Appendix A. Mapping of Science Objectives and Research Focus Areas to Investigations

Science Objective 1: Find out what powered the Big Bang.

Research Focus Area 1. Search for gravitational waves from inflation and phase transitions in the Big Bang.

- Search for gravitational wave emission from the early Universe
- Detect the signature of gravitational waves from the Big Bang
- Directly detect gravitational waves from the Big Bang

Research Focus Area 2. Determine the size, shape, and energy content of the Universe.

- Measure gravitational wave energy content of the Universe
- Measure the matter and energy content and the shape of the Universe
- Measure the geometry of the Universe using merging black holes as self-calibrated candles
- Map the polarization of the cosmic microwave background and determine sources of this polarization of both large and small scales
- Accurately determine the amount of dark energy in the Universe
- Directly determine the expansion history of the Universe by timing binaries throughout the Universe
- Measure the amount of quantum fluctuation and graviton fluctuation during inflation

Science Objective 2: Observe how black holes manipulate space, time, and matter.

Research Focus Area 3. Perform a census of black holes throughout the Universe.

- Perform an imaging census of accreting black holes, including hidden black holes, in the local Universe
- Determine the masses and spins of accreting massive black holes through observation of broadened emission line from matter near the black hole
- Determine the masses and spins of supermassive black holes through measurement of their gravitational waves
- Observe gravitational radiation from all merging neutron stars and stellar-mass black holes

Research Focus Area 4. Determine how black holes are formed and how they evolve.

- Observe gravitational waves from merging black holes
- Investigate how matter releases energy close the event horizon
- Perform population studies of the life cycle of black holes
- Trace the evolution of supermassive black holes in active galaxies
- Study the role of massive black holes in galaxy evolution through the detection of black hole mergers
- Observe gravitational waves from the formation of black holes

Research Focus Area 5. Test Einstein's theory of gravity and map spacetime near the event horizons of black holes and throughout the Universe.

- Observe the gravitational redshift of line emission from gas as it enters a black hole
- Determine the spacetime geometry down to the event horizon by detecting gravitational radiation from compact stars spiraling into supermassive black holes
- Test Einstein's theory of relativity under extreme conditions, such as merging supermassive black holes
- Observe gravitational radiation from the formation of black holes and other singularities
- Map the motions of gas near the event horizons of black holes

Research Focus Area 6. Observe stars and gas plunging into black holes.

- Dynamically observe the behavior of gas as it enters a black hole
- Investigate how matter releases energy close the event horizon
- Observe compact stars spiraling into supermassive black holes through their gravitational radiation
- Discover ordinary stars being torn apart as they approach black holes
- Observe the gravitational radiation from stars plunging into black holes throughout the Universe
- Map the motions of gas as it enters a black hole
- Map the release of energy in black hole accretion disks
- Determine how relativistic jets are produced and the role of black hole spin in this process

Science Objective 3: Identify the mysterious dark energy pulling the Universe apart.

Research Focus Area 2. Determine the size, shape, and energy content of the Universe.

- Measure the matter and energy content and the shape of the Universe
- Accurately determine the amount of dark energy in the Universe

Research Focus Area 7. Determine the cosmic evolution of the dark energy pulling the Universe apart.

- Measure the equation of state of dark energy
- Measure the cosmic evolution of dark energy
- Accurately determine the amount of dark energy in the Universe
- Directly determine the expansion history of the Universe by timing binaries throughout the Universe

Science Objective 4: Explore the cycles of matter and energy in the evolving Universe.

Research Focus Area 8. Determine how, where, and when the chemical elements were made.

- Observe the formation of the first generation of stars
- Determine the explosion mechanisms in supernovae where the heavy elements are created

Research Focus Area 9. Understand how matter, energy, and magnetic fields are exchanged between stars and the gas and dust between stars.

- Observe the formation of the first generation of stars
- Observe the evolution of the heavy elements through the history of the Universe
- Determine the role of black holes in the formation of galaxies
- Measure the nuclear burning and dynamics of supernovae

Research Focus Area 10. Discover how gas flows in disks and how cosmic jets are formed.

- Observe the emission from accretion disks around compact objects in all relevant bands of the electromagnetic spectrum
- Observe the motions of material flowing around the black hole at the center of the Milky Way galaxy
- Determine the physical processes giving rise to the formation of cosmic jets

Research Focus Area 11. Identify the sources of gamma-ray bursts and cosmic rays.

- Enhance our understanding of the physical processes that give rise to gamma-ray bursts
- Identify the high-energy cosmic rays
- Determine the amount and origin of the highest-energy cosmic rays

Science Objective 5: Understand the development of structure in the Universe.

Research Focus Area 12. Discover how the interplay of baryons, dark matter, and gravity shapes galaxies and systems of galaxies.

- Observe the formation of the first generation of stars and galaxies
- Observe the formation of the first heavy elements in supernovae in the early Universe
- Determine the role of black holes in the formation of galaxies
- Determine the role of dark matter in the formation of galaxies

Research Focus Area 13. Explore the behavior of matter in extreme astrophysical environments.

- Observe extremes of density, pressure, temperature, and field energy in compact objects
- Determine the physical processes giving rise to the formation of cosmic jets
- Measure the nuclear burning and dynamics of supernovae
- Map sources of annihilation radiation in the Milky Way galaxy and nearby galaxies

Research Focus Area 2. Determine the size, shape, and energy content of the Universe.

- Observe the formation of the first generation of stars and galaxies
- Map the dark matter in the Universe
- Detect the absorption of light from distant quasars by dark matter

Research Focus Area 4. Determine how black holes are formed and how they evolve.

- Enhance our understanding of the physical processes that give rise to gamma ray bursts
- Observe the emission from accretion disks around compact objects in all relevant bands of the electromagnetic spectrum
- Determine the role of black holes in the formation of galaxies

Appendix B. Acronyms

AASC ..... Astronomy and Astrophysics Survey Committee of the National Academy of Sciences

AGN ..... Active Galactic Nuclei

ALMA ..... Atacama Large Millimeter Array (NSF/Europe, planned)

ASCA ..... Advanced Satellite for Cosmology and Astrophysics, Japan/NASA (defunct)

Astro-E2 ..... An X-ray and gamma-ray satellite jointly developed by the US and Japan (planned)

BE ..... Beyond Einstein

Beppo-SAX ..... Satellite per Astronomia, Italy/Netherlands (operating)

BOOMERanG ..... Balloon Observations Of Millimetric Extragalactic Radiation and Geophysics (defunct & 2003)

CCD ..... Charge Coupled Device. A solid state detector of electromagnetic radiation, pioneered in the 1970s for military and astronomical use now also found in consumer digital cameras.

CGRO ..... Compton Gamma-ray Observatory (defunct)

Chandra ..... Chandra X-ray Observatory (operating)

CMB ..... Cosmic Microwave Background

COBE ..... Cosmic Background Explorer (defunct)

Con-X ..... Constellation X-ray Mission (planned)

CPU ..... Comittee on the Physics of the Universe of the NAS

DOE ..... Department of Energy

EGRET ..... Energetic Gamma Ray Experiment Telescope on CGRO.

ESA ..... European Space Agency

FUSE ..... Far Ultraviolet Spectroscopic Explorer (operating)

GALEX ..... Galaxy Evolution Explorer (2003)

GLAST ..... Gamma Ray Large Area Telescope

GPB ..... Gravity Probe B (2003)

GRACE ..... Gravity Recovery and Climate Experiment, NASA/Germany (operating)

GRB ..... Gamma-ray burst.

Herschel ..... ESA/NASA far infrared mission (planned)

HST ..... Hubble Space Telescope (operating)

INTEGRAL ..... International Gamma-Ray Astrophysics Laboratory, ESA/Russia/NASA (operating)

JWST ..... James Webb Space Telescope (formerly Next Generation Space Telescope - NGST, planned)

LIGO ..... Laser Interferometer Gravitational-wave Observatory, NSF (operating)

LISA ..... Laser Interferometer Space Antenna (planned)

MIDEX ..... Medium-class Explorers. The most expensive class of

NASA Explorer mission.

NAS ..... National Academy of Sciences

NASA ..... National Aeronautics and Space Administration

NGC ..... J.L.E. Dreyer's 1887 New General Catalog (of nebulae and bright galaxies)

NICMOS ..... Near Infrared Camera and Multi-Object Spectrometer on the Hubble Space Telescope

NSF ..... National Science Foundation

OSS ..... Office of Space Science (NASA)

PI ..... Principal Investigator

Planck ..... ESA/NASA cosmic microwave background mission (planned)

ROSAT ..... Röntgen (X-ray) Satellite, Germany (defunct)

RXTE ..... Rossi X-ray Timing Experiment (operating)

SEU ..... Structure and Evolution of the Universe (OSS Theme)

SIRTF ..... Space Infra-red Telescope Facility (2003)

SMEX ..... Small Explorers. The less expensive class of NASA Explorer mission.

SNAP ..... Supernova/Acceleration Probe, DOE (planned)

SOFIA ..... Stratospheric Observatory for Infra-red Astronomy, NASA/Germany (planned)

SMART-2 ..... ESA Small Mission for Advanced Research in Technology 2: LISA Test Package (planned)

SPIDR ..... Spectrometry and Photometry of the Intergalactic mediums' Diffuse Radiation (planned)

ST7 ..... Space Technology 7. NASA Disturbance Reduction System technology project. (planned)

Swift ..... A multi-wavelength gamma-ray observatory (2003)

ULDB ..... Ultra-Long Duration Balloons

VLBI ..... Very Long Baseline (radio) Interferometry

WMAP ..... Wilkinson Microwave Anisotropy Probe (operating)

XMM ..... X-ray Multi-mirror Mission, ESA/NASA (operating)

"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

Appendix C. Glossary of Terms

Accretion. Accumulation of dust and gas onto larger bodies such as stars, planets, and moons.

Accretion Disk. A relatively flat sheet of dust and gas surrounding a newborn star, a black hole, or any massive object growing in size by attracting material.

Active Galactic Nuclei (AGN). A core region in certain galaxies that, like a powerful engine, spews large amounts of energy from its center. Believed to be powered by the accretion of matter onto black holes.

Baryon. Any subatomic particle of half-integral spin that interacts via the strong nuclear force. (Most commonly, these are protons and neutrons.) The term "hadron" includes the lighter integer spin mesons as well the half-integral spin baryons.

Big Bang. A theory of cosmology in which the expansion of the Universe is presumed to have begun with a primeval explosion.

Big Bang Observer. A *Beyond Einstein* gravitational wave detector vision mission.

Brane. An object or subspace in string theory that can have various spatial dimensions. A 1-brane is a string; a 2-brane is a surface or membrane; a p-brane has lengths in p dimensions.

Brane World. A four-dimensional surface (brane) in a higher-dimensional spacetime.

Black Hole. An object whose gravity is so strong that not even light can escape from it.

Black Hole Imager. A *Beyond Einstein* X-ray interferometer vision mission.

Coded aperture mask. A plate with both opaque and transparent elements placed in front of a position-sensitive gamma-ray detector. Sources at different places in the sky cast shadows of the grid at different positions on the detector, allowing an image of the entire sky to be reconstructed, with an angular resolution set by the size of the mask elements.

Cosmic Background Radiation. Radiation of the cosmos left over from the Big Bang.

Cosmological Constant. A term Einstein added to his equations of the general theory of relativity, to account for an apparently non-expanding Universe, but later rejected when Hubble's observations seemed to indicate it was not needed. Can be interpreted as a special form of Dark Energy.

Cosmology. The astrophysical study of the history, structure, and dynamics of the universe.

Dark Energy. The residual energy in empty space which is causing the expansion of the Universe to accelerate. Einstein's Cosmological Constant was a special form of dark energy.

Dark Matter. Mass whose existence is deduced from the analysis of galaxy rotation curves and other indirect evidence but which has so far escaped direct detection.

Doppler Effect. An observer receives sound and light from bodies moving away from her with lower frequency and longer wavelength than emitted (see Redshift) and from bodies moving toward her with higher frequency and shorter wavelength. The shift in frequency increases as the speed of the body increases.

eV. Electron Volt. The energy an electron has after being accelerated by a 1 volt potential. Quanta of visible light (photons) have energies of a few eV.

Event Horizon. The boundary of the region around a black hole from which nothing can escape once crossed.

General relativity. The theory of gravitation developed by Albert Einstein incorporating and extending the theory of special relativity and introducing the principle that gravitational and inertial forces are equivalent.

Graviton. The quantum particle, associated with gravitational waves, which carries the gravitational force.

Inflation. Postulated period in the very early Universe of extremely rapid expansion, inflating what is now the observable Universe from an atomic size to its cosmological size in a fraction of a second. This process makes the Universe very smooth and flat, as observed.

Interferometry. The use of interference phenomena of light waves to measure distances and angles between objects.

Jets. Beams of energetic particles, usually coming from an active galactic nucleus or a pulsar.

keV. kilo electron Volt. A unit of energy equal to one thousand **eV.** X-ray photons have energies of 0.1-100 keV.

L2. The second of five Lagrangian equilbrium points, approximately 1.5 million kilometers beyond Earth, where the gravitational forces of Earth and Sun balance to keep a satellite at a nearly fixed position relative to Earth..

Light Year. The distance light travels in a year (9.5 million million kilometers, or 5.9 million million miles).

MeV. Mega electron Volt. A unit of energy equal to one million **eV.** Gamma-ray photons are those with energies greater than 0.1 MeV, equal to 100 keV.

Neutron Star. The imploded core of a massive star remaining after a supernova explosion. Contains about the mass of the Sun in less than a trillionth of the Sun's volume.

Parsec. The distance to an object that has a parallax of one arcsecond (equivalent to 3.26 light years).

Polarization. A property of light in which the planes of vibration of the (electric field of the) light are at least partially aligned.

Pulsar. A rotating neutron star which generates regular pulses of radiation.

Quantum Mechanics. The well-tested theory of the behavior of matter on the microscopic scales of atoms and computer chips, where the constituents of matter behave simultaneously like waves and particles.

Quasar. Enormously bright objects at the edge of our Universe that emit massive amounts of energy and are likely powered by black holes.

Redshift. An apparent shift toward longer wavelengths of spectral lines in the radiation emitted by an object caused by motion of the emitting object away from the observer.

Singularity. A place where spacetime becomes so strongly curved that the laws of Einstein's general relativity break down and quantum gravity must take over. Found inside black holes and perhaps at the beginning of the Big Bang.

Spectroscopy. The study of spectral lines (light given off at a specific frequency by an atom or molecule) from different atoms or molecules that can indicate the chemical composition of stars, gas, or dust.

String Theory. A theory that what we perceive as particles are actually vibrations on strings or membranes in a 10- or 11-dimensional space, respectively. These theories resolve the incompatibility between general relativity and quantum mechanics and unify them.

z. The symbol for the amount of redshift. The ratio of the observed change in wavelength of light emitted by a moving object to the rest wavelength of the emitted light. The most distant known galaxies and quasars have values of $z = 6$ or greater.

Appendix D. Sources of Further Information

- NASA Office of Space Science
  http://spacescience.nasa.gov/
- Structure and Evolution of the Universe Theme
  http://universe.nasa.gov/
- Laser Interferometer Space Antenna (LISA)
  http://lisa.nasa.gov/
- Constellation-X
  http://constellation.gsfc.nasa.gov/
- Space Technology 7
  http://nmp.jpl.nasa.gov/st7/
- Astro-E2
  http://astroe.gsfc.nasa.gov/docs/astroe/astroegof.html
- High Energy Physics
  http://doe-hep.hep.net/
  http://doe-hep.hep.net/HEPAP/lrp_report0102.pdf
- Laboratory Astrophysics
  http://web99.arc.nasa.gov/~astrochem/nasalaw/whitepaper.html
- Chandra X-ray Observatory
  http://chandra.harvard.edu/
- Rossi X-ray Timing Explorer (RXTE)
  http://heasarc.gsfc.nasa.gov/docs/xte/xte_1st.html
- Wilkinson Microwave Anisotropy Probe (WMAP)
  http://map.gsfc.nasa.gov/
- Gamma-ray Large Area Space Telescope (GLAST)
  http://glast.gsfc.nasa.gov/
- Gravity-Probe B
  http://einstein.stanford.edu/
- Swift
  http://swift.gsfc.nasa.gov/
- Planck
  http://sci.esa.int/home/planck/

"The effort to understand the Universe is one of the very few things that lifts human life a little above the level of farce, and gives it some of the grace of tragedy."
—Steven Weinberg
[Nobel Prize, 1979]

Appendix E. Contributors to the Roadmap

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