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	POSTDOCTORAL FELLOWSHIP Radiation encountered in deep space poses a significant threat to the health of astronauts and the success of future NASA missions to destinations such as asteroids and eventually Mars. Modern technology cannot provide full protection against such an environment. Thus, it is paramount to develop an effective method of radiation shielding to safeguard against this risk. Constant, high-energy GeV range, isotropic galactic cosmic ray (GCR) flux and intermittent, MeV-range plasma from solar particle events (SPEs) present significant risks to astronauts of exceeding NASA's stringent permissible exposure limits (PELs), developing potentially catastrophic acute radiation sickness during a mission, increasing the long-term risk of cancer, and even death. Thus, the first line of defense for alleviating these vulnerabilities requires a countermeasure that will reduce the total amount of radiation reaching the spacecraft habitat.		

Task Description:

We have investigated a previously unexplored architecture for a radiation-protected deep space expedition. The Orion spacecraft itself will not be altered. Instead, a number of relatively small independent mobile satellites, each containing superconducting coils, will form a protective array around the spaceship. These satellites will act as magnetic lenses whose purpose is to reduce the radiation flux passing through the volume occupied by the spaceship, thus limiting crew exposure. The magnet array will be reconfigurable and its formation will exploit the principles of swarm-bot technology. Protection against both isotropic GCRs and late-phase SPEs require an evenly spherical magnetic shield which can be created by an array of magnets in a form of a regular polyhedron. The goal of the magnet array is to provide a safe region around the spacecraft in which the number density of the charged particles is lower than it would be in the absence of such a shield. Since magnetic fields do not change GCR and SPE particle energy, the dose of radiation absorbed by the biological tissue inside the protected region is reduced by the same proportion as the number density of the particles. This protection will also provide improved constraints for future models of biological responses to radiation and reduce uncertainties in studies of radiation effects.

We have built an infrastructure of robust particle tracking simulations of 10^4-10^5 particles that create an isotropic flux of high order. This infrastructure can build evenly symmetric shields comprised of numerous dispersed magnetic dipoles. We have completed scaled-down, low energy (0.01 MeV) simulations showing that a dispersed 20-dipole shield at 50 m radius can successfully deflect significant isotropic radiation from a 10 m radius central volume (i.e., spacecraft). Despite the scaled-down energies and spatial scale, the code infrastructure is promising in showing that it is indeed feasible to shield a central volume from an isotropic particle flux using a dispersed magnetic shield. Continued work need only to properly scale up the simulation in size and energy.

A particle-in-cell (PIC) algorithm has also been built to accurately represent SPE plasma interactions with a magnetic shield. Unidirectional plasma has been shown to be deflected away from a downstream protected volume, and the code is adaptable to numerous initial conditions. Initially, this technology was at a Countermeasure Readiness Level (CRL) of 3 and a Technology Readiness Level (TRL) of 2. We will show that, to date, research outcomes have elevated the technology to CRL 3 and TRL 3.

Future plans include a NASA HERO Omnibus Appendix C submission to further study this promising concept. The tasks will include an incremental scaling up of isotropic GCR particle tracking simulations, different magnetic shield configuration investigations, full solutions for the PIC algorithm, and the addition of higher-order physics. Our team is extremely committed to the continued success of this project.

Rationale for HRP Directed Research:

Research Impact/Earth Benefits:

Many NASA Human Research Program (HRP) radiation effects studies, including others in this report, are focused on models that constrain the biological responses of certain tissues to space radiation. Knowledge of these responses and these model constraints are necessary to understand if NASA is going to accept the risks associated with subjecting astronauts to long duration deep space missions. As the main impact variable in these studies is the absorbed dose of radiation in tissue (measured in Gy), this study holds the potential for allowing a reduction in the necessary exposure for animal subjects, and thus the development of more feasible biological mitigation techniques. The educational, academic, and pure scientific benefits of this new field of superconductor applications is broad. The field of distributed magnetic shielding for spacecraft has the potential to grow into numerous computational, material, experimental, and engineering subfields that all have the common goal of protecting humans in space. The benefits of such studies, not only for young scientists, but for Earth-based applications of superconductors, such as MRI machines and clean wind power generation, can only be speculated about. The expansion of space applications for NASA's Cryogenic Select Surfaces can be extended to major superconductor studies, not just for radiation shielding, but other innovative technologies requiring low power and high current.

Task Progress:

#1 We have built a 3D computational infrastructure of a "swarm-bot" configuration of magnetic fields that act as a shield against isotropic charged particle radiation. It has been shown in that scaled-down simulations have provided the proof-of-concept that evenly dispersed magnetic fields can protect an interior volume from isotropic radiation.
#2 This radiation shielding mechanism is shown here to be feasible, and future constraints of particle momentum cutoffs will add to NASA's knowledge of what type of countermeasures, and combinations of countermeasures, will be needed for long-duration human missions beyond LEO (low Earth orbit). This shielding mechanism can be the first line of defense for reducing the total equivalent dose of radiation reaching the astronaut habitat and decrease the reliance on bodily-invasive countermeasures that currently have undetermined long-term effects.

#3 Particle tracking and PIC simulations have shown that unidirectional radiation can be protected against using one or more magnetic fields. This would protect against early-phase SPEs. However, late-phase SPEs and the constant threat of GCRs are much more significant and require shielding from isotropic radiation. We have shown that shielding against such a distribution is possible with a dispersed shield. It is now anticipated that the shield does not have to be reconfigurable at all.

#4 We anticipate the high-temperature superconducting material YBCO (yttrium barium copper oxide) to be the prime candidate for constructing loops that produce the magnetic fields. We have calculated that a loop 20 cm in radius producing a magnetic moment of 10^5 A m^2 would require 56 kg of YBCO material. That is a reasonable payload mass to include on a satellite and would only require perhaps twice that mass in supporting structure and electronics. Additionally, through a partner at Kennedy Space Center (KSC), we have identified a potential technology push for the YBCO superconducting material to be kept at its critical temperature in space. This KSC Cryogenic Select Surface technology is still under development at KSC through a NIAC (NASA Innovative Advanced Concepts) grant, but it holds significant promise for power-efficient superconducting applications such as this shielding concept.

#5 We have constructed our software infrastructure to optimize protection against isotropic radiation for a spherical protected region of 10 m in diameter. Such a volume will easily encompass the Orion MPCV (multi-purpose crew vehicle), and is on the order of size scale for future deep space habitats such as the Bigelow Aerospace BA-330.

#6 The First Award Fellow visited his former high school, LaSalle College High School in Wyndmoor, PA, on December 21, 2015, to deliver a presentation entitled "The Future of Space Exploration" for six 45-minute presentations to a total of about 600 students. On March 18, 2016, the Fellow was a Career Day STEM (Science, Technology, Engineering and

	Mathematics) panelist at the at Robert L. Stevenson School of the Arts located in Merritt Island, FL, for two 30-minute sessions to about 120 elementary school students.
Bibliography Type:	Description: (Last Updated:)