SMALL SPACECRAFT SOLAR SAILING MISSION AND DEEP SPACE OBSERVATORY

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Abstract

Vigorous research has been done on developing a concept to propel a spacecraft to outer space without using fuel and significantly in less time from the past many decades. In these efforts, the concept of solar sailing came into the limelight. After years of research and theoretical proofing, JAXA launched the world's first-ever interplanetary solar sailing spacecraft IKAROS in 2010 to test the technology of solar sailing practically, to pave a pathway for future missions. Later many researchers came up with theoretical and simulation proofs on how we can use the same solar sailing propulsion to propel the spacecraft to outer space and interplanetary missions. The VAM-ANGEL mission is a proposal to propel a small spacecraft (<500kg (about (1102.31 lb.)) which has solar sailing as the main propulsion by solar photonic assist maneuvers using significantly less amount of fuel and more solar radiation pressure to reach interstellar space like a slingshot with a wide range of science goals and instruments tackling planetary observations, Kuiper belt objects, and solar sailing capabilities.

Keywords: Solar sailing propulsion, solar photonic assist, deep space mission, planetary science, scientific observatory.

1. Introduction

We are entering into a new age in space exploration where both governmental organizations and private sector participation are unprecedented. so, resembling this new age, we present a spacecraft concept that can reach the farthest distances in our solar system in considerably very less time of flight, is lightweight, cost-efficient, and very low fuel/ no fuel propulsion system [1,2]. The spacecraft is propelled by solar sailing. In the space environment, a solar sail utilizes the solar radiation pressure (SRP) of the photons emitted by the sun. By impinging on a large, very thin sail film which is only a few microns reflective surfaces, the momentum of photons emitted by the sun is transferred to the sail and applies a force that accelerates the spacecraft to travel.

To travel faster and deeper into space the sail first may gain a large amount of energy by first making one or more close approaches to the sun, thereby performing a so-called Solar photonic assist (SPA) [3] maneuver, turning the trajectory of the spacecraft into a hyperbolic one.

Fig.1: solar sail spacecraft at a minimum solar distance

The mission begins at the launch from the earth on reaching into the earth's orbit VAM-ANGEL spacecraft deploys its 200 square meters solar sail [4], by varying the cone angles based on solar sail orbital dynamics, the sail passes from the earth and moves towards the sun until it reaches minimum solar distance (the closest distance spacecraft can reach to the sun). On reaching the minimum solar distance sail's cone angle will be changed to raise the orbit. the amount of solar radiation received by the spacecraft due to the proximity to the sun [5], the spacecraft gets accelerated and gains a significant amount of velocity needed to travel deep into space. The equipment used onboard the VAM-ANGEL spacecraft starts its mission plans of observing the atmosphere of the different planets, in-depth Planetary science observations, Kuiper belt objects, Solar system, and Exoplanets.

2. Context

2.1. Industry

As aforementioned, In the Space industry currently, most of the deep space or interplanetary missions either use traditional chemical propulsion methods (Mangalyaan, Chandrayaan, etc) or electric propulsion methods (NASA DART mission). Based on their trajectory, propulsion method, the weight of the spacecraft, and mission goals; the time required to reach the desired destination and life of the spacecraft is reduced also maximum volume and weight is occupied by fuel, which results in compromising in scientific equipment.

A deep space mission planned with the implementation of the use of these traditional propulsion methods results in reducing the life of the spacecraft; as soon as the fuel is completely utilized, the spacecraft stops working. In the other case to produce power to run the electronics onboard, many spacecraft (Voyager 1,2, etc) use RTG (radioisotope thermoelectric generators), but RTG doesn't help in propelling the spacecraft. To achieve the fastest deep space travel, the concept of solar sailing came into the limelight. Until now only a total of 4 space crafts have successfully tested and used solar sailing propulsion [6,7].

1.IKAROS – JAXA, 2010
2.Nano sail- D2 – NASA, 2010
3. Light sail 1 – Planetary society, 2015
4. Light sail 2 – Planetary society, 2019

All these missions had different objectives and scientific goals, using solar sailing as a propulsion method.

2.2. Science

Missions to outer space are investigated several times and a lot of teams are working on designing new spacecraft missions to deep space. NASA's Voyager 1 & 2, Pioneer 10, and new horizons are the only missions that have crossed the Kuiper belt so far.

However, the time taken by these missions to reach the farthest distance is greater than 10-15 years. It's high time we used new propulsion and maneuver methods to reach distances at relatively least time of flight and solve all the mysteries which are revolving around this our outer solar system. To plan a mission to deep space requires a complex mission plan, a lot of funding, and a high amount of fuel to reach the farthest distances. The VAM-ANGEL mission significantly reduces the time to reach the planet and the costs of spacecraft and spacecraft launch.

3. Methodology

3.1. Solar sailing

A solar sail utilizes the solar radiation pressure (SRP) [8] of the photons emitted by the sun. By impinging on a large, very thin sail film which is only a few microns reflective surfaces, the momentum of photons emitted by the sun is transferred to the sail and applies a force that accelerates the spacecraft to travel. The resultant force vector of sail F_{SRP} is approximately perpendicular to the sail craft surface and always directed away from the sun. But F_{SRP} is slightly deflected from the sail normal due to the non-ideal properties of the sail membrane.

3.1.1. Solar sailing force models

The magnitude and direction of the solar radiation pressure force acting on a flat and perfectly reflecting solar sail are considered the ideal sail due to momentum transfer from the solar photons is completely characterized by the minimum solar distance and the sail attitude. The latter is generally expressed by the sail normal vector n, whose direction is usually described by sail clock angle α and sail cone angle β.

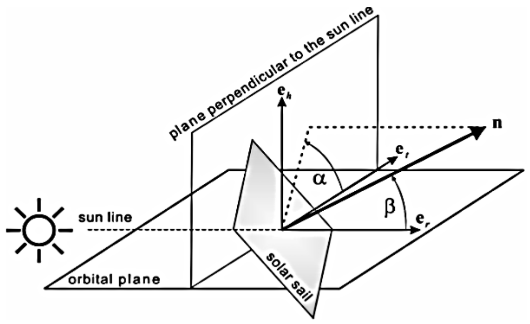

Fig.2. Clock angle and cone angle

As Fig.3 represents forces exerted on an ideal solar sail of area A by the solar radiation pressure P acting on the sail's center of the surface. From the geometry, the total Solar radiation pressure force F_{SRP} can be calculated easily by using the below-mentioned formulae, [9]

$F_r = P\ A\ (e_r \cdot n)\ er$, $F_{r'} = - P\ A\ (e_r \cdot n)\ e_{r'}$

And making use of $e_r - e_{r'} = 2(e_r \cdot n)\ n$:

$$F_{SRP} = F_r + F_{r'}$$
$$= 2\ P\ A\ (e_r \cdot n)^2\ n$$
$$= 2\ P\ A\ \cos^2\beta\ n$$

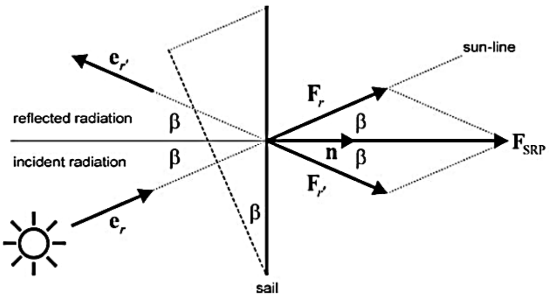

Fig.3. Ideal Reflection

As stated in the case of perfectly reflecting sails, ideal sails, the thrust force is always along the direction of the sail normal vector n. At 1AU, the solar radiation pressure on an absorbing body is $(P_0)_{1AU} = 4.463\ \mu N/m^2$. Therefore, the effective pressure acting on an ideally reflecting sail perpendicular to the sun line is twice this value $2(P_0)_{1AU} = 9.126\ \mu N/m^2$. A real solar sail however is not a perfectly reflecting solar sail and through trajectory analysis must consider the optical properties of a solar sail. Since in this case a small but significant fraction of incoming sunlight is absorbed or reflected non-specularly, a tangential force component is acting on the non-ideal solar sail [10], so that F_{SRP} is no longer along the direction of sail normal n. In the case of interplanetary or deep space transfer trajectories where beta is usually less than 50^0, the resultant small angular deviation of F_{SRP} from the sail normal may be compensated by the sail steering strategy. An overall sail efficiency factor or parameter Ƞ should be considered, which considers the reduced magnitude of F_{SRP} due to the non-perfect reflectivity of the sail including its deflection under load.

$(P_{eff})_{1AU} = 2\ Ƞ\ (P_0)_{1AU}$

3.1.2. Solar sailing orbital dynamics

The orbital dynamics of a solar sail are like the orbital dynamics of any other low-thrust spacecraft. [11] Any other low thrust spacecraft can point their thrust vector in any desired direction, but the thrust vector F_{SRP} of the solar sail is constrained to lie on the surface of the bubble that is always directed away from the sun. Indeed, by adjusting the solar sail attitude relative to the sun [12], the sail either produces a positive- along the flight direction or negative- against the flight direction orbit transversal acceleration component. In this context, the solar sail either gains angular momentum and moves away from the sun or loses angular momentum and moves towards the sun [13], which enables a wide of mission applications. For the solar photonic assist (SPA) Trajectories, the minimal flight time depends not only on the lightness of the solar sail but also on minimal solar distance along the trajectory.

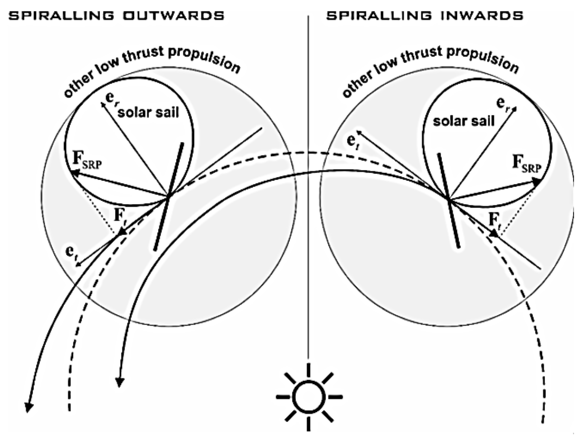

Fig.4. Spiralling inward and outward

The smaller the minimum solar distance, the larger the amount of energy that can be gained during the solar photonic assist (SA). the sails equilibrium temperature at a distance r from the sun can be calculated by the formula which is

$$T = \left(\frac{1-\ \rho}{\varepsilon f - \varepsilon b}\ \frac{So}{\sigma}\ \frac{ro^2}{r0}\ cos\beta\right)^{1/4} \propto\ \frac{\cos^{1/4}\beta}{r^{1/2}}$$

Where σ is the Stephan- Boltzmann constant. Therefore, the minimum distance to the sun is for a given sail attitude limited by the temperature limit of the sail film of the spacecraft [14]. Trajectory optimization for SPA trajectories is exceedingly difficult because spacecraft only flies too close to the sun but also the trajectory must not become too hyperbolic too early so that no additional energy can be gained other than required.

3.2. Solar Photonic Assist

Solar sails enable missions into deep space even though solar radiation pressure force decreases with the square of the sun-to-sail distance. So, in this mission, the sail first may gain a large amount of energy by first making one or more close approaches to the sun, thereby performing a so-called Solar photonic assist (SPA) maneuver, turning the trajectory of the spacecraft into a hyperbolic one.

The trajectory around the sun turns hyperbolic, allowing reasonable trip time to the outer space system without performing any gravity assists. This type of trajectory was first analyzed by C.G. Sauer [15] and described as indirect transfer shown in the Fig.5 shows the heliocentric orbit, an ecliptic projection for a typical SPA trajectory for a sail with a_c = 1 mm/s^2 and with c3 =0. The size of the initial heliocentric orbit in this case is 1.77 x 0.45 AU. The trajectory turns hyperbolic after the perihelion passage.

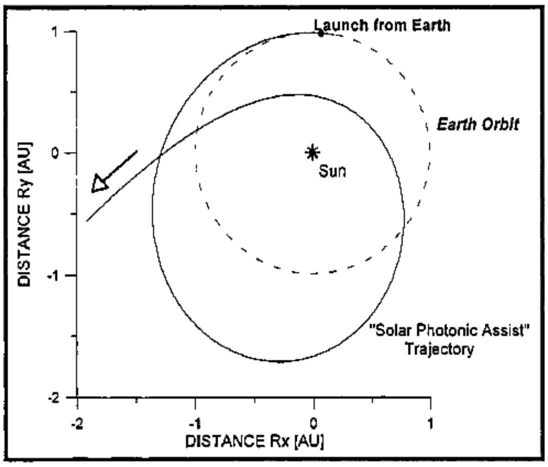

Fig.5. SPA trajectory for a sail with ac = 1 mm/s2 and with c3 =0 by C.G. Sauer

In the trajectory analysis given by Bernd Dachwald 2005 [16] for a Neptune flyby trajectory, minimal flight times have been presented for ideal solar sails because all the previous solar sail trajectory analyses for solar system escape missions use ideally reflective sails. A real solar sail, however, is not an ideal reflector [17] and a thorough trajectory analysis must consider the optical characteristics of the real sail film. In Fig.6,7,8,9 flight times are shown for ideal solar sails at a different characteristic acceleration of sail and taking a constant minimal solar distance of 0.1 AU.

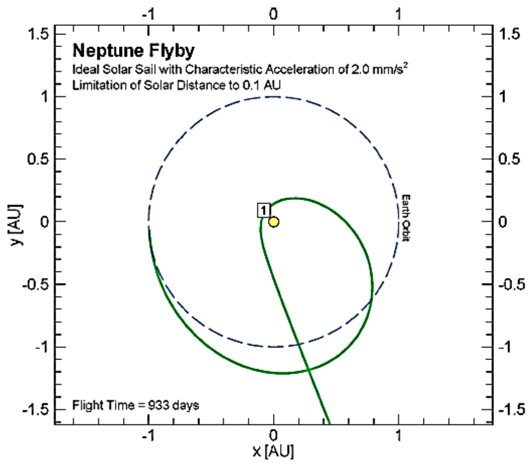

Fig.6. a_c=2.0 mm/s2, one SPA

It can be observed from the analysis that for a spacecraft with an ideal solar sail with the characteristic acceleration of 2.0 mm/s^2 and minimum solar distance of 0.1 AU, it takes a single SPA maneuver and the flight time for Neptune flyby is estimated to be 933 days,

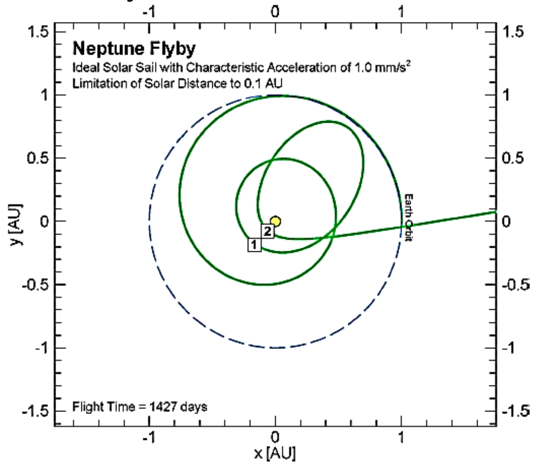

Fig.7. a_c=1.0 mm/s2, two SPA

For a spacecraft with an ideal solar sail with the characteristic acceleration of 1.0 mm/s^2 and minimum solar distance of 0.1 AU, [16] it takes two SPA maneuvers and the flight time for a Neptune flyby is estimated to be 1427 days.

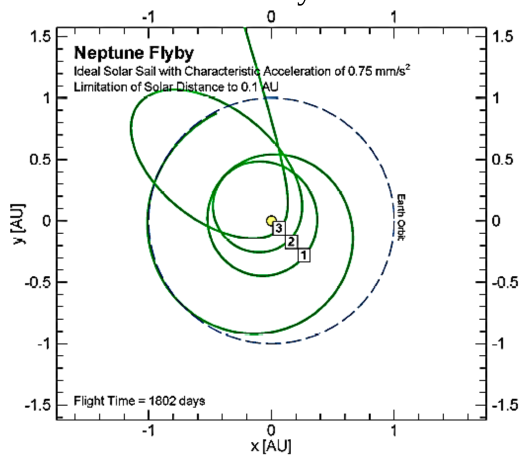

Fig.8. a_c=0.75 mm/s2, three SPA

For a spacecraft with an ideal solar sail with the characteristic acceleration of 0.75 mm/s^2 and minimum solar distance of 0.1 AU, [16] it takes three SPA maneuvers and the flight time for a Neptune flyby is estimated to be 1802 days.

For a spacecraft with an ideal solar sail with the characteristic acceleration of 0.5 mm/s^2 and minimum solar distance of 0.1 AU, it takes four SPA maneuvers and the flight time for a Neptune flyby is estimated to be 2348 days.

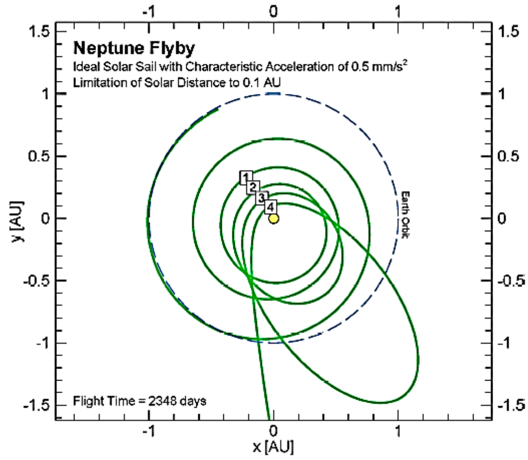

Fig.9. a_c=0.5 mm/s2, four SPA

Through this flight time estimation considering the varying characteristic acceleration of the solar sails, considering the best- and worst-case possibilities, the flight time of a spacecraft with solar sail propulsion, considering SPA maneuvers ranges anywhere from 2.5 years to 6.4 years to reach 30 AU into the outer solar system. This enables a faster reach to the outer solar system with less time of flight and more scientific goals with longer spacecraft life.

3.3. Scientific Objectives

The VAM-ANGEL mission is designed around science goals for a diverse range of targets. This mission consists of a wide range of instruments to support various scientific goals. The below-mentioned goals are not the only aims of this mission, can also be added furthermore, in future research [18].

A. Planetary science observations
B. Kuiper belt objects
C. Solar system
D. Exo planets

The mission begins at the Launch and continues throughout the trajectories, into deep space. And ends with travel into the farthest distances. This reflects the gathering of data during all the phases of the mission aimed to address the scientific goals.

After reaching the minimum solar distance to gain maximum thrust due to proximity to the sun, during the solar photonic assist, the spacecraft is placed into a hyperbolic trajectory, this being a trajectory towards deep space. This trajectory enables the spacecraft to observe the planets and objects which come into proximity with the spacecraft.

3.3.1. Planetary Observations

Planetary atmospheres are dynamic systems, interacting with the solid body via processes such as subduction and outgassing, and escaping through atmospheric erosion by stellar winds caused by host star emissions [19].

When Host star emissions like solar emissions, hits the atmosphere of any planet, a shockwave forms as dense solar wind plasma where the number of charged particles Is enhanced. The solar wind then interacts with the atmosphere and ions are created. At the same time, an electric field is generated around the planet, pointing away from the planet, causing the ions to move away from the planet's atmosphere and follow the electric field line, and be lost in space. A general loss rate can be estimated by mapping the high and low ion escape regions.

Similar Instruments like the Solar wind electron analyzer (SWEA) [19] which was used on the MAVEN mission to mars will serve the purpose of this mission. SWEA produces an energy spectrum, selecting electrons with energies within the region where most atoms ionize in planetary atmospheres. These spectra provide information about the distribution of energy fluxes, giving insight into the loss and ionization of species in the atmosphere.

3.3.2. Kuiper belt objects

Many objects in the Kuiper belt indicate larger mass in the outer solar system, beyond the orbit of Pluto, [20] having a closer observation of these objects, provides more insights regarding the solar system formations and mass distribution pattern. A closer study of these objects using a spacecraft that passes through these objects into interstellar space, helps us understand even better than ground-based and near-earth-based observations.

3.3.3. Solar system

The outer solar system structure remains many questions to astronomers [23]. The questions related to Heliopause, heliosphere, bow shock, and terminal shock, ort cloud remain a mystery, as only 3 spacecraft have reached these areas, and the data received was not quite adequate to answer the mysteries. a dedicated mission like VAM-ANGEL will help to understand the outer solar system structure in depth.

3.3.4. Exoplanets

The understanding of exoplanets formation and atmospheres is of great interest in and of itself. When considering whether the exoplanet is habitable, [24] its planetary properties, most specifically atmospheric composition plays a major role. Based on the research and technology which is present, it states that life only exists if the planet is composed of an atmosphere. The key to answering if the planet contains life is by studying the atmosphere of the planet.

Exo solar systems are at the farthest distance from our reach, to study the atmospheres of different exoplanets, different methods need to be implemented. One promising and well-practiced technique currently being utilized by the Hubble space telescope is transit spectroscopy. In this context when the host star of the exoplanet emits photons at varying wavelengths, some of these photos are then absorbed by the atmosphere of the exoplanets orbiting the host star, depending on the photon wavelength and atmospheric composition. [24] The resultant transmission spectrum can be used to identify atmospheric loss.

4.Mission Design

VAM-ANGEL mission architecture and key mission elements can be seen in Fig.10 and have been defined according to standard practice. These help us by guiding the mission study, with somewhat of an asymmetrical approach taken given the setting spacecraft propulsion, trajectories, and mission subject.

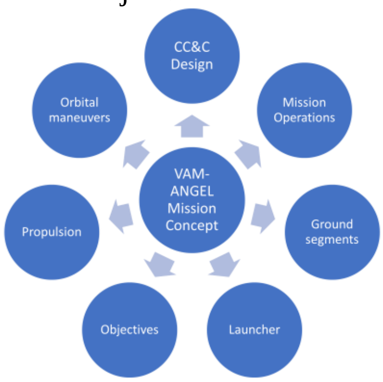

Fig.10. VAM-ANGEL mission concept

4.1. Mission timeline

The VAM-ANGEL mission can be divided into six phases as mentioned in Fig.11

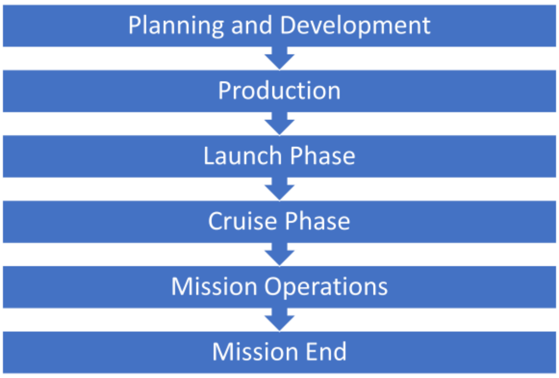

Fig.11. VAM-ANGEL mission timeline

Initially, the planning and development of the mission are required, in the current phase. Following this is a production phase, where the building and testing of the spacecraft take place. 10-15 years can be considered for each of these, taken from the approximate timelines of similar work on previous missions.

The operations of the mission begin with the launch phase. As shown in Fig.12 This consists of the integration of the spacecraft with the launcher, pre-launch preparations and launch, and the release of the spacecraft into the targeted orbit, all the responsibility of the launch provider.

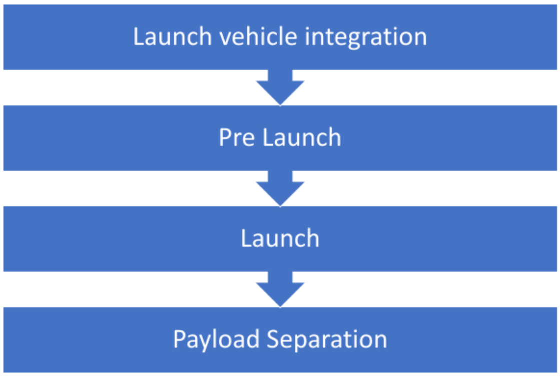

Fig.12. Launch Phase Timeline

Once the spacecraft has been released, the cruise phase begins. As shown in Fig.13. This includes the earth departure, adjusting the orbital dynamics, reach to the minimum solar distance, performing the SPA maneuver, and being placed into a hyperbolic trajectory into deep space.

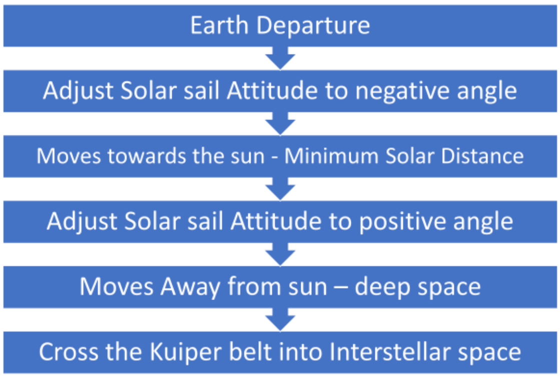

Fig.13. Cruise Phase Timeline

During the interval, interplanetary observations are performed, if Venus comes in proximity to spacecraft or any other near-earth asteroids. No specific targets have been identified yet, as this is completely dependent on the launch window. The exact duration of the cruise phase is undetermined yet, as during its entire lifetime and beyond that, the spacecraft keeps on traveling into deep space. The time of flight for the spacecraft from a minimum solar distance to 30 AU can range anywhere from 2.5 years to 6.4 years. Using SPA maneuvers.

After crossing Neptune's orbit, the actual operational phase of the mission starts and lasts until the end of the life of the spacecraft. During its entire lifetime, the

spacecraft keeps on following its scientific goals and keeps sending data to improve our understanding of outer space.
In the end, the spacecraft will cruise into interstellar space traveling through a distance that is difficult for a man to ever reach with present and near-future technology.

5. Discussion

The considerations of such a one-of-a-kind mission proposal for the outer solar system are wide-ranging scientific goals, thus limiting the scope of a single conference paper. Nonetheless, the necessity of such a mission can be demonstrated, and the paradigm shift attempted with such a proposal is of interest to the discussion with new propulsive methods and maneuvers for faster and optimal reach into deep space. The definitive publication of the Phase 1 study of this mission will be forthcoming and, in the meantime, selected topics, such as those mentioned in this paper, attempt to both raise awareness of the feasibility of such missions with SPA maneuvers and demonstrate one possible concept for a comprehensive science platform for deep space missions.

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Conflict of Interest

The authors declare that there are no conflicts of interest. The authors also declare that the present article does not contain any studies with human or animal subjects and we have no known personal relationships or competing financial interests.

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