Statement of David N. Spergel

I thank Chairwoman Horn, Ranking Member Babin and other committee members for the opportunity to testify on NASA's science program. My name is David Spergel. I am Charles Young Professor of Astronomy on the Class of 1897 Foundation at Princeton University and Director of the Center for Computational Astrophysics at the Flatiron Institute, a new institute funded by the Simons Foundation to conduct basic research in computational sciences. I am also a past chair of the Space Studies Board, serve on the JPL advisory board, and am currently co-chair of the WFIRST Formulation Science Working Group. While these experiences inform my testimony, these views are my own.

Our multi-generational program of exploring and studying space is the modern version of the construction of the great medieval cathedrals of Europe. Many of NASA's most important activities from sending humans to Mars to studying extrasolar planets to understanding the cosmos are century-long projects.

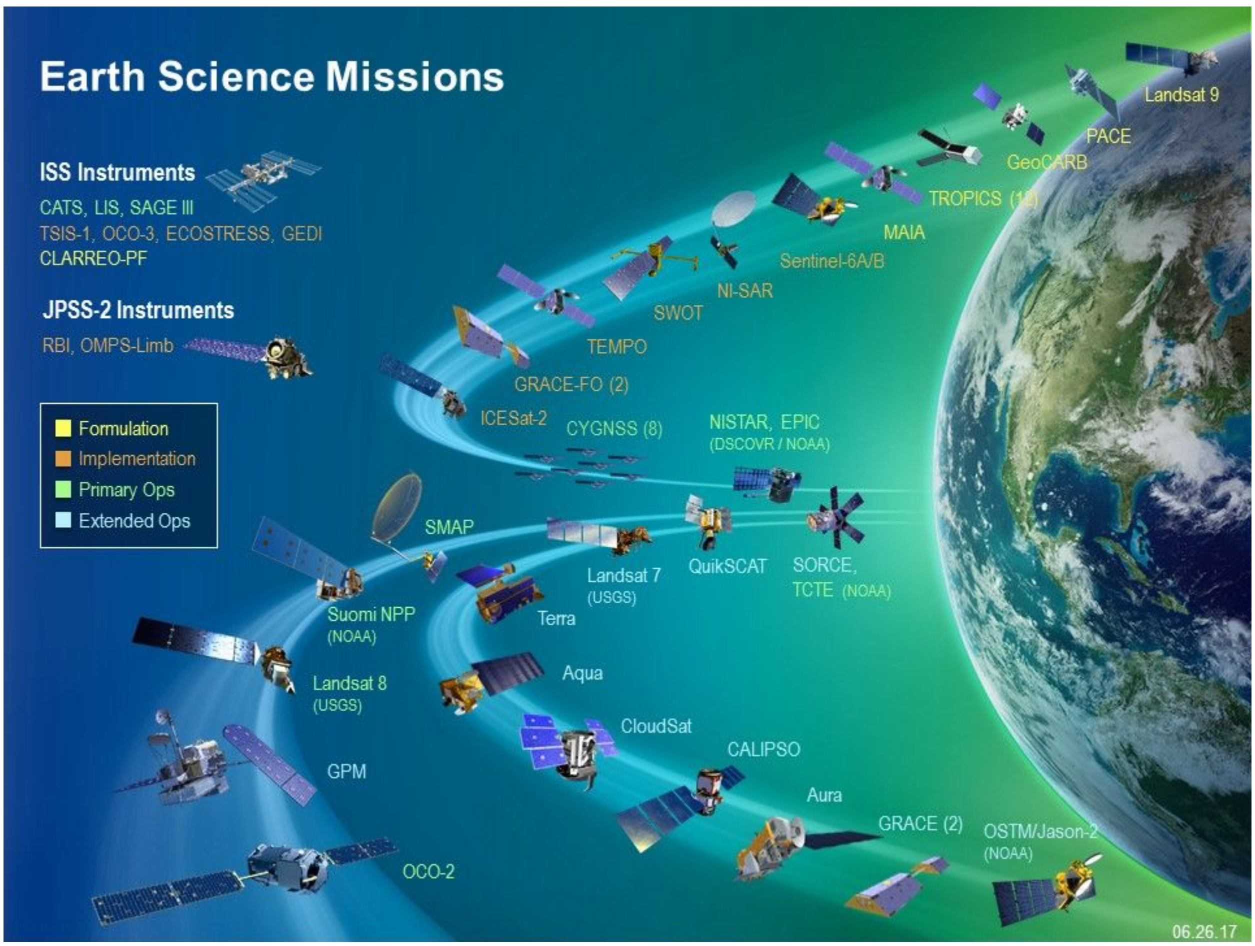
For the NASA Science Mission Directorate, the National Academies' decadal survey process provides a blueprint for constructing these cathedrals. They bring together an entire community to create a vision for each subfield. The Science Mission Directorate has been effective at implementing these plans and launching missions that produce transformative science. As chair of the International Astronomical Union's committee on international collaboration, I see how other nations look to our decadal process and the interactions between the Federal government and the Academies as a model. I have been consulted by colleagues from Canada, New Zealand and India on how to implement their own processes. Both Europe and Japan have developed their own version of the decadal process modelled on the Academies' reports.

Understanding our rapidly changing planet is perhaps NASA's greatest scientific challenge and a pressing societal need. As the recent NAS report, "Thriving on a Changing Planet: A Decadal Strategy for Earth Observation from Space" finds:

> Space-based Earth observations provide a global perspective of Earth that has
>
> - over the last 60 years, transformed our *scientific understanding* of the planet, revealing it to be an integrated system of dynamic interactions between the atmosphere, ocean, land, ice, and human society across a range of spatial and temporal scales, irrespective of geographic, political, or disciplinary boundaries.
> - In the past decade in particular, enabled *societal applications* that provide tremendous value to individuals, businesses, the nation, and the world. Such applications are growing in breadth and depth, becoming an essential information infrastructure element for society as they are integrated into people's daily lives.

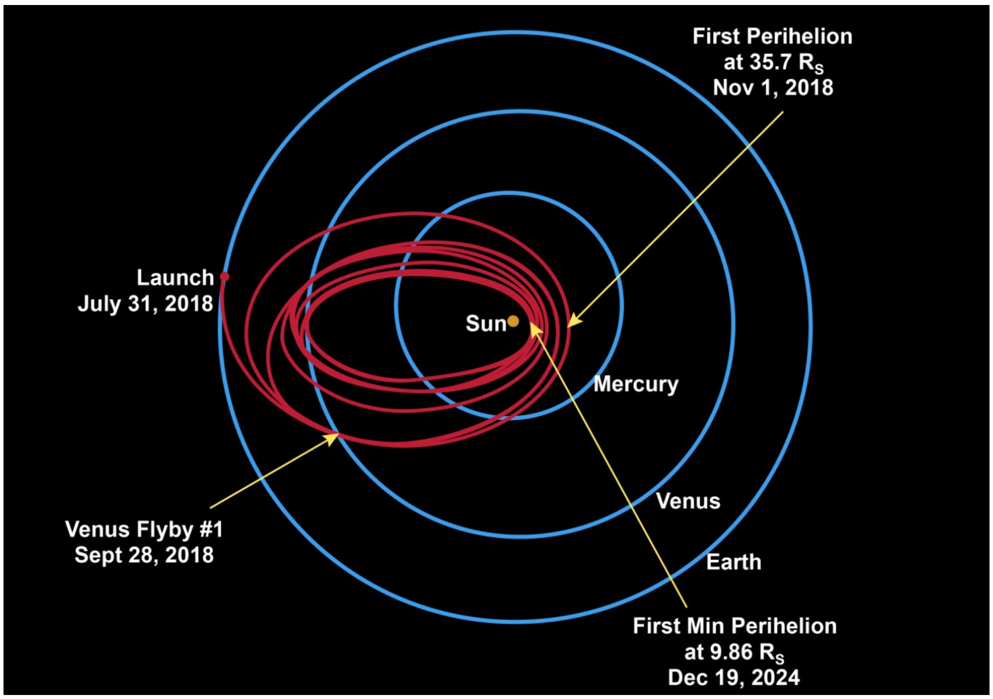
Monitoring the Earth from space requires a robust, resilient and appropriately balanced constellation of satellites that will provide the observational capacity to address our most profound problems.

"Thriving on Our Changing Planet" identified six main categories for study: the coupling of the water and energy cycles, ecosystem change, extending and improving weather and air quality forecasts, sea level rise, reducing climate uncertainty and informing societal response and surface dynamics, geological hazards and disasters. The report recommended augmenting the program of record with eight priority observables and recommended structuring new NASA missions to address these areas of study. They also recommended ways in which NOAA and USGS can leverage NASA investment in these capabilities.   I hope that as this committee considers reauthorizing NASA that it will charge the agency to implement these decadal priorities.



Earth scientists utilize a large constellation of current and planned missions to monitor the changing planet. NASA image

Understanding the physics of our Sun and the many ways that it affects the space environment and the Earth itself is another one of NASA's grand challenges. What is the origin of the Sun's activity? How does this affect the space environment, the solar system and the Earth itself? These questions are not only profound physics questions but have important economic consequences as space weather could devastate our technological society. Last year, NASA launched the Parker Solar Probe, an ambitious mission that will effectively touch the Sun and directly probe the origin of Solar activity. My Princeton colleague Dave McCommas is leading the next heliophysics mission, the Interstellar Mapping and Acceleration Probe. IMAP will help researchers better understand the boundary of the heliosphere, the magnetic bubble surrounding and protecting our solar system. The DRIVE initiative is an important complement to these major missions: a combination of cubesats, small sats, and theoretical work. Both pieces are needed for a healthy space science program.



The Parker Solar Probe is enroute to the Sun. It will pass far closer to the Sun than any other satellite. Parker Solar Probe will study the origin of the Sun's activity. NASA image

Within our own solar system, we have learned that water, the most essential ingredient for life is seemingly ubiquitous in our solar system. Comets have brought water to burning hot Mercury and the seemingly barren Moon. Mars had not only a wet past but as recent observations reveal has liquid water. Outer planet moons such as Europa host vast oceans beneath their icy shells, a discovery that suggests new potential habitable destinations. Did any of these systems once host life? Do they still host life today?

The exploration of Mars is another one of humanity's multi-generational challenges being addressed with NASA's Mars program with a set of interlocked missions exploring the Red Planet. The Mars 2020 mission is the next step in this program culminating with the return of carefully selected samples. As the NAS report "Vision and Planetary Sciences in the Decade 2013-2022" recommends:

> Mars is unique among the planets in having experienced processes comparable to those on Earth during its formation and evolution. Crucially, the martian surface preserves a record of earliest solar system history, on a planet with conditions that may have been similar to those on Earth when life emerged. It is now possible to select a site on Mars from which to collect samples that will address the question of whether the planet was ever an abode of life.

Besides the enormous scientific value of the samples, the process of sample return should be an important step towards NASA's horizon goal of sending humans to Mars and returning them safely to Earth.

NASA is also making progress in building the planetary science decadal survey other priority mission, the Europa Clipper. Europa is one of the most fascinating objects in the Solar system with its deep oceans, underwater vents, and the tantalizing possibility that it might host life.

Neither the planetary science decadal survey nor its more recent mid-decadal report have identified a major investment in lunar science as one of the highest priorities of the planetary science community. Speaking as an individual and as a reader of the various community decadal reports, I am concerned by the potential reallocation of resources from the top priorities of the scientific communities towards the lunar program. In its recent report, the National Academies' Committee on Astrobiology and Planetary Sciences' *Review of the Planetary Science Aspects of NASA SMD's Lunar Science and Exploration Initiative* noted,

> The program as currently formulated, while aligned with decadal priorities, does not, however, replace the lunar science priorities and missions recommended in *Vision and Voyages*, the latter of which remain competitive in the New Frontiers class. It remains the responsibility of the next planetary science decadal survey to evaluate these missions as well as the planetary science aspects of the Lunar Discovery and Exploration Program in the context of the planetary program.

I am concerned that high priority programs in Earth Science, Heliophysics, and Astrophysics could be terminated so to enable projects that were not identified as decadal priorities in the planetary science program.

The Event Horizon Telescope's image of an accretion disk is the most compelling astronomical image of the year. While the image is a triumph of a long-term NSF-funded project, its scientific value rests on the synergies of Earth-based and space-based measurements. By combining the Hubble Telescope's image of its powerful jet, the radio interferometric measurements of M87's central ring, and NASA's *Chandra* and *NuSTAR* measurements of the X-ray luminosity, astronomers have been able to infer the presence of supermassive rotating black hole. Similarly, the combination of LIGO's detection of a neutron star-neutron star merger and *SWIFT*'s detection of its electromagnetic counterpart has led astronomers to an understanding of both the origin of gold and platinum and one of the most powerful tests of alternatives to general relativity. These discoveries demonstrate the power of multi-wavelength and multi-messenger astronomy.

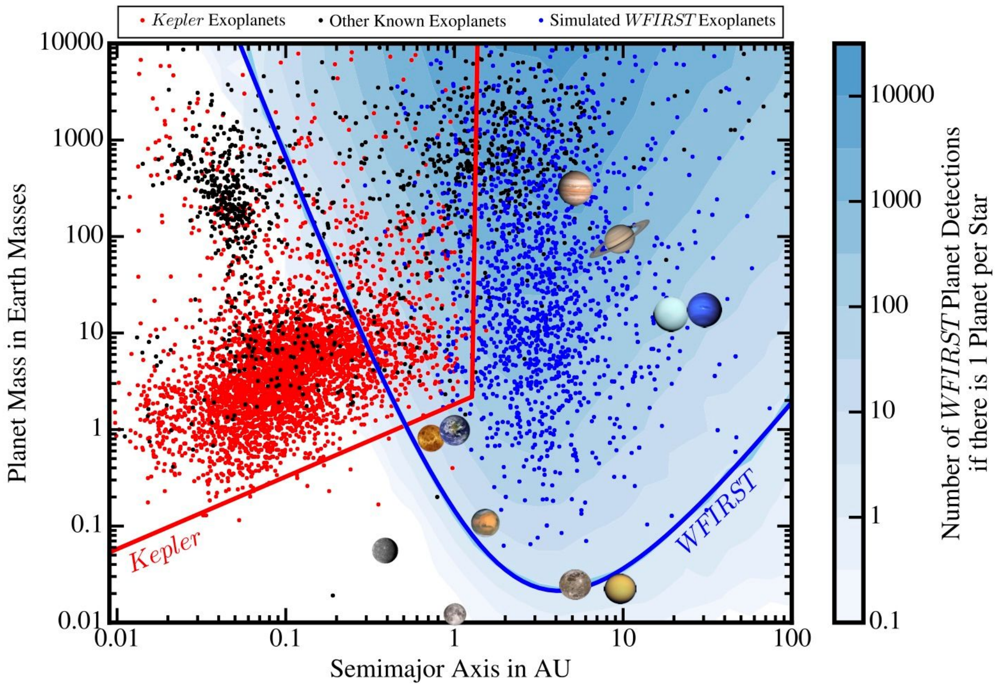
In cosmology, we have learned that our universe is both remarkably simple and remarkably strange. Nearly a century ago, Dr. Edwin Hubble's work at Mount Wilson observatory began our program of measuring the size and shape of our universe. Today, the Hubble Space Telescope and measurements of the microwave background continue this program. Over the past two decades we have learned that a simple model with only five parameters (the age of the universe, the density of atoms, the density of matter and the properties of the initial fluctuations), describes all of the basic properties of the observed universe. While successful, this model implies that atoms make up only 5% of the universe. Most of the universe is in the form of *dark matter* and *dark energy*.

Understanding the nature of dark energy is one of the most compelling problems in physics. Both Europe and China are leading missions to study dark energy. When I was in Beijing, I was impressed by China's plans to launch a large space telescope off of its new space station with a primary focus on studying dark energy. This telescope will have the world's largest space camera and use Chinese military technology to construct a large off-axis telescope. Fortunately, NASA is moving forward with the premier dark energy mission, WFIRST, the top ranked large space project in the 2010 astronomy decadal survey. It will measure the expansion rate of the universe and the growth of structure to unprecedented precision. WFIRST is meeting all of its technical requirements and is on track for a 2025 launch.

Astronomers have also learned that the solar system is far from unique. Using observations from the Kepler spacecraft and ground-based observatories, they have discovered thousands of exoplanets revealing a diversity of planetary architectures and a diversity of planetary properties. Shakespeare's line, "There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy" is perhaps our best guide as we contemplate whether there is life elsewhere in the Milky Way.

Just as the exploration of the cosmos has driven telescope design for the past century, the study of exoplanets and the search for life beyond our solar system will likely shape the telescopes of the coming century. NASA's TESS mission has begun revealing many new nearby transiting planets. When launched, the James Webb Space Telescope will be able to characterize the atmospheres of some of these planets. This is one of the powers of a flagship mission: JWST was not designed for transit spectroscopy but its enormous sensitivity in the infrared will enable it to make potential transformative measurements of planetary atmospheres. WFIRST's coronagraph is poised to be the next step in exoplanet characterization. The coronagraph should be more than 1000 times more sensitive than previous coronagraphs aboard Hubble and JWST. It will not only be able to image massive planets around nearby stars but will be the stepping stone for developing technologies for the next generation of great observatories.

Understanding planet formation requires use of a wide range of observational approaches. Within our own solar system, comets and asteroids are fossils of the early solar system. Radio and infrared observations reveal extrasolar planetary system in formation. With its microlensing observations, WFIRST will complete the census begun by Kepler and TESS. These should reveal thousands of planets in the outer regions of their solar systems.



This figure shows the discovery space for the Kepler and WFIRST mission as a plot of distance from the host star (measured in astronomical units (AU)) and planet mass. The Earth distance from the Sun is 1 AU. The plot also shows the planets of our own Solar system. The black points in the plot are the planets discovered by ground-based measurements of stellar radial velocities. Plot courtesy of M. Perry.

The astronomy community has just begun its next decadal survey. Led by Fiona Harrison and Robert Kennicutt, the survey is considering a range of possible projects including large optical telescopes likely launched in the 2030s that will be capable of characterizing extrasolar planets. Even these telescopes will likely be stepstones to even more sensitive telescopes that we will develop in the 2050s that will enable detailed characterization of planetary atmospheres.

Scientific advances in all of these fields are driven both by science pull and technology push. The desire to address major scientific questions pull technology development. Advances in technology pushed open the opportunity to study the universe in novel ways.

Historically, NASA has invested in technology development to enable its future missions. Over the past decade, the Space Technology Mission Directorate (STMD) has made these investments for both NASA's science and exploration programs. Regrettably, STMD is reducing these long-term investments for its future science missions and is focusing its resources towards the short term goal of returning humans to the Moon by 2024. I fear that this is eating

NASA's "seed corn" for future transformational science missions. I encourage the committee to consider directing the agency to make these long-term technology investments through instructing STMD to continue support SMD objectives.

NASA has long exploited technologies originally developed for our nation's defense, ranging from rockets to sensitive infrared detectors. In recent years, commercial advances are providing new technologies that should be repurposed by NASA for scientific discovery and exploration. The desire to build self-driving cars has led to substantial advances in autonomous systems. The machine learning revolution is not only improving facial recognition on Facebook and login-screens, but also providing novel tools for analyzing NASA's images of the changing Earth and of distant galaxies. The tools are also beginning to transform how we simulate complex physical systems. High performance computing hardware is shifting from CPUs to GPUs. These processors have not yet been used in space and are not being fully utilized in ground-based computation and analyses.

One of the challenges for NASA and for the scientific community is to be open to these innovations coming from new sources. Students will need to be trained not only in physics, chemistry and biology but also in data science and computer science. NASA's grant programs (and its referee process) will need to be open to entrants with non-traditional intellectual backgrounds. NASA will need to engage suppliers beyond its "usual suspects".

Perhaps, there is no area of technology that is changing faster than software engineering. NASA has been a leader in its open data policies and now has the opportunity to be a leader in open code policies. As the Academies' recent report on "Open Source Software Policy Options for NASA Earth and Space Science" notes, an open code policy can enhance and enable innovation and discovery, facilitate scientific reproducibility and encourage collaboration. Across both academia and industry, open software is transforming code development. While some of the scientific communities that work closely with NASA have adopted open software practices, others are fearful of their loss of control. The report recommends

> NASA Science Mission Directorate should explicitly recognize the scientific value of open source software and incentivize its development and support, with the goal that open source science software becomes routine scientific practice.

NASA's open data policy has been a model for other scientific agencies and for foreign space agencies. I hope that its software policies will also become a model through incentivizing openness.

I want to conclude by thanking the committee for the opportunity to discuss developments in NASA Science Mission Directorate. This is an exciting time for space science and a moment where our observations of Earth from space are vital for monitoring the health of our planet and determining appropriate policies. While NASA does face immediate challenges like successfully completing and launching JWST, this is an incredibly exciting time in space science. NASA satellites have enabled the discovery of 1000s of exoplanets, are detecting the optical counterparts of merging neutron stars whose gravitational waves have travelled for billions of light years to Earth, and are tracing the large scale distribution of dark matter and dark energy in the Universe. It has launched a satellite that will literally touch the Sun. NASA exploration of our solar system is revealing new insights into the origin of the solar system and perhaps even of life itself. Its satellite observations are deepening our understanding of the rapidly changing Earth. Most importantly, each of these discoveries raises new questions that future satellite missions will address in the years to come.