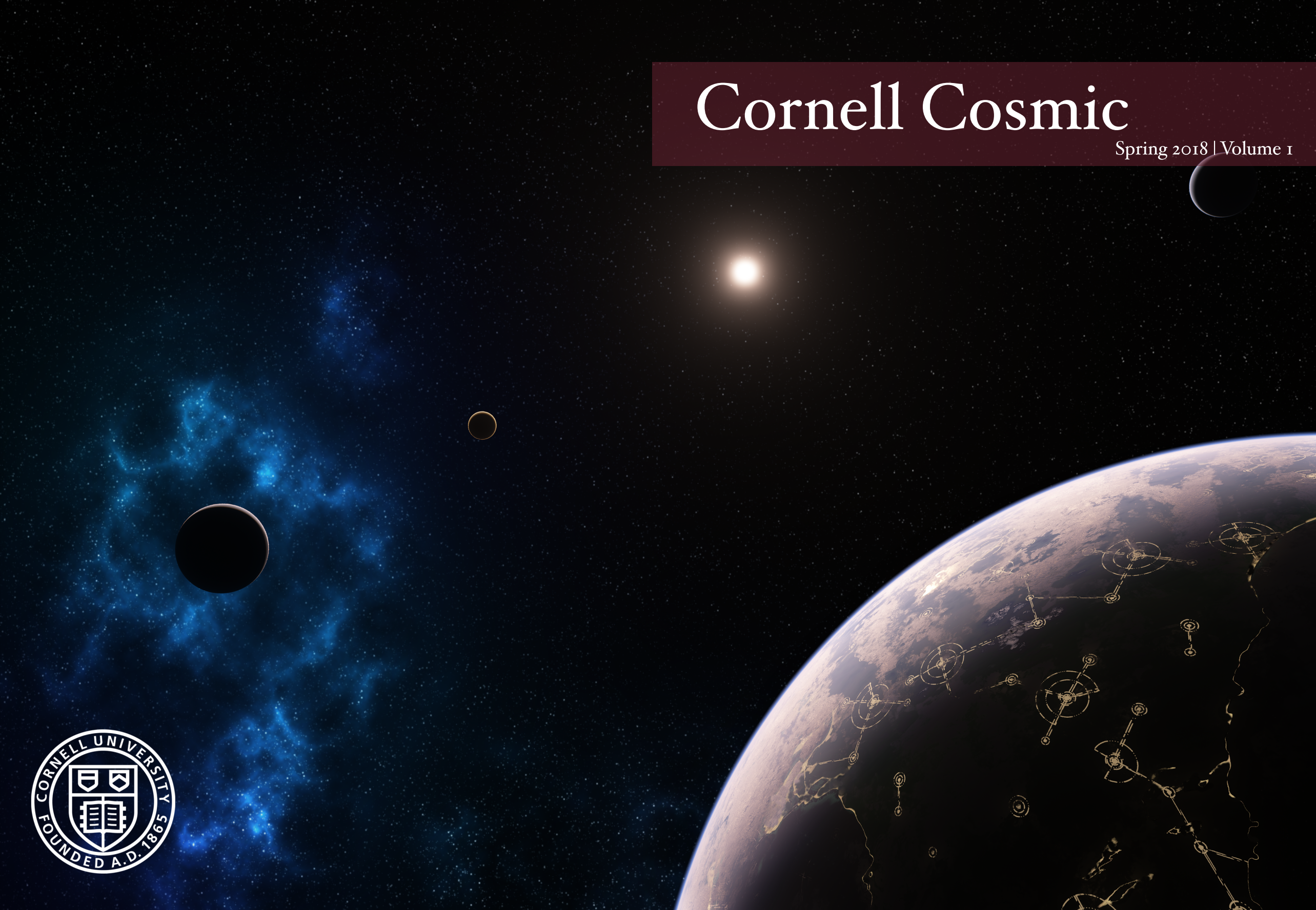
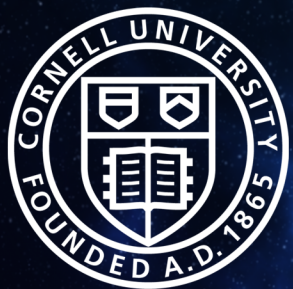


Cornell Cosmic

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Mission Statement

Our purpose is to inform the Cornell Community of contemporary developments in outer space, whether it be through scientific advancements or the changing dynamics in international relations. We hope to foster a futuristic mindset by emphasizing the search for new life as well as the possibility of inhabiting planets other than Earth. Furthermore, we seek to investigate how outer space operations reflect the shifting dynamics among countries on Earth. Through intertwining these various elements we offer you a holistic representation of our newest frontier.

Cover Photo Designer: Jack Madden

Faculty Advisor

Professor Lisa Kaltenegger

Director of the Carl Sagan Institute

Lisa Kaltenegger is an Associate Professor at Cornell University and Director of the Carl Sagan Institute. Her research focuses on rocky planets and super-Earth atmospheres in the habitable zone, as well as the spectral fingerprint of exoplanets that can be detected with the next generation of telescopes.

Lisa Kaltenegger was named one of America's Young Innovators by the 2007 Smithsonian Magazine, selected as one of the European Commission's Role Models for Women in Science and Research, and recently received the Heinz Meier Leibnitz Prize for Physics of Germany in 2012. She was also awarded the Christian Doppler Prize for Innovation in Science from Austria in 2014 and the Kavli Plenary Prize lecture at the IAU in 2015. She has been featured in the 2016 IMAX documentary "The Search for Life in Space."

She hopes that Cornell Cosmic will bring greater awareness to the groundbreaking developments that are currently underway, and in particular, shed light upon Cornell University's leading role in this avant-garde field.

Introduction to Authors

Jack O'Malley-James is an astrobiologist working at the Carl Sagan Institute at Cornell University. With a background in both environmental biology and astronomy, he explores questions at the borders between these fields to figure out how biology would influence habitable exoplanets – their atmospheres, climates, and appearances – and, crucially, how astronomers could detect life on these alien, but not so Earth-like worlds.

Jack Madden is a PhD student in astrophysics at Cornell working on characterizing potentially habitable exoplanets. His primary research focus is to explore the relationship between the surface and the atmosphere of a habitable world and how that relationship manifests itself in the measurements our telescopes can make. Jack is also involved in education research as fellow for Cornell's Center for Teaching Innovation. As an educator, Jack taps into everyone's innate curiosity for the unknown and plans on pursuing a career as a college level professor.

Joseph McCracken is a freshman writer and editor for Cornell Cosmic. He plans to major in astronomy, and is especially interested in cosmology and astrobiology. He was born and raised in State College, Pennsylvania. When he's not busy with schoolwork, Joe enjoys playing basketball and volleyball, hiking, video games, music and hanging out with friends. In addition to Cornell Cosmic, he is a member of the Cornell Concert Commission. In the future, Joe plans to attend graduate school and conduct research in the field of cosmology.

Seréna Pilkington is a recent graduate from the School of Politics and International Relations (SPIRe) at the University College Dublin, Rep. of Ireland. She completed her bachelors thesis on modern space relations with a focus on international security. She later won the UCD Tom Garvin award for highest graded thesis. She plans to pursue a Masters in International Security in 2018, with a special focus on space relations.

LOOKING FOR LIFE AT THE END OF WORLDS

JACK O'MALLEY JAMES

INTRODUCTION

The year is 2,000,000,000 AD (not that anyone is keeping count anymore) and a new day is dawning somewhere on planet Earth. An unusually bright Sun sluggishly climbs through the sky, for the Earth spins much slower in this future time. Days and nights last many hours longer than seems sensible. Eventually the Sun crests the peak of a gigantic volcano that has been allowed to soar far above the height of Everest, thanks to the lack of eroding rain and the slowing of plate tectonics. The dusty terrain rapidly warms to around 120°C, which is not much hotter than the night before, given that powerful winds continually transfer heat from the day-side to the night-side. The dry landscape is composed of grays, reds and browns; bare rock and sand cover the entire globe, unbroken by vegetation, rivers or seas. The only sounds are the howling of the scorching wind and the distant hissing of gases escaping from nearby vents. Clear skies, tinted pink with dust, are broken only very occasionally by small wisps of white cloud. This is life's final home.

Almost nothing can live here. People vanished over a billion years ago. Such a long time ago that barely a trace remains now; only thin veins of ancient rock rich in rare metals hint at our past existence. Were a human to suddenly find themselves waking up on this far future morning, they would not last very long. Before the far-too-bright Sun and the lack of an ozone layer joined forces to cause extreme sunburn, the high surface temperatures and pressure would boil the unfortunate traveler alive ... unless the absence of oxygen in the atmosphere suffocated them first. However, despite appearances, this extremely inhospitable world is not yet devoid of life. Nature's greatest survivors are still clinging to an existence, using up Earth's last few drops of water to continue living. If we ascend the gigantic volcanic mountain, tell-tale clues of their existence can be seen. Clinging to the inside edges of volcanic vents and sheltered from the Sun's harsh radiation, a slight discoloration of the rock hints at their presence. Hardy

microorganisms in small colonies use the volcanic carbon dioxide and steam as fuel to slowly, laboriously produce copies of themselves. This is not a story of survival though. These microbes are living on borrowed time. Soon the grand sequence of extinctions that have led to this day will be complete and these hardy survivors will run out of water.

Many hours later, the Sun sets on this long-lived day. The Moon becomes visible in the night sky, but it is oddly small. It has moved so far away from Earth now that it barely gives any appreciable light to this dark night under a sky of alien stars. This is a night that stands on the cusp of the end of all life on Earth.

The scene described above is based on scientific predictions for Earth's, and life's, far-future. How do we go from a planet teeming with a rich variety of life to the scenario described above? This is a question I began investigating at the beginning of my PhD in the small university town of St. Andrews on the east coast of Scotland. My bleak and isolated new home town at the edge of the cold North Sea, once described as the edge of the world, was a perfect environment for contemplating the world's end. However, the task at hand was far from an exercise in post-apocalyptic fantasy; it was about equipping astrobiologists with extra tools in our quest to find evidence of life elsewhere in the universe.



St. Andrews, Scotland. Courtesy of J. Llama.

The search for life beyond Earth involves looking “up”, looking outward into the solar system and into the vast spaces beyond. However, the tools we need to carry out this search also require us to spend as much time, if not more, looking back down at our own planet and the life living on it. To look for life on other worlds, we must know what life does to its home world that makes it stand out from a sea of lifeless, rocky planets. The only example we currently have is the one we are all bound to: a middle-aged, small, rocky world at a comfortable distance from a medium-sized star; a world that happens to have a rich, diverse layer of life clinging to its surface.

By studying this life in a planetary context, we have found that biology has shaped Earth with the power of a geological force, influencing climate, the gases in the atmosphere, the kinds of clouds that form, the types and chemical compositions of the rocks making up the land and ocean floor, and even the overall color of the planet. These are vital clues in the hunt for signs of life on other planets that appear habitable. If we know that an atmosphere with large quantities of certain gases, or a planetary surface with certain widespread colorations, can be uniquely explained by the presence of life, then, if we see these things when we study an Earth-like planet around another star, we can cautiously argue that it may have life on it too. These unique “fingerprints of life” are referred to as biosignatures. For them to be useful in the search for life, they need to be strong enough for us to detect over vast interstellar distances, and we need to be confident that biology is their most likely cause.

We know a lot about the biosignatures an alien astronomer observing our planet today would see. Life on Earth currently maintains levels of atmospheric oxygen, ozone, and methane that cannot be explained by any process we know of apart from widespread biology[1], and crucially, the quantities of these gases are large enough that they could be detected from beyond our solar system with telescopes like the ones astronomers are developing today. Furthermore, the plants on our land surface reflect a lot of infrared radiation, enough that with a very sensitive telescope their presence could also be detected. However, these signatures are not all we can look for in our search for life on other worlds. The way biology shapes the world around us today is just the latest example of what it can do to a planet. Over Earth’s long and varied evolutionary history, the biosphere has had many forms that have shaped the planet in sometimes very different ways. What life does to our planet today is not necessarily what it did

in the past. If we take a (very) brief tour through the history of life on Earth, it becomes clear why life on Earth today is just one piece in a complex jigsaw puzzle of possible biologies.

Earth formed 4.54 billion years ago, one of the many rocky bodies in our solar system that emerged from gas and dust remnants left over from the Sun's formation. Initially beginning its life as a molten ball of rock, Earth soon cooled enough for its outer layer to form a solid crust. Gases from the interior, released through vents and volcanoes, helped to form an atmosphere. Frequent collisions with icy bodies from the debris-strewn young solar system, along with out-gassing from Earth's deep interior, delivered water, which cooled and condensed into oceans over time. Geological evidence shows us that life first emerged at least 3.5 billion years ago[2], but some hints in the rock record suggest that life might have appeared as early as 4.1–4.2 billion years ago[3],[4]. Either way, it seems that almost as soon as the planet cooled and liquid water existed on the surface, life emerged. However, this was not life as we know it today. The early Earth was populated by simple, single-celled organisms: the prokaryotes. They did not need oxygen – in fact, there was no oxygen in the atmosphere at this time – and they did not look like the plants and animals we see around us today. This was a very alien world. The largest “lifeforms” would have been interacting communities of microorganisms, joining together to form macroscopic structures called stromatolites[5].

For over two billion years, prokaryotes dominated the planet until the first multicellular life (eukaryotes) appeared and bacteria began producing oxygen, via oxygenic photosynthesis, in sufficient quantities to start oxygenating the atmosphere. Plants evolved from green algae somewhere in the region of 500 million years ago, colonizing the land and further contributing to an increasingly oxygen-rich atmosphere. Finally, the abundance of highly reactive oxygen enabled energy-hungry modern animals to emerge: the world, more or less, that we know today[6].

If we limit our studies of the detectable changes life can bring about on a planet to what happens on Earth today, we may miss signs of life on worlds where biology has not evolved into the complex forms that terrestrial biology has, very geologically recently, achieved. That's why astrobiologists use the early Earth to provide windows into “almost alien” worlds, adding to our list of potential fingerprints of life. Much can be written (and has been[7],[8]) about the possible biosignatures associated with life at different stages in Earth's history, but here I want to focus on the future of life on Earth over the next few billion years of its

journey.

If life has changed so much on Earth, will it continue to change just as dramatically in the future? If we can answer that question, we will gain even more clues for our search, further increasing our chances of a successful life detection mission. However, whereas Earth's geological past is revealed through rock records, fossils, ice cores, etc., no information can tell us anything about the planet's geological future. Luckily, we understand enough about how the planet works to predict, in a general way, what the future has in store. The future in this context does not refer to years, decades, centuries or even millennia from now, but hundreds of millions to billions of years; enough time for the planet to be so completely changed from its present state that it would be almost unrecognizable to us as home.

How do we begin to make these predictions? For astrobiologists, there are two main things we want to know about the far-future: what kinds of life will live there, and what detectable biosignatures will that life produce? Climate determines what kind of life can live in a given environment. If we imagine cooling down the modern-day Earth, many forms of life may die out, while others may flourish. On the contrary, heat the world up and different forms may die out, while another set could flourish. If temperatures become too extreme, all life as we know it ceases to be possible. So, to find out what will happen in Earth's geological future, we first need to find out how the climate will change.

The Sun acts as the main driver for the state of the climate, providing the initial energy (along with some influence from geological activity) for the system. From there, internal effects from the atmosphere, geosphere, hydrosphere and biosphere, along with external forcings from the Earth's orbital parameters (the planet's tilt and the circularity of its orbit), modulate global and regional climate. Changes to the climate can cause changes to the composition of the atmosphere, the oceans, and the biosphere, which can in turn cause further changes to the climate. This hugely complex, dynamic system can result in many different climate states. The scientific world is becoming increasingly adept at predicting how this system will respond to changes, in large part thanks to our efforts to predict the consequences of anthropogenic climate change – the release of vast reservoirs of geological carbon into the atmosphere, via the burning of fossil fuels, enhancing Earth's heat-retaining greenhouse effect – which is currently altering the climate system at an unprecedented rate. However, even under the worst-case

predictions for near-future climate change scenarios, although the losses to the biosphere and Earth's biodiversity would be enormous, the planet's biosignatures are unlikely to alter much from the ones we have today. Furthermore, from a geological perspective, life would survive and rebuild (with or without humans; human civilization is particularly sensitive to the impacts of climate change), much as it has done after mass extinction events in the past. To imagine a truly different phase of Earth's future history we need to look much further forward in time.

The main influence on the climate of the far-future Earth will be the Sun. From observing other stars like the Sun, some that are older, some that are younger, astronomers have been able to piece together what happens to a sun-like star over the course of its lifetime. After a dramatic and energetic birth, stars settle into a calmer, steadier state of existence, referred to as their main sequence life. The Sun is about halfway through its allotted 10 billion years of time on the main sequence, after which it will swell into a red giant and enter a new phase of existence. However, for our investigation into the future of life on Earth, we only need to consider the remainder of the Sun's main sequence life. As stars age during their main sequence phase, they become gradually more luminous, increasing the amount of energy they release in any given moment of time. This change is imperceptible over human timeframes, but when you look at billion-year-long snapshots of the Sun's life, this increase becomes notable. These very long-term changes cause the boundaries of the habitable zone (the region around a star where a planet would have the right surface temperatures for liquid water – a prerequisite for life as we know it – to exist) to move further from the star over geological time[9]. This means that, eventually, Earth will get hotter and hotter until all the liquid water evaporates and the planet becomes uninhabitable; a transition that will take place within the next few billion years[10],[11]. In the build-up to this ultimate extinction event, we can expect some dramatic changes to the climate and biology on our planet.

Over the next billion years, the energy Earth receives from the Sun will increase such that, a billion years from now, the Sun's luminosity will be 10% higher than it is today[12]. This does not seem like a huge change, but this extra energy will be amplified by Earth's climate system. Predicting these changes is a much fuzzier and less precise art than the highly detailed simulations we have for changes to Earth's climate over the next few decades. Nevertheless, we can still make some general predictions about what could happen and what these changes would mean for life on Earth. It makes sense to start by thinking about the foundation of

the modern biosphere: plants.

If you look around you anywhere on Earth, you will probably see some kind of vegetation; pushing its way through cracks in a road, clinging to the side of a cliff, or even huddling around an artificial light left shining for long enough deep within the darkest of caves. Many more plants will be invisible, microscopic organisms floating in the air around us, just waiting for the right conditions to photosynthesize and multiply. Plants are everywhere and this is not surprising. There is an abundant amount of energy arriving on Earth from the Sun every day; it would be surprising if life did not find a way to use it. Photosynthetic life uses mostly the visible part of the spectrum (the rainbow of colors that our eyes can detect) and in almost every terrestrial environment where these colors of light are available, we find plants. Even extremely inhospitable environments, from frozen glaciers to scorching deserts, have been conquered by them. Photosynthesis is one of life's greatest success stories. It has, throughout most of the biosphere's history, been the foundation of almost all food chains, thereby making our Sun the fundamental driving force behind all life on Earth. Even creatures making a living from the geothermal energy released by deep-sea hydrothermal vents indirectly use the left-over energy from the formation of the solar system. So what happens to this state of affairs when we crank up the Sun's energy output? In addition to sunlight, photosynthesis needs carbon dioxide and water. The availability of both of these could substantially decrease under a hotter Sun.

1. The Expansion of Deserts

Rising temperatures will increase the power and range of warm air currents flowing out from the equator, increasing the extent of arid climate zones[10]. Meanwhile, hotter temperatures on Earth lead to increased evaporation of surface water, which means more water vapor in the atmosphere. Water vapor is a very potent greenhouse gas that produces a much stronger warming effect than an equivalent amount of carbon dioxide (CO₂). More water vapor entering the atmosphere would enhance the planet's greenhouse effect, rapidly amplifying a small increase in temperature, causing further heating of the planet and further expansion of desert regions[10].

Liquid water is at a premium in deserts, but it is essential to all life as we know it. Furthermore, heat and intense radiation can damage or kill cells,

making the process of living difficult, or sometimes impossible. Consequently, this scenario does not bode well for life on Earth, but biology has developed various clever ways to combat the problems of high temperatures and scarce water supplies. The types of life best suited to meeting those challenges will be able to survive for longer.

What would a biosphere founded on the hardiest survivors of the plant world be like? Our best clues come from life in Earth's hottest deserts. Desert plants survive by reflecting excess light, keeping themselves as cool as possible and stockpiling water. For example, cactus spines do not just act as a defense against predators; they are also highly reflective, reducing the surface temperature of the plant and encouraging water vapor from the air to condense around the plant[13]



Cactus spines not only help the plant defend itself from grazers, but also play many roles in keeping the plant cool. Image source: Wikipedia Commons

– perfect for hot deserts. Plants have many other protective mechanisms, from reflective waxy leaf coverings to leaves that fold up when light levels become too intense[10],[11]. As conditions get tougher on the future Earth, life will probably need to get more creative than this.

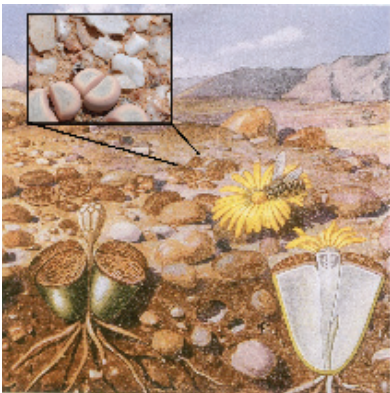
Ideally, we would figure out how life would adapt to this hotter, drier future Earth by taking some living specimens from today's biological world and gradually introducing them to increasingly extreme conditions over generations. Unfortunately, this would require millions of years of dedicated work from generations of scientists. Luckily, Nature has already done this experiment for us. One particularly notable example of this kind of natural experiment is the island of Socotra, a UNESCO World Heritage Site in the Arabian Sea. Socotra has been geologically isolated from Earth's main land masses for millions of years and has a very dry, hot climate. This isolation has caused some bizarre and unusual forms of vegetation to evolve[14] that just might give us some insight into the directions life could take in the far future. The island provides a home to some truly alien-looking landscapes, sparsely populated with plants like the Desert Rose and Dragon Blood tree (named for its red sap) that have developed their own unique ways of surviving



(Left) The Desert Rose (*Adenium obesum*) or Bottle Tree stores vast amounts of water to combat aridity. (Right) The umbrella-like shape of the Dragon Blood Tree (*Dracaena cinnabari*) keeps the ground around the tree cool, slowing water loss while preventing the tree from overheating. Image source: Wikipedia commons.

in an environment with very little water: perfect abilities for surviving on the future Earth.

We can find more inspiration for imagined landscapes of the future in other desert regions. Stone plants from South Africa deal with hot, dry environments by living underground. They use two specially adapted transparent leaves as a window-like cover that allows light to pass through to its underground leaves[15]. In this way, the plant can stay cool in the desert, filter out damaging ultraviolet (UV) radiation from the Sun and, because from the surface it looks like a stone, remain relatively safe from anything that might want to eat it.



South African Stone Plants live underground to keep cool. Image Source: Wikipedia Commons

Some plants take climate control a step further. Living at high altitudes in the Himalayas, the Noble Rhubarb faces similar challenges to desert plants. Although excess heat does not present a problem, aridity caused by drier air at high altitudes, along with higher levels of harmful UV radiation, mean that plants need some kind of protection to survive. The Noble Rhubarb deals with this environment by creating its own. It grows a

leafy outer “shell” of leaves that provide a more tolerable micro-climate beneath them, while also filtering out harmful UV rays. Perhaps plants on the future Earth will make use of similar forms of self-regulated climate control[16].

As Earth creeps toward the inner edge of the habitable zone, life across the globe could begin emulating places like the island of Socotra. However, this would just be the very beginning of the end for life on Earth. Eventually, photosynthesis itself could become an unsustainable reaction and even the hardiest of desert-adapted plants will be no more[10],[11].

2. The Death of Photosynthesis

Life also depends on carbon, but animals cannot directly use the carbon in the air around us. Plants solve this problem by “fixing” carbon from CO₂ in the atmosphere and turning it into a biologically available form, enabling other organisms to gain the carbon their bodies need by eating plants, or by eating things that have eaten plants. To fix carbon in the first place, plants need access to a sufficient amount of CO₂ gas. Earth’s atmosphere today has plenty of CO₂, and that amount is currently growing at an alarming rate. Yet, on the hot, future Earth, the increased rainfall we discussed before can cause CO₂ levels to gradually reduce over the course of a billion years, making it increasingly difficult for plants to photosynthesize.

As rain falls, it can react with CO₂ in the air to form carbonic acid. If this carbonic acid then comes into contact with certain types of rock, such as silicate rocks, it undergoes a chemical reaction that produces solid bicarbonates. These dissolve in soil water, find their way into rivers and ultimately end up in the oceans. Over the course of a cycle that lasts hundreds of millions of years, this carbon gets deposited in ocean sediments, then buried deep



The Noble Rhubarb (Rheum nobile) creates its own microclimate to cope with environmental stresses. Image source: L'illustration horticole, 1874, Hooker Thomson; Wikipedia Commons.

beneath the Earth's surface. It is eventually released back into the atmosphere again via volcanic eruptions and undersea vents. Prior to the Industrial Revolution, this cycle was reasonably balanced – the rapid burning of fossil fuels by humans has led to millions of years worth of carbon being released over just decades, unbalancing the present-day system. This is causing, and will likely continue to cause, problems for life on Earth today as we all struggle to adapt to rapidly changing conditions. However, if we look deeper into the geological future, the next billion years could see CO₂ levels fall to worryingly low levels.

Driven by the the aging Sun, hotter temperatures cause more rainfall, which speeds up the removal of CO₂. As this continues over hundreds of millions of years, this runaway feedback starts to make quite a dent on atmospheric CO₂ levels[10],[11],[12]. Plants need a certain amount of CO₂ to perform the photosynthesis reaction. Some need less than others, and use CO₂ efficiently. However, most plants today can get away with being lazy; they are surrounded by more CO₂ than they need, so why bother to save it for a rainy day? These types of plants – all of the common forest trees and familiar food crops like wheat and potatoes – will be the first to face extinction, perhaps within just a few hundred million years. The plants that make the extra effort to do more with less CO₂ – plants like cacti and certain grasses – could last for nearly a billion years. By then, there could be as little as 3% of the modern levels of CO₂ in the atmosphere. Only the simplest of plants – algae – could exist under those conditions, but, with CO₂ levels still falling, their reprieve would not be a long one[10],[11].

So if plants, the basis of almost all food chains on Earth, seem destined to decline into extreme forms before then disappearing entirely, what happens to the rest of life on Earth?

3. The End of the Age of Animals

Animal life on Earth today is powered by oxygen, a rich fuel that supports their complexity and high rates of energy consumption. However, this life-sustaining oxygen in the air we breathe only exists because plants continually produce it. Oxygen in our atmosphere rapidly reacts with other substances (think about metals rusting) such that, if the supply from plants gets cut off, Earth's atmospheric oxygen supply would quickly become depleted, falling to trace levels within just a few million years[10],[11],[17]. Disappearing oxygen also

causes the decline of one of its photochemical byproducts: ozone (O_3). The ozone layer in the atmosphere acts as a protective barrier to life on the surface by blocking out the worst of the UV radiation from the Sun. Low-energy UV can bypass the ozone layer and causes problems like sunburn or skin cancer after long exposure times. However, the high-energy UV that does not make it to the surface would be lethal to most forms of life within as little as 0.3 seconds[18]. Therefore, without an ozone layer, life on the surface of the Earth would become very challenging. Perhaps the first big change in the animal world will be a shift from surface living to subsurface living. Soil, sand or water acts as a shield to UV radiation while also providing a cooler shelter from hot surface temperatures. The Sahara Desert ant uses this underground-living strategy to survive in an environment where temperatures reach 70°C , sustaining body temperatures of over 50°C [19], the highest known temperature at which an animal has been observed to operate. They do this by spending most of their time underground, emerging very briefly at the hottest point in the day to collect the remains of the animals that could not stand the heat. Animals could also become predominantly nocturnal, sheltering underground during the day and emerging at night. Unfortunately, these subtle changes will not solve the problem of a decreasing food supply.

Eventually, the extinction of all animal life as we know it would be inevitable under these conditions. Firstly, as the plants disappear, animals in food chains dependent on live plants will begin declining shortly afterwards[10]. This would be especially challenging for large land animals that need to eat vast amounts of vegetation to survive. Large animals will suffer further as oxygen levels fall



The Sahara Desert Ant carries out its life at temperatures of 70°C for brief periods of time between periods of cooling down in its nest. Image credit: Creative Commons Licence

because they also have the highest oxygen requirements[10]. A third pressure on large animals – increasing temperatures – would make life even less favorable for them. Larger animals are less able to dissipate excess heat compared to smaller mammals, which have a higher surface-to-volume ratio[10]. While some representatives from these larger animal species could survive for longer in the oceans, where phytoplankton would outlast land plants and they would initially be buffered against the worst

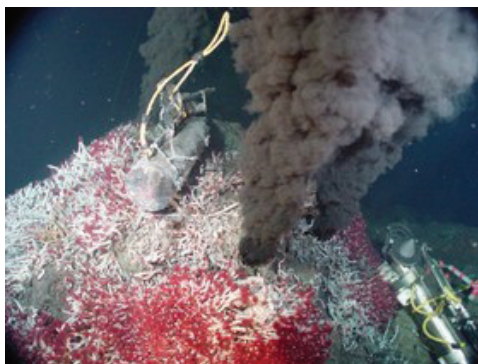
of the increasing temperatures, it is likely that another impact of the warming future Earth on the animal world will be to make things smaller[10].

Among small animals, birds may be better suited to survive than mammals since they can migrate more easily to suitable climates. Fish, amphibians and reptiles, given their abilities to cope with heat and low oxygen levels, could be the best survivors of the vertebrate world. Of these, marine species may be able to survive for longer than freshwater species. The volume of ocean water is hundreds of times greater than the volume of liquid freshwater, so freshwater habitats will be lost before marine habitats. Ultimately, loss of plant life on land prevents nutrients from reaching ocean soils[10].

The hardest animal survivors are likely to be the insects and other invertebrates. Some insects, like the Sahara Desert ants, have been observed to survive in high temperatures, while others, such as the spider beetles *Mezium affine* and *Gibbium aequinoctiale*, have been observed to survive (but not necessarily to complete their life cycle) in temperatures of up to 56°C[20]. Furthermore, there are some insects that can eat dead plant tissues, which could give them a brief advantage in a world where plant life is beginning to die out.

Termites, for example, digest dead wood due to a symbiotic relationship with microorganisms in their guts[21], while some crustaceans are able to digest dead wood without the aid of symbiotic microbes[22].

The most isolated animal communities, such as those that live around volcanic vents, would likely survive the longest[10],[11]. Tube worms that feed directly off of chemical energy from deep-sea hydrothermal vents make particularly good candidates for the last animals on Earth, because they do not rely on nutrients from other plants, or animals, and they can tolerate high temperatures. Despite this, all animals need oxygen, so even these creatures would face extinction when the



Tube worms living around deep-sea hydrothermal vents are good candidates for the last animals on Earth. Image credit: IFE, URI-IAO, UW, Lost City Science Party; NOAA/OAR/OER; The Lost City 2005 Expedition

oxygen content of deep waters is depleted.

4. *A New Age of Microbes*

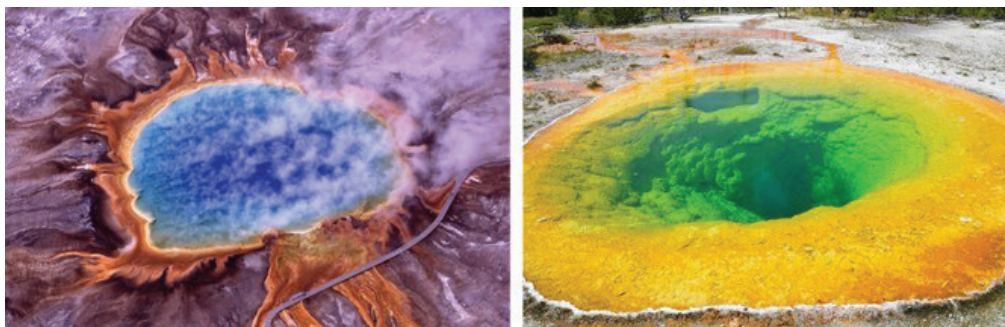


The tardigrade (Milnesium tardigradum) is arguably Nature's greatest survivor. Technically a micro-animal rather than a microbe, it can withstand boiling, freezing, years without water and even exposure to space. Image credit: Wikipedia Commons.

Within approximately a hundred million years after the end of all plant and animal life, Earth will once more become a microbial world[10] (perhaps with the exception of tardigrades: microscopic animals with extreme survival abilities). This all seems like a reversal of the sequence that the evolution of life on Earth has followed from its beginning to the present day. A world full of microbes could look very similar to the early Earth during its first two billion years.

Microbes are Nature's greatest survivors. Some species can grow in temperatures as low as -20°C [23], while others can withstand temperatures as high as 122°C [24]. Others can tolerate high pressures, high radiation environments, extremely acidic and extremely alkaline environments, and even extremely dry environments. For this reason, a new reign of microbes could last well into Earth's distant future, but this future phase of the biosphere would also have an end. As the habitable zone boundaries move ever outward, temperatures on Earth will continue rising. Life as we know it is based on biochemistry that breaks down at certain temperatures. There are some things that life can do to buffer itself against high temperatures, but eventually the chemistry that powers living things will cease to function. If we give future evolutionary innovation a little room to maneuver and assume that life will find a way to push its temperature tolerance to somewhere in the region of 150°C , all we need to do to predict the end of life on Earth is to figure out when the Earth's surface temperature will reach 150°C . Before Earth reaches this temperature, it will undergo another dramatic change: the rapid evaporation of the oceans.

Shortly (geologically speaking) after the dawn of the second age of microbes, Earth will enter a moist greenhouse state[10],[11],[12]. Water vapor is normally



Heat-loving microbes (thermophiles) are abundant in hot spring habitats like those in Yellowstone National Park (pictured). The communities they form come in a variety of vivid colors. Perhaps the far-future Earth would appear in vivid technicolor, rather than the shades of blue and green we are familiar with. Image credit: Wikipedia Commons.

trapped in the lower atmosphere. Any surface water that evaporates rises until it gets cool enough to condense (after an average of 10 km of so), then falls back down as precipitation. Very little water vapor makes it into the upper parts of the atmosphere. This is a good thing for life on Earth, because any water that enters the upper atmosphere is vulnerable to high-energy UV radiation, which breaks water molecules apart into hydrogen and oxygen. Hydrogen is very light, so it can easily escape the pull of Earth's gravity into space. If significant levels of water vapor make it into the upper atmosphere, a significant amount of Earth's water would effectively be lost to space as a result of this destructive process, leaving only oxygen gas behind. In just over a billion years from now, the water vapor that has been entering the atmosphere at increasing rates as the Sun ages will finally find its way into the upper atmosphere, super-charging the greenhouse effect, and kickstarting the rapid evaporation of Earth's oceans. This eventually saturates the whole atmosphere with water vapor. The water vapor gets ripped apart by UV and escapes to space, marking the beginning of the end of Earth's time as an ocean world. Around two billion years from now, there could be little water left on Earth.

Could life make it beyond this phase? Maybe, but only in certain, small, isolated refuges where temperatures remain slightly cooler and a little water still exists[10],[11]. Earth's last life may come in the form of thin crusts of microbes on rocks, or as communities living off the chemical energy contained within rocks in sheltered cave habitats. Certain cave systems can act as cold traps, keeping constant temperatures year round[10]. However, a cold trap can only trap the

coldest temperatures a region experiences. Therefore, once winter temperatures reach 150°C, this form of underground shelter will cease to help.

This target of 150°C could be reached just over two billion years from now[10], but the timing depends on how Earth's orbit evolves. If the tilt of the planet were to increase, temperature extremes between summer and winter could become large enough to delay the time it takes to reach 150°C by almost a billion years; nearly three billion years from now[10]. This is a real possibility thanks to the fact that the Moon, which currently stabilizes Earth's tilt, is moving away from the Earth over time[25] as a result of the conservation of angular momentum. However, the cold-trap cave survival strategy would still be dependent on how well the future atmosphere re-distributes and evens out surface temperature differences.

If the surface and subsurface become too hot, life might find cooler refuges at high altitudes, like the tops of high mountains and volcanoes[10]. The flow of gases, including some water vapor, from active volcanoes could support communities of microbes like those observed currently living around a volcanic vent in the Atacama Desert. However, based on our current understanding of how plate tectonics works, over the next two billion years, Earth's interior may cool enough that it no longer has the energy to drive tectonic plate movements[10]. No more plate movements means no more mountain-building, so any high ground will gradually be weathered away over eons, not to be replaced. Some volcanic activity (hot spot volcanism) could still continue, and, on a drier world without eroding rainfall, volcanoes may be able to grow to enormous heights. Landscapes on a world like this would be similar to the scene outlined at the beginning of this article; largely flat, but occasionally overshadowed by mountains that rise higher than Everest. Unfortunately, high ground of this nature would only be a temporary refuge. Rising temperatures would make even the tallest mountains uninhabitable within only a few hundred million years after the surface temperatures cross the threshold for habitability[10]. Perhaps the very last inhabitants of Earth will be creative and innovative enough to find refuge in the atmosphere itself. We know that on Earth today there are numerous transient microbial communities in the atmosphere, and some may even be actively living out their lives within clouds where they have access to water and nutrients[26]. Maybe this will be life on Earth's final refuge, riding the clouds of the planet's last water vapor in the cool upper atmosphere.

No matter where life on Earth makes its last stand, it is likely to exist in such low numbers, hidden away in sheltered habitats, that a remote observer

looking at the Earth for signs of life would see no indication that anything was living there. If, starting today, that observer watches Earth for a few billion years, they would see oxygen disappear, CO₂ levels plummet, and the distinctive infrared reflectance signature of vegetation vanish. In place of these biosignatures, they may see new ones, like strange new surface colorations from the spread of heat-tolerant microbes clinging to the ground, a surge in methane levels from anaerobic microbes, and maybe even the sudden arrival of a glowing UV halo around the planet as huge amounts of hydrogen escape into space from the evaporated oceans.

What does this mean for our search for life on other Earth-like worlds? There are many sun-like stars out there that are older than our Sun[27]. Perhaps any older analogs to the Earth orbiting these stars will show no signs of life, making them poor targets to choose if we want to maximize our chances of successfully detecting life. Then again, perhaps such worlds could tell us more about our own planet's fate than we can figure out using the models and theories we currently have. Perhaps the fate of life on Earth will not be so dire.

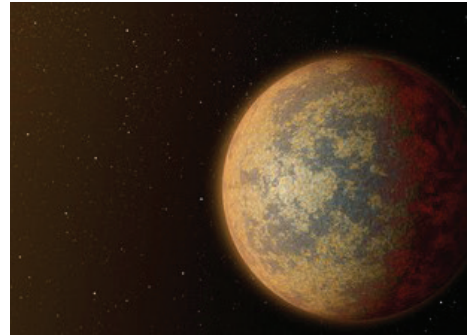
The events laid out here constitute a possible future best thought of as the worst-case scenario. There are many uncertainties that could change the timings of events, the severity of climate changes, or the ability of biology to respond to those changes. Evolution is one of the biosphere's most powerful tools. Faced with changing environments, life can adapt to survive over successive generations, a process that can occur over both geological timescales and, as we are beginning to learn, over very short timescales. Nature does not engineer perfect organisms; it works with the random set of tools it has at its disposal (inactive genes, "junk" DNA) to put together something that enables survival and reproduction to continue over successive generations. Not all forms of life will have the right materials to "re-model" themselves in time to adapt to change, so big upheavals in environmental conditions tend to lead to mass extinctions. However, any forms of life able to survive a mass extinction event become the progenitors of a new biosphere, adapting into a variety of new species over time, filling the voids left behind by the life that did not make it. Perhaps the future Earth will be biologically reformed in such a way that a rich, but somewhat alien biosphere could last much longer than the predictions set out here.

While there are many paths that lead to the end of the world, they all appear to lead to only one, fairly inevitable destination. Based on our knowledge

of biology, chemistry and physics, life will eventually face challenges on the far-future Earth that it cannot overcome. However, biology has come up with a very productive way of making uninhabitable environments habitable: the human brain. What if our problem-solving, tool-wielding abilities (or those of some future intelligent form of life that arises on Earth) were put to the task of prolonging life on Earth?

As current events are increasingly showing us, we collectively as a species have the power to change global climate, create and destroy habitats, and alter species distributions. Largely, these have been accidental side-effects of a population of billions going about their 20th and 21st century lives. Now that we are becoming more aware of our impact on the planet, we are starting to realize how we can change things in a planned, directed way that causes more good than harm. Whether we will succeed is another question, but assuming we do, this seed of direct intervention with our planet could give far-future generations the ability to preserve life against even the extreme climate changes brought about by an aging Sun. It can even be argued that, because we are smart enough to know that life is fragile and could face extinction at one point or another, we have a moral obligation to preserve life indefinitely by managing our planet's climate, or even seeding life elsewhere to survive beyond Earth's eventual end.

Large-scale geoengineering could maintain clement, habitable conditions for far longer than would naturally be the case. This could include anything from the relatively simple idea of placing large mirrors into space to reflect away excess sunlight, to the somewhat more challenging idea of literally moving the Earth further from the Sun over time so that it stays at the same position within the habitable zone. However, the resource and energy cost associated with preventing the extinction of the entire biosphere may eventually become too great to be the best route to maintaining life, especially toward the end of a Sun-like star's main sequence lifetime, when luminosity would rise rapidly and the expansion of the star's outer envelope would disrupt planetary orbits. It may be more cost-effective to transport life to other locations that are, or



*A future hot, dry Earth? Image credit:
NASA JPL*

could be made to be, habitable and would remain that way for geologically long periods of time.

Another option would be to alter life, rather than the environment, essentially accelerating, and possibly out-performing, the relatively slow, haphazard process of natural selection. By altering existing organisms, or creating entirely new ones that can survive under future environmental extremes, the continued existence of a rich, diverse biosphere could be prolonged on a planet past the predicted endpoints for plant and animal life. Nevertheless, artificial organisms would presumably still be limited by the tolerances of biochemistry, so the overall lifespan of the biosphere would probably remain unchanged.

These speculations are feasible if we assume that humans continue to exist far into the future and that we continue to follow an exponential curve of technological advancements. However, this could be a speculation too far. As Carl Sagan often pointed out, we as a species have a tendency to put ourselves on a pedestal at the center of the universe. Perhaps, like other complex life on Earth, we too are doomed to extinction, maybe even long before the events outlined here come to pass. The average species lifetime for mammals (the point at which a species first originates to the point at which it becomes extinct) is about a million years. This is an average, so some mammal species will persist for longer than others, but it would be biologically unprecedented for humans to still be here a billion years from now. Fortunately, intelligence as a trait, provided it remains useful to survival, may still persist in the biosphere for long enough to influence the future habitability of the planet. So maybe, if we as a species do not make it to the future, some distant intelligent cousins to the human race will. Genetic material from extinct species can persist in the genetic code of extant species. Today, each of us carries a tiny fraction of Neanderthal DNA (a species of hominid with whom modern humans interbred, while also out-competing them into extinction)[28]. This tiny fraction of the Neanderthal genetic code varies enough from person to person that, when summed over the entire human population, it turns out that we still safeguard a significant fraction of the full Neanderthal genetic code. There is a relatively short geological time between the extinction of Neanderthals and now, so our descendants millions of years from now may not carry as much of this extinct genome around with them. Yet, this scenario nicely illustrates the point that, whether or not humans are around to face this future, the interrelatedness of all the life that makes up the biosphere

means the odds are good that at least some part of us will survive. Surviving to witness the planet age, heat up and dry out. Surviving to watch as plant and animal kingdoms fall while an alien new world rises in their place, and, ultimately, surviving to experience the end of life's multi-billion year journey on the pale blue dot we call home.

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COMPETITION VERSUS COOPERATION: A NEW AGE OF SPACE EXPLORATION

JOSEPH MCCracken

INTRODUCTION

Though it began as a fierce competition between feuding nations, space exploration exemplifies one of the most cooperative scientific fields. Combined international efforts have led to outstanding achievements for humankind – most notably the International Space Station, a partnership of fifteen nations which orbits high in Earth’s atmosphere. In the early 2000s, however, improvements in aerospace engineering and budget cuts to NASA’s space exploration engendered private space exploration and space travel companies such as SpaceX, Orbital Sciences, and Blue Origin. Now that these businesses have had sufficient time to develop and implement new technology, they have achieved remarkable feats – the first ever reusable rockets, successful cargo deliveries to the International Space Station, and the launching of hundreds of satellites[3]. They propose even more ambitious plans for the future, including the colonization of Mars and tourist flights around the moon. The start of a privatized space industry means a return to competition, but this time, between companies instead of countries. Naturally, industrial growth and development brings both breathtaking advancements and dangerous repercussions. Space privatization may brew secrecy, blur professional ethics and lower safety standards; however, these side effects are counterbalanced by cooperation alongside national space agencies. Government funding combined with the technological innovation of the private companies will boost human development and exploration of space.

The competitive, privatized side of space exploration will likely spark a period of rapid economic and technological development for the field. The financial potential is immense – Elon Musk, the billionaire entrepreneur behind companies such as SpaceX, Tesla, and PayPal – claims SpaceX’s reusable

rockets will reduce prices for delivering cargo to Earth's orbit by a hundredfold or more. He has also estimated ticket prices for trips to the moon or a permanent move to Mars to be several hundred thousand dollars each, which means several million dollars in revenue per trip. Assuming these costs drop as the technology becomes more accessible, there is an expansive market with a lot of potential[8]. Privatized space exploration could be beneficial not only economically, but also technologically. Competition between the existing space exploration companies has already produced technological advancements. For example, SpaceX's Dragon spacecraft holds several remarkable titles: the only spacecraft capable of carrying large amounts of cargo back from space, the first private spacecraft to deliver cargo to the ISS, and the first reflight of a private spacecraft to and from the ISS[3],[7]. The company also is currently working on modifications to make Dragon suitable for crew[7]. If the industry ignites as its supporters predict, it will create even more rapid and wide-scale progress. The rockets currently in use and the ones still under production are the most advanced the world has ever seen. If space becomes more traversable and cheaper to travel, perhaps Elon Musk's vision of humans as an interplanetary species will come to life.

The growth of a private space industry unfortunately has negative implications as well. Firstly, privatized companies lead to privatized information, an untraditional and dangerous aspect of space exploration. Government space agencies such as NASA have always had close ties with the public, engaging and educating whenever possible. Even when countries competed to launch satellites and race to the moon, the public was kept informed and engaged in the progress as a matter of patriotism. In this new age of space exploration, however, private companies have no obligation to share the discoveries that they are bound to make. With the best rockets on the planet, a private company could travel farther, faster, and safer throughout the solar system. None of the current businesses show much desire for scientific research, but if they begin landing unmanned rockets and eventually colonizers on asteroids or Mars, they will inevitably gather data and make discoveries about these locations beyond Earth. For widespread advancement of knowledge, information regarding the biology, geology and chemistry of extraterrestrial bodies should be passed on to astro-biologists, geologists and chemists, not held by a private business with little focus on scientific research. Ideally, the private companies would openly share information since it has little influence on their revenue, and scientists can build upon, publish, and spread

the findings throughout their community. The problem is, private businesses have the option to sell the data too, which may tempt them to keep secrets. This practice would not only cripple the longtime connection between space exploration and the public, but also spawn the potential for one corporation monopolizing crucial information; both are predicaments that hinder the advancement of astronomy as a whole.

In addition, space privatization creates an ethical issue for the businesses. If private companies create the most advanced rocket technology to maximize their profit, they would surely want to keep their secrets hidden from rivals and that is understandable. Problems arise, however, due to the numerous risks that come along with launching a rocket (especially one with human cargo) which render the level of technology a matter of life and death for those who man the missions. The private sector has already seen tragedy in its short existence – Scaled Composites pilot Michael Alsbury was killed during a test flight of one of Virgin Galactic’s tourism rockets in 2014[9]. It feels unethical when a private company possessing the most advanced and safest rockets withholds information at the stake of people’s lives, yet at the same time, it is anti-capitalist for a business to willingly give away its spot atop the industry – especially if it were forced by the government to do so. The balance between revealing or hiding company secrets constructs a heavy dilemma for rising corporations that may be forced to sacrifice some of their own success in the name of safety.

Finally, space privatization’s ambitious edge alone creates serious safety concerns; some speculate that Williamson’s death is a result of the private sector’s tendency to rush development. Just like its rival corporations, Virgin Galactic is known for bold timelines – chief executive Richard Branson claimed at the first presentation of SpaceShipTwo (the one Alsbury was co-piloting) that it would be ready for commercial flight by 2011. It is important to be first in the growing competitive market of space travel, but some fear that these lofty goals caused the agenda to be pushed too hard[2]. If the business was already three years behind on its promise, Virgin Galactic naturally would rush to put SpaceShipTwo on the market as soon as possible. Although it eventually surfaced that the crash was due to human error (Alsbury activated the braking system too soon) and not the technology, this still means that the design had not accounted for the possibility of human error[1]. Perhaps this detail was overlooked as part of the

hurry to begin commercial flights, or maybe Alsbury did not have time to become familiarized with the machine and receive enough training. Either way, his death should not be forgotten, and ought to serve as a reminder of the dangers of rockets and rushed development.

Williamson's death is reminiscent of the infamous Challenger disaster – on that day, all signs indicated that the shuttle clearly should have stayed grounded, but pressure from the public after a series of delays caused NASA to proceed with the launch anyway. There appears to be a general trend here: A process as complicated as rocket launch and flight is bound to have issues and delays, but as these dilemmas pile up the pressure to not fall behind grows as well. This pressure leads to rushed and risky launches with deadly consequences. As the industry develops and manned rockets become more common, one can only hope that companies break the pattern, and never overlook safety in the name of competition and being first.

Privatized space travel and exploration is clearly troubled by a variety of issues. However, only time will tell how problematic they actually become. Further, the general concerns raised by the private sector can be ameliorated by collaboration between government administrations and the space industry. The historically friendly and cooperative national space agencies should effectively counter the more cutthroat corporations to create a balanced and ideal future for space exploration. Thankfully this appears to be the direction the United States is headed. The Trump presidency so far has made changes to NASA that emphasize combined efforts between government and private space companies. For starters, NASA's overall budget is now \$19.5 billion, which is a \$200 million increase from last year[5]. Nevertheless, even with such lofty goals, it still is only receiving .5% of the federal budget. This allows and encourages private companies to continue making their own way into space travel and exploration. The breakdown of the spending for each department is provided in *Figure 1*.

Included in the same law, which is called the NASA Transition Authorization Act, are plans for a manned mission to Mars and an emphasis on public and private cooperation. The text specifically suggests that NASA further develop the programs which allow for private companies to deliver cargo and crew to the International Space Station (National Aeronautics and Space Administration Transition Authorization Act of 2017). Interestingly, it states that every one of these rockets carrying government astronauts will undergo federal inspection –

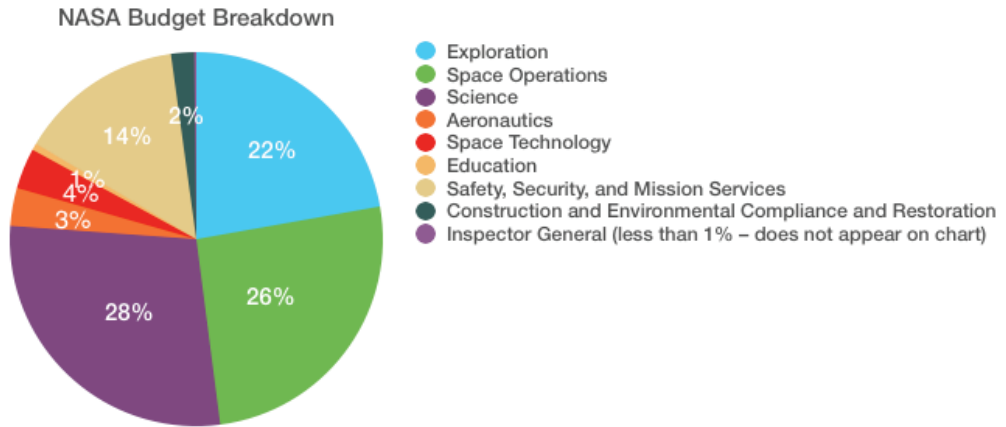


Figure 1. Note that education is receiving the second smallest portion at about 1%, which furthers the concerns about public connection and information availability.

this greatly improves the safety concern and provides a prime example of how cooperation with governments counters the negative effects of privatization. The law also directly indicates a united approach to the Mars mission, with help coming both from other countries and from the private sector of space industry (National Aeronautics and Space Administration Transition Authorization Act of 2017). This hopefully means lower costs and a shorter timeline for the trip, as it will limit technical delays and not rely so much on Congress approving funding (Masunaga & Puzanghera, 2016).

Having been a business tycoon for most of his life, President Trump would want his government working alongside these new developing space exploration and travel companies. Such goals of cooperation indicate an effective and amicable work environment between the two moving forward. On the other hand, there is plenty of time for circumstances to change. Elon Musk has stated his plans to have humans on Mars by the mid 2020s while the Transition Authorization Act aims for the 2030s (and Musk is notorious for pushing back deadlines). For now at least, it appears that the United States government will attempt to accommodate and work alongside other nations and the private industry. Ideally, the private and public sectors will create a kind of equilibrium between competition and cooperation, and result in technological advancement without major safety or information concerns.

As the world changes and develops in the coming years, the current vision

of our species' destiny beyond Earth will shift as well. Currently, however, the overall outlook looks bright in the new age of privatized space exploration. As long as the private corporations and governments adhere to their plans of cooperation to promote advancement, safety, and disclosure of information, feats which would have seemed impossible just a few decades ago may become realized. The vision of humans as an interplanetary species capable of traveling to and colonizing other worlds will spring out of the pages of science fiction books and into reality. Competition between companies plus cooperation between public and private sectors looks to be a healthy balance that will drive humans to unprecedented achievements and new worlds.

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DISRUPTING OUR COSMIC SOLITUDE

JACK MADDEN

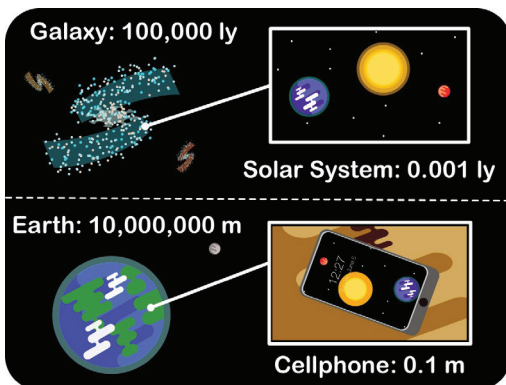
INTRODUCTION

The evidence we will collect to confirm signs of life outside our solar system is likely traveling toward Earth right now. Hurling through space on its lightyears-long journey, those innocuous rays of light, full of information, will bump electrons in our telescopes and in turn shift how humanity views its place in the universe. But when will we be ready to catch the light? A couple of years, a few tens of years, or perhaps even further into the future? Where will our telescopes be pointed to catch it? What types of data will we gather? How will we make sure we have found life? Understanding the answers to these questions will give you insight into the effort that a mere handful of scientists around the world are making to find life beyond our solar system.

WHAT WILL WE LOOK FOR AND HOW WILL WE MAKE SURE IT MEANS LIFE?

The first obstacle worth examining in our search for signs of life beyond our solar system is the forever present challenge of scale. In many fields of science, scale makes measurement or analysis difficult. Biology must deal with molecules and mechanisms that act on very small, atomic, scales but astronomy must wrangle with the largest scales possible. Our solar system is made up of a single star, eight planets, many dwarf planets, and many more smaller asteroids and dust particles.

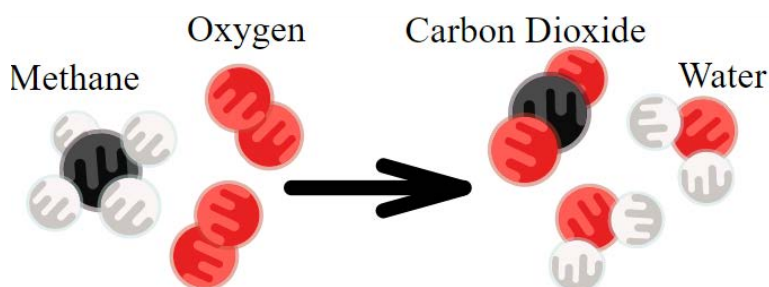
Together, our solar system influences roughly one trillionth of the real estate in our galaxy, a sand grain in a gymnasium. Due to the sheer vastness of space and the orders of magnitude in scale that separate humans from the cosmos, we as a species have so far been unable to reach beyond our solar system. A relatable analogy would be imagining your cellphone as the solar system; the Earth would



represent the size of the galaxy. We are physically unable to reach across such vast distances with current spacecraft if we want to examine a star or planet more closely. The only way to learn about what is beyond our cellphone-sized solar system is through interpreting the light and gravity that make their way through time and space to reach us.

We may not be able to reach out and plant rovers on the surfaces of the planets around other stars, but the light that reaches Earth from these worlds holds a wealth of information that scientists have learned to unlock. To human eyes, light gives our brains color and brightness information in a fairly narrow range of energies. Along with comprehending how light is emitted on an atomic scale, we have learned to interpret light so as to reveal an object's composition in addition to its overall color and brightness. We do this using a spectrum, which is the unique distribution of light intensities for a given object. Similar to a light-based fingerprint, every object has its own spectrum; as a matter of fact, all of the objects around you right now could be uniquely identified by taking their spectrum. Scientists will use the idiosyncrasy of spectra to determine the atmospheric and surface composition of exoplanets that we believe might be habitable.

The first signs of life we hope to detect will be oxygen, methane, carbon dioxide, ozone, and water vapor in the atmosphere of a rocky planet in the habitable zone of its host star. On a planet full of life, the plants, animals, and microbes are as big a part of the chemical cycles in the atmosphere as the non-biological processes. This means that the presence of certain combinations of molecules in the atmosphere could imply the existence of life on the surface. For example, methane will break down into water and carbon dioxide in the presence of oxygen. If we see stable amounts of methane and oxygen together this will lead us to believe that there must be a mechanism to add methane to the air as fast as it is being broken down.



Life is one such mechanism. Seeing methane and oxygen in abundance together along with water and CO₂ is a strong case that points toward the possibility of life. Because of this, we call it a biosignature, or a combination of measurements and circumstances that indicates life without its direct detection. The first big announcement of life found on an alien world will be the detection of multiple biosignatures. While the detection of biosignatures do not guarantee detection of life, a strong enough set of biosignature detections will lead to a widely accepted base of evidence that life does exist beyond our planet.

HOW WILL WE ACCOMPLISH THESE MEASUREMENTS?

The most precise and sensitive instruments ever constructed will be required. Current telescopes are unable to perform the task mainly due to their small size and low sensitivity. However, telescopes in development are larger which allows them to collect more light and thus more information; meanwhile, the greater sensitivity of these future telescopes will permit scientists to extract the faint signals that they are searching for from the plethora of incoming data. New telescopes will soon be able to meet the high standards of precision needed for us to find signs of life outside our solar system. Specific instruments will be discussed but first it is crucial to examine how biosignature detections work in principle.

There are two main ways that biosignatures can be detected and each method relies on obtaining a planet's spectrum so that we can ascertain its atmospheric composition. The simpler of the two methods, called 'direct imaging' observes the sunlight being reflected off the atmosphere and surface of the planet like a simple photograph. The second method involves measuring the sunlight that glances through the uppermost layers of the atmosphere; we call this a transit spectrum because it can only occur when the planet 'transits' or moves in front of its star as we view the planet from Earth. Each method carries with it a host of advantages and disadvantages and are being refined by teams of scientists to achieve the sensitivity required to make detections of biosignatures on Earth-like exoplanets.

The Direct Imaging Method

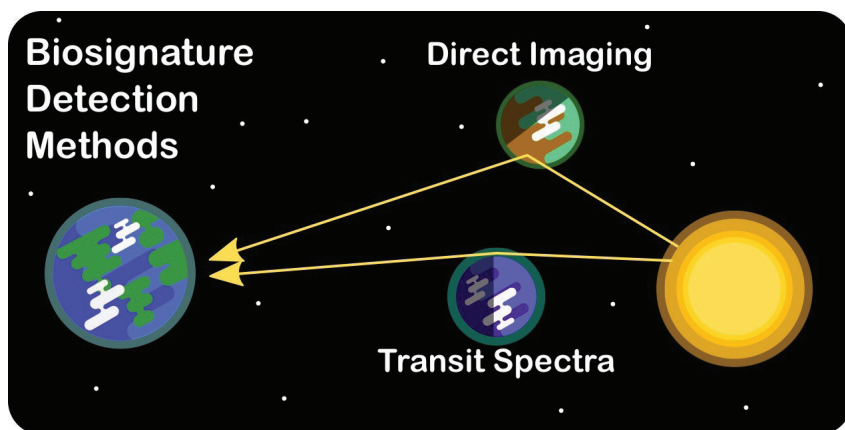
Imagine you are driving down an empty road on a dark night. A car comes over a distant hill several miles down the road and is headed toward you; its bright white lights are the only indication it is even there. If I asked you the color of a moth flitting just in front of that car's headlights, miles off, you would tell me it's impossible. This is the same challenge faced when attempting to get the spectrum

of a planet orbiting a distant star. The brightness of the star and the distance away from us make discerning the planet from the glow quite tricky. In fact, the analogy would be more accurate if the car was not just a few miles down the road but more than one-hundred.

The Transit Method

Let us go back to that dark road and look again at the headlights of the distant car. Now instead of asking about the color of a moth, I tell you that there is a fly walking across the headlight. I also inform you that some of the light from the headlight is passing through the semi-transparent wings of that fly and now the question is: what color are the fly's wings? With the transit method, in order to obtain an object's spectrum, the object must pass in front of the light source; in this case the fly's wing must pass in front of the headlight, and in the case of an exoplanet's atmosphere, it must pass in front of its host star.

Both of these detection methods have already been successful at detecting molecules in the atmospheres of uninhabitable, Jupiter-sized, gas giants^{1,2}. The effective utilization of the direct imaging and transit spectroscopy methods depends on many factors including planet size and planet-star separation. In the case of direct imaging a widely separated, large planet is easier to photograph. The moth next to the headlight of a distant car was a challenge to see but a nearby tree that has been illuminated is easier to observe since it is so much larger. For transit spectroscopy, the easiest planets to measure are also large and orbit as close as possible to their star. What needs to be maximized in the transit method is the proportion of light that passes through the atmosphere. Potentially habit-



able planets are small and moderately separated from their host star so they will be the ultimate challenge for both methods, but scientists have a plan.

WHEN WILL WE LOOK AND WHERE?

If we predict that an upcoming telescope mission will detect biosignatures on an exoplanet in one of the intriguing solar systems we have found, then the signal could have started its journey in the year 1980, nearly a decade before we had evidence exoplanets even existed. As it turns out, the telescope might be the James Webb Space Telescope (JWST) and the system might be Trappist-1.

JWST will float steadily in space after its launch in Spring 2019. Through the transit method, its large aperture and sensitive instruments will give us the best chance yet to find the biosignatures discussed here. JWST's transit observations will take many years to complete if we want to find biosignatures in the atmospheres of Earth-sized planets^{3,4}. Ground-based telescopes such as the Giant Magellan Telescope (GMT), Thirty Meter Telescope (TMT), and European Extremely Large Telescope (E-ELT) may provide us the answers we seek using direct imaging methods when they come online in the next decade⁵. Other telescopes have been proposed that will also assist in the biosignature search, namely, HabEx,

LUVOR, and the Origins Space Telescope. These are only in the initial stages of proposal and if selected would be launched around 2035. One thing for sure is that the discovery of life will need to be as certain as it is profound, and that grounded certainty will take considerable time and effort in the form of observation and analysis.

Fortunately, there will not be a shortage of targets to observe once these telescopes are in operation. Deeming an exoplanet 'habitable' is a prediction based on the planet's positioning relative to its host star. Depending on how conservative you are when determining what 'habitable'



means, there are between 10 and 50 ‘habitable’ planets that have been discovered so far.

Of these potentially habitable planets there is one system of immense interest that I mentioned earlier, the Trappist-1 system. It contains seven planets, all Earth-sized or smaller that orbit a dim red star⁶. The system is very tightly packed compared to our solar system; standing on one planet and looking at the next nearest planet would be like seeing the Moon from Earth. Particularly intriguing is the estimate that three of the planets could potentially be habitable since most habitable systems only contain one potentially habitable planet. This rarity makes the Trappist-1 system a favorable place to begin the search for biosignatures.

Each of the challenges I’ve discussed, whether it be biosignature detection, spectra measurement, transit and direct imaging methods, or building telescopes, are the focus of some scientist’s mission. Every day, professors, students, researchers, and citizen scientists are making headway toward refining these techniques and preparing for future observations. So out of the numerous instances when you glance at your phone, give a moment to visualize the headlights of a car on a dark road or contemplate the scale of the solar system; imagine the challenges of detecting biosignatures. The pace of development in exoplanet exploration means that the next time you remember this article, even if it is only tomorrow, we will be a little closer to disrupting our cosmic solitude.

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2017: A SPACE ODDITY

THE IMPACT OF EMERGING SPACE NATIONS ON INTERNATIONAL SECURITY

Seréna Pilkington

ABSTRACT

The paper's objective is to identify the critical factors that have shifted the priorities of international space security. International space security will be viewed through the context of heightened security risks both between nations and as consequences of the densely populated space system. The analysis will focus on three fundamental fields of the modern space dynamic: international cooperation, technological development, and economic investment. These fields will identify the security priorities of the modern space system by comparing both emerging and developed space nations. The multipolar system in this context is here defined as numerous actors of relatively similar capabilities interacting within the space system. The results and analysis of the chosen space actors show the international space dynamic and thus illuminate the shifting issues of international security from the previous bipolar state of the Cold War between the US and the USSR. This shift is due to the promotion of peaceful relations through a rise in international cooperation. Contrastingly, the evolution of technology and an increase in investment has produced exponential growth in the number of spacecraft; this growth has ultimately increased threats to orbiting satellites. In conclusion, the rise of emerging space nations has created a new space dynamic in political, technological, and economic dimensions; internationalization of space has subsequently caused traditional threats like the space race to decrease and contemporary risks such as orbital debris to intensify.

INTRODUCTION

The following thesis will analyze the role of emerging space nations in the modern space system. Here, the definition of space nations will be space actors who possess autonomous development in space technology, the ability to launch

spacecrafts, and national space agencies. Emerging space nations, in this context, refers to their recent emergence into the world of space relations in contrast to those who have long had a presence in space, such as the US, Russia and Europe. The thesis will identify the link between the new space actors and the shifting focus of international security to a wider variety of issues.[1] To understand the impact that emerging space nations have had on international security, one must first analyze the components of the modern system. The neorealist theory provides an overall context for the analysis, particularly on the concepts of bipolar and multipolar systems. The transformation from bipolar structure of the Cold War to today's more liberal, multipolar system is fundamental to the geopolitical shift in space relations.[2] Multipolarity lies at the core of this thesis since the ultimate result of modern space relations is a diversification of international security risks. In order to fully exhibit the shift from bipolarity, I will focus predominantly on six main space actors that will be divided into two groups: emerging and developed space nations.[3] The shift in political, economic, and technological capabilities has created a strand of space actors with new and contrasting plans for space.[4] The analysis will discuss the new system in the context of these actors having a wider impact on the international system.

Current analyses of international relations often overlook space relations; however, the unique dynamic of politics, technology, and economy of space relations is integral to examining the overall shift in the geopolitical system. Similarly to space relations, international security is often dictated through political, technological and economical themes, and through analyzing space relations the origins and impacts of arising threats can be understood. Comprehending the issue is imperative for future analyses of international relations where the rise of technology and interdependence will only continue to dictate the security of space nations. The findings of this thesis will show that the development in the three highlighted areas have created an entirely new space system. As such, the shift in international security can be traced back to the rise of the number of space actors.

The thesis will adhere to the following structure. First, a critical analysis will be undertaken on the relevant literature. The review of the literature will create a theoretical framework to analyze the new space system with respect to both emerging and developed space actors. The framework will be divided into four indicators: diverging space actors, international cooperation, technological advancement, and economic investment. Following this, the research methods section will outline the research design which includes the sampling approach

and data access. Next, the results of the research will be presented. Developing further on the results presented, the discussion section will examine the results in the context of international security within the new space system.

2. THEORETICAL FRAMEWORK

Literature relating to the space development including individual country analysis and specific security issues is analyzed to create a theoretical framework. The theoretical framework will explore the main factors that map the internationalized space system. The literature review discusses emerging space nations in the new space system in four ways: diverging space actors; international cooperation; technology advancement; economic investment. Through these aspects, I will outline the rise of a new space dynamic with respect to the increase in emerging space actors. In addition, this framework will provide a basis to later discuss the new system with respect to international security.

2.1. *Diverging Space Actors*

The first indicator identified from the literature is the divergence in the type of space actors in the modern spacescape. The actors are categorically the states driving the shifts in the internationalized system. This study will continue the approach posited by Petroni and Bianchi (2016)[5] by separating the space actors in the modern system into two groups. The first outlined are the developed space actors (DVSAAs) who are predominantly made up of the winners of WWII. These are the major nations who have traditionally had a leading role in space relations. The actors included in this category are the USA, the European Union, and Russia. The second category is emerging space nations (EMSAAs). The actors who fall under this category are Brazil, China and India. Unlike the Petroni and Bianchi (2016)[6] theory, which encapsulates the entirety of nations who possess any space capabilities, this study will only focus on the dominant actors in the system.

Sheehan (2016)[7] reveals that developing nations have a critical role in the space system specifically in relation to space security. Sheehan's approach is similar to that of Delgado López (2016)[8] who evaluates emerging space nations' sustainability issues solely in Latin America. Similarly, Paikowsky et al (2014) [9] identify developing nations differing from the traditional space actors with respect to their approach to political, economic and technology developments.

Finally, the chart in Wood et al (2012)[10] displays the satellite programs of developing nations who face different challenges than that of traditional space actors. My study therefore concurs that developing and traditional space nations act differently in the space system. As such, the increase of developing nations has fundamentally shifted and internationalized the spacescape. This theory is reflected in the literature of Petroni and Bianchi (2016)[11], Sheehan (2016) [12] and Delgado López (2016)[13] who recognize the pivotal role of developing nations; they essentially find that emerging space nations are creating a multipolar system and are reflecting the rise of developing nations in the international system. In sum, emerging space nations has caused the space dynamic to become an internationalized system due to their rise as new actors.

2.2. International Cooperation

The second indicator I developed is the role of international cooperation in the modern space system. Many scholars have referenced the importance of international cooperation in the development of technological advances. These include Petroni and Bianchi (2016)[14] who mentioned cooperation tangentially when discussing the technology development of India and China, both dominant among emerging space nations. They found that direct cooperation only happened with the “Big Three” i.e. developed space nations, an approach that diminishes the possibility of encouraging space actors. This study will contradict such results and instead I argue that the modern space system has internationalized through increased cooperation. Hays and Lutes (2007)[15] corroborate the trend toward greater cooperation because they theorize that as the classic space paradigm changes, increasing vulnerabilities will lead nation states to develop alliances based security arrangements and cooperation frameworks for sustained space stability. Nonetheless, for the framework of the thesis, I focus only on direct links of collaboration through International Cooperation Agreements (ICAs). Partnership agreements gives platforms to view the rise of dominant space actors, specifically those emerging in the modern space system. Also focusing on cooperation, the approach Peter (2006)[16] adheres to finds that the growing number of international actors in the space system is from the expansion of international cooperation. While Peter (2006)[17] outlines the evolution of international cooperation from the Cold War era until now, this thesis will build on these findings to illustrate the modern space dynamic between multiple actors with a variety of objectives. Moreover, this thesis has outlined the number of direct

international cooperation agreements between the EMSAs and DVSA's. My additional critique of DVSA's and EMSAs builds upon Peter's (2006)[18] model which acknowledges the similarities and differences between the two types of space actors that were unaddressed in his model. Similarly, Sheehan (2016)[19] picks up the concept of differing actors when analyzing the role of emerging space nations in security. The increase in ICAs are found to have given rise to a more internationalized space systems through technological cooperation. Wood et al (2012)[20] include international cooperation when analyzing a state's technological development through an international context. Specifically, they focus on the strategic motivations for undertaking certain types of joint ventures. Such reasoning of state actions is outside the scope of this analysis. Instead, this analysis remains focused on the extent to which international cooperation confirms the internationalization of the modern space system and the decline of technological brinkmanship. Therefore, this thesis focuses on how the rise in cooperation has enabled EMSAs to become substantial space nations, ultimately shifting the dynamic from the classic spacecape.

2.3. Technology Advancement

A third indicator developed from the literature is the role technology plays in the international space system. Technological indicators are crucial in measuring space actors' capabilities and differentiating between DVSA's and EMSAs respective abilities. The literature has varied from focusing on specific technology such as Wood et al (2012)[21] to global space relations such as Peter (2006)[22] and Paikowsky (2014)[23]. Relevant literature significantly addresses the increased accessibility and reliability on national space capabilities. This study will incorporate the technological indicators to contend that EMSAs have cultivated a larger role in the modern space dynamic; these indicators are divided into subcategories: satellites, launching capabilities, and Global Navigation Satellite Systems (GNSS).

The literature extensively addresses the technological importance of satellites in the contemporary space system. Satellites are becoming more relevant in today's modern world, but the significance is moot without the development of small satellite technology. As outlined by Petroni and Bianchi (2016)[24] modern satellites have become smaller and less expensive to produce; as a result, the number of satellites and the ways in which they are used have

increased exponentially. Petroni and Bianchi (2016)[25], Paikowsky (2014)[26] and Sheehan (2016)[27] all discuss the numerous and vital ways in which satellites are used. Following this emphasis, I remain focused on the importance of satellites and the possession of both satellites and resulting debris in the new space system. The analysis continues that of Petroni and Bianchi (2016)[28], both of whom develop cross tables of the space actors and their corresponding satellites; however, they fall short when analyzing the specific uses of satellites and the different types in the system. This is where the results of Sheehan (2016)[29] and Petroni et al (2009)[30] provide important insight into the uses of satellites in internationalized system. The additional context counteracts the weakness in the literature that discusses satellites in general terms instead of the measurable differences between EMSAs and DVSA's. Orbital debris is also mentioned in these previous journals but is fully outlined in the Congressional Report of Hildreth and Arnold (2014) [31]. Information is gathered about satellites and resulting debris to outline the modern space landscape. This approach gives additional understanding into the changes to the modern space system. Certainly the role of technology capabilities allows for the critique of space actors in the internationalized space system.

Another touchstone for the modern space dynamic of the EMSAs and DVSA's is launching capabilities. Relevant literature applies here especially when discussing the latest developments in EMSAs. The launching capabilities of a space actor are often an indicator of independence, and as such, shows the nation to have extensive space capabilities. Petroni and Bianchi (2016)[32] find that launching satellites in developing nations is linked to their geographical location, yet the two authors fail to address the impact of such capabilities on the system overall. Specifically, this thesis argues that just as launching capabilities rise, so too does the number of satellites and space actors in the space system. Sheehan (2016)[33] and Pace (2016)[34] fill this gap through analyzing not only the reasons for developing launching capabilities, but also the impact these capabilities have on the overall system. Therefore the argument for technological significance is that launching capabilities indicate how the space system has changed as a result of EMSAs creating an internationalized space system.

The final technological indicator is the Global Navigation Satellite System (GNSS) which appears most frequently in relevant literature. Both developed and emerging space nations strive to develop a system independent from the US operation, commonly known as GPS. The development of their own GNSS is the ultimate step in the modern space technological evolution. To possess a

GNSS represents both technological and political independence and thus is a critical indicator of the modern space dynamic. Sheehan (2016)[35] and Paikowsky (2014)[36] recognize the significance of GNSS when they discuss the influence and creation of GNSS systems by the space actors in the system. Additionally, Petroni and Bianchi (2016)[37] outline the GNSS's importance in the new internationalized system of developing and developed nations. Therefore, this thesis asserts that the creation of one's own GNSS is an indicator of a changed space system. The technological factors support the argument that EMSAs are becoming dominant nations to counterbalance traditional powers.

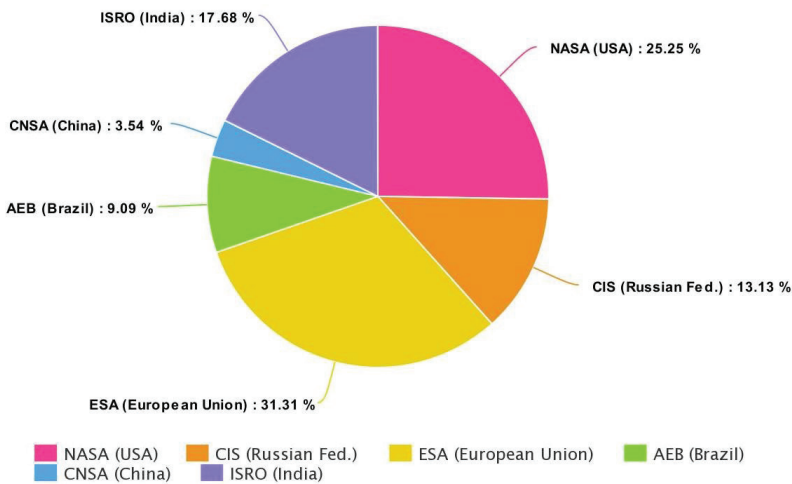
2.4. ECONOMIC INVESTMENT

The final indicator extracted from the literature is the role of the economic investment in national space development as it is a recurring factor in measuring the development of a nation's capabilities. This study will concentrate on the economic investment and budgets of the space nations. Previous literature touched on this such as Sheehan (2016)[38] who attributed the rise of China and India's space capabilities to their corresponding rise in economic power. This study will advance the thought process by comparing the economic investments of the EMSAs and DVSA's. Paikowsky et al (2014)[39] discuss the space economy in relation to the 2013 fiscal year; however, after discussing the dominant powers of the US, Russia, and China, they develop a much too generalized analysis. The reference to entire regions such as Latin America instead of individual EMSAs limits the application of this for future analysis and fails to discuss an eminent EMSA, Brazil. Petroni et al (2009)[40] and Delgado López (2016)[41] succeed in drawing attention to the importance of the economic emergence in EMSAs. Yet because the discussion of Petroni et al (2009) taking place relatively soon after the 2007 global financial crisis and subsequent recession, further updated analysis is needed to fully understand the divergence in economic investment between DVSA's and EMSAs. Ultimately, the literature continuously combines the role of economy with the strategic actions of the space actors. The role of the economy particularly assists space actors in developing their space capabilities. As such the study will utilize the economic indicator to analyze the modern space dynamic between emerging and developed nations, often developing economies like India, China and Brazil, and developed economies like the USA, the European states, and Russia.

With the continued growth of the developing economies and the stagnation of the developed economies, focus on economic strength is pivotal in mapping the shifts of the current internationalized spacecape.

3. RESEARCH METHODS

I have used both quantitative and qualitative methods to map the current space system in the context of emerging and developed space nations. The adoption of data in relation to the main areas of the space system allows for the alternative positions of the emerging and developed space nations. The development of the international space system is measured by political, technological and economic factors. These three factors were then represented by measuring the proxy variables of international cooperation, space technology advancement, and national space budgets. The data regarding international cooperation was adopted from studies that specifically researched direct cooperation agreements of modern space actors. The data regarding technological aspects is drawn from the international satellite geolocation site, Celestrak. Not only does this site track operational satellites, but it also tracks the decaying and disintegrated pieces of satellites known as debris. Finally, the economic aspects of the space system are found in the Association of Europe's Aerospace and Defense industries 2014 analysis and the OECD Space Economy Report 2014.[42][43] In conclusion, the rise of EMSA's with respect to the traditional space leaders is quantified by exploring these factors. This allows the chance of the



Source: Peter, Nicolas. 2006. "The changing geopolitics of space activities." *Space Policy* 22 (2): 100-109

Table 1										
Satellite data of EMSAs and DVSA's										
	Payloads				Debris			All		
	On Orbit	Decayed	Total	Active	On Orbit	Decayed	Total	On Orbit	Decayed	Total
EMSAs										
Brazil	17	2	19	12	0	0	0	17	2	19
India	78	10	88	49	114	322	436	192	332	524
PRC	239	74	313	195	3603	1205	4808	3842	1279	5121
DVSA's										
ESA	75	13	88	45	60	24	84	135	37	172
US	1421	970	2391	638	4684	5148	9832	6105	6118	12223
Russia	1496	1999	3495	143	5018	13079	18097	6514	15078	21592

Source: <http://celestrak.com/satcat/boxscore.asp> [up-to-date as of 19th April 2017]

system to be mapped. Furthermore, these themes provided data of the new system that can be analyzed further to discuss their impact on international security.

Additionally, the countries selected for analysis were chosen to represent both the emerging and developed space nations in the modern system. Those who represent the emerging space nations are Brazil, China and India. Similarly, the developed space nations are the USA, Russia and Europe (as in the joint space agency rather than the national agencies of member states). They were chosen because of their extensive space capabilities, and additionally, their positions as important leaders in their respective regions around the world, a diversity which exemplifies the internationalization of the space system. Meanwhile, there are several other states who present space capabilities on a smaller scale such as Israel, South Africa, Iran and Argentina. Later analysis can focus on widening the data sample to include states possessing elemental space capabilities, but remain dependent on external support. In the final analysis of the data, a series of graphs and cross-tables to produce clear juxtaposition between the space nation levels.

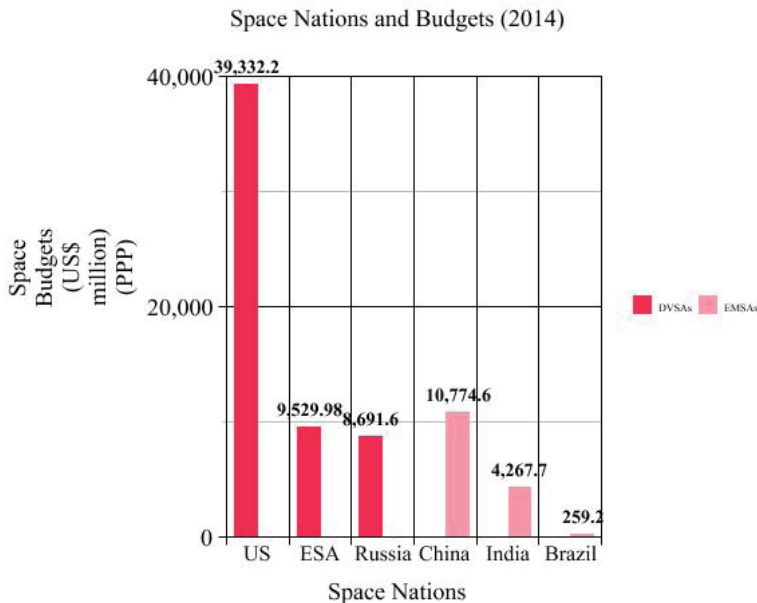
4. RESULTS AND ANALYSIS

The findings below portray the role of emerging space nations in the current space system. The three largest emerging space nations are contrasted with the three largest developed space nations. The results are displayed to represent the political, technological and economic aspects of the current space system. Specifically, the results demonstrate how the emerging space nations make up a substantial part of the space landscape compared to the past bipolar system of the Cold War.

The first set of results appertains to the role of international cooperation of national (and intergovernmental in the case of the European Space Agency) space

agencies in the modern space system. The pie chart presents the data composed by Peter (2006) who charts the cooperation agreements between the major space agencies from 1992-2004. This presents the space system in two aspects. The first is the clear internationalization of the new system by the increase of international cooperation agreements. Secondly, the emerging nations form a substantial bloc of the system, approximately 30% of the current sample.

The next theme depicted is the technological aspect of the current space system. The table below consists of the data on orbiting satellites and debris. The left side axis shows the space nations divided by the headings EMSAs and DVSA's. The top-axis represents the materials being tracked. This table is divided into 3 sections that are then further subdivided. First is the "On orbit" label which means that the material remains on its original orbital path. The "Active" label represents the technological materials that are currently in use. Finally, the "Decayed" label applies to the materials that are no longer used and have substantially deviated from their original orbital geolocation. The classification of the materials is important because it is often forgotten that not all the satellites and technology sent up to space return to Earth.



Source: OECD Space Economy at a Glance 2014

Evidently, the emerging space nations have made large gains in their possession of space materials. China and India have even surpassed the DVSA, the ESA, with respect to the number of satellites and debris, with the ESA having 172 units and China and India having 524 and 5121 units respectively. Note that the divide between the emerging and developed space nations is substantially smaller when only focusing on the payloads that are currently active. This shows the definite rise of the emerging space nations in the space system. Clearly, their role in the system has substantially expanded from the bipolar system of the Cold War. When analyzing space nations' active payloads there appears to be less of a difference between the emerging and developed space nations. Moreover, the large amount of debris is another core factor when analyzing the technological theme as it is often exponentially higher than active payloads in the system. Surprisingly, orbiting debris has as much relevance as satellites, if not more, to the modern space security. For instance, orbiting debris can be in a stable (unmoving) or decaying (slowly falling towards earth) orbit. As such the debris can hit other satellites inflicting a huge amount of damage and in doing so exponentially increase the amount of debris in the system. Not forgetting, the debris can often crash land on earth. With this growing problem, those involved in developing space capabilities will have to focus more and more on limiting the creation of debris. With the rise of objects in space, satellites and debris alike, the consequences of satellite collisions and damages will play a larger role in future space actor plans. Thus, taking account of the data such as that above is indispensable for gauging space actors role in technological development.

Finally, the economic aspect of the space system is represented by the space nations respective budgets. The budgets are taken from the financial year of 2014 and are made up of both aerospace and space revenues. The space actors are color coded to define the EMSAs and DVSA's under study. Despite the clear exorbitant budget for the US, the remaining space actors appear not to vary widely in their budgets. However, for context it must be noted that these numbers were taken before international sanctions were placed on Russia which no doubt would substantially influence their space activity budgets.

The data gathered represents the three core themes of the modern space system that were outlined during the previous section of the theoretical framework. In each case the data has been divided to reflect the role of emerging space nations against the traditional developed space nations that are under study. Furthermore, they are then subdivided into each of the six space actors. The results represent the

extensive role that emerging space nations hold in all aspects of the modern space system. In summation, the increase of emerging space nations across numerous fields as evident in the data shows the internationalization of the modern spacescape.

5. DISCUSSION: INTERNATIONAL SECURITY IN THE NEW SPACE SYSTEM

The mapping of the current space system can be discussed through numerous perspectives. Emerging nations solidified their position was measured through three sectors. This aims to demonstrate a clear picture of the current multipolar space system, which becomes clear by examining the levels of the emerging space nations compared to the traditional developed space nations. It becomes evident that the emerging nations in all three sectors make up a significant percentage of each industry. This is a vital topic to study in the future as the system will only change further with the rise of more emerging space nations. This thesis analyzed the findings through the lens of international security. Uniquely, the rise of the emerging space nations as described through the research presents a clear challenge to the predetermined space system, none more so than to international space security. This discussion will consist of analyzing the new space system of emerging space nations in two parts. The first will discuss how the new space dynamic of the emerging space actors has shown a de-escalation of international security. The second section of the discussion will outline the new space structure as a system displaying an escalation of international security issues. The results uncovered support the hypothesis that the emerging nations have created a new space system that has ultimately influenced international security.

5.1. DE-ESCALATION OF INTERNATIONAL SPACE SECURITY

The first part of this discussion will be focused on the new era of de-escalation and its relation to international cooperation. The emerging space nations have obviously adopted the behavior of partaking in formal ICAs to increase their relative space capabilities [46]. This is evident from the fact that they make up 30% of ICA from the period under investigation. These agreements allow for space nations to create a more integrated and multipolar system; additionally, they have eroded the Cold War mentality by encouraging the sharing of information. There has clearly been a de-escalation of inter-bloc tensions with respect to the security developments during the Cold War. As such cooperation

is a critical measure of how international security has indeed shifted from the Cold War, not only in the number of agreements but in the number of actors participating. As such, the system appears to have transformed into a system of multipolarity representing a plurality of interests.[47]

A new emerging space actor dynamic in international security becomes evident when considering the analysis of data discussed previously. Yet, there is still variation among the specific actors, both DVSA's and EMSA's, who follow this more open approach to space development and hold a more multipolar view of the international system. While all space actors partake in some sort of ICA there are differing levels of participation. In the DVSA's, the highest number of agreements are from India (17.68%), followed by Brazil (9.09%) and finally China (3.54%). [48] Unusually, despite China being the most advanced in all other respects to their EMSA counterparts, they hold the least amount of ICA, which exhibits how their suspicious approach to international security spills over into their space security agenda. Notably among the EMSA's, is the fact that India and China never engaged in any ICA with each other despite being regional neighbors. This shows that while the overall modern space system appears to be one of multipolarity, there remains partnerships that selected countries refuse to make due to their foreign economic and/or political relations. China, the US, and Russia especially exhibit these non-cooperative tendencies. For example, China has never engaged with the US and the US and Russia have never entered into any ICA. Overall, the focus on ICAs provides a format to analyze how the modern space system has altered. Such a large shift is due to emerging space nation with regards to international security. When reviewing these results, the rise of emerging space nations creates a system of multipolarity. Multipolarity leads to increased ICAs and as such international security can be interpreted as having de-escalated.

5.2. ESCALATION OF INTERNATIONAL SPACE SECURITY

The second section is concerned with analyzing how the emergence of new space actors creates an escalation in international security issues.[49] My fundamental hypothesis of emerging actors having created a new multipolar system and therefore internationalized the space system also applies to threat escalation. This section draws upon the space budgets and technology data analyzed in the previous sections. The data is analyzed jointly because of their self-reinforcing nature—the more developed the economy, the more advanced the technology. Where these elements prosper significant space actors emerge with substantial

capabilities. It is no coincidence that they are all members of the BRICS, a major group of emerging economies. This economic strength has been used to build their capabilities and therefore develop their technological power. Since economic development translates into technological power, developing nations' rising economic power naturally facilitates a rise in space technology. It is this concept that leads me to attribute the emerging space nations to cause a rise in the technology through GNSS, launching capabilities, and ultimately, satellites. Each of these developments of the spacecraft can be analyzed in terms of security, more specifically they show a rise in international security risk.

The technological developments made by the emerging space nations have significantly altered the space system in relation to international security.[50] First of which has been seen in the rise of emerging space nations developing GNSS (Global Navigation Satellite System) or RNSS (Regional Navigation Satellite Systems). With the increase in the technological developments there has been a trend of emerging space nations in developing regional and global navigation systems. The goal is to become independent from the current "free" navigation system, the US GPS. This move towards self-reliance is seen in China with the development of the BeiDou Navigation Satellite System since early 2000s, which began as a regional effort but will soon consist of full global coverage. Similarly, the Indian space program has Indian Regional Navigation Satellite System (IRNSS) with an operational name of NAVIC ("sailor" or "navigator" in Sanskrit, Hindi and many other Indian languages, which also stands for NAVigation with Indian Constellation). Both intend to accomplish the feat of having global systems fully independent in the near future. While not directly confrontational the strategic importance of having regional and global navigation systems in future conflicts cannot be underestimated. This stop gap approach shows that space, and specifically the GPS, can no longer be viewed as passive territory. It goes that the rise of regional and global navigation systems by emerging space nations shows that international security has become increasingly reliant upon space capabilities in times of conflict.

The next technological development that outlines the impact of emerging space nations is launching capabilities.[51] The features that makes a successful launching site is a combination of technology and, most importantly, geographical location. The location is paramount for increased launching rate because of the higher velocity from the earth's rotation making it easier for satellites to gain

momentum. It is an advantage to the emerging space nations who rest closer to the equator, the optimal location for launching spacecraft. It has been particularly true for the EMSA, Brazil. They have developed significant launching capabilities and have also become a key location for DVSA's to launch their satellites. The influx of DVSA's not only provides Brazil with an income but additionally assists them in learning from superior space powers. Their role in providing a successful launching base has been clear over the years. For instance, 10% of the launches in the last decade have originated in Brazil, 40% of which would have previously been launched in the United States. Clearly, location matters and emerging space nations are capitalizing on this fact. However, an outcome of the space nations ensuring a decrease in satellites loss means that there are now more satellites in the system as a whole.

Ultimately, there are more satellites in the system leading to several issues becoming more apparent. The increase of satellites in the system poses risks for international space security. The emerging space nations' on orbit satellites number 4051 which translates to 31.76% of the data set under study. Clearly, the emerging space nations have significantly contributed to the persistent crowding of space. Consequently, risks can be further divided into two subsections: intentional and unintentional. The intentional risks arise with respect to the space nations satellite maintenance. Often it can be forgotten that satellites have a finite lifespan and they must be removed from the system eventually. The method that has created the most controversy is the anti-satellite weapon (ASAT).[52] Such an instrument shoots the satellites down from orbit and lets the debris fall to earth, at least that's the plan. Unsurprising several concerns for the EMSA's and DVSA's alike arise from such a method. First of all, the ASAT may miss its intended target and therefore destroy one of its functioning counterparts, by accident or on purpose. Next, the debris may hit a counterpart on its descent. An event such as this happened when the Chinese destroyed one of their satellites and on its way down destroyed a three-month old Venezuelan satellite. Evidently, ASAT systems can very easily be turned against other space nations' spacecraft. As a result, with the rise of satellites comes with the rise of technology that destroys them. As such, the emerging space nations increase of technology has created a system where satellite security has become a high-risk issue. The unintentional threats faced by space nations continues this frame of thought. These range from scattered debris orbiting, satellite collisions to communication interference. All of these issues originate from the spacescape becoming increasingly overcrowded. The most critical issue is space debris, which

allocates 1,613 fragments over 10cm to the emerging space nations, in addition to the already 21,235 fragments allocated to DVSA's.[53] The critical issue with debris is that a piece measuring 1 micron can break a satellite lens or even a fragment of 1 centimeter can destroy a whole satellite due to the velocity the pieces orbit. Undoubtedly, this presents a significant threat to all space nations as debris destroys indiscriminately. Thus, as emerging space nations continue to add to the orbiting community they are inadvertently adding to the debris levels also. Indeed, as the new multipolar space system continues, the risk developed through intentional and unintentional consequences of surge in satellite causes international security to escalate.

5.3. SUMMARY OF INTERNATIONAL SPACE SECURITY

In the analysis, the emerging space nations compose a significant portion of the space system in political, economic and technological facets. When this new system is analyzed in the context of international security, the specific role of emerging nations can be seen. The overall impact of emerging space nations creating a system of multipolarity has had clear impacts on the international security dynamic. By using the three core themes to address this shift, a pattern begins to emerge. The pattern is that the internationalization of the space system that has shifted the risks and priorities of all space actors. International security has developed in two distinct ways. The first development is how multipolarity has facilitated a de-escalation of tensions through increased international cooperation. De-escalation is perfectly exhibited by the EMSAs and DVSA's forming extensive international cooperation agreements. Conversely, the new space system of the emerging space nations has caused international security to escalate in several ways. This has been represented by looking at the consequences of the economic and technological developments of the modern space system. The self-reinforcing nature of economic and technology developments in space capabilities reveals a clear link to modern emerging space nations. The development of launching capabilities has facilitated an overall higher number of successful spacecraft. Following this, the evolution of technology has seen emerging space nations develop their own independent navigation systems, preparing for when space is drawn into conflicts on the ground. Finally, the overall rise in the number of spacecraft and debris has resulted in collateral damage on ground and in orbit. As a consequence, there is a possibility for the

risk of purposeful damage between actors as a result. This study has uncovered the ways in which emerging space nations have created a new space dynamic that has subsequently changed international security

6. CONCLUSION

The modern space dynamic created by emerging space actors significantly impacts the critical issues of international space security. Due to emerging space nations, there has been a shift in the focus of international space security issues from the race to the moon to satellites overpopulating orbit. Multipolarity has been firmly reinforced as emerging space nations surge in the political, technological, and economic fronts of space development. The internationalization of these three key areas has given rise to a new array of issues for international security, and as a result, the rise of emerging space actors has fostered a domino impact on the already developed space nations. These outcomes are ultimately positive because they increase international cooperation. Meanwhile, the repercussions of the rising space actors is viewed through increased national surveillance systems as well as the dangerous uptake of spacecraft and their accompanying debris. The increase of emerging space actors has created an altogether different system than that of thirty years ago. Therefore, international space security within the modern space dynamic has also inevitably changed. Continuous development of space capabilities in both current and future space actors entails that the system will endure greater changes and security threats will intensify. Gone are the days when security within space was stable and predictable; today's international security climate is precarious both in the long term and the short.

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