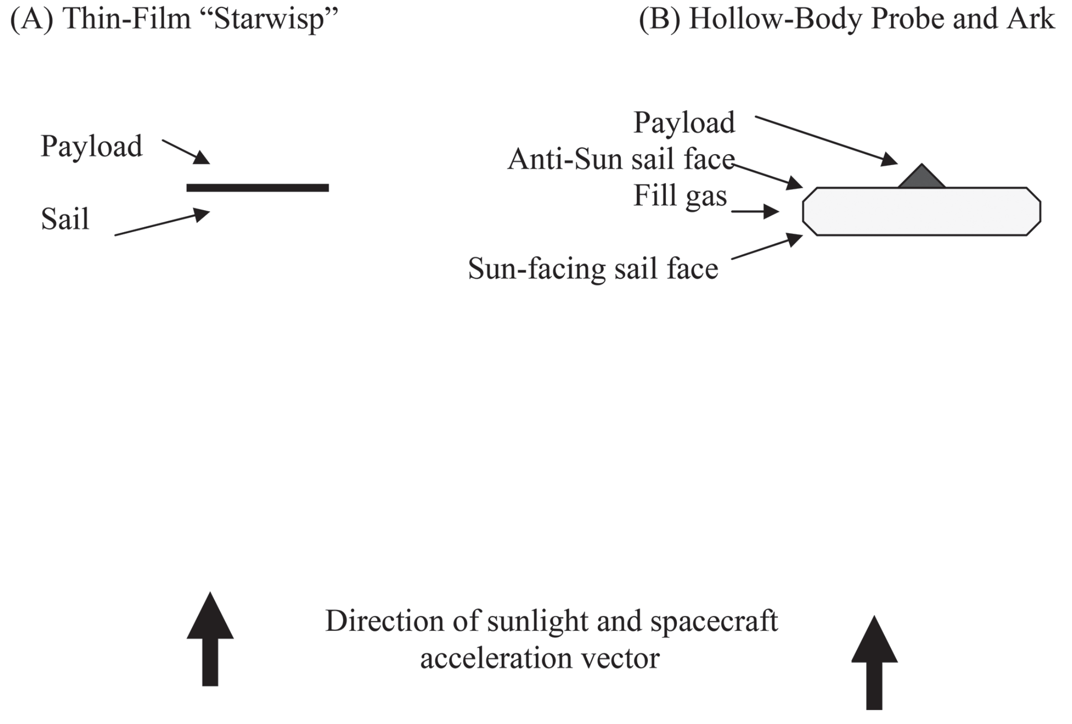
From Eq. (6), the emissivity of this sail is 0.44. Applying Eq. (7), the peak sail temperature at 0.1 AU is 1021 K. The maximum stress on the sail caused by its contact with the payload at 0.1 AU is, once again, far below the tensile limits of graphene.

5.3 Scenario 3: An Interstellar Ark

We consider a 5×10^6 kg payload, which might be required for a small interstellar ark [24]. If this vehicle has the same performance as the craft in Scenario 2 and the sail is composed of the same material, the sail radius is 733 km.

This craft departs the solar system at 0.00307c. It reaches

Fig. 1 Graphene solar-photon sail configurations.


(A) Thin-Film "Starwisp"

(B) Hollow-Body Probe and Ark

TABLE 1: *Graphene Sail Scenario Summary*.

Scenario	Disc Sail Properties					Payload Mass	σ_{sc}	D_{au}	ACC_{max}	T_{max}	V_{fin}
	Radius	Mass	R	A	ε						
1. Starwisp	2 km	9.3 kg	0	0.023	0.023	5 kg	1.14E-6 kg/m^2	0.1 AU	0.94 g	1047 K	524 km/s
								0.07	1.91	1251	627
2. Probe	1	15.7	0.05	0.40	0.44	9.3	8.0E-6	0.2	0.73	722	652
								0.1	2.9	1021	922
3. Ark	733	8,44E6	0.05	0.40	0.44	5E6	8.0E-6	0.2	0.73	722	652
								0.1	2.9	1021	922

the Alpha Centauri system in about 1,400 years, in about two-thirds the time required by the beryllium hollow-body sail in Ref. [8].

All peak perihelion temperatures listed for these three scenarios in Table 1 and above are far below the reported melting point for graphene [25].

8. CONCLUSIONS

Graphene appears to be a superior solar-photon-sail material. It has a very low areal mass thickness, is relatively impermeable to sail fill gases and his a non-zero fractional absorption. With additional layers and additives, the fractional reflectance can be as high as 0.05 and the fractional absorption can approximate 0.5.

In its application to interstellar solar sailing, it seems that graphene can exceed the performance of beryllium with less extreme perihelion requirements, peak temperatures and maximum accelerations. Thousand-year transits to Alpha Centauri do not seem out of the question for probes and generation ships using this mode of acceleration and deceleration.

One might argue that graphene remains a laboratory curiosity because of difficulty of large-scale preparation. Some research, however, has addressed methods of preparing bulk-quantities of high-purity graphene [26].

Much research is required to accurately assess the viability of graphene in this application. Of particular significance is the interaction of the space environment with a graphene sail during a close solar pass, following the logic of the previous analysis for beryllium sails [9].

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