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Space Radiation Countermeasures In A Life Support System Of Extraterrestrial Environments

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Space Radiation Countermeasures in a Life Support System of Extraterrestrial Environments

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Dedication

To my father, Jerry Odell Thompson, who kindled my love for the sciences, bringing purpose to one of my most cherished memories of childhood prior to his untimely death in 2001. I love you and miss you dearly. I also dedicate this to my daughter, Ariel Nicolette, for being the inspiration to begin my journey to fulfill my ambitions to learn. And to my husband, David, my mother, Diana, Uncle Michael, Aunt Arvella, and Dorian, to all my family, and most of all my heavenly Father. I am more than grateful to have you all to be a part of me, because of you all, I have emerged, and of me, I will give back to you.

Acknowledgements

I wish to extend immense gratitude to my advisor Dr. Gregory Goins for assisting me on this research. You were my inspiration for attending North Carolina A&T State University, and I am grateful to have had you as a mentor. I have acquired a new family through my professors during my time here, with special regards to Dr. Doretha Foushee and Dr. Perpetua Muganda. You have lead me to understanding in the classroom and provided me with encouragement in life as well. I am grateful to the administrative officials of the biology department offices, to include Dr. Mary Smith, Dr. Goldie Byrd, and namely Ms. Donna K. Robertson. You have worked hard for me and others. Your dedication is much obliged. I also acknowledge my colleagues, Ms. Rasheena Edmondson and Ms. Quantil Melendez. I am appreciative to have gained your companionship. Through the difficult times in this period of my academic career, you were there to support me educationally and as a friend. Thank you. I am also thankful for the support provided by the iBLEND Project (NSF UBM Grant No. 1029426), and the entire Department of Biology at North Carolina A & T State University.

Biographical Sketch

From 2005 to 2010, Candice Thompson Young attended Averett University (AU) where she received a bachelor's degree in biology with a concentration in biomedical sciences in May, 2010. In addition to biology and biomedical courses there, Candice minored in English and enrolled in classes that would enable her to gain a secondary teaching certificate for biology. Towards the end of her bachelor's degree, she was early admitted into AU's graduate program in 2009, where she intended to obtain a MEd in biology with teaching certification. Once completing her degree at AU in May of 2010, Candice earned a certification as a Qualified Mental Health Professional (QMHP). This was the result of three years of work experience at an adult group home plus other mental health experience combined with her Bachelor's degree. Following graduation from AU, she was awarded a summer internship with Virginia Advanced Studies Strategies (VASS) as the science lab assistant to the Virginia Director of Sciences of the VASS program, Susan Ramsey, PhD. Ramsey is also the Coordinator of Assessment and Remediation of Deep Run High School in Henrico County, VA (2011). VASS is a program created from a partnership with the National Math and Science Initiative (NMSI) and Exxon Mobile to encourage US high school students to enroll in Advanced Placement classes to improve our nation's overall STEM scores. Working with Ramsey allowed Candice to engage in developing strategies and assistance for educating elite high school science teachers with innovative laboratory exercises to incorporate into the classroom curriculum.

Afterwards, Candice continued on to pursue her science education by transferring from AU’s graduate MEd program to the North Carolina A&T State University (NCAT) graduate biology program in the fall semester of 2010. Each semester of enrollment at NCAT, Candice independently taught undergraduate non-major biology labs at the university level while there.

In the spring semester of 2011, Candice was inducted into Beta Beta Beta, the national honor society for biology students. Another highlight of her academic studies at NCAT was the honor of being selected to present her thesis research in molecular and computational biology at the Annual Biomedical Research Conference for Minority Students 2011 (ABRCMS) in St. Louis, Missouri. Candice's research advisor at NCAT was Dr. Gregory D. Goins. The decision to transfer to NCAT early in her graduate career was based on Dr. Goins' previous work with NASA and associated grants. Immediately assuring her ambitions to attend NCAT, she began research with Dr. Goins right away. The compassion for biology and space science was simultaneously fulfilled through her time at NCAT. Candice's research reflects her interests in the space sciences and computational biology, being an extension of her broadly spanned interests in science. In April of 2012, Candice was inducted into Beta Kappa Chi Scientific Honor Society of natural sciences and mathematics for traditionally Black colleges. She will be receiving a thesis-track Master's degree in biology in May of 2012 from NCAT. Meanwhile, Candice has been accepted into two non-traditional doctorate programs and is awaiting notification from other schools to which she has applied. Candice intends to begin a doctoral program in the fall semester of 2012.

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CLESS	Closed Ecological Life Support System
CME	Coronal Mass Ejection
CNS	Central Nervous System
CO^2	Carbon Dioxide
DNA	Deoxyribonucleic Acid
DSB	Double Strand Break
GBR	Gamma Ray Burst
GCR	Galactic Cosmic Radiation
Gy	Gray
HZE	High Ionizing Energy Particle
IR	Infrared
kPa	Kilopascal
LSS	Life Support System
LOE	Low Earth Orbit
MATLAB	Matrix Laboratory
Mb	Millibar
mmHg	Millimeters Mercury
mSv	milliSievert
NASA	National Aeronautics Space Administration
nT	NanoTesla
Psi	Pound Per Square Inch

SNC	Shergottites, Nakhlites, Chassignites
SPE	Solar Particle Events
SSB	Single Strand Break
Sv	Sievert
UV	UltraViolet

Abstract

A Life Support System (LSS) sustains life for an extended period of time in a closed system that includes waste recycling as a functional method of support. For future space missions, the goal is to build extraterrestrial space bases which employ the concept design of a radiation free LSS environment. Effectively maintaining a LSS in an extraterrestrial space environment is difficult without protection from harmful space radiation such as galactic cosmic radiation (GCR) and solar radiation. Radiation produces high energy ions which penetrates tissue and destroys DNA. Without radiation protection, life in an extraterrestrial environment will perish. Therefore, it is necessary to design a model which not only supports life within the LSS, but also prevents the harmful effects of external destruction from radiation. We must reduce the exposure of the radiation in order to maximize the potential for human survival in a LSS. We hypothesize that countermeasures taken to reduce the effects of radiation will increase safety within a LSS. The specific aims included in this study are to 1) identify various shielding methods for the model which will inhibit radiation exposure from impacting the LSS and 2) reduce the cancerous effects of radiation through Paclitaxel drug treatment. We use numerical integration computer software to simulate our model. Through mathematical modeling we are able to better define treatment options within a LSS with different types of radiation shielding and countermeasures. Results from the model indicate the rate at which tumors occurs with drug treatment. In conclusion, we were able to design an effective model which may help prevent the cancerous effects of radiation exposure through treatment with the Paclitaxel drug.

CHAPTER 1

Introduction

The future of the planet Earth is not guaranteed. Humans are depleting natural resources at an alarming rate as shown by shifts in global temperatures. The need to begin conducting and accomplishing plans to colonize other planets is in the best interest of humans to ensure survival, given the possibility of Earth's untimely destruction. Our celestial neighbor, Mars, is the most likely candidate for future human habitation. Unlike the gaseous planets in the solar system, Mars has a solid surface. Most importantly, the recent probable discovery of water in the form of dry ice has made Mars a place for colonization. Despite Mars' advantageous qualities for supporting advanced life and the presence of inhospitable weather conditions that challenge human colonization. For instance, dust storms frequently engulf the entire surface of the planet blocking sunlight from reaching the planet for days at a time. Temperatures on Mars range from extremely cold temperatures of 0°C – -100°C. These storms block sunlight from reaching the surface allowing for temperatures to plummet even more. Planet Mars' conditions make it almost impossible to fathom that advanced life may soon be able to survive there.

With the recent probable discovery of water on Mars, research for colonizing the planet has accelerated. Photo evidence suggests that Mars has water in the form of dry ice at both its North and South polar caps (Titus, et al., 2003). Mars has permanent polar caps composed of water ice, and seasonal polar caps composed of carbon dioxide ice (dry ice) (Hansen, 2010). This has created a great headway for the urgent priority in the efforts to provide resources for the expansion of human colonization.

NASA has formulated the idea to have a manned mission to the Red Planet. The approximated length of time for the mission will take approximately four years. This time period only applies to when Earth and Mars are in their closest distance in orbit, to allow for the shortest travel time. Otherwise, the mission could take much longer. To make this mission feasible, the space craft must be self-sufficient and safe enough to support humans for more than the allotted period of time without supply from Earth. The basic necessities required for advanced life are air, water, food, and energy. To achieve sustained support for advanced life in space it is imperative to create a system for a spacecraft that allows the support, storage, and resupply of all vital components. Various proposed Life Support Systems (LSS) research projects coincide with NASA's vision to conduct a manned space mission to the planet Mars. A LSS is the focus for creating a model to efficiently maintain life in a closed system.

A looming issue is that the even with the most effectively designed LSS, life would be unable to survive without protection from space radiation. Space radiation results from energy that arises due to space weather occurring within outer space. Space weather events include galactic cosmic radiation (GCR) derived from cosmic rays, gamma ray bursts, super novae, and other galactic phenomenon. These events spew a collage of radiation particles into the environment. Solar particle events (SPE), another form of harmful radiation initiate from solar flares and coronal mass ejections (CME). CMEs occur when the outer layer of the Sun erupts from the surface, sending solar radiation particles barreling through space. On Earth, we are more affected by solar radiation but attribute our protection from this form to our magnetosphere, the Van Allen Belt.

Radiation from space is biologically harmful because of its ionizing properties. Ionizing radiation has a high energy level, travels nearly at the speed of light, and is capable of stripping electrons from the atoms that it penetrates. These highly charged ions are called HZE particles. This effect is very damaging at the cellular level. Injury at the cellular level caused by radiation destructs DNA and has the potential to lead to fatal cancer. Life in a LSS must be shielded from radiation or it will serve no purpose to develop a biologically supportive model system if it is incapable of inhibiting hazards that originate from the outer surroundings. Invading particles of radiation null the efforts of even the best constructed LSS habitat.

Avoiding space radiation is difficult. It does not contain a purely defined energy form. It consists of various types of energy in the form of particles, waves, or rays, therefore, all risks must be eliminated in order to reduce its harmful effects as a whole. It is imperative to keep exposure limits to a minimum in the LSS, although it is inevitable that humans will encounter radiation at some times. Once exposed, countermeasures to reduce cancer include treatment with drugs such as Paclitaxel.

Due to hostile and unpredictable conditions, it is necessary to develop a Life Support System (LSS) which is capable of sustaining advanced life on the planet Mars. The significance of the LSS research project coincides with NASA's visions to conduct a manned mission to MARS in the near future. A LSS is the focus for creating a system to efficiently maintain life in a closed system in which the recycling of products and wastes sustains a functional method of support for an extended period of time. The long term goal for LSS research is to construct permanent Martian space bases housing advanced life by the year 2020. The objective of this research is to construct a computer graphic model for radiation treatment following GCR exposure on the

Martian surface. Advanced life on the hostile planet is not possible without providing countermeasures for which to prevent radiation damage. The central hypothesis is that advance life can successfully survive on planet Mars within a LSS with successful radiation therapy. The rationale behind the LSS research utilized for the advancement of life and space colonization may extend an even greater opportunity to improve life on Earth as well. Understanding the radiation treatment for radiation exposure is important in prolonging mission time and safety within the LSS.

The research project will employ the use of numerical integration computer software MATLAB (Matrix Laboratory) and its add-on SimBiology. The two programs collaborates biology and mathematics to create models for research without using human test subjects or animal models. The purpose of the radiation countermeasure research is to design a system using MATLAB and SimBiology to understand drug treatment for humans in response to radiation exposure in an extraterrestrial environment. Ultimately, life in the hostile Martian environment is not possible without radiation countermeasures, therefore research for the designing the system is much needed.

CHAPTER 2

Literature Review

2.1 Life Support Systems

The field of space exploration and extra-terrestrial human colonization is barely an unearthed gem in the light of human survival. Humans take for granted just how fortunate we are to live in such a unique world. We have yet to find a celestial body like that of our own planet. Earth is an even rarer and amazing occurrence in our own Milky Way Galaxy (which contains at least 200 billion stars) than imaginable. It has been most difficult and unsuccessful to find a planet that is capable of supporting the advanced life that flourishes here on this planet. Earth is so unrecognizably distinctive that it may take many lifetimes before we discover an Earth-like planet in the vast universe. Remarkably, all the conditions that have come to be in order to allow for the possibility of life thriving on Earth are just right. We are just the right distance from the sun that it is not so cold that the oceans freeze, or so hot that they boil and evaporate away. The seasons are relatively mild in the most locations of the populated areas which give rise to an abundance of individually distinct organisms. We have an ample supply of water in the fresh supply on land and from the oceans, which is absolutely required for all living beings. The harmonious gas exchange between plants and animals allow life to have a boundless breathing capacity. An infinite number of factors make our planet a faultless domain for supporting life.

We must search the far-stretching realms of the universe to seek out Earth-like planets that are able to support the multitude of life as is here. Therefore, space missions are necessary in the future of the continuance of mankind. Many questions arise when considering the reasons why it is necessary to advance into domain of space exploration. In addition to gaining a better understanding of our celestial surroundings, it is important also to know that the research that supports life in space will provide opportunities to improve life on Earth. Radiation prevention and LSS research fosters the improvement of resource management and recycling efforts, as well as ways to help understand the response to radioactive environments. A subsequent goal of space exploration can also be applied to the development and progress towards ways in which we perform technologically, medically, and ecologically on Earth.

Several threatening dilemmas stand in the way of making space exploration a more common area of research. The first and most obvious is the lack of funds that is required to launch these expensive missions (Drysdale, et al., 2004). An ingeniously engineered design is imperative to support life upon the craft. Space missions could take an inconceivable amount of time, another dilemma that affects the likelihood of space mission development. Another issue would include equipment. The materials that are required for creating the craft to transport the crew members and equipment in the space environment must be ingeniously constructed to ensure the maximum potential for safety and efficiency for the duration of the journey to the extraterrestrial environment, time spent on the surface of the planet, as well as to include the safe return to Earth. A LSS must function as a habitable atmosphere inside and out. The LSS is the bio-dome which will represent the Earth environment and atmosphere.

There are at least six reasonable answers for humans to engage in space colonization: (1) To increase our knowledge of the universe and to answer questions such as “Are we alone?” and “Does life exist elsewhere in the universe?” (2) To explore and discover new frontiers; (3) To advance the engineering practice and generate new technologies that might be useful for Earth, knowing that there is a 9:1 return on investment by way of spin-offs from space technology; (4)

To enable the commercialization of space by using seemingly limitless, untapped resources, which could prove to be “profitable”; (5) So we don’t destroy each other or planet Earth. It is known that cooperative peaceful endeavor unites the people of the world; and (6) Humans need to push the boundaries of our species or risk extinction, given that the current projections for severe energy and resource shortages by year 2100 (Clément, 2006). These reasons are among only a few to include the benefits of space exploration. In relation to radiation countermeasures, exploring the possibilities to inhibit radiation damage to cellular DNA can be used to better understand new methods for counteracting radiation and developing new therapies and treatment following lethal exposure.

2.2 Components of a Life Support System

Earth has a protective atmosphere that prevents most galactic cosmic radiation from reaching the terrestrial layer of the planet. The Earth’s atmosphere is comprised of 78% nitrogen, 21% O_2, 0.5% water vapor, along with very small amounts of argon, CO_2, neon, helium, krypton, xenon, hydrogen, methane, and other trace gases. We depend on the correct mixture of gases in the atmosphere to sustain our lives. We also depend of the pressure of our atmosphere to be able to breathe (at sea level, atmospheric pressure is 1 atm = 760 mmHg = 101.1 kPa =14.7 psi) (Clément, 2006). Without this unique blend of gases and pressure, life on Earth could present in a much more drastic appearance. In order to survive on any extraterrestrial surface, it is necessary to recreate the atmospheric conditions on Earth in order to maximize the full potential of the LSS. There are several requirements for human life to proceed, with these basic necessities being air (atmospheric), food, water, and suitable temperatures, waste management, and external elements prevention such as radiation. Therefore, at least minimally accommodating these resources is of utmost importance when considering the design of a LSS. Controlling the atmosphere to create Earth-like conditions must include the production and storage of biologically necessary gases (O_2 and CO_2 among other less apparent gases). Oxygen in an ideal LSS would not only be stored in pure quantities, but also allow for these components to move freely throughout the system as it does so naturally on Earth.

Water accounts for the majority of the mass supply contained within a LSS. Seeking alternate methods in which to harvest or produce potable water for the duration of the mission would reduce the mass requirements allowing for more energy efforts to be concentrated elsewhere in the LSS design. No living thing can survive without water. In recent discovery, should water exist upon Planet Mars, it becomes an even more suitable candidate for habitation. This means that the LSS can feed from current water resources on Mars, if available, if the process of acquiring water through the LSS design should become compromised. The complimentary processes of photosynthesis and human respiration support each other for dependency of survival in a LSS. Plants within the system will be used for food, oxygen, filtration, and water production (Mitchell, 1993). Plants growth and support in the LSS will also be discussed later.

Food production in a LSS is derived mainly from agricultural efforts in the plant growth. A major mass requirement embodies the space that is required to have ample plant growth to supply oxygen and food needs for human survival. Treating and recycling waste water for the long mission is necessary to allow maximum operational efficiency while also reducing resource depletion. Gray water recycling to include biological waste within the gray water (human fecal deposits) will be utilized to fertilize plants within the LSS (Figure 2.1). A simple model is outlined below to describe the overall LSS model (Figure 2.2).

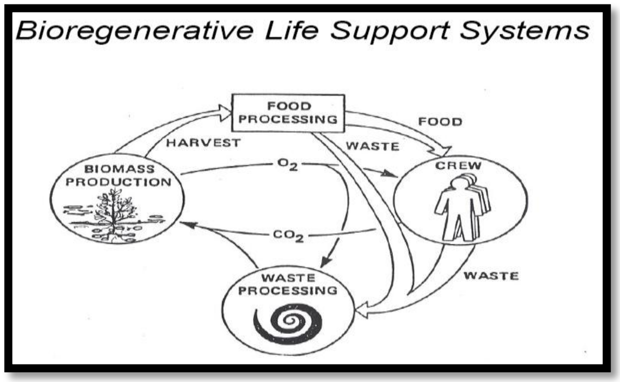


Figure 2.1. Bioregenerative life support systems simple diagram

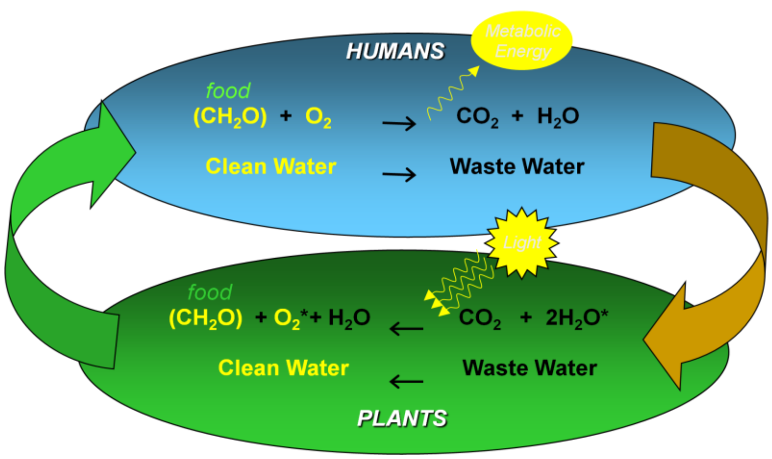


Figure 2.2. Simplified equations showing energy metabolism

The products of photosynthesis can be utilized as food and water for humans living in the LSS. Through the process of transpiration, plant systems can be used to purify waste water where the transpired humidity can then be condensed as clean water. In addition to water production and purification by plants, management of water resources also consists of mechanical filtration and distillation. Waste water (urine) may be distilled and recycled for use as for potable drinking and hygienic water. Through the process of evapotranspiration, the oxygen and water needs of humans in the LSS will be met with the cultivation of plants. How much vegetation would produce enough drinking water by leaf transpiration? A human typically requires about 30 cm^3 of water per kilogram body weight per day. For a reference man, this amounts to only 2.4 liters of water per day. This requirement can be met quite easily by plant vegetation, which typically transpires water vapor at a rate between 100 and 1000 times faster than CO^2 molecules enter those pores in the opposite direction. It would take about 0.5 m^2 of vegetation to satisfy the drinking water requirements for one person or twice that if a 12-h photoperiod is used. The photoperiod is the amount time that the plant will be subjected to light for energy. If cooking, washing, and sanitary water is factored in, the requirement leaps to at least 40 liters day^{-1}. Ten m^2 of vegetation illuminated constantly could easily supply this. Actually, the 55 m^2 of vegetation required for two, with full waste recycling would generate as much as 220 liters of water per day, which is far more than needed (Mitchell, 1993). Therefore, with plant cultivation in a LSS, life could possibly survive in a desert environment with the needed water supply.

Prepackaged food on the LSS will be kept to a minimum. Resupply from Earth will not be facilitated, therefore once the prepackaged food source is depleted, there will be no more. It is demanded that the vast majority of food that is used for human consumption will be grown and harvested within the system. The plants aboard the LSS will include various leafy greens and legumes most suited according to certain desirable characteristics. The LSS plants should 1) Exhibit ease of rapid growth, maintain minimal energy for maximum growth output; 2) Demonstrate ease of growing in a hydroponic setting; 3) Be of high nutritional value and of high dietary content per required food group; 4) Be completely edible or have a very low non-edible mass; 5) Have a high crop yield when grown in a modified environment; 6) Require a relatively low area of crop size. Until further advanced studies take place, the only food that will be cultivated is of a vegetarian diet (Mitchell, 1993).

2.3 A Mars Environment

Before constructing a mathematical model, it is necessary to gather data from all probable sources in order to provide the most accurate representation. Mars' environment is extremely different from Earth's therefore, as much information must be gathered about the planet as has been provided by NASA and other space exploratory educational studies. With the use of telescopes and robotics much information about Earth's celestial neighbor has been made available. Secondly, information about the atmosphere (outer space) in which the journey will have to travel must be considered as well.

Although humans have never set foot there, we already have a plethora of information about our neighbor. Nicknamed the Red Planet, Mars is the fourth planet from the sun in celestial orbit. It has been nicknamed the Red Planet for its dusty brick colored terrain which is made from iron oxide, more commonly called rust. Mars has a thin atmosphere which is comprised of 95% carbon dioxide, 2.7 % nitrogen, 1.6% argon and other trace elements. The orbital speed is 24.2 km/sec. Temperatures on Mars can range anywhere from 0° C – -100°C. The average Martian temperature is ~210 K (-63 C). Slightly smaller than planet Earth, Mars' is 6,794 km in diameter. Almost double the length of a year on Earth, Mars' revolution takes 686.98 Earth days to complete. However, one day on the dusty planet, is only equal to 24.6 Earth days which is only slightly longer. The distance from the sun is 227, 940, 000 km. Mars has two moons, Phobos and Deimos.

Since Mars has a very thin atmosphere, it is not adequately shielded from cosmic rays, solar flares, and meteor strikes. Another important factor is the difference in the field of gravity in relation to that of the Earth. Mars' gravity is 3/8 that of Earth's gravity. For this reason, plants and humans will be negatively affected by this phenomenon. In atmospheres with low gravity, the body begins to lose muscle tone and bone mass. Reduced gravity creates weightlessness upon the body which is equivalent to not using the muscles at all. Musculoskeletal conditions affecting human development and maintenance are a major issue in zero gravity environments which will also be discussed.

We must know information about Mars to accurately design an effective LSS model. For instance, we know that the pressure on Mars is significantly lower than that of Earth's. Very low pressures (<5 kPa) are associated with the boiling point of water near temperatures suitable for plant growth. The surface pressure on Mars is less than one-hundredth the sea level surface pressure of Earth. Free water boils at this pressure (Corey, 1991). We must determine the atmospheric limits for normal plant growth and development on Mars. It is obvious that we must use a LSS, for any life to survive on the planet, so this is why we still must consider all limits of interest on Mars. A concern in designing the model is to construct a model structure that will allow plants to grow and develop normally at or slightly above pressures for the boiling point of water (Corey, 1991). Nourishment for plants must be allowed to occur in a manner that the water remains in a liquid state upon the surface. It is likely that water on the Martian surface is in the form of dry ice.

2.4 Galactic Cosmic Radiation

Radiation is a form of energy that is emitted in the form of rays, electromagnetic waves, and/or particles (Rask et al., 2006). Radiation can be either non-ionizing (low energy) or ionizing (high energy). Ionizing radiation consists of particles or photons that have enough energy to ionize an atom or molecule by completely removing an electron from its orbit, thus creating a more positively charged atom. Less energetic non-ionizing radiation does not have enough energy to remove electrons from the material it traverses. Examples of ionizing radiation include alpha particles (helium atom nuclei moving at very high speeds), beta particles (high-speed electrons or positrons), gamma rays, x-rays, and galactic cosmic radiation (GCR). Examples of non-ionizing radiation include radio frequencies, microwaves, infrared, visible light, and ultraviolet light (Rask, et al., 2006).

In outer space, radiation is difficult to assess because it does occur in so many different forms. The many forms of radiation can be visible and invisible. Typically, the most harmful type of radiation is the invisible forms, or the ionizing radiation. Radiation has extremely damaging effects which can penetrate the skin and harm organisms at the cellular level. Radiation has the potential to cause single and double strand breaks in the DNA. These mutative breaks in the DNA can become duplicated if unchecked in cellular proliferation and induce fatal cancer. GCRs are mostly composed of 85% hydrogen protons, 14% helium, and 1% high energy and highly charged particles called HZE particles (high ionizing energy particles). An HZE is a heavy ion having an atomic number greater than that of helium and having high kinetic energy. Examples of HZE particles include carbon, iron, or nickel nuclei (heavy ions). In summary, GCR is heavy, high-energy ions of elements that have had all their electrons stripped away as they journey through the galaxy at nearly the speed of light. They can cause the ionization of atoms as they pass through matter and can pass practically unimpeded through a typical spacecraft or the skin of an astronaut (Rask, et al., 2006). Ionizing radiation changes the charge of atoms in the material that it transverses through this process of ionization. This occurs because the particles strip the electrons away from the material that is being crossed. Secondary particles may also result from this primary atomic blasting of material, causing even more damage to the surrounding material. HZE particles crossing through DNA is the equivalent of shooting a cannon ball through the DNA at the speed of light. Whatever the particles dissect, cause extensive damage to the genetic material. For these reasons, space radiation is a major concern in space travel.

In space, radiation is omnidirectional, which means it is present in all directions and cannot be pinpointed from one particular source. The sun is the greatest source of radiation affect the Earth. On Earth, we are mostly protected from solar (and other types) radiation by the magnetosphere. Our magnetosphere is called the Van Allen Belt. The Van Allen Belt is Earth's protective shielding against GCRs (Figure 2.3). Without the Van Allen Belt, life as we know it would not be possible. Radiation would freely bombard the surface of the planet and life would not be able to exist due the radioactive environment. The magnetosphere (Figure 2.3) is responsible for deflecting radiation particles that come barreling toward the Earth. The majority of those particles are deflected, whereas few are trapped within the low-earth orbit (LOE) layers of the atmosphere within the magnetosphere. However, a minute amount of this radiation does

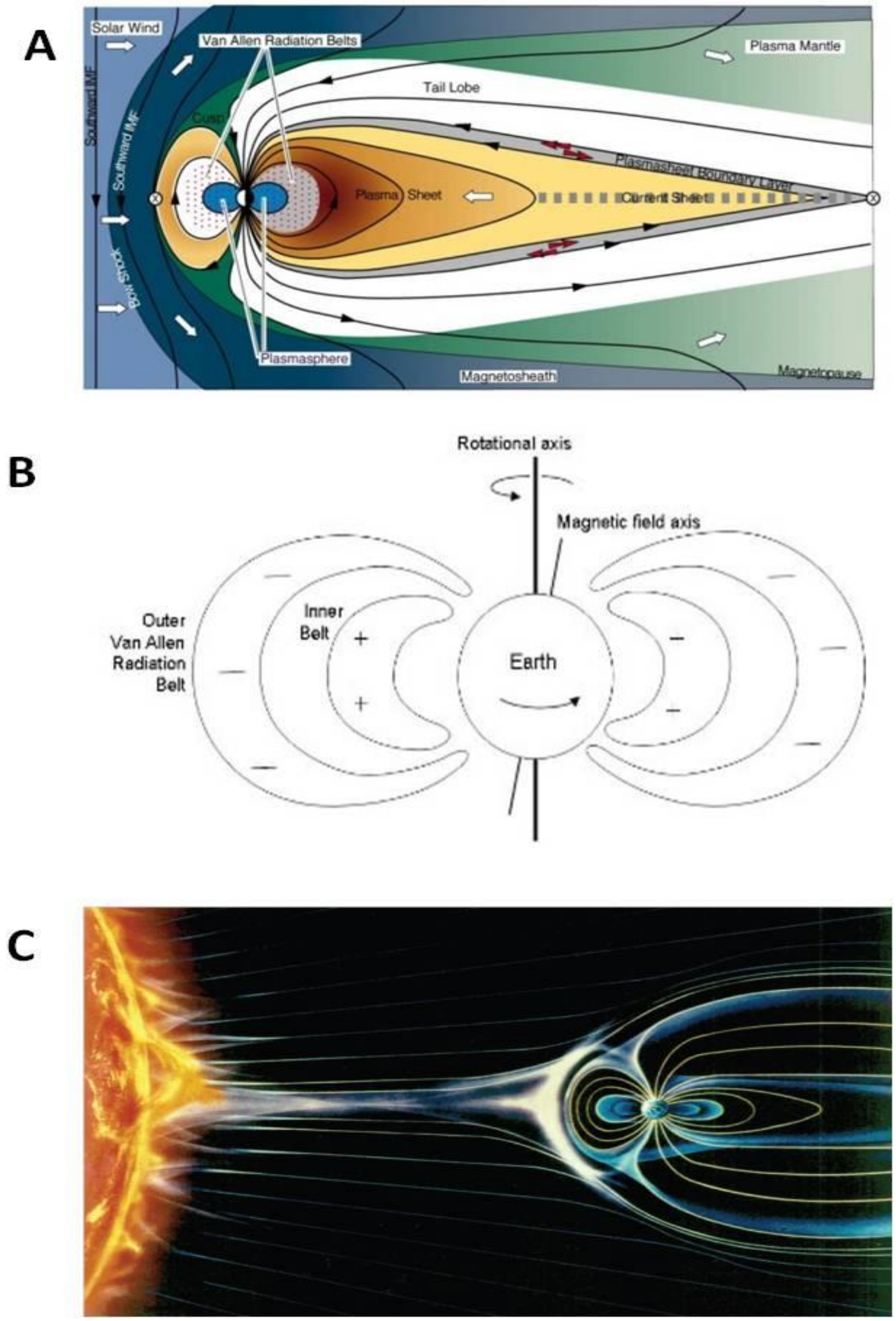


Figure 2.3. The Van Allen Belt and Earth's magnetic field waves

eventually pass through the magnetosphere and is capable of reaching the terrestrial layers of Earth.

2.5 Solar Radiation Exposure

The sun's terrestrial radiation is of the most concern for humans and other organisms on Earth. Radiation emitted by the sun in different forms is UV radiation, visible light, and infrared radiation being the most common forms. The Sun's radiation consists mostly of UV, visible, and infrared light occurring at the respective wavelengths as measured on Earth (Figure 2.4). High levels of exposure to the Sun's radiation are not recommended. It can burn the skin and cause undesirable skin pigmentation leading to melanoma, or skin cancer. At low levels of exposure, the amount radiation is not entirely harmful; however, it is actually necessary for the facilitation of Vitamin D synthesis and absorption. Homebound individuals, women who wear long robes and head coverings for religious reasons, and people with occupations that limit sun exposure are unlikely to obtain adequate vitamin D from sunlight (NIH, 2011). Some amount of sunlight is necessary for normal human development and metabolism.

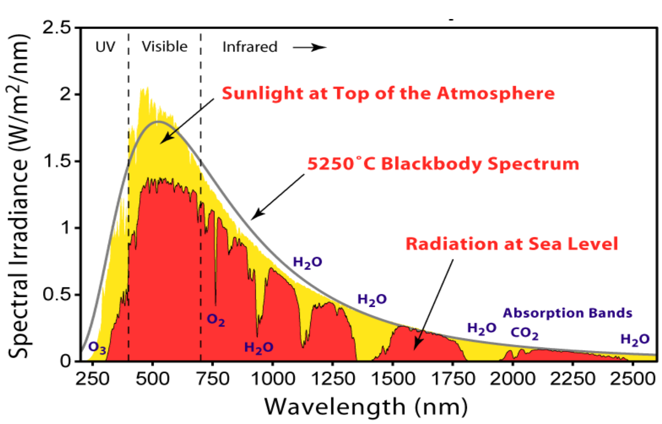


Figure 2.4. The Sun's electromagnetic spectrum and wavelengths

HZE particles in GCR are affected by the Sun's magnetic field whereas their average intensity is highest during the period of minimum sunspots when the Sun's magnetic field is weakest and less able to deflect them (Rask, et al., 2006). During the periods in which there is a solar minimum, HZE particles are least able to be deflected by the Sun's weak magnetic field, therefore they are able to escape into the surrounding space. During the periods of solar maximum, the sun's magnetic field is stronger, thus maintaining HZE particles within its magnetic field (Figure 2.5).

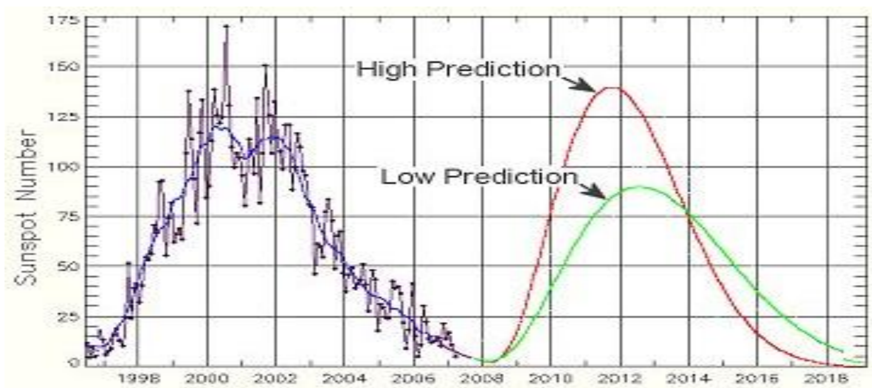


Figure 2.5. Solar minimum and maximum sunspot period

Observations show that the sun reverses the polarity of its general magnetic field every 11 years, in synchronism with its sunspot cycle. When the number of sunspots is at a minimum, the observed field on a large scale has its lines of force going mainly north and south. As the number of sunspots begins to increase, the strength of the north-south part of the field diminishes. In about 5.5 years the north-south component has diminished to zero and the number of sunspots is at a maximum. Then things begin to happen in reverse. A south-north part of the field appears in the opposite direction from its predecessor and the number of sunspots starts to diminish. After another 5.5 years, the number of sunspots is at a minimum again, and the field is back to its original shape, but with the north and south poles of the field having switched places, that is, the sun's magnetic field has reversed its polarity. Physicists and astronomers do not yet have a theory that completely explains this complex reversal phenomenon (Snelling, 1991). The increases and decreases in the number of sunspots in the solar cycles is representative of the intensity to which HZE particles from solar activity can escape. In Figure 2.5, the forecast for a solar maximum at the high prediction entails an increase in the number of sunspots which leads to a high influx of HZE. At the low prediction during the solar maximum, a reduction in the number of HZE particles is expected. The higher the number of escaping HZE particles results in greater exposure to radiation in space and on Earth.

2.6 Magnetospheres

Space missions to other planets of the solar system have shown that most of them are magnetized or have significant magnetospheres. In particular, the giant planets are magnetized much more strongly than Earth and their magnetospheres are all much larger than ours, in part because of the stronger dipole moments, in part because the solar wind becomes increasingly rarefied far from the Sun. Tiny Mercury has a magnetic moment only about 1/2000 that of Earth and a very small magnetosphere, Venus seems non-magnetic and Mars may or may not have a weak field. The magnitudes of the dipole moments of Mercury, Earth, Jupiter, Saturn, Uranus and Neptune, in units of 10^25 Gauss-cm3, are 0.004 (approximately), 7.9, 150,000, 4300, 420 and 200, respectively (Stern,1996). It is generally believed that the earth's magnetic field is generated by electric currents in the earth's innermost region, the core, which is presumed to consist of a metallic iron-nickel mixture. However, according to the 'dynamo' hypothesis, these electric currents and/or magnetic fields are believed to be produced by the slow circulation of molten material that carries unequal amounts of positive and negative electric charge. The energy for this is thought to come from the earth's rotation and/or its internal heat (Snelling, 1991).

The more dangerous HZE particles of ionizing radiation are derived from trapped radiation particles within the Van Allen Belt, GCR, and solar flare particles. These solar flare particles or solar particle events (SPE) occurs in the form of coronal mass ejections or CMEs. CMEs are stellar events in which plasma from the surface of the sun is spewed out into space as a result of the complex magnetic field line fluctuations that occur within the Sun. CMEs are massive solar flares erupting from the solar surface. This deadly space weather is associated with periods of the solar cycle. CME eruptions are more likely to occur during the time of the solar maximum. Hazardous CME space weather is devastating to the inner planets. Outside Earth's protective Van Allen Belt, CMEs and other forms of SPE can prove deadly to astronauts. The magnetosphere will trap and deflect most of the GCR particles on Earth, but other planets such as Mars, are not so fortunate. Earth's Van Allen Belt is the strongest magnetosphere of the inner planets (Figure 2.6). Earth has more radiation protection than that of the other inner plants in the solar system. Measured in nanoTeslas, Mars' magnetosphere seems almost nonexistent in comparison to Earth's massive protective magnetic field.

Mars has extremely weak magnetic fields which were previously thought to be nonexistent (Figure 2.7). There are theories that attempt to explain why the magnetic field on Mars is not as apparent as on Earth and the outer planets. Such an occurrence includes the possibility that a meteor impact inhibited the dynamo function. Planet Mars currently has no dynamo, that is, the metallic core of the planet is not liquefied and has ceased to churn. The churning mechanism within the metallic core is required for the electrically charged conducting fluid to provide the energy for convection that creates the magnetic fields on the outer surface (Schubert and Spohn, 1990). The rotation rate of Mars is approximately that of Earth and is thus sufficient for the operation of this initial dynamo. The other necessary ingredient of a convection driver in the core was supplied by heat left over from the accretion of the planet, which may have been effective for up to a few billion years.

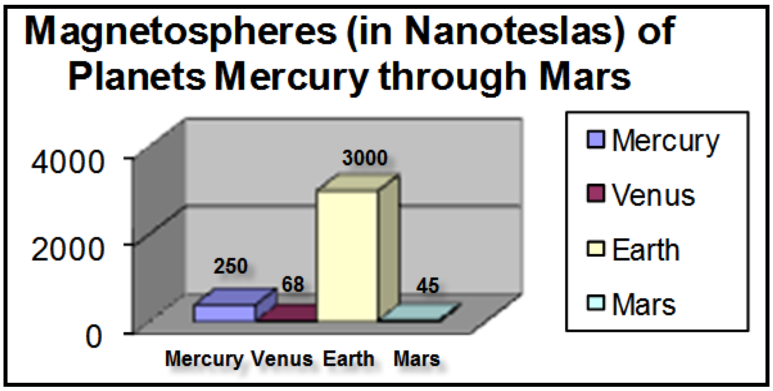


Figure 2.6. Magnetospheres (in Nanoteslas) of planets Mercury through Mars

If a magnetic field did indeed exist resulting in a dynamo, evidence of it may still be present on the surface in the form of magnetized rocks and crustal regions like those observed on the Moon. Today, the only other 'direct' information that Martian magnetism exists is from a special class of meteorites known as the SNC meteorites which are thought to come from Mars. Magnetic field analyses of these possible samples of the Martian crust indicate that magnetic fields of ~ 1000 nT may have been present on the surface of Mars at the time that these meteorites were ejected by a giant impact some 180 million years ago. (For comparison, the present field on Earth near the equator is about 3×10^4 nT. The present upper limit on the dipole moment implies surface fields of only a few tens of nanoTesla (Russell, 1997). The fields are measured in nanoTeslas. Although the dynamo on Mars is extinct, there are still small pockets where magnetic fields exist upon the crust (Figure 2.7).

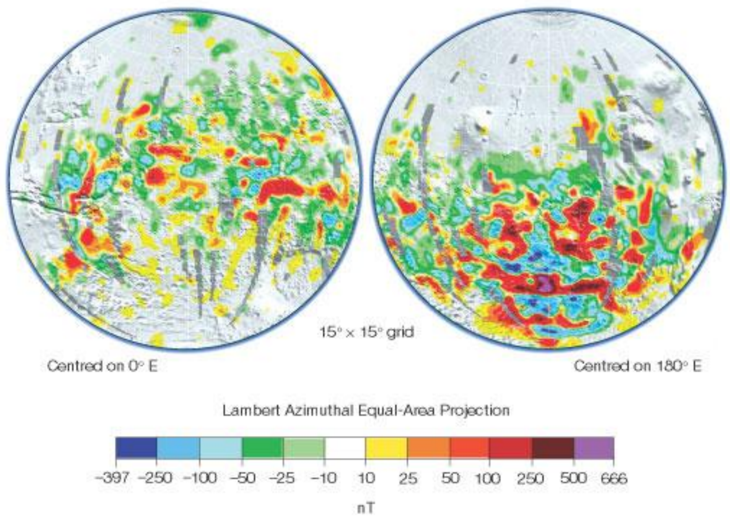


Figure 2.7. Magnetic field projections on Mars

Placing a LSS within the confines of a location on the Martian surface that has a higher magnetic field projection may be more suitable for optimal chance of survival in a LSS. These regions would serve to possibly hinder more radiation from impacting the LSS and will be introduced into later models with further research.

2.7 Unique Forms of Galactic Cosmic Radiation

On the electromagnetic spectrum, radiation is described in the various forms of radio waves, microwaves, infrared (IR), visible (photons of light), ultraviolet (UV), x-ray, and gamma rays. Major forms of space weather such as cosmic rays are materialized in several forms. Cosmic rays are derived from all types of elements. These types of radiation can be created from the event of explosions of super novae. Super novae are essentially the aftermath resulting from the death of a massive star. Upon the exhaustion of a star's fuel supply, the fusion of elements that allow it to shine brightly are depleted. The star is no longer supported by nuclear fusion. The star's core will implode causing a mega explosion under the intense pressure. If the star's iron core is massive enough, it will collapse and become a supernova. The resulting outer layers of the star will illuminate the surrounding space, and is a beautiful sight in the vast interstellar space. However, to be in within the close proximity of the supernova explosion can be fatal to planets within and nearby that solar system from the cosmic radiation that ensues with the event. Cosmic rays are always present and if a star goes supernova near Earth, it could have extreme effects which most likely would shorten life expectancy on our planet even if fortunate enough to survive the event.

Stars which are at least eight times or more massive than our Sun end their lives in a most spectacular way; they go supernova. A supernova explosion will occur when there is no longer enough fuel for the fusion process in the core of the star to create an outward pressure which combats the inward gravitational pull of the star's great mass. First, the external layers of the star will swell into a red supergiant. In the internal layers, the core yields to gravity and begins shrinking. As it shrinks, it grows hotter and denser. A new series of nuclear reactions begin to occur, temporarily halting the collapse of the core. But alas, it is only temporary. When the core contains essentially just iron, it has nothing left to fuse. Due to iron's nuclear structure, fusing iron does not result in a net yield of energy. Since energy production cannot then be maintained, the star begins to collapse. Fusion in the core ceases. In less than a second, the star begins the final phase of gravitational collapse. The core temperature rises to over 100 billion degrees as the iron atoms are crushed together. The repulsive force between the nuclei is overcome by the force of gravity. So the core compresses but then recoils. The energy of the recoil is transferred to the envelope of the star, which then explodes and produces a shock wave. As the shock encounters material in the star's outer layers, the material is heated, fusing to form new elements and radioactive isotopes. The shock then propels that matter out into space. The material that is exploded away from the star is now known as a supernova remnant. All that remains of the original star is a small, super-dense core composed almost entirely of neutrons -- a neutron star. If the original star is very massive (15 or more times the mass of our Sun), even the neutrons cannot survive the core collapse, and a black hole forms. Many supernova phenomena produce X-rays and gamma rays, including hot material given off by a supernova, and the free electrons moving in the strong magnetic field of the neutron star (NASA: Supernovae, 2011).

Once the elements used in nuclear fusion to provide the energy that illuminates the star is depleted, the star's core explodes. Under the instability, the outer layers of the star explode and become a supernova. The resulting images are the radioactive elemental layers that have been blasted off from the core. The radiation from the super nova explosion can be devastating to surrounding celestial bodies (Figure 2.8).

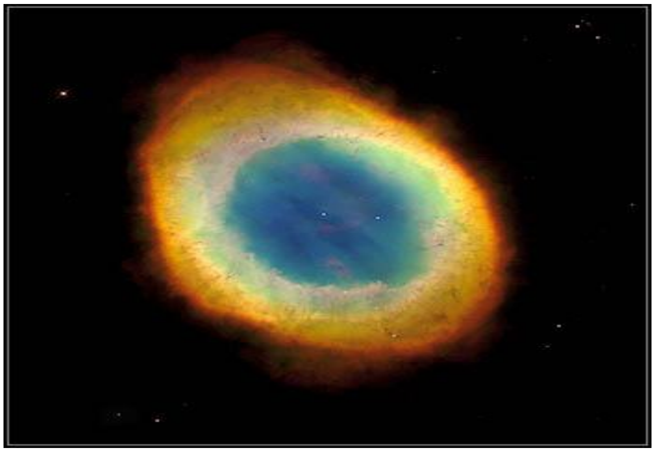


Figure 2.8. Remnants of supernova explosions of massive stars

This diagram shows a simplified cross-section of a massive, evolved star with a mass greater than eight times the Sun (Figure 2.9). Where the pressure and temperature permit, concentric shells of Hydrogen (H), Helium (He), Carbon (C), Neon/Magnesium (Ne), Oxygen (O) and Silicon (Si) plasma are burning inside the star. The resulting fusion by-products rain down upon the next lower layer, building up the shell below. As a result of Silicon fusion, an inert core of Iron (Fe) plasma is steadily building up at the center. Once this core reaches the Chandrasekhar mass, the iron can no longer sustain its own mass and it undergoes a collapse. This can result in a supernova explosion (Hall, 2006). The Chandrasekhar mass is the maximum mass of a stable white dwarf star, defined as the mass above which electron degeneracy pressure in the star's core is insufficient to balance the star's own gravitational self-attraction (Bethe, et al., 2003). In the process of nucleosynthesis, lighter elements undergo nuclear fusion to combine and make heavier elements such as the fusion of hydrogen into helium, helium into carbon, and so on (Figure 2.9). Once that energy from nuclear fusion is depleted, the star will become a supernova.

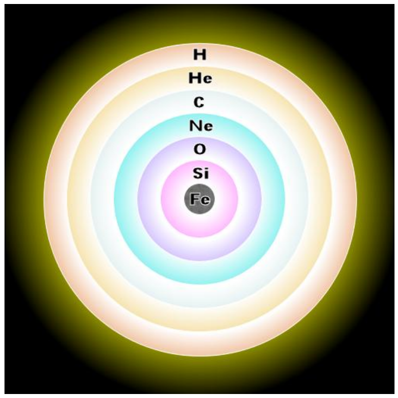


Figure 2.9. Cross-section of a massive evolved star

Gamma Ray Bursts, or GRB are the most energetic and intense form of radiation occurring in known universe. GRB occur as a result of supernovae explosion in which narrow beams of light are ejected from two poles of the dying star's remaining core. These jets of streaming radiation are typically short-lived but occur frequently. Lasting anywhere from a few milliseconds to several minutes GRBs shine hundreds of times brighter than a typical supernova and about a million trillion times as bright as the Sun, making them briefly the brightest source of cosmic gamma-ray photons in the observable universe. GRBs are detected roughly once per day from wholly random directions of the sky (NASA: Gamma Ray Bursts, 2008).

Figure 2.10. GRB from the explosion of massive death stars

GRBs located anywhere in the galaxy can deliver a lethal radiation dose in space and a significantly elevated dose at the Earth's surface. Supernovae can deliver an elevated gamma radiation dose over relatively short distances and a long time interval. However, because of the attenuation provided by the Earth's atmosphere, it is unlikely that the direct gamma ray dose from such events is sufficient in and of itself to have caused the majority of mass extinctions that have been recorded in the geologic record. These cosmic events occur and any planets unlucky enough to be nearby may be sterilized, but the probability of one of these events occurring so near Earth is very low (Karam, 2002).

However, on planets such as Mars, where the magnetosphere is not very effective, remnants from supernovae and GBRs can severely alter the DNA structure of life. These challenging effects necessitate the research of LSS housing and radiobiology prior to considering human colonization of extraterrestrial domains. It is noteworthy to understand that there are higher exposure limits set for astronauts that are older. It is expected that being exposed to higher doses of radiation early in life may lead to increased health risks later. Therefore, the exposure limits are kept at a minimum for astronauts and future space dwellers. A biological explanation for this reasoning is that younger individuals' cellular components are more constantly undergoing cellular division and proliferation than older individuals. Radiation as a mutating factor negatively affects the constantly dividing cells. This creates an increased chance of the proliferating cells becoming damaged and actively passing on the damaged multiple hits to successive generations. Women are more prone to radiation injuries than men, due to the sensitive nature of the reproductive organs and the breasts high affinity for cancer. Therefore, the average exposure limits for women are lower than for men over the career period. The exposure limits for a mission to Mars would be significantly higher, because the amount of radiation encountered would increase significantly with the space mission. With further research it is possible to better understand these limitations.

2.8 Space Radiation Countermeasures

The information in Tables 2.1 and 2.2 represented below shows radiation types, dosage equivalents and the exposure limits for astronauts. More specifically, Table 2.1 represents the most common types and dosage equivalents for radiation. Equal doses of different types of radiation do not possess equally destructive forces on the material that is being exposed (Rask, et al., 2006).

Table 2.1

Radiation Measurements and Descriptions

Parameter	Radioactivity	Absorbed Dose	Dose Equivalent	Exposure (x-rays and gamma rays)	Energy
Definition	Rate of radiation emission (transformation or disintegration) from a radioactive substance	Energy imparted by radiation per unit mass onto an absorbing material	Expression of dose in terms of its biological effect	Quantity that expresses the ability of radiation to ionize air and thereby create electric charges that can be collected and measured	The capacity to do work
Common Units Measurement Label	Curie (Ci) 1 Ci = 37 GigaBq (this is a large amount)	rad 1 rad = 100 ergs/g	rem	Roentgen (R)	Joule (J)
International System of Units (SI) Measurement Label	Becquerel (Bq) 1 Bq = 1 event of radiation emission per second (this is a very small amount)	Gray (Gy) 1 Gy = 100 rad	Sievert (Sv) 1Sv = 100rem 1 Gy air dose equivalent = 0.7 Sv 1 R ≈ 10 mSv of tissue dose	Coulomb/kilogram (C/kg) 1 R = 2.58 × 10-4 C/kg air	electronvolt (eV)

Table 2.2

Exposure Limits For Astronauts Measured in Sieverts

Career Exposure Limits for NASA Astronauts by Age and Gender				
Age (years)	25	35	45	55
Male	1.50 Sv	2.50 Sv	3.25 Sv	4.00 Sv
Female	1.00 Sv	1.75 Sv	2.50 Sv	3.00 Sv

The average distance from Earth to Mars at a minimum is 55.7 X (10^6 km) and has a maximum distance of 401.3 X (10^6 km).The level of radiation exposure is much higher than the normal amount of radiation that is encounter at LOE, for instance. The average GCR measured in mSV, is in the following table. The total exposure level corresponds to the round mission exposure plus the amount of exposure from the time required to remain on Mars before planetary alignment will allow for the shortest travel distance back to Earth.

The expected average of radiation exposure during a Mars mission is as follows in Table 2.3. One mSv is equivalent to 3 chest x-rays, therefore, a mission to Mars is equivalent to being exposed to 3000 chest x-rays. This amount is considerably more than the allowable exposure limits over a career. Cancer will indefinitely develop at these exposure limits. Astronauts and space dwellers are at more of an increased risk for developing cancer during their career than most than the general public. Practicing countermeasures for radiation exposure is a necessity. Described in Table 2.4, is the depth of radiation exposure to astronauts compared to the general public according to the blood forming organs, eyes, and the skin. The exposure limits for astronauts is approximately 120- 2000 times higher depending upon the body organ in comparison to the general public.

Table 2.3

Expected Average of Radiation Exposure During a Mars Mission

Expected Radiation Exposure for Mission to Mars	
One-Way Trip	300 mSV
Round Trip	600 mSV
Planetary Alignment	400 mSv
Average Total Exposure	1000 mSV

Table 2.4

Depth of Radiation Exposure Compared to the General Public

Depth of Radiation Penetration and Exposure Limits for Astronauts and the General Public (in Sv)				
Astronauts	Exposure Interval	Blood Forming Organs (5 cm depth)	Eyes (0.3 cm depth)	Skin (0.01 cm depth)
	30 Days	0.25	1.0	1.5
	Annual	0.50	2.0	3.0
	Career	1-4	4.0	6.0
General Public	Annual	0.001	0.015	0.05

2.9 Radiation Shielding

There are four basic types of ionizing radiation. These include alpha and beta particles, gamma rays and neutron particles. Ionizing radiation strips away the electrons of atoms as it penetrates material and tissue. Lead has been a favored choice for radiation against most of these forms of ionizing radiation shielding on Earth, and it is assumed that lead will also be a good shield against radiation on an extraterrestrial surface as well. However, lead is extremely dense in mass and it would be too costly and space consuming to transport to another planet. Lead is also a poorly effective shield against neutron particles of radiation. Therefore, it is necessary to consider other building components to structure the LSS design. Underground placement of the LSS could be an effective shielding method, although due to the fact that the Martian surface environment is not yet well understood, research efforts should primarily be familiar with the surface before underground expeditions ensue. Creating an artificial magnetosphere by way of inducing a magnetic field surrounding the LSS has been a method which has been considered for radiation shielding as well. Research in the use of more practical and economical methods of radiation protection is most preferable in choices for shielding for the time being.

Wearing white clothing works well in reflecting particles of radiation from penetrating the skin. In of how radiation is able to penetrate clothing, causing burns to the surface of the skin. This example is from the radiation contaminates of nuclear fallout on Earth however the source is gamma radiation (just one of the radiation sources that is expected to be encountered in space). The color white is the best color for reflection of solar radiation particles and other forms of radiation. In Figure 2.11, clothing is unable to attenuate gamma radiation. Beta burns are known to cover the body due to contact with fallout. Furthermore, thermal burns are often on one side of the body as heat radiation does not penetrate the human body. In Figure 2.11 (courtesy U.S. National Archives and Records Administration) for the depicted individual, the dark clothing pattern has burned into the skin. This is because white fabric reflects more infra-red light than dark fabric. As a result, the skin underneath dark fabric is burned more than the skin covered by white clothing.

Figure 2.11. White clothing attenuating gamma radiation

The amount of solar radiation striking a perpendicular surface located beyond the earth's atmosphere at the mean earth-sun distance is called the solar constant Esc ≈1366 watts/m2 (127 W/ ft2; 433 BTU/ (h • ft^2). Absorption by water vapor, dust and ozone, while passing through the earth's atmosphere will reduce this value. The percent of solar energy absorbed by an enclosure is dependent on surface color finish and texture (Table 2.5) (Hoffman, 2009). In the table below (Table 2.5), darker colors on a surface tend to absorb radiation at a higher rate than lighter colors. The lighter colors reflect radiation at better rate leading to less radiation exposure to the material that is being shielded by that surface. Low temperature radiation (larger wavelengths) presents a different set of values for surface color. Low temperature values affect an enclosure surface's ability to absorb internal heat loads and dissipate radiant heat to the sky and surrounding objects (Hoffman, 2009). The absorption is a measurement of the ratio of the amount of radiation that a material is exposed to compared to the amount of radiation that traverses that material.

Table 2.5

Low Temperature Radiation Color

Surface Color	Solar Radiation Absorption	Low Temperature Radiation (25° C) Emission and Absorption (%)
White	0.14	0.97
Yellow	0.30	0.95
Cream	0.25	0.95
Black	0.97	0.96
Polished Aluminum	0.15	0.06

All objects whose base temperature is above absolute zero, emits radiation. The higher an objects temperature means the shorter the wavelength of the light that is being emitted. Shorter wavelength on the energy spectrum is equivocal at a higher energy level, known as blackbody radiation. Darker colors emit and absorb radiation at a higher rate than lighter colors. Solar radiation is emitted in the visible light range. Therefore, it is most beneficial for astronauts to dress in white colored space suits and any surfaces of the LSS should also be in white where materialistically possible in order to prevent radiation absorption.

Typically, the thicker the barrier between those occupying the LSS and the radiation within the environment, the greater the protection provided. Providing more of or various types of shielding between the external atmosphere and the LSS optimizes safety. Mars has a thin atmosphere, so there will be some protection from radiation exposure from this effect. The goal is to reduce radiation exposure as much as possible to increase the safety within the LSS. Employing the use of different, yet effective materials to reduce radiation exposure decreases the risks of exposure. Since radiation is ubiquitous and all-encompassing in space, it is more feasible to use various types of shielding to inhibit the several forms (Table 2.6).

Polyethylene has been deemed a practical radiation shield in outer space. Polyethylene is a light weight plastic material that has a great capacity for ionizing radiation particles, such as HZE and SPE. Materials with atomic structures that are high in hydrogen are good for shielding. Due to the high hydrogen content in polyethylene (8.0 x 10^{22} atoms/cm^3), it absorbs and disperses the radiation once they penetrate the material. Polyethylene has a melting point temperature ~ 262 °F. It is flexible and light weight as well, making it a good candidate for radiation shielding. The development of polyethylene material with a higher density and thickness provides increased stability against micrometeorites and increased absorption. The level of absorption depends on the thickness of the material. The addition of boron to polyethylene increases the propensity for radiation shielding by absorbing the neutron particles which subsequently reduces this byproduct caused by gamma radiation. This following table (Table 2.6) displays a summary of radiation types and characteristics. Gamma and neutron radiation are the most damaging forms of ionizing radiation. The necessary shielding agents are listed in Table 2.6 as well. Polyethylene is the most effective shield against radiation as denoted by this table, since it has the ability to shield the most penetrative form of radiation.

Table 2.6

Summary of Radiation Types and Characteristics

Type of Radiation	**Alpha**	**Beta**	**Gamma**	**Neutron**
Penetrating Power	Very low	Low	High	High
Exposure Hazard	Internal	Internal/external	External	External
Shielding Material	Paper	Plastic, aluminum	Lead, steel, concrete	Water, concrete, steel (high energy), polyethylene

Water is also an effective shield against ionizing radiation for the same reasons as polyethylene. Water has a high hydrogen concentration and is able to absorb and disperse the highly active radiation particles as well. Since water on Mars is under such pressure it will be in the form of dry ice, yet it forms a good absorbent barrier for the radiation particles.

Countermeasures for radiation primarily rely on adequate shielding, and decreasing the time of exposure. Providing “adequate” shielding will always result in a compromise in the design of the spacecraft because of mass constraints in the construction of the craft. A spacecraft could have a “storm shelter” area with enhanced shielding, to which the crew retreats to during a SPE. GCR offers the additional challenge that high energy particles can easily penetrate and pass through shielding. Also, in the process, these can produce secondary particles. There are other strategies under consideration and research such as new types of material which absorb radiation as well as the use of anti-oxidants and radio-protective agents by individual crewmembers (Gushin, et al., 1993). The use of anti-cancer drugs will also be implemented in research as a part of the astronaut medical regime during and/or after the Mars mission to counteract the effects of radiation exposure.

Lack of knowledge about the biological effects of and responses to space radiation is the single most important factor limiting the prediction of radiation risk associated with human space exploration. For longer-duration lunar and Mars missions the currently large uncertainties in radiological risk predictions could be reduced by future research. Without such research, it may be necessary to baseline large shielding masses and reduced-length missions, and/or delay human exploration missions until uncertainties in risk prediction and radiobiological methods of risk management have advanced to the point that they can be conducted within the limits of acceptable risk. Overall one concludes that not all radiation exposure can be fully protected against. Nor are all the health effects of radiation known, especially with respect to GCR. The proposition that radiation is the single, most important issue must be considered in comparison to the other space environment hazards. The comparison must be made in regarding both known effects and maturity of the countermeasures developed which provide mitigation (Gushin, et al., 1993).

2.10 Specific Aims and Objectives

The first specific aim is to determine effective countermeasures to allow for safer living conditions in the LSS to prevent radiation penetration and long term cellular damage. The working hypothesis for the first aim is that through various shielding methods and therapeutic agents the level of radiation exposure can be reduced and the effects of exposed radiation harm can be prevented or reversed. The approach for the first aim is to employ previous shielding methods from existing models in addition to countermeasures for radiation that have been used to treat Acute Radiation Syndrome (ARS) victims and patients with cancer on Earth. The second specific aim is to determine if the Paclitaxel drug treatment can effectively diminish cancerous cells if exposed to GCR. The working hypothesis is that the fitness level of the cell will facilitate the growth or destruction of malignancy in the cancerous cells. The approach taken using the research will determine how quickly Paclitaxel decreases malignant cells as demonstrated by the model design using MATLAB and SimBiology.

From the LSS research, the expected outcome is that humans will expand the realms of the domains for which is capable of supporting life. The definition of a habitable planet will change due to innovations of LSS research. In addition to successfully inhabiting other worldly domains, more efficient ways to harvest energy and improve recycling will drastically reduce the need for depletion of resources here on Earth. The impact of this LSS research will also implement radiation research for not only Mars, but Earth as well. Exploring new possibilities to inhibit radiation damage to cellular DNA can be used to better understand new methods for counteracting radiation and developing new therapies and treatment following lethal exposure. A benefit of this research is intended to aid in the extension of new habitats for advanced life in otherwise uninhabitable environments throughout the universe. With this research, the LSS model represented here in addition to the radiation therapies and countermeasures outlined in this literature can lead to a safer plan of treatment for astronauts, space dwellers and Earth inhabitants.

This research entails the design of a model built using the numerical integration computer software MATLAB (Matrix Laboratory), and its add-on SimBiology. SimBiology allows for the visual simulation of cause and effect relationships in a biological system. Creating models using these software programs also allow simulation of the medication effects without using humans or animals, allows more freedom for the experimental variables.

1. Specific Aim: Determine effective countermeasures to allow for safer living conditions in the LSS to prevent radiation penetration and long term cellular damage.

    1.1 Working Hypothesis: Through various shielding methods and therapeutic agents the level of radiation exposure can be reduced and the effects of exposed radiation harm can be prevented or reversed.

    1.2 Approach: Employ previous shielding methods from existing models in addition to countermeasures for radiation that have been used to treat patients with cancer on Earth.

2. Specific Aim: Determine if the Paclitaxel drug treatment can effectively diminish cancerous cells if exposed to GCR.

    2.1 Working Hypothesis: The fitness level of the cell will facilitate the growth or destruction of malignancy in the cancerous cells.

    2.2 Approach: The software employed will address how Paclitaxel decreases malignant cells demonstrated by the model design using MATLAB and SimBiology.

CHAPTER 3

Materials and Methods

3.1 MATLAB and SimBiology

MATLAB is a high-level technical computing language and interactive environment for algorithm development, data visualization, data analysis, and numeric computation. Using the MATLAB product, it is possible to solve technical computing problems faster than with traditional programming languages, such as C, C++, and Fortran (MathWorks, 2011). MATLAB is a numerical integration program which enables users to create models with mathematical data. The program is currently the leading technological computing software. The software has the capability to transform complex formulas into images and diagrams that can be easily interpreted. This modeling software also uses add-on tools such as SimBiology in order to simulate model input and output tasks and automate MATLAB models. Simbiology provides graphical and programmatic tools for computational systems biology and pharmacokinetics. It contains functionality for creating, simulating, and analyzing biological models (MathWorks, 2011). MATLAB and SimBiology will facilitate the use of mathematical modeling to conduct the research.

A model is a representation of an idea that has been developed for a purpose or to complete a given assignment. Mathematical modeling is an important innovative tool which provides much more practical testing of scientific experiments. Systems can be tested using less time and effort than in constructing an actual replica of the model being evaluated. Mathematical modeling is a set of equations or another mathematical structure (as for instance a directed graph) which is the image of a well-defined sector of reality (Kappel, 2008). Models may be either descriptive or explanatory which is the representation of causal relations. When modeling, it is important to obtain as little complexity as required. Models are best interpreted because of their simplicity. There are always particular aspects which cannot be represented and tested by modeling. However, the represented idea must be simplified in order to convey the clear rationale behind its purpose. As the model is generated into a tangible structure, multifaceted criteria may be applied in their most simple context as well.

In modeling, there are a few exceptions that lead up to the completion of a satisfying and accurate finalized product; 1) The purpose must be defined. 2) Models may be constantly modified or entirely recreated. 3) Models are created in relationships to simulate reality. 4) Models simplify reality. 5) The simulations of a model must be valid. Modeling also provides several advantages over performing actual experiments and in many cases, such as research, it is much more practical to use modeling to initiate plans for future testing. 1) Modeling is much less expensive. Constructing systems can be extremely costly for materials. Modeling takes much of potential money wasted out of the equation. 2) It reduces time. Drafting a greater project which may have to be modified several times is much less time consuming when developing a model to stem from. 3) Modeling reduces the size and space. Sometimes models can represent very large and complex objects. Modeling can all be created within the confines of a laptop computer, significantly reducing the need for large work areas.4) Modeling adds control. Often experiments can be hazardous and dangerous to conduct. In many cases it is even impossible to physically enter into an environment which is being tested. Usually there is an educated theory or hypothesis formulated, however the reality is that the outcome is not known. Otherwise, there would be no need for an experiment. Modeling levels a controlled environment which can be safely accessed and manipulated at the creator's discretion. 5) Models can be used in diagnostics. Understanding mechanisms and pinpointing problems is an important reason for performing experiments. Modeling aids in bringing the much clearer and simpler picture of a problem into view enabling better understanding of finding and diagnoses of potential problems. 6) The predictability modeling is an advantage over experiments. If the model doesn't work the first time, there is no problem to start over and retry it again. One major disadvantage to modeling is that the creator is not performing the experiment in an environment conducive to the real one. Many concepts that are factored in to a real life experiment do not apply in modeling. This is why modeling is so uncomplicated. However, those factors must not remain unaccounted for when conducting the actual experiment, to avoid potential dangers and pitfalls. The pitfalls and barriers to modeling will be discussed later.

3.2 Specific Methods

We started with base models from the literature of Michor, F. et al., 2004, and Simeoni, M. et al., 2004, and Roccetti, et al., 2004 that were refined with parameters for radiation and mutations in space. The individuals that created the base model extrapolated their data from the experiments using athymic mice models. Athymic mice have no thymus which means that they lack t-Cells. The thymus is the location of t-cell maturation therefore they lack the t-cell. The mice were inoculated with A2780 human ovarian cancer cell lines. However, the model of this research predicts colorectal cancer types. The associated cancer forms present in the form of polyps as a representation for the growing tumor mass. The authors of the base model link plasma concentrations of anti-cancer compounds to tumor growth used the model to describe the growth of the total tumor mass from mice receiving the drug (Simeoni, et al., 2004).

In formulating the model, we used the drug Taxol (Paclitaxel) to treat tumors in astronauts who have been affected by radiation. Paclitaxel is an influential drug in treating breast, ovarian, and colon cancer which are common forms of cancer. Due to its commonality for various cancer treatments, Paclitaxel was chosen as a broad method of drug treatment. The injection is a clear, colorless to slightly yellow viscous solution. It is supplied as a non-aqueous solution intended for dilution with a suitable parenteral fluid prior to intravenous infusion. Taxol is available in 30 mg (5 mL), 100 mg (16.7 mL), and 300 mg (50 mL) multidose vials. Each mL of sterile nonpyrogenic solution contains 6 mg Paclitaxel, 527 mg of purified Cremophor® EL (polyoxyethylated castor oil) and 49.7% (v/v) dehydrated alcohol. Paclitaxel is a natural product with antitumor activity. TAXOL (Paclitaxel) is obtained via a semi-synthetic process from *Taxus baccata*. The chemical name for Paclitaxel is 5β, 20-Epoxy-l,2α,4,7β,10β,13α-hexahydroxytax-l l-en-9-one 4,10-diacetate 2-benzoate 13-ester with (2*R*,3*S*)-*N*-benzoyl-3-phenylisoserine (R_xList, 2012). Paclitaxel has the following structural formula:

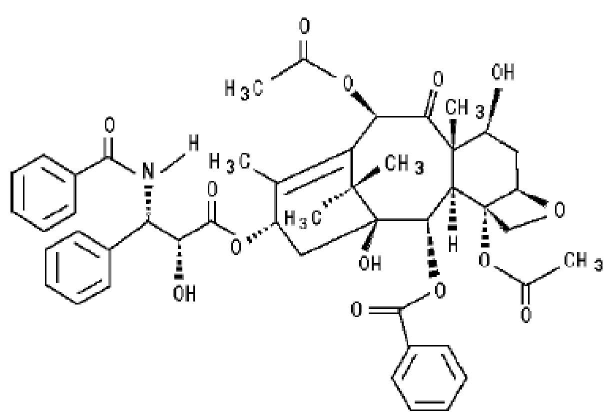


Figure 3.1. Molecular representation of Paclitaxel

Paclitaxel is a white to off-white crystalline powder with the empirical formula $C_{47}H_{51}NO_{14}$ and a molecular weight of 853.9. It is highly lipophilic, insoluble in water, and melts at around 216-217° C (R_xList, 2012).

Biology and applied mathematics together make up the principle for mathematical modeling. The set of parameters and equations used in the progression of cancer that represent each model 3 (Michor, et al., 2004) is listed in Figure 3.2. In the first part of this model, the probability that at least one mutated cell has arisen in a compartment of *N* cells before time *t* is given by *P*(*t*) = 1 – *e–Nut*. Here, *u* denotes the mutation rate per gene per cell division, and time is measured in units of cellular generations. In the second part of this model, the probability that a compartment of *N* cells has been taken over by mutated cells by time *t* is given by *P*(*t*) = 1 – *e–Nu*ρ*t*.

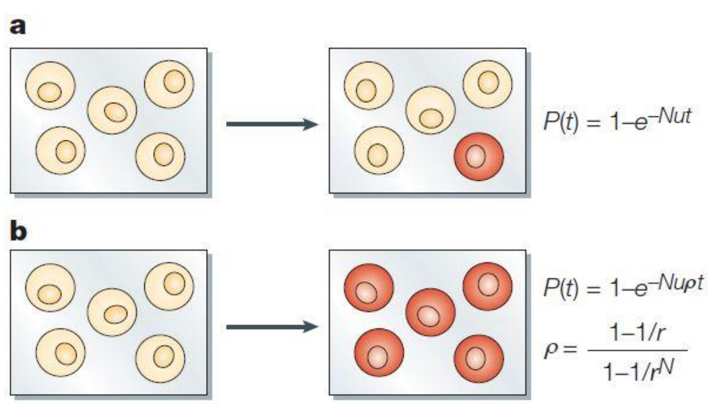


Figure 3.2. Oncogene dynamics

The probability that a single mutant cell with relative fitness *r* reaches fixation is given by ρ = (1 – 1/*r*)/(1 – 1/*r N*) is shown in Figure 3.3 (Michor, et al., 2004).

$$P(t) = 1 - e^{-Nut} \qquad P(t) = 1 - e^{-Nu\rho t}, \quad \rho = \frac{1-1/r}{1-1/r^N}$$

Figure 3.3. Rate equation formulas

In 2004, Simeoni, et al. proposed a PK/PD model to quantify the effect of anticancer drugs on tumor growth kinetics from *in vivo* animal studies. The drug pharmacokinetics were described by a 2-compartment model with bolus IV dosing and linear elimination (ke) from the Central compartment. Tumor growth was described as a biphasic process with an initial exponential growth followed by linear growth (Figure 3.4). The growth rate of the proliferating tumor cells, x1, was described by the equation in Figure 3.4. In this equation, λ_0, λ_1, and ψ are tumor growth parameters, χ_1 is the weight of the proliferating tumor cells, and w is the total tumor weight.

$$\frac{\lambda_0 \cdot x_1}{\left[1+\left(\frac{\lambda_0}{\lambda_1 \cdot} \cdot w\right)^{\psi}\right]^{1/\psi}}$$

Figure 3.4 Growth rate proliferating tumor cells

In the absence of drug, tumor is comprised only of proliferating cells, i.e. $w=x_1$. In the presence of an anticancer agent, it was assumed that a fraction of the proliferating cells were transformed into non-proliferating cells. The rate of this transformation was assumed to be a function of the plasma drug concentration and an efficacy factor, k2. The non-proliferating cells, x2, go through a series of transit stages (x3 and x4) and are eventually cleared from the system. The transit stages were added to incorporate delay between the addition of the drug and observable reduction of tumor weight. Flow through the transit compartments was modeled as a first order process (k1) (Simeoni, et al., 2004).

CHAPTER 4

Results

4.1 Compartmental Simulation of Paclitaxel Drug Treatment

The central, peripheral and tumor growth model compartments represent the organ tissues within the body. The peripheral compartment is where the drug is administered and has not reached the target (central compartment), therefore it accounts for the drug k1/k2 that will not be absorbed by the tumor. At x1 (Figure 4.1, top), the tumor is present and is treated with the drug Paclitaxel. The first plot, (Figure 4.1, bottom left) shows how tumor growth increased without drug treatment and continued to exhibit further growth over time (x1). Figure 4.1, bottom right, shows the various tumor growths at transient stages x2, x3, and x4. As the drug is absorbed by the tumor, the tumor size decreases until it is eliminated from the system (k1).

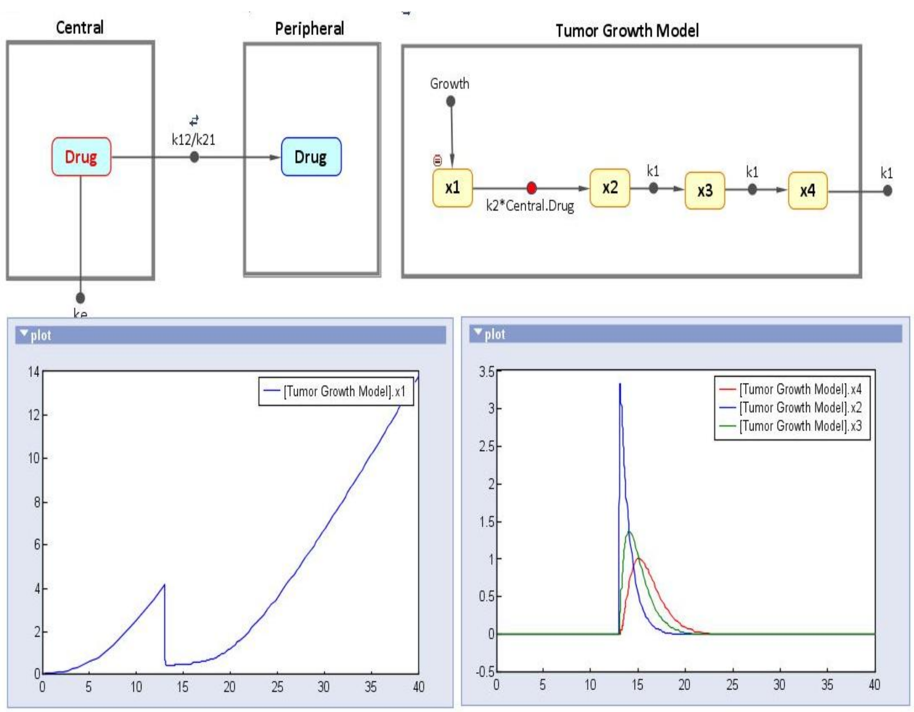


Figure 4.1. Compartmental simulation of Paclitaxel drug treatment

In Figure 4.2, the first plot indicates 60 μg/ml of treatment with Paclitaxel, the second plot indicates treatment at 45 μg/ml treatment of Paclitaxel. The black line is a marker to indicate that at 60 μ/ml of treatment, the Paclitaxel was able to effectively clear a larger tumor in the same period of time and eliminate it from the system following treatment. This means that if an astronaut develops a cancerous growth due to radiation exposure during the time of a Mars mission, he should acquire the maximum allowable dose of Paclitaxel drug treatment to effectively clear the tumor more quickly.

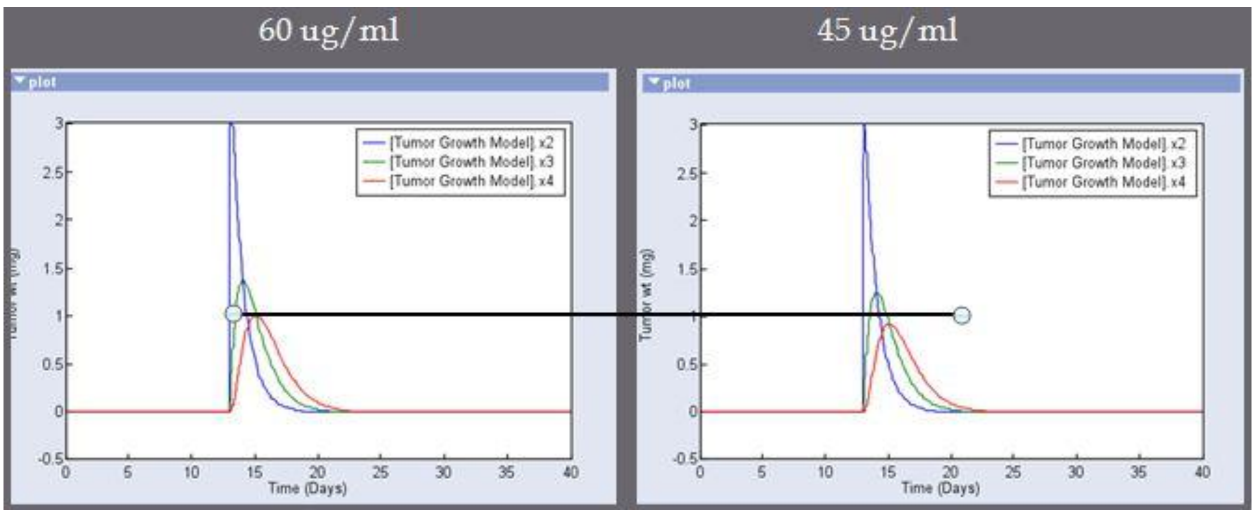


Figure 4.2. Paclitaxel treatment level clearance

4.2. Cancer Progression Mathematical Model Using Paclitaxel

The blue line or line P1 (t) in Figure 4.3 represents the probability that at least one mutated cell has arisen by time t. The pink line or line P2 (t) represents the probability that a mutation has been fixed by time t. A fixed mutation (or cancerous tumor) means that a normal compartment has been overtaken by that mutation. The normal relative fitness of a cell is 1. The fitness of a cell is indicative of how rapidly that cell is able to divide. As the relative fitness of the cell increases, the probability that the fixed cell will overcome the compartment by time t, also increases. A relative fitness of less than or equal to 1 will lead to the probability of 0% chance that a tissue compartment (or organ) will be overcome by a fixed mutation. At a fitness equal to 1, the probability that a fixed cell will overcome a tissue compartment is less than 1% (Figure 4.3). The probability that a single mutated cell will eventually overcome an entire compartment has a 0% chance. The amount of fixed cells within the compartment is 1% and the total number of mutated compartments is at 255. However, as the relative fitness of the cell rises, the probability that a cell will be overtaken by a fixed mutation exponentially rises.

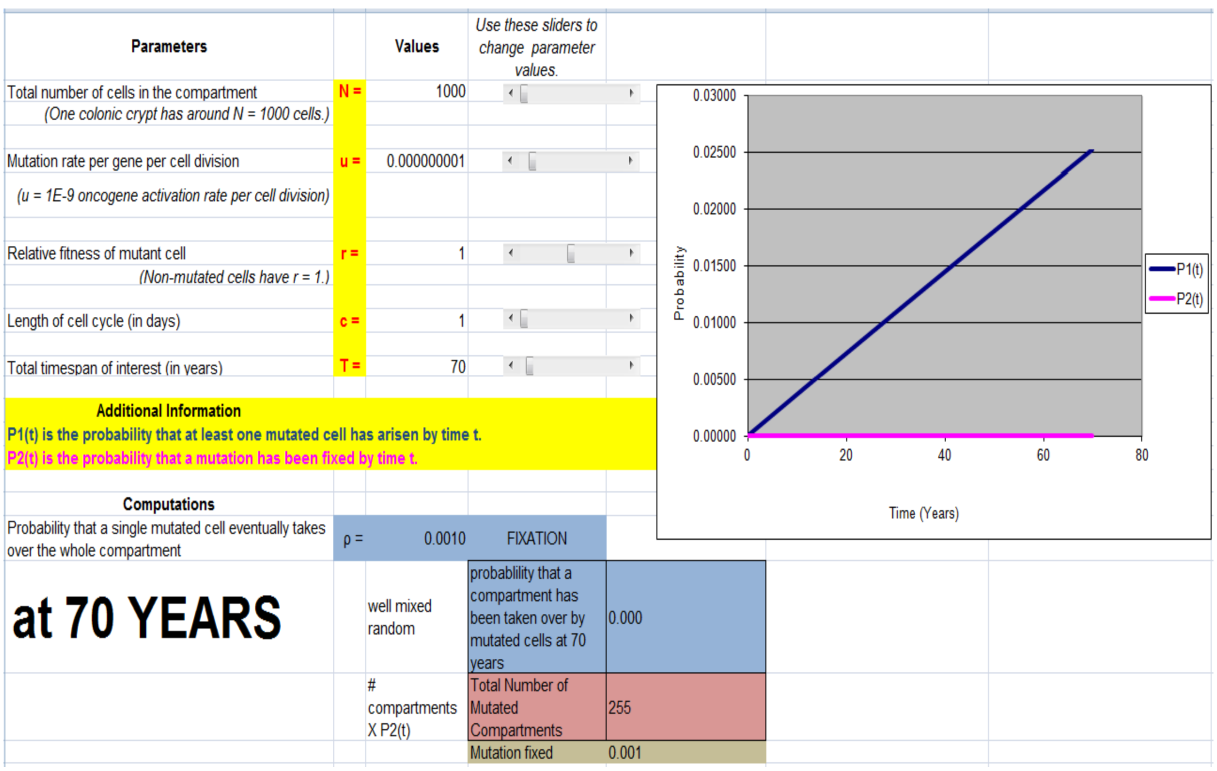


Figure 4.3. Normal relative fitness of cell

In Figure 4.4 below, the relative fitness of the cell has been increased from 1 to 1.5. With these new parameters, the probability that a single mutated cell will eventually overcome an entire compartment has increased to an 8% chance. The amount of fixed cells within the compartment is 33% and the total number of mutated compartments has risen to 84,805.

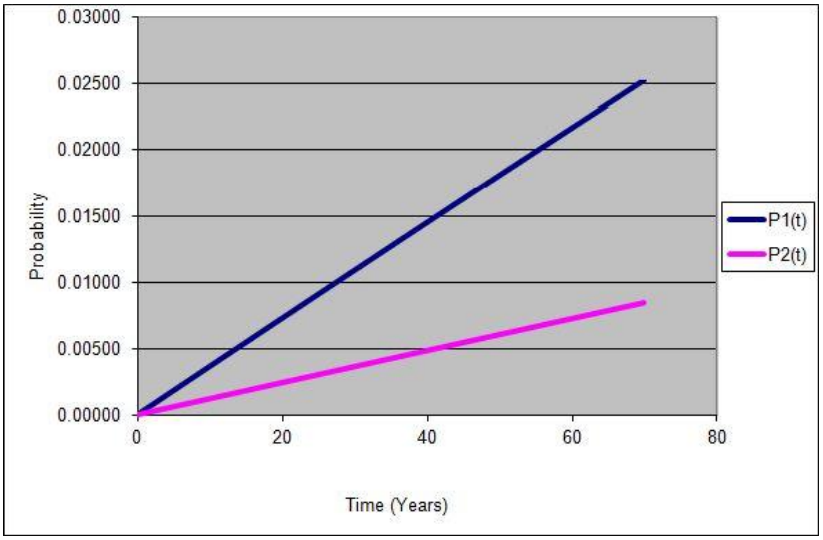


Figure 4.4. Relative fitness increased to 1.5

In Figure 4.5, several parameters have been altered. Here, it is shown that a cell with a relative fitness of 1.21 increases tumor growth by 17.36%. This figure represents a scenario for when conditions are not represented by the expected normal values. This indicates that a different factor must influence the tumor growth, compartment size, and fitness rate of an individual for the model such as unpredictable and immeasurable space radiation exposure. In space, we can expect that conditions would not be as uniform as those we encounter here on Earth, therefore modeling allows us to explore these possibilities by shifting the parameter controls to understand the changes that may result in varying situations.

Parameters		Values	Use these sliders to change parameter values.
Total number of cells in the compartment	N =	1E+07	
(One colonic crypt has around N = 1000 cells.)			
Mutation rate per gene per cell division	u =	2E-10	
(u = 1E-10 is typical for human cells.)			
Relative fitness of mutant cell	r =	1.21	
(Non-mutated cells have r = 1.)			
Length of cell cycle (in days)	c =	1	
Total timespan of interest (in years)	T =	29	

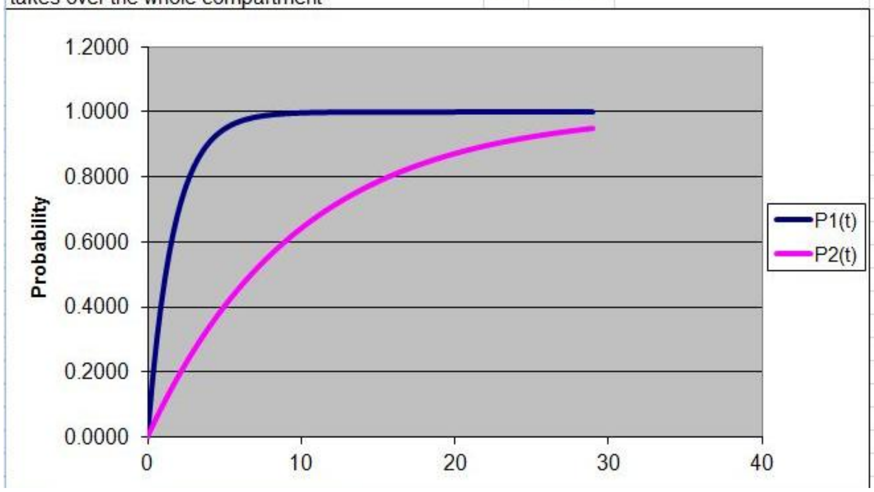
Additional Information

P1(t) is the probability that at least one mutated cell has arisen by time t.

P2(t) is the probability that a mutation has been fixed (entirely taken over its compartment) by time t.

Computations

Probability that a single mutated cell eventually takes over the whole compartment	ρ =	0.1736



Data

Time	# Cell Cycles	P1(t)	P2(t)
0	0	0.0000	0.0000
0.058	21.17	0.0336	0.0059
0.116	42.34	0.0661	0.0118
0.174	63.51	0.0975	0.0177
0.232	84.68	0.1279	0.0235
0.29	105.85	0.1572	0.0292
0.348	127.02	0.1855	0.0350
0.406	148.19	0.2129	0.0407
0.464	169.36	0.2394	0.0464
0.522	190.53	0.2650	0.0520
0.58	211.7	0.2897	0.0576
0.638	232.87	0.3136	0.0632
0.696	254.04	0.3366	0.0688
0.754	275.21	0.3590	0.0743
0.812	296.38	0.3805	0.0797
0.87	317.55	0.4013	0.0852
0.928	338.72	0.4215	0.0906
0.986	359.89	0.4409	0.0960
1.044	381.06	0.4597	0.1013
1.102	402.23	0.4779	0.1067
1.16	423.4	0.4954	0.1119
1.218	444.57	0.5124	0.1172
1.276	465.74	0.5288	0.1224
1.334	486.91	0.5447	0.1276
1.392	508.08	0.5600	0.1328
1.45	529.25	0.5748	0.1379
1.508	550.42	0.5891	0.1430
1.566	571.59	0.6029	0.1481
1.624	592.76	0.6162	0.1531
1.682	613.93	0.6291	0.1581
1.74	635.1	0.6416	0.1631
1.798	656.27	0.6537	0.1681
1.856	677.44	0.6653	0.1730
1.914	698.61	0.6766	0.1779
1.972	719.78	0.6874	0.1828
2.03	740.95	0.6979	0.1876
2.088	762.12	0.7081	0.1924
2.146	783.29	0.7179	0.1972
2.204	[illegible]	[illegible]	[illegible]

Figure 4.5. Mathematical model simulation of cancer progression using Paclitaxel

CHAPTER 5

Discussion

An important disadvantage is the inability to perform the experiment in the proposed Space and Martian environment. Instead, the research is performed using MATLAB, which disables the benefits of being able to obtain real life data and conclusions. However, if we were able to perform this research in the real life environment, the most important barrier in this research is the most obvious one, outer space. Time and distance would be a major factor. Also, it costs millions of dollars to conduct space missions and test experiments, so the lack of a substantial amount of money required to conduct the research would also be an obstacle to overcome. This will most definitely hinder the final aspirations of this research which involves testing the real model on the Martian surface.

However, if expenses, space, distance, and time were no issue, there are still other factors that must be considered. They are all environmental. These factors include zero gravity (space voyage to Mars), lowered gravity (on Martian surface), solar radiation (solar flares), cosmic rays (continuous radiation emitted from distant galaxies that is multi-directional and present in space at all times), and gamma ray bursts (most intense light energy from the explosions of massive dying stars). Gravity poses a problem in that the muscles of humans must constrict and contract under the weight of natural gravity. With lowered or no gravity the muscles lose tone because they are unable to contract against the force of gravity. Plants also use it to pattern their upward growth against the downward pull of gravity. This would affect plant growth as well. Solar flares, cosmic rays, and gamma ray bursts have the ability to cause cancer from their exposure. The countermeasures from shielding as well as the therapeutic agents that are utilized in the model are only at a basic minimum. There is an abundance of factors to be taken into consideration when encountering energy forms such as the GCR and solar radiation that the astronauts and plants will be exposed to. These factors should be accounted for when the actual space base is created.

Musculoskeletal de-conditioning issues are also a prime example of factors that are not taken into account for long duration space missions. Musculoskeletal countermeasures have been in use for decades in the US and Russian space programs. Countermeasures generally include exercising on a treadmill, a cycle ergometer, resistance training. While not perfect, these countermeasures are mostly effective. That is, they enable crewmembers maintain are higher level of strength and fitness during a flight, and tend to diminish the amount of bone loss during a flight. Importantly, long-duration crewmembers function reasonably well within several hours upon return to the 1 G environment of earth (Myasnikov and Zamaletdinov, 1998).

It is noteworthy to understand that even with the best parameter structuring in the formation of this model, shielding, and therapeutic countermeasures to prevent radiation, this research serves only as a guide to better understand the mechanisms associated with space radiation and the LSS design through mathematical modeling. The model will facilitate understanding how radiation exposure can affect advanced life within the LSS and the methods which are required to make the environment safer. True awareness of the biological issues that arise in occupying extraterrestrial environments is far from solved. Until this research is conducted in an actual setting that fosters the Martian atmosphere, it will not be known whether the methods outlined here or in any other related research are of a significant benefit to counteract the harsh encounters of the alien world.

CHAPTER 6

Conclusion

The pharmacodynamic/pharmacokinetic and tumor progression models facilitate better treatments for astronauts exposed to GCR. If radiation exposure during the mission significantly impacts the selective advantage to mutated cells, significant tumorigenesis can be expected. Space radiation has the ability to increase the fitness (r) of cells with a fixed mutation. Fitness on the mutated cell was responsible for the most significant changes in the model. With an increased fitness, the mutated cells have the ability to overcome a compartment or organ (group of tissue) within a given amount of time as indicated by the model. Given a sufficient efficacy factor (of Paclitaxel) and significant plasma drug concentration, the PK/PD model predicted that a fraction of proliferating cells were transformed into non-proliferating cells in the presence of a anti-cancer agent (Michor, et al., 2004). Predicting genetic instability and changes in a population of cells can be helpful in formulating hypothetical situations when comparing to models that are used in extraterrestrial environments and surfaces. The mathematical modeling provides the ability to understand growth rates of drug dosages, tumor growth rates (and transient stages), as well as the estimated time that it takes to clear these transient stages of tumor growths. Through the modeling in this research, we are able to employ various drug types as well, to understand their effect on exponential tumor growth and disintegration in cancer.

With this model, we can use various drugs types to understand their effect on tumor growth. It also opens the possibility to bring a large supply of anti-cancer agents, which have high efficacy factors and excellent delivery methods to the tumor compartments creating an unlimited number of experimental criteria. It is very difficult to predict what radiation exposure will be encountered during the Mars mission, but this research will serve as a guide to increase the awareness of expectations. Several innovative radiation countermeasures can be arrived using modeling. The final frontier of space and the dangers that are associated with travel and colonization will soon be made possible to safely explore with tumor progression and PK/PD drug modeling.

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