NASA's Cosmic Journeys Missions: A Quest for the Nature of Gravity

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Abstract—Cosmic Journeys is a new series of NASA space science missions housed within the Structure and Evolution of the Universe science theme. The central goal of the Cosmic Journeys missions is to solve the mystery of gravity, a fundamental force that is all around us but about which very little is known. Cosmic Journeys will use the power of resolution far greater than what current telescopes can muster to virtually transport us to regions in space and time where gravity is most compelling: at the rim of a black hole, across galaxy clusters and voids that pervade the Universe, and at the moment after the Big Bang when the four fundamental forces may have been intertwined.

Cosmic Journeys will have a fleet of orbiting observatories at its command capturing the full range of the electromagnetic spectrum. The NASA Journeys program is also forging a partnership with the National Science Foundation (NSF) and the Department of Energy (DOE), called "Connections: From Quarks to the Cosmos," with hopes of bringing together physicists, astronomers and other professionals who have traditionally worked independently. Together, the three agencies will fund a variety of ground- and space-based research.

Table of Contents

1. INTRODUCTION
2. DISCUSSION
3. CONCLUSION
4. REFERENCES

1. INTRODUCTION

The central goal of the Cosmic Journeys missions is to solve the mystery of gravity. Gravity affects all that is seen and much of what remains unseen, such as the mysterious dark matter that comprises perhaps as much as 90 percent of the mass of the Universe. This force can never be completely removed from an environment, unlike sound or light waves. Even in the "zero gravity" of space, there is still the force of gravity that cannot be avoided or screened. We clearly understand what gravity does, but we do not fundamentally know how it does it. Yet it is this force that holds the answers to the most basic questions of our humanity -- the whys, hows, and whens of the Universe and all the matter and energy contained within.

Albert Einstein described gravity in his Theory of General Relativity by stating that mass distorts space and time to produce the force of gravity. He also predicted that gravity propagates in waves, just like light. These would be ripples in the fabric of space that move at the speed of light. Gravity may be associated with a particle, called the graviton. If so, gravity may be similar to the other fundamental forces of nature.

Gravity, however, doesn't fit into the Standard Model, which describes the behavior of light and subatomic particles. We instead have two theories to describe the Universe: General Relativity and Quantum Physics. General Relativity accounts for gravity, the force that acts across large scales. Quantum Physics, part of the Standard Model, describes the behavior of the other three

fundamental forces: electromagnetism, weak forces (seen in radioactive decay), and strong forces (holding subatomic particles together). These forces act over small scales.

Today, we may be very close to merging these concepts of Quantum Physics and General Relativity into the "Theory of Everything," a unified theory that predicts the behavior of all matter and energy in all situations. Such a theory would be a triumph for science, likely leading to spectacular technological advancements that we cannot even begin to imagine. Gravity is the secret ingredient in this unified theory. We must move beyond the Standard Model to reach our goal.

Moving beyond the Standard Model requires us to investigate the connection between General Relativity and Quantum Physics. Do these two theories meet in the earliest moments after the Big Bang, when the size of the newly formed, ultra-hot Universe was confined to quantum (very small) scales possibly described by quantum gravity? The answer may lie at 10^{-44} second after the Big Bang, when the Universe visible to us today was only 10^{-33} cm wide and when gravity -- confined within what physicists call the Planck scale -- played a role equal to the other forces. Also, is General Relativity the ultimate theory of gravity in the Universe? Do black holes, predicted by General Relativity, truly exist? Or are these black holes that fill the Universe some different type of phenomenon? These environments exist for us to visit today in the vicinity of black holes, where gravity is king; in the extreme early Universe, where space was perhaps hot and dense enough to unite gravity with the other three fundamental forces; and on a universal scale, where the gravity of dark matter shapes galaxies and clusters of galaxies into walls and voids. The Cosmic Journeys missions aim to take us to these regions. Tables 1, 2 and 3 contain a brief description of key missions.

Table 1. Approved Cosmic Journeys Missions

MAP, the Microwave Anisotropy Probe, will produce an accurate full-sky map of the cosmic microwave background with high sensitivity and angular resolution. Launch planned for spring 2001.

Swift is a mid-size satellite mission that will detect gamma-ray bursts and "swiftly" (within a minute) point its UV/optical and X-ray telescopes at the bursts, while at the same time relay the information to other telescopes so that they too can observe the bursts. Launch planned for 2003.

GLAST, the Gamma-ray Large Area Space Telescope, will measure the most energetic form of light in the Universe, called gamma rays. One of GLAST's many targets will be black hole jets. Launch planned for 2004.

FIRST, the Far InfraRed and Submillimetre Telescope, is a cornerstone mission of the European Space Agency (ESA) that will probe a poorly studied region of the electromagnetic band. Launch planned for 2007, with Planck.

Planck, named after Max Planck, is another ESA mission and will probe the cosmic microwave background with even greater accuracy than MAP. Launch planned for 2007, with FIRST.

Table 2. Cosmic Journeys Missions Under Formulation

ACCESS, the Advanced Cosmic-ray Composition Experiment for the Space Station, is a cosmic ray detector for the International Space Station to help us understand the origin, variety, distribution and life span of elementary particles in our galaxy. Launch planned for 2006.

Constellation-X is an X-ray spectroscopy mission with four separate telescopes working in unison that will investigate black holes, Einstein's Theory of General Relativity, galaxy formation, the evolution of the Universe on the largest scales, the recycling of matter and energy, and the nature of dark matter. Launch planned for 2008.

LISA, the Laser Interferometer Space Antenna, will observe gravitational waves from very massive black holes found in the centers of many galaxies. The LISA mission will consist of three spacecraft forming an equilateral triangle with a distance of five million kilometers between any two spacecraft. Launch planned for 2008.

Table 3. Cosmic Journeys, Proposed Mission Concepts

HSI, the High-resolution Spectroscopy Mission, will study the highest-energy X-rays with unprecedented sensitivity, addressing fundamental questions on the origin of heavy elements and black holes.

MAXIM Pathfinder, part of the Micro Arcsecond X-ray Imaging Mission program, will test visionary technology as well as carry out important scientific objectives. The Pathfinder will be about 10,000 times more sensitive than Chandra, and will bring us ever closer to the disks and jets associated with black holes.

MAXIM, the Micro Arcsecond X-ray Imaging Mission, will image a black hole, a primary goal of NASA's Office of Space Science and Cosmic Journeys. MAXIM's unsurpassed resolution -- equivalent to resolving a feature the size of a dinner plate on the surface of the Sun -- will yield untold discoveries and tremendously improve our understanding of a multitude of cosmic sources.

EXIST, the Energetic X-ray Imaging Survey Telescope, will collect the highest energy X-ray photons from sources such as neutron stars, galactic black holes, dust-enshrouded supermassive black holes and regions of nucleosynthesis -- a complement to HSI that will sit on the International Space Station.

ARISE, the Advanced Radio Interferometry between Space and Earth, comprises one (or possibly two) 25-meter radio telescopes in highly elliptical Earth orbit in conjunction with a large number of radio telescopes on the ground. ARSIE will have the resolution needed to zoom in on the base of a black hole jet to see how matter is fed into a black hole and how these jets of particles form.

CMBPOL, the Cosmic Microwave Background Polarization Experiment, is a follow-up to the MAP and Planck missions. This mission will test inflation theory and discriminate between competing models for how the earliest galaxies and supermassive black holes formed.

OWL, Orbiting Wide-angle Light-collectors, will detect the highest energy cosmic rays, a long-standing mystery.

event horizon, it is lost forever. The light we see, therefore, has escaped that final plunge.

A direct image of a black hole will be of fundamental importance to Physics. Yet imaging a black hole requires a million times improvement over the Chandra X-ray Observatory. That's a big step. Over the next 20 years, the Cosmic Journeys missions will take us closer and closer to a black hole through the power of resolution. Each successive mission will further us in our journey by 10- or 100-fold increases in resolution, step by step as we approach our goal of zooming in a million times closer. And each stop along the way will bring us new understandings of the nature of matter and energy.

GLAST is a gamma-ray observatory mission that will observe jets of particles that shoot away in opposite regions from a supermassive black hole at near the speed of light. We do not fully understand how a black hole, which is known for pulling matter *in*, can generate high-speed jets that stretch *out* for billions of miles. GLAST, up to 50 times more sensitive than previous gamma-ray observatories, will stare down the barrel of these jets to unlock the mechanism of how the enigmatic jets form.

The Constellation-X mission will probe the inner disk of matter swirling into a black hole, using spectroscopy to journey 1,000 times closer to a black hole than any other mission before it. With such resolution, Constellation-X will be able to measure the mass and spin of black holes, two key properties. This X-ray mission will also map the distortions of space-time predicted by Einstein. Constellation-X draws its superior resolution by pooling the resources of four X-ray satellites orbiting in unison into one massive X-ray telescope.

The ARISE mission will produce radio-wave images from the base of supermassive black hole jets with resolution 100,000 times sharper than Hubble. Such unprecedented resolution can reveal how black holes are fed and how jets are created. ARISE will attain this resolution through interferometry -- one large radio telescope in space with many other radio telescopes on Earth, bringing what is now a land-based technology to new heights.

The MAXIM mission, a million times more powerful than Chandra, will capture a direct image of a black hole. MAXIM will be another interferometry mission; its microarcsecond resolution could see features on distant stars as clearly as we see our Sun today.

LISA will probe the Universe through the detection of gravitational waves. Gravitational waves can pierce through regions of space that light cannot shine through, for matter does not absorb these waves. As such, LISA can detect black hole activity buried within the dust and gas that other types of telescopes cannot see. With gravitational waves unimpeded by even the foggiest

2. DISCUSSION

2.1 Part 1 -- Journey to a black hole:

Nowhere is gravity greater than in the region around black holes. Their intense gravitational fields pull in surrounding matter, perhaps from a nearby star or from interstellar gas floating freely. This transfer of gas spiraling toward the black hole, called accretion, is amazingly bright in many wavelengths of light. Once light crosses the boundary of a black hole, called the

patches of the Universe, LISA will detect far more binary black holes than any satellite that will come before it.

2.2 Part 2 -- Journey through dark matter:

Over 90 percent of the matter in the Universe is in a form we cannot see with any type of telescope. This so-called "dark matter" might be composed of exotic particles that do not readily interact with our detectors on Earth. It may be invisible matter that is all around us everyday. The nature of dark matter is one of astronomy's greatest mysteries.

All matter exerts gravity; dark matter is no exception. The gravitational influence of ubiquitous dark matter is responsible for the very shape of the Universe. This is particularly evident over large scales. There is not enough visible mass in clusters of galaxies to hold all the contents together. There must be the additional mass of abundant dark matter forming the glue. Cosmic Journeys will search for dark matter by following the gravity trail.

Two Cosmic Journeys missions, MAP and Planck, will probe the microwave background with even greater resolution than COBE. NASA's COBE mission searched for and found density fluctuations in the early Universe. The Universe started as a dense, ultra-hot bundle of subatomic particles. Slight density fluctuations gave way to the large-scale structure we see today. As the Universe expanded -- cooling and heating once again -- dark matter collapsed under the force of gravity. Ordinary matter followed this dark matter. Denser regions of dark matter attracted greater amounts of ordinary matter. MAP and Planck will place greater constraints on density fluctuations, determine the shape of the Universe, and establish the ratio of ordinary matter to dark matter.

Constellation-X will search for the missing baryons (ordinary matter) trapped in the channels of dark matter that connect galaxy clusters. Large amounts of baryonic matter formed in the Big Bang and are seen in the early, distant Universe in the spectra of light from quasars as it passes through clouds of hydrogen, known as the Lyman alpha forest. This matter seems to have disappeared in recent times because, over billions of years, the hydrogen heated -- and hot hydrogen is harder to see. Constellation-X will have the sensitivity to see absorption lines from oxygen and other elements heavier than hydrogen. These elements, which constitute perhaps only 1 percent of the missing baryons, tell us how much hydrogen is out there. With absorption lines from the Lyman alpha forest and emission lines from Constellation-X's X-ray surveys, we will have an unbiased way of finding dark matter potentials over a wide range of redshifts and masses.

Other Cosmic Journeys missions will search for the effects of gravitational lensing, or the bending of light, produced by dark matter. The distortion of light by dark matter, as opposed to galaxies or black holes alone, is

subtle. To observers, the light from distant spherical objects is pulled by gravity into elliptical shapes, an effect known as cosmic shear. By analyzing the cosmic shear produced in thousands of galaxies, we can determine the distribution of dark matter over large regions of the sky -- a powerful tool to test the foundations of cosmology.

The GLAST mission will search for dark matter by observing the gamma rays produced in the interactions of certain exotic particles -- matter yet to be observed in nature but predicted by scientists. WIMPs, weakly interacting massive particles, may be major contributors to dark matter. WIMPs may have formed in the early Universe and may now reside in dark matter halos that surround galaxies. GLAST will be sensitive enough to detect the gamma rays produced when two certain types of WIMPs collide.

Dark matter may be "cold" and "hot". An example of cold dark matter would be WIMPs and axions. An example of hot dark matter is the neutrino, a particle similar to an electron but with zero charge and very little mass. Neutrinos have been detected, namely by the Super-Kamiokande neutrino detector in Japan. The types of dark matter and their amounts are key factors in determining the structure of the Universe as well as its fate -- whether it will collapse or expand forever. The evidence available to us today points to a universe with more cold dark matter than hot dark matter. Thus, we see a clumpy universe, but one that distributes its clumpiness. The collapse of dark matter created this structure, with galaxies and hot gas trapped like flies in a spider's web.

2.3 Part 3 -- Journey to the beginning of time:

What happened in the first second after the Big Bang is as important as the billions of years that have followed. During this time, temperatures were so hot that matter and radiation as we see them today could not exist. What did exist, perhaps, were the many theorized particles that physicists hunt for today. Also, such high temperatures may have allowed gravity to merge with the other three forces.

Physicists have used giant, earthbound particle accelerators to reproduce an environment similar to when the Universe was a ten-billionth of a second old, a period called the electro-weak era when electromagnetism and weak forces became distinguishable. Using space as a laboratory, Cosmic Journeys hopes to see the inflation era, the Grand Unified Theory (GUT) era, and the speculative superstring era -- all occurring in the first fraction of a second after the Big Bang and all crucial to our understanding of physics beyond the Standard Model. During the inflation era, a 10^{-32} second after the Big Bang, the Universe grew trillions of trillions of times larger in a mere thousandth of a second. In the GUT era, when the Universe was only a 10^{-35} second old, the strong force was united with the electro-weak and quantum gravity may have existed. In the superstring era at 10^{-44} second, all forces may have been indistinguishable.

The MAP and Planck missions will detect the cosmic microwave background, radiation produced when the Universe was only 300,000 years old, before all other forms of light. Slight temperature differences in this microwave radiation reflect density difference from when the Universe was less than a 10^{-25} second old. This places us at the end of the inflation era. MAP and Planck will, in fact, provide the first solid test of the inflation theory.

The CMBPOL mission will also observe the cosmic microwave background, but it will search for the polarization of the microwave radiation, not temperature. This mission depends on MAP and Planck's confirmation of inflation theory predictions: a flat Universe with primordial perturbations. Inflation would produce gravitational waves, which could be detected via the unique polarization pattern they inscribe upon the cosmic microwave background. With CMBPOL, we journey to the beginning of the inflation era, at 10^{-32} second, closer yet to the secrets held in the GUT era.

A mission to follow after LISA will directly detect gravitational radiation from this period of inflation. The mission involves two independent gravitational wave antennae tuned to a wave period one second long, where the Universe is quiet in all other forms of gravitational radiation. These gravitational waves, relics from the Big Bang, fill the Universe now, only they are too subtle to detect with our current technology.

The OWL mission may also probe the inflation era with its detection of rare, high-energy cosmic rays. These cosmic rays are subatomic particles moving so fast that they possess more energy than scientists thought was possible. The cosmic rays had to be produced in the local Universe, for any known particle farther than 150 million light-years would have lost energy on the long journey to Earth by colliding with cosmic microwave background radiation. Some scientists believe that the highest-energy cosmic rays come from the annihilation of topological defects formed during the inflation era.

2.4 Part 4 -- Cosmic Connections:

NASA's Cosmic Journeys is forging partnerships with NSF and DOE, called "Connections: From Quarks to the Cosmos." The NSF and DOE conduct major research projects involving particle accelerators and underground particle detectors; ground-based observations of ultra-high energy cosmic rays, high-energy gamma rays, dark matter and dark energy; large-scale sky surveys in microwave, radio and optical wavelengths; spaced-based observations of cosmic rays and gamma rays; and theory and computer simulation work.

The NSF and DOE supports the Super-Kamiokande neutrino detector, a 50,000-ton tank of ultra-pure water buried nearly one kilometer underground in Japan. The agencies will also construct WIMP and axion detectors. Axions, theoretical exotic particles, may burst into

detectable microwaves when they encounter very strong magnetic fields. DOE-supported particle accelerators are used to produce dark matter particles, discover new forces, and understand the basis of why we see more matter than antimatter in the Universe. Cosmic Journeys will benefit from this ground-based research.

3. CONCLUSION

The Cosmic Journey missions are inspired by gravity. Each Cosmic Journeys mission will transport us closer to a black hole, closer to the invisible gases the percolate between stars and galaxies, closer to the very beginning of time. These phenomena, dictated by gravity, hold secrets about the birth of the Universe, its fate, and all the swirling and glowing that goes on in between. We are on the verge of major breakthroughs based on connecting particle physics, gravity and cosmology. As with previous advances in fundamental physics, this new program may yield Nobel Prize discoveries and perhaps even more dramatic Cosmic Journeys.

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