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Nanotechnology in Space Exploration

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ABSTRACT

Nanotechnology is revolutionizing space travel and reshaping our understanding of the cosmos. The realm of space exploration has always been about pushing boundaries, seeking new frontiers, and advancing technology to achieve the seemingly impossible. Harnessing the power of nanotechnology has the potential to revolutionize space exploration and colonization in ways that were once the stuff of science fiction. Nanotechnology has the potential to greatly enhance the capabilities of future space missions and increase their efficiency and effectiveness. This paper examines the implication of nanotechnology in space and its effects on geopolitics.

KEYWORDS: *nanotechnology, nanomaterials, space exploration, space colonization*

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INTRODUCTION

Nanotechnology is a rapidly developing field that has the potential to revolutionize many aspects of our lives, including space exploration and colonization. It is a young and dynamic discipline that manipulates matter at the atomic and molecular level to alter its qualities and improve its performance. Although it is still in its early stages of development, it has the potential to revolutionize space exploration and colonization. The main objective of nanotechnology research is to reduce weight and improve the performance and durability of materials, electronics, and power systems. Nanotechnology has the potential to significantly enhance mission capability by enabling, among others, the development of materials that are significantly lighter and have mechanical properties and durability superior to those available today [1].

Space development, the practical application of the capabilities of spacecraft and of the data collected from space, has evolved in parallel with space exploration. Many space applications have both civilian and military uses, and thus similar systems have been developed by both sectors.

WHAT IS NANOTECHNOLOGY?

Technologies impact every aspect of our modern society. There are many ways in which our society and technology are interlinked. Nanotechnology has the potential to provide huge benefits, just like any useful technology.

The term "nano" means something small, tiny, and atomic in nature. The application of the term in science led to a field called nanotechnology. Nanotechnology refers to the characterization, fabrication and manipulation of structures, devices or materials that have one or more dimensions that are smaller than 100 nanometers. It may be regarded as an area of science and engineering where phenomena that take place at the nano-scale (10-9m) are utilized in the design, production, and application of materials and systems. It is an emerging area of that integrates chemistry, biology, and materials science to create new properties that can be exploited to gain new market opportunities [2].

Nanotechnology deals with the characterization, fabrication, and manipulation of biological and nonbiological structures smaller than 100 nm.

Dimensions between approximately 1 and 100 nanometers are known as the nanoscale. To put this in perspective, a single nanometer is about 100,000 times smaller than the width of a human hair. As indicated in Figure 1 [3], the nanoscale is so small that we cannot see it with a light microscope. It is the scale of atoms and molecules. Nanotechnology involves the creation and application of materials and devices at the level of molecules and atoms. It may be regarded as the science that is conducted, researched, investigated, and experimented at the nanoscale. Nanotechnology is a multi-disciplinary field that includes biology, chemistry, physics, material science, and engineering. It is the science of small things—at the atomic level or nanoscale level. The past three decades has witnessed an increased interest and funding in nanotechnology. This has led to rapid developments in all areas of science and engineering [4].

- Richard Feymann, the Nobel Prize-winning physicist, introduced the world to nanotechnology in 1959 and is regarded as the father of nanotechnology. Nanotechnology involves the manipulation of atoms and molecules at the nanoscale so that materials have new unique properties. Nanomaterials are expected to have at least one dimension (length, width, height) at the nanoscale of 1 – 100 nm. One nanometer is a billionth of a meter, too small to be seen with a conventional lab microscope. Nanomaterials include nanofilters, nanosensors, nano photocatalysts, and nanoparticles. Nanomaterials are known as nanoparticles when they have nanoscale length, width, and height. Figure 2 portrays a technique for the preparation of nanoparticles [5].

Today, nanotechnology is part of our daily lives. Nanotechnology will leave virtually no aspect of life untouched. Its usages include everything from safer food processing to more efficient drug-delivery systems to powerful computer chips. Three steps to achieving nanotechnology-produced goods are [6]:

1. Scientists must be able to manipulate individual atoms.
2. Next step is to develop nanoscopic machines, called assemblers, that can be programmed to manipulate atoms and molecules at will.
3. In order to create enough assemblers to build consumer goods, some nanomachines called replicators, will be programmed to build more assemblers.

Nanotechnology is trending among scientists and engineers. Here are some underlying trends one should look for [7]:

1. Stronger Materials: The next generation of graphene and carbon devices will lead to even lighter but stronger structures.
2. Scalability of Production: One big challenge is how to produce nanomaterials that make them affordable. Limited scalability often hinders application.
3. More Commercialization: In addition to transforming the automotive, aerospace, and sporting goods fields, nanotechnology is facilitating so many diverse improvements: thinner, affordable, and more durable.
4. Sustainability: One main goal of the National Nanotechnology Initiative, a US government program coordinating communication and collaboration for nanotechnology activities, is to find nanotechnology solutions to sustainability.
5. Nanomedicine: There will be a mindboggling impact of nanotechnology on medicine, where advances are being made in both diagnostics and treatment areas.

Applications of nanotechnology are found in a wide range of industries, including engineering, medicine, microelectronics, manufacturing, biology, chemistry, energy, and agriculture, and life sciences. Figure 3 shows some applications of nanotechnology [8]. Although nanotechnology has been successfully applied in various industries, its use in the oil and gas sector is still limited.

SPACE NANOTECHNOLOGY

Nanotechnology deals with manipulating matter at the nanoscale, typically in the range of 1 to 100 nanometers. It is revolutionizing space exploration by driving breakthroughs in space research. It may hold the key to making spaceflight more practical. The use of nanomaterials, such as carbon nanotubes, is transforming spacecraft design, making them more robust yet weightless. Carbon nanotubes have exceptional mechanical properties that make them ideal for spacecraft components. As shown in Figure 4, carbon nanotubes are cylinder-shaped molecules that consist of rolled-up sheets of single-layer carbon atoms [9]. Carbon nanotubes have been used to develop lightweight and strong materials for spacecraft, such as solar sails, which use the pressure of sunlight to propel a spacecraft through space. Since the invention of carbon nanotubes in 1991, there has been an uproar in the scientific community around the various applications of this material.

The exploration of space is no easy task due to its sheer vastness. Space visionaries in the early 20th century recognized that putting satellites into orbit could furnish direct and tangible benefits to people on earth. Modern space age began with the launching of the Sputnik satellite in October of 1957. The Mercury Seven, shown in Figure 5, was the first group of American astronauts [10]. The goal of Project Mercury was to see if it was possible to land a man on the moon. Neil Armstrong became the first person to leave a footprint on the surface of the moon on July 20, 1969. It has been over 50 years since the first human walked on the Moon. The Voyager is a space probe that was designed to explore the furthest reaches of the Solar System. NASA successfully landed two rovers (robots) on the surface of Mars in January of 2004. International Space Station, shown in Figure 6, is a joint project between several countries [10]. It is currently the largest space station ever constructed

APPLICATIONS OF SPACE NANOTECHNOLOGY

Nanotechnology, the manipulation of materials and devices at the atomic and molecular scale, has the potential to revolutionize space science and exploration. From improving spacecraft materials to enabling resource utilization on distant worlds, the applications are vast and exciting. Nanotechnology is used in many ways in space exploration, including [11,12]:

- *Sensors:* Nanoscale sensors are an exciting application of nanotechnology in space exploration. Nanoscale sensors play a critical role in capturing data and monitoring the space environment. Nanotechnology can be used to create miniature sensors that can collect data and take images in space. Nanosensors can be used to monitor the levels of trace chemicals in spacecraft to monitor the performance of life support systems. Nanosensors can also be used to monitor spacecraft systems and the health of astronauts. By harnessing nanomaterials and nanoscale sensors, we are paving the way for unprecedented achievements in space research. By leveraging nanoscale sensors, scientists and engineers are able to gather data and monitor the space environment with unprecedented precision. Energy fuels sensors, devices, and communication systems, enable astronauts to interact efficiently with their surroundings.
- *Spacecraft:* Nanomaterials can make spacecraft lighter and stronger, which can improve propulsion efficiency and reduce launch costs. Nanomaterials can also be used to shield spacecraft from radiation. Materials made from carbon nanotubes can be employed to reduce the weight of spaceships. NASA is developing a nanomaterial-based coating for spacecraft that can protect them from the harsh space environment. At the moment, 95% of the weight of a spacecraft at launch is fuel, leaving only 5% for the craft itself, payload and astronauts. The development of nanomaterials could lead to lighter and more efficient fuel storage, and the use of nanoscale structures in propulsion systems could increase their performance.
- *Spacesuits:* Nanomaterials can be used to make spacesuits lighter and more flexible, which can help astronauts explore and maneuver more easily. Nanomaterials can also be used to create self-repairing spacesuits that can seal punctures and protect astronauts from toxic atmospheres. New materials combined with nanosensors and nanorobots could improve the performance of spaceships, spacesuits, and the equipment used to explore planets and moons. There could be layers of bio-nano robots in spacesuits. The outer layer of bio-nano robots would respond to damages to the spacesuit. An inner layer of bio-nano robots could respond if the astronaut was in trouble, for example by providing drugs in a medical emergency. Nano-coatings applied to space suits ensure the safety and comfort of astronauts during their missions.
- *Propulsion:* Propulsion is one of the most significant challenges to developing fast and convenient space travel. Nanoparticles can be used in rocket propellants to improve thrust and fuel efficiency. Nano-engineered propulsion systems, such as ion thrusters, offer significant advantages in space exploration. The integration of nanotechnology will be critical in developing advanced propulsion systems that can revolutionize space travel. Nanotechnology can be used to create nano-engineered propulsion systems, such as ion thrusters. Nanoparticles can also be integrated into rocket propellants to enhance thrust and fuel efficiency. This breakthrough in propulsion technology will open up new frontiers for human exploration, enabling us to reach further into the depths of our solar system.
- *Space Colonization:* Nanotechnology plays a pivotal role in resource utilization on celestial bodies like the Moon or Mars. In space colonization efforts, life support systems are crucial for maintaining the health and well-being of astronauts. Nanotechnology can contribute to

the development of compact, efficient life support systems that are essential for the sustainability of human colonies in space self-replicating nanobots hold promise for space colonization.

- *Energy:* Energy harvesting is another area where nanotechnology plays a vital role in space exploration. Nanotechnology is employed in advanced solar cells, like quantum dot solar cells, which can efficiently convert sunlight into electricity. Nanotechnology is transforming energy harvesting in space exploration. Nanogenerators, powered by piezoelectric nanomaterials, capture energy from vibrations and temperature variations in space. This energy fuels sensors, devices, and communication systems, enabling astronauts to interact efficiently with their surroundings. Nanogenerators powers sensors, communication systems, and other devices, reducing the reliance on traditional energy sources and extending the capabilities of astronauts during their missions. By leveraging nanotechnology in space suit technology and energy harvesting, we are taking significant steps towards enabling longer-duration space missions and ensuring the well-being of astronauts.
- *Nanomedicine:* This offers groundbreaking possibilities for healthcare in space colonization. Nanoparticles can be designed for targeted drug delivery, ensuring that medications reach specific cells or tissues precisely when needed. Advancements in healthcare can enhance the overall quality of life for space colonists and provide essential medical care during extended missions. Researchers at the University of California, Berkeley are developing a nanomaterial-based drug delivery system that can be used to treat astronauts for medical conditions in space. Figure 7 shows biological and health features of spaceflight [13].
- *Military:* A nation's global power is influenced by several different elements including military prowess, economic strength, diplomatic relations, and soft power. Advancement in technology can also enhance a country's overall development and contribute to a country's hegemony. Some nations and organizations were quick to recognize the great usefulness of space-based systems in military operations. Apart from land, air, and sea, space has become the fourth military dimension. The United States, Russia, the United Kingdom, France, China, the North Atlantic Treaty Organization (NATO), and other European countries have deployed increasingly sophisticated space systems. These nations are working to develop military-grade materials and systems based on nanotechnology. The relationships and rivalry between space-faring nations, nations mold the geopolitical environment of space operations.
- *Materials:* Nanotechnology can create lighter, stronger, and more durable materials for spacecraft components. Development of advanced materials using nanotechnology can improve performance in the following areas: electrical energy generation and storage, propulsion, sensors, instrumentation, signal and power transmission, thermal protection, and active structures sensing, healing, and shape control. NASA's internal development program should focus on the testing and use of nano-enhanced materials and structures and understanding their performance in the extreme environment found in space. NASA is developing carbon nanotube (CNT) reinforced composite overwrap pressure vessels (COPVs). Future NASA missions depend highly on advancements such as lighter and stronger materials, increased reliability, and reduced manufacturing and operating costs

SPACE NANOTECHNOLOGY AROUND THE WORLD

Historically, government-sponsored spaceflights were mission-based and geared towards national interests, e.g., technological leadership, improving national security, creating high-quality jobs, or advancements in research. Only a few nations, known as the space-faring nations, are predominantly in possession of space capabilities. Such nations, including the US, Russia and China, already have either built or are developing the technology to construct ground-based directed energy weapons. A nation that is behind in nanotechnology will be marginalized in the changing space environment, which could result in geopolitical instability and conflicts. We now consider how some nations are incorporating nanotechnology into the space programs [14]:

- *United States*: North America holds the largest market share for nanotechnology, largely attributed to the influence of large research labs. The National Nanotechnology Initiative (NNI) is a US government research and development initiative. It focuses on applications that include nanomedicine, nanoelectronics, water treatment, precision agriculture, transportation, and energy generation and storage. It ensures that the United States remains not only the place where nanoscience discoveries are made but also where these discoveries are transported and manufactured into products to benefit society.

The overall market for nanotechnology in defense and homeland security is expected to reach $9.9 billion by 2028 and the market for nanosensors is expected to reach $21.4 billion by 2028.

- *China:* There is no doubt that China is active in scientific development and nanotechnology. China is a leading country in nanotechnology research. China's success in nanotechnology is raising the standard for other globally competitive nations. Research and development in nanotechnology and nanoscience is the key component of the ambitious "Made in China 2025" initiative aiming at making China a high-tech manufacturing powerhouse. In 2020, researchers in China`s state key laboratory of robotics produced a laser that generates a small gas bubble that can be utilized as a nanorobot, designed to move materials at the nanoscale. Figure 8 shows the Xuntian space telescope, which is scheduled for launch in 2025 [15].
- *India*: The Indian government has been actively promoting the development of the space sector, and private companies are playing an increasingly important role. The nanotechnology market in India is expanding quickly, with numerous applications in the healthcare, consumer items, energy, and military sectors. Building upon the promotional activities carried out as part of the Nano Science and Technology Initiative (NSTI) in the highly promising and competitive area of Nano Science and Technology, which was formed in 2001. Recognizing the success of the Nano Mission, the Union Cabinet accorded approval for the continuation of the Nano Mission in its Phase II during the 12th Plan period with an allocation of Rs. 650 crores. The Department of Science and Technology is the nodal agency for implementing the Nano Mission. India has been increasing its national number of nanotechnology scientific and technical publications. Indian government took special initiatives to provide world-class education and opportunities for research and development to the students. However, India still has a long way to go. More funds should be allocated by the Indian government for further research. Figure 9 shows space exploration in India [16].
- *Iran:* With the support of talented academicians and knowledge-based companies, the nanotechnology sector has indigenized many technologies to solve the main challenges of the country in various areas, including industry. The national document on promoting the application of nanotechnology has outlined the path to achieving the major goals of the development of nanotechnology in the country. According to the document, 12,199 articles by Iranian researchers related to nanotechnology were indexed in the Web of Science (WoS) in 2021. This share of the nanotechnology articles placed Iran fourth in the world in 2020 and 2021. Iran currently ranks fourth in nanotechnology in the world after the United States, India, and China. The expansion of exports in recent years and the creation of bases in China, India, Indonesia, Syria, Turkey, and Iraq have provided a platform for the entry of Iran's nanotechnology goods, equipment, and services into the world markets.

BENEFITS

Nanotechnology may hold the key to making space flight more practical. Advancements in nanomaterials make lightweight solar sails and a cable for the space elevator possible. By significantly reducing the amount of rocket fuel required, these advances could lower the cost of reaching orbit and traveling in space. Other benefits include [17]:

- *Space Suits*: Nanotechnology could be used to create space suits that provide astronauts with additional protection and can seal and repair breaches.
- *Space Tourism:* Nanotechnology holds great potential in the field of space tourism. As space tourism continues to gain traction, nanotechnology can play a crucial role in developing lightweight and durable spacecraft, enhancing the safety and comfort of future space travelers.
- *Miniaturization*: Nanotechnology can lead to the creation of miniaturized devices and instruments that can be used for space missions. This will result in smaller and lighter payloads, which will reduce launch costs and increase the efficiency of space missions.
- *Improved Materials*: Nanotechnology can lead to the development of new materials with improved properties such as increased strength, durability, and thermal resistance. These materials can be used to construct lighter and more robust spacecraft.
- *Energy Efficiency*: Nanotechnology can contribute to the development of more efficient solar panels and energy storage devices, enabling spacecraft to generate and store more energy. This will increase the autonomy of spacecraft and reduce the need for frequent recharging or refueling.

- *Radiation Shielding:* This is an area where nanotechnology could make a major contribution to human space flight. Human tissue and electronic component protection from the harmful effects of space radiation is essential for extended deep space exploration voyages. NASA says that the risks of exposure to space radiation are the most significant factor limiting humans' ability to participate in long-duration space missions. A lot of research therefore focuses on developing countermeasures to protect astronauts from those risks. Another area of required radiation shielding is the protection of onboard electronics. It has been reported that electronic devices become more radiation tolerant when their dimensions are reduced.
- *Nanorobots:* Exploring space with a swarm of nanobots is another popular application of nanotech in space. These robots can be very small and grouped to create autonomous nanotechnology swarms (ANTS). Nanobots can effectively cover more ground and explore at much faster rates.
- *Energy:* Energy generation and energy storage will remain a top technical challenge for all future space-related missions. Batteries and power generation account for a significant amount of weight in any launch vehicle. Efficient methods to generate and recover energy, reduce overall power requirements, and reduce weight will benefit future NASA missions. Nanotechnology can improve performance for energy generation, energy storage, and energy distribution.

CHALLENGES

Space exploration is not without challenges. Space missions aim to reach Mars and beyond, but many challenges must be overcome before this can be achieved.

Safety concerns, ethical dilemmas, and the unknown risks of deploying nanoscale technologies in space must be carefully addressed. Additionally, international cooperation and regulations will be crucial to ensure responsible and equitable use of these technologies. Other challenges include the following [14]:

- *Ethical Concerns*: Space exploration brings with it an increasingly diverse set of space travelers, raising new and nontrivial ethical, legal, and medical policy and practice concerns which are still relatively underexplored. Commercial spaceflight raises new ethical considerations. Principles of health ethics encompass avoiding harm, beneficence, achieving a favorable risk-benefit balance, respecting autonomy, fairness, and fidelity.
- *Health Risks:* Health concerns regarding commercial space travel are of great importance considering that the aforementioned potential hazards can severely interfere with many physiological processes. Exposure to galactic cosmic rays and solar particle events is potentially the most significant single health hazard. Recently, NASA increased an individual astronaut's total career effective radiation dose (independent of age at exposure and sex) due to spaceflight radiation exposure to less than 600 mSv. Figure 10 depicts the five hazards in space contributing to increased health risks [13].
- *Space Radiation:* NASA believes the risk of exposure to space radiation is the most significant issue restricting humans' capacity for long-duration spaceflight. Nanotechnology could contribute to improving the spacecraft themselves, while also protecting both astronauts and equipment. For space travel, participants must have a good understanding of the space environment, the nature of associated environmental hazards.
- *Space Race*: The space race promoted exploration and use of outer space including the moon, Mars, and other celestial bodies as well as technological development
- *Global Tensions:* Rapid advancements in space technology have been accompanied by an increase in global tensions between world powers, which was a distinguishing feature of the Cold War since it was the first time mankind sought to compete in the space arena. It became a matter of pride for both the US and the erstwhile USSR of their control over space and so technological superiority was necessary to control its national security. After two space-faring nations the US and the USSR, China, Japan, France, the European Space Agency, and Israel joined the club.
- *Regulation*: As new technology emerges, there is a chance of missing it and causing crimes, which creates a need to alter the nature of warfare and requires new negotiation of standards of arms control and compliance with international law. The science of nanotechnology is constantly developing, and new advancements can have impacts in ways hitherto unknown. To ensure security in the future, it is vital to have more understanding and regulation. Some of the regulatory authorities of the United States and the

European Union have started assessing the potential risks of nanoparticles.

CONCLUSION

Nanotechnology is working with things at the nanoscale. The exciting thing about nanotechnology and nanomaterials is that they begin to exhibit weird and unique properties which can be very useful especially for space exploration. By leveraging the properties of nanomaterials we can create lighter and stronger spacecraft. We are currently witnessing the remarkable impact of nanotechnology in pushing the boundaries of exploration. Nanotechnology may hold the key to making space flight more practical.

Looking ahead, the future of nanotechnology in space exploration holds immense promise and is filled with possibilities. It will play an important role in future space missions. More information about nanotechnology and nanomaterials in the space exploration and colonization can be found in the books in [18-20] and the following related journals/magazines:

- Nanotechnology
- Nanoscale.
- Nano: The Magazine for Small Science
- Micro and Nano Technologies
- Nanotechnology News
- Nature Nanotechnology
- Current Research in Nanotechnology
- American Journal of Nanotechnology & Nanomedicine
- Nanomedicine: Nanotechnology, Biology and Medicine
- Journal of Nanotechnology
- Journal of Nanoparticle Research
- Journal of Bioelectronics and Nanotechnology
- Journal of Nanoscience and Nanotechnology,
- Journal of Micro and Nano-Manufacturing
- Journal of Nanoengineering and Nanomanufacturing
- Nanotechnology and Precision Engineering

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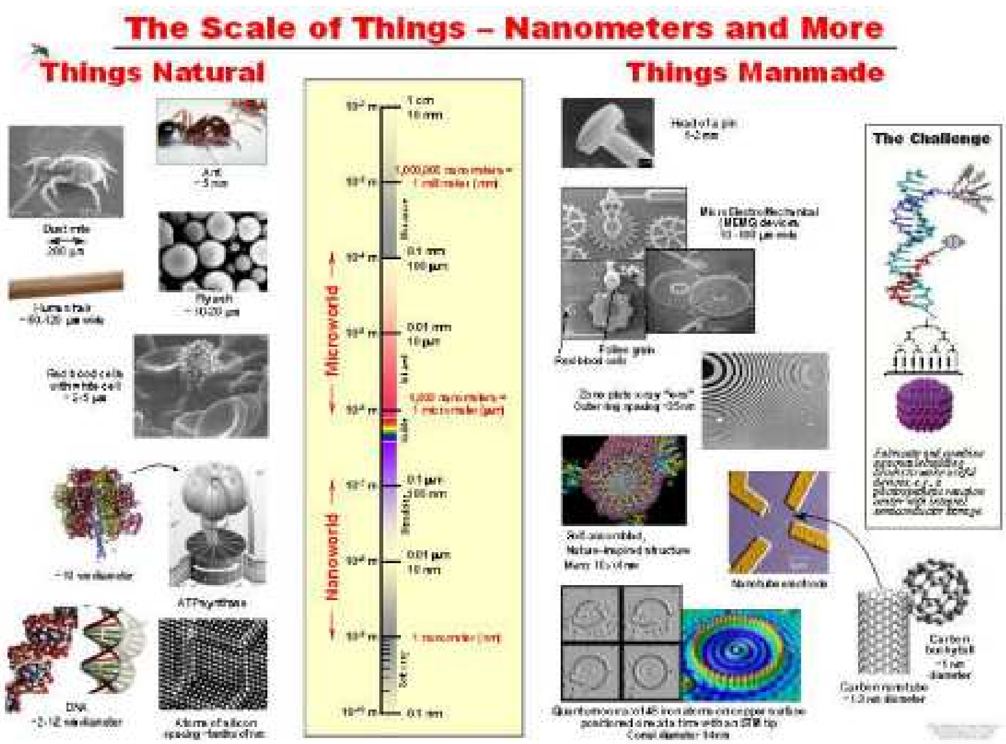

Figure 1 Indicating the relative scale of nanosized objects [3].

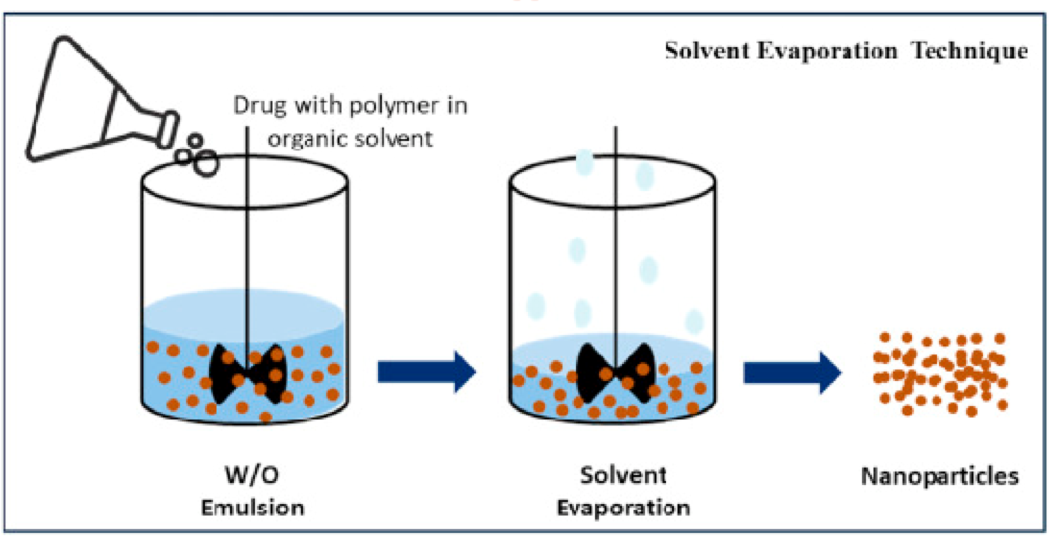

Figure 2 A technique for the preparation of nanoparticles [5].

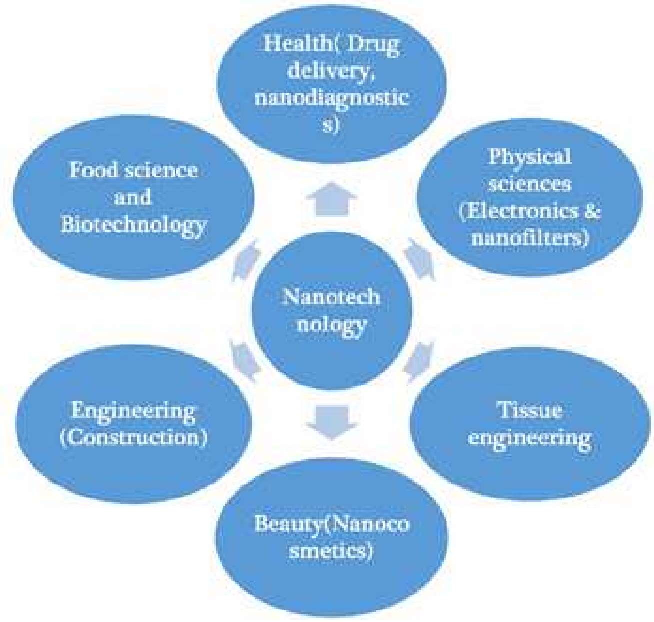

Figure 3 Some applications of nanotechnology [8].

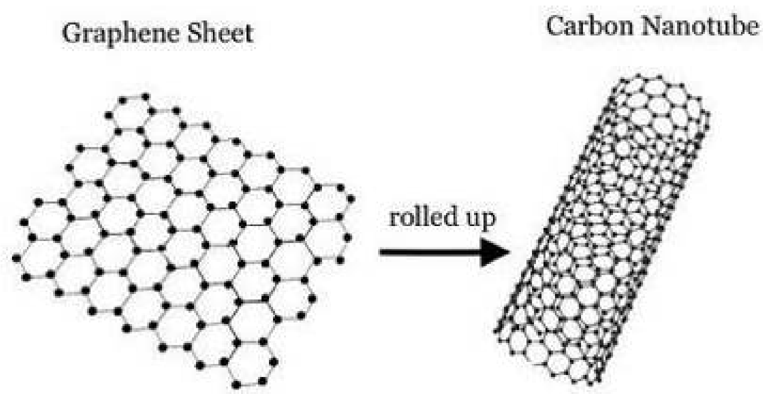

Figure 4 Carbon nanotubes are made from graphene sheet [9].

Figure 5 The Mercury Seven of American astronauts [10].

Figure 6 International Space Station [10].

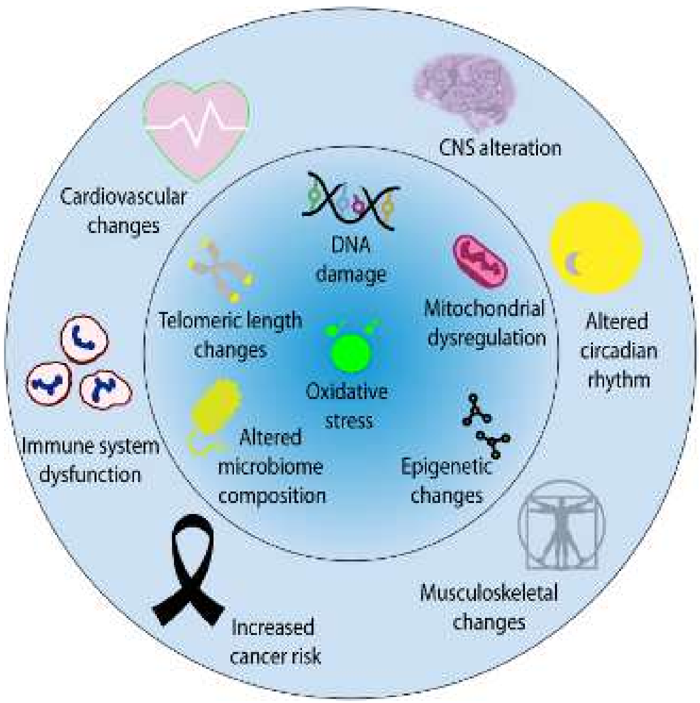

Figure 7 Biological and health features of spaceflight [13].

Figure 8 The Xuntian space telescope, which is scheduled for launch in 2025 [15].

Figure 9 Space exploration in India [16].

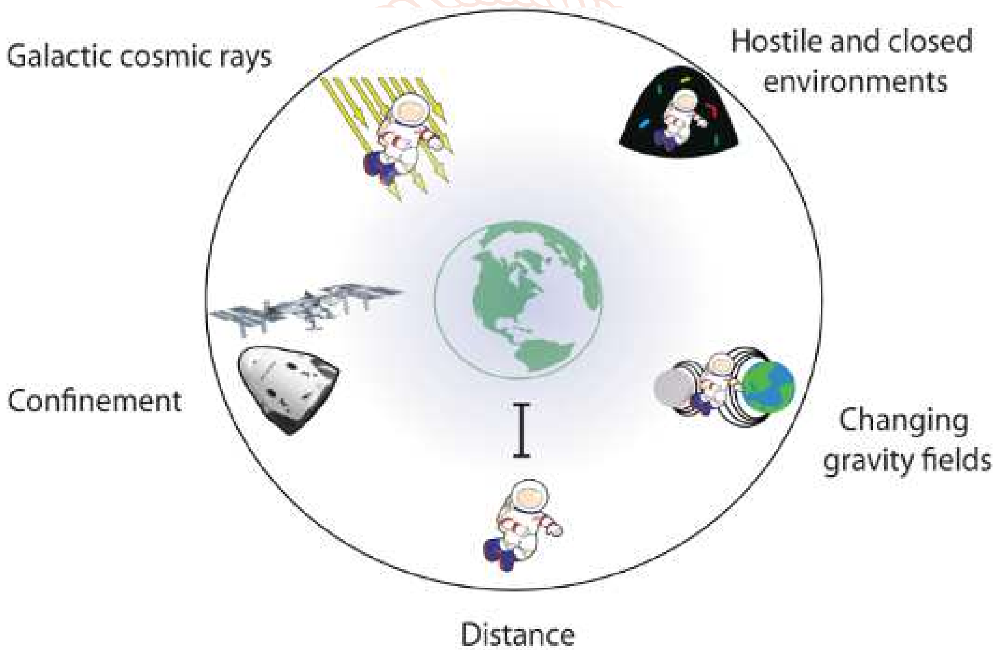

Figure 10 Five hazards in space contributing to increased health risks [13].