Acta Astronautica 129 (2016) 316–324

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/aa

Project Dragonfly: A feasibility study of interstellar travel using laser-powered light sail propulsion

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ARTICLE INFO

Keywords:
Interstellar travel
Light sail
Laser
Mission analysis

ABSTRACT

Light sail-based propulsion systems are a candidate technology for interplanetary and interstellar missions due to their flexibility and the fact that no fuel has to be carried along. In 2014, the Initiative for Interstellar Studies (i4is) hosted the Project Dragonfly Design Competition, which aimed at assessing the feasibility of sending an interstellar probe propelled by a laser-powered light sail to another star system. We analyzed and designed a mission to the Alpha Centauri system, with the objective to carry out science operations at the destination. Based on a comprehensive evaluation of currently available technologies and possible locations, we selected a lunar architecture for the laser system. It combines the advantages of surface- and space-based systems, as it requires no station keeping and suffers no atmospheric losses. We chose a graphene-based sandwich material for the light sail because of its low density. Deceleration of the spacecraft sufficient for science operations at the target system is achieved using both magnetic and electric sails. Applying these assumptions in a simulation leads to the conclusion that 250 kg of scientific payload can be sent to Alpha Centauri within the Project Dragonfly Design Competition's constraints of 100 year travel duration and 100 GW laser beam power. This is only sufficient to fulfill parts of the identified scientific objectives, and therefore renders the usefulness of such a mission questionable. A better sail material or higher laser power would improve the acceleration behavior, an increase in the mission time would allow for larger spacecraft masses.

1. Introduction

The long distances associated with interstellar travel prohibit the use of conventional chemical or electric propulsion systems due to the extremely large propellant masses required. More advanced propulsion methods have been suggested to overcome this barrier. They aim to limit the propellant mass carried on board by achieving very high specific impulses, thus enabling shorter trip durations. Notable mission design examples use fusion-based propulsion [1] or propellant-less methods such as large light sails [2,3]. In 2014, the Initiative for Interstellar Studies (i4is) hosted the Dragonfly Design Competition. Participants were asked to design an unmanned probe that would be capable of flying to a nearby star system, and assess the technical feasibility and scientific value of such an endeavor. The spacecraft was to be equipped with a light sail as its primary means of propulsion. A powerful laser system placed somewhere in the Solar System constitutes the required light source. The competition requirements formulated by i4is were [4]:

1. To design an unmanned interstellar mission that is capable of delivering useful scientific data about the Alpha Centauri system, associated planetary bodies, its solar environment, and the interstellar medium.
2. The spacecraft shall use current or near-future technology.
3. The Alpha Centauri system shall be reached within a century of the probe's launch.
4. The spacecraft propulsion for acceleration shall be mainly light sail-based.
5. The mission shall maximize encounter time at the destination.
6. The laser beam power shall not exceed 100 GW.
7. The laser infrastructure shall be based on existing concepts for solar power satellites.
8. The mission design should allow missions to a variety of target stars within a 10-light-year radius.

We studied the laser system used for accelerating the probe. Its positioning properties are discussed in Section 2. Candidate sail

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http://dx.doi.org/10.1016/j.actaastro.2016.09.030
Received 9 June 2016; Accepted 28 September 2016
Available online 30 September 2016
0094-5765/

materials and their design characteristics are discussed in Section 3.

The mission analysis was separated into the three distinct phases—acceleration, cruising, and deceleration—as described in Section 4. The analysis of the design was carried out according to the simulation model presented in Section 5. The results of the mission analysis and the final spacecraft design are outlined in Sections 6 and Sections 7, respectively. For the design, we assessed the feasibility of building a small interstellar probe based on current or soon-to-be available technologies. One of the mission requirements defined by i4is is the collection of scientifically valuable data. Maximizing the number of instruments that can be incorporated into the spacecraft has a direct impact on the scientific value of such a mission. We discuss the required instrumentation and current trends for miniaturization briefly in Section 8. Finally, concluding remarks on the scientific reward and the feasibility of the mission are presented in Section 9.

2. Laser system and optics

Due to the requirement of focusing extreme amounts of energy (up to hundreds of GW) over large distances, the laser system used for the acceleration phase is one of the main challenges for the Dragonfly mission. The first concern is the placement of the laser, with several options available. For our study, we assumed that the laser is to remain either in a stable orbit or on a planetary surface to allow reuse after the mission either for additional probes or for other purposes. This should help to justify the enormous costs for building such a system. The Alpha Centauri system has an inclination of −60° [5] and is hence visible in latitudes smaller than 30° South. While construction and energy resources are readily available on Earth's surface—even near the South Pole where an Alpha Centauri-facing laser would need to be built—the losses and pointing disturbances encountered while traversing the atmosphere mandate laser placement in space. A laser system orbiting Earth or the Sun would need to constantly maintain its orbit against the recoil caused by the emitted beam, requiring a powerful propulsion system and additional energy sources. For these reasons, we propose to position the laser on the Moon. Assuming development of lunar infrastructure takes place until the time frame of the Dragonfly mission, the construction of large lunar structures should be possible. The required location near the Moon's south pole also enables energy production via perpetually lit solar arrays.

While high-power scientific lasers in the desired 100 GW range are available, they are solely pulsed lasers. For the Dragonfly mission, a continuous wave (CW) laser would be required in order to reduce loads on the sail. It would be very desirable to find a different application for high-powered CW lasers in order to utilize synergy effects. The most promising option seem to be MW-class military laser systems. These lasers could be assembled into very large arrays. By the time the Dragonfly mission is supposed to be launched, CW lasers in the MW range should be mass-producible in relatively small form factors with very rugged designs based on military requirements. These properties will allow the installation of GW-class laser arrays without extensive adaption. The free-electron lasers currently being developed for military applications only require electric energy, without any additional medium to be refreshed (as is the case for chemical lasers).

Depending on the mission parameters, focusing distances up to several light years may be necessary. This requires an optical system focusing the laser beam onto the sail of the accelerating probe. Forward [2] proposed a Fresnel zone lens, which would have a diameter of hundreds to thousands of kilometers at the desired light frequencies and focal distances. Unfortunately, building this lens anywhere near a celestial body would likely cause it to be torn apart by gravitational gradients, and building and positioning such a large structure far away from any planets or stars was dismissed because of the associated effort and cost. In addition, extremely accurate pointing down to 10^{-12} rad, several orders of magnitude better than the capabilities of current space telescopes, is required to keep the beam focused on the probe over such long distances. This seems very difficult for a large and not very stiff structure.

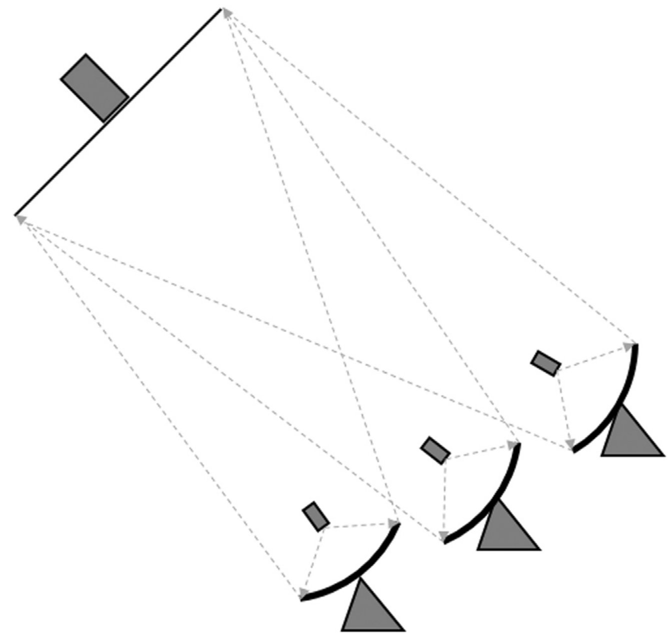

Fig. 1. Mirror array concept.

As an alternative to a lens-based system, a membrane reflector system as described by Taylor [6] could be based on the Moon's surface. It uses mirrors consisting of dual reflecting aluminum sheets with a high voltage applied between them. The resulting electrostatic forces pull the surfaces together, creating a parabolic shape that can be controlled by changing the applied voltage. We propose to build an array of several hundred relatively small (100 m diameter) mirrors instead of one monolithic multi-kilometer mirror, creating a flexible and extendable modular system (Fig. 1).

A mirror array would allow repairs and upgrades during the acceleration phase and could be re-purposed for powering multiple outposts or spacecraft inside the solar system after the primary mission is over. By positioning the mirrors on telescope mounts, it is easier to track the target across the sky. It is not entirely clear whether the required pointing accuracy could be achieved in this way—to our knowledge no estimation of pointing accuracy for Moon-based telescopes exists—but due to the practically non-existent atmosphere and low seismic activity it does not seem completely impossible. Compared to a spacecraft-based telescope, the problems of limited accuracy of the attitude control and jitter caused by on-board mechanical systems can be eliminated. Since the achievable pointing accuracy is unknown, it was used as a variable parameter in the analysis of the mission duration and maximal achievable payload, as described in Section 6.

3. Laser sail material

The light sail material's properties have a great impact on the performance of the proposed mission and influence the mass that can be sent. The two major factors increasing a light sail's acceleration characteristics are low density and high reflectivity. The absorptivity and maximum operating temperature influence the maximum surface power that can be applied to the sail and thus determine the minimal sail diameter and mass. A small diameter may be beneficial due to its low mass, however, it is not always the optimal solution. As the laser pointing accuracy is restricted, a larger sail can be accelerated by the full beam for a longer time and the optimum is no longer the smallest possible sail.

A state-of-the-art solar sail material is aluminized Mylar, whereas a possible future material may be graphene. These materials have been

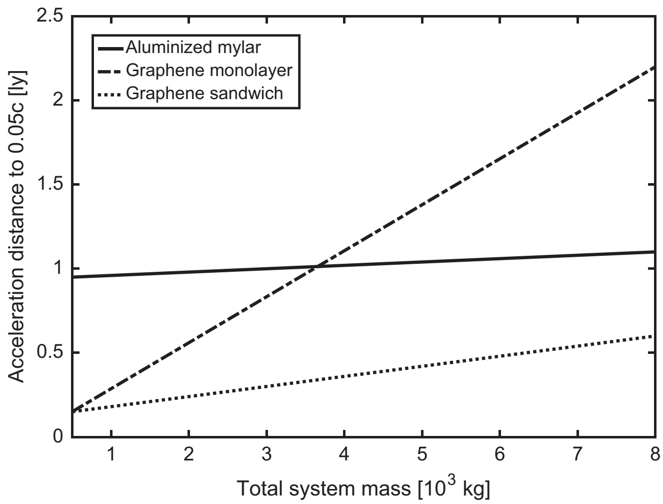

Fig. 2. Comparison of sail materials: acceleration distance needed to reach 0.05c as a function of spacecraft mass.

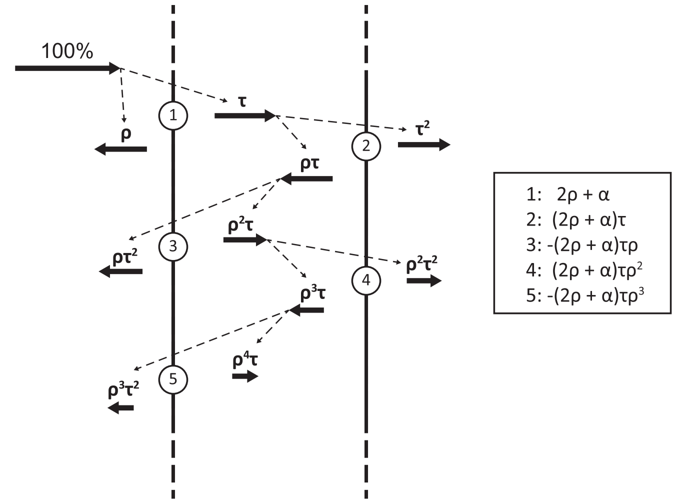

Fig. 3. The effect of two layers on the sail performance.

compared by Matloff and the results showed that a single graphene layer cannot compete with Mylar, since its low density cannot compensate for its very low reflectivity [7]. To overcome the very high transmittance τ of graphene, Matloff proposes a sandwich structure composed of graphene superimposed between two appropriate monolayers, which can increase the fractional absorption α up to 40%. Adding alkali atoms to the outer surface (the one facing the light) increases the reflectivity ρ to 5%. This comes at the expense of higher density but demonstrates a much better acceleration potential.

If used in a sandwich structure, the properties of the graphene sail improve, leading to a better performance than aluminized Mylar. In order to compare the materials, we calculated the acceleration distance required to reach 0.05c for different spacecraft masses. Smaller distances are favorable to avoid pointing and beam spread losses. The spread losses were assumed to be corrected by an optical system and were therefore not considered in the analysis, as explained in Section 4.

The results of this analysis are presented in Fig. 2. The curves clearly show the dominance of the graphene sandwich compared to Mylar and a graphene monolayer. Therefore, a graphene sandwich light sail has been chosen for the Dragonfly propulsion system.

In order to increase the performance of the material even further, we examined the idea of superimposing more than one sandwich layer. This concept reduces the transmittance of the sail even further. By placing a second graphene sandwich sheet behind the first layer, part of the transmitted light will be absorbed or reflected by the second sheet, thereby increasing the total impulse transferred to the structure. Of course, one has to take into account that reflected light is absorbed by the front sheet as well, effectively reducing the total impulse, in order to arrive at the final values for equivalent reflectivity and absorptivity of the system. This idea of superimposing layers is visualized in Fig. 3.

In case of two layers, the impulse component f that is transferred to the structure is

$$f = (\alpha + 2\rho) + \tau(\alpha + 2\tau\rho) - \tau\rho(\alpha + 2\rho) + \tau\rho^2(2\rho + \alpha) - \tau\rho^3(2\rho + \alpha) + \dots = (\alpha + 2\rho)\left[1 + \tau\sum_{n=0}^{\infty}(-\rho)^n\right] = (\alpha + 2\rho)\frac{1 + \rho + \tau}{1 + \rho} = \frac{(\alpha + 2\rho)(2 - \alpha)}{1 + \rho} \tag{1}$$

For a larger number of layers, we used an approximation taking into account only first order terms, leading to Eq. (2). This expression converges asymptotically to the analytical result for high numbers of layers κ and has a maximal error of 4% for $\kappa = 1$ in the case of a graphene sandwich:

$$f = (\alpha + 2\rho)(1 - \rho\tau)\sum_{n=0}^{\kappa-1}\tau^n \tag{2}$$

The force on the sail F_{Lsail} is proportional to f as shown in Eq. (5) and hence increases with κ. At the same time, every additional sheet increases the mass of the system linearly

$$m = m_{Lsail} + m_{rest} = \kappa \cdot m_{layer} + m_{rest} \tag{3}$$

where m_{layer} represents the mass of a single graphene sandwich layer with alkali metals and m_{rest} the remaining mass of the system, excluding the laser sail.

With this consideration, the acceleration of the sail a_{Lsail} exhibits a maximum for a specific number of layers, as it is defined as

$$a_{Lsail} = \frac{F_{Lsail}}{m} \tag{4}$$

and both m and F_{Lsail} are proportional to κ as shown in Eqs. (3), and (5) respectively. The number of layers is thus an optimization parameter when designing the mission architecture. It was included in the simulation of the system, as described in Section 5.

4. Mission analysis

The Dragonfly mission is designed with the purpose of reaching Alpha Centauri and performing scientific measurements in the target star system. This requirement adds some complexity to the mission architecture, since it implies the necessity for deceleration of the spacecraft. The mission outline is thus discretized into three separate phases preceding the scientific operations within the target system: acceleration, cruising phase, and deceleration.

4.1. Acceleration

Acceleration takes place exclusively by means of laser-powered propulsion, using a laser module placed on the Moon and a light sail aboard the spacecraft. As described in Section 2, the laser beam power is restricted to 100 GW. The force exerted on the light sail is described by

$$F_{Lsail} = f\frac{S}{c}A \tag{5}$$

where $f = (\alpha + 2\rho)$ in the case of a single layer or equal to the expression in Eq. (2) for a higher number of superimposed sheets. A is the area of the sail, c the speed of light, and S the beam intensity at the location of the spacecraft. It can be expressed as

$$S = \frac{P}{\pi r_{\text{laser}}^2} \quad (6)$$

with r_{laser} being the laser beam radius at the location of the spacecraft. Assuming perfect pointing accuracy and no divergence losses, r_{laser} remains constant throughout the whole mission, thereby producing a constant force on the sail. Realistically, this radius will increase with the distance from the laser source due to free space losses, producing a force which decreases quadratically with the distance. This effect was not modelled in the present analysis for simplicity reasons.

The pointing accuracy of the laser system θ defines the maximum distance at which the sail can still be accelerated by the laser beam according to

$$r_{max} = \frac{d}{2\cdot\tan\theta} \quad (7)$$

where d is the diameter of the light sail. It is clear that the concept of laser propulsion is not effective at large distances from the source unless pointing accuracy is sufficient. On the other hand, a larger acceleration distance ensures a higher cruise velocity and can thus reduce the mission duration. As described in Section 3, the reflectivity of the alkali metal doped graphene sandwich is 5% and its absorptivity 40%. Larger acceleration distances (and hence better pointing accuracies) are thus preferred to reach high cruise speeds. It is important to mention that the highest achievable cruise speed is not the optimal solution for the mission design. This is due to the fact that deceleration to orbital velocities requires a deceleration system whose mass depends directly on the cruise velocity. Therefore higher cruising speeds increase the overall mass that needs to be brought on board. This result will be further elaborated on in Section 5.

4.2. Cruising

The requirements of the Dragonfly competition state that the trip duration should not exceed 100 years. This means that the cruise speed should be higher than 4.35% c, assuming that the distance to Alpha Centauri is 4.35 light years.

After the optimal cruise speed has been achieved, the laser sail is no longer useful for the mission and is ejected from the spacecraft. At the same time, the laser system ceases operation. The cruise velocity is retained until the deceleration phase begins.

4.3. Deceleration

During the deceleration phase, the speed of the spacecraft has to be gradually reduced to a velocity sufficient for orbital insertion into the target system. This implies that a Δv almost equal to the one gained by the laser propulsion has to be imparted on the spacecraft.

Deceleration methods involving propellant consumption (chemical or electric) are ineffective because they require extreme amounts of propellant mass to be stored on board and also reduce the efficiency of the laser propulsion system, since the extra inertia upon acceleration leads to a significantly smaller cruising speed.

The system chosen in the present analysis relies on the combination of a magnetic sail [8] and an electric sail [9]. The operating principle of the two sails is very similar, since they utilize magnetic or electric fields to deflect the trajectories of incoming ions to reduce the speed of the spacecraft. In the case of interstellar travel, the ions of the interstellar plasma (which are travelling towards the spacecraft in its moving coordinate frame) are the ones producing this force.

According to Freeland [10], magnetic sails produce a force equal to

$$F_{Msail} = 0.354\pi\left(m_{\text{p}} n_{\text{o}} \mu^{\frac{1}{2}} I R^2 v^2\right)^{\frac{2}{3}} \quad (8)$$

where m_p is the mass of the proton, n_o is the number density of interstellar ions, μ is the free space permeability, I is the current through the sail, R its radius, and v its speed. The properties of interstellar plasma, and hence n_o, pose a big source of uncertainty for the performance of the magnetic sail. In the present analysis, a conservative value was used with $n_o = 0.03\ \text{cm}^{-3}$ [11].

Eq. (8) states that magnetic sails are effective for higher speeds and that their force drops asymptotically to zero for lower velocities, making it difficult for the spacecraft to enter an orbit around a star system.

Electric sails on the other hand demonstrate a more complex force–velocity dependency, according to Eq. (9) [9]:

$$F_{Esail} = NL\frac{3.09\cdot m_p n_o v^2 r_o}{\sqrt{\exp\left(\frac{m_p v^2}{eV_o}\ln\left(\frac{r_o}{r_w}\right)\right) - 1}} \quad (9)$$

with N being the number of tethers, L their length, V_o the voltage of the sail, e the charge of the electron, r_w the wire radius, and r_o the double Debye length λ_D, given by

$$r_o = 2\lambda_D = 2\sqrt{\frac{\epsilon_o k_b T_e}{n_o e^2}} \quad (10)$$

In the Debye length definition, ϵ_o is the electric permittivity of vacuum, k_b the Boltzmann constant and T_e the electron temperature of the interstellar plasma.

A qualitative description of this profile can be seen in Fig. 4. The force at higher speeds is almost zero and increases to a maximum value as the velocity decreases. After this peak, the force begins to decrease and reaches zero when the sail is stationary relative to the incoming ion flux. In order to decelerate from a large cruise velocity with an electric sail, the applied voltage has to be high enough to ensure that the peak deceleration occurs close to the cruise speed. This of course implies that the mass of the sail increases, leading to a smaller acceleration magnitude.

The combination of the two components was found to be more effective than each of the individual systems operating in the absence of the other. The results from Perakis and Hein [12] describe how the combination of the two sails leads to a better performance and were used within the frame of the mission design.

The combination of the two sails relies on minimizing the effects of their respective disadvantages. The magnetic sail is used for the first stage of the deceleration. As soon as the deceleration becomes smaller than the one that the electric sail can produce, the magnetic sail is detached, and deceleration using electric tethers takes over. The designs of the magnetic sail (radius and current), of the electric sail (operating voltage and tether length), as well as the velocity at which

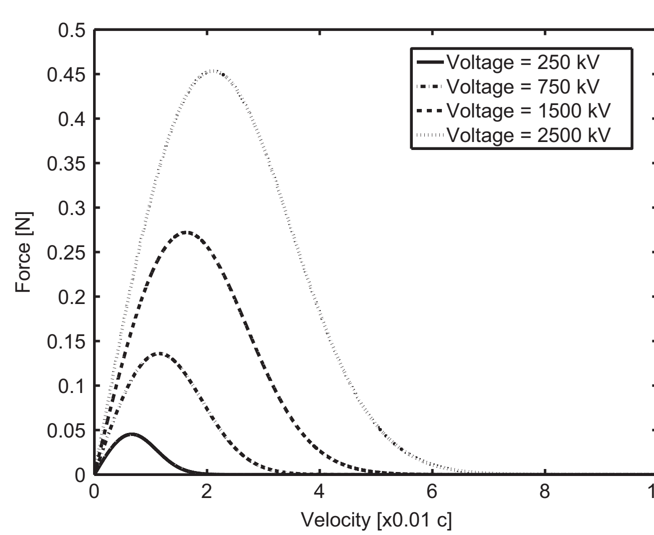

Fig. 4. Force on an electric sail as a function of velocity for different voltages.

the latter takes over, have to be chosen in a way that ensures the smallest deceleration duration and distance, while achieving the lowest mass possible.

In the following, we describe a representative case demonstrating how the combination of the two sails in series can bring additional benefits to the mission. In this test case, the mass of the spacecraft $m_{s/c}$ was chosen to be approximately equal to the launch mass of Voyager 1 (750 kg). Voyager is a space probe which was launched to perform flybys of Jupiter, Saturn and Titan, and continued to explore the boundaries of the outer heliosphere [13]. Voyager 1 is the man-made probe closest to entering the interstellar space [14]. Therefore, it is relevant to consider how its deceleration would look like in the case of a mission to another star system.

In this analysis, only the deceleration phase of the mission was examined for a given cruise speed $v_{cruise} = 0.05c$. The target speed is set to be 35 km/s, corresponding to the approximate orbital speed at a distance of one astronomical unit around Alpha Centauri A, which has a mass of 1.1 $M_\odot$ [15]. We examined three configurations:

1. Deceleration with Msail only,
2. deceleration with Esail only, and
3. deceleration using a combination of Msail and Esail.

For an effective comparison between the separate architectures, the total mass of the deceleration system was constrained to remain below $m_{decel} = 7500$ kg or else $m_{decel} = 10 \cdot m_{s/c}$. We optimized each system by minimizing the total deceleration duration required to bring the probe from v_{cruise} to v_{target}. The results of this analysis are presented in Table 1.

Fig. 5 shows the velocity profiles for each of the deceleration architectures. One observes that the combination of the two sails results in a faster deceleration. The magnetic sail seems is very effective at higher speeds, outperforming the other two methods for the first 27 years of operation. After this point, it reaches its performance limit and the velocity curve flattens out. The findings of this short test case show why the deceleration architecture of the Dragonfly mission was based on a combination of the two sails.

It was also examined whether a solar sail deceleration in parallel to the combination of Msail and Esail could further improve the performance of the system. In principle, the laser-powered light sail used during the acceleration phase could be kept on board during the cruising phase and later on utilized for deceleration purposes using the photon pressure stemming from the Alpha Centauri system. However, it was discovered that the efficiency of the system is quite low. The additional force from the solar sail becomes significant only in very short distances from the target star system and does not compensate for the extra mass that needs to be decelerated as well (the light sail itself). A detachment of the light sail directly after the acceleration phase was hence found to be more effective, leading to a deceleration phase based purely on the electric and magnetic sail.

5. Simulation model

A simulation model was developed with the purpose of determining the shortest possible mission duration for every spacecraft configuration. In this model, the three phases described in Section 4 were simulated and optimized. The cost function of the optimization problem was defined as the total mission duration $T_{mission}$ with:

Table 1
Deceleration duration for different deceleration methods.

Deceleration method	Duration (years)
Pure Msail	39.7
Pure Esail	34.9
Tandem (Msail and Esail)	28.8

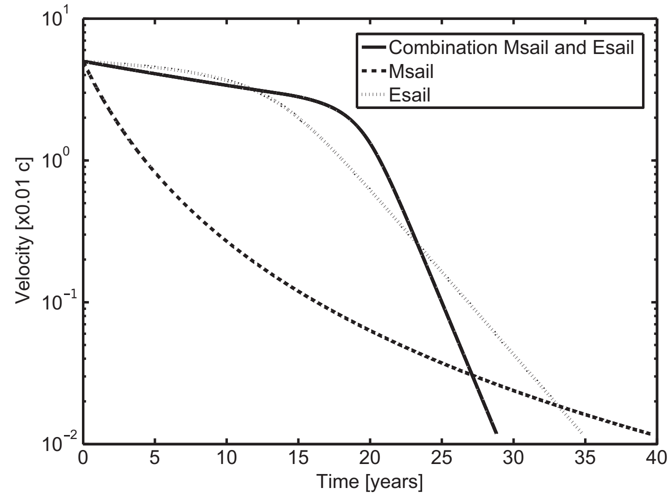

Fig. 5. Comparison of deceleration methods: velocity profile over time [12].

$$T_{mission} = T_{accel} + T_{cruise} + T_{decel} \tag{11}$$

where T_{accel} represents the acceleration duration, T_{cruise} the duration of the cruise phase, and T_{decel} the time required for deceleration. The parameters to be optimized for the minimization of $T_{mission}$ are

1. the number of light sail layers, κ,
2. the diameter of the light sail, d,
3. the distance of acceleration, r_{accel},
4. the current of the magnetic sail superconductor, I,
5. the radius of the magnetic sail, R,
6. the total length of the electric sail tethers, $N \cdot L$,
7. the voltage of the electric sail, V_o, and
8. the velocity at which the electric sail starts to dominate deceleration, v_{switch}.

For a specific configuration of κ, d, I, R, $N \cdot L$, and V_o, we define the masses of the three sails m_{Lsail}, m_{Msail}, and m_{Esail}. κ and d also determine the force on the light sail. Hence, the acceleration a_{Lsail} can be calculated according to

$$a_{Lsail} = \frac{F_{Lsail}}{m_{Lsail} + m_{Msail} + m_{Esail} + m_{s/c}} \tag{12}$$

where $m_{s/c}$ is the spacecraft mass being sent to the target system. It consists of the spacecraft bus and the scientific payload. The laser sail mass m_{Lsail} is given according to

$$m_{Lsail} = \kappa \cdot m_{layer} = \kappa \cdot \pi \sigma \frac{d^2}{4} \tag{13}$$

where σ stands for the areal density of the chosen sandwich material. The minimal diameter d is dictated by the maximal power density that the sail can withstand without melting. A constraint for the acceleration distance r_{accel} is the pointing accuracy of the laser system θ according to

$$r_{accel} \le \frac{d}{2 \cdot \tan \theta} \tag{14}$$

For larger distances it cannot be ensured that the Moon-based laser system can direct its power onto the sail and propel it further, as a better pointing accuracy would be required. For a specific distance of the acceleration phase, the achievable cruise speed is expressed by

$$a_{Lsail} = \frac{dv}{dt} = \frac{dv}{dr}\frac{dr}{dt} = \frac{dv}{dr} v \Rightarrow v_{cruise} = \sqrt{2 \int_{r_0}^{r_{accel}} a_{Lsail}(r) dr + v(r = r_0)^2} \tag{15}$$

where r_0 is the distance of the probe from the laser source at the beginning of the mission and $v(r = r_0)$ is its speed relative to the target system at this point. The direct integration shown in Eq. (15) can be used, since a 1-D acceleration path is assumed for the probe. The probe is accelerated along the line of sight between the laser and the sail and travels in the absence of other external forces. No change of direction takes place during the acceleration, cruising and deceleration phases and hence a motion along a straight line is modeled. Following a similar procedure, the acceleration time T_{accel} is given by

$$v = \frac{dr}{dt} \Rightarrow dt = \frac{dr}{v} \Rightarrow T_{accel} = \int_{r0}^{r_{accel}} \frac{dr}{v(r)} T_{accel} = \int_{r0}^{r_{accel}} \frac{dr}{\sqrt{2\int_{r0}^{r} a_{Lsail}(r)dr + v(r = r_0)^2}} \tag{16}$$

Knowing the cruise speed and the masses of the magnetic and electric sails, we can calculate the magnitude of acceleration during the deceleration phase. The switch from magnetic to electric sail deceleration occurs at a speed v_{switch}. For a given v_{switch}, the acceleration becomes

$$a_{decel} = \begin{cases} \frac{F_{Msail}}{m_{s/c} + m_{Msail} + m_{Esail}}, & \text{for } v > v_{switch} \\ \frac{F_{Esail}}{m_{s/c} + m_{Esail}}, & \text{for } v < v_{switch} \end{cases} \tag{17}$$

where F_{Msail} and F_{Esail} are described by Eqs. (8) and (9), respectively. A further constraint is that the acceleration profile should remain continuous at the switch from magnetic to electric deceleration. Hence

$$a_{Msail}(v = v_{switch}) = a_{Esail}(v = v_{switch}) \Rightarrow \frac{F_{Msail}(v = v_{switch})}{m_{Msail} + m_{Esail} + m_{s/c}} = \frac{F_{Esail}(v = v_{switch})}{m_{Esail} + m_{s/c}} \tag{18}$$

With the profile of the acceleration magnitude a_{decel} as a function of speed, we can calculate the duration and distance required for sufficient deceleration using

$$T_{decel} = \int_{v_{cruise}}^{v_{switch}} \frac{dv}{a_{Msail}(v)} + \int_{v_{switch}}^{v_{target}} \frac{dv}{a_{Esail}(v)} \tag{19}$$

$$r_{decel} = \int_{v_{cruise}}^{v_{switch}} \frac{v dv}{a_{Msail}(v)} + \int_{v_{switch}}^{v_{target}} \frac{v dv}{a_{Esail}(v)} \tag{20}$$

v_{target} is the predefined end velocity of the probe before it enters an orbit in the star system. For the distances traveled in the acceleration and deceleration phases, a constraint has to be applied to ensure that they do not exceed the total distance to the target system r_{target}:

$$r_{accel} + r_{decel} \le r_{target} \tag{21}$$

In the case of Alpha Centauri, r_{target} is equal to 4.35 light years. Finally, the cruising phase is modeled with the information of r_{accel}, r_{decel} and v_{cruise}:

$$r_{cruise} = r_{target} - r_{accel} - r_{decel} \tag{22}$$

$$T_{cruise} = \frac{r_{cruise}}{v_{cruise}} \tag{23}$$

With this expression, the model is complete and the cost function $T_{mission}$ is fully defined according to Eq. (11). The optimization objective is defined as:

$$T_{mission} = min! \tag{24}$$

It is evident that the function for $T_{mission}$ is non-linear. Since the calculation of the function's gradient would require extra computational effort, we minimized the cost function with a pattern search method similar to the "direct search" method proposed by Hooke and Jeeves [16].

6. Results

The design guidelines for the Dragonfly mission included a maximum mission duration of 100 years [4]. In this paper, we generalize our analysis to include different mission classes and mission durations.

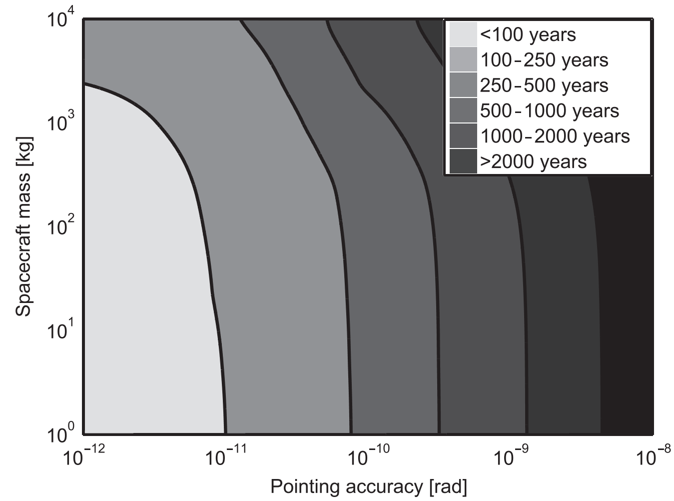

Fig. 6. Dependency of the mission duration on spacecraft mass and pointing accuracy.

We established a design map, showing the importance of the laser system's pointing accuracy and the spacecraft mass for the overall mission duration. The common denominator for all the combinations described here was the technical description of the subsystems and the separation of the mission into three phases, including the separate magnetic sail and electric sail deceleration phases. The calculations were carried out with the optimization process described in Section 5.

We already stressed the importance of the pointing accuracy for the overall mission design in Section 4. A better accuracy leads to a longer acceleration distance and hence to a larger cruising speed. The imparted Δv is also influenced by the spacecraft mass, since it defines not only the initial acceleration, but also the design point of the deceleration system, which serves the purpose of decelerating the spacecraft into orbit around the target star. In our analysis, the term "spacecraft mass" describes the mass of the spacecraft bus sent to Alpha Centauri with all its subsystems and scientific payload, but excluding the laser sail, and the magnetic and electric sails. We calculated the optimum solution (i.e. the shortest possible mission duration) for each combination of pointing accuracy and spacecraft mass (see Fig. 6).

It is evident from that missions matching the profile of the Dragonfly design competition (i.e. duration shorter than 100 years) are possible but limited to low spacecraft mass and high pointing accuracy of the laser system. Given a very accurate pointing system, achieving 10^{-12} rad of deviation or better, spacecraft masses up to 2000 kg can be sent to Alpha Centauri within a century. Decreasing the pointing accuracy by an order of magnitude restricts the mass of the spacecraft to a maximum of 1 kg. Lower pointing accuracies fail to fulfill the 100 year requirement. If, however, this requirement is considered to be secondary, other possible design points can be identified. A 1000 kg spacecraft can reach the star system within 250 years after launch, assuming that the pointing accuracy is close to 10^{-10} rad. Fig. 7 shows the dependency of the mission duration on the pointing accuracy.

The general trend shows that the design chosen for the Dragonfly mission promotes missions with smaller spacecraft mass. Larger mission classes, although potentially more significant from a scientific point of view, require much more accurate pointing, and cannot be effectively achieved with a laser-powered propulsion system. For the propulsion to become efficient for these mission classes, alternative sail materials will have to be utilized, combining higher reflectivity with lower densities.

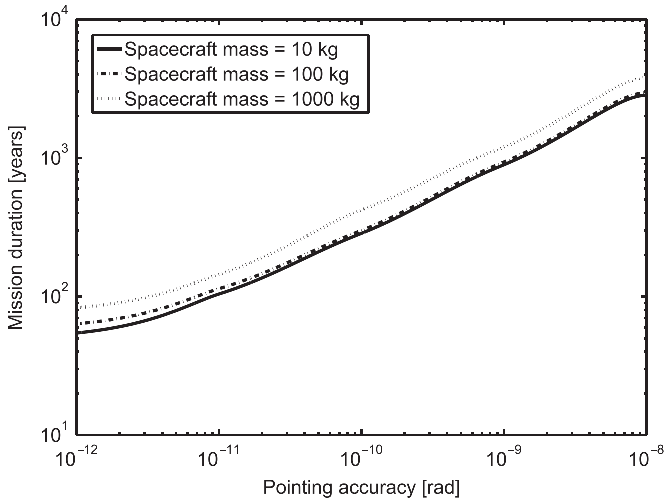

Fig. 7. Mission duration as a function of pointing accuracy for three spacecraft masses.

7. Spacecraft design

In our mission analysis simulation we determined the feasible spacecraft mass range for a 100 year long mission to Alpha Centauri to be 1–2000 kg. Based on the current development and limitations in miniaturization of scientific instrumentation and spacecraft systems explained in Section 8, we concluded that a swarm of small, CubeSat-sized spacecraft cannot achieve a scientific gain justifying the effort and cost required to conduct an interstellar mission. Therefore, we designed a single spacecraft with a maximum possible mass of 2000 kg (light, magnetic, and electric sails not included). Table 2 summarizes the mass budget for the designed spacecraft.

For the preliminary design of the spacecraft (see Fig. 8) a payload fraction of 12.5 % (250 kg) has been assumed. The remaining 1750 kg are available for the spacecraft bus, containing

1. sail deployment mechanisms,
2. a thermal control system,
3. a position determination and control system,
4. a data handling system,
5. a power system, and
6. a communication system.

The sail deployment mechanism is required to deploy the light, magnetic, and electric sails when required and ejects them after they are no longer used. The thermal control system regulates the temperature of the Dragonfly systems by rejecting heat from the laser during acceleration and providing heat for critical systems during transfer across interstellar space. The position determination and control system uses an on-board telescope—also used for scientific measurements—to determine its position and hall thrusters for course corrections. The data handling system processes and stores the collected data from scientific measurements and prepares them for their transfer to Earth by the communication system.

The power system is the core element of the spacecraft bus, supplying the other systems with energy during the different operational phases, namely acceleration, cruise, deceleration, and target star operations. For this design we chose a combination of photovoltaic cells and electromagnetic tethers as power supply. The photovoltaic cells are designed to provide sufficient power for communication and scientific observations in the target star system. During acceleration, they transform parts of the laser light into electrical energy. During cruise the electric sail is used as an electromagnetic tether. This concept relies on long tethers moving through the interstellar magnetic field creating a voltage difference between the end of the tether and the spacecraft and collecting ions from the interstellar medium [17]. With these two systems, the scientific instruments can operate during transfer and within the target star system.

To send the gathered data back to Earth, an interstellar communication system is required. The ability to send data over a distance of several light years requires either large transmitter and receiver antennas, or a large power system. For the Dragonfly mission we chose an optical communication system that uses the acceleration laser optics as its receiver. The diameter of the optical transmitter on the spacecraft is limited by the achievable pointing accuracy. With these assumptions a trade-off analysis involving laser system, transmitter, and power system mass has been conducted. The resulting system is able to send 100 bit/s over 4.35 light years and weighs 1000 kg, including the power supply.

Table 2
Mass budget for the Dragonfly spacecraft.

Systems	Mass (kg)
Scientific payload	250
Spacecraft bus	1750
Light sail	4290
Magnetic sail	1970
Electric sail	1690
Total	9950

8. Science

Manned and unmanned missions to other stellar systems have—due to the advanced technologies and long time spans required—never been undertaken by the human civilization. A successful mission to a nearby system would therefore be an achievement in itself, propelling humanity further ahead in its evolutionary voyage. An interstellar mission without extensive scientific payload would, however, be a questionable endeavor. Large-scale space programs either require the potential for commercial or scientific benefit, or the full financial support of governments. Analyzing potential stakeholder groups, Hein et al. come to the conclusion that political stakeholder scenarios are not likely to result in continued support for major space programs required to sustain an interstellar mission [18]. They state that “the main direct output of an interstellar exploration mission will be knowledge about the universe”—a conclusion that highlights the importance of identifying possible scientific areas to be investigated. For maximum return on investment, a mission should be designed to cover as many of these areas as possible. According to Webb [19] and Crawford [20], the main areas of interest are

1. studies of the interstellar medium,
2. astrophysical studies of the target star(s),
3. investigations of planetary system(s), and
4. biological studies of life forms.

Studies of the interstellar medium take place *en route* to the target star system and provide valuable information for the understanding of physical processes in our universe. The scientific value of astrophysical studies increases with observation time. In the near future, basic observations of the target star and its planetary system may be conducted using Earth-based observatories that implement new technologies—such as the European Extremely Large Telescope [21]. In order to study stars and planetary systems in detail, the spacecraft will have to decelerate or even enter a stellar or planetary orbit in order to increase the observation time. For astrobiological studies deceleration is inevitable as most respective measurements require surface operations. Crawford concludes that deceleration cannot be avoided to produce new and significant scientific results [20]. Hein et al. identified planetary geology and astrobiology as the most relevant science stakeholder groups, which leads to a high priority of surface missions

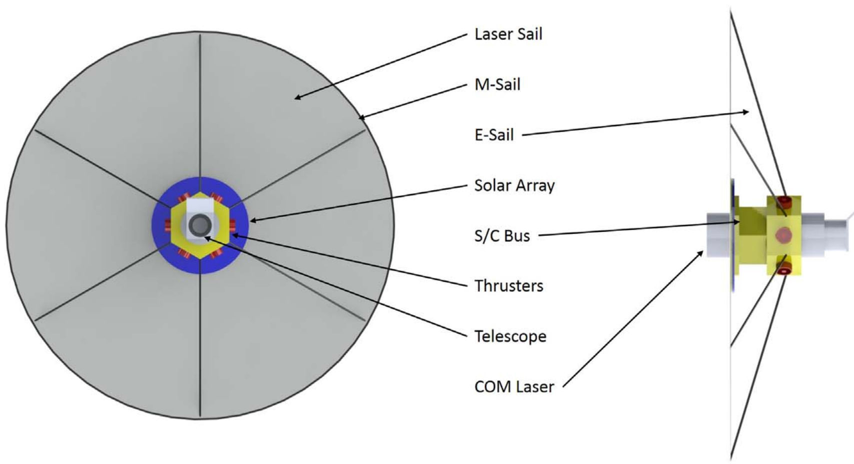

Fig. 8. Dragonfly spacecraft design. The sail diameter has been reduced for visualization.

[18].

8.1. Instrumentation

The instrumentation of the Dragonfly spacecraft is necessarily based on the technology available today. Near-future developments will likely result in the further miniaturization of some instruments, albeit to different degrees. Many currently available devices are already being built close to the minimum dimensions possible, as miniaturization is in many cases limited by physics (e.g. optics for telescopes).

Studies of the interstellar medium require the least sophisticated instruments. Simple Geiger or solid-state detectors can be used to assess the radiation level during the travel phase. Much more advanced miniaturized particle physics experiments, capable of providing more detailed information, are in development and will be tested within the next few years [22]. Astrophysical studies of stars today are mainly focused on optical observations in the ultraviolet, visible, and infrared ranges. However, miniaturization of optical instruments is severely limited by physics, as the achievable resolution directly depends on the observable wavelength and the mirror or lens diameter. At a fixed wavelength, achieving higher resolution inherently means using either larger mirrors or lenses, or using an array of smaller instruments. Both options result in an increased system mass, of which a large portion are the optics themselves. Depending on the orbit that the probes may be deployed to, decreasing resolution requirements will allow smaller systems—but bringing the probes to lower orbits requires significantly more fuel and sophisticated propulsion systems.

The most important instruments for the direct observation of planets are optical telescopes. Recent developments have shown that spacecraft with a sub-10 m resolution in low-Earth orbit can be built in small form factors. The Dove satellites of Planet Labs are a notable example, achieving a 3–5 m resolution in a 3-unit CubeSat platform [23]. However, the usability of the generated data is being questioned by the authors, both because of the limited resolution and because the satellites do not deliver data in enough wavelength regimes. Flying Dove-type satellites in formation to build an array and increase their overall resolution requires a better attitude control system and a propulsion system, which is currently completely missing. The propellant for formation keeping is in the order of a few kilograms at best, even if highly efficient, not-yet-available systems are assumed. Also, the Dove satellites are designed for short lifetimes (in the order of a year or two), as are basically all miniaturized satellites today. Even assuming that making these systems radiation-hard and adding the required redundancies will be possible without making them heavier, the total mass would still be in the order of 10 kg. There is not much, if at all any, room left to build these platforms even smaller, as the main limitations are not imposed by today's technology, but mostly by the laws of physics.

Staehle et al. [24] give a few examples for realistically achievable interplanetary science missions on 6-unit CubeSats, including imaging spectrometers, magnetometers, and radio antennas. Recent advances in manufacturing technology and high-resolution imaging sensors led to the miniaturization of camera systems in the computer and hand-held device industry. These cameras mostly have lenses with focal lengths smaller than 50 mm, which render them practically useless for any scientifically meaningful observation duty in orbit (compare to 1.14 m focal length of the Dove satellites). Mason et al. [25] present a miniature x-ray spectrometer for solar observations in 3-unit CubeSat form factor, which seems to be a possible candidate technology for the Dragonfly mission. The search for biological markers and live forms will almost certainly require to land instruments on the surface of planetary bodies, as does the determination of surface composition. Although measurements of trace gases in a planet's atmosphere can provide hints about the possibility of having live on the surface, many phenomena have to be investigated *in situ*. This requires heat shields, rocket motors or other means of propulsion, and parachutes, adding significantly to the mass of the spacecraft.

From the four areas of interest identified above, studies of the interstellar medium and astrophysical studies of the target star seem to be feasible to some extent with a small-scale mission. We have limited ourselves to analyzing these two categories of instruments, as at least some reference material is available. A full analysis of all categories was not within the scope of this paper. It is, however, evident that the payload mass of 250 kg is a significant constraint that cannot be easily overcome. All of the instruments presented here (with the exception of the x-ray spectrometer) require the spacecraft to be in a low planetary orbit. To bring the spacecraft from the solar orbit assumed in Section 4 to a planetary orbit requires significant amounts of propellant, potentially using up most of the available mass. Although propellant-less methods could potentially be utilized for an orbital insertion (Esail, solar sail), they can only be applied in specific configurations of the exoplanet's orbital geometry. Since no information about the planets' orbits is known *a priori*, including a conventional chemical or electric propulsion system is necessary for the flexibility of the system. We therefore conclude that Dragonfly could, for example, be equipped with a simple particle detector, an optical telescope, and some form of spectrometers for solar observations, remaining in its initial solar orbit. Whether the data that can be gathered with such instrumentation would be worth the financial investment necessary to realize the mission is questionable from our point of view. Advances in Earth- or Solar System-based observation technologies may provide data of similar quality in the not-too-distant future.

9. Conclusion

For the Project Dragonfly design competition the feasibility of an interstellar light sail propelled probe has been analyzed. The mass that can be sent and decelerated into an orbit around the Alpha Centauri star system depends strongly on the performance of the laser system, the sail material, and the transfer time constraint.

The critical performance criteria identified for the laser system in this analysis are the achievable pointing accuracy and the quality of the beam determining the spread losses. The system does not rely on a single large lens, because a system with a single lens that can focus the beam on the sail over large distances would be too large and therefore require tremendous efforts to be positioned close to the laser system.

The choice of sail material has a large impact on the acceleration behavior of the spacecraft. A graphene sandwich structure has been selected as the best option due to its low density. The performance may be improved if a material will be developed that combines a higher reflectivity than graphene with an equal or smaller density.

To ensure valuable scientific measurements, a deceleration system is necessary in order to bring the probe down to orbital speeds. A combination of magnetic and electric sails was utilized for this purpose, which was found to outperform each of the two systems operating on their own. The use of the light sail for deceleration purposes (using the light from Alpha Centauri) was also examined, but was discarded due to its low efficiency.

The last parameter impacting the maximum mass of an interstellar spacecraft is the mission time. We conclude that a maximum of 250 kg of scientific payload can be sent to Alpha Centauri within a timeframe of 100 years. In accordance with the analysis in Section 8, an instrument capable of measuring the properties of the interstellar medium should be included. As a second instrument a telescope has been selected to observe the target star from a stellar orbit. Sending planetary observers and landers to Alpha Centauri requires more than 250 kg of payload, assuming current and near-future technology. Miniaturization of instruments is limited by physics or has not progressed to a point where it can improve the scientific gain of a 250 kg payload.

Alternative solutions to increase the payload mass are therefore a larger laser beam power or a longer transfer duration. As the results from Section 6 show, longer mission times can significantly increase the possible spacecraft mass. As shown in Fig. 7 an increase of the mission time to 150 years could increase the possible system mass by a factor of 100.

To summarize, we conclude that an interstellar laser-propelled light sail probe using current and near-future technology is feasible under the assumptions made in this analysis. However, the scientific measurements that can be conducted by a mission of this size are fairly limited and might not justify the cost and effort that is necessary to construct and operate the propulsion laser system.

Acknowledgements

The authors would like to thank the Initiative for Interstellar Studies (i4is) for organizing the Project Dragonfly Competition, which gave the inspiration for the present study. Specifically, the authors would like to express their gratitude to Andreas M. Hein for the organization of the competition as well as for his input and comments.

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