Collaboration for the Analysis of Photonic and Ionic Bursts and Radiation from Barcelona (CAPIBARA): Preliminar Report for the SPARK Program

Joan Alcaide-Núñez*[1], Martí Delgado Farriol[2], Lluc Soler Manich[3], Anna Abadal Garrido[4], Emma Massó Sala[3], and ...[1]

[1]Deutsche Schule Barcelona (DSB), Av. Jacint Esteva i Fontanet, 105, 08950 Esplugues de Llobregat (Barcelona), Spain.

[2]Col·legi Pureza de Mara Sant Cugat, Carrer de Merc Vilaret, 21, 08174 Sant Cugat del Valls, Barcelona

[3]CIC Escola de Batxillerats, Via Augusta, 205, 08021, Barcelona

[4]Salesians Sarri, Passeig Sant Joan Bosco, 42. 08017 - Barcelona

[5]New affiliation

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Abstract

An overview or summary of the document, written at the end.

*Corresponding author: joanalnu@outlook.com

Contents

1 Introduction

Cosmic Rays (CRs) or cosmic radiation are charged particles coming from the Universe at high energy due to their high velocities. These particles are mainly protons (87%) and Helium nuclei (10%) (de Espectroscopía Gamma y de neutrones, 2014), see table 1 for a complete composition. We refer to these particles as Primary Cosmic Rays (PCRs).

Type	Percentage
Protons	$\sim 87\%$
α particles	$\sim 10\%$
Electrons	$\sim 2\%$
Light elements (Li, Be, B, ...)	$\sim 0.25\%$
Antimatter	$\sim 0.01\%$

Table 1: Composition of primary cosmic rays from de Espectroscopía Gamma y de neutrones (2014).

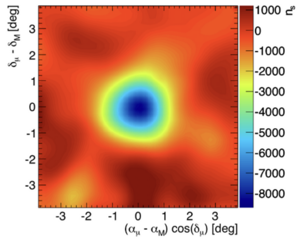


Figure 1: Contour plot of the muon deficit as measured by IceCube in the region around the Moon's position, the so-called on-source region (credit: IceCube Collaboration)

When these particles interact with a medium, they decay in other, lighter particles, called Secondary Cosmic Rays (SCRs). For instance, SCRs are produced as a consequence of PCRs decaying when hitting molecules in Earth's upper atmosphere. As a result, protons, alpha particles, pions, kaons, muons, electrons, and neutrinos are created (Morison, 2008), becoming a way of indirect detection (see **??**).

Furthermore, another radiation helps trace CRs, however, it is not categorized as cosmic ray due to its lack of electric charge. The interaction of both PCRs and SCRs emit light, for instance in accretion disks, nebulae, interstellar dust, quantum decays, atmospheres, among others. This type of light reaches us in high-energy wavelengths, mostly in X-rays and γ-rays, but also in ultraviolet (UV) and infrared (IR). Photons have different properties as fermions and hadrons, opening a complete new way of study.

On the other hand, another way of separating CRs is by origin, into galactic and extragalactic CRs. Galactic CRs emerge mainly from the sun, other nearby stars, and other objects such as neutron stars (NSs). This category may be estimated by the source coordinates, where low latitudes more likely correspond to the position in the galactic plane, whereas high latitudes likely come from other galaxies. Knowing the distances to the source is also a useful tool for estimating the origin[1].

Although CRs are known to come from outside of Earth (), we do not know specific sources of CRs. As these are charged particles, they interact with magnetic fields through their way to Earth. Therefore, when we detect cosmic rays, we cannot determine their provenance. However, there are probable sources of CRs discussed: supernovae explosions (SNe) and remnants (SNRs), neutron stars (NSs), microquasars (Quasi Stellar Object, QSO), active galactic nuclei (AGNs), and gamma-ray bursts (GRBs).

2 Mission Objectives

Our objective is to explore high-energy phenomena, both in the form of light (photons) and particles (mainly protons and alpha particles). In this section, the mission objectives and technological requirements of the mission are described. For further details on the experiment design, i.e. how we aim to accomplish these goals, see section 5

2.1 Primary CRs Detection

2.2 Secondary CRs Detection?

2.3 Electromagnetic Detection

Moreover, we want to accomplish the observation of electromagnetic radiation emitted by CRs interactions, as they give us different information about CR sources and physical processes of their interactions due to the difference in nature of light. To do so, we have to be capable to detect photons in the X-ray and γ-ray range of the spectrum, as high-energies are where CR are expected to emit on account of their initial energy and velocity.

[1]This technique is only applicable to electromagnetic radiation, as charged particles interact with magnetic fields, therefore making their direction an unreliable source of origin information.

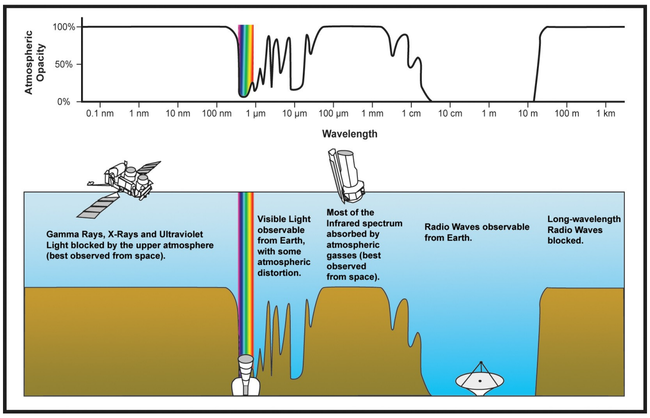


Figure 2: Atmospheric electromagnetic opacity by wavelength. (credit: NASA)

Neither X-ray nor γ-ray radiation do penetrate Earth's atmosphere, which means that their detection is only possible with space-based telescopes Brandt et al. (1992). Therefore, the observation of this type of emission is of huge importance, as it is the only way to possibly study CR sources (Lyman Spitzer, 1990).

A cosmic X-ray Background (CXB) was claimed with the launch of the first X-ray telescopes (e.g. ROSAT) in the alte 20th century. Gilli (2013) showed a collection of different CXB measurements. However, more modern space telescopes have resolved the vast majority of this background into discrete, faint sources. As a consequence, with enough resolution, this 'background' radiation is negligible. For reference, see Figure 7 of Tozzi et al. (2001), where high-energies are expected to be filled by dust-obscured AGNs Schneider (2006).

The existence of a cosmic gamma-ray background (CGRB) has been studied by the FERMI-LAT instrument in detail. It is believed that this radiation emerges from unresolved sources (e.g. SNe, pulsars, or AGNs) and possible exotic processed like dark matter (DM) annihilation or decay. The background is far from negligible and must be accounted in γ-ray data analysis. Common techniques to consider this radiation are image background subtraction (both instrumental background and template fitting), background modeling, and likelihood analysis (e.g. Markov Chain Monte Carlo (MCMC)).

Technical requirements to consider are that we expect to perform both photometric and spectroscopic analysis of observations. This is really important, as both approaches provide different information about the phenomena, complementing each other.

Further, we also require the capability of pointing in the sky to localize sources. We intend to use a wide-field γ-ray camera to monitor events, this does not need a more precise accuracy than to localize the source in a $5 - 1''$ (arcseconds). While a secondary instrument, with a narrower field of view (FoV), should have a pointing accuracy between $0.5''$ and $5''$.

2.4 Deorbitation Sustainability

3 Justification

The radiation we aim to detect, which consists of both particles and light, is not possible to study from the Earth's surface.

PCRs interact with Earth's upper atmosphere, creating particle showers, which are detectable from Earth, and so-called SCRs. However, the particles resulting from these interactions have lost part of the information inferable from Primary Cosmic ray detections. Furthermore, Earth's magnetic field also shapes how SCRs are detected. Therefore, the effect of magnetic paths should be smaller using space-based detectors.

Additionally, we also aim to observe the light CRs emit as they interact in outer space. Due to the high-energy nature of CRs, we receive such light mainly in the X-ray and γ-ray wavelengths (the most energetic ones). Although there are ground-based observatories, it is not possible to detect such wavelengths of light from Earth, as the atmosphere has an opacity effect, see figure 2 for reference.

All in all, high-energy particles and light with cosmic origin do not reach Earth's surface, meaning the development of space-based detection mission is crucial for the study of these phenomena.

Furthermore, the fundamental research in cosmic rays has wide applications. The most obvious are particle physics, nuclear and atomic physics, as well as astronomy and astrophysics.

However, also geophysics and climate studies benefit, as CRs can help us study the formation of clouds, monitor the atmosphere, and develop techniques for geologic dating. What is more, medicine benefits from both the best medical imaging methods, e.g. positron emission (PET); as of radiotherapy, the research of radiation for the development of medical treatments.

The improvement and development of new imaging techniques inspired by cosmic ray detection help to study the strength and durability of objects and substances, advancing in material science. Likewise, imaging methods allow the study of the interior of pyramids, caves, volcanoes, and other structures.

In addition, living beings in space suffer from the impact of radiation against their bodies, therefore, studying the nature of cosmic rays would help us innovate in potential solution for the protection against such radiation, which would allow very long duration crewed missions.

Finally, given the current landspace in space observation, the study of cosmic rays and high-energy phenomena seemed particularly compelling. Although these topics are at the forefront of modern astrophysics, representing relatively new areas, many modern telescopes, such as the James Webb Space Telescope (JWST), Euclid, the Vera C. Rubin Observatory (LSST), or the Nancy Grace Roman Space Telescope (WFIRST), focus primarily on electromagnetic radiation in wavelengths close to the optical range (partially covering the UV and IR).

Furthermore, two of NASA's Great Observatories[2] were once dedicated to high-energies, Compton (CGRO) and Chandra (CXO). However, the Compton Observatory was deorbited in 2000, and the Chandra Observatory is going decommissioned soon without direct replacements[3]. Other γ-ray telescopes such as SWIFT (launched 2004) or FERMI (launched 2008) are also turning old.

All in all, these factors are leaving a research gap in the area of cosmic particles and high energy phenomena, which we intend to address with our mission.

Therefore, our objective of exploring the high-energy range by observing light as well as particles (CRs) align with the current gap in observational capabilities, which develops a gap in research.

All in all, these factors highlight a limitation in observational capabilities that develops a research gap, which we intend to address with our mission by exploring the high-energy range through the observation of both light and cosmic rays.

4 Scientific Research

Totes les que vulgueu fer un treball científic expliqueu aquí les vostres idees. Per a que voleu utilitzar les dades? No cal que sigui un projecte completament desenvolupat, pero estaria bé tenir una idea dels vostres interessos.

4.1 Hubble-Lemaître Constant with Cosmic Rays

- Author: Joan Alcaide-Núñez
- Field: Cosmology and Nongalactic Astrophysics
- Context: The Hubble-Lemaître constant (Hubble, 1929) (Lemaître, 1927) represents the local expansion rate of the Universe, sets its overall scale, and enables determination of its age and history, therefore it is a fundamental measure in cosmology (Freedman et al., 2010). Since its first derivation in the 1920s, it has been recomputed multiple times (Freedman, 2021) (Valentino et al., 2021). However, its exact value is not yet known, as different methods result in different values (Freedman et al., 2010) (Aghanim et al., 2020) (245 et al., 2017). Not only that, but as techniques and instrumentation have become more precise, the discrepancy has gotten stronger (Riess et al., 2024) (Valentino et al., 2019) (Freedman, 2021). This problem is called the Hubble Tension, often also referred to as the Crisis in Cosmology. For reference, consult recent results for each method: (1) Local Distance Ladder ()[4]

  See the latest results for each method in Local Distance Ladder ()[5] ()[6]; CMB[7] (); BAO[8] (); Gravitational Waves (245 et al., 2017)[9].

  Furthermore, relatively recently it was discovered that the expansion rate of the universe is accelerating, having this discovery has very important implications in our understanding of the Universe and the crafting of the ΛCDM model[10]. so, do so it was required to observe SNe in very distant galaxies. This has additional difficulties due to the reduction of spatial resolution (crowding effect) and the diminishing of luminosity with distance. Only at greater distances, the effect of an accelerating, neutral, or decelerating expansion rate are observable.

[2] Spitzer (IR), Hubble (NIR, Optical & UV), Chandra (X-ray), and Compton (γ-ray)
[3] Chandra Decommissioning
[4] JAG
[5] JAGB (J-region Asymptotic Giant Brach), TRGB (Tip of the Red Giant Branch), Cepheids and Ia SNe (Type Ia Supernovae)
[6] the things used by riess
[7] Cosmic Microwave Background
[8] Baryonic Acoustic Oscillations
[9] Standard Siren method
[10] A model for a Universe with dark energy (Λ) and Cold Dark Matter (CDM).

There is plenty of good-quality redshift archival data, however, considering the nature of the Hubble Tension, the capability of having redshift in the same spectrum range as

- Goals: to compute the Hubble-Lemaître constant velocities and distances to galaxies are required. Type Ia supernovae (SNIa) have been proven to be precise cosmological distance indicators (Riess et al., 1994) (Riess et al., 1996) (Dhawan et al., 2017) (Alcaide Núñez, 2024). Further, SNe remnants are believed to be an interacting medium for CRs. Thus, we could detect X-ray radiation from these interactions. By analyzing the X-ray spectrum of the observation, we want to derive accurate radial velocities. With that information, we could then compute the Hubble-Lemaître constant.

  Using X-ray and γ-ray we aim to test new methods and techniques for the determination of cosmological distances and ultimately, the Hubble constant as well as other cosmological parameters. The change of the expansion rate of the Universe has a huge impact on cosmology, to begin with, the Friedman equations, and also implication in our understanding of the Universe via the (Λ-)CDM model.

- *Goals: To compute the Hubble constant using the local distance ladder (standard candles method) both velocities and distances to galaxies are required. Velocities are derived from redshift measurements. There is plenty of good-quality archival data on redshift. However, considering the nature of the Hubble Tension, the capability of having redshift in the same spectrum range as the distance-related measurements is*

  There is plenty of good-quality redshift archival data, however, considering the nature of the Hubble Tension, the capability of having redshift in the same spectrum range as

- *Goals: to compute the Hubble-Lemaître constant velocities and distances to galaxies are required. Type Ia supernovae (SNIa) have been proven to be precise cosmological distance indicators (Riess et al., 1994) (Riess et al., 1996) (Dhawan et al., 2017) (Alcaide Núñez, 2024). Further, SNe remnants are believed to be an interacting medium for CRs. Thus, we could detect X-ray radiation from these interactions. By analyzing the X-ray spectrum of the observation, we want to derive accurate radial velocities. With that information, we could then compute the Hubble-Lemaître constant.*

  Using X-ray and γ-ray we aim to test new methods and techniques for the determination of cosmological distances and ultimately, the Hubble constant as well as other cosmological parameters. The change of the expansion rate of the Universe has a huge impact on cosmology, to begin with, the Friedman equations, and also implication in our understanding of the Universe via the (Λ-)CDM model.

- *Methods: identification of Ia SNRs as CR-related X-ray sources; redshift (spectroscopic or photometric) of X-ray radiation; Doppler effect; radial velocities*

4.2 Exoplanet Atmosphere/Host Star Characterization from CR Interaction Radiation

- Author:

- Field: Earth and Planetary Sciences

- Context: On the one hand, secondary Cosmic rays (SCRs) can be detected on Earth's surface (at sea level) due to the decay of Primary Cosmic Rays (PCRs) as they hit molecules in the upper atmosphere (). This event is also called particle shower, an example of which is shown in figure 3.

  On the other hand, since the discovery of the first exoplanet in 1992 (Wolszczan et al., 1992) and the discovery of the first exoplanet around a star in 1995 (Mayor et al., 1995), the discovery of new exoplanets has been exponential and the field has grown immensely (Editorial, 2024). In 2001 the first exoplanetary atmosphere was confirmed via spectroscopy during planetary transits[11] (Charbonneau et al., 2002). The first direct image of an exoplanet was achieved by the VLT[12] (ESO)[13] (Song et al., 2006).

- Goals: We aim to detect the SCRs forming from the interaction of PCRs with exoplanetary atmospheres.

- Methods: Transit observation, X-ray/γ-ray astronomy, exoplanets, host stars, direct imaging

[11] A planetary transit happens when a planet passes between its host star and the observer. It is one of the most used methods for exoplanet discovery and characterization.

[12] Very Large Telescope

[13] European Southern Observatory

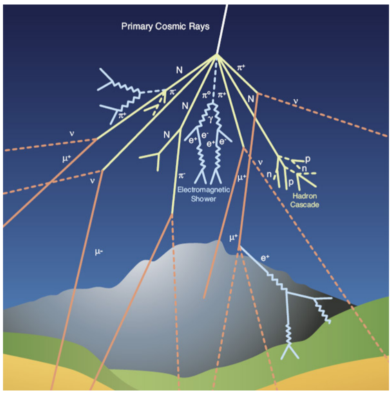


Figure 3: Cosmic ray air shower scheme by the European Council for Nuclear Research (CERN, acronym in French). It is an example of the particles resulting from the decay of PCRs in Earth's atmosphere.

4.3 Characterization of PCR Radiation in Day/Night Side of Earth's Orbit

Are the PCR from the Sun, or do they have other origins but are accelerated by the sun's magnetic field?

- Author:
- Field: Solar and Stellar Astrophysics, Earth and Planetary Sciences
- Context: Primary Cosmic Rays (PCRs) are thought to come from high-energy phenomena, however, it is argued whether sun-like stars could be PCR sources too (). Stellar (and/or solar) wind is a flow of particles that get ejected from the Sun's atmosphere (the corona).
- Goals: Our goal is to differentiate between solar PCRs and those coming from outside the solar system. By comparing particle radiation (mainly protons) during orbiting Earth's day and night side, we aim to characterize the sun's radiation and understand the physical background of it being a PCR source. We expect solar PCRs to have slower velocities and lower energies. Furthermore, their interaction with magnetic fields should be easy to track due to the short distance. The understanding of CRs within the solar system is key to developing practical applications to protect long-duration missions.
- Methods: Particle detection, magnetic fields, orbit trajectories

4.4 My Research Idea

Empleneu aquesta informació segons us sentiu còmod@s. Copieu la plantilla abans d'editar-la. :)

- Author(s)
- Field
- Context: What is the context/previous research on your research idea.
- Goals: What do you want to make on that context?
- Methods: How will you do it? What are the technological requirements for the satellite's experiments?
- Expected results: What do you expect?

5 Experiment Design

Engineering people, please do this. A specific list of the experiments/instruments is not yet determined, but you can start drafting about what technology is needed for these types of detections.
You can see specification on https://spark-program.pldspace.com/es/descripcion.html or ask for detail in the slack channel.

5.1 Primary Cosmic ray Detector

This experiment must be capable of detecting CR protons and, is possible, α-particles. The two most frequent CR particles (see 1).

5.2 Secondary Cosmic ray Detector

5.3 X-ray Observatory

Electromagnetic detection in the X-ray range. **Pointing system with a pointing accuracy of about $5''$ and $0.5''$ in both right ascension (RA) and declination (DEC) coordinates.**

5.4 γ-ray Observatory

Wide-field camera for surveying *gamma*-ray sources, less pointing capability is required.

5.5 Other stuff

- Communications
- Energy/Electricity
- Software
- Protection over radiation
- Pointing/orbit correction systems
- ...

6 Data Management Plan

We expect to collect 5 different types of data: (1) CR particle count, (2) particle energy spectra, (3) photometric and (4) spectroscopic data from X-ray and γ-ray cameras, as well as (5) environmental data from the satellite. This data is going to be collected by: (1,2) p^+/He^{2+} detectors, (3) X-ray and γ-ray cameras, (4) spectroscopic instruments, and (5) specialized sensors around the satellite.

Onboard data processing is necessary, and as a consequence temporary onboard storage. Some high-energy phenomena only last for minutes or even seconds, therefore it is crucial to have onboard data processing to live monitor observations and identify and localize potential detections, as well as creating alerts. Another consideration is to perform early-stage data reduction (e.g. instrumental background subtraction and image calibration) onboard, this way we would reduce the amount of data transmitted back to ground.

Regarding ground data processing, an automated (or semi-automated) data reduction pipeline will be developed and made available. Afterwards, each research project will analyse the data to their convenience, focusing on specific research.

Data will be made public by steps, and different depending on the data type. Firstly, regular observations will be reduced and made public internally in the collaboration as soon as possible. The data will be made totally public 180 days (6 months) after the observation. For transient events[14] data will follow the same path as regular data. However, due to the transient nature of these phenomena, some data will be shared via an alert through the General Coordinates Network (GCN). This alerts enable quick follow-up observations with other telescopes and instruments in various wavelengths, as well as cross-check observations. Additionally, we expect publish a formal data release paper, where we will extensively explain the data reduction pipeline and data accessing procedure.

We are exploring various data-sharing options, including: (1) a collaborative repository for project partners, (2) public databases like NASA's Planetary Data System (PDS) and the ESA Science Data Archive, and (3) other tailored solutions. Internal data-sharing protocols are still under development, with decisions on storage solutions, licensing, and cybersecurity measures to be made as the project advances. Further, storage capacity and data load expectations will be evaluated once the instrument specifications are finalized.

7 Risk Analysis and Mitigation Strategies

7.1 Technical Risks

- **Instrument Malfunction:** Partial of total failure in an instrument's performance.
- **Radiation Effects on Electronics:** Potential damage to electronic components from high-energy cosmic rays or radiation in space.

[14] As transient events we are considering GRBs, SNe, transient CRs, and any other temporary events observed.

- **Data Transmission Issues:** Problems related to data transfer between the satellite and ground stations, including signal degradation and loss of data integrity.

Mitigations:

- **Instrument Malfunction:** Implement rigorous testing and validation procedures, and redundant design of instruments.
- **Radiation Effects on Electronics:** Utilize radiation-hardened components and implement shielding solutions to protect sensitive electronics, without affecting the performance of radiation detecting instruments.
- **Data Transmission Issues:** Employ error correction protocols and data multiple-check possibility. Also include, automated protocols (i.e., self deorbit) in case of lost of communications.

7.2 Schedule Risks

Schedule risks refer to potential change or delays in the project timeline that could impact mission success. These include:

- **Possible Schedule Changes:** Unforeseen delays in development, testing, or launch preparation.
- **Launch Window:** Risks associated with timing and availability of launch opportunities, which may affect the mission schedule.

Mitigations:

- **Possible Schedule Changes:** Develop a detailed project timeline with built-in buffer periods to accommodate unexpected delays. Regularly review and adjust schedules as necessary. Also, enable overlapping activities and parallel processes, minimizing the impact on critical deadlines.
- **Launch Window:** Coordinate closely with launch providers to secure a suitable launch window and have contingency plans in place for alternative dates.

7.3 Financial Risk

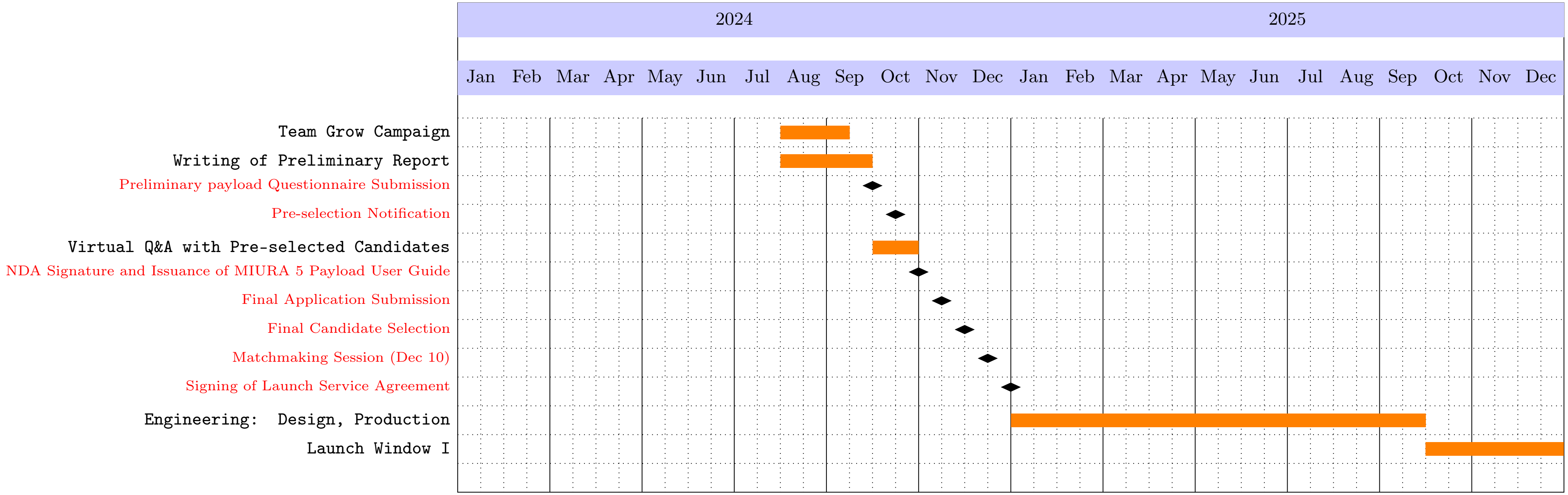
Financial risks involve potential issues related to funding and budget constraints. We are a student organization (see section 9), without any source of funding, operating fully voluntarily.

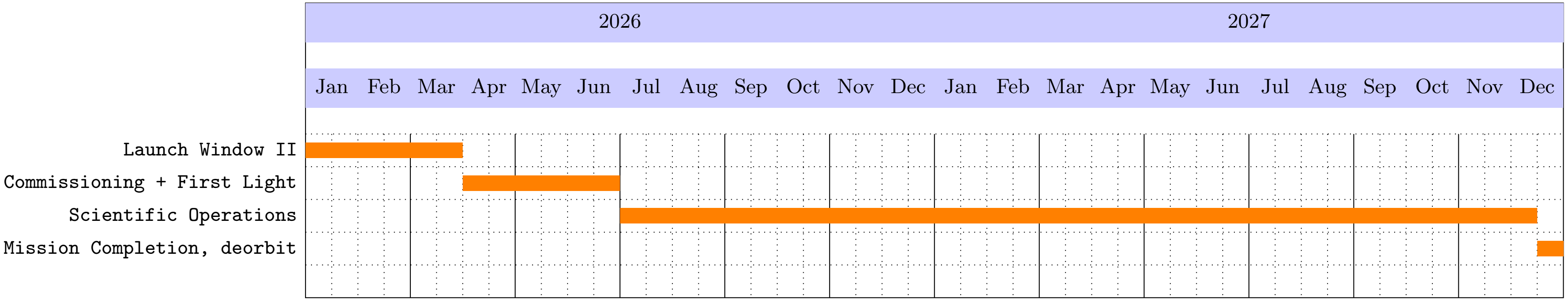
7.4 Risks Monitoring

Monitoring the status of instruments and software, and deadlines throughout the mission is crucial to ensure proper timely identification and response to potential issues. Risks are evaluated using a risk matrix, which assesses both the severity of potential impact and the probability of their occurrence.

- **Monitoring Process:** Establish a risk monitoring plan that includes regular reviews and updates of risk status.
- **Frequency:** Conduct risk assessments at key project milestones and during critical phases of the mission, such as pre-launch, launch, and operational phases.
- **Responsibility:** Each member of the collaboration is responsible of monitoring potential risks on the outcomes of her/his work to ensure that risks are identified effectively.

8 Project Timeline





Red text indicates deadline established by PLDSpace (from Application Stages). Also, note that the duration of the scientific operations is not yet decided. (last checked Aug 24, 2024).

9 Team Presentation

We are a group students from various schools in the greater Barcelona metropolitan area with an interest in scientific research and space exploration. We are united by the motivation to participate in the Spark program and the excitement to carry out this project. Each person has a different profile and field or expertise, so we all bring our knowledge and skills to the team. Below is a brief presentation of all participants. Empleneu aquesta informació segons us sentiu còmod@s. Copieu la plantilla abans d'editar-la si us plau, :)

9.1 Joan Alcaide-Núñez

- Contact: joanalnu@outlook.com
- Course: 12th grade, 2º Bachillerato (DSB)
- Field of work: Astronomy & Astrophysics, Cosmology
- Experience: Joves i Ciència '23, Jugend Forscht '24, Explainers '22
- Hobbies: playing the piano, reading, traveling, coding
- Links: LinkedIn, Personal website

9.2 Martí Delgado Farriol

- Contact: marti.delgado.farriol@gmail.com
- Course: 2º Bachillerato (Pureza de María, Sant Cugat del Vallès)
- Field of work: Astronomy & Astrophysics
- Experience: Joves i Ciència '23
- Hobbies: Astrophotography, Chemistry, Garden agriculture.

9.3 Lluc Soler Manich

- Contact: llucsoler.m@gmail.com
- Course: 12th grade / 2º Bachillerato (CIC Escola de Batxillerats)
- Field of work: Astrophysics, Engineering (Aerospace)
- Experience: CIC-MIT Hackathon '22, Bojos per la física '24, BIYSC (Cosmic Rays) '24
- Hobbies: cycling, skiing, playing the guitar, physics

9.4 Anna Abadal Garrido

- Contact: talaxar07@gmail.com
- Course: 2º Bachillerat (Salesians of Sarrià)
- Field of work: Engineering
- Experience: Explainers '24, Dissabtes de la Física '24
- Hobbies: Building models, climbing, chemistry, football and reading.

9.5 Emma Massó Sala

- Contact: emmamassomail@gmail.com
- Course: 12th grade, 2º Bachillerato (CIC Escola de Batxillerats)
- Field of work: Engineering
- Experience: Joves i Ciència '23, CIC-MIT Hackathon '22, '23 & '24, Explainers '22
- Hobbies: reading, traveling, singing & dancing.

9.6 Your Beautiful Name

- Your weird **email address**
- Course
- Cool **field of work**
- Amazing **experience**
- Looooong **links**
- Interesting **hobbies** (or comments)

10 Conclusion

Summarize with key points of proposal, reaffirmation of mission relevance, outline of the expected impact, and next steps for the project.

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