NATIONAL CENTER FOR CASE STUDY TEACHING IN SCIENCE

Sheer Dumb Luck: A Space Weather Emergency

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The thrust had pushed strongly against her back, making breathing difficult. The countdown seemed to have lasted much longer than she knew it actually had, especially after the two-minute mark. This was the first manned mission beyond low-Earth orbits since the Apollo missions had been stopped in 1972, long before she was born, and Dana felt extremely fortunate to have been chosen to command this mission and assume responsibility for the crew. At sixty seconds, she had thought about her dreams of being an astronaut since she was a girl at Space Camp in Huntsville, Alabama, and her goal of achieving this dream was the main reason why she had majored in physics in college and completed a master's degree in astronomy. At thirty seconds, Dana recalled how she had signed up for NASA, the National Aeronautics and Space Administration, a few years earlier and the grueling selection process she had endured. And then it was five, four, three, two, one, liftoff! Dana was on her way to the Moon.

Earth was now receding fast beneath her, and Dana was two Earth radii above ground. She had already passed through the inner Van Allen belt—the belt of energetic protons and electrons held together by Earth's magnetic field—and was fast approaching the outer belt, which is composed mostly of electrons even more energetic than those in the inner belt. Dana knew that she was still in the safe zone between the inner and outer belts, but she also knew that once she passed through the outer belt, she would be exposed to solar wind and cosmic rays. She knew that solar wind consisted of energetic charged particles hurtling outward from the upper atmosphere of the Sun, and that Earth's magnetosphere provided protection from these particles, which would otherwise be so dangerous that cancer would be the problem of only the lucky few who would not die from lethal doses of radiation. Dana also knew that without the precious protection from Earth's magnetic field the solar wind could literally blow away the atmosphere. As Dana continued to ascend she reflected on that last thought and began wondering whether Mars had lost its magnetic field and suffered a similar fate; perhaps that's why Mars had such a rarified atmosphere, about one one-hundredth of the pressure of Earth's atmosphere. Of course Mars' weaker gravity was an important factor too, as weaker gravity may have influenced that process in two ways: exerting a weaker hold on the elements of the atmosphere, and causing Mars' core to cool down and solidify more rapidly, thereby losing the magnetic field it once had, in addition to shutting down plate tectonics. To have a magnetic field, Dana recalled, a planet must have a core made of an electrically conducting fluid like the Earth's iron-rich core, internal temperatures must be just right to generate convection in the core, and the planet must rotate sufficiently rapidly. These thoughts made Dana start wondering how much the habitability of Earth was a fluke; perhaps with a slightly smaller mass her home planet would be as barren as Mars is today? And why were Moon rocks brought to Earth by Apollo astronauts magnetized even though the Moon too, not just Mars, had a negligibly small global magnetic field? Dana was excited that part of her mission was to collect Moon rocks for studying their magnetism in an attempt to answer this long-standing open question.

Dana's excitement about going to the Moon was hardly diminished by concerns for her own safety and that of the crew she was commanding. The electronics on her spacecraft and the shielding provided by the spacecraft itself—the thick metal shielding and the insulating layer of lightweight hydrogen-rich polyethylene plastic, called RFX1—were hardened to provide more than enough protection against levels of radiation even higher than those likely to be present most of the time, and more than enough to protect against a strong solar radiation storm, rated S3 on the space weather scale by the National Oceanic and Atmospheric Administration (NOAA). She was feeling lucky to have those radiative countermeasures as she reflected on the much humbler protections provided to the Apollo astronauts. Astronauts at the time of the Apollo missions were just gambling that the environment would be sufficiently safe. Her sense of safety and confidence in the advanced engineering of her spacecraft and competence of her crew allowed her to doze off as the Moon voyage continued.

When she woke up, Dana was almost all the way to the Moon, and in less than two hours would start orbiting it for a few times before landing at the center of Mare Tranquillitatis, the Sea of Tranquility, the same site that Apollo 11 visited back in 1969. Its very name was a misnomer: astronomers of old thought it was an ocean because of the unscarred surface. In contrast with the lunar highlands, there are very few impact craters in the maria, but the correct interpretation—and Dana remembered it well from her astronomy classes—was that the maria surface was much younger, and formed well after the age of late heavy bombardment. Earth seemed to be getting smaller and smaller, and the Moon was growing larger. Dana could see the pale blue sphere of Earth, patched with a white cloud coverage over the oceans and over the green and brown continents on the day side, and the darkness of the night side interspaced with the jewels of big city lights that she could see only when eclipsing the day side with her hand. She never thought anything could be so beautiful. If everything in the next few hours went according to plan, she would be the first woman to walk on the Moon. She would see the Earth rise over the horizon of the Moon. She would make the childhood dreams of that little girl in Alabama come true!

The alarm sound took her abruptly away from her daydreaming. Houston radioed a warning message. Space weather forecast was for an extreme storm, S5 on the NOAA scale, a very rare event that occurred less frequently than once per solar cycle. But this alert was even worse; the strength of this event could perhaps even exceed that of the 1859 Carrington event or that of the solar storm of 2012. Houston's message was that about five minutes earlier a giant solar storm had been observed, sending high-energy charged particles at such numbers that would undoubtedly give her, and her crewmembers, lethal radiation doses. She could sense restrained panic in the Houston communication. A lot was on the line with this mission, and failure would put the entire manned exploration program of the solar system in jeopardy. Dana was of course mostly concerned at this point with the safety of herself and of her crew, but Dana was confident that NASA would do everything they could to save them.

Depending on the energy of the burst, the solar particles could reach the spacecraft in as little as 15 minutes, as in the case of the January 20, 2005 event, or in several hours, which was more common. Regardless, it was certainly too late to abort the mission and return to Earth, where they would be relatively safe underneath the protective shield of Earth's magnetosphere. The NASA expert continued to detail the different options. But they didn't have enough time to reach the Moon if the particles were so energetic that they would reach the Earth–Moon system in just 15 minutes. In that case, they could all be dying before even getting to the Moon. Dana couldn't help thinking of how lucky the Apollo astronauts had been to have had calm space weather. With only two hours available to them assuming optimistic conditions, they wouldn't have enough time to land on the Moon, even if the particles were less energetic, and even if they could land safely without orbiting the Moon first. The situation looked dire as Dana brainstormed possible solutions.

NASA experts radioed them reporting that they could not propose anything that would be useful, and that for the time being they would be continuing on the predetermined trajectory toward the Moon, toward what increasingly seemed to be certain death.

Dana expected her whole life to flash before her eyes. It didn't. All she could hear was a countdown to the most likely time of arrival of the radiation. Unlike the previous countdown, she wasn't looking forward with anticipation this time around. The two hours were almost gone, and the computer was about to start the Hohmann maneuver that would transfer them to a circumlunar orbit. If only the spacecraft had stronger radiation shields! But Dana knew that stronger protective measures would have made the spacecraft much heavier and therefore make the mission much more expensive. In view of the rarity of such strong solar storms, she knew the design compromise was a very reasonable one, although she kept feeling betrayed by the design team. Dana knew they needed more robust shielding.

Their spacecraft was about to start orbiting the Moon, a spacecraft that increasingly seemed likely to become an orbiting sarcophagus... But wait! The Moon could shield them! The Moon could stop these charged particles! After all, this was how the Earth naturally blocked half of all the damaging cosmic rays particles, except that in the case of the solar wind, the directionality of the flow was such that the far side of the Moon—the side far from the Sun—was totally safe. How come she hadn't thought of that before instead of just listening to the annoying countdown?

She could change the parameters of the coming Hohmann transfer from those that would result in a circular Moon orbit followed by another transfer to the lunar surface, to those that would result in a very high eccentricity orbit. Such an adjustment would allow them to hide in the Moon's shadow for much longer than the 48 or so minutes that the pre-chosen circular orbit would allow. If they stayed in the Moon's shadow long enough, in a way that they would be in the Moon's shadow when the storm arrived, and they stayed in its shadow for the duration of the storm until the storm's trailing edge passed, they would be safe. It could take hours for the storm to pass, but it could also take days. Now it would all come down to a matter of chance whether the parameters Dana chose would be such that the orbit would shield them for long enough. When all was said and done, despite their advanced science, despite their advanced engineering, despite their advanced technology, despite the redundant life support systems, despite their ingenuity, it was all going to be just a matter of sheer dumb luck.

Questions

1. The mass of Venus is very close to that of Earth (81.6% of Earth's mass), and it is only a little closer to the Sun, located 0.723 astronomical units (AU) from the Sun. Venus does not have a strong magnetic field, with the measured upper limit being 1 part in 10^5 the strength of Earth's magnetic field. Yet, Venusian atmosphere is much denser than Earth's, with surface pressure of about 100 atm. Explain how Venus can have a thick atmosphere without having a magnetic field, and why Mars has a very thin atmosphere, even though it has no strong magnetic field.
2. The Apollo missions to the Moon had hardly any protection from solar wind or cosmic rays, yet many Apollo astronauts are still alive and appear to have normal health. Explain how Apollo astronauts did not suffer from acute radiation sickness. Could the same be applicable for Mars flights?
3. What is radiation sickness? What are the common symptoms of radiation sickness? Of the three types of radioactivity (alpha, beta, and gamma radiation), which is the most dangerous in causing radiation sickness?
4. What are cosmic rays, and what are their different kinds (by source)? How is life on Earth protected from cosmic rays?
5. This question set is about Earth's magnetic field.
   a. What causes the magnetic field?
   b. Is Earth's magnetic field shaped like a dipole magnetic field? What shape does it have? What is the reason for that shape?
   c. Describe Earth's magnetic field starting with interplanetary space and moving inward toward the Earth. What are the main parts of the magnetic field and the transitions from one part to another? Draw a diagram showing the main regions and boundaries of the Earth's magnetosphere.
6. What are the main explanations for magnetized Moon rocks?
7. What is the National Oceanic and Atmospheric Administration (NOAA) and what are the main things that it does?
8. What are the NOAA space weather scales? Describe the different categories, scales, effects (biological, satellite operations, power systems, other systems, radio communications, navigation operations), physical measures, and average frequencies.
9. What is the Late Heavy Bombardment (LHB)?

10. What is the solar cycle?
11. The text refers to three historical space weather events. Look them up and summarize them.
    a. The Carrington event of 1859.
    b. The January 20, 2005 event.
    c. The solar storm of 2012.
12. What are solar storms? Solar flares? Coronal mass ejections?
13. The text refers to a Hohmann transfer.
    a. What is it, and how can it be used to create the type of eccentric orbit described in the text? Sketch what the original trajectory of the spacecraft might look like, and what the new trajectory would be.
    b. What considerations may be useful in determining the parameters of the needed eccentric orbit? Specifically, what are the arguments for and against eccentricity that is too high or too low?
    c. Explain the luck element at the end of the text.
14. The text mentions the magnetism of lunar rocks brought to Earth with Apollo astronauts. Does the Moon have a global magnetic field like Earth does, or only localized magnetic fields? How does the nature of the lunar magnetic fields affect the radiation levels at the lunar surface?
15. What are radiation countermeasures? What are the three classes of radiation countermeasures used in space travel? Give examples for each.

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