SOL: Solar Observatory at distant Lagrange point

Aurélien GENIN⋆†*, Adrien DUPONT*⋆ *and Alexandre CORBAZ*⋆
⋆*Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland*
[first name].[surname]@epfl.ch
†Corresponding author

Abstract

The Sun's activity, such as solar flares and coronal mass ejections, can have very harmful consequences on Earth (telecommunications and electrical networks), on satellites and for future crewed missions on the Moon or Mars where the astronauts will not be safe-guarded by the Earth's magnetic field. It is therefore crucial to monitor solar activity. For now, this surveillance has only been done from around the Earth (on ground (NSO), in Earth orbit (SDO [20]) and at Sun-Earth L1 (SOHO [6] and DISCOVR [4]), giving us only one point of view of the Sun. However, having another perspective of the Sun would enable earlier alerts of solar events that would impact the Earth, as well as providing new measurements to better refine models of the Sun and better understand stars' activity.
We present in this article a new concept of M-class mission aiming at positioning a solar observatory at Sun-Earth L4 Lagrange point, developed as a student project in a masters course. This spacecraft named SOL - Solar Observatory at distant Lagrange point - will weigh around 3,000kg and monitor the Sun for at least 5 years, targeting a launch NET 2033, offering a great symbiosis with future ESA mission Vigil [8] towards L5, planned NET 2031. SOL will be equipped with various instruments, all having flight heritage from other missions. These include remote sensing payloads to study the Sun's corona, chromosphere and magnetic field, as well as observing the evolution of the solar wind between the Sun and the Earth. Being positioned at L4 will allow SOL to directly observe the region of the Sun producing the solar wind continuously hitting the Earth and the Moon, crucial for future crewed missions, but hidden from current observatories. It will also enable follow-up observations of Sun's active regions detected from the Earth. *In-situ* instruments will also allow measurement of the solar wind composition and electromagnetic properties from another point in the Solar System. SOL will also be equipped with instruments to detect, and possibly flyby, Earth trojan asteroids. For now, only two such asteroids have been detected at L4 (2010 TK7 [7] and 2020 XL5 [22]), but simulations have shown that Earth trojan asteroids could be thrown towards Earth and become threats for our planet. All data acquired by SOL will be freely accessible through Web access to anyone, for commercial or research uses.

1. Introduction

Living near a star is a very strong prerequisite for life on Earth as it is the origin of virtually every usable energy we know, except for nuclear energy. However, living near a star can also be dangerous. The Sun exhibits a strong activity, rythmed in 11-year long solar cycles. We are currently in the 25^{th} solar cycle, expected to end in 2031 and be followed by the 26^{th} solar cycle with a maximum of activity around the year 2036 [14]. Monitoring this next cycle is crucial to protect human activity on and around Earth.

1.1 Solar activity surveillance

In 1852, Wolf [28] discovered a correlation between the number of sunspots and the geomagnetic activity on Earth. This led to the discovery of the Sun's magnetic field and how it interacts with the Earth's magnetic field. In 1958, Parker [19] predicted that the solar magnetic field had to twist in interplanetary space, leading to a phenomenon now called the Parker spiral. This spiral shows how the solar wind is guided from the Sun through interplanetary space. Because of this phenomenon, the solar wind hitting the Earth originates mostly from the eastern solar limb, hardly visible from our planet (see Fig.1). This solar wind creates a constant source of radiation affecting space missions (crewed or not) escaping the Earth's magnetic field, for example to the Moon or Mars. It also feeds the Van Allen radiation belts [26] creating zones of very high radiation levels around the Earth, dangerous for electronics and humans crossing them without proper shielding.

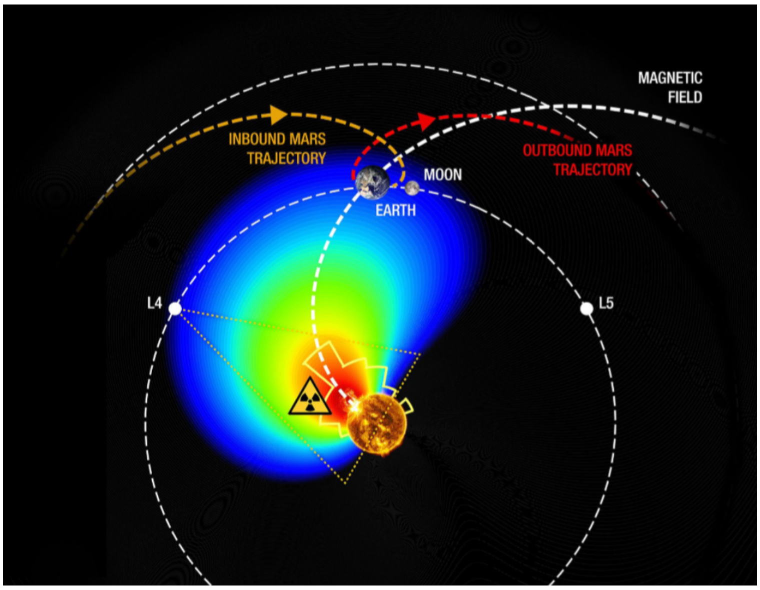

Figure 1: The Solar Radiation Hemisphere is the region from the Sun that produces the solar wind hitting a specific observer in the Solar System. Because of the Parker spiral, this region is not always directly the one facing the observer. In the case of the Earth, this hemisphere is leading it by around 60°, perfectly in view of an observatory at the Sun-Earth Lagrange point L4. This figure also shows trajectory to and from Mars for future crewed missions. Figure from [21].

Along this continuous solar wind, solar eruptions cause huge ejections of magnetized plasma and energetic particles from the solar atmosphere. These solar energetic particles (SEPs), protons and heavy ions which can reach energies of 100s MeV, can reach the Earth and impact human's activities, even on the ground. They can cause malfunctions in electrical components or disturb the ionosphere leading to perturbations in radio signals. For instance, the Carrington event in 1859, the most powerful solar event ever recorded, caused widespread telegraph outages and even wildfires. The electrical and telecommunication networks were still in their infancy at that time and it is reasonable to expect that such a geomagnetic storm would have disastrous effects today without proper protections and warnings. Moreover, the SEPs can cause irrecoverable damages to satellites, orbiting our planet out of its protective atmosphere, further impacting human activities on Earth if critical space infrastructures such as GNSS, telecommunications or Earth monitoring satellites are out-of-service. In 2023, the Council of the European Union published a report on solar storms and on the actions needed to protect human activities from them [16].

1.2 Previous missions

For decades, solar activity has been monitored from ground observatories around the globe, especially with the National Solar Observatory of the NSF established in 1952. However, these observatories were dependent on the weather and were also unable to measure the composition of the solar wind or the Sun's magnetic field because of the protection of the Earth's magnetic field and atmosphere.

To overcome this issue, satellites were launched in orbit to provide new insights on solar activity. Most notables, and still functioning spacecrafts are the following.

The Solar and Heliospheric Observatory (SOHO [6]) is the oldest still in operation, having been launched in 1995. It is an ESA/NASA spacecraft positioned at the Sun-Earth L1 point giving it constant vision of the Sun. Its LASCO coronagraph still provides the best images of the solar corona. SOHO acquired millions of images and measurements leading to ground-breaking results revolutionizing our understanding of the Sun.

The Solar Dynamics Observatory (SDO [20]) is a NASA satellite launched in 2010 in GEO. It provides the most detailed images of the Sun's surface and chromosphere in ten wavelengths in the ultraviolet and even in the extreme ultraviolet at high cadence (every 10s). It also maps the Sun's surface magnetic field and its evolution through time thanks to its Helioseismic and Magnetic Imager (HMI).

The Deep Space Climate Observatory (DISCOVR [4]) is a small NASA satellite launched in 2015 and positioned at L1 to observe the Earth and measure the solar wind an hour before it impacts it.

The Solar Terrestrial Relations Observatory (STEREO [4]) is a twin satellite mission developed by NASA and launched in 2006. Its goal was to understand the mechanism triggering Coronal Mass Ejections (CMEs) and improve our understanding of the solar wind evolution in interplanetary space. For this, NASA developed a mission with two satellites that would fly in heliocentric orbits in opposite directions. STEREO-A was placed in a 347d orbit and STEREO-B in a 387d orbit, increasing the angle between the two spacecraft by 43° each year. In 2009, they respectively reached the Sun-Earth Lagrange points L4 and L5.

SOL builds on the heritage from these previous missions and plans to re-use some of their instruments to benefit from their flight heritage.

2. SOL spacecraft

The SOL mission - standing for Solar Observatory at distant Lagrange point - consists of an M-class spacecraft that will be placed in orbit around the Sun-Earth Lagrange point L4. After a cruise phase of 2 years, SOL will observe the Sun for at least 2 years to study our star and raise early warnings concerning solar activity which could impact human's activities on and around the Earth. This section details the objectives and the architecture of the 3,000kg spacecraft and of its instruments and subsystems.

2.1 Mission objectives

The SOL mission aims at positioning a satellite at the Sun-Earth Lagrange point L4, leading Earth by 60°. Its primary objective will be to perform continuous observations of the Sun and the space between the Sun and the Earth, to provide measurements for space weather. The goal is to be able to provide nowcasting and forecasting and to raise alerts and early warnings when solar events occur. These observations from L4 will complement space weather monitoring performed on and around Earth by the US (NOAA and NASA) with a continued presence in L1, and those from the future ESA Vigil mission [8] at L5, giving a total range of observations of the Sun's surface of more than 240° [5]. SOL's mission objectives are the following:

1. To forecast solar activity and coronal mass ejections towards Earth by observing the Solar limb;
2. To study all layers of the Sun, from its interior to its corona;
3. To better understand the evolution of the solar wind during its journey from the Sun to the Earth.

With various instruments, SOL will be able to closely monitor CMEs as well as the evolution of the solar corona using coronagraphs. By positioning our spacecraft at L4, we enable continuous observations of the Solar Radiation Hemisphere (see Fig.1), the origin of the solar wind reaching the Earth and the Moon [21]. Monitoring this region and being able to raise early warnings is therefore crucial for future crewed missions and continuous presence on and around the Moon, and for journeys to Mars.

A large field-of-view imager will enable observations of the solar wind during its journey from the Sun to the Earth, allowing monitoring of mid-journey evolutions. These observations, combined with *in-situ* measurements at L1, L4 and L5, will allow researchers to refine solar wind models by giving for the first time data in very different locations on the Earth's orbit. A Helioseismic Magnetic Imager (HMI), combined with measurements from L1, will allow for the first time to measure the Sun's surface magnetic field in 3D, giving ground-breaking data to better understand stars' activity and interior [5].

Similarly to the very successful EU's Copernicus program, all data acquired by SOL will be made freely available on the Web. This will enable anyone - governmental agencies, private companies, academic researchers, individuals... - to use these data for various applications. These will range from better protection of electrical and telecommunications ground networks, vulnerable to strong solar events, to ground-breaking research on the Sun and stars, more resilient satellites and operations to protect them from the Sun's activity, and many more.

SOL has been designed with a secondary objective: detecting and studying Earth-trojan asteroids. Similarly to the Trojan asteroids located at Sun-Jupiter L4 and L5 points, the Sun-Earth L4 and L5 points are stable basins of attraction for asteroids. Currently, only two Earth-trojans have been detected at L4: 2010 TK7 [7] and 2020 XL5 [22]. SOL will be equipped with a large field-of-view imager which, combined with images from its star sensors, will allow it to monitor the space around L4 and detect new Earth-trojan asteroids. Depending on their orbit, SOL will be able to slightly deviate from its resting location at L4 to observe, and hopefully flyby, them. This survey would provide more detailed understanding on this population of asteroids, as some hypothesis suspect that L4 might be a trap for Near-Earth Objects (NEOs) that could be catapulted towards the Earth in a near future [13].

2.2 Concept of operations

The concept of operations for the SOL mission is described on Fig. 2. It shows the different phases of the mission from launch to end-of-life (EOL). The trajectory to L4 is based on the work of Sullivan et.al. [24]. It consists of a direct launch to L4, passing through the L1 unstable manifold [25], with a characteristic energy $C_3 \sim 25 km^2/s^2$ [21]. The insertion in orbit around L4 is performed by a 1-year-long low-thrust maneuver, detailed in 2.5.

The main modes of operation of the spacecraft are defined in Table 1. It presents the active subsystems and their specific mode of operations for the different steps of the mission and states of the spacecraft.

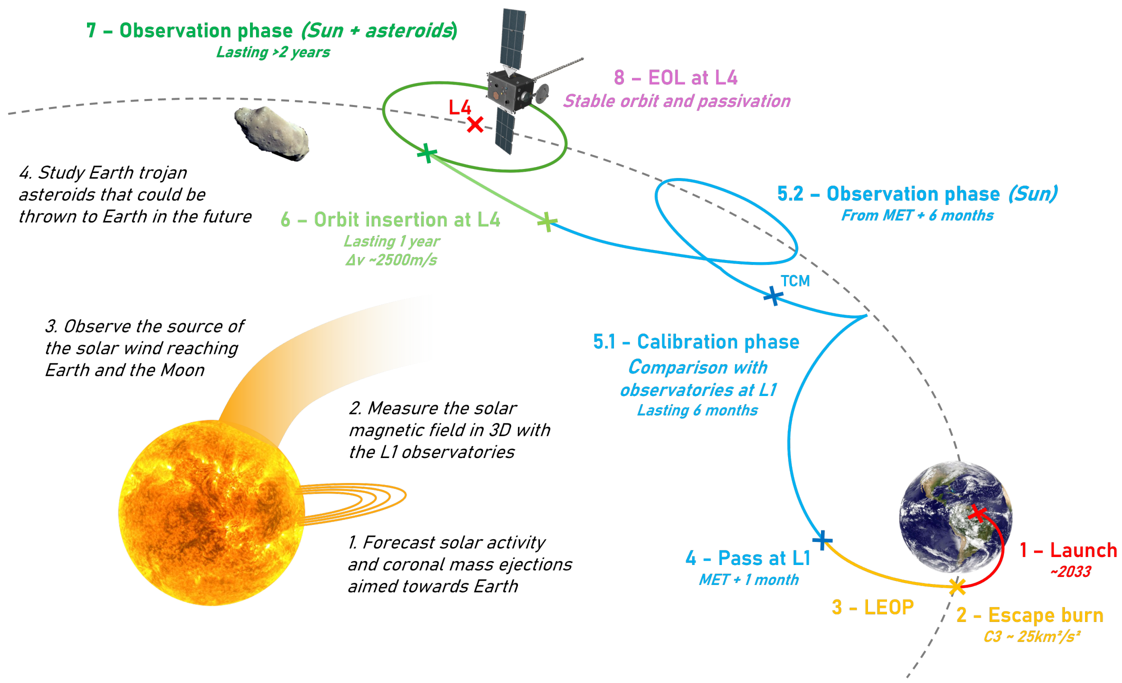

Figure 2: Concept of operations of the SOL mission from launch to end-of-life.

Table 1: SOL main modes of operation

Mode	AOCS	COM	EPS	PL	PROP	TCS
Science	Face +Y towards the Sun (RW+RCS)	TT&C (HGA) + Science (Optical)	Solar arrays towards the Sun	ON / Sequential (calibration)	OFF	Heaters ON
Propulsion	Face +X towards the maneuver vector (RW+TVC)	TT&C (HGA)	Solar arrays towards the Sun	ON (*in-situ*)	ON (alternate A/B)	OFF
Safe	Detumbling (RW+RCS) / Face +Y towards the Sun (RW)	TT&C (HGA)	Solar arrays towards the Sun	OFF	OFF	Heaters ON
Asteroid	Face -Y towards asteroid (RW+RCS)	TT&C (HGA)	Solar arrays towards the Sun	ON (asteroid)	OFF	Heaters ON

2.2.1 Deployment and commissioning

After spacecraft separation, SOL will go through a sequence of deployment and commissioning. This phase is shown in Fig. 2 as LEOP (Launch and Early Orbit Phase). It is expected to last a few hours for the first steps, and up to a month for the instruments deployment and testing. The main steps are described below:

1. Acquisition of signal (AoS) using the omnidirectional S-band antenna to NASA's DSN or ESA's ESTRACK;
2. Detumbling using the reaction wheels to point face +Y towards the Sun;
3. Solar array deployment;

4. High gain antenna (HGA) deployment and AoS;
5. Instruments deployment (antennas, boom, mechanisms unlocking...).

2.2.2 Cruise phase

During the cruise phase between L1 and the insertion burn, the spacecraft will calibrate its different instruments (detailed in 2.4) and realize a first observation campaign of around 1 year. This phase will give preliminary results and enable to observe the rise of solar activity between the beginning of the 26^{th} cycle (~2031) and its maximum (~2036). This motivated to choose a launch NET 2033.

2.2.3 Orbit insertion at L4

During the orbit insertion at L4, the spacecraft's attitude will be imposed by the thrust vector direction. Therefore, the remote sensing instruments will not be able to point at the Sun. To enable to perform measurements during this phase, we devised the following operation cycle. This cycle also allows to alternate between the two electric thrusters (see 2.5) to age them evenly and prevent failures.

1. During 2 weeks: Propulsion mode with thruster A;
2. During 1 day: Science mode;
3. During 2 weeks: Propulsion mode with thruster B;
4. During 1 day: Science mode.

2.2.4 Observation phase

The observation phase around L4 is the longest, with a minimal duration of 2 years, around the maximum of the 26^{th} solar cycle. This phase can be extended if the spacecraft is still in good health and sufficient funding is allocated to ensure safe operations.

During this period, SOL will be mostly in the science mode, with all its instruments active (except the asteroid's High Resolution Camera). The remote sensing and *in-situ* instruments will monitor the Sun and solar wind activity. The scientific data will be down-linked to Earth directly using a high bandwidth optical link (see 2.7). The raw data produced by SOL will be made available, within 24h, on an online platform. On-ground processing will analyze the data from the spacecraft to raise early space weather warnings. These warnings will be published as soon as possible depending on the type of event [16]. They will enable various stakeholders (electric and telecommunications network operators, satellite operators...) to protect their system from this sudden high solar activity.

During the observation phase, SOL will search Earth-trojan asteroids using its star trackers and Detection and Navigation camera. The captured images will be processed onboard to flag asteroid candidates (see 2.10). An on-ground astrodynamics team will search for possible flybys of these detected Earth-trojans with SOL. The spacecraft will then be able to divert mildly from its L4 orbit to flyby the targeted asteroid (distance less than 10,000km and relative velocity less than 10km/s) and study it with its High Resolution Camera (see 2.4).

2.2.5 End of life (EOL)

The end of life for SOL will be decided by assessing the health of the spacecraft, the available resources on-ground to operate it and its operational interest. The plan for EOL is to let the spacecraft in a stable orbit around L4, spin-stabilize it around its Y axis, and fully passivate it (tanks venting, solar arrays disconnection, batteries depletion) making it inert. The spacecraft's position could be monitored from Earth thanks to the reflection of the Sun's light on its solar arrays. This requires to orient the spacecraft's Y axis such that the solar arrays provide a direct reflection of the Sun's light to the Earth. Its apparent magnitude from Earth would be ~ 27, making it visible with medium-large telescopes.

The rotation of the spacecraft would make the satellite blink when observed from Earth, as the two solar arrays reflect the Sun's light directly towards Earth or not. This could be used to assess the rotation rate of SOL after EOL. We further propose to orient the solar arrays 5° off-axis, in different orientation to create a "solar-wind-mill". Because of the solar radiation pressure, this differential orientation will slowly accelerate the spacecraft rotation around the Y axis. With a solar array orientation of 5°, we estimate that this rotation will accelerate at a rate of 2°/s/yr [9].

2.3 Spacecraft architecture

The SOL spacecraft is built around a standard rectangular-shape architecture with sides of $3\times2\times2$ m. The solar arrays, folded during launch, give the satellite a total span of 12m when deployed. It will weigh around 3,000kg (see 3.1 for the full mass budget). A rendering of the SOL spacecraft is shown in Fig. 3 with the instruments and critical platform components are labeled. The faces occupation and orientation in the nominal science orbit are defined in Table. 2.

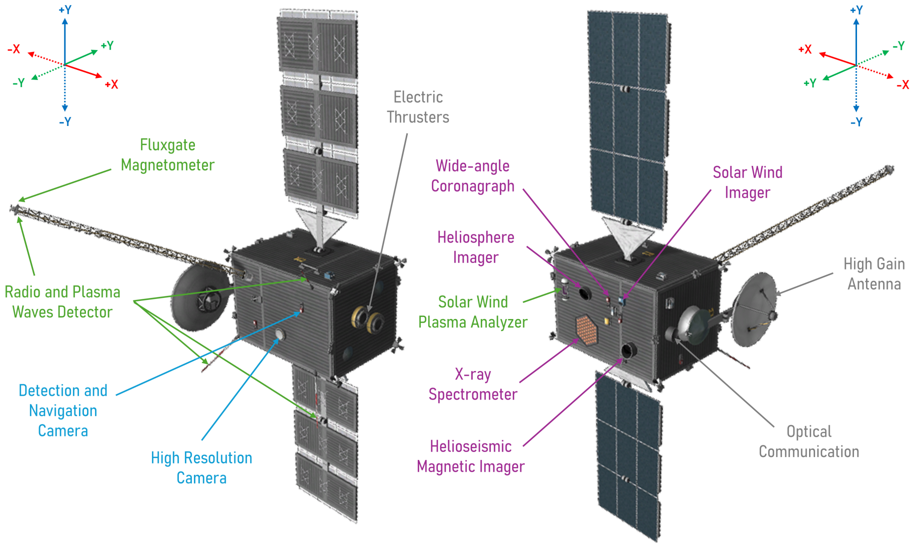

Figure 3: 3D rendering of the SOL spacecraft fully deployed. The instruments and critical platform components are labeled. Base axes show the spacecraft reference frame and the names of the faces. Rendering have been made in Kerbal Space Program.

Table 2: SOL faces orientation and occupation

S/C frame	Orbit frame @ L4	Components
+Y	Nadir	Remote sensing instruments, solar wind analyzer
-Y	Zenith	*In-situ* instruments, asteroid observation instruments
+X	Forward	Electric thrusters
-X	Aft	High Gain Antenna, optical communication
+Z	Port	Solar array A
-Z	Starboard	Solar array B

2.4 Payloads (PL)

To fulfill the mission objectives detailed in 2.1, we chose different instruments, inspired from [5, 12]. They all come from previous, already flown missions. This ensures to provide necessary measurements that will be useful for science and solar activity warnings. Furthermore, this choice gives flight heritage and will help reduce development time and cost. However, because some instruments were developed more than thirty years ago, it will be interesting to upgrade some of them to improve their capabilities. The chosen instruments, with some technical data and their reference mission, are presented in Table 3. The main instruments are in bold, whereas the other ones could be discarded in following design phases if they impose too many technical and financial constraints on the spacecraft. Removing them would lower the scientific achievements of the SOL mission, but not hinder the main mission objectives. This choice will need to be further assessed with the main stakeholders and deciders.

The **remote-sensing instruments** observe the Sun full-disk, as well as the corona using coronagraphs. An additional wide-field imager is used to observe the space between the Sun and the Earth to monitor the evolution of the solar wind, especially in the case of a CME targeting Earth. Fig. 4 presents how the field of views of the main imagers are organized to acquire the most interesting data.

The ***in-situ* instruments** will measure the solar wind composition and electromagnetic field at L4. This will give an additional point of measurement in the solar system, allowing for finer and more precise models and predictions of the heliospheric current sheet [21]. A CME from 28/10/2021, recorded by multiple probes around the Earth, the Moon and Mars, proved how important it is to acquire data from very different positions across the solar system [10].

The **asteroid instruments** aim at detecting Earth-trojan asteroids in orbit around L4, surveiling them and possibly studying them in more detail with a flyby. The main requirement for this task is to monitor a wide area of the sky, in the hemisphere opposite to the Sun to not be blinded by it and to see the light reflected from these asteroids.

Table 3: SOL instruments

	Instrument	Measurement	Mass (kg)	Power (W)	Data rate	Reference
Remote sensing	**EUV + White-light imager**	Full-disk photosphere and chromosphere (< $1.3R_\odot$)	155	160	23Mbps[a]	AIA (SDO) & EIT (SOHO)
	Wide-angle Coronagraph	Sun's corona ($1.1 - 30R_\odot$)	50	88	180kbps	LASCO (SOHO)
	Heliosphere imager	Solar wind between the Sun and the Earth ($25R_\odot$ – 0.75AU)	15	13.5	12kbps	SOLOHI (Solar Orbiter)
	X-ray spectrometer	Solar X-ray emissions	6.5	8	0.7kbps	STIX (Solar Orbiter)
	Helioseismic Magnetic Imager	Sun's surface magnetic field	73	95	20Mpbs[a]	HMI (SDO)
In-situ	**Solar Wind Plasma Analyzer**	Composition of the solar wind (ions, protons, e^-)	10	15	10kbps	SWA (Solar Orbiter)
	Fluxgate magnetometer	Local magnetic field	7	24	1kbps	MAG (Solar Orbiter)
	Radio and Plasma Waves Detector	Electromagnetic field of the solar wind	5	5	5kbps	RPW (Solar Orbiter)
Asteroid	**Detection and Navigation camera**	Earth-trojan asteroids survey	3	5	27kbps	TTCam (Lucy)
	High resolution camera	Asteroid observation during flybys (panchromatic)	12	10	10kbps	L'LORRI (Lucy
	Doppler shift (HGA)	Gravitational pull from asteroids	-	-	-	Lucy

Instruments in **bold** are the primary instruments needed for the mission. [a]Uncompressed data rate.

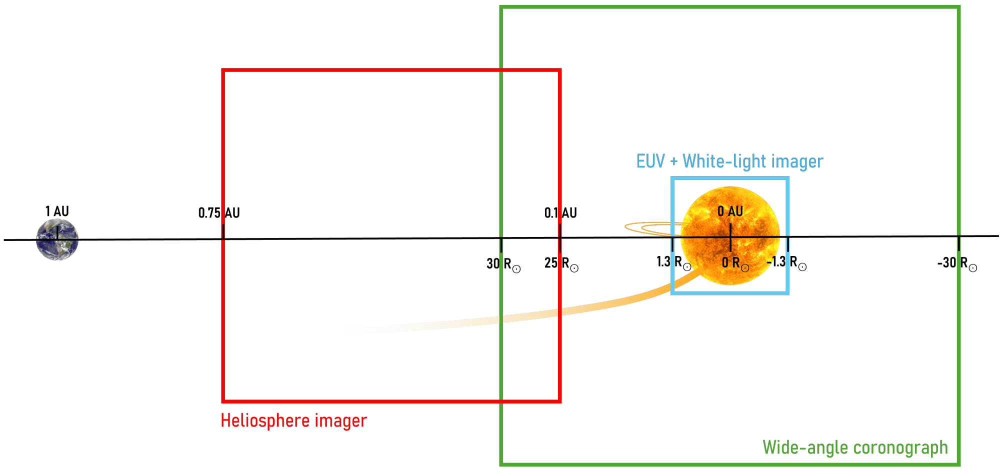

Figure 4: Distribution of the field of views of SOL's main imagers. They allow a full coverage of the Sun's photosphere, chromosphere and corona, as well as monitoring the space between the Sun and the Earth. Figure is not to scale and the AU and $R_\odot$ axis are not linear.

We chose to cover at least 800deg^2, around 4% of this hemisphere. This coverage will be performed by a specific camera, inspired from the TTCam of Lucy [18], as well the star trackers that will be repurposed for this task when not needed for attitude control (see 2.8). On-board processing, detailed in 2.10, will analyze the images to identify asteroid candidates.

2.5 Propulsion (PROP)

A direct launch to L4 passing through an unstable manifold at L1 makes use of low energy trajectories to minimize the total Δv requires. It however requires an insertion burn at L4. Given the Δv requirement of approximately 2500 m/s [21, 25], using chemical propulsion would require approximately 90% of the spacecraft mass in fuel, grandly impacting the payload mass. Instead, electric propulsion with Hall-effect thrusters (HET) was chosen with a low-thrust trajectory to L4 [24].

Low-thrust electric propulsion implies an insertion maneuver of one year, and the thruster parameters extrapolated from [24] are presented in Table 4. The propellant mass has been extrapolated from [24] and verified using Tsiolkovsky's equation to account for the difference in Isp with HET. By adding a 20% margin to account for trajectory and design uncertainties, the total Xenon fuel mass is 600 kg.

Table 4: SOL thruster design and choice

Parameters	Extrapolated [24]	PPS-5000	SPT-140
Isp (s)	1370	1730-2000	1800
Thrust (mN)	220	150-300	280
Power (W)	4000	2500-5000	900-4500
Mass (kg)	-	12.3	8.5
Volage (V)	-	300-400	250-400

To meet these requirements, two solutions were evaluated for our mission: the SPT-140 Hall Effect Thruster (by OKB Fakel) and the PPS-5000 (by Safran). The PPS-5000 was selected because of its European manufacturing origin, reducing dependencies on non-European suppliers and better suited for geo-return.

Because propulsion is critical for inserting into orbit at L4, redundancy is implemented by incorporating two thrusters into the propulsion system. This allows to alternate between the thrusters to mitigate wear and aging during this particularly long burning phase. This redundancy strategy is further detailed in 2.2.3.

2.6 Electric Power System (EPS)

The main requirements identified for designing the EPS are as follows:

- The EPS shall provide over 5500 W for one year during the insertion phase.
- The solar arrays shall fit on the +Z and -Z faces.
- The solar arrays shall point towards the Sun with a ±5° accuracy.
- The battery pack shall power the spacecraft for at least 2 hours with no solar arrays.
- The EPS shall be protected against short circuits and overvoltages.
- Solar arrays shall be disconnected at EOL.
- Batteries shall be depleted at EOL.

Regarding the dimensioning of the solar arrays, the power budget requires 5500 W for the 1-year-long burn phase (see Table 5). To meet the launcher dimension requirements, the solar panel design involves two arrays of three deployable segments, each measuring 1.5 m by 2.5 m, with a total weight of ~250 kg. This configuration provides a total solar panel area of 22.5 m². The solar arrays will be mounted on drive mechanisms (SADM) to always point them towards the Sun. These are necessary for the insertion maneuver, where face +Y will not always point towards the Sun. Because mechanisms are sensitive components, they have been integrated in the risk analysis (see 3.3).

With an average solar irradiance at L4 (1 AU) of 1361 W/m² [23], a cell efficiency of 20% [27], and an aging factor of 10% at the end of three years (coasting and insertion), the initial total power is 6100 W, decreasing to 5500 W after three years (end of insertion at L4). This value suits the electrical requirements and maximal power budget with 20% margin (see Table 5). Solar arrays are largely over-sized for the science mode, where some excess power will be used for thermal control (see 2.9).

Energy storage is needed only for two phases, as the spacecraft will never be eclipsed from the Sun: from launch to solar array deployment, and in case of AOCS or SADM malfunction. In the first case, the spacecraft will be hibernating, using minimal power for its computer, AOCS (after separation) and communication. In the second case, it is very unlikely that both solar arrays will face away from the Sun completely: electrical power will always be produced and enough for safe mode. For the battery pack, we chose two 1 kWh batteries for redundancy, granting 2.7h in safe mode each with no input from the solar arrays. This is more than SOHO's two 560 Wh batteries [6]. These two batteries will weigh ~40 kg.

Table 5: SOL power budget

Subsystems	LEOP	Safe	Science	Propulsion	Asteroid
Payloads	0	0	430	45	15
Propulsion	0	0	0	4000	0
Communication	20	40	50	40	40
AOCS	200	100	200	200	200
CDH	200	100	200	200	200
Thermal	50	50	50	0	50
Mechanisms	100	20	20	20	20
Total (+20%)	**370**	**610**	**1140**	**5400**	**630**

All values in W.

2.7 Communication (COM)

The communication strategy is divided into three separate modules: S-band, X-band, and optical.

2.7.1 TT&C

The first module, consisting of two patch omnidirectional S-band antennas (6 dBi gain), is designed to uplink and downlink TT&C information. Telecommunication in S-band is intended solely for the LEOP phase, during which the X-band antenna remains undeployed. The maximum distance used in the link budget is therefore conservatively set at 1,000,000 km, 2.6 times the Earth-Moon distance (see Table 6).

The second module used for TT&C corresponds to a High Gain Antenna (HGA) associated with a 1.6m reflector dish, a design implemented in the Mars Express mission. This antenna requires deployment and tracking mechanisms for precise pointing, resulting in a gain of 35 dBi and an EIRP of 80.5 dBW (see Table 7).

Table 6: Downlink budget for SOL's S-band module

Item	Value	Unit
Frequency	2.25	GHz
Data Rate	15	kbps
Tx Output Power	10	W
Tx antenna Gain	6	dBi
Line loss	1	dB
EIRP	45	dBW
S/C max. altitude	10^6	km
Free Space Path Loss	219.50	dB
GS Dish Diameter	15	m
GS Efficiency	60	%
GS antenna HPBW	0.62	deg
GS antenna Gain	16.46	dBi
GS noise T°	75.1	K
GS FoM	29.7	dB/K
Implementation losses	0.3	dB
E_b/N_0	8.16	dB
Required E_b/N_0 (BER = 1e-6)	2.1	dB
Margin	**6.06**	dB

Table 7: Downlink budget for SOL's X-band module

Item	Value	Unit
Frequency	8.4	GHz
Data Rate	15	kbps
Tx Output Power	40	W
Tx antenna Gain	35	dBi
Line loss	0.5	dB
EIRP	80.5	dBW
S/C max. altitude	1.5×10^8	km
Free Space Path Loss	274.47	dB
GS Dish Diameter	35	m
GS Efficiency	60	%
GS antenna HPBW	0.07	deg
GS antenna Gain	67.55	dBi
GS noise T°	43	K
GS FoM	50.9	dB/K
Implementation losses	0.3	dB
E_b/N_0	8.10	dB
Required E_b/N_0 (BER = 1e-6)	2	dB
Margin	**6.1**	dB

2.7.2 Science data

Concerning the continuous downlink of science payload data, the last module will implement optical communication. The Deep Space Optical Communication (DSOC) demonstrator used in the Psyche mission has shown a data rate of 25 Mbps at a distance of 1.4 AU [2]. With further development, we can aim to achieve an optical data rate of 30 Mbps at 1 AU, and up to 50 Mbps. The latter would be sufficient to transmit the full payload data, at an identical cadence as SDO and SOHO. However, it is possible to lower the cadence, and thus the data rate, if necessary (for instance in case of cloud coverage over the ground stations on Earth, see 2.10). A reduced data rate is also provided in Table 8 to stay within DSOC's proven 25 Mbps. A 5% margin has been applied because these instruments are all already known and should receive only minimal upgrades.

Table 8: Payload and Science Data Rates

Payload	Nominal	Reduced	Low-cadence
Helioseismic Magnetic Imager	20 Mbps	10 Mbps	500 kbps
EUV + White-light Imager	23 Mbps	11.5 Mbps	500 kpbs
Wide-angle Coronagraph	180 kbps	180 kbps	90 kbps
X-ray spectrometer	700 bps	700 bps	700 bps
Heliosphere imager	12 kbps	12 kbps	12 kbps
Solar Wind Plasma Analyzer	10 kbps	10 kbps	10 kbps
Fluxgate magnetometer	1 kbps	1 kbps	1 kbps
Radio Plasma Waves Detector	5 kbps	5 kbps	5 kbps
Detection and navigation camera	27 kbps	27 kbps	10 kbps
High resolution camera	10 kbps	10 kbps	0 kbps
Total (+5% margin)	**45.4 Mbps**	**22.8 Mbps**	**1.18 Mbps**

2.7.3 Ground segment

In order to continuously operate the spacecraft and receive the payload scientific data, three different networks are considered :

- S-band and X-band: ESA ESTRACK and NASA DSN;
- Optical: Network of receiving telescopes in development currently by ESA (European Optical Nucleus Network) and NASA (DSN hybrid antennas).

The main difficulty with optical communication is the possible cloud coverage over ground stations. They will be located in regions with minimal clouds over the year (similar to the current locations of ESTRACK and DSN). If optical communication is not possible at a station, this will disrupt the science downlink for a few hours, until another station is in view. For that time, data will be stored on board the satellite (see 2.10).

2.8 Attitude and Orbit Control System (AOCS)

SOL will be 3-axis stabilized. This is required by the face +Y having to be pointed towards the Sun in science mode. This pointing shall be precise to $\pm 1'$ and stable to 0.3"-rms for the Sun to remain sharp and in the imager's field of view.

The perturbations felt by the spacecraft will be minimal at L4, with only the solar pressure being non negligible at ~0.01 mN.m. During propulsion, a mis-alignement of the thruster by 1° will produce a torque of about~10 mN.m.

To measure its attitude, the spacecraft will be equipped with different sensors, used for different purposes and with different accuracies and speed ranges:

- 6 coarse Sun sensors (-Y,+Y,-X,+X,-Z,+Z) for detumbling and coarse pointing (±1°, <10°/s);
- 1 Inertial Measurement Unit (IMU) for high frequency measurements (100Hz);
- 2 Star trackers (-Z, +Z) + Detection and Navigation Camera (-Y) for fine pointing (±1') and asteroid survey (total field of view of 890deg²);
- 1 Fine sun sensor (+Y) for fine remote-sensing instruments pointing (<0.3"-rms).

To control its attitude, SOL will be equipped with 4 reaction wheels (RW) for 3-axis stabilization with redundancy. We will use similar wheels as the ones on board Lucy capable of producing 0.25 Nm torques, with a total momentum of 25 Nm.s [18]. To de-saturate the reaction wheels and to allow for more reactive control during possible asteroid flybys, SOL will use 12 RCS hydrazine thrusters, inspired from Lucy. Six of them produce ~1 N of thrust, and six of them produce ~10 N. The spacecraft will carry 39kg of fuel in a bladder tank by ArianeGroup, which gives 35 m/s of Δv across its life.

2.9 Thermal control system (TCS)

The spacecraft will be in a stable thermal environment as its only external source of heat will be the solar illumination, which will remain constant as no eclipses will occur. The main internal sources of heat are the electric thrusters (3 kW when functioning), electronics and additional heaters. For simple thermal studies, the spacecraft is modeled as rectangular box of dimensions $3 \times 2 \times 2$ m. To compute the steady-state temperature, we used the following equation:

$$T^4 = \frac{A_\alpha \cdot J_{sun}}{A_\epsilon \cdot \sigma} \cdot \frac{\alpha}{\epsilon} + \frac{P_{int}}{\sigma \cdot A_\epsilon \cdot \epsilon} \tag{1}$$

Computations were made for different materials to find the ideal coating for passive temperature control. Epoxy black paint on all faces was deemed the most suitable. The two following cases have been studied:

- Hot case (thruster ON, maximum illuminated surface): 40°C
- Cold case (thruster OFF, face +Y towards the Sun): -35°C

Table 9: Values and thermal main requirements

Variable	Value
A_α	4 - 16 m²
A_ϵ	32 m²
P_{int}	500 - 4000 W
J_{sun}	1361 W/m²

Equipment	Operational [°C]	Survival [°C]
Electronics	-20 to 60	-40 to 75
Batteries	10 to 30	0 to 40
Solar Arrays	-150 to 110	-200 to 130
Antennas	-100 to 100	-120 to 120
Reaction Wheels	-10 to 40	-20 to 50
Xenon fuel	15 to 40	5 to 50
Hydrazine fuel	15 to 40	5 to 50

For thermally sensitive equipments such as batteries and fuel, active temperature control is required. Heaters will be specifically located at crucial regions. Other heaters will raise the overall temperature in the cold case. A minimal power of 50 W should be sufficient. However, when the thrusters are off, solar arrays will produce a very large quantity of excessive electrical power (up to 4 kW) which will be used for this purpose. To choose the placement and size of the heaters, a multi-node thermal model simulation will be performed in future project steps.

2.10 Command and Data Handling (CDH)

Regarding the CDH subsystem, we designed requirements in three principal categories: on-board computer resistant to radiation, science data storage, and asteroid survey.

Because of the positioning of the SOL spacecraft outside the Earth's magnetic field, it will receive a significant radiation dose. The exposure to radiation will be continuous because of the solar wind, with more punctual peaks because of solar events (CMEs, SEPs, X-ray bursts). For this reason, SOL will be equipped with a rad-hard and shield on-board computer (OBC). It will be similar to the ones used for other interplanetary missions, or the solar observatories in L1 [4, 6, 11, 15, 18]. To ensure safe operations, the spacecraft will have a redundant OBC. A Fault Detection Isolation and Recovery (FDIR) system shall be implemented, with more details to be decided in following project phases.

The instruments on board SOL will produce a very large amount of data (see 2.7). To lower the downlink data-rate required, this data will have to be compressed on-board. For scientific purposes, it is necessary to transmit the raw data to Earth, meaning that the compression will need to be lossless. To be ready for communication blackouts (clouds blocking the optical science link, issues on-board the spacecraft...), the spacecraft will be equipped with on-board storage. We chose to store at least 24h of data, which would require 4Tb. Because, this is a very large storage amount for spacecrafts, we chose to reduce the cadence of the most productive instruments (HMI and EUV + White light imager) to only 1.2 Mbps (2.6%), requiring a more reasonable 100Gb on-board storage. This sacrifices temporal resolution, but will still be sufficient to monitor the solar activity. This storage will be used in regular operation to store high cadence data that could be downlinked if a particularly interesting event is detected by the ground processing center.

To look for Earth-trojan asteroids, SOL will use a dedicated camera as well as its star-trackers (see 2.4). An on board digital processing unit (DPU) will store and analyze the images. It will compare images taken at different epochs to search for moving sources. These will be flagged as asteroid candidates and an initial orbit will be computed. Follow-up observations will be performed from Earth to confirm these asteroid candidates.

2.11 Structure (STR)

The satellite structure will be designed in later phases to make the satellite resist to the launch phase and hold the different instruments and subsystems according to the spacecraft architecture. It will mostly be made from standard honeycomb panels. The xenon tanks for the electric thrusters will be housed in the center of the spacecraft for rigidity. The instruments on the face +Y will be fixed on a payload deck inside the spacecraft that will enable for organized harnessing of the power and data wires. Because the structure design comes mainly in future phases, we estimate the structure mass as 20% of the total wet mass, a standard value for such spacecrafts [27].

2.12 Launch segment

2.12.1 Launcher constraints

The European launcher **Ariane 64** is compliant with the necessary characteristic energy (C_3) for the SOL mission [3, 17] and follows ESA's strategy of European independence. Table 10 summarizes the key launch constraints of Ariane 64 and compares them to SOL requirements.

Table 10: Launcher constraints and SOL compatibility.

Parameter	**Ariane 64 Constraint**	**SOL**
Characteristic Energy (C3)	≤ 30 km^2/s^2	25 km^2/s^2
Diameter	≤ 4.6 m	3.0 m
Height	≤ 5.0 m	3.5 m
Static Load	$-5g$ to $0g$	To be tested
Dynamic Load	$-6g$ to $2.5g$	To be tested
Vibration	10–3,000 Hz, < 136 dB	To be tested
Shock	$1,000g$ at $1,000$ Hz	To be tested

2.12.2 Deployment mechanisms

The SOL spacecraft integrates several deployable mechanisms to ensure optimal functionality during its mission. The solar arrays are designed to continuously point towards the Sun, ensuring optimal power generation throughout all mission phases. The high-gain antenna incorporates a pointing mechanism that enables precise long-distance communication with ground stations, meeting strict high-frequency pointing requirements. In addition, scientific instruments, including antennas, booms, and protective covers, are deployed to support data collection and ensure protection during transit.

2.12.3 Assembly, Integration, and Testing (AIT)

The SOL spacecraft will undergo rigorous testing at ESA's ESTEC facilities to verify compliance with mission requirements. NASA's infrastructures are also considered as backup options for testing. Vibration testing will take place in the ESTEC Vibration Facility, which has dimensions of $5 \times 5 \times 5$ m. Thermal vacuum testing (TVAC) will be performed in the Large Vacuum Chamber, which has a diameter of 4.5 m and a height of 7 m, to simulate the conditions of space. Finally, communication and electromagnetic compatibility tests will be conducted in the Maxwell Chamber, which features dimensions of 6 m in diameter and 11 m in height.

3. Systems engineering

With the preliminary design presented above, we detail some systems engineering considerations. These include summary budgets (financial cost estimation and total spacecraft mass), a definition of mission success criteria, an assessment of the major risks with some mitigation options, and a project timeline up to the end-of-life of the mission.

3.1 Budgets

The SOL mission aims to be a medium-class mission (M-class), in the ESA's projects organization. This class of mission incorporates stand-alone missions with a budget of approximately €500 million. Examples of such missions are Solar Orbiter [15], Euclid, PLATO or EnVision. Comparing to other space solar observatories, this class of mission seems the most appropriate: SOHO's budget was around $1 billion; SDO's cost is around $850 million including the development, launch and 5yr of operations [1]; STEREO's cost was around $550 million. Since we plan to reuse instruments already developed in previous missions, with only upgrades, aiming for a total budget for the SOL mission of €500-800 million seems appropriate to us.

As presented in 2.3, the target total wet mass for the spacecraft is 3000 kg. In Table 11, we present the mass budget of SOL, detailed by subsystem. Because our work is a concept study, we considered a 20% margin for all subsystems [27]. This margin might be excessive for some parts, such as the payloads since we plan to use instruments that are already mostly developed. However, it is well justified for other parts with much more uncertainties like the communication and propulsion (see 3.3 for more details). The structure and harness mass has been estimated as 20% of the total wet mass, a standard mass distribution for spacecrafts [27].

Table 11: SOL mass budget

Subsystems	**Mass (kg)**	**+20% margin (kg)**
Payloads	350	420
Propulsion (wet)	650	780
Communication	300	360
AOCS	150	180
EPS	350	420
CDH	100	120
Thermal control	100	120
Structure + Harness[a]	370	450
Total	**2370**	**2880**

[a]Estimated as 20% of total mass

3.2 Mission success criteria

To validate the mission success, we devised mission success criteria. They are presented in Table 12. We separated them as partial, complete, and additional successes. This gives flexibility on the qualification of the mission achievement, even in the case of some failures, or if some uncertain events occur (such as the flyby of an Earth trojan asteroid).

Table 12: SOL mission success criteria

Partial	Obtain scientific measurements of the solar activity (remote and *in-situ*) from off-axis perspective (at L4 or during cruise phase)
Complete	Reach orbit around L4 with >90% instruments functioning, and downlink science data at >90% of defined data rate for >2yr
Additional I	Raise alerts about solar activity impacting Earth, and improve its characterization
Additional II	Detect Earth-trojan asteroids and flyby at least one

3.3 Risk assessment

Because our study is still an early-phase mission concept, some uncertainties on the design of the spacecraft, and on the mission, remain. These main uncertainties are summarized in Table 13. The risks are classified in terms of their likelihood and impact on the mission. Mitigation plans are proposed for the different risks. The mitigation aims at reducing the risk to an acceptable level (at least the yellow level). These risks and mitigation plans should be further studied in the following phases of the project to re-evaluate their likelihood and impact, and therefore the necessity to apply mitigation. Many of the risks involve the failure of a component (usually mechanisms).

One of the major risks (A) is due to uncertainties on the trajectory of the spacecraft to L4. This uncertainty will be solved by a further mission analysis, performed in Phase B. Depending on the result of this analysis, changes to the spacecraft architecture or operations may be needed.

Table 13: Risk assessment of the SOL mission

	Risk	Impact	Mitigation
A	Insertion burn range of direction too big for TT&C communication	No TT&C link during some phases of insertion burn	-Install two HGA antennas -Burn with no TT&C link, and frequent stops in burn to communicate with Earth
B	Space weather event	Electronics errors, shortcuts, computer crash	-Radiation shielding -Redundant computers
C	Optical communication development not fast enough	Not enough data-rate to downlink science data	-Bigger HGA antenna, used for science downlink -Lower data acquisition cadence
D	Optical communication pointing mechanism fails	No science high data rate	-Rely on HGA antenna instead -If precision of AOCS is enough, stop science from time to time to downlink science
E	Electrical thruster fails during insertion burn	Impossible to insert into orbit around L4	-Redundant thruster used 50% of time each -Split thruster in two lower thrust -Change mission plan (traj like STEREO)
F	HGA antenna pointing mechanism fails	No TT&C link	-Rely on optical link for TT&C -Stop science from time to time to communicate with Earth
G	Solar array drive mechanism fails during insertion burn	Suboptimal electric power generation for full thrust	-Longer insertion burn, may not have enough fuel
H	One solar array fails to deploy	Loss of half power generation, insertion burn compromised	-Longer insertion burn at lower thrust
I	Micro-meteorids	Solar arrays loss of power, optics deterioration	-Avoid pointing optics towards velocity
J	Instrument failure	Loss of data	-Redundancy, tests
K	Solar array drive mechanism fails to reorient towards Sun at L4	Lower electric power generation at L4	-Sufficient power generation with only one solar array

Impact \ Likelihood	1	2	3	4	5
5	F,H	D,E	A,C		
4	G	J			
3					B
2	K				
1				I	

3.4 Project timeline

The SOL mission has started in Q3 2024, as a student project in a masters course. We present in Fig.5 the predicted timeline up to the end of life. This timeline is organized using the standard phases of space programs [27]. We aim for a launch in 2033 to arrive at L4 in 2035, in time for the 26^{th} solar cycle maximum, predicted for 2036 [14]. This leaves 8yr for the development, production and test of the spacecraft, close to development times of previous similar scale missions, taking into account that we would reuse existing instruments and use commercial off-the-shelf components. The planned lifetime of the mission is 5yr, with a possible mission extension depending on the health of the spacecraft, and on the interests of its results.

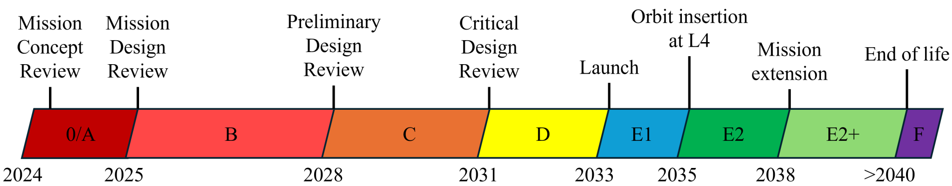

Figure 5: Planned timeline for the SOL mission. Main project phases, reviews and milestones are presented.

4. Conclusion

We have presented our mission concept SOL, a 3000 kg spacecraft placed in orbit around the Sun-Earth Lagrange point L4 to observe the Sun in the dual objective of providing early warnings and characterizations of solar activity that could impact human activities on and around Earth, and of acquiring scientific data to improve the understanding of stars. SOL will also look for Earth-trojan asteroids, a still very mysterious population.

The next steps for the mission would be to enter the circuit of ESA mission proposals. This should allow for funding and support to be allocated to the SOL mission. The development would then transition to the preliminary design phase, where the design of the whole spacecraft, system and operations would be further studied and detailed. Mission analysis would have to be conducted in detail quickly to confirm major design choices such as antenna and thrusters positioning for the insertion maneuver. The laboratories that worked on the instruments from previous missions we plan to reuse would have to be contacted to ensure their willingness to participate to SOL, and how to upgrade and adapt their instruments for it. Multiple reviews would be called, and a PDR would be excepted in 2028.

References

[1] National Aeronautics and Space Agency. Guide to the Mission and Purpose of NASA's Solar Dynamics Observatory, 2009.

[2] Abhijit Biswas, Meera Srinivasan, Ryan Rogalin, Sabino Piazzolla, John Liu, Brian Schratz, Andre Wong, Erik Alerstam, Malcolm Wright, William T. Roberts, Joseph Kovalik, Gerardo Ortiz, Arthur Na-Nakornpanom, Matthew Shaw, Clay Okino, Kenneth Andrews, Michael Peng, David Orozco, and William Klipstein. Status of nasa's deep space optical communication technology demonstration. In *2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS)*, pages 23–27, 2017.

[3] Pontus C. Brandt, David J. McComas, Fran Bagenal, and et al. Synergies between interstellar dust and heliospheric science with interstellar probe. *Journal of Geophysical Research: Space Physics*, 126(10):e2021SW002777, 2021.

[4] J. Burt and B. Smith. Deep Space Climate Observatory: The DSCOVR mission. In *2012 IEEE Aerospace Conference*, pages 1–13, March 2012.

[5] Kyung-Suk Cho, Junga Hwang, Eun-Kyung Lim, Jeong-Yeol Han, Seonghwan Choi, Jungjoon Seough, Rok-Soon Kim, Young-Soo Kim, Jongdae Sohn, Jihun Kim, Jaejin Lee, Young-Deuk Park, Yong-Jae Moon, Jong-Ho Seon, Ho Jin, Soojong Pak, Dong-Hun Lee, Kwangsun Ryu, Jaemyung Ahn, Kyung-Wook Min, Dae-Young Lee, Yu Yi, Kee-Chang Yoon, Sung-Joon Ye, Jongchul Chae, Sung-Hong Park, Insoo Jun, Nat Gopalswamy, Jeffrey Newmark, and Nick Arge. Open New Horizon with L4 Mission. Decadal Survey for Solar and Space Physics (Heliophysics) 2024-2033 white paper e-id. 064, July 2023.

[6] V. Domingo, B. Fleck, and A. I. Poland. The SOHO Mission: an Overview. *Solar Physics*, 162(1-2):1–37, December 1995.

[7] R. Dvorak, C. Lhotka, and L. Zhou. The orbit of 2010 TK7: possible regions of stability for other Earth Trojan asteroids. *Astronomy & Astrophysics*, 541:A127, May 2012.

[8] ESOC. Vigil Mission Objectives and Payload Description. Technical Report ESA-S2P-LGR-MO-0002, ESA, 2022.

[9] R. M. Georgevic. The Solar Radiation Pressure Forces and Torques Model. *The Journal of the Astronautical Sciences*, 27, January 1973.

[10] Jingnan Guo, Xiaolei Li, Jian Zhang, Mikhail I. Dobynde, Yuming Wang, Zigong Xu, Thomas Berger, Jordanka Semkova, Robert F. Wimmer-Schweingruber, Donald M. Hassler, Cary Zeitlin, Bent Ehresmann, Daniel Matthiä, and Bin Zhuang. The first ground level enhancement seen on three planetary surfaces: Earth, moon, and mars. *Geophysical Research Letters*, 50(15):e2023GL103069, 2023. e2023GL103069 2023GL103069.

[11] M. L. Kaiser, T. A. Kucera, J. M. Davila, O. C. St. Cyr, M. Guhathakurta, and E. Christian. The STEREO Mission: An Introduction. *Space Science Reviews*, 136(1-4):5–16, April 2008.

[12] S. Kraft, K. G. Puschmann, and J. P. Luntama. Remote sensing optical instrumentation for enhanced space weather monitoring from the L1 and L5 Lagrange points. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, volume 10562 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 105620F, September 2017.

[13] Renu Malhotra. The case for a deep search for Earth's Trojan asteroids. *Nature Astronomy*, 3:193–194, February 2019.

[14] M. Miesch. Solar cycle progression updated prediction (experimental): Validation document. Technical report, NOAA Space Weather Prediction Center, 2024.

[15] D. Müller, O. C. St. Cyr, I. Zouganelis, H. R. Gilbert, R. Marsden, T. Nieves-Chinchilla, E. Antonucci, F. Auchère, D. Berghmans, T. S. Horbury, R. A. Howard, S. Krucker, M. Maksimovic, C. J. Owen, P. Rochus, J. Rodriguez-Pacheco, M. Romoli, S. K. Solanki, R. Bruno, M. Carlsson, A. Fludra, L. Harra, D. M. Hassler, S. Livi, P. Louarn, H. Peter, U. Schühle, L. Teriaca, J. C. del Toro Iniesta, R. F. Wimmer-Schweingruber, E. Marsch, M. Velli, A. De Groof, A. Walsh, and D. Williams. The Solar Orbiter mission. Science overview. *Astronomy & Astrophysics*, 642:A1, October 2020.

[16] Council of the European Union and General Secretariat of the Council. *Solar storms – A new challenge on the horizon?* Publications Office of the European Union, 2023.

[17] Andreas Ohndorf, Bernd Dachwald, Wolfgang Seboldt, and Karl-Heinz Schartner. Flight times to the heliopause using a combination of solar and radioisotope electric propulsion. 09 2011.

[18] Catherine B. Olkin, Harold F. Levison, Michael Vincent, Keith S. Noll, John Andrews, Sheila Gray, Phil Good, Simone Marchi, Phil Christensen, Dennis Reuter, Harold Weaver, Martin Pätzold, James F. Bell III, Victoria E. Hamilton, Neil Dello Russo, Amy Simon, Matt Beasley, Will Grundy, Carly Howett, John Spencer, Michael Ravine, and Michael Caplinger. Lucy mission to the trojan asteroids: Instrumentation and encounter concept of operations. *The Planetary Science Journal*, 2(5):172, aug 2021.

[19] E. N. Parker. Dynamics of the Interplanetary Gas and Magnetic Fields. *The Astrophysical Journal*, 128:664, November 1958.

[20] W. Dean Pesnell, B. J. Thompson, and P. C. Chamberlin. The Solar Dynamics Observatory (SDO). *Solar Physics*, 275(1-2):3–15, January 2012.

[21] A. Posner, C. N. Arge, J. Staub, O. C. StCyr, D. Folta, S. K. Solanki, R. D. T. Strauss, F. Effenberger, A. Gandorfer, B. Heber, C. J. Henney, J. Hirzberger, S. I. Jones, P. Kühl, O. Malandraki, and V. J. Sterken. A Multi-Purpose Heliophysics L4 Mission. *Space Weather*, 19(9):e02777, September 2021.

[22] T. Santana-Ros, M. Micheli, L. Faggioli, R. Cennamo, M. Devogèle, A. Alvarez-Candal, D. Oszkiewicz, O. Ramírez, P. Y. Liu, P. G. Benavidez, A. Campo Bagatin, E. J. Christensen, R. J. Wainscoat, R. Weryk, L. Fraga, C. Briceño, and L. Conversi. Orbital stability analysis and photometric characterization of the second Earth Trojan asteroid 2020 XL_5. *Nature Communications*, 13:447, January 2022.

[23] Sami Solanki, Natalie Krivova, and Joanna Haigh. Solar irradiance variability and climate. *Astronomische Nachrichten - ASTRON NACHR*, 323, 06 2013.

[24] C. J. Sullivan, I. Elliott, N. Bosanac, F. Alibay, and J. R. Stuart. Exploring the low-thrust trajectory design space for smallsat missions to the sun-earth triangular equilibrium points. In *Advances in the Astronautical Sciences Journal*, 29th AAS/AIAA Space Flight Mechanics Meeting, pages 19–280, 2019.

[25] A. Urruticoechea Puig. Study and optimization of transfer orbits to the L4 and L5 Lagrange Points of the Earth-Sun system. Master's thesis, Universitat Politècnica de Catalunya, 2022.

[26] J. A. van Allen. Observations of high intensity radiation by satellites 1958 Alpha and 1958 Gamma. In Paul A. Hanle, Von Del Chamberlain, and Stephen G. Brush, editors, *Space Science Comes of Age: Perspectives in the History of the Space Sciences*, pages 58–73, January 1981.

[27] James Richard Wertz and Wiley J. Larson. *Space mission analysis and design*. 1999.

[28] R. Wolf. Sonnenflecken-beobachtungen in der ersten hälfte des jahres 1852; entdeckung des zusammenhangs zwischen den declinationsvariationen der magnetnadel und den sonnenflecken. *Mittheilungen der Naturforschenden Gesellschaft in Bern*, 245:179–184, 1852.