THE HONORABLE DANIEL S. GOLDIN became NASA's Administrator in 1992. Since then he has initiated a revolution to transform America's aeronautics and space program. Through his aggressive management reforms, annual budgets and the civil work force have been reduced, productivity gains have climbed, and his "faster, better, cheaper" approach has enabled the agency to deliver programs of high value. He has been credited with bringing NASA "back from the brink of a black hole."

Among Dr. Goldin's many accomplishments, he initiated the Origins Program to understand how the universe has evolved, to learn how life began on Earth, and to see if life exists elsewhere. He led a rescue plan for the successful installation of a "contact lens" on the Hubble Space Telescope, leading to startling discoveries of the cosmos. To expand public and educational outreach, he directed NASA's program managers to incorporate Internet access into mission plans. In addition, he has challenged NASA's Aerospace Technology Program to make space travel 10,000 times safer and 100 times cheaper.

Before coming to NASA, Dr. Goldin was Vice President and General Manager of the TRW Space and Technology Group in Redondo Beach, California. During his 25 years there, he led projects for America's defense and conceptualized and managed production of advanced communication spacecraft, space technologies, and scientific instruments. He began his career at NASA Lewis Research Center, Cleveland, Ohio, in 1962 and worked on electric propulsion systems for human interplanetary travel.

Dr. Goldin is a member of the National Academy of Engineers and International Academy of Astronautics, a Fellow of the AIAA, and a recipient of 13 honorary doctorate degrees.

Dr. Goldin spoke at the Millennial Challenges Colloquium series on 10 October 2000.
The text of "NASA in the 21st Century" follows.

NASA in the 21st Century

Daniel S. Goldin

Good afternoon. I am pleased to be at the Applied Physics Laboratory because many of the world's most talented scientists are right here. And this incredible facility is a critical element not just to America's space program but to our national security and our technical vitality as well. If I listed all the collaborative efforts of NASA, The Johns Hopkins University, and APL, I'm afraid I would go far beyond the time scheduled for my presentation. Suffice it to say that the University is a primary recipient of NASA contracts and grants. What a testament to the excellence of the people and the facilities here. You are an essential part of America's space program's history, and you are even more important to our successes in the future because you have the talented and innovative people who will take us boldly forward.

You may not know this, but no less a luminary than Albert Einstein once said, "I never think of the future. It comes soon enough." However, that's precisely why I want to talk to you about the future today, because it is coming very soon, and we as a country need to be ready. What I'm about to discuss is not a comprehensive checklist for the success of our space programs. Nor is it prioritized. Instead I want to highlight some of the extremely interesting areas we are working in and areas we should set unbelievably high goals for. We will achieve some of our goals, and we will fail at a few. But that's OK. When the people at Johns Hopkins are involved, we know the goals will be lofty, the achievements will be grand, and we won't be afraid of the failures that occur along the way.

ACCESS TO SPACE

A major area of focus right now is the International Space Station, which will accept its first human inhabitants in about three weeks if all goes well. We are excited about the Station, because it will be our primary means for conducting long-term space-based research that will allow us to ultimately send humans beyond this planet and will ensure the continued health and safety of our astronauts.

The Station is a cooperative endeavor among 16 nations, some of them former enemies. Each participant is providing critical expertise to the project, and the Station is much better because of that international cooperation. Together we are building a world-class research platform in space that will yield an incredible scientific bounty and dramatically improve life here on Earth. There are fantastic research opportunities available on the Station, including biomedicine, biotechnology, advanced communications, and advanced materials to name a few, and I am here today because I want to encourage those in the Johns Hopkins community to come forward with research ideas that will help us tap the Station's full potential. In fact, the University, and APL by extension, is part of the National Space Biomedical Research Institute which is working on some of those problems, and I know that APL will be an integral part of NASA's space programs in the future.

Now let me take a few minutes to tell you about how I view the future of the space program and what it will take for us to get there. Again, this is not a comprehensive checklist, but I'd like to get your ideas flowing and help you understand that dreaming is OK in the 21st century. In a highly competitive area—access to space—our goal is not evolutionary progress in our vehicles through updates. Instead, we want major revolutionary improvements in the reliability of our next-generation vehicles. That's why the work we've done on X-vehicles and the competition we're running for second-generation launch vehicles is wide open. An upgraded shuttle is an option. Lockheed Martin's Venture Star Project is also a viable option that uses a new engine concept called the Linear Aero-Spike, which is single-stage. Think of this concept as an inverted bell engine that uses a ramp on one side and the atmosphere on the other to constantly adjust area ratio to get amazing performance.

We are also seeing some formidable possibilities from emerging rocket companies. And NASA is willing to do the high-risk, high-payoff research that is needed so that within a decade we will have a radical change for second-generation, low-cost launch vehicles. We're looking at ideas like integrated airframes and load-carrying cryotanks with lifetimes of at least 500 missions instead of today's 1 or 2. We're exploring vehicle health management systems that can provide an assessment of current vehicle performance and predict problems in failures before they occur to make the system safer and eliminate the necessity of having hundreds of people operate the vehicle.

Then for the third-generation space vehicles, we are working with a variety of established companies, universities, and government laboratories because we are actively seeking the best ideas for even more revolutionary systems. This research will pursue concepts like combined-cycle engines so that instead of carrying our oxygen, we'll take it out of the atmosphere. We are also looking at electromagnetic enhancement to launch the vehicles and at making diffuse plasmas to reduce drag and to get higher lift. We're talking about materials that operate routinely at 5000°.

Why are we pursuing such technologies? Because we want to take the probability of a major failure in the Space Shuttle from today's 1 part in about 200 to 1 part in 10,000, and eventually to 1 part in 1,000,000, or about the same reliability as today's commercial aircraft. And we want to do it while reducing launch costs—first from \$1000/lb within a decade to \$100/lb within a generation. And as we do that, we want to develop high-output engines with reliable lifetimes of 100 missions, and eventually 500 missions.

ASTROPHYSICS

As we look out from Earth orbit to the heavens, NASA has two broad, long-term goals in astrophysics:

1. To understand the origin, evolution, and destiny of our universe and the fundamental physical laws that govern it
2. To search for other Earth-like planets and life itself

Although these two goals may appear different, the technologies and learning steps required are very similar. In both cases, we must make major advances in technologies that enable much clearer and sharper spatial and spectral resolution than we have today.

For example, the event horizon of a black hole is where matter disappears from this universe as it "falls" into a singularity. If the fundamental laws of general relativity are ever to break down, this is the spot. To actually image this phenomenon, we must improve the spatial resolution of X-ray systems by a factor of about 10 million over the recently launched Chandra X-Ray Observatory. We also need many orders of magnitude more sensitivity to achieve our resolution goals, thus requiring ever-larger apertures.

But we can apply the lessons of radio astronomy here. Decades ago, radio astronomers turned to interferometry to improve both spatial resolution and sensitivity. They combined the radiation received by many single telescopes into one image in such systems like the Very Large Array and now the Very Long Baseline Array. Interferometry allows us to use the virtual size of the array of smaller antennas to achieve the desired degree of spatial resolution.

This lesson is especially important for optical and X-ray astronomy. Chandra achieved 10 times the resolution of HEAO-2 (the second of three NASA High Energy Astrophysical Observatories), called the Einstein Observatory, by going to a larger single aperture with more accurately ground mirrors, but at about 10 times the cost. We certainly can't afford the cost of scaling up single apertures using the same technology to achieve the needed 10 million factor of improvement in resolution.

Moving to separated aperture interferometric systems using multiple X-ray telescopes is an unbelievably daunting task. But these telescopes won't use solid glass mirrors. They will initially use lightweight, replicated metal films that greatly lower the weight and cost of any single element, and we've achieved some breathtaking results to date.

And we are heading in that direction. NASA recently started the Micro-Arcsecond X-Ray Imaging Mission (MAXIM) to conceive a constellation of X-ray telescopes that ultimately will have a resolution of 0.1 micro-arcsecond, more than 10 million times better than Chandra. MAXIM will allow us to do much more than detect event horizons. Perhaps if we are successful in this area, we will be able to image the event horizons around massive black holes.

Although the scientific objective of imaging the surface of Earth-like planets is very different than imaging the event horizons of black holes, the learning process is very much alike. Again, we will need to turn to interferometric techniques for help.

It is my deep conviction that advances in biology will bring about the technology revolution of the 21st century.... It is time to put biology on an equal footing with physics and chemistry as the underpinning of advanced technology.

The Hubble, like our other space telescopes, was built like a ground-based telescope, even though it operates in the microgravity environment of space. It has a very rigid, massive, and expensive mirror. However, our next instrument, the NGST (Next-Generation Space Telescope), will use a deployable, thin, segmented-glass mirror that has active control, is flexible, and has a mass density that is more than an order of magnitude smaller than the Hubble mirror by taking advantage of the absence of gravity.

But to reach our ultimate goal of micro-arcsecond imaging of the extra-solar planets, we will need far more spatial resolution and sensitivity than NGST will provide. Thus, we will explore the possibility of using an array of separated telescopes comprising an interferometer with optical elements that are 50 to 100 m in diameter and separated by thousands of kilometers.

Although each element will be far bigger than NGST, we hope they will be assembled using even lighter-weight technologies such as thin films that may have 10 to 100 times less density than the newest technologies on the NGST. Active optical figure control will be the key to enabling these large systems to perform like their rigid counterparts on Earth. Breathtaking optical and metrology technology will be required to coherently combine signals. Imagine it! If we succeed in developing an optical interferometer comprising 50 to 100 very large reflectors, spread out over thousands of kilometers of space, we might resolve continents, mountain ranges, and oceans on planets within 100 light-years of Earth, if they exist.

Finally, developing these interferometric technologies will lead the way to opening another window on the high-energy universe: gravitational-wave astronomy—the Holy Grail of where physics needs to go. Using gravitational-wave detection systems like the LISA (Laser Interferometer Space Antenna), we will be able to probe the universe of gravity waves. If we succeed, LISA will help us to see the effects of objects orbiting black holes, see objects being swallowed by black holes, and observe the formation of black holes themselves.

By using gravity waves, we can even begin to probe beyond the microwave background barrier to just 300,000 light-years after the Big Bang and push backward in time to almost the very moment of the primordial explosion itself. This is just 10 years out, not decades away. What a legacy for our children! But to realize this vision we have started to develop these technologies *now,* instead of deploying the next system before we look at the one after that. And that requires the concerted and combined efforts of NASA and America's premier universities like Johns Hopkins.

SOLAR SYSTEM EXPLORATION

As we explore the universe, some of our efforts will be a bit closer to our home planet. Some of NASA's scientific goals for solar system exploration include

- A detailed study of the planet Mars (its geology and climate, the history of water, and the presence of past or current life)
- Exploration of Europa to map its subsurface ocean, with an eventual landing to perform surface and subsurface exploration
- Exploration of primordial objects such as comets, asteroids, Pluto, and Kuiper Belt objects to understand the basic building blocks of the solar system
- An in-depth study of the outer planets to understand their climates and their satellites

How can we achieve these goals? The key is new technology. Power is a critical area that affects our ability to move forward on all of these goals. We must develop lightweight, ultra-safe, compact systems that have 5 to 10 times the conversion efficiency of today's thermal-to-DC systems.

Ample power is also the key to future human exploration on Mars, as it will enable the conversion of potential subsurface water into oxygen for breathing and hydrogen for fuel and power for the infrastructure.

And beyond Mars, we cannot contemplate aggressive exploration of the outer planets and the Kuiper Belt until advanced power systems are available. Solar power is simply not an option beyond the asteroid belt.

New systems will have to be compact, lightweight, efficient, and *safe* so as not to impact the population here on Earth during a launch. But we haven't really developed anything new in over a generation!

Even as we improve safety and dramatically lower the costs of Earth-orbit launch systems, we will also need revolutionary new methods of in-space propulsion. In October 1998 we launched Deep Space 1, which tested 12 advanced technologies for use in future missions. This was the first time we used electric propulsion as the primary method of propulsion on a planetary spacecraft, so Deep Space 1 only needed to carry 80 kg of xenon fuel—about 20% of the craft's total weight. For planetary spacecraft, the reverse is typically true. Normally it is the spacecraft that is about 20% of the total weight, with the rest taken by fuel.

We are looking at advanced concepts for propellantless spacecraft propulsion systems. One possibility is to use light sails that use photons from the Sun or lasers to propel spacecraft at over 20 km/s. This could be incorporated into a hybrid system to achieve maximum performance in deep space missions.

We are studying concepts that could generate plasma bubbles that will move us at twice the speed of light sails. Plasma bubbles would be generated by the spacecraft, surround it, yet remain attached to the craft. We believe that solar particles would then interact with the bubble, pushing it and the craft through the cosmos. If this proves successful, the technology could allow us to reach our dreams of going to interstellar space. Also, astronaut Franklin Chang-Diaz is developing a magnetic expansion plasma propulsion system to propel astronauts and cargo to places like Mars much faster and much more cost-effectively.

Again, we are engaging the most innovative minds we can find, because we don't want to spend a decade traveling to Pluto. In fact, we want to go to interstellar space and get there as quickly and safely as possible. That's why we are open to *radical* and unconventional approaches. Once again, this is where Johns Hopkins comes in.

We are entering a revolution in electronics. We must develop nanotechnologies and bioelectronic systems, which I will discuss later on, that reduce mass and power requirements on all of our missions by orders of magnitude. Lower-mass electronics and power systems will enable us to carry less spacecraft fuel and thus avoid the cost penalty of larger and larger launch vehicles while also enabling shorter trip times.

Lastly, we must build smart active and passive sensing systems that will allow us to observe planetary surfaces from orbit and land safely on hazardous locations on such places as Mars and Europa. The scientifically most interesting places are often the most dangerous. We must have the ability to land where the exploration and science goals drive us, not where it is safe.

THE EARTH SYSTEM

As we seek to explore the solar system in specially designed cocoons to keep humans safe, and as we scan the farthest reaches of space in the hope of finding Earth-like planets around other stars, one fact comes sharply into focus: Earth is the only accessible planet capable of sustaining the human race that we know of for certain. It will remain home for all but a few of us for a long time to come.

Yet the stresses we place on our home planet are enormous. In the past 15 years, scientists have been speaking in terms of global change and worrying about the regional impacts of those changes. Population growth and a quest for improved quality of life continue to exert tremendous pressure on the availability of Earth's precious natural resources for our generation and future ones. In just the span of my lifetime, the Earth's human population has tripled, and it is projected to double again in the lifetime of my grandchildren.

As we see signs of stress in the chemistry of the atmosphere and changes in land cover, polar regions, and the health of ocean fisheries, there is an increasing demand for information and knowledge of the consequences for life on Earth. We need to understand the forces of nature and be able to separate them from the forces induced by our own human species. It's the year 2000, and we still cannot do that. The space community has got to deliver.

We are the first generation with the ability to observe global-scale changes from the perspective of space and the scientific knowledge to link them with their causes and consequences. This ability to record and understand global change will be among the greatest gifts that we can offer our children and their children after them, for it will put in their hands the power to make informed decisions about the environmental challenges of the future.

So how is the Earth changing? What promise does our present progress hold for the future of Earth science from space?

The Earth functions as a system—a large, complex, and dynamic one, but a system nonetheless. It is affected in measurable ways by external forces such as the Sun and its variability, and by the internal forces that are shaped by variations in the atmosphere, oceans, continents, life, and the complex web of interactions among them.

Earth's responses to these changes may also serve as forcing functions themselves through complex feedback loops. Perhaps the best example is the cycling of water and energy through the Earth system, where changes in remote corners of our oceans manifest themselves in the form of floods and droughts thousands of miles away, with tremendous impacts on food and fiber production and other industrial and societal activities. Because the Earth is a system, we have to follow a path of characterizing, understanding, and ultimately predicting these changes and their impacts on society.

Working with our international partners, NASA is deploying the Earth Observing System to characterize the key Earth system interactions among land, oceans, atmosphere, ice, and life. Over 20 EOS and related satellites will be launched between 1999 and 2003. The success of this effort will enable us to better understand the causes and consequences of change in the Earth system.

How well can we *predict* future changes? Today we can make 3- to 5-day weather forecasts with nearly 80% accuracy. That's fantastic. In 10 year's time, with all we can learn from our upcoming missions, we intend to push that out to 7 to 10 days with the same accuracy. With the right investments in observations and computational modeling, we might even push that out to 14 days perhaps 20 years from now.

While we're working the shorter-term weather problems, we will be using the same tools for 6- to 12-month regional rainfall predictions for agriculture and pushing the world's El Niño forecasting capability out 15 to 20 months. In Brazil, before we could forecast El Niño, the farmers had a 20% crop return in some areas. When we were able to forecast El Niño, it went to 80%. It really makes a difference.

The quest for a true predictive capability for Earth system changes requires a flexible and progressive space system architecture. That's why we need to design and establish a smart, autonomous, and flexible constellation of Earth observing satellites that can be reconfigured based on the contemporary science and specific issues at hand.

Such a constellation of exceptionally small, ultra-efficient spacecraft would exploit a combination of active and passive sensors. It would also exploit new vantage points, such as solar libration points L-1 and L-2, stationary orbits over the poles, and highly elliptical orbits. This will provide us with holistic views of Earth from pole to pole, minute by minute. These Earth observing systems will use lightweight telescopes, solar sails, inflatable or deployable antennas, and advanced electronic and information technologies to achieve unprecedented remote sensing of Earth with radiometric, spatial, and temporal characteristics.

The knowledge we gain if this system of satellites is successfully deployed should enable us to build a series of conceptual Earth system models that can properly mimic the behavior of the Earth system and its variables. Once we are convinced of the consistency in performance of these models to reconstruct the Earth's changes in the past, we can use them with confidence to predict future changes.

ADVANCED TECHNOLOGIES

That's a brief look at where we are going. As you can see, we have achieved some amazing things, but we do not yet have the advanced technologies we need to attain all of our goals. And we believe that Johns Hopkins will play an essential role in helping us get there. But the best and the brightest people across the nation are at work already on those technologies. In the labs of our nation's world-class universities, and especially in our medical schools, the mysteries of biology and biological processes are being uncovered and understood to cure disease. The science and technology that is at the core of all living things is more complex and at least as powerful as any science and technology we have yet studied.

It is my deep conviction that advances in biology will bring about the technology revolution of the 21st century, akin to the impact of Newton's laws on gravity in the 1600s, Maxwell's laws of electromagnetism in the 1800s, and Einstein's laws of relativity in the 1900s. It is time to put biology on an equal footing with physics and chemistry as the underpinning of advanced technology.

Let me be more specific. NASA's current challenge is to develop space systems that can accomplish our missions significantly more effectively and economically. To do this, those systems will have to be much more capable than today's spacecraft. The major characteristics these systems must have are

- Autonomy to think for themselves
- Self-reliance to identify, diagnose, and correct internal problems and failures
- Self-repair to overcome damage
- Self-assembly and evolvability to adapt to and explore new and unknown environments
- Extreme efficiency to operate with very limited resources and without input from Mission Control

These are typically characteristics of biological systems, but they will also be the characteristics of future space systems.

Coupled with biology in addressing the challenges of future missions is nanotechnology—technology at the atomic and molecular scale. Nanotechnology will enable us to take the notion of "small but powerful" to its extreme limits.

For example, nanotechnology might allow us to develop and use carbon nanotubes—tiny cylinders of carbon atoms a billionth of a meter across—to build structures 100 times stronger than steel at one-sixth its weight. And the implications for nanotechnology are immense. A single-stage reusable launch system constructed of carbon nanotube filaments might be 80% lighter than the aluminum launch systems we use today.

Nanotechnology could also allow us to develop intelligent, multifunctional material systems consisting of a number of layers, each used for a different purpose. The outer layer would be selected to be tough and durable to withstand the harsh space environment, with an embedded network of sensors, electrical carriers, and actuators to measure temperature, pressure, and radiation and trigger a response whenever needed.

The network would be intelligent. It would automatically reconfigure itself to bypass damaged components and compensate for any loss of capability.

The next layer could be an electrostrictive or piezoelectric membrane that works like muscle tissue with a network of nerves to stimulate the appropriate strands and provide power to them. The base layer might be made of actual biomolecular material that would sense penetrations and tears and could then flow into any gaps. It would trigger a reaction in the damaged layers and initiate a self-healing process.

When we look to biotechnology and nanotechnology for inspiration, we will also be able to develop the information systems we need for the future. For example, the information contained in a DNA molecule is a billion times more dense and energy efficient than anything we can build out of silicon. And the model of the ultimate thinking computer is the brain. Think about it this way: A computer capable of a trillion operations per second built the way we fabricate microelectronics today consumes on the order of hundreds of kilowatts of electricity and does simple, sequential numeric processing.

Although the analogy is difficult to construct, the human brain is probably capable of as much as a million more operations per second by using its inherent massively parallel connectivity and by seamlessly integrating multisensory information and stored knowledge. And the brain does all this while consuming only watts of power. We simply do not know how to create a similar computational engine within the limitations of silicon chips. Biology is the answer.

Ultimately, biology will provide many of the paradigms and processes for designing and building the revolutionary new computational and vehicle systems we need. Consider the characteristics of biological systems we need for our future space systems:

- Selectivity and sensitivity at a scale of a few atoms
- The ability of single units to massively reproduce with near-zero error rates
- Hierarchical organizational capability to self-assemble into highly complex systems
- The ability to communicate among themselves
- The ability to build systems, literally atom by atom, with zero errors

By mimicking biology, using hybrid biological concepts, and combining them with nanotechnology, we will be able to create both the brains and the body of future systems with the characteristics we need. Together, nanotechnology, biotechnology, and information technology form a powerful and intimate scientific and technological triad that will enable the advanced aerospace systems of the future. Just imagine some of the possibilities.

- Vehicles with nervous systems that tell us their health and performance
- Vehicles that are not just computing, but thinking and responding to their environments
- Multifunctional structures with imbedded sensors and actuators to respond to their environment, such as deforming for minimal drag and altering optical properties for optimal thermal control
- Intelligent engines that predict the onset of internal failures before they affect safety and reliability
- Autonomous landing systems that automatically avoid hazards and find safe landing spots
- The use of principles of biology to find biology away from Earth, through detection of molecular signatures like metabolic products or through direct DNA detection
- Intelligent vehicles that could operate autonomously in the most extreme conditions in space, such as searching for life kilometers below the surface of Mars or searching for liquid water dozens of kilometers below the surface of Europa's ice cap

When the universities of America work together, the revolutionary technologies we develop will open up the space frontier and revolutionize the economies of many nations. Beyond this, the same information technology that will allow us to achieve bold new goals in space will help us to ensure the safety of our people, whether on the ground or in the depths of space.

We will develop intelligent systems with high-assurance software that is either free of errors or completely tolerant of errors in order to improve the reliability of our missions. While our systems are becoming intelligent and more capable, we must use this same technology to make our astronauts safer and more capable. The same advanced technologies that will enable us to send intelligent systems into space will also help us to train the next generation of space pioneers. We will let the astronauts gain experience in fully immersive, multisensory environments that provide a truly realistic learning experience—without the consequences of the real thing.

And we will not stop there. These tools will enable lifelong learning to occur throughout the workplace. We will be able to bring the professor to the shop floor and take the working engineer to a university so lifelike that geographic reality will become irrelevant. Such a learning environment will also allow us to easily convey the knowledge and experience of mentors anywhere at any time to younger and less experienced people. And it will allow the best and the brightest from around the world to work together as if they were in the same room.

CONCLUSION

What an amazing set of possibilities lie before us! A tsunami is coming. *Everything* is going to change—how we function, do our jobs, interact, maintain our health. And you can be sure that Einstein was right in one regard: the future will be here soon enough.

The big questions, though, are: Will we be ready for it? Will we have the technology we need to reach the goals and dreams that we have? Of course we will, but only if we think about the future we want, dream about it, and plan for it. Only when NASA can rely on the immense talents of our partners in academia, world-class partners like the Applied Physics Laboratory. Because it is only when we work together, allowing our strengths to complement each other, that we will develop revolutionary new technologies and usher in the space program of the 21st century.

I can't wait to see where our partnership will take us in the coming decades. Thank you very much. Now let's get to work!