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

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Abstract

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

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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).

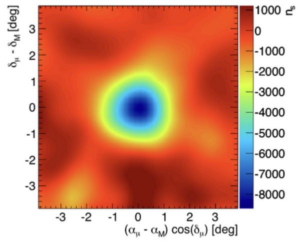


Figure 1: Contour plot of the muon deficit as measured by IceCube in the region around the Moon's position, the so-called on-source region (credit: IceCube Collaboration)

When these particles interact with a medium, they decay in 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 Figure 1).

Furthermore, there is another radiation which helps trace CRs. However, it can not been categorized as cosmic rays 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 the ultraviolet (UV) and infrared (IR) spectrum. These photons have different properties as compared with fermions and hadrons, opening a complete new way of study.

Furthermore, CRs can also be divided by origin, which enables differentiation between galactic and extragalactic CRs. Galactic CRs emerge mainly from the sun, other nearby stars, or 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 distance to the source is also a useful tool for estimating the origin[1].

Although CRs are known to come from outside of Earth (Hess, 1912), 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

As explained before (see table 1), CRs mainly consist of protons (p^+) and α-particles, i.e. Helium nuclei, (α, α^{2+}, or He^{2+}); summing up to 97%. In order to explore the high-energy particles, providing useful data for the study of CRs, solar wind, astroparticle physics, and further topics of research, we aim to detect these particles using a variety of detectors. Each of the types of detectors, outlined in section 5 are capable of detecting a different property of these particles (e.g. velocity, energy, etc.). Therefore, all of them are needed to provide complete and reliable datasets.

[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.

2.2 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 CRs are expected to emit on account of their initial energy and velocity.

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 γ-ray background (CGRB) has been studied by the FERMI-LAT instrument in detail. It is believed that this radiation emerges from unresolved source (e.g. SNe, pulsars, or AGNs) and possible exotic processes 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 especially important, as both approaches provide different information and data about the phenomena, complementing each other.

Further, light observations 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 sources in $5''$ to $1''$ (arcseconds). While a narrower field of view (FoV), should have a pointing accuracy between $0.5''$ and $1''$.

2.3 Deorbitation & Sustainability

A crucial aspect of modern space mission is ensuring they adhere to sustainability guidelines, including proper end-of-life procedures for deorbitation. Space debris represents a danger to space traffic and human spaceflight, as well as posing a threat to Earth and Space based astronomical observations. Therefore, we want our mission to incorporate well-defined deorbitation plan to ensure that the satellite does not contribute to this growing problem., following international space mitigation standards. Applicable measures orbital decay monitoring, end-of-mission deorbit burn, sustainability compliance, and post-mission disposal.

Given that our satellite will operate in a Sun-Synchronous Orbit (SSO), as given by the Spark program, we aim to perform a controlled deorbitation maneuver at the end of the mission's operational lifetime. While natural orbital decay due to atmospheric is slower at the higher altitudes typical of SSO, we plan to initiate a controlled deorbitation sequence. This will involve reducing the satellite's altitude through propulsion-based maneuvers, eventually leading to a final derobit burn. The objective is to ensure that the satellite safely reenters Earth's atmosphere, where it will burn up, minimizing the risk of debris surviving re-entry and reaching the surface.

3 Justification

3.1 Atmospheric Opacity

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 PCRs 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, neither X-ray nor γ-ray radiation do penetrate Earth's atmosphere (see Figure 2, which means that their detections 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 study high-energy phenomena(Lyman Spitzer, 1990).

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.

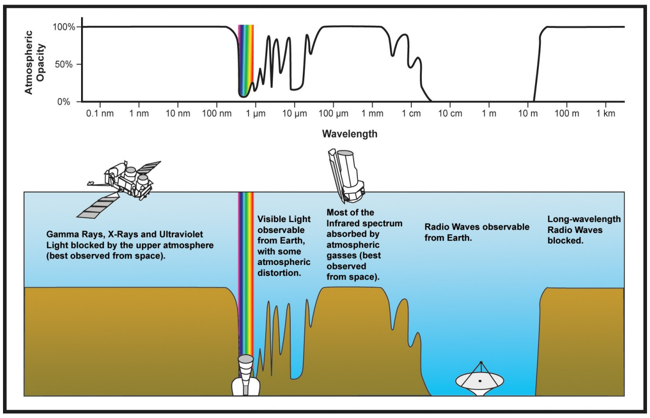


Figure 2: Atmospheric electromagnetic opacity by wavelength. (credit: NASA)

3.2 Application

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.

3.3 Observational and Research Gap

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.

[2]Spitzer (IR), Hubble (NIR, Optical & UV), Chandra (X-ray), and Compton (γ-ray)
[3]Chandra Decommissioning

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 Gamma-Ray Burst Cosmology

- Author: Joan Alcaide-Núñez
- Field: Cosmology and Extragalactic 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. It is a fundamental measure in cosmology and a key stone for cosmological models of the Universe (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., 2024a) (Valentino et al., 2019) (Freedman, 2021). This problem is called the Hubble Tension, often also referred to as the Crisis in Cosmology.

  For reference, see the latest measurements for each method in Figure 3; Local Distance Ladder (Freedman et al., 2024)[4] (Riess et al., 2024b)[5]; CMB (Aghanim et al., 2020)[6]; BAO (Collaboration et al., 2024)[7]; and Gravitational Waves (245 et al., 2017)[8].

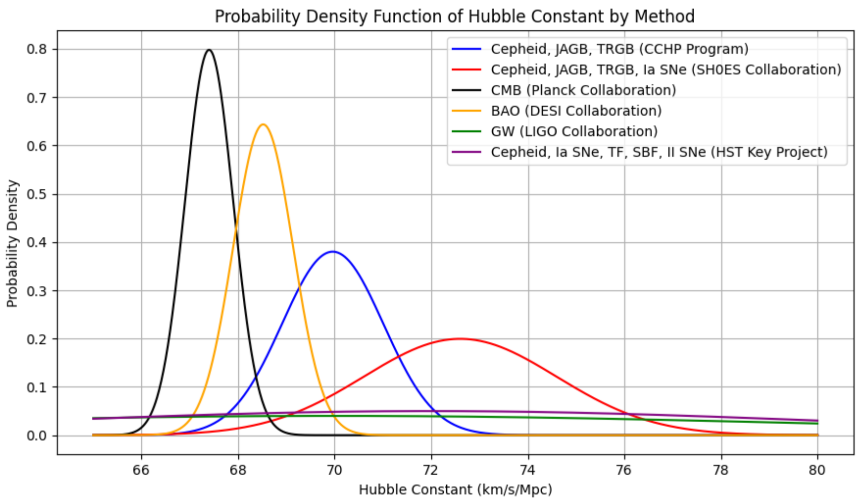


Figure 3: Probability Density Function diagram for different measurements of the Hubble Constant. Data from: Freedman et al. (2024) (blue), Riess et al. (2024b) (red), Aghanim et al. (2020) (black), Collaboration et al. (2024) (orange), 245 et al. (2017) (green), Freedman et al. (2001) (purple).

  Furthermore, relatively recently it was discovered that the expansion rate of the Universe is accelerating, this discovery having very important implications in our understanding of the Universe and the crafting of the ΛCDM model[9] To 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 luminosity. However, only at this greater distance, the effect of an accelerating, neutral, or decelerating expansion rate are observable. More recently, some research has posed that dark energy, the substance responsible for accelerating the expansion, is evolving in function of time. If true, this could be the first hint about the nature of dark energy since its discovery.

[4] JAGB (J-region Asymptotic Giant Branch), TRGB (Tip of the Red Giant Branch), Cepheids, and Ia SNe (Type Ia Supernovae)
[5] Different Ia SNe catalogs
[6] Cosmic Microwave Background
[7] Baryonic Acoustic Oscillations
[8] Standard Siren method
[9] A cosmological model for a Universe with dark energy (Λ) and Cold Dark Matter (CDM).

- Goals: Our aim is to use Gamma-Ray Bursts (GRBs) as cosmological distance indicators. GRBs are the most energetic events in the Universe, releasing in just a few seconds more energy than the Sun emits over its entire lifetime. Hence, they can be observed at great distances. For reference GRBs have been observed up to $z > 8$, while the more distant Ia SN is at $z < 2$. The standardisation of their high luminosity and the use of GRBs as cosmological distance indicators will provide very valuable data for the study of the Hubble Tension, the nature of dark energy, and thus the validation of ΛCDM. Furthermore, the impact on the field is considerable, as greater distances will enable more precise fitting of cosmological parameters to the data, and new measurements.

- Methods: γ-ray photometric and X-ray photometric and spectroscopic analysis; identification of GRBs; study of new methods for the standardization of GRBs cosmological distances; cross-check with external databases for redshift data.

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 4.

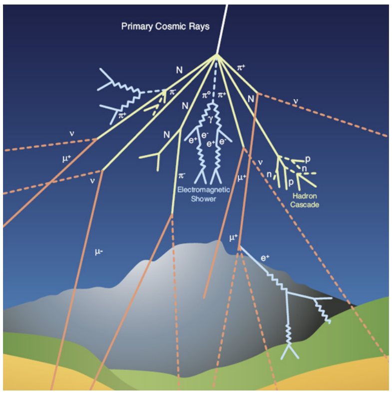


Figure 4: Cosmic ray air shower scheme by the European Council for Nuclear Research (CERN, acronym in French). It is an example of the particles resulting from the decay of PCRs in Earth's atmosphere.

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[10] (Charbonneau et al., 2002). The first direct image of an exoplanet was achieved by the VLT[11] (ESO)[12] (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

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: Martí Delgado Farriol

- Field: Solar and Stellar Astrophysics, Earth and Planetary Sciences

[10] 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.
[11] Very Large Telescope
[12] European Southern Observatory

- 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

You can see specifications 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, if possible, α-particles. The two most frequent CR particles (see 1).

When considering direct measurements, as this is the case, combining different detectors is essential to obtain a full characterization of the particles (Piera, 2012). Therefore, the detector should be "layer" built, basically stack the detectors together obtaining a relatively compact device (taking into consideration the distance between detectors needed to perform some detections). There are three types of measurements which need separate devices, which are the following:

- **Time-of-Flight (TOF):** Time-of-flight detectors work by pairs, and they trigger a clock when a particle hits the first one, which is stopped when the second one is hit. Then, through a series of calculations, the particle velocity can be obtained. In our case, and as many other satellites CR detectors (i.e. PAMELA, AMS), scintillators will be used. These are plastics or liquids which emit a flash of light when they are hit by a charged particle, for instance protons or *alpha* particles. This light is then detected with photomultipliers which are part of an electrical circuit the can recognize a difference in the voltage. The main disadvantage of scintillators is that the light produced is not linear, that means that the energy can not be inferred (Zeitlin, 2012).
- **Charge Detector:** Essentially, this detector determines whether the charge is positive or negative and the value itself. Among the available options, on that is fairly used in other detectors are Silicon Detectors. They work as a diodes to which a voltage is applied, acting as a parallel-plate ionization chamber, that is, when a charged particle passes through it generates a current. (Zeitlin, 2012)
- **Energy Detector:** The principal function of this apparatus is to establish the total energy of the particle. In this case, an electromagnetic calorimeter is required. It works by the principle of "destruction", that means a particle loses all its energy passing through the detector, which is converted into a signal (Masciocchi, 2017).

5.2 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.**

Many x-ray detection methods have been discovered and evaluated, but the one that has been the most successfully applied within scientific purposes are Charged-Coupled Devices (CCDs). CCDs are arrays of linked capacitors. When this device is exposed to electromagnetic waves, photons interact with the semiconductor substrate. When these photons pass through the CCDs, they lose energy through different effects (Compton scattering, fluorescence or photoelectric effect) generating electron-hole pairs. Considering a Silicon substrate, an average ionization energy of $3.65eV$ is required. Therefore, we can estimate the energy of the X-ray with the following formula $N_e = E_x/w$. Where N_e is the number of electrons, E_x is the energy of the X-ray photon and w the ionization energy ($3.65eV$). This charge is collected under one gate, and then is transferred through adjoining gates to the output amplifier.

To ensure high quality measurements, each photon should be collected within only one pixel. Nevertheless, it is possible that one photon interacts with two, or more, different pixels. To address this situation, when the detector is used in a photon-counting mode, an intensity-threshold is used to distinguish between single-pixel and multiple-pixel events. A grading system is used in X-ray telescopes with this technology, such as ASCA (see figure 5), to discriminate between X-ray and cosmic rays (Grant, 2011) (Teledyne, 2024).

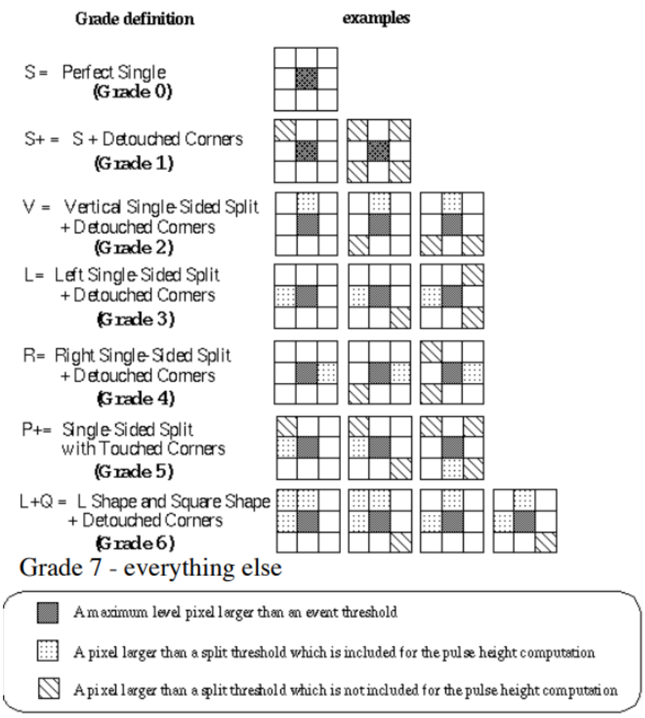


Figure 5: ASCA Grade Codes (credit: (Grant, 2011))

5.3 γ-ray Observatory

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

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.

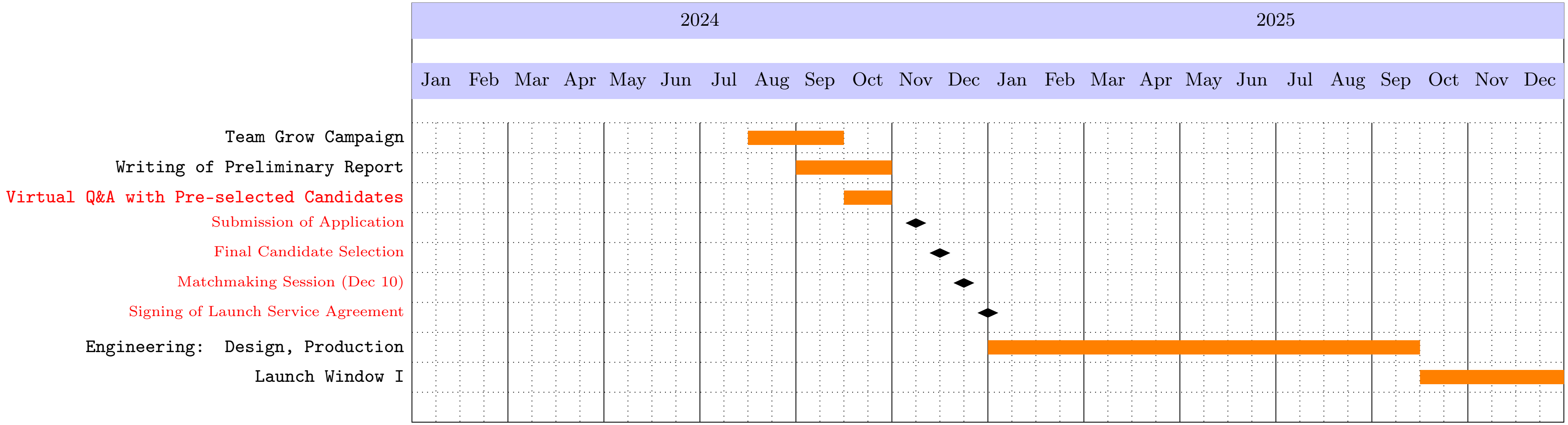
Regarding ground data processing, an automated (or semi-automated) data reduction pipeline will be developed and made available. Afterwards, each research project will analyse the data to their convenience, focusing on specific research.

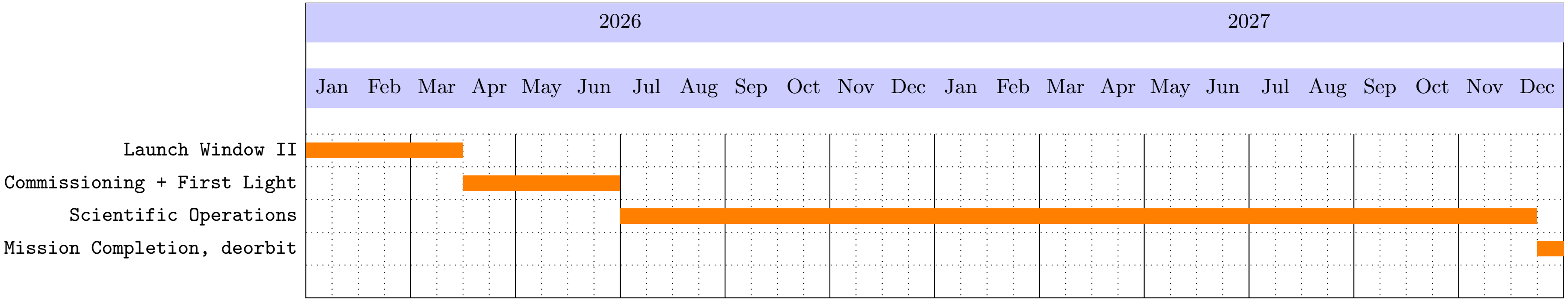
Data will be made public by steps, and different depending on the data type. Firstly, regular observations will be reduced and made public internally in the collaboration as soon as possible. The data will be made totally public 180 days (6 months) after the observation. For transient events[13] data 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.

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

7 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).

8 Team Presentation

We are a group of students from various schools in the greater Barcelona metropolitan area with interests 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 member has a different profile and field of expertise, so everyone brings their own knowledge and skills to the team. Furthermore, we appreciate and are grateful for the support of science and technology teachers supporting us. Below is a brief presentation of all participants. Empleneu aquesta information segons us sentiu còmod@s. Copie la plantilla abans d'editar-la si us pla, :)

8.1 Joan Alcaide-Núñez

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- 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

8.2 Martí Delgado Farriol

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- Experience: Joves i Ciència '23
- Hobbies: Astrophotography, Chemistry, Garden agriculture.

8.3 Lluc Soler Manich

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- 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

8.4 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.

8.5 Emma Massó Sala

- Contact: emmamassomail@gmail.com
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- Field of work: Engineering
- Experience: Joves i Ciència '23, CIC-MIT Hackathon '22, '23 & '24, Explainers '22
- Hobbies: reading, traveling, singing & dancing.

8.6 Christian Schaefter González

- Contact: chrsch@tinet.org
- Course: 12th grade, 2º Bachillerato (DSB)
- Field of work: Engineering
- Experience: Jugend Forscht '24
- Hobbies: CAD Design, 3D-printing, rocketry, skiing

8.7 Hongda Zheng

- Contact: zhenghongda7@gmail.com
- Course: 12th grade, 2º Bachillerato
- Field of work: Engineering
- Experience: Explainers '24, Anem per més Mates
- Hobbies: Playing Tennis, Reading, Mathematics

8.8 Your Beautiful Name

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

9 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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