LOW-ENERGY COSMIC RAYS: RADIATION ENVIRONMENT STUDIES AND ASTROPHYSICS ON THE DEEP SPACE GATEWAY.

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Introduction: Low-energy cosmic rays and solar particles are of key interest for human space flight and astrophysics. The proposed location of the Deep Space Gateway (DSG) in orbit around the moon places it in a location that is uniquely suited not only for the investigation of the low-energy radiation that astronauts will be subjected to in deep space, but also to help shed light on one of the most intriguing astrophysical mysteries of today: What is the universe made of?

We propose to place an experiment on the DSG whose observations would facilitate the research of many different scientific communities. By concentrating the efforts of scientists from around the world, the limited resources of the DSG could best be utilized.

Crew Radiation Exposure: Mitigating the effects of radiation exposure poses a serious challenge for plans to send astronauts back to the moon and, ultimately, to Mars and other deep-space destinations. Current measurements [1, 2] suggest astronauts would reach or even exceed their lifetime dosage limits after a single mission to Mars, but such predictions have large uncertainties stemming from the currently limited experimental input. Research into improving shielding technologies and accurately estimating doses and their health impacts—which is crucial to successful long-term spaceflight—requires accurate measurements of the radiation environment and benchmarking against radiation transport simulations.

The space radiation environment is dominated by charged-particle radiation of cosmic origin, the solar wind, and short bursts of energetic particles released by the sun at irregular intervals. Many experiments have been performed to characterize this environment, for example by using particle detectors on the International Space Station (ISS) [3, 4].

Few measurements, however, were performed beyond low Earth orbit (LEO). Spacecraft in LEO are partially shielded from charged-particle radiation by Earth's magnetosphere, which deflects particles with too low energies to penetrate the field. A welcome natural protection for astronauts on the ISS, this effect severely limits our knowledge of the space radiation environment at lower particle energies, because experiments can only detect cosmic rays with energies above the cut-off value at their respective orbital positions. The few measurements available were taken aboard spacecraft enroute to or in orbit around other planets of the solar system—such as aboard the Mars Science Laboratory on its way to Mars and on the Mars surface [1, 2], and the Lunar Reconnaissance Orbiter in orbit around the moon [5]. The primary missions of these spacecraft were, however, not to characterize the space radiation environment. Consequently, the capabilities of their detectors were limited—mostly due to mass constraints—and the measurements therefore only provide a subset of the full picture. Additionally, many measurements were performed over a limited period of time, giving us only a snapshot view at a given point in time and space.

In orbit around the moon or one of the Earth-moon Lagrange points, the DSG will spend about two thirds of its time outside of Earth's magnetosphere. A charged-particle detector would thus be able to access the full spectrum of cosmic rays, allowing the comprehensive and long-term characterization of low-energy cosmic radiation for the very first time. Such a measurement could help to build the future foundation of radiation protection in manned space flight.

Cosmic Ray Studies and Heliophysics: The characterization of the space radiation environment would not only support the manned exploration of space, but also deliver invaluable data for astrophysical studies. Even though a recent measurement seems to confirm the long-standing theory that cosmic rays are, at least partially, created in stellar explosions [6], other measurements indicate that additional sources must exist [7], but their nature has yet to be revealed. An experiment on the DSG could contribute to solving this issue by characterizing the cosmic radiation environment at the low energies that are inaccessible to detectors in LEO. Scientists studying the sun could also greatly benefit from such measurements, as a substantial amount of charged solar-wind particles is deflected by Earth's magnetosphere.

The Search for Dark Matter: One of the most intriguing mysteries in astrophysics today is the question of the composition of the universe. We know that only about 4% of the mass of the universe is made of matter as we know it. About a quarter is made of what scientists call *dark matter*: electromagnetically invisible particles that primarily interact with ordinary matter through gravity. The rest is made of even stranger stuff, which is usually referred to as *dark energy*. We can infer the existence of dark matter from astronomical observations—such as the otherwise unexplainably high rotational velocities of galaxies—cosmological considerations, and directly observable gravitational effects. These observations are very strong hints for the existence of dark matter. They do not, however, let us draw conclusions about the nature of it, nor are they a definite proof of its existence. We only detect the gravitational presence of something that we cannot observe directly by traditional means of astronomy, i.e. using telescopes sensitive in the electromagnetic spectrum.

To understand the nature of dark matter, experiments must be performed that observe the interaction of dark matter and ordinary matter in the context of nuclear and particle physics, that is, at atomic and sub-atomic levels. Several ground-based experiments (e.g. CRESST, DarkSide) attempt the direct detection of such rare interactions, and some supporting data may come from high-energy colliders (LHC, SuperKEKB). Other scientists focus on indirect detection techniques: Theoretical models predict that dark matter particles could decay into detectable ordinary-matter particles, such as gamma rays, neutrinos, and antimatter particles. While experiments focusing on gamma rays (e.g. Fermi LAT) and neutrinos (e.g. IceCube) have so far been unsuccessful in observing a convincing signal, space-based particle detectors measuring cosmic-ray antimatter found a more significant anomaly that may be caused by dark matter. The PAMELA [8], Fermi LAT [9], and AMS [10] collaborations reported consistent measurements of a so far unexplainable excessive flux of positrons at high energies. Even though this could very well be a first piece in the puzzle, the available data is not sufficient to draw a scientifically profound conclusion about the existence and nature of dark matter.

The issue can only be solved through a combination of particle physics and astrophysics experiments. One of the most promising candidates that could complement existing findings is a measurement of the cosmic-ray antiproton and antideuteron fluxes [11]. At very low energies, there are virtually no other known processes that produce these particles. Any unambiguous signal would thus strongly support some existing dark matter theories. Again, experiments in LEO cannot perform such a measurement due to the shielding effects of Earth's magnetosphere. A low-energy particle detector on the DSG, however, would be ideally located to do so.

An Experiment on the DSG: We propose to install a charged-particle detector on the DSG that facilitates the research of scientists from all aforementioned communities—and perhaps even from ones we overlooked so far. We believe there is an overlap significant enough for a single instrument to serve all disciplines, without the need for disruptive compromises. The capabilities of such a detector should complement those of existing and future instruments in LEO or elsewhere, with only a slight overlap in sensitivity to allow the cross-calibration of measurements. We see no apparent reason for duplicating capabilities that can be achieved with less effort at more accessible locations.

The detector should be sensitive at energies below the cut-off values in LEO caused by Earth's magnetosphere. The lower sensitivity limit in energy should be discussed amongst scientists from all interested disciplines, as should the sensitivity in flux. We suspect that much of that discussion may be driven by more 'exotic' disciplines, such as the search for dark matter.

The sensitivity at lower energies means that the detector can be built much lighter and more compact than comparable instruments (e.g. AMS-02 on the ISS), since the magnets required for spectrometry do not need to be as powerful. New technologies may even render the use of a magnetic spectrometer superfluous, reducing the mass and the power consumption of the system further. Recent advances in semiconductor technologies and processing electronics should also ensure an increased efficiency and performance of the detector, as they did in ground-based experiments. Accumulating experiences from previous space-based instruments should help to streamline the detector design.

The instrument would need to be mounted with a free line of sight on the exterior of the DSG, ideally pointing away from the moon surface at all times. There is no need for a particular type of orbit. We estimate that an instrument mass of as low as 100 to 200 kg, a volume of less than 1 m^3, and a power consumption of 200 to 400 W are achievable. After installation, the detector would operate autonomously at all times and would not need any crew interaction.

Conclusion: We believe there is a strong case for cosmic-ray science on the DSG. The gateway will be ideally located to access parts of the cosmic and solar radiation spectrum that are hidden to instruments in LEO. Also, it will provide all the necessary infrastructure to support such an experiment. By concentrating the efforts of different disciplines, one relatively compact instrument could serve a multitude of astrophysical and medical science communities. While we have tried to identify some disciplines that would benefit from such a collaborative effort, we by no means assume our list to be exhaustive. We hope, though, that it will serve as a starting point for discussions.

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