BEYOND EINSTEIN:
from the Big Bang to Black Holes

SEU Roadmap Team

August 5, 2002

Introduction

0.1 Introduction

The Structure and Evolution of the Universe (SEU) theme within NASA's Office of Space Science encompasses almost all of astronomy and astrophysics. As the science community has made clear through workshops, roadmaps, and studies, there are many high priority science objectives within the theme, and many of them can be accomplished within the next 25 years. This SEU Roadmap draws upon this community input and incorporates the recommendations of the community and of the National Academy of Sciences. This roadmap identifies NASA's science objectives for the SEU theme for the next 25 years.

This roadmap also recognizes that, within the resources available, not all of these science objectives can be realized immediately. Constructing a roadmap entails making choices.

The science objectives described in the *Beyond Einstein* program (Part I) are the highest priority science objectives for SEU at this time, and a roadmap is presented for realizing these objectives with the understanding that this program should be undertaken now.

The science objectives described in the Cycles of Matter and Energy program are also presented (Part II), as these are also high priority science objectives for SEU. The beginning of the roadmap for realizing these science objectives is presented with the understanding that this program will be undertaken after the Beyond Einstein program has begun.

Part III describes the SEU activities which are vital to maintaining the technical base to implement these missions and develop future ones: the Research and Analysis program, the Explorer program, and critical factors.

0.2 BEYOND EINSTEIN: From the Big Bang to Black Holes

How did the Universe begin? Does time have a beginning and an end? Does space have edges?

Einstein's theory of relativity made three startling predictions about these questions: that the Universe is expanding from a Big Bang, that Black Holes so distort space and time that time stops at their edges, and that a Dark Energy might be pulling space apart. Observations confirm these startling predictions, the last only 3 years ago. Yet Einstein's legacy is incomplete, for his theory fails to explain the very places it led us:

1. What powered the Big Bang?
2. What happens to space, time and matter at the edge of a Black Hole?
3. What is the mysterious Dark Energy pulling the universe apart?

The *Beyond Einstein* program aims to answer these questions, using a series of missions linked by new technologies and complimentary approaches to shared science goals.

1. "Einstein Great Observatories": Facility-class Missions

    - Constellation-X: Uses X-ray-emitting atoms as clocks to follow the fate of matter falling into black holes.
    - LISA: Uses gravitational waves to measure the dynamic activity of space and time around black holes.

    These missions will also pioneer technologies and approaches needed for the Vision Missions.

2. "Einstein Probes": Fully competed, moderate-sized, PI-class missions launched every three years

    - Dark Energy Probe: Determine the properties of the Dark Energy that dominates the Universe.
    - Inflation Probe: Detect the imprints left by gravitational waves at the beginning of the Big Bang.
    - Black Hole Probe: Take a census of Black Holes of all sizes in the local Universe.

    These will answer sharply focussed critical questions. Competition ensures flexibility, and keeps costs low: by competing methods and technologies for readiness, and reordering the missions to reflect that readiness.

3. Vision Missions (after 2015) A technology program to enable two missions reaching to the farthest reaches of space and time:

    - A Big Bang Observatory to directly detect gravitational waves echoing from the earliest moments of the Big Bang.

- A Black Hole Imager to make direct images of matter near the edge of a black hole.

The public has demonstrated enthusiasm for the science objectives of Beyond Einstein. Beyond Einstein includes an education component that is aligned with science education standards and science literacy benchmarks.

Contents

Part I: Beyond Einstein

Chapter 1

Beyond Einstein: Executive Summary

1.1 Executive Summary: Beyond Einstein Science

How did the universe begin? Does time have a beginning and an end? Does space have edges? The questions are clear, and deceptively simple. They are as old as human curiosity. But the answers have always seemed beyond the reach of scientific observation. Until now.

In their attempts to understand how space, time, and matter are connected, Einstein and his successors in the 20th century made three predictions about space and time. First, space is expanding from a big bang; second, space and time can tie themselves into contorted knots called "black holes" where time actually comes to a halt; third, space itself contains a strange new form of dark energy that is pulling the universe apart. Each of these three predictions seemed so fantastic when they were made that no one, including Einstein, thought they could possibly be true. Incredibly, each of these predictions has been shown to be true: in the last 40 years, the big bang; in the last 20 years, black holes; and in the last 3 years, dark energy. Yet Einstein's legacy to us is one of deep mystery, because Einstein's theory fails to explain the very places to which his work led us: 1) What powered the Big Bang? 2) What happens to space, time and matter at the edge of a Black Hole? 3) What is the mysterious Dark Energy pulling the universe apart? Einstein is silent on all of these.

Modern theories, such as the inflationary universe and string theory, go beyond the work of Einstein. Like Einstein's theory, they make fantastic predictions that seem hard to believe. Predictions of new unseen dimensions and entire universes beyond our own are beyond even Einstein's vision of the universe. We must find facts to confront and guide these new theories.

Here is where the Beyond Einstein story starts. By exploring the three deep mysteries of space and time that are Einstein's legacy, we begin the next revolution in understanding our universe.

We chart our way forward using clues from recent observations and from new ideas connecting the world of the very small and the very large.

1.1.1 What powered the Big Bang?

During the last decade, sky maps of the radiation relic of the Big Bang —first by NASA's Cosmic Background Explorer (COBE) satellite, and more recently by other experiments including Antarctic balloon flights and NASA's MAP spacecraft now collecting data— have given us a direct view of wrinkles imprinted on the universe by fundamental particles at the first moments of the big bang. The wrinkles COBE discovered include distinct contributions from two kinds of primordial particles– the inflaton particles of the energy field that drove the Big Bang, and the gravitons that are fundamental particles of space and time themselves. A new level of technology for measuring polarization will allow a sharper separation of these different contributions, and allow us to piece together the story of how time, space, and energy worked together to create the Big Bang.

1.1.2 What happens to space, time and matter at the edge of a black hole?

The greatest extremes of gravity in the universe today are the black holes formed at the centers of galaxies and by the collapse of stars. Today, their properties are beginning to be deduced from close study of matter swirling into them. New data from X-ray satellites such as NASA's Chandra X-ray Observatory and ESA's XMM-Newton show spectral signs of matter whizzing about black holes at close to the speed of light, displaying the slowing of time as it approaches and plunges into the event horizon, beyond which there is no escape. The missions in our roadmap will perform a census of black holes throughout the universe, and give increasingly detailed pictures of these roiling vortices. They will also listen for the sounds of spacetime carried by a new form of energy, predicted by Einstein but not yet directly detected, called gravitational waves. We will hear the booming, hissing, and humming of colliding and merging black holes and other extreme flows of matter throughout the universe, detailing the conversion of matter and energy into warpage of space and time.

> "The black holes of nature are the most perfect macroscopic objects there are in the universe: the only elements in their construction are our concepts of space and time." —Subrahmanyan Chandrasekhar [Nobel prize, 1983]

1.1.3 What is the mysterious dark energy pulling the universe apart?

"Dark energy" is the name recently adopted by physicists for the energy carried by the emptiest possible space– the vacuum devoid of all forms of matter and radiation. Einstein conjectured that the universe might be permeated by this stuff (that he called a "Cosmological Constant"), but later rejected his own idea, saying "I am unable to believe that such an ugly thing should be realized in nature."

> Possible Sidebar or box. Phinney has obtained permission from Hebrew University & Einstein Papers Project for us to quote from a Sept 26, 1947 letter from Einstein to Lemaître "I found it very ugly indeed that the field law of gravitation should be composed of two logically independent terms which are connected by addition. About the justification of such feelings concerning logical simplicity it is difficult to argue. I cannot help to feel it strongly and I am unable to believe that such an ugly thing should be realized in nature." [acknowledgement should read "permission granted by the Albert Einstein Archives, the Hebrew University of Jerusalem, as well as by the Einstein Papers Project."] For more details on Einstein and Lemaître and a possible image, see `http://www.its.caltech.edu/~esp/esp/EinsteinLem.pdf`

Through recent measurements of its effect on the expansion of the universe, astronomers have discovered that some form of dark energy does indeed appear to dominate the total mass-energy content of the Universe, and that its weird repulsive gravity is pulling the universe apart. A mission in our roadmap will study the expansion closely enough to determine details about the form of this energy, for example whether it is simply a constant property of empty space (as Einstein conjectured) or whether it shows signs of a richer structure now thought to be possible in string theory.

1.1.4 Einstein's Vision

Einstein sought— but never achieved— an understanding of how nature works at its deepest level. We now seek the next level of understanding through a concrete program of missions we can conceive and design today, and carry to completion over the next decade. In the far future we may extend these ventures, in the "vision missons" of this roadmap, even closer to the edges of space and time. We aim to create detailed images of matter right down to the very brink of the event horizons of black holes, and to detect the gravitational quanta from inflation— the smallest detectable "particles of time", left over from the beginning of time— directly. Our vision, following that of Einstein, is to establish a program that will use NASA's technology to reveal the uttermost extremities of existence.

1.2 Executive Summary: Beyond Einstein Missions

Two facility-class missions, Constellation-X and LISA, together with a line of PI-class moderate-sized probes, and a forward-looking program of technology and theory development lead towards our farthest imaginable vision: to directly detect those gravitational waves [which are the primordial particles of time/from the beginning of time] and to directly image matter near the edge of a black hole.

1.2.1 Einstein Great Observatories

The Constellation-X mission will consist of four 1.6m X-ray telescopes orbiting the earth/sun system at L2, providing nearly 100 times the collecting area of previous instruments. They will be instrumented with detectors covering a range of more than a factor of 100 in X-ray energy, with unprecedented energy resolution.

Constellation-X will address the question "What happens to matter at the edge of a black hole". Gas near a black hole moves at nearly light speed, and when gas streams collide, they become so hot that their atoms emit X-rays. The atomic vibrations, which we see as the frequency of the X-ray light, act as clocks that we can use to trace the motions of the gas and the distortions of space and time near the hole. The great sensitivity of Constellation-X will allow us to track these rapidly moving, changing gas streams by making "movies" of the gas spectra at a high frame rate. Current instruments are not sensitive enough to detect the X-rays in the short exposures needed to freeze the motion around the black hole. Constellation-X will enable us to make movies, and replay them in slow-motion to understand what is happening to the matter.

The Laser Interferometer Space Antenna (LISA) will consist of three spacecraft orbiting the sun, separated from each other by 5 million kilometers. Each spacecraft contains freely falling 'proof masses' protected within the spacecraft from all forces except for gravity. The relative motion of the masses is measured, to sub-nanometer precision, by combining laser beams shining between the spacecraft. As passing gravitational waves ripple space and time, they will reveal their presence by changing the relative velocities of the proof masses.

LISA will answer the question "What happens to space and time at the edge of a black hole?", by directly listening to the sounds of vibrating spacetime: the booming roar of supermassive black holes merging, the chorus of death cries from stars on close orbits around holes, the ripping noise of zipping singularities, and possibly even whispers from the time in the early universe when our our three-dimensional space formed within the true unseen space of six or seven dimensions that still surrounds us. LISA will make precision measurements of the orbits of stars around holes and determine whether Einstein's predictions apply to these extreme environments. Together, LISA and Constellation-X will help us to understand where the giant black holes in the centers of galaxies came from, and how they grew.

1.2.2 Einstein Probes

Besides these facility-class missions, a series of smaller scale missions PI-class missions will enable NASA to respond to exciting new science more quickly than the decade timescales of National Academy reviews. [??? The questions listed below are the most exciting *now*, but the list will doubtless evolve with time as knowledge of this rapidly changing frontier advances.] [??? For example, dark energy was not discovered in time to make it into the A&A decadal survey, although it was rightly ranked very highly in the CPU report]. For these missions, the science question to be addressed will be defined, but the scientific approach and technology will be determined by peer review.

The question "How did the universe begin" is in many physicists' minds answered by "inflation": a period when the universe expanded so rapidly that parts of it began to separate from other parts faster than the speed of light. This expansion is believed by many to have been driven by a quantum-mechanical energy of the vacuum similar to the dark energy today. But the evidence for all of this is circumstantial at best. One way to find out if this is really true is to look for relics of this quantum mechanical activity in the form of fluctuations. Gravitational waves are the most direct relics since they penetrate the heat and density of those early days. It is technically feasible to look for the quantum effect of gravitational waves ("gravitons") nearly as big as the universe, and distinguish them from the quantum effects of the primordial energy ("inflatons"), by examing their distinctive effects on the polarization of the cosmic microwave background. An "Inflation Probe" with this capability would help to define the nature of the vacuum which drove inflation.

"What is the mysterious energy pulling the universe apart" is a question that would not have been asked five years ago: there was then no evidence that the universe was being pulled apart. Now there is, and it is provoking a crisis in physics. To understand the nature of this energy, we need to understand if and how it changes with time, which in turn requires measuring the expansion of the universe with high precision both now and at much earlier times. We must find and exploit suitably precise cosmic yardsticks for this purpose. Several ideas for space missions have been proposed—for example, precision measurement of distant supernovae by a wide-field space telescope. The best of these methods will be competitively chosen for a "Dark Energy Probe."

"How did black holes form and grow?" Most astronomers believe that the black holes in the centers of galaxies grew by swallowing stars and gas from their galactic hosts, in the process emitting light. Yet today there is an accounting problem: the light which we see from the black holes in active galaxies does not seem to explain the growth of the black holes which we find at the centers of nearby galaxies. There are hints that much of the growth occurred in dark galaxies enshrouded in dust. To see into these dark corners, we must look using the most penetrating of X-rays. The "Black Hole Finder Probe" will perform a census of the black holes hiding their growth. Combining this census with the studies of accretion by Constellation-X and of black hole merging by LISA will tell us how the giant black holes formed and grew in galaxies.

1.2.3 Vision Missions

Technology development in support of these projects, including tools of hardware, software and astrophysical theory, will also lead the way forward to two visions in the decades ahead:

To fully decode the beginning of time, a "Big Bang Observatory" will *directly* measure graviton quanta coherently amplified from inflation and still present in the universe today, with periods of order 1 second. Unlike the frozen images of vastly longer waves affecting the microwave background, these will be observed still in their original form, vibrating as gravitational waves. To do this, all the astrophysical sources of waves since the Big Bang in this frequency band will have to be decoded as well.

Constellation-X will tell us how fast gas moves around a black hole, and LISA will give us the tune to which stars dance around a black hole. But to really be sure that we understand the motions in the complicated space-time, there can be no substitute for a direct picture of things moving around the black hole. A "Black Hole Imager" based on X-ray interferometry could bring us such a direct view.

Boxes on E/PO opportunities [box 1: people love BH; box 2: people like cosmology], evidence of public interest, etc.

Picture: What is GR, how do we know it is right? GP-B, solar system tests (including Beyond Einstein ones -explorer class). Beyond Einstein goes further: nonlinear gravity, cosmic censorship, quantum, dark energy. LIGO. Flow chart: which missions answer which RFAs, how do answers combine to make big picture, what holes are left?

1.2.4 Research Focus Areas

Research Focus Areas for Beyond Einstein Program

these are all that go up to Space Science Strategic Plan.

1. Perform a census of black holes throughout the universe. [Con-X, LISA, Black Hole Probe, Big Bang Observatory]
2. Determine how black holes are formed, and how they evolve. [Con-X, LISA, Black Hole Probe, Big Bang Observatory]
3. Observe stars and gas plunging into black holes to map the spacetime near the event horizon. [Con-X, LISA, Black Hole Imager, Big Bang Observatory]
4. Determine the size, shape, age and energy content of the universe.
5. Search for gravitational waves from inflation and phase transitions in the very early universe. [Inflation Probe, LISA, Big Bang Observatory]
6. Determine the cosmic evolution of the dark energy pulling the universe apart. [Dark Energy Probe, Big Bang Observatory]

Chapter 2

Beyond Einstein: Scientific Goals and Missions

2.1 Beyond Einstein: The Science

Hogan

About a century ago, Albert Einstein began creating his theory of relativity— the ideas we use to understand space, time and gravity— and took some of the first steps towards the theory of quantum mechanics, the ideas we use to understand matter and energy. Einstein was named the "Person of the Century" because his ideas transformed civilization, but his work is not finished: spacetime is not yet reconciled with the quantum.

Einstein's theory of General Relativity made unbelievable predictions about the extremities of existence, all of which are now confirmed: that the whole universe began in a hot, dense big bang from which all of space expanded; that dense matter and energy could tie spacetime into tangled knots, called black holes; that "empty" space might contain energy with repulsive gravity. These phenomena represent the most extreme configurations of the world, and the most exaggerated interactions of spacetime with matter and energy. They are the places to look for clues to the next fundamental revolution in understanding— Beyond Einstein.

[could have a box here about Einstein's methodology of thinking about extreme situations, such as trying to travel at the speed of light]

2.1.1 The Beginning of Time

The universe is expanding, and abundant evidence now shows that it has expanded from a very hot, dense, rapidly expanding early state— the Big Bang. Einstein's Theory of General Relativity explains how the expanding universe works, but on its own it does not explain what made the Big Bang happen in the first place. For many years it was thought that perhaps time and expanding space simply began abruptly.

"Inflationary cosmology" is one set of simple ideas proposed to explain what made the Big Bang big and how it started expanding. The interactions of a new postulated field, called the inflaton, lead to repulsive gravity, a force that drives the original expansion of the universe by making everything fly apart from everything else.

In the same way that black holes can make big things small, inflation makes small things big, so the universe acts like a giant microscope. This allows us to study details of the extreme early universe directly. We may be able to obtain direct images of the beginning of time, and figure out how it worked.

Quantum effects lead to a subtle but direct imprint of inflation on the present day universe. The inflaton field was not perfectly smooth, but contained imperfections or "fluctuations". The subatomic inflaton that created the universe, like all energy fields of nature, was a quantum field. All such fields fluctuate even in "empty" space— the physical vacuum is a roiling sea of such fluctuating fields. The primordial inflaton fluctuations led to imperfections in the cosmic expansion— the big bang got a slightly bigger kick in some locations than in others. The effect of a single inflaton quantum was enormously inflated, in the same way that the universe itself was, so a single inflaton quantum left its influence on an astronomically vast tract of space.

These fluctuations are very important. For one thing, they are the reason that the universe eventually broke up into galaxies, stars and planets. The inflaton fluctuations froze into the fabric of space, and converted to overdense and underdense regions of matter. The overdense regions eventually collapsed due to gravity. Without these perturbations, the universe would still be perfectly smooth today. Every galaxy we see, even whole clusters of galaxies, ultimately derives from about one elementary inflaton particle in the early universe.

The most persuasive data backing up this story are the sky maps of the primordial radiation. This cosmic background of light appears almost but not perfectly uniform in all directions, with a blackbody temperature of 2.725 degrees above absolute zero. The gravitational effect of the inflaton perturbations, in addition to creating structures like galaxies, also creates patterns on the sky of very slightly hot and cold spots. They are very subtle— temperature differences of less than a part in ten thousand— but the pattern preserves considerable primordial information and so far, at the present level of experimental precision, agrees very well with what theory predicts.

In addition to the inflaton perturbations, quanta of another field are created during inflation: those of gravity itself, called gravitons. These may also leave imprints on spacetime (and background anisotropy) today, in the form of large scale gravitational waves. They are direct imprints of single quanta— single "particles of spacetime"— that fluctuated during the inflationary period. By observing fluctuations in great detail, we aim to learn more about the inflaton and graviton quanta.

The "Inflation Probe" will use the best available technology to decode the information in the primordial pattern painted on the sky. One specific proposal is to study polarization in the anisotropic radiation. Certain patterns of polarization can only be created by the gravitons (not inflatons) so polarization experiments have the potential to disentangle the two contributions. The detection of single graviton quanta, a plausible outcome of this program, would correspond to detecting the primordial particles of time itself.

2.1.2 Edges of Spacetime and Black Hole Horizons

Gravity is the one universal force connecting all forms of mass and energy. Einstein saw that this universal character arises because it is a behavior of space and time itself. At the same time, gravity, and therefore space and time, also are themselves forms of energy. While we are used to thinking of the large things of the world, like planets and stars, being made of (many) small things, like atoms, very strong gravity creates exceptional circumstances where the opposite is true. Because gravity can squeeze anything to almost zero size, it can also make small things out of big things. This process, and its time reverse in the early universe, really happens in nature.

Gravity appears in its purest form— on its own, so to speak— in dense knots of curved spacetime called black holes (as well as in vibrations of spacetime called gravitational radiation,discussed below). A black hole has mass and spin but no matter— it is made of pure gravitational energy. Its structure is entirely determined by Einstein's theory of gravity, so although we have not yet seen one in any detail we have a good mathematical idea of what it is like. At the heart of a black hole is a singularity, a point or a ring where the spacetime curvature is infinite and energy is infinitely concentrated. Surrounding the singularity is a region of no escape, where time and space have reversed roles and anything must inevitably fall into the singularity. The edge of this region, called the event horizon, is the boundary of space outside of which escape is possible. Time is highly warped. An observer falling in with a watch will look outside and see everything appear to be happening quickly, yet if we observe the watch falling into a black hole, we see it appear to slow down. If it crosses the event horizon at high noon local time, we observing from far away see the watch gradually fade from view, slowing down forever as the hands creep towards but never reach noon.

Gravity leads to transformation of energy— that is why things fall down— and the extreme gravity around black holes leads to extreme transformations of many kinds. Matter falls in and accelerates to great speed; when it runs into other matter, it heats up and radiates light. The energy available from a given amount of mass far exceeds even nuclear energy; a car powered with a black hole engine would get a billion miles to the gallon. Energy not radiated falls into the hole, adding to its mass and spin– thereby converting into purely gravitational form. The spin of the hole can give matter nearby a kick, and with the aid of magnetic fields can even accelerate it into powerful jets of outflowing particles.

We can get a detailed view of the warped spacetime near black holes by observing radiation from atoms of gas as they fall in. The frequency of the light we see traces both the orbital motion of the gas— the familiar "Doppler effect" known to ambulance chasers— and to the gravitational redshift due to spacetime curvature. Watching the the spectra of these flows as they change in time should inform us of many details of the matter and its spacetime environment.

Beyond Einstein missions launch a coherent program to study this X-ray emission: Black Hole Finder will survey the universe seeking the X-ray signature of matter falling into holes, presenting us with the locations of black holes; Constellation X will study the spectra of atoms in the dynamic infalling flows; in the distant future, Black Hole Observatory will create actual moving images of the swirling matter right down to the edge of the event horizon.

2.1.3 Cosmic Cacophony: Gravitational Waves

In addition to studing black holes by watching the matter falling in, we can also study them by listening directly to the "sounds" created by their dynamic spacetime. The sounds of black holes are emitted as a new form of energy predicted by Einstein, the tiny vibrations in spacetime called gravitational radiation.

Since ancient times, astronomers have used the same form of energy to study the universe that our animal eyes use to see the world. Called simply "light", it includes X-rays and radio waves and all the colors of the rainbow in between. Light is made of vibrations of electric and magnetic fields travelling through space.

Einstein predicted that energy can also be carried by vibrations of spacetime itself. Indeed, the most powerful outflows of energy of any kind come when two black holes orbit, collide, and merge, radiating not light but gravitational radiation. During a brief interval of final merging (up to an hour or so for very large holes) just one of these mergers radiates a gravitational power of about 10^{52} watts, a million times more power than all the light from all the stars in all the galaxies in the visible universe put together. We guess (and right now this is only a guess) that on average black holes create an amount of gravitational radiation in the universe comparable to all the light. Black holes colliding and merging may also briefly expose the singularity to observation, rendering it "naked" rather than clothed by the event horizon— creating, quite literally, a ripping sound caused by the tearing of an edge of time.

In Einstein's theory of gravity, space and time are not fixed, static entities, but are floppy, dynamical things, responding to the mass and motions of matter and energy. Space and time are also active on their own— they can sustain waves that travel at the speed of light and themselves carry energy. In the same way that black holes are made just of space and time— pure gravitational energy holding itself together with gravity— gravitational waves are a kind of energy also "made of" just space and time, but which cannot stand still. They interact very weakly with matter, and penetrate any astronomical body with almost no attenuation.

Gravitational waves are of great interest both for fundamental physics and for astronomy. Detecting them will give Einstein's theory of space and time a workout like it has never had before. We know that it works pretty well in normal circumstances— without "spacetime curvature technology" in their software, airplanes using GPS navigation would be missing their runways by miles— but gravitational radiation will go far beyond this and let us listen carefully to the most violent events in the universe, the collision and mergers of black holes. What goes on there is a swirling mass of spacetime interacting mostly with itself. The sounds of the universe will tell us enough details about what is really going on in black holes to see in detail if Einstein's theory of space and time was right. They will also let us listen to an inventory of what is going on in the universe in an entirely new way. There are even places way out there, especially the very early universe, that are literally impossible to observe with ordinary light; only the exceptionally penetrating gravitational radiation can bring us information about some kinds of possibly very violent events, such as the formation of our three dimensional space from an original space with more dimensions.

Gravitational waves can be detected using a system sensitive to exquisitely small jiggles between masses that are floating freely in space, isolated from all forces other than gravity. The distances between the masses can be monitored using laser interferometry. An early generation of such systems has now been deployed on the ground— the LIGO observatories in the US, and other similar systems worldwide. It is hoped that these systems will make the first detection of gravitational waves sometime in the next five or ten years, probably from the final few minutes of a merger of a pair of black holes in a distant galaxy, at frequencies of 100 to 1000 Hz. The LISA Observatory, sensitive to much lower frequency waves, will upon deployment almost certainly hear a strong signal— a blended cacophony of many kinds of astrophysical sources.

The most powerful sources of gravitational waves are quickly-changing systems with very strong gravity, so LISA's strongest signals will probably be tones from a few very loud binary massive black holes. But it could be that the first waves detected in space are a noisy blend of sounds from more numerous and less exotic sources, binaries with two white dwarf stars orbiting each other. LISA will be able to pick out the sounds of a few nearby binary sources which are already known and named by astronomers, who have studied their starlight.

The Big Bang Observatory vision merges the study of inflation with that of gravitational waves. For waves with periods of about 1 second, a system might be built able to hear and pick out all the strong sources of gravitational waves in the universe, so that the strongest remaining sound is the quantum noise from the inflationary universe. These new areas of science are of course changing so rapidly that both the vision and the means to achieve it will be rapidly changing over the coming years, but there will undeniably be rich new sources of information about the behavior of space and time throughout the audible universe.

2.1.4 Dark Energy and the Accelerating Universe

Einstein's Theory of General Relativity, still our deepest theory of spacetime and its interaction with matter and energy, is nevertheless silent on one of the simplest of questions: Is empty space really empty? Einstein introduced a "cosmological constant"— a symbol, Λ, with an unknown value— into his equations, to represent the possibility (if Λ is not zero) that even empty space has energy and couples to gravity. The value of Λ in the real universe derives from another, deeper level of physics beyond Einstein's theory.

The newly discovered fact that the expansion of the universe appears to be accelerating suggests the presence of a new force, now dubbed dark energy, that drives space apart. It seems likely that we have now at least measured the value of Λ or something like it. However, unlike inflation, gravitational radiation or black holes, we have no theory of dark energy. The simplest estimate of the amount of dark energy is wrong by a famous factor of 10^{120}. For this very reason, dark energy is the most exciting new development in fundamental physics. When we understand the physics of the dark energy, we will probably also understand the physics that controls the future of the universe, so we will be able to answer another simple question: will the universe last forever?

Although dark energy was discovered only in 1998, it is already widely acknowledged as a firmly established phenomenon because of a number of completely independent pieces of evidence. The first indication was the discovery of an ongoing increase in the expansion rate of the universe, as directly revealed by the supernova Hubble diagram. However, a broad concordance of other evidence concerning global geometry, structure formation, cosmic age, and galaxy clustering leave little doubt that in some crude sense, Einstein's conjectural "cosmological constant" is a reality: the energy of the universe is dominated by empty space, and its gravity is repulsive.

To learn how dark energy really works, we need to measure its properties in more detail. The gravitational effects of this energy are too weak to study in the laboratory, and must be sought in space where the effects of the dark energy accumulate enough, due to the enormous volume, to be noticed. The next step in deciphering the character of dark energy is to measure its density and pressure and how they change with time. These are sometimes encapsulated into the equation of state parameter w, the ratio of density to pressure. (The pressure is important because it is the large negative pressure that causes repulsive gravity.) Einstein assumed that $w = -1$ because it is the simplest case; but other theoretical ideas, with various different assumptions about ultrafundamental physics, make different predictions. The Dark Energy Probe will deploy the best available technology to study this effect.

We know at least one way to study w in detail: to improve upon the supernova technique. The very small number of objects observed from space with the Hubble Space Telescope give us enough data to know that with a dedicated, special-purpose instrument in space, it would be possible to measure the bulk properties of the dark matter with good accuracy— certainly enough to distinguish whether the energy is really constant, as Einstein conjectured, or whether it has undergone significant dynamcal changes over cosmic time, as conjectured by some string theorists. Real data on this question would help us discover where dark energy comes from, and where the universe in the far future is going.

Many past, present and future NASA missions have laid the groundwork for the *Beyond Einstein* program, and will complement it. NASA's *COBE* satellite discovered the first evidence for primordial density fluctuations in the microwave background. NASA's balloon program (e.g. *BOOMERanG, MAXIMA*) has led to the discovery of the interaction of those fluctuations with matter in the universe, allowing us to determine that the universe is flat, and that only a small fraction of the matter in the universe is the familiar matter known to mankind. NASA's *MAP* satellite, and the ESA/NASA *Planck* satellite will extend these discoveries, and make measurements of components of polarization of the microwave background, vital precursors to the proposed Inflation Probe. *Hubble Space Telescope* has helped to find and measure the distant supernovae which have forced us to accept the Dark Energy that Einstein introduced, but so disliked. The X-ray missions *Chandra*, *XMM* and *RXTE* have discovered X-ray emissions from matter spiralling near black holes, giving hints of the potential of Constellation-X. *Gravity Probe B* will test one of Einstein's exotic predictions: that the rotation of the earth drags space and time around the earth into a mild version of the tremendous vortical spin Einstein's theory predicts near a spinning black hole. *GLAST* will study the high-energy emissions from particles accelerated into jets (astronomers believe) by the tremendous electric fields which in Einstein's theory can develop near accreting spinning black holes. *Astro-E2* will demonstrate in flight the detector technology of Constellation-X, while *ST-7* will do the same for LISA.

2.2 Beyond Einstein: The Program

White

The "Beyond Einstein" program contains three interlinked elements. Together they address the science challenges outlined in the previous sections, and provide coupled technology and science advances towards the long term visions of directly detecting the gravitational radiation emitted from the earliest moments of the big bang and obtaining sufficient angular resolution to resolve the event horizon of a black hole. The first element in this integrated program is the pair of facility-class Einstein Great Observatories, Constellation-X and LISA. These missions will investigate the origin and evolution of black holes and key questions about the structure and evolution of the universe. The second element is a series of PI-class Einstein Probes that are designed to rapidly address focused and topical science issues, e.g. the nature of dark energy, that can have a direct bearing (technology and/or science) on the implementation approach or feasibility of implementing a pair of vision missions. The third element is a technology program to enable a future decision on whether to proceed with these vision missions: the Big Bang and Black Hole Observatories. Each element is dependent on the other either in terms of addressing science questions or developing a progressively more advanced technological capability. The program also maximizes competitive opportunities for mission leadership, instrument development, technology research and participation in observation programs.

National Priorities The Beyond Einstein program represents NASA's response to the recommendations by the three most recent National Academy of Sciences reports: The Committee on the Physics of the Universe (the 2002 Turner report), the National Academy of Sciences decadal survey of Astronomy and Astrophysics (the 2000 McKee-Taylor report), and the National Academy of Sciences decadal survey of Physics (the 2001 "Physics in a New Era" report, and the 1999 "Gravitational Physics: Exploring the Structure of Space and Time"). LISA was the highest priority new mission after GLAST in the medium mission category of the McKee-Taylor report, and was endorsed by the Turner report. Constellation-X was the highest priority new mission after NGST in the McKee-Taylor report in the large mission category, and was endorsed by the Turner report. Possible implementations of the black hole finder probe (EXIST) and the Black Hole Imager (iARISE) were also endorsed as priority missions in the McKee-Taylor report. The Einstein Probes to determine the nature of dark energy and measure the signature of inflation in the microwave background were high priorities in the Turner report. The physics reports did not identify missions by name, but endorsed the science of all the Beyond Einstein missions.

Interagency Connections Astronomical discoveries are driving the frontiers of fundamental physics, and progress in fundamental physics is driving progress in understanding the universe and its contents. Realizing the scientific opportunities of Beyond Einstein cut across the disciplines of physics and astronomy as well as the boundaries of DOE, NASA, and NSF. The unique capabilities of all three agencies as well as cooperation and coordination between the three will be essential to address the science questions. The National Academy of Sciences Committee on the Physics of the Universe (CPU) was convened in recognition of these connections. The report and recommendations of this committee provided a key input in developing the Beyond EInstein roadmap. It is expected that inter-agency partnerships will form a key component in many of the Cosmic Probes.

International Connections Substantial international participation is a key feature of Beyond Einstein. The LISA mission is a collaborative equal venture between NASA and ESA, with the ESA participation fully approved. There is substantial international interest in the Constellation-X mission that will be realized when the instruments are competed. Like-wise international participation is expected to be developed when the Einstein Probes are competed.

2.2.1 The Einstein Great Observatories

Constellation-X and LISA are facility-class missions that will use the complimentary techniques of X-ray spectroscopy and gravitational waves to study black holes. They will investigate the extreme environment found in the vicinity of black holes and track their evolution with cosmic time. They both, in different ways, represent major steps forward that will open up major new opportunities for discovery across a very broad spectrum of both astronomy and physics research. These two missions will be a major resource used by the entire astronomy and physics communities. Both have been identified as high priorities in the National Academy of Science (NAS) Astronomy and Astrophysics Survey Committee (AASC) as new astronomical facilities for this decade (see box).

Constellation-X increases the capability for high resolution X-ray spectroscopy by 25 to 100 times over the Chandra X-ray observatory with a key goal to observe in detail spectral features emitted close to the event horizon of a black hole, and obtain detailed spectra of the faint quasars at high redshift detected by Chandra. The mission is optimized for this challenge, but also provides the ability to observe other objects with unprecedented sensitivity such as the formation of the first clusters of galaxies or supernovae in nearby galaxies.

LISA will provide the first capability to observe long wavelength gravitational waves. Opening up this new window on the universe will allow observations of the merger of black holes, anywhere in the universe. By opening up this new window on the universe, LISA will also detect the gravitational radiation from binaries in our galaxy, and set important limits on any background radiation from the early universe.

Competition The Einstein probes will be fully competed missions. The competition will cover not only the groups selected to lead each mission, but also the scientific and technological approach to the science question identified in this roadmap. This competed approach will ensure the most cost effective, science-driven approach to the missions.

2.2.2 The Einstein Probes

The Einstein Probe missions are PI-class mission opportunities designed to address in a timely fashion critical science topics and mysteries identified as part of this strategic planning process. These topics are too narrowly focused for a facility class mission. The science areas are also too specific to be consistent with the broader mandate of the Explorer missions. Also the estimated cost of a Einstein Probe mission is a factor of two to three larger than possible within the Explorer program. We envision that some Einstein Probes will include substantial contributions from other agencies (national and inter-national). The goal is to launch one every 3 years, starting in 2010.

The first three Einstein Probe missions identified will

1. Determine the nature of the dark energy that dominates the universe.
2. Search for the signature of gravitational radiation from the big bang in the polarization of the comic microwave background
3. Survey the Universe for black holes.

The exciting new science challenge of dark energy only emerged recently, after the AASC had completed the bulk of its work, and this Einstein Probes line is ideal to rapidly respond to this new development. The search for polarization of the Cosmic Microwave Background caused by the imprint of gravitational radiation from the period of inflation is a critical step to constrain the amplitude and frequency distribution of this radiation, which is essential before embarking on a much more expensive mission to directly detect the radiation. This topic is also identified as an important area for the future by the AASC report. Surveying black holes will be important to find targets for the black hole imager and also to provide a monitor for transient events that can be follow up with Constellation-X and LISA. The importance of a mission to address this topic is given by its identification in the AASC report (the EXIST mission).

2.2.3 Advanced Technology and Theory

The advanced technology program will develop the capabilities required for the Black Hole and Big bang Observatories. The technologies required for these two ambitious missions are not available today and requires a focused technology program so as to be able to make a future decision to proceed with either or both of these missions. The black hole imaging mission requires major advances in X-ray imaging, to achieve a 10 million times gain over that achieved with Chandra. The most promising technique to achieve this is X-ray interferometry, a capability that was specifically called out in the AASC report as a priority for investment this decade. The advanced gravitational wave detection mission to directly detect the big bang will probably require the capability to "null out" other sources of background to achieve sensitivities several orders of magnitude below the levels achieved by LISA.

The successes of COBE and MAP, and indeed all of the background anisotropy experiments, owe considerable debt, in all stages from initial planning to final reduction and interpretation, to theoretical studies. All of the complex programs of our roadmap require a similar highly integrated approach that includes theoretical modeling at all levels from astrophysical sources down to instrument response, and cannot rely on the traditionally modest support allocated by NASA and NSF to a relatively small community of astrophysical theorists. As recommended by the Decadal Survey, theory should be viewed as part of the forward-looking advanced technology needed for program success. Early, explicit and stable support for theory will lay the conceptual foundations of projects, develop mission-critical analysis and modeling software, foster the growth of teams and centers, provide training for a larger community, and help provide leadership in educational outreach.

2.2.4 An Integrated Program

The three elements of the "Beyond Einstein" program are critically interlinked. The vision missions will carry direct measurements to the absolute extremities of our universe— to the edge of what is physically possible. The Constellation-X and LISA missions are realizable within the next decade and address pressing near term science questions. The answers to these questions are critical to prove the basic feasibility of the missions to follow and will critically influence their design. They also build the foundations for the basic technologies required for the more ambitious missions. The Einstein Probes address focused science questions that also feed into the decision process whether or not to proceed with the more ambitious missions. The overall program is knitted together by research groups in theory and technology.

Constellation-X will determine the geometry of the emission region close to a black hole, parameterize in detail the line features that have been resolved close to the event horizon, and determine if there is obscuring material These observations are essential step to both prove the feasibility of getting a clear view of X-ray emission from close to the event horizon and also to optimize the parameters for a black hole imaging mission (energy, bandpass, and angular resolution). The technology developed for Constellation-X is an extension of current technologies, and will contribute towards developing light weight X-ray optics and large format detectors needed for the Black Hole Observatory.

LISA will pioneer gravitational radiation detection in space and will make the first direct detection of waves in the frequency range $0.1 - 0.0001$ Hz. The mission will quantify the backgrounds such as binaries in our galaxy, and set limits on possible strong backgrounds from the early universe, from catastrophic events such as dimensional compactification or brane formation. The constraints placed by LISA, combined with those from the measurements of polarization of the microwave background by gravitational radiation, will determine the frequency range and sensitivity requirements for the Big Bang Observatory.

2.3 Beyond Einstein: The Missions

2.3.1 Constellation X

White

Constellation-X will provide up to a one hundred-fold increase in sensitivity for high resolution X-ray spectroscopy to address many fundamental astrophysics issues including determining the evolution of super massive black holes and probing strong gravity in their vicinity. The Constellation-X design achieves its high throughput and reduces mission risk by dividing the collecting area across four separate spacecraft launched two at a time into an L2 orbit.

Optical astronomy transitioned into astrophysics more than a half-century ago when it became routinely possible to obtain high resolution spectra. Velocities of hundreds of kilometers per second, ubiquitous in many types of astronomical objects in the Universe, then became measurable, and key multiplets of common nuclei could be resolved to yield quantitative plasma diagnostics. The X-ray band contains the K-shell lines for all of the abundant metals (carbon through zinc), as well as many of the L-shell lines. The detailed X-ray line spectra are rich in diagnostics that provide unambiguous constraints on physical conditions (temperature, density, velocity, and abundance). As X-ray astronomy approaches its half-century anniversary, however, imaging capabilities have far outrun spectroscopy. Constellation-X is the x-ray astronomy equivalent of large ground-based optical telescopes such as the Keck and the VLT, complementing the high spatial resolution capabilities of Chandra. Constellation-X will provide a 25-100 fold increase in sensitivity over the high resolution spectroscopy capabilities of current missions such as Chandra, XMM, and ASTRO-E2. This will result in a fabulous harvest, making X-ray spectroscopy of faint X-ray sources routine and enable the use X-ray spectroscopy to probe close to the even horizon of black holes.

The major science objectives of Constellation-X include:

- Observations of broadened iron emission lines in Active Galactic Nuclei to determine black hole masses and spins. The iron K emission line can be used as the equivalent of a precise clock to map out space and time in the vicinity of the event horizon. Constellation-X will study this spectral feature with extremely high sensitivity and, in particular, its time variability in detail. Line variability signatures can be understood within the framework of General Relativity (GR), and can be used to infer the fundamental parameters of the black hole (mass and spin).

- Investigate energy release processes close to the black hole event horizon. Using the iron K line (and possibly other lower energy spectral lines) the emissivity of the inner accretion disk can be mapped out and used to test models for energy release in accretion disks. Processes more exotic than accretion are also believed to be important in at least some galactic nuclei. A spinning black hole may interact with surrounding magnetized gas - and the result can be the extraction of black hole rotational energy. These processes may be the power source for relativistic jets seen in many galactic nuclei, or may deposit large amounts of power into the inner region of the accretion disk. X-ray spectroscopic observations with XMM-Newton are already suggesting the reality of spin-energy extraction, which Constellation-X will be able to map in much more detail.

- Trace the evolution of super massive black holes in quasars and active galaxies. Constellation-X will use the many black holes being found by Chandra at high redshift to trace black hole evolution with cosmic time. The X-ray band above a few keV is relatively immune to obscuration and thus allows a clear view of AGN properties at high redshift. Optical samples suggest that AGN activity peaked at a redshift of 2-3, falling off before the peak of star forming activity (at z 1.5). X-ray selected quasars, which extend to redshifts as high as 4, show no evidence for a decline in the population towards higher red shift, e.g. Chandra has easily detected three QSOs at redshift 6 discovered in the Sloan DIgital Sky Survey. Constellation-X observations of the formation and evolution of black holes in the early universe will address the question as to their origin and relationship to the evolution of the host galaxies.

- Determine the total accretion energy released by AGN and their contribution to the energy output of the Universe. The energy output of AGN may be comparable to that of the stellar population, but mostly hidden behind obscuring gas and dust associated with starburst regions within 100pc of the AGN. If most of accretion in the Universe is highly obscured, then the amount of emitted power per unit galaxy based on optical or UV quasar luminosity functions may have been under estimated. The broad band pass of Constellation-X is optimized to study these obscured AGN. Constellation-X will also study the overall geometry of the accretion flow, as well as the relationship of the black hole properties to those of the host galaxy.

- Using X-ray plasma diagnostics the Constellation-X mission will address many other key science topics related to the ”cycles of matter and energy” in the universe. By looking across a broad range of redshifts, Constellation-X will reveal the formation epoch of clusters of galaxies and relate them to Cosmological models to constrain the nature of dark matter and dark energy. Present inventories indicate that many baryons predicted by Big Bang nucleosynthesis and subsequent stellar processing seem to be missing in the relatively nearby universe (Z ¡ 1), and Constellation-X will search for them-for example, in a hot metal-enriched intergalactic medium. Constellation-X will identify large numbers of X-ray spectral lines in stellar coronae, supernova remnants, and the interstellar medium providing essential information on chemical enrichment processes as well as detailed measures of plasma temperature, pressure, and density over a wide range of astrophysical settings.

The Constellation X-ray mission has been in formulation since 1996 with a focussed technology development program underway since then. Constellation-X was included as a near term priority in the 1997 OSS Strategic Plan as a candidate New Start for 2004 and is the only near term mission from that plan not yet in implementation. The priority of Constellation-X was reaffirmed again in the 2000 Strategic Plan for a New Start before 2007. The Constellation-X technology development effort is substantially ramping up from FY2002 through 2004 and is on track to support a new start in 2007, with launches in 2010 and 2011.

The Constellation-X design achieves its high throughput and reduces mission risk by dividing the collecting area across four separate spacecraft launched two at a time into an L2 orbit. This will facilitate high observing efficiency, provide an environment optimal for cryogenic cooling, and simplify the spacecraft design. The interval between the two launches will be of order 1 year. The mission lifetime with all four satellites on orbit will be exceed 4 years. Each spacecraft is designed to have a separate spacecraft bus and an instrument module containing the optics, optical bench and detector assemblies. This will allow for a standard off the shelf spacecraft bus and parallel production line development.

All of the Constellation-X technologies are an evolution of existing, flight proven instruments and telescopes. On each satellite a 1.6 m diameter spectroscopy X-ray telescope (SXT) covers the 0.25–10 keV band and a hard X-ray telescope (HXT) extends the energy band up to 60 keV. The combined collecting area of the four SXT telescopes is 3 sq m, a factor of $\sim$ 25 larger than Chandra. This larger aperture, combined with more efficient X-ray spectrometers results in an overall increase in sensitivity for high resolution spectroscopy of 25-100 (depending on the energy of interest). The SXT uses two complementary spectrometer systems to achieve the required energy resolution of 300–3000: an array of high efficiency quantum micro-calorimeters with energy resolution of $\sim$ 2eV, and a set of reflection gratings with a resolution of $\sim$ 0.05A in the first order. The gratings deflect part of the telescope beam away from the calorimeter array to a CCD array in a design similar to *XMM-Newton*, except that the Constellation-X direct beam falls on a high spectral resolution quantum calorimeter instead of on a CCD. The baseline field of view of the calorimeter is $2.5'$ square, with a minimum of 900 pixels spatial resolution. The SXT telescope point spread function is $15''$ half power diameter (HPD), with a goal of $5''$.

The Constellation-X hard X-ray telescope (HXT) baseline design has 3 telescopes per spacecraft. The HXT uses multi-layers to provide a focusing optics system that for the first time operates in the band above 10 keV band. The improvement in the signal to noise results in a factor of 100 or more increased sensitivity over non-focussing methods previously used in this band. The FOV is $8'$, or larger. The requirement for the HXT angular resolution is $1'$ HPD (with a goal of $30''$) There are no strong atomic lines expected above 10 keV, so there is a relatively modest HXT spectral resolution requirement of R >10 across the band.

Very substantial progress has been made in all key areas including lightweight X-ray mirrors, improved energy resolution and construction of larger arrays of X-ray microcalorimeters, multi-layer depositions for hard X-ray telescopes, CZT detectors for hard X-rays, and the overall multi-satellite approach to the mission. This mission approach will facilitate high observing efficiency, provide an environment optimal for cyrogenic cooling, and simplify the spacecraft design.

2.3.2 LISA: the Laser Interferometer Space Antenna

Phinney

The Laser Interferometer Space Antenna (LISA) will open a new window on the universe through the study of low frequency gravitational waves. LISA consists of three spacecraft orbiting the sun in a triangular configuration with a baseline of 5 million kilometers between spacecraft.

LISA will detect low frequency gravitational waves by measuring the changes in the relative velocity of two approximately freely-falling proof masses within each spacecraft. Sources of gravitational waves which LISA should detect include compact binaries in our own Galaxy, the merger of supermassive black holes in the cores of distant galaxies, and the inspiral of white dwarfs, neutron stars, and stellar-mass black holes into supermassive black holes. None of these can be detected by ground-based detectors, which are not sensitive to gravitational waves of periods longer than 0.03 seconds; by contrast LISA is sensitive to gravitational wave periods between 1 second and 10,000 seconds. LISA may also detect violent mass density flows in the early universe if their (much more uncertain) amplitude permits.

LISA science addresses fundamental issues in astrophysics, cosmology, and relativity.

- LISA will study the population of ultra-compact binaries in our Galaxy through the identification of thousands of individual compact white dwarf binaries. These include several already-known verification binaries having well-measured properties from optical/IR observations, which can be used to verify LISA's performance and calibration.

- LISA will detect compact stars spiraling into supermassive black holes in galactic nuclei. Such stars radiate gravitational waves at multiples of their characteristic orbital frequencies, which will slowly change as the radiation drag causes the orbit to sink ever closer to the black hole. The orbital trajectories precisely determine the full space-time geometry down to the horizon of the black hole, and will enable the first high-precision tests of General Relativity and the nature of black holes, including the famous "black holes have no hair" theorem. The desire for high precision meaurements of these relatively weak signals set the sensitivity goals for LISA.

- LISA will study the role of massive black holes (MBH) in galaxy evolution through the detection and characterization of mergers of massive black holes. LISA will be able to detect mergers of supermassive black holes in merging galaxies during an observation period lasting a year or more with total signal-to-noise ratio of over 1000 at redshifts of 1-5. This will allow precision observations of the information-rich, complex gravitational wave forms predicted by strong-field general relativity, and will severely test the predictions of general relativity. LISA will also detect or severely constrain the rate of mergers of intermediate mass BHs or seed BHs, out to z 30.

- LISA will search for gravitational wave emission from the early universe. Many models of the earliest instants of the universe predict the production of gravitational waves. Gravitational waves from the simplest models of inflation predict a level below the sensitivity of LISA, but other models could produce measurable amplitudes. Other processes believed to occur in the very early universe —for example phase transitions in the nature of the vacuum energy or dimensionality of the universe— can also produce gravitational waves detectable by LISA. These will probe energy and length scales that were characteristic of the universe 10^{-15}s after the big bang. LISA's ability to synthesise multiple types of interferometer with differing sensitivities to gravitational waves is crucial to its ability to discriminate these isotropic stochastic wave backgrounds from instrumental noise.

LISA has been developed and is envisaged as a joint mission of NASA and the European Space Agency. LISA is an approved European Cornerstone Mission, with a start in 2007 and launch planned for 2010 or 2011, consistent with NASA's plans. ESA has under construction a LISA technology validation mission (SMART-2) for launch in 2006. NASA is providing its own technology validation payload for launch on the ESA spacecraft through the ST7 project of the New Millenium program.

LISA consists of three spacecraft orbiting the sun in earth-trailing orbits. The chosen orbits keep the three spacecraft in triangular configuration with a baseline of 5 million kilometers between spacecraft. At the heart of each spacecraft are two free-flying test masses which act as the reference masses for the detection of gravitational waves. Each spacecraft also contains two 30-cm telescopes which direct the beams from two cavity-stabilised lasers toward the other two spacecraft of the triangular configuration. The laser light received from the two distant spacecraft is combined with the light from the local lasers on each spacecraft; changes in the 'beat note' between the local and distant laser light are caused by changes in the relative velocity of the spacecraft: the signal of gravitational waves. Combining the signals from all the pairs of spacecraft permits detection of both polarizations of gravitational waves and also synthesis of a combination insensitive to gravitational waves which will provide an independent measure of the instrument noise.

LISA will be most sensitive to gravitational waves of periods of 100-1000 seconds, and will be able to detect gravitational wave bursts with space-time strains as small as 6×10^{-21} (5σ all sky-average), corresponding to measuring 3×10^{-12}m (1σ) changes in the 5×10^{6}km separation between spacecraft over each wave period. In one year of observation LISA will detect gravitational waves from sources of $10^2 - 10^3$s periods producing space-time strains as small as 10^{-23} (5σ detection).

LISA will detect and study, simultaneously, a wide variety of different sources scattered over all directions on the sky. The key to distinguishing the different sources is the different time evolution of their waveforms. The key to determining each source's direction is the manner in which its waves' phase and amplitude are modulated by LISA's orbital motion around the Sun and its changes in orientation.

The spacecraft use sensitive position-measuring devices to monitor the position of the proof-masses within the spacecraft ("gravitational reference units"). MicroNewton thrusters will maintain drag-free control of the spacecraft about the proof masses. These two elements, viewed as the most critical to LISA's success, will be space-tested by ESA and NASA on the ESA SMART-2 mission, to be launched in 2006. Both ESA and NASA (through the ST-7 project of the New Millenium program) will provide independent gravitational reference units and microNewton thrusters for test on SMART-2.

LIGO, VIRGO and other ground-based laser-interferometer gravitational wave observatories are beginning operation. With technological advances during the next ten years, these detectors may become sensitive enough to detect gravitational waves directly for the first time. Although they run on general principles similar to LISA, there are important differences. Because they are on the ground, the proof masses are not freely falling, but are suspended on pendulums; because they must use an artificial vacuum (the world's largest), the arms are 4 km long, rather than LISA's 5 million km. As a result they are optimized to detect much higher frequency waves— 100 to 1000 Hz, rather than LISA's 0.1 to 10 mHz— and will therefore hear completely different sources. For example, LIGO will hear the final few minutes of radiation from merging black hole remnants of ordinary binary stars (about 10 times the mass of the sun). LISA will hear the final year's radiation from black holes (of masses ten to a million times the mass of the sun) captured by supermassive (millions of solar masses) black holes in the centers of galaxies.

2.3.3 Dark Energy Probe

Carroll

The nature of the mysterious dark energy which dominates our universe is one of the most important questions facing cosmology and fundamental physics today. Probing the dark energy amounts to measuring the evolution of the expansion rate of the universe over time. There are a number of different plausible strategies toward this goal, including using supernovae or other standard candles as a direct test of the distance/redshift relation; probing the evolution of linear growth of cosmological perturbations through observations of clusters and large-scale structure; or measurements of the number density of objects (whose evolution must be understood) in a given volume as a function of redshift. A common feature of these strategies is the need for an optical/infrared telescope with a wide field of view and large-scale detector arrays. A mission in space is crucial to obtain high-quality data at the large redshifts ($z \sim 0.5 - 2$) necessary to probe cosmological evolution.

The leading candidate for dark energy is the cosmological constant, or vacuum energy. It has long been appreciated that our naive estimates of what the vacuum energy density should be differ from experimental limits by 10^{120}, and a conclusive demonstration of a small but nonzero cosmological constant bears directly on the search for a quantum theory of gravity. Alternatively, more dramatic candidates for dark energy include dynamically evolving fields or even a breakdown of general relativity. Choosing between these alternatives requires new observational input. We therefore recommend a Dark Energy Probe to study the evolution of the dark energy; this information represents the most direct handle available on the fundamental character of the dominant component of the universe.

The Dark Energy Probe will be able to accomplish a number of measurements of great importance to cosmology:

- An accurate measurement of the amount of dark energy, currently believed to comprise approximately 70% of the density of the universe. Pinning down the precise value will both verify the existence of this mysterious component beyond a reasonable doubt, and contribute to a comprehensive view of the matter content and geometry of the universe.

- Greatly increase our sensitivity to time-variations in the dark energy density. If the dark energy is a true cosmological constant, the equation of state parameter $w = p/\rho$ (where p is the pressure and ρ the energy density) should be $w = -1$, and its derivative should be $w' = 0$. If these values are verified to high precision, we have discovered a nonzero vacuum energy, which is a priceless empirical clue in the quest to reconcile quantum mechanics with general relativity. If either $w \neq -1$ or $w' \neq 0$, we have discovered a new dynamical field (or a departure from Einstein's general relativity), opening the door to an entire phenomenology of dark energy.

One implementation of The Dark Energy probe involves a wide field optical/infrared space telescope with primary aperture ~ 2 m, and a field of view ~ 1 degree. The focal plane should consist of billion-pixel arrays of CCDs and near-infrared detectors (e.g. HgCdTe) collectively providing multicolor coverage over the range 0.4–1.7 microns. The sensitivity should be designed to allow source detection down to 29th magnitude at 1 micron, and spectroscopy and precision photometry down to 25th magnitude.

A mission of this type could search for large numbers of Type Ia supernovae in the redshift range 0.7–1.7, and provide follow-up spectroscopy and multicolor photometry for detected events. This could be accomplished by repeatedly scanning a limited region of sky ~ 10 sq. degree. Considerable technology investment would be necessary to develop reliable detector arrays of such large format. The Department of Energy has begun such development, and is an interested partner in such a mission.

2.3.4 Inflation Probe

The "Inflation Probe" will search for the imprint of gravitational waves produced during inflation on the Cosmic Microwave background (CMB) radiation. One promising approach to the mission would comprise a 2m cooled telescope located at L2 and equipped with large arrays of polarization-sensitive detectors operating between 50–500 GHz.

Thomson-scattering of the CMB just before the universe becomes neutral generates a polarization pattern that is related to quadrupole moments in the temperature pattern of the CMB. These moments are produced not only by the density fluctuations that are the seeds of present day large-scale structure, but also by the gravitons produced in the early universe. Temperature anisotropy measurements of the CMB, such as those made by COBE and MAP, are insufficient to distinguish the density and gravity wave components. Fortunately, these two sources of fluctuations generate different patterns of polarization on the sky, allowing them to be separated. However, the gravity wave component to CMB polarization is likely to be at least two orders of magnitude fainter than the dominant density component, which will be mapped to high sensitivity by the Planck Surveyor mission (to be launched in 2007).

- The Inflation Probe will search the CMB for the signature of gravity waves from the very first moments of the universe. These observations can be used to test inflation, and/or other theories of physics, in the very early universe. *Detection of the gravity-wave component to the polarization pattern will test physics at energies that are currently inaccessible by any other means.*

- The Inflation Probe will also detect other sources of CMB polarization, such as polarization induced by gravitational lensing, which can be used to map the integrated line-of-site distribution of matter from the present time back to a redshift of 1100, when the CMB was produced. The Inflation Probe will therefore also be sensitive to the distribution of dark matter from epochs where luminous matter does not yet exist.

To detect the gravity wave component will require all-sky maps of CMB polarization with sensitivity $\sim 1\mu$K per pixel, about 20-100 times better than Planck. This will require an equivalent improvement in the control of systematic effects. The sensitivities of the detectors that will fly on Planck are already close to fundamental quantum limits and so improvements in mapping sensitivity must come from large increases in the number of detectors, and cooling the telescope and other optics to reach the background limit of the CMB itself. The angular resolution of the maps must be a few arcminutes to allow the true gravity wave signal to be distinguished from secondary sources of polarized CMB signals, such as the lensing of the density component to CMB polarization. Consequently, the Inflation Probe will require at least a 2m class telescope, probably cooled, and equipped with focal plane arrays containing thousands of pixels. Each pixel must also be observed simultaneously from 50-800 GHz to allow astrophysical foregrounds to be subtracted from the polarization maps. The signals from inflation are likely to be mixed with confusing foregrounds and effects from gravitational lensing, so preparatory theoretical and observational work are essential to the success of this effort.

2.3.5 Black Hole Finder Probe

Kahn-Grindlay

The Black Hole Finder will perform the first all-sky imaging survey for black holes of all masses: from supermassive BHs in the nuclei of galaxies, to intermediate mass (∼100-1000 solar mass) holes likely produced by the very first stars, to stellar mass holes in our Galaxy. A wide-field telescope operating in the hard X-ray band is a promising approach since hard X-rays penetrate the veil of dust and gas which currently hide most black holes from our view.

Recent evidence has suggested that a large fraction of massive black holes in the centers of galaxies are obscured by surrounding gas and dust in the nuclear vicinity. Indeed the three closest supermassive BHs are in the nuclei of obscured and optically dull galaxies. The Black Hole Finder would make the first census of such massive black holes in the local universe and distinguish them from "starburst" nuclei (in comparably dusty environments) by the hard X-ray spectra and variability unique to a central black hole. Such a census is needed to determine if massive black holes are present in all galaxies and were grown by accretion during the epoch of galaxy formation, as suggested by the density of light emitted by active galactic nuclei throughout the universe.

The Black Hole Finder would enable a range of studies of black holes and the extremes of astrophysics:

- Black Hole Finder will measure the supermassive black hole content of galaxies in the local universe for a wide range of both obscuration and accretion rate. Black Hole Finder can identify the most luminous obscured black holes at larger redshifts to constrain the growth rate of massive black holes. Followup detailed studies with Constellation-X and eventually the Black Hole Imager may measure fundamental black hole properties (spin, mass) in the most optimal targets.

- Black Hole Finder will perform the first continuous variability survey for black holes in the hard X-ray band. This will enable systematic discovery of ordinary stars being torn apart as they approach too close to the black holes; LISA will see the gravitational waves from the initial phases of those these events involving small stars, and also the capture of neutron stars and black holes too small to be torn apart. The combination of these data will teach us how the destruction of, and light emission from stars near black holes depends on their motion.

Several mission concepts for the Black Hole Finder are possible, and would be competed. One concrete implementation is the EXIST mission concept. The AASC (NAS McKee-Taylor report) endorsed this as a priority mission to be conducted in this decade, which would allow it to support both Constellation-X and LISA and still operate in the same timeframe with GLAST.

The Black Hole Finder would most likely be a hard X-ray survey mission, consisting of a very large area ($\sim$4-8m^2) array of imaging solid-state detectors (CdZnTe; CZT) which view the sky through wide-field coded aperture masks. The required angular resolution is $\sim$ 3–5 arcmin. The Black Hole Finder should be sensitive in the 10-600 keV band. The survey flux sensitivity (20-100 keV, 5σ, 1y) should be $F_{lim} \sim 5 \times 10^{-13}$erg cm^{-2}s^{-1}, comparable to the flux limit of the all-sky soft (0.5-2.5keV) X-ray survey conducted by ROSAT. At this sensitivity level, the Black Hole Finder will reveal the black holes obscured from view in soft X-rays by gas and dust, and allow the complete spectrum of accreting black holes to be studied.

Bright sources will be located by centroiding to $\sim$10 arcsec so that counterparts at optical/IR/radio wavelengths can be identified. The faintest survey sources would have 1 arcmin centroids, sufficient for identification with bright galaxies.

2.3.6 Vision: Big Bang Observatory

Phinney

Gravitational waves from different astrophysical sources, and from different times in the very early universe are expected to have an extraordinarily wide range of frequencies. LISA will observe frequencies 0.0001-0.01Hz; ground-based interferometers cover 30-1000Hz, and the Inflation Probe will probe around 10^{-16}Hz. Understanding the expansion history of the universe at the moments when quantum foam was becoming our familiar space and time requires measuring the gravitational wave relics from this era at at least two widely spaced frequencies. If Inflation Probe succeeds at the lowest frequencies, this program will require measurements at a much higher frequency. At LISA frequencies and below, the confusion background from astrophysical sources (merging black holes and binary stars in our Galaxy and beyond) is hopelessly large. The expected signal from inflation decreases with increasing frequency, putting it out of reach of ground-based observatories.

In between, at frequencies of 0.01-10Hz, lies a window of opportunity: the number of astrophysical background sources drops to a resolvable number in this band: white dwarf binaries have merged and disappeared. The primary source of background signals is from neutron star binaries several months before coalescence. Angular resolution of arcminutes is achievable with 1AU orbits. Yet the signal from the quantum foam of the early universe is still within reach. The ultimate vision is to reach the sensitivity required to directly detect the gravitational wave background from standard 'slow-roll' inflation. This is a technical challenge within reach. But to reduce the risks, it may be desirable to begin with a less sensitive pathfinder mission to make the first exploration of the universe in this gravitational wave frequency window, whose astrophysical sources are expected to include the seeds of black hole formation, the first stars, and galaxy formation.

- The vision Big Bang Observatory has the goal of direct detection of quanta of the gravitational field created during inflation. This could give us a direct view of the creation of space and time, and in combination with results from the Inflation Probe, determine the nature of the vacuum at energies far higher than we can hope to reach with ground-based accelerators.

- To reach this goal, the Big Bang Observatory will identify (and subtract) the gravitational wave signals from every merging neutron star and stellar-mass black hole in the universe.

- The precision measurement of these binaries will directly determine the rate of expansion of the universe as a function of time, extending the results of the Dark Energy Probe.

- The Big Bang Observatory (or a less sensitive pathfinder) can also pinpoint gravitational waves from the formation or merger of intermediate mass black holes. These are believed to form from the collapse or merger of remnants of the first massive stars to form in our universe, and may have controlled galaxy formation and been the seeds from which supermassive black holes grew. These sources will also enable even finer measurements of the structure of spacetime around black holes than will be possible with LISA.

One possible implementation of the ultimate vision Big Bang Observatory would consist of three triangular formations of sets of three spacecraft similar in design to LISA's. Within each set, the separation between spacecraft is 50,000 km, 100 times shorter than the 5 million km separations of LISA. Three spacecraft is the minimum number that allows for cancellation of laser frequency noise (by approximating an equal-arm Michelson interferometer), has sensitivity to both polarizations of gravitational waves, and permits synthesis of a Sagnac configuration insensitive to gravitational waves for calibration of the system. Success will require only modest improvement in the noise forces relative to LISA, but a large (factor of x1000) improvement in laser interferometer sensitivity relative to LISA. The noise goal would be 10^{-16}m Hz$^{-1/2}$ at 0.1Hz. This could be achieved by use of $10^2 - 10^3$W stabilised lasers (demonstrated in the laboratory, but not yet space-qualified) and 3-m class mirrors. Telescope pointing stability of 100 picoradHz$^{-1/2}$ at 0.1Hz is required.

The mission includes two co-located triangular formations which can be cross correlated to further reduce instrumental noise for searching for a broadband background signal. The sensitivity will be sufficient to detect gravitational waves from neutron star binaries throughout the observable universe. In order to model these signals with enough precision to remove them from the data stream and allow a search for stochastic background signals, the directions to the neutron star binaries must be determined. Because the signals in will be short-lived, the Doppler technique used by LISA will not work, and time-delay interferometry must be used. In order to determine both direction angles, three different detectors are required, so the Big Bang Observatory contains of two additional formations of three spacecraft each, located 120 degrees ahead of, and behind of, the twin-triangle formation, for a total of 12 spacecraft. The figure shows the configuration.

2.3.7 Vision: A Black Hole Imager

White

Direct imaging of supermassive black holes, on an angular scale comparable to the event horizon, will have a major impact on our understanding of the exotic physics and astrophysics at work in these systems. A black hole imaging mission with an angular resolution of 0.1 micro arc second is required to resolve the event horizon of accreting black holes at the center of nearby galaxies (e.g. M87).

Obtaining a simple image, while exciting in concept, is ultimately not sufficient to study the dynamics of the inner regions. To better disentangle the complicated dynamics near the black hole will ultimately require spectroscopic features that can be used to map the speeds as well as positions of gas in the accretion flow close to the event horizon.

The science objectives for a black hole imaging mission are:

- Map the space-time geometry in the vicinity of a black hole event horizon and compare it to the predictions of general relativity. The efficient and geometrically-thin disks found in higher luminosity systems (e.g., nearby Seyfert galaxies) are high surface brightness sources, with the black hole itself appearing as a central hole in the image of the disk. In this case, the dynamics of the disk can be diagnosed via imaging spectroscopy of fluorescent features from the disk surface, thereby allowing a quantitative test of strong field general relativity. The Constellation-X mission provides an important first step by demonstrating the spectroscopy of relativistically broadened X-ray lines, but without imaging, to demonstrate the basic feasibility.

- Directly observe the mechanism by which energy is released in black hole accretion disks. The underlying mechanisms by which an accretion loses energy is not well understood. A direct image of the inner disk could e.g. resolve magnetic loops and activity above the disk. For the inefficient, quasi-spherical accretion disks thought to exist in low-luminosity galactic nuclei (e.g., the center of our own Galaxy or M87), the X-ray source is rather extended and the black hole will reveal itself via its ”shadowing” effect on background emission. In either of these cases, direct imaging provides the most direct evidence for black hole event horizons. If energy extraction from the black hole is an important contribution, combined imaging and spectroscopy will provide the most direct route to test models.

- Determine the mechanism by which relativistic jets are launched from black holes and the role of black hole spin in this process. The ultimate irony of black hole accretion is that somehow the black hole manages to launch relativistic jets, probably from a region very close to the event horizon. A direct image of the event horizon wil allow the direct observation of the base of relativistic jets, and how it relates to the ”plunging” region in which material undergoes the final spiral towards the event horizon. Combined X-ray and radio imaging studies will directly probe the physics of jet formation and other manifestations of black hole spin extraction.

The high X-ray brightness of optically thick accretion disks close to the event horizon and the strong evidence that X-ray line emission originates from this region makes X-ray interferometry ultimately the most promising approach to a black hole imaging mission. This would allow both imaging and spectroscopy of the inner region, close to the event horizon. A successful laboratory demonstration of this technique has recently been made with a baseline of 1 mm. A baseline of 100m to 1,000m is required to achieve the required angular resolution. One possible approach makes use of flat mirrors, which are within today's technological grasp, and have comfortable tolerances. The MicroArcsecond X-ray Imaging Mission (MAXIM) is a possible approach to such a mission. It involves up to 34 spacecraft flying in formation, with precision metrology and tolerances at the 10 nano-meter level.

Radio interferometry observations in the tens of giga-hertz band with baselines of hundreds of thousands of kilometers using a space based antennae can also provide micro-arc second resolution. If the accretion disk is in a radiatively-inefficient (i.e, an advection-dominated) state, it will be a prolific and rather extended source of synchrotron radio emission. Radiatively efficient accretion disks are expected to be rather quiescient in the radio band, however, the region where a relativistic radio jet is initially accelerated should also be a compact and time-dependent source of radio emission. The Galactic Center and the core of M87 will be particularly good targets; the latter possesses a strong radio jet. There are mature mission concepts under study e.g. the international Advanced Radio Interferometry between the Space and Earth (iARISE) that build on the success of the Japanese Halca technology demonstration of space VLBI.

Chapter 3

Beyond Einstein: Technology Roadmap

3.1 Technology Roadmap: Beyond Einstein

Kahn, and others indicated

The SEU Technology Working Group, under the SEUS, has envisioned focused technical approaches toward the ultimate objectives of the Beyond Einstein program:

1. Learn what powered the Big Bang.
2. Observe what black holes do to space, time and matter.
3. Identify the mysterious dark energy which is pulling the universe apart.

Recap interrelations of missions?

The technical content of the Beyond Einstein Roadmap is focused on the detection, measurement and imaging of the curvatures of space and time predicted by Einstein, but whose nature is still unexplained and unexplored.

The Technology roadmap is guided by six key principles:

1. Close Coupling of Technology Development to Scientists. Scientists are the end-users of these technologies and must be kept intimately involved in the development programs to ensure that their needs are met.
2. Balance. While emphasizing near-term mission goals, the program is balanced to enable revolutionary technology developments that may lead to dramatic scientific breakthroughs in support of our "mid-term" and "vision" missions.
3. Return on Investment. Highest priority is reserved for programs that demonstrate that technological investment will lead to significant progress. SEU will follow an integrated strategy that coordinates technology developments for different programs and leverages technology advancements from academia, industry, and government to insure maximum return on investment.
4. Peer Review. Community oversight is essential to maintain a well-focused and efficient program that is responsive to scientific needs.
5. Integrated Technology Strategy. SEU will coordinate its technology developments with the other Space Science themes to identify leveraging and cost sharing opportunities.
6. Strategic Planning. Technology from early missions contributes to later more technically demanding missions.

3.2 Einstein Great Observatory Technologies

We here describe the technology development needed to enable the two Einstein facility-class missions: LISA and Constellation-X.

3.2.1 Constellation-X

Constellation-X will open new windows in cosmology and relativistic astrophysics using X-ray spectroscopy to test the strong gravity limit of general relativity, map the formation and evolution of dark matter, and survey the formation of the large-scale structure.

- Lightweight, grazing incidence X-ray optics

Constellation-X will use two sets of telescope systems on each of four satellites: 1) a high throughput spectroscopy X-ray telescope (SXT) for the low energy band up to 10 keV, and 2) three hard X-ray telescopes (HXTs) for the high energy band. The SXT uses highly-nested light-weight grazing incidence X-ray optics in a Wolter I design coupled to an array of micro-calorimeters cooled to 50 mK plus a reflection grating/CCD system. The HXT employees multilayer-coated grazing incidence optics coupled to a solid state imaging spectrometer. The highly nested, grazing-incidence X-ray mirrors must simultaneously meet the angular resolution, effective area and tight mass constraints. To mitigate optic and grating fabrication, cost, schedule and mass risk, Constellation-X must invest sufficient resources over the next 3 to 5 years with the explicit goal to advance 3 to 5 different and independent X-ray mirror and grating fabrication/assembly technologies to TRL-5. Specific research should include research into material properties (CTE, creep, etc.), stress-free replication processes, stress-free athermal passive assembly techniques and low-cost mass-fabrication methods. Downselecting the telescope technology should not occur until at least the Phase A/B transition or even mid-Phase B.

- X-ray Calorimeter Arrays with 2 eV spectral resolution

Two detector technologies are being developed in parallel to realize the cryogenic X-ray calorimeter arrays: semi-conducting bolometers read out by JFET amplifiers and voltage-biased transition-edge superconducting (TES) thermistors read out with SQUID current amplifiers. Semi-conducting bolometers are generally demonstrated, but difficult to scale up to large arrays due to the dissipation of the JFET amplifiers. TES bolometers are coupled to time-multiplexed SQUID readouts operating at sub-K temperature with the detectors to produce large arrays (32 x 32). Single-pixel architectures are under development to meet the required energy resolution of 2 eV at 6 keV. A small 32-channel SQUID multiplexer is being developed based on the successful development of an 8-channel multiplexer. Although parallel development in component technology has been rapid, the fabrication issues associated with arrays - uniformity, lifetime, yield - must be demonstrated in the near future with a concerted effort of building complete arrays of increasing format.

- Long-duration cooling technology to 50 mK

The cooling technology required by Constellation-X benefits from the Advanced Cryocooler Technology Development Program (ACTDP), the goal of which is to develop reliable long-life coolers operating at 5-10 K for Constellation-X, TPF, and NGST. The ACTDP parallel development of 4 study-phase contracts using multi-stage Stirling, turbo-Brayton, and pulse-tube coolers will lead to a selection in 2002 of 2 candidates for construction of full

FIGURE

Figure 3.1: Current development under CETDP and CTD Projecting need for 5 microwatts at 50 mK; have demonstrated 6 microwatts at 50 mK controlled to 8 microKelvin rms Heat rejection to superfluid He at 1-2 K; next to 4.2 K normal He

FIGURE

Figure 3.2: The LISA mission requires development of inertial sensors of the kind shown here.

demonstration coolers to be completed in 2005. The ultimate temperature of 50 mK will be provided by an ADR operating from the 6 K heat sink of the intermediate cryo-cooler. A continuous ADR, using multiple parallel chains of salt pill and heat switches to provide uninterrupted cooling with a significant reduction in refrigerant mass, is being developed as an advanced option.

- Grazing incidence reflection gratings coupled to X-ray CCDs

A grating CCD combination provides imaging spectroscopy in the 0.2 - 1.5 keV energy range. The grating will either incorporate an in-plane reflection grating as an outgrowth of XMM, or an alternate off-plane grating pending a selection in mid-2003. EDCCDs, Event-Driven CCDs using novel readout electronics to select and digitize pixels with X-ray hits, provide significant improvements in power dissipation and radiation hardness, less susceptibility to optical/IR radiation, and higher frame rates.

- Solid-state hard X-ray imaging detectors

In the hard X-ray, CdZnTe detectors bonded to ASIC readouts provide ¡ 1.2 keV resolution and high optical efficiency over the 6 - 50 keV energy range. Further development is required in materials properties to improve response at low energies and reduce the effects of electron trapping.

At this phase of development, before more specific high-TRL issues must be confronted, future missions with technological commonalities may benefit from the promising Constellation-X mirror, detector, grating, and cryo-cooler technologies.

3.2.2 LISA

Harvey Moseley

LISA will open a new window on the universe by enabling the detection of gravitational radiation from a wide variety of astronomical systems, ranging from compact Galactic binary systems, to mergers of supermassive black holes in the far reaches universe, to the inspiral of solar-mass objects into massive black holes.

The observatory consists of a triangle of drag-free reference masses in solar orbit connected by a precision metrology system. The measurement of the relative motion of these drag-free masses allows us to sense the passage of gravitational waves through the solar system.

The LISA science program imposes a set of challenging technical requirements on the observatory. Separate observational objectives impose different technical requirements on the facility. The observation of the capture of a compact object by a massive black hole sets the sensitivity requirement in the 10^{-2} to 10^{-3}Hz range. This is perhaps the most demanding requirement on system sensitivity, but is justified by the importance of the measurement of spacetime around the massive black hole. The sensitivity requirement at low frequencies is set by the supermassive black hole merger observation. Good sensitivity in the 10^{-4}Hz region is necessary to allow accurate parameter and distance determination.

The requirement to simultaneously meet the science requirements sets the mission design and defines the technology developments required for success. The key technologies required for any gravitational wave detector are those which will minimize external disturbances of the test masses, and those which allow precision measurement of the test mass separation. In the case of LISA, the disturbance reduction system is most critical in the low frequency range ($10^{-3} - 10^{-4}$Hz), while laser power and sensor system sensitivity dominate in the $10^{-2} - 10^{-3}$Hz range. Finally, in the high frequency range, the sensitivity is controlled by the interferometer arm length. Higher sensitivity can be had at high frequencies by shortening arm length, but at the cost of lowered low frequency sensitivity, making the choice of arm length a major system tradeoff.

- Disturbance Reduction System

Significant technology development is required to provide the disturbance reduction required to produce LISA's low frequency sensitivity. The the disturbance reduction system requires inertial sensors with noise $< 10^{-16}$g in a 1000 s integration, and low noise microNewton thrusters which can close the loop to minimize disturbances on the test masses.

- Laser Measurement System

Changes in the 5×10^6km test mass spacing must be measured to 10^{-12}m. This requirement can be met with lasers an detection systems which are now the present state of the art. Given the orbital dynamics, however, the spacing must be measured to 10^{-5} fringes while changes in spacecraft spacing are creating a fringe rate as large as 15 MHz. This imposes stringent requirements on the laser frequency stability, frequency correction, and precision pointing and dimensional stability of the telescopes. The phase measurement system may require improvements in ultra-stable oscillators.

- System Verification

A validation flight is planned in June 2006 on the ESA SMART-2 spacecraft, with US participation through the New Millenium mission ST-7. The validation program is essential to test the critical disturbance reduction system components, the gravitational sensors, microNewton thrusters, and the laser interferometer to measure test mass spacing.

In order to assure the success of the LISA mission, the very challenging disturbance reduction system must be validated and the sensing system proven. A robust program of technology development and flight demonstration must be maintained, and adequate system verification procedures and facilities must be developed.

3.3 Example Einstein Probe Technologies

The Einstein Probe line is to be competed: the best scientific and technical approaches to the goals will be chosen from the community offerings at the time each mission is selected. Nevertheless, all of the measurements planned for the three Einstein probe missions are technically very challenging, and it will be essential to validate the technical readiness of potential mission concepts before embarking on each competition. This can be accomplished by means of an Einstein Probe Technology Development line, in which technology programs associated with candidate mission concepts for the various probes are proposed and competed, in advance of the actual mission selections. The Einstein Probe Technology Development line should be instituted as early as possible to enable the most promising technical approaches for each mission to be thoroughly vetted.

To date, some approaches (which may or may not be the ones ultimately selected as best) to each of these goals have already undergone some development as mission concepts. So to demonstrate the feasibility of the goals, and as examples of the sorts of technology development which should be supported to enable the probes, we describe the technology needs for sample concepts of the Einstein Probes.

3.3.1 Dark Energy Probe

Kahn

The Dark Energy Probe will be designed to perform measurements of the geometry of space-time in the redshift range $z = 0.7 - 1.7$, where the effects of dark energy are expected to leave their most prominent signature. A particularly promising approach (and the one emphasized in the NAS Committee on the Physics of the Universe Report) is to perform highly sensitive, wide field imaging in space in the visible and near infrared bands. Such measurements could provide: (1) A large sample of Type 1a supernovae out to redshifts beyond $z = 1.5$. Such a sample is necessary to reduce both statistical and systematic errors in the measurements of w and w'. (2) A reasonable sample of Type 2 supernova out to $z = 1$. Through the expanding photosphere method, these provide a constraint on the apparent magnitude - redshift relation, completely independent from that provided by the Type 1a's. (3) Weak lensing data of high statistical quality. Measurements of weak lensing constrain the power spectrum of fluctuations as a function of redshift, also sensitive to dark energy. (4) Strong lensing data in clusters of galaxies. These results can be used to constrain the energy density in dark energy.

A mission capable of performing such observations should incorporate a moderate aperture telescope ($\sim$ 2 m diameter), diffraction-limited down to 1 micron, and large arrays of optical and infrared imaging detectors. The telescope is challenging, in that the primary mirror must be constructed with significantly lower areal density and at much lower cost than the primary mirror flown on HST. However, the very large detector arrays raise even more serious technical concerns. Of order a billion pixels are required. For the optical detectors, silicon-based CCDs provide the most obvious candidate technologies, however the joint demands on read noise, dark current, pixel size, array size, charge transfer efficiency, spectral coverage, and radiation hardness are beyond the capabilities of current commercially available devices. Some progress has been made with alternative CCD architectures, but further development is definitely required. For the infrared detectors, low band gap (e.g. HgCdTe) detector arrays look promising, but here again the demands imposed by this application are beyond the current state-of-the-art. In both cases, there are significant risks associated with cost, production schedule, and quality assurance, considering that a large number of devices must be procured, and accurately characterized. Considering the uncertainties, significant technology investment is essential before NASA can confidently proceed with a mission of this type on a fixed budget and schedule.

3.3.2 Inflation Probe

Kahn

The Inflation Probe will be designed to detect low frequency gravitational waves produced by inflation via the "imprint" they leave on the CMB - a weak component of polarization with non-zero curl. This is often referred to as "B-mode" polarization, in analogy with the magnetic field of electromagnetism. Alternative theories, e.g. the "cyclic universe" theory, do not predict this B-mode signal.

Even for standard models, however, the B-mode component of polarization is very difficult to detect. Fluctuations in this component are an order of magnitude weaker than those of the curl-free component, and three orders of magnitude weaker than the fluctuations in the CMB temperature that we are measuring today with MAP. The improvement in sensitivity required is roughly 20 - 100 times better than the HFI focal plane detector on Planck, which is itself roughly 20 times more sensitive than MAP. Achieving such vast increases in sensitivity will require significant technological advances in several areas. Of particular importance will be a substantial increase in the sky coverage per frequency, from ~ 0.1 square degrees for Planck to ~ 25 square degrees. That will require a large array of polarization-sensitive detectors, with frequency multiplexing to obtain coverage from 50 - 500 GHz simultaneously from each pixel. There are conceptual designs for detector arrays that might have these properties, but none has been developed to the appropriate level of technical readiness. Other technical challenges include the need for cold optics and 100 mK detector operating temperatures with very stable temperature control. Significant technology development in all of these areas is required.

Since the measurement of B-mode polarization in the CMB may eventually be limited by systematics, rather than statistics, it is also extremely important for the community to gain experience in using this technology to make real polarization measurements of the sky from the ground, before attempting the full-fledged space implementation. This will enable an improved understanding of systems issues that is crucial for refining the mission technical requirements. For optimum efficiency, such a ground-based testbed effort should be incorporated into the NASA technology program directly, rather than relying on funding from other federal agencies, as has been the paradigm in the past.

3.3.3 Black Hole Finder Probe

Swordy/Kah

Black Hole Finder probe will conduct a wide field survey of black holes at hard X-ray/soft γ-ray energies, where radiation emitted from these objects can penetrate any surrounding veil of gas and dust.

The survey instrument for this science needs to be sensitive over an energy range of $\sim$10keV-600keV, and to have angular resolution $\sim$5 arcmins. Since reflective optics provide very limited fields of view at these high energies the telescope must function using the techniques of coded aperture imaging. To provide sufficient sensitivity the detector plane must have an area of several m^2 with mm^2 sized pixels to provide the required angular resolution.

A key technology development will be the development and operations of a suitable detector array. An array of CdZnTe seems the most likely candidate. While this material has been the most promising room-temperature high-Z detector developed so far, there remain some significant technical challenges. The detector array has to be constructed from a large number of small (few cm^2) devices. The development of a manufacturing and quality assurance scheme to provide unformity between these devices will be crucial. The detectors need ASIC electronics to keep within likely power margins. The connection of the mm^2 detector pixels to the far smaller pitch of typical ASIC inputs requires development. The development of a suitable scheme to provide adequate dynamic range and 'depth-sensing' for these devices is also very important. The poor electron lifetime in typical CdZnTe devices is a fundamental issue which can only be addressed if the interaction depth is known. Other technology issues for this telescope are the refinement of the manufacturing techniques for the mask and the development of a sufficently fast data acquisition system to cope with the high trigger rate of the detector array.

3.4 Beyond Einstein Vision Mission Technologies

The ultimate visions of the Beyond Einstein program stretch well beyond what will be accomplished with either the mid-term missions or the Einstein probe missions. These stretch our imagination, both scientifically and technically. Although, detailed designs for such missions cannot be constructed now, it is important that we begin addressing some of the anticipated technology needs, if we are to be ready to realize these goals in the coming decades. Below, we discuss some possible technology development programs associated with these vision missions.

- Directly image matter near the edge of a black hole
- Directly detect gravitational waves echoing from the beginning of the Big Bang.

3.4.1 Black Hole Imager

Dan McCammon

The goal of the Black Hole Imager is to enable direct imaging of the distribution and motion of matter in the highly distorted space-time near the event horizon of a black hole. This will require angular resolution of a microarcsecond or better —almost five orders of magnitude beyond that of the Hubble Space Telescope. An X-ray interferometer seems naturally matched to this task, since accreting black holes are expected to have a high surface brightness in X-rays, and this, coupled with the short wavelength, allows an instrument of relatively modest aperture and baseline to be used.

An X-ray interferometer with 0.1 microarcsecond (μas) resolution poses some outstanding technical challenges. At wavelengths near 1 nm, the required baselines are about 1 km, and focal distances must be 1000 to 10,000 km to obtain reasonable detector scales. This means that separate spacecraft are needed with highly controlled formation flying. Nominal requirements are: position accuracy of a fraction of a nanometer, angles known to 0.1 μas, and optical surfaces figured to 0.05 nm.

- Pointing

Changes in the space orientation of the line from the center of the detector spacecraft through the center of the baseline of reflector spacecraft must be known to a precision of 0.1μas, and controlled to a few hundred times this. This is probably the greatest technical challenge, and it is shared in some form by other planned missions such as TPF. One possibility is a "super star tracker", operating as a telescope or interferometer at any convenient wavelength. However, to provide adequate centroiding in visible light would require a Hubble telescope to get to 15th magnitude, and even at this level, targets would be scarce. Target availability is an even larger problem for any X-ray interferometric system with a reasonable aperture. An alternative is to use an inertial reference. This might seem more difficult, but the quartz sphere gyroscopes on Gravity Probe B (GPB) have drift rates under 0.5 μas per day, so the option should be given serious consideration. The GPB gyroscopes have superconducting readouts and require 4 K cooling. Mechanical coolers with this capability are being developed for Constellation-X and other missions. Atom interferometer gyroscopes are potentially even more sensitive, but are at a much lower level of development.

- Formation flying

Given this knowledge of relative positions and absolute orientation, station-keeping requirements are simply to keep the target reasonably centered on the detector. If detector array size is 30 cm, then control of the detector spacecraft need only be at this level, while ∼10 m control of the optics spacecraft would be required. If each of these spacecraft contains optics for two grazing reflections in a "periscope" configuration, the first order dependence on the space orientation of the pair is removed, and only ∼1 arcsecond control and knowledge of the spacecraft orientation is required.

- Mirror figuring

Grazing incidence relaxes the necessary surface figure accuracy by a factor of $1/\sin\theta$, where θ is the graze angle. Since this angle must be smaller than ∼1 degree for broad-band X-ray mirrors, surface requirements are reduced to about 3 nm, or 1/200 wave for visible light. This accuracy can currently be obtained for flat surfaces up to 15 cm diameter. However, given the way these flats are fabricated, extending the size even to 30 cm by 1500 cm will not be a trivial task.

To reduce the risks associated with making such large technical advances as these in one step. it would be desirable to first fly a pathfinder mission, with angular resolution requirements reduced by about two orders of magnitude, to 100μas. This requires a baseline of about 1 m, and all the optics could therefore be placed in a single spacecraft. The stationkeeping requirements are then for the detector only, and are quite modest (several cm). The angular orientation of the optics spacecraft is uncritical, but changes in the LOS must be known to 30 μas and controlled to ∼5 mas, either with a star tracker (much more feasible at this level) or inertial sensors. The knowledge requirement is about a factor of 30 better than the Hubble FGS.

3.4.2 Big Bang Observatory

Phinney, based on tech presentation

The ultimate goal of a Big Bang Observatory is to directly observe gravitational waves with sufficient sensitivity to observe the background due to the quantum fluctuations in 'slow roll' inflation, characterised by a fractional energy density for gravitational waves of $\Omega < 10^{-15}$. These waves have been propagating to us since they emerged when the universe was only 10^{-34} seconds old. This must be done in the face of a strong astrophysical foreground ("night sky") of gravitational waves produced by all the binary stars and black holes in the universe (formed mainly in the past 12 billion years).

To separate these foreground sources requires extraordinary sensitivity *and* angular resolution. One possible solution consists of a four separate interferometers, each including three spacecraft separated by 50,000km (with peak sensitivity to gravitational waves near 0.1Hz). Three of the interferometers would be spaced in a triangle around the earth's orbit about the sun (separations of 1.7AU), and the fourth would be collocated with one of them for independent correlation.

With such a configuration, several technical challenges must be met to achieve the required sensitivity:

Measure changes in distance between spacecraft separated by 50,000 km with a power spectral density of displacement noise of less than $10^{-28}\mathrm{m}^2\mathrm{Hz}^{-1}$ at an observation frequency of 0.1 Hz. This is equivalent to a strain sensitivity one thousand times better than planned for LISA. The strain sensitivity noise is limited by mirror diameter; mirror figure; laser power; laser frequency stability; laser phase measurement accuracy; instrument pointing accuracy. Laser power and mirror diameter can be traded: one solution would consist of 100W lasers and 3m-diameter mirrors.

Measure changes in distance between spacecraft referenced to freely-floating test masses which have residual acceleration power spectral density less than $10^{-31}\mathrm{m}^2\mathrm{s}^{-4}\mathrm{Hz}^{-1}$ at an observation frequency of 0.1Hz. This is equivalent to requiring a gravitational reference sensor with acceleration noise performance ten times lower than planned for LISA.

Perform strain measurements with at least three instruments separated by more than 1 AU in order to localize all detectable binary systems. This drives the mission to including three spatially-separated interferometers in order to characterize individual binary sources.

Compare changes in distance between two nearby instruments to cancel random noise to one part per thousand for a one-year average. This drives the mission to include a fourth interferometer co-located with one of the other three interferomete

The technology development needs for the Big Bang Observatory are listed below in order of decreasing priority.

- Laser, 100-1000 W output, stable, space qualified, high efficiency
- Laser phase measurement system, 10^{-9} cycles $\mathrm{Hz}^{-1/2}$, 0-1 MHz
- Signal processing algorithms for removing signals for the background search.
- 3-m mirror of high quality and low cost.
- Pointing system - need picoradians/$\mathrm{Hz}^{-1/2}$.

- Frequency standard, $< 10^{-13}$ Allan deviation 0.01-1 Hz.
- Optical (as opposed to capacitive for LISA) read-outs for gravitational disturbance reduction system. These are needed to reduce the disturbances introduced by the measurement system.

To reduce the risks associated with making such large technical advances as these in one step, it could be both scientifically and technically desirable to first fly a pathfinder mission, with fewer spacecraft and more modest improvements on LISA's technology. This would make a first exploration of the universe in the $0.03 - 10$Hz region of the gravitational wave spectrum between that studied by LISA (< 0.03Hz and by ground-based interferometers like LIGO (> 10Hz). Such a mission would give understanding of the astrophysical sources in this waveband, and assist in designing the Big Bang Observatory to avoid confusion from them.

Chapter 4

Beyond Einstein: Research and Analysis

4.1 Theory and Laboratory Astrophysics

Theoretical studies— here taken to include development of software technologies supporting data exploration, astrophysical simulations, and combinations of these— were recognized by the National Academy's Decadal survey as a central component of modern mission technology development. That survey recommended that supporting theory be explicitly funded as part of each mission funding line, because detailed modeling connecting the elements of a mission to the system under investigation is critical to design and even to conceive successful and cost-effective missions. Rigorous modeling is an important factor in reducing mission risk, and simulations can vividly demonstrate mission goals. Beyond Einstein explores to the boundaries of foundational knowledge as well as the boundaries of spactime, so detailed and quantitative theoretical studies are indispensable, starting with the earliest design phases.

The following are examples of mission-critical theoretical, laboratory astrophysics and ground-based studies:

- Constellation-X. Models of relativistic hydrodynamic flows in accretion disks, including radiative transfer models supported by solid laboratory data, leading to simulated, time-dependent spectra.
- LISA. Studies and simulations of signal extraction (the "cocktail party problem"); numerical relativity, aimed at accurate calculation of predicted gravitational waveforms for the whole range of merging and orbiting systems; astrophysical modeling and simulations to connect binary population predictions with other data sets.
- Inflation Probe. Theoretical studies of early universe cosmology, including tensor and scalar mode predictions and their connection with fundamental theory; simulations of polarization effects, including the contamination effects of astrophysical foregrounds; development of optimal statistical signal extraction techniques.
- Dark Energy Probe. Theoretical studies of Type Ia supernovae and other candidate systems for calibrating cosmic distances, including simulations of statistical effects of gravitational lensing by dark matter, supported by ground-based studies of nearby supernovae to obtain detailed and reliable spectrophotometry for a high-quality calibrating sample.
- Big Bang Observatory. Early universe cosmology and phenomenology of quantum gravity, string theory, and brane world models; models of coalescing white dwarf and neutron star binary foregrounds.
- Black Hole Imager. Comprehensive simulation of black hole environments, including electromagnetic field interactions with flows and the spacetime metric, and radiative transfer over many decades of dynamic range.

Chapter 5

Education and Public Outreach

5.1 Education, Outreach and the Public Mandate

Gould

You don't have to search far for evidence of the public's intrigue with black holes, the origin and mystery of time, multiple universes, or dimensions beyond our own —this is the stuff of Hollywood movies, television series, best-selling books and popular articles galore. What has changed is that what was once armchair philosophy is now serious science. The public has taken note accordingly.

The Office of Space Science has developed a major education and outreach initiative designed to involve the public in the excitement of space science exploration, as well as to cultivate the next generation of scientists. The cornerstone of this effort is a network of partnerships throughout the education and outreach communities. In fact, OSS products and programs now reach virtually every avenue of public interest, including the nation's schools, science museums and planetariums, media outlets, after-school programs, libraries, and community groups. Outreach programs for the Beyond Einstein theme will build on these existing partnerships.

The missions and probes in the Beyond Einstein theme offer unique opportunities for advancing science education, both in the nation's classrooms and in informal education venues as well. For example, the origin of the universe is considered such an important part of science education —and of cultural literacy generally— that it is featured in the National Science Education Standards, which form the basis for most state education frameworks. Missions such as MAP, the Inflation Probe, the Big Bang Observatory, and LISA offer the opportunity to develop a comprehensive and coordinated set of materials with which teachers and students can examine evidence for the Big Bang and trace the underlying idea that scientific inquiry can address even the most ancient and difficult questions.

Similarly, black holes are cited in the Benchmarks for Science Literacy —published by the American Association for the Advancement of Science and widely used along with the National Standards— as an excellent way to introduce students to the important idea that "under extreme conditions the world may work in ways very different from our ordinary experience, and that the test of scientific theory is not how nearly it matches common sense, but how well it accounts for known observations and predicts new ones that hadn't been expected." The Benchmarks mandate that by the end of 12th grade, "students should know that... many predictions from Einstein's theory of relativity have been confirmed on both atomic and astronomical scales. Still, the search continues for an even more powerful theory of the architecture of the universe." Missions such as Constellation-X, LISA, and the Black Hole Finder Probe will provide students and the public with a front-row seat for one of the great scientific explorations of our time.

An area of growing importance in the classroom is the "interaction of light and matter," especially students' understanding of the various forms of light, from radio waves to gamma rays, which is central to all modern scientific exploration regardless of discipline. The Beyond Einstein missions span the electromagnetic spectrum, and they collectively provide teachers with clear, graphic, and compelling examples of the wide variety of information about our universe that light can provide. In fact, more than 10,000 teachers have already requested education materials from Beyond Einstein because they provide such compelling classroom examples of light beyond the visible.

Another crucial area of opportunity is technology education. Many states now require technology education in middle school, and science museums across the country are building "Current Science and Technology Centers" to address the public's interest in new technologies. The fantastic requirements of a mission like LISA —which will measure an object being jostled by less than the width of an atom— provoke the kind of excitement and questioning that draws young people into science and technology in the first place.

Educational products and programs developed for the Beyond Einstein theme are expected to be extremely popular, as they have been in the past. For example, the television shows and educational materials for "Live from a Black Hole" and "Live from the Edge of Space," reached an estimated 5 million students. Either directly or indirectly, the Beyond Einstein theme now provides much of, and soon the majority of, all materials on these subjects in our nation's schools.

Finally, Beyond Einstein missions will weave an ongoing story that is considered one of the most compelling in all science —a story that will form the raw material for museum exhibits, planetarium shows, radio programs, and other media outlets. We know that the public clamors to be involved in this story, because they vote with their feet and their pocketbooks: More Americans visit science museums and planetariums than attend all sporting events combined —more than 120 million in 2001— and the Beyond Einstein theme remains a favorite there. For example, a recent planetarium show on black holes and the Big Bang (*Journey to the Edge of Space and Time*) increased attendance in both Boston and Philadelphia by more than 20% above normal. Public television's NOVA show on dark energy (*Runaway Universe*) was seen by more than 2.1 million Americans — almost as many as watch all three cable news networks combined. And a national traveling exhibition featuring mysteries from the Beyond Einstein theme (*Cosmic Questions*) is expected to reach up to 4 million visitors.

Among the hallmarks of Beyond Einstein's approach to education and outreach are: the participation of space scientists at all levels of outreach; an emphasis on the diversity of people and cultures who contribute to the questions and the quest; an emphasis on professional development of pre-service and in-service teachers; the link between technology and the advancement of science; and an emphasis on the nature of scientific inquiry, including the human drama of planning, building, and launching the great missions of exploration.

Possible Sidebars/ Callouts

Several million people visit websites on the Beyond Einstein theme each year.

"Thank you for such an educational site for children. I am a homeschooler and this is so comprehensive." - Mrs. D.

"I was immediately hooked! You are stirring the imagination and interest of today's kids!" - Testimonial from user of Chandra education materials

Public interest in the Chandra X-ray Observatory has led to more than 850 newspaper articles and wire stories — including 27 in the NY Times, Washington Post, and USA Today — and more than 10 newscasts, including CNN, ABC, CBS, and NPR.

NOVA's television show on Dark Energy was watched by 2.1 million Americans —almost as many as all cable news network stations combined.

The show, Journey to the Edge of Space and Time, increased attendance at planetariums in Boston and Philadelphia by more than 20%.

Imagine the Universe!, a website on Beyond Einstein themes, has been visited by millions of Americans (http://imagine.gsfc.nasa.gov).

The Starchild web site for elementary students was one of the first winners of the Webby award for Education. (http://starchild.gsfc.nasa.gov)

"I am so thankful that I just saw on TV the RUNAWAY UNIVERSE today and then discovered this website tonight. How can we be so lucky as to have these educational tools available? While I am a great-grandmother of two and have not studied chemistry, math or physics ever, I am hooked. Please keep giving this inspiring information to us and especially to the young future scientists. - Betty H., NC.

"I [attend school] in Nacogdoches, Texas. I feel that more astronomy-based learning should take place— in history and English classrooms as well as science. The heavens are very important to many cultures and I feel our studies in school do not show a true picture of these cultures without a focus on astronomy". - Bethany G., Texas

"Exploring the cosmos has been something I have been drawn to for as long as I can remember. I am most interested in learning about the beginning and end of the universe, and also exploration into black holes in terms of their role in the universe." —from a high school sophomore responding to the GLAST website

"We seize only a bit of the curtain that hides the infinite from us." —Maria Mitchell

Part II: Cycles of Matter and Energy

Chapter 6

Science Objectives: Cycles of Matter and Energy

See separate word/pdf file at

`http://www.its.caltech.edu/~esp/seus/RMII_7-02-02.pdf`

Linked at

`http://www.its.caltech.edu/~esp/seus/sources.html`

6.1 Science Objectives: Cycles

To explore the cycles of matter and energy in the evolving Universe.

To understand the development of structure in the universe.

for each, declarative and interrogatory version

Research Focus Areas for Cycles Roadmap:

1. Learn what physical processes gave rise to galaxies and systems of galaxies.
2. Explore where and when the chemical elements were made.
3. Understand how matter, energy and magnetic fields are exchanged between stars and the gas and dust between stars.
4. Discover how gas flows in disks and how cosmic jets are formed.
5. Identify the sources of gamma-ray bursts and high-energy cosmic rays.
6. Explore the behavior of matter in extreme environments.

Chapter 7

Technology Roadmap: Cycles of Matter and Energy

Our efforts to probe the structure and evolution of the Universe will entail a diverse array of observational strategies, encompassing measurements across the entire electromagnetic spectrum, from radio waves to gamma-rays. Order of magnitude improvements in sensitivity, spectral and spatial resolution, and collecting area will be required for each of these regimes in order to make fundamental advances. This will not be possible without vigorous technology development. In the earliest stages (TRLs 1-3), new space technologies are invented and pursued under the auspices of the R& A programs. However, as these concepts mature, detailed engineering issues associated with real space implementation must be addressed. Such investigations require more focused and more stable funding mechanisms. A dedicated technology development line for future SEU missions will meet this need.

Highlighted below are the general technologies required to implement some the future SEU missions that are currently envisioned. The discussion is organized around three major areas: optics, detectors, and spacecraft systems. By their nature, these technology areas overlap heavily and are only meant as general categories.

7.1 Large, Lightweight Optics

Optics is essential enabling technology for many NASA missions (astrophysics, planetary science and Earth resources). Continuing exploration of the universe requires bigger and better space telescopes. To answer the next generation of questions, space telescopes need to double in size. Robust large-aperture lightweight optics and optical systems are not only critical to reducing launch costs, but in many cases are critical to launch feasibility itself. This challenge applies equally to normal and grazing incidence optical systems and leads to a clearly defined technology roadmap. Technology and processes must be developed to increase apertures, lower areal density, lower operating temperatures and improve diffraction limited surface quality. But most importantly, this must all be accomplished rapidly and cost effectively.

To achieve these goals requires continuous effort in 5 technology areas: Materials, Design Architectures, Fabrication Processes, Performance Characterization and Mechanisms. Material properties impose fundamental limits on how large, how cold and how good of a telescope one can make. Stiffer materials enable larger apertures with lower areal densities — for both optics and structures. Low and uniform coefficients of thermal expansion (CTE) allow cryogenic performance without the need for cryo-null figuring. Stress free material deposition and/or curing enable low cost replication for mass production. Design architecture must be developed and validated to take maximum advantage of the new materials. For example, how would one make use of advances in mirror substrates made of glass or silicon foam? Can actively cooled high-power laser mirrors developed for the defense industry be adapted for use at 5K? Or, is it possible to reduce structural mass 50

In the area of fabrication processes, there are multiple challenges. First, there are the simple logistics of how to physically handle and manipulate large and more fragile optical components. Then there is the question of how to obtain the desired surface figure quality. Current research is investigating stress mirror and stress lap polishing. Future research needs to investigate a broader range of applications, including: electro-chemical grinding; magnetorhealogical fluid (MRF) or water jet polishing; liquid or gaseous etch polishing;

room temperature epoxy curing; chemical vapor growth of silicon carbide (SiC) or hard carbon surfaces on mandrills; etc. Critical to how one fabricates an optical component is how one characterizes its performance. An optic's performance is only as good as one can measure it to be. As optics become larger and lighter, a time is rapidly approaching when it will not be possible to test them on the ground. Soon, a telescope will be launched that has been completely validated by analysis. For that to occur, a rigorous effort must be undertaken to model, build and test the operational performance of optical systems - to challenge engineering boundaries and validate model non-linearities.

Finally, we must not concentrate so much on optics and structural materials that we forget about mechanisms — hinges, latches, actuators, etc. The ability of these components to function in a cryogenic space environment is also a critical enabling technology.

The purpose of NASA's mirror technology development program is to 'buy-down' technical (weight & performance) and programmatic (schedule & cost) risk associated with the design, fabrication and testing of large-aperture lightweight space qualified mirror systems. Given the leverage that optics exert on programs, small improvements in technology maturity can have a very large cost and schedule impact.

7.2 Detectors

Advances in detector technologies, in all wavebands have been dramatic in recent years, and have directly enabled most of the SEU missions that are currently flying or are nearing launch (e.g. Chandra, SIRTF, GLAST). In general, a detector is categorized by its quantum efficiency, its spectral bandpass, and in some cases, its intrinsic spatial and spectral resolution. Auxiliary technologies include the read-out electronics, the digital processing units, and the detector cooling systems. The demands of upcoming missions will require major engineering advances in all of these areas. We detail a few examples below:

7.2.1 Submillimeter/Far Infrared:

The development of large format detector arrays is critical for the submillimeter and far infrared. Both direct detectors (such as bolometers and photoconductive devices) and heterodyne instruments are required. There are challenges in improving sensitivity, scalability to large arrays, and, for heterodyne systems, local oscillators and backend electronics, especially at the highest frequencies.

7.2.2 Near Infrared/Optical:

In the near infrared and optical bands, imaging detectors based on charge coupled devices (CCDs), and low bandgap array detectors (e.g. HgCdTe), have been available for a number of years now. However, future missions will require extremely large (billion-pixel) arrays of such detectors, introducing new challenges in production yield, detector uniformity, detector packaging, high-speed readout, and on-board data storage. In addition, improvements in readout noise, quantum efficiency, spectral coverage, charge transfer efficiency, and radiation hardness will be necessary.

7.2.3 Ultraviolet:

For the ultraviolet, significant improvements in detector sensitivity are possible and must be achieved. Photocathode-based photon counting detectors, like microchannel plates (MCPs) offer the advantage of high counting rate and good background rejection, but suffer from low quantum efficiency (typically below 25 percent). Further developments in novel photocathode materials may achieve significant improvements in quantum efficiency and should be pursued. For some applications, solar blindness is important. UV-sensitive CCDs have higher quantum efficiency, but the read noise is currently too high to make such devices useful for faint source spectroscopy, given the low photon fluxes in the ultraviolet band. So-called "3-D" energy-resolving detectors like superconducting tunnel-junction arrays or transition-edge sensors with SQUID readout offer tremendous promise, but the currently available array sizes are too low for the anticipated applications.

7.2.4 X-Ray:

At X-ray energies, the development of cryogenic detectors (X-ray microcalorimeters) has revolutionized the field in recent years. 30×30 arrays of microcalorimeters are envisioned as the principal focal plane detectors for Constellation-X. However, such small arrays yield very limited fields of view when implemented behind conventional grazing incidence telescopes. For future missions, such as Generation-X, much larger array sizes (e.g. 1000×1000) are required. That is unlikely to be achieved using conventional technological approaches.

7.2.5 Gamma-Ray:

The principal technical challenge for gamma-ray astronomy will be the development of an advanced Compton telescope, for the study of nuclear lines and continuum emission at MeV energies. A factor of 25-100 improvement in sensitivity is required compared to the MeV instruments flown on CGRO and INTEGRAL. The increase in sensitivity requires major improvements in angular resolution (achieved through position and energy resolution), detector effective area and field of view, and background rejection. The Compton telescope relies on gamma-ray tracking to determine the incident direction of the incoming photon. If only the interaction event locations and energies are determined, the direction is only localized to a ring on the sky. However, if the direction of the recoil electron can be determined, the ring can reduced to a much smaller arc, thereby yielding a tremendous increase in source detection sensitivity. A variety of approaches incorporating both solid-state and noble gas detector technologies should be investigated to try to realize this goal. Further advances in front-end electronics, detector cooling technology, and event processing are also required.

7.3 Spacecraft systems

Accompanying the development of novel instrumental techniques, continued advances in enabling spacecraft technologies will be crucial to meeting the SEU science goals. Several of the envisioned missions (Black Hole Imager, SPECS, iARISE) incorporate interferometric systems on separate spacecraft that involve precision formation flying systems. Stringent requirements on relative positional accuracy and pointing are beyond the state of the art. MicroNewton thruster technologies, currently under development for LISA, will demand further study to determine their applicability to these other missions. Thermal and mechanical stability tolerances are very tight. The development of advanced inertial reference systems may be applicable. Cryogenic technology is important, especially for the submillimeter and far infrared systems where a cooled primary mirror (operating at ~ 5 K) is required.

Part III: Supporting the Roadmap

Chapter 8

The Explorer Program

8.1 The Explorer Program

NASA's Explorer program is a vital element of the SEU science enterprise. It offers frequent opportunities to carry out small and intermediate-sized missions which can be completed and launched on a short (approximately four-year) timeframe. Small and Medium-class Explorer (SMEX and MIDEX) missions, which are scientifically more focused than large-scale missions, can address some of the most significant scientific topics in the Structure and Evolution of the Universe theme. For example, the Microwave Anistropy Probe (MAP), a MIDEX mission, will answer fundamental questions about the age and mean matter density of the Universe, and is a vital precursor to the Inflation Probe of the Beyond Einstein program. Astro-E2, a mission of opportunity on a Japanese spacecraft, will in 2005 fly for the first time the advanced spectroscopic detectors which are prototypes of those to be flown on Constellation-X. Many other proposed Explorers are relevant to the Beyond Einstein program, ranging from missions of opportunity (e.g. attaching laser ranging equipment to missions to other planets, to enable precision tests of Relativity in the solar system) to full-fledged Explorers (tests of the equivalence principle, Lorentz invariance, radio interferometry of black holes ...).

Important SEU science for Cycles of Matter and Energy will be done by Astro-E2, and by other Explorers. The Galaxy Evolution Explorer (GALEX), a SMEX mission, will map the global history and probe the causes of star formation over 80and Photometry of the Intergalactic medium's Diffuse Radiation Explorer (SPIDR), a SMEX mission, will detect the dark matter that makes up the "cosmic web" from which the structure of the Universe evolved. SWIFT, a MIDEX mission to be launched in late 2003 is a multi-wavelength observatory dedicated to the study of gamma-ray bursts.

Contributions by future Explorer missions to our understanding of the structure and evolution of the Universe promise to be equally important. Each solicitation for proposals elicits many more high-quality experiments than can be implemented. Peer review, the ability to implement new, creative ideas and react quickly to recent scientific discoveries, is essential elements of the "faster, better, cheaper" philosophy which lies at the heart of the Explorer program. Suggesting a queue of future explorer missions would countermand this mandate.

[COULD CUT HERE IF NEEDED?]

The Microwave Anisotropy Probe (MAP), a MIDEX mission launched in June 2001, is making differential measurements of the cosmic microwave background (CMB) temperature on the full sky using pseudo-correlation radiometers coupled to back-to-back 1.4×1.6 meter primary Gregorian reflectors. Five frequency bands from 22 GHz to 90 GHz allow emission from the Galaxy to be modeled and removed. The resulting map of the sky should allow an unambiguous determination of the geometry of the Universe and of the spectrum and nature of primordial perturbations. MAP will also provide unique information that will help determine the baryon density, Hubble constant, dark-matter density, and dark energy density.

The Galaxy Evolution Explorer (GALEX), a SMEX mission to be launched in late 2002, will map the global history and probe the causes of star formation over the redshift range $0 < z < 2$, 80% of the life of the Universe, the period over which galaxies have evolved dramatically, and the time that most stars, elements, and galaxy disks had their origins.

GALEX uses the space ultraviolet to simultaneously measure redshift and star formation rate (using the UV luminosity). GALEX will perform spectroscopic and imaging surveys of the sky during its 28-month mission, measuring 100,000 galaxy spectra in one year. GALEX will launch in 2002.

SWIFT, a MIDEX mission to be launched in late 2003 is a multi-wavelength observatory dedicated to the study of gamma-ray bursts. It will monitor bursts shorter, fainter and farther away than ever before, identify their positions through their afterglows, and use them to probe the high-redshift universe.

Astro-E2 is a Japanese X-ray astronomy mission, to be launched in 2005, for which the US is supplying (under an Explorer MO) the X-ray telescopes, imaging X-ray spectrometers, and the first cryogenic X-ray micro-calorimeter in orbit. The detectors are prototypes of those to be flown on Constellation-X.

Should ACCESS (NAS survey recommendation) be mentioned here?

The main mission of the Spectroscopy and Photometry if the Intergalactic medium's Diffuse Radiation Explorer (SPIDR), a SMEX mission to be launched in early 2005, is to measure the amount of hot (10^5 to 10^6 degree) gas found between galaxies in what is referred to as the inter galactic medium (IGM). The spectrum and intensity of the gases (primarily five times ionized Oxygen and four times ionized Carbon) will be analyzed and the gathered data can be used to tell us how far away the gas is, and how much of it there is. With this information maps of the filamentary structure of the cosmic web can be made and used to shed light on many of the problems in cosmology and astronomy. including the question of how much of the unobserved dark matter lay in this form of hot gas.

Chapter 9

Research and Analysis

9.1 Research and Analysis

The SEU Research and Analysis (R&A) program gives scientists the opportunity to explore the new ideas that lead to better understanding of astrophysical concepts and methods. Such fundamental knowledge is crucial to achieving the scientific goals of the SEU program, and often goes on to form the basis for future mission concepts.

9.1.1 Experimental Research: Creating the Tools of Investigation

Experimental research supported by the R&A program is essential to the development of novel tools to do new and better science. Innovative concepts, technologies and techniques are tested in laboratory proof-of-concept demonstrations and validated through suborbital flights by balloon or rocket. This provides a rapid and cost-effective mechanism for bringing the latest technology to the point where it can be selected for use in a future SEU mission.

This leads to three principal areas of investigation:

- Hardware Development
- Suborbital Payloads
- Laboratory Astrophysics

Hardware Development

The R&A program has long been the cradle for the technology of SEU's strategic missions. It provides the springboard for innovative concepts and seminal development of detectors, optics, gratings, coatings, filters, electronics and other devices, technologies and techniques that support SEU science and future SEU missions. The R&A program is the first step in a development sequence that turns concepts into SEU missions. As such, the R&A hardware program fosters development to the proof-of-concept level. At the point when engineering issues dominate, the SEU's Technology Line provides the resources for further development. When instrument selections are made, mission-specific funding carries the instrument development to completion. This sequence provides the means for SEU mission development in a cost-effective, efficient approach that minimizes risk.

One of the prime contributions of the R&A program has been the development of detectors. X-Ray CCDs were developed under R&A and have flown on ASCA and Chandra. X-Ray microcalorimeters also have R&A heritage and are selected for flight on ASTRO-E2. CdZnTe detectors likewise owe their development to the R&A program. These are candidate detectors for Constellation-X and other missions in this Roadmap.

Future strategic missions will rely heavily on the development of optics. Hard X-Ray Optics are being developed under R&A, often employing multilayer coatings to extend the energy range. High Resolution Segmented Optics, used on ASCA, were first developed under R&A. These technologies are feeding the development of X-ray optics for Constellation-X, and the optic requirements of the Black Hole Imager will redefine the envelope for surface figure and alignment.

Nanotechnology is critical for Constellation-X and the Black Hole Imager. X-ray photons in the band of interest have a wavelength of 1 nanometer, requiring X-ray optic components shaped and assembled to ultra-high accuracy. High-resolution imaging requires optic components in the micron-size range and nano-accurate shaping and assembly technology. The high-resolution spectroscopy of Constellation-X requires diffraction gratings with nanometer periods and nano-accurate geometry control.

Past research supported by the R&A Program has developed precision phase measurement techniques and a crucial laser frequency correction algorithm known as Time Delay Interferometry, key components of LISA. The Big Bang Observatory will need performance two to three orders of magnitude better. Analogous levels of improvement will be required for disturbance reduction. While technology for LISA will be developed by the technology line and the LISA Project, the advances needed for the Big Bang Observatory must begin with the R&A Program.

The R&A hardware program is the natural site for new concepts, and as such will be crucial to the future SEU Vision Missions. It is impossible to anticipate all the areas encompassed by the program, but some future directions are:

- For SUBMILLIMETER WAVELENGTHS, large-format arrays of superconducting transition-edge sensor bolometers with SQUID readouts, cryogenic photodetectors with single-electron transistor readouts, and novel bolometer designs.
- At UV WAVELENGTHS, lithographic silicon microchannel-plate detectors with high-efficiency photocathodes and advanced readouts.
- For COSMIC RAYS, Large area, million channel, charged particle detectors. Advanced, on-board intelligent data compression systems and high-speed computing power. Low power, million channel level, acquisition electronics. Large field of view optics and fast, million-pixel, light detectors for observations of cosmic-ray showers in air fluorescence.
- For X-RAY WAVELENGTHS, large (e.g. 1000 X 1000) imaging arrays of cryogenic X-ray microcalorimeters, Ultra-large X-ray telescopes (which may require a fundamental new approach to X-ray focusing, i.e., refractive X-ray lenses, large arrays of micro-fabricated grazing incidence devices, or novel implementations of multicoated X-ray optics), and X-ray interferometric systems.
- For GAMMA-RAY WAVELENGTHS, true gamma-ray imaging (novel approaches include crystal or Fresnel lens type geometries), and advanced gamma-ray detectors (i.e., tracking the photoelectron or Compton electron associated with the primary interaction).
- For IR WAVELENGTHS, TBD.

Suborbital Program

The suborbital program produces exciting scientific results of the highest caliber while also serving as a test bed for future flight hardware and training future instrument and mission scientists. Data from the BOOMERanG and MAXIMA balloon payloads have yielded the best measurements to date of the power spectrum of the CMB temperature anisotropies.

When combined with measurements of large scale structure, these CMB data reveal a universe that is 70one of the most important and exciting results in cosmology.

The Suborbital Program (SP) provides the quick turnaround, low cost launch opportunities needed to achieve the ambitious science goals set forth by SEU. Flights via balloon or rocket (or even occasionally the Shuttle) are a crucial testbed for new capabilities and data products directly derived from the other elements of the R&A program. These launch opportunities have, in the past, been vital to mission development, leading to successful tests of key instruments on GLAST, FUSE, Chandra, XMM and ASTRO-E2.

In contrast to space missions, an R&A investigation can be carried out on a short timeline. As an example, a campaign of scientific balloon flights with gamma-ray detectors developed under the R&A program was carried out to make time-critical observations of supernova 1987A, complementing HST and Chandra observations to provide multiwavelength coverage.

The SP contributes to critical path technologies such as large ultra-lightweight mirrors, cryocoolers, deployable optics and high energy detectors. Emerging programs will provide longer duration flight testing, which is crucial for technologies requiring stable thermal or positional environments. The candidate technologies for Constellation-X draw on the suborbital program: Balloon experiments carry CdZnTe detectors and hard X-ray optics, and X-Ray microcalorimeters were first demonstrated on rocket payloads. Suborbital flights constitute a much-needed low cost, quick turnaround option for the risk prone technologies so essential to SEU mission development.

A fascinating development in the SP is the emerging capability to carry payloads of several thousand pounds for long periods at altitudes within a fraction of percent of the top of the atmopshere. For some areas of SEU science this provides a truly low cost carrier that will provide access to space that is competitive or sometimes superior to the current rocket launchers for many missions. The key elements of this Ultra Long Duration Balloon (ULDB) system are a superpressure balloon capable of 100 day flights without consumables at any latitude, active trajectory control and advanced recovery systems. The capability to fly at mid-latitudes, rather than the present, shorter polar flights, opens up the full sky for SEU science. The potential of the ULDB program has been widely recognized including an explicit recommendation by the NAS Decadal Survey for its development and operations costs.

The Suborbital program has strong involvement by universities, providing an additional return on investment: The training and education of graduate students and instrument builders for future generations of space missions. Investigators who come through the suborbital program frequently go on to become Principle Investigators of flight missions, major instrument builders, and astronauts!

Laboratory Astrophysics

By utilizing a combination of laboratory experiments, modeling, and theoretical calculations, the Laboratory Astrophysics program provides scientists with the fundamental knowledge they need in order to make sense of data collected by space missions. Lab Astro is an essential link between raw observation and the meaningful, scientific conclusions the SEU program strives towards. The program explores a tremendous breadth of topics, from the very coldest regions deep in dark molecular clouds, to the extraordinary heat around supermassive black holes. It supports NASA's space missions from conception to completion, defining mission parameters and providing post flight analysis.

The Laboratory Astrophysics program includes work on atomic and molecular energy levels, transition rates and other processes needed to interpret astrophysical spectra and physics. It encompasses all wavelengths as well as studies that have no particular wavelength-dependence (e.g., the measurement of collisional cross sections or chemical reaction rates or the laboratory study of high-energy-density physics). An up-to-date overview of current research and identified priorities in the Lab Astro program can be found at http://www.astrochemistry.org/na

In the high-energy realm, Chandra and XMM-Newton have clearly demonstrated the power of high resolution spectroscopy in X-Ray astronomy, and missions to come such as Astro-E2 and Constellation-X will emphasize this as well. The level of detail available in the grating spectra have uncovered discrepancies between observed cosmic x-ray line emission, laboratory measurements, and theoretical calculations. Plasma models of weak or blended features, such as the complex iron-line region, are often inadequate to represent the observed cosmic spectra. In order to physically interpret the cosmic emission, we need a sound laboratory and theoretical basis to support the observations. Lab Astro studies are equally necessary in other wavelengths to support the goals of SEU. In the IR-submillimeter, planned and potential future NASA missions include SAFIR, SIRTF, SOFIA, Herschel and NGST, all of which will work toward a better understanding of star formation, the galactic and extragalactic life cycle of the elements, and the molecular universe. These missions will provide observational data on spectral regions where little is known about line wavelengths, f-values, excitation cross sections, and molecular and dust physics. Lab Astro work is therefore needed over all wavelengths for determining atomic rate coefficients for physical processes, line wavelengths and the other processes needed to interpret spectra.

Another area of importance for future NASA programs and missions is the establishment and maintenance of critically compiled databases for atomic and molecular physics. In order to be of use to the general community, these data must be placed in archives and datasets that can be accessed online by the observer community. Long-term stability and on-line accessibility must be established for archival databases on atomic and molecular energy levels, rates, and other processes needed to interpret astrophysical spectra and physics.

9.1.2 Theory, Observations, and Data Analysis: Reaping the Benefits of Investment

Before any space based experiments can be designed, the scientific objectives of the SEU program must be firmly rooted in ground based observation and theoretical calculation. This, combined with later data analysis, closes the loop of scientific investigation, and is the only mechanism through which NASA can draw meaningful conclusions and ultimately achieve the goals of the SEU program.

This requires a multi-lateral effort focusing on

- Theory
- Ground-based Observation
- Archival Research

Theory

Theoretical studies are absolutely essential to the SEU program. They contribute broad understanding of the relevant questions, in addition to establishing the framework within which those questions are asked. Such studies exclusively allow scientists to make predictions, interpret and analyze data, and fully exploit observations. Theory provides the intellectual context for any scientific enterprise, and without which progress is impossible.

A strong theory program is of paramount importance for the success of Beyond Einstein. The questions that are central to Beyond Einstein challenge our understanding as strongly as the missions in this roadmap will extend the envelope of technology. Theory is not only needed to make sense of the observations, but is part of the process which drives mission design.

The burgeoning importance of gravitational wave astrophysics places new emphasis on theory in support of mission such as LISA and the Big Bang Observatory. It has been estimated that more than a hundred theorist-years of effort are required in preparation of LISA to benefit fully from the observations! Gravitational wave sources involve compact objects such as white dwarfs, neutron stars, stellar mass black holes, intermediate mass black holes and supermassive black holes, as well as extreme physics from the early Universe. The R&A Program has already supported work on these sources relevant to LISA. A future program combining theory, data analysis algorithms and strategies can fruitfully address the exciting research questions bearing on the astrophysics of these sources. Source event rates (e.g., supermassive black hole mergers, inspiral of stellar mass black holes into supermassive black holes) are currently not well constrained by theory and bear directly on the level of science that can be expected from LISA. Other relevant areas include supermassive black hole formation, black hole coalescence, the waveforms of stellar mass black holes inspiraling into supermassive black holes, templates searches for separating thousands of compact binaries in the galaxy, and calculations of cosmological backgrounds from the early Universe. The Big Bang Observatory will need the calculation of gravitational wave spectra from the early Universe predicted by candidate cosmologies.

The proposed Dark Energy Probe and Inflation Probe are concrete examples of opportunities to obtain empirical input to the leading questions of fundamental physics; the theoretical research necessary to interpret this input will require an interdisciplinary effort between cosmologists, particle physicists, astrophysicists, and gravitational physicists.

The dark energy is an observed phenomenon at a low energy scale (one thousandth of an electron volt), which is related directly to theoretical issues at the highest imaginable energies (the Planck scale, 10^{27} electron volts). The discrepancy between these scales is completely unexplained. A comprehensive theoretical program is required to link ideas in quantum gravity (including supersymmetry, extra dimensions, and string theory) to those of dynamical fields with ultra-low masses. Meanwhile, advances in astrophysical theory will be required to model and understand the phenomena which will be used as standard measuring tools by the mission (whether they be supernovae, gravitational lenses, or clusters of galaxies).

The simplest models of inflationary cosmology invoke a period of exponential expansion at an energy scale of order 10^{24} electron volts, a full twelve orders of magnitude above those of the most powerful particle accelerators. The Inflation Probe will test a primary prediction of these models, the existence of a nearly scale-free spectrum of primordial gravitational waves. If observations are consistent with simple models of inflation, we will be able to directly infer the energy scale at which it occurred. Intriguing alternatives to this picture include non-minimal inflation, extra dimensions and pre-big-bang phenomena, and direct creation of fluctuations via quantum gravity. A robust theoretical effort is required to systematically study these possibilities, and ones not yet proposed, in order that we may understand how processes in the early universe reveal themselves through cosmological perturbations, and what the resulting observations can teach us about particle physics and unification. A strong theory program also impacts mission design. Recent simulations have shown that lensing of the CMB temperature anisotropies themselves can mimic the gravity wave signal and can only be removed by making observations to much smaller angular scales than was previously thought necessary for CMB polarization measurements. *Recent progress with this problem is a direct result of NASA theory programs.* More work is needed in this area and also in modeling expected foregrounds in order to optimize the design of the Inflation Probe.

Ground-based Observations

Ground-based observations play a key role in supporting SEU science in several ways. These observations provide the possibility of multiwavelength analysis and contribute to the development and validation of techniques and instruments in support of missions.

Development, deployment and analysis of data from the next generation of ground-based Cosmic Microwave Background experiments will be essential preparation for the Inflation Probe. The Inflation Probe will require new generations of polarization-sensitive detectors which will require excellent control of systematic effects and a thorough understanding of astrophysical foregrounds. These can be achieved through experience gained in the ground-based program. (Both the MAP and Planck satellites are carrying technology that was developed as a direct result of ground based experiments.) The development of ground-based experiments is therefore an essential step towards the development of the Inflation Probe.

The scientific return of NASA missions can be greatly enhanced by multiwavelength observations across the electromagnetic spectrum, and many of these observations are best performed from the ground. Optical observations of gamma-ray burst afterglows are essential to determining the distance and the nature of these sources. The nonthermal emission of active galactic nuclei is probed by the entire spectrum from radio to optical to X-ray to gamma-ray. Correlated variability on time scales of less than a day strongly constrains the emission from and the environments around massive black holes, so that contemporaneous observations are required. These are precisely the kinds of observations that will support gamma-ray burst detections by SWIFT and AGN observations by GLAST and future X-ray survey satellites.

Archival Research

As data from previous and ongoing NASA missions mounts, so to does the value of archival research. Through the multiwavelength data already available, researchers have gained a much better understanding of a variety of important and interesting astrophysical phenomena without ever using a telescope. Though current wavelength-specific archives are readily available, they are growing exponentially in both content and diversity. The development of more sophisticated software tools would prove invaluable to scientists, permitting queries spanning all available archives and enabling valuable scientific investigations long after an observatory has ceased operation. The proposed National Virtual Observatory would constitute such a research capability, enabling investigations otherwise too resource-intensive to undertake.

Chapter 10

Critical Factors

10.1 Critical factors/External Assessment/GPRA

To enable the most productive path to uncovering the fundamental laws of the universe, we must draw upon the talents and resources of the entire research and engineering communities. This will require an integration across nations, agencies, academia, and industry that will need to follow a new model to be successful. Given the very austere budget situation as this roadmap goes to print, it is desirable to seek partnerships to ensure that we optimize the use of scarce resources in fulfilling the objectives we have before us.

It is therefore critical that this Roadmap incorporate the highest scientific priorities of the nation. The results of several recent and relevant studies by the National Acendemy of Sciences are reflected in this Roadmap. These include *Astronomy and Astrophysics in the New Millennium* (Astronomy and Astrophysics Survey Committee, C. F. McKee and J. H. Taylor, co-chairs, 2001) and *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (Committee on the Physics of the Universe, M. S. Turner, chair, 2002).

A long-term partnership among government instrumentalities that includes the Department of Energy and the National Science Foundation is necessary: we share resources, and the final fruits of our research labors. There are several opportunities for collaboration that take advantage of the strength of each partner. In addition, the collective knowledge of our universities engaged in astrophysical research will be tapped to its fullest in developing future missions. NASA will function in several ways; as the lead on some of the more complex missions, as the enabler and facilitator in several other missions, reliant upon academic, industrial and international partnerships to attain the priorities of the National Academy of Sciences. Collaborations with international partners will be sought whenever possible so as to further maximize the use of existing capabilities, and to minimize duplication of efforts. For example LISA has been proposed as a 50/50 split between NASA and the European Space Agency and its member states, with each partner bringing its greatest strengths.

New knowledge must be exported quickly to the general public and as a part of the Agency's new education initiative, we will undertake alliances with the education and communications communities to ensure that our discoveries become embedded in the lexicon and consciousness of the masses. This will require a concerted effort and investments in the processes and institutions to bring as many people along the journey of discovery as we can.

The manner in which we pursue science will require a greater level of integration with other disciplines. The traditional boundaries of disciplinary science will need to be broken down in order to facilitate information sharing and building of models that are broader in scale. The Beyond Einstein Program brings NASA to the frontiers of fundamental physics. Many of the envisaged missions will involve experimental and theoretical physicists supported by DOE and NSF. Another example would be the initiative to understand how life formed in the midst of the evolving universe. A greater sharing of information to create models that link processes of fundamental physics with chemical and biological processes in the formation of pre-biotic and emergent life forms is required. This may also involve a new way of organizing information for teaching the sciences to both the specialized communities as well as an interested citizenry.]

Technology is often the throttle by which the pace of progress is controlled. The Agency faces a shortfall in technology investment funds that are critical to the development of future missions. (NEED HELP HERE) Furthermore, investments in the infrastructure necessary to communicate, organize and share the information gleaned from these new missions must be made in order to ensure the widest audience has access to the information. This will require continual investment in the Deep Space Network, supporting orbital and ground networks, data archival and distribution networks, as well as high speed ground links.

The Agency must find new ways in which to collaborate with industry and to enable the development of critical technologies. Where shared investment makes sense, we need to create the institutions or the contractual mechanisms that will allow such initiatives to proceed expeditiously. A new paradigm is required that allows the government to continue to invest in high risk areas, but which also plants seeds for "almost ready" technologies that have both government and commercial application, and allows for leveraged investment to accelerate these innovations into the marketplace.

The availability of launch delivery systems for future probes is a continuing concern. Investments in future launch vehicles and supporting infrastructure is needed. This would include infrastructure used primarily to test new instrumentation as well as providing launch conveyances such as the orbiting Ultra-long Duration Balloons and the associated supporting ground systems. The community also relies upon Long Duration Balloons from Antarctica, and recognizes the importance of the National Science Foundation's role in continuing to support the launch infrastructure there.

Chapter 11

Last Word

11.1 Last Word: SCIENCE BEYOND EINSTEIN

NASA's Vision:

— To improve life here,

— To extend life to there,

— To find life beyond.

NASA's Mission:

— To understand and protect our home planet.

— To explore the Universe and search for life.

— To inspire the next generation of explorers —as only NASA can.

Beyond Einstein is a bold attack on the most basic and challenging of today's science issues. It will study the underlying laws of nature that govern the assemblage of the building blocks of life. It will investigate the extreme conditions near black holes. And it will uncover important relics of the birth of the universe. Together, these studies will help us to understand why the nature of the universe permits the existence of life, the likely future of the universe, and even the apparently complicated nature of the vacuum that remains when matter is removed.

The missions involved will enable human beings to explore environments completely different from those they experience on Earth and even in our solar system. They will extend our senses to the edges of black holes and the very beginnings of the universe itself. This quest will inspire all humanity with the images and knowledge gained from this cosmic journey.

Late 19th century observations raised basic questions about the universe and the nature of space and time. Einstein and others provided early 20th century answers. It was not until the late 20th century that we had the technology to verify those answers. In doing so deeper questions arose. *Beyond Einstein* will provide 21st century answers to those deeper questions.

> "The most beautiful thing we can experience is the mysterious. It is the source of all true art and science. Those to whom this emotion is a stranger, who can no longer pause to wonder and stand rapt in awe, are as good as dead: their eyes are closed."
> —*Albert Einstein*

Appendix A

Appendices

A.1 Acronyms, Glossary

A.2 Contributors to the Roadmap:

The SEU Roadmap Team	
E. Sterl Phinney —Chairman	California Institute of Technology
Joel N. Bregman	University of Michigan
Sean Carroll	University of Chicago
Sarah Church	Stanford University
Lynn R. Cominsky	Sonoma State Univ.
Charles D. Dermer	Naval Research Lab
Wendy Freedman	Carnegie Observatories
Roy R. Gould	Harvard-Smithsonian Center for Astrophysics
Craig J. Hogan	University of Washington
Steven M. Kahn	Columbia University
Dan Lester	University of Texas
Robert March	University of Wisconsin
Michael Shull	University of Colorado
Simon Swordy	University of Chicago
Nicholas White	NASA/Goddard Space Flight Center
Harold W. Yorke	Jet Propulsion Lab
Ex-Officio Members:	
Paul Hertz (SEU Theme Scientist)	NASA HQ
Rocky Kolb (SEUS Chairman)	Fermilab
Paul DeMinco	NASA/GSFC
Michael Salamon	NASA HQ
Chris Schwartz	NASA/GSFC
Technology subgroup	
Steven M. Kahn —Chairman	Columbia University
Jamie Bock	NASA/JPL
Kathryn Flanagan	MIT
Dan McCammon	University of Wisconsin
Michael Moore	NASA HQ
Harvey Moseley	NASA/GSFC
Steve O'Dell	NASA/MSFC
Chris Schwartz	NASA/GSFC
Phil Stahl	NASA/MSFC
Simon Swordy	University of Chicago
Education/Public Outreach subgroup	
Roy R. Gould —Chairman	Harvard-Smithsonian Center for Astrophysics
James Lochner	NASA/GSFC

A.3 Index?