New Worlds, New Horizons
in Astronomy and Astrophysics

NAC – Sci 28 Sep 2010
U.S. Decadal Surveys

• 1964: Ground-based Astronomy: A Ten Year Program (Whitford)

• 1972: Astronomy and Astrophysics for the 1970s (Greenstein)

• 1982: Astronomy and Astrophysics for the 1980s (Field)

• 1991: The Decade of Discovery in Astronomy and Astrophysics (Bahcall)

• 2001: Astronomy and Astrophysics in the New Millennium (McKee-Taylor)

• 2010: New Worlds, New Horizons in Astronomy and Astrophysics
The Committee on Astro2010 will survey the field of space- and ground-based astronomy and astrophysics, recommending priorities for the most important scientific and technical activities of the decade 2010-2020. The principal goals of the study will be to carry out an assessment of activities in astronomy and astrophysics, including both new and previously identified concepts, and to prepare a concise report that will be addressed to the agencies supporting the field, the Congressional committees with jurisdiction over those agencies, the scientific community, and the public.

Scope

- NASA, NSF, DOE
- Remote observing of cosmos, theory, physics, computation and simulation, laboratory astrophysics, solar astronomy (excluding space missions), and technology development
- Activities and infrastructure (broadly defined)
- Balance
- Partnerships: international, private, state ….
Astro2010

Charge led to

• Significant community engagement
• Science First
• Independent analysis of risk, technical readiness, schedule, and life cycle costs.
• Recommended program under different budgetary scenarios
• Consideration of unstarted projects from previous surveys - no “grandfathering”
Community Input

An unprecedented response

- 324 Science White Papers (a unique snapshot of the field)
- 69 State Of The Profession Position Papers
- 70 White Paper on Technology Development, Theory, Computation, and Laboratory Astrophysics
- 108 Community Responses to a Request for Information on Research Activity Proposals
- Email Inputs to the Committee
- Community-organized Town Halls
New for this Survey

• Consideration of the key science themes was done by a group separate from those considering projects. The science deliberations were done first.

• Projects recommended by earlier Surveys but not completed were assumed to be part of the process unless they were already well underway. There were no grandfathered projects.

• Medium and large recommended activities would be subjected to an independent risk assessment and cost appraisal.

• The recommended program would need to fit within a plausible budget profile.

• DOE joined NASA and NSF in providing funding for the execution of the Survey.
Approach

The three pillars of the survey

- Astro2010: Science Frontiers
- Astro2010: State of the Profession / Infrastructure
- Astro2010: Activities / Program Prioritization

Some features of Astro2010

- Started with the science
- Solicited and received unprecedented community buy in to process
- Includes unstarted projects from previous surveys
- Improved assessment of technical readiness and risk, and cost drivers
- Changing economic political background and increased international and private collaboration
Astro2010 Committee

Roger Blandford, Chair, Stanford University
Lynne Hillenbrand, Executive Officer, California Institute of Technology

Subcommittee on Science
Martha P. Haynes, Vice Chair – Science Frontiers, Cornell University
Lars Bildsten, University of California, Santa Barbara
John E. Carlstrom, The University of Chicago
Fiona A. Harrison, California Institute of Technology
Timothy M. Heckman, Johns Hopkins University
Jonathan I. Lunine, University of Rome Tor Vergata
Juri Toomre, University of Colorado at Boulder
Scott D. Tremaine, Institute for Advanced Study

Subcommittee on State of the Profession
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Debra M. Elmegreen, Vassar College
Joshua Frieman, Fermi National Accelerator Laboratory
Robert C. Kennicutt, Jr., University of Cambridge
Dan McCammon, University of Wisconsin-Madison
Neil de Grasse Tyson, American Museum of Natural History

Subcommittee on Programs
Marcia J. Rieke, Vice Chair – Program Prioritization, University of Arizona
Steven J. Battel, Battel Engineering
Claire E. Max, University of California, Santa Cruz
Steven M. Ritz, University of California, Santa Cruz
Michael S. Turner, The University of Chicago
Paul Adrian Vanden Bout, National Radio Astronomy Observatory
A. Thomas Young, Lockheed Martin Corporation [Retired]
Science Frontier Panels

Planetary Systems and Star Formation (PSF) - Lee Hartmann
- Solar system bodies (other than the Sun) and extrasolar planets, debris disks, exobiology, formation of individual stars, protostellar and protoplanetary disks, molecular clouds and the cold ISM, dust, and astrochemistry.

Stars and Stellar Evolution (SSE) - Roger Chevalier
- The Sun as a star, stellar astrophysics, structure and evolution of single and multiple stars, compact objects, supernovae, gamma-ray bursts and solar neutrinos. Extreme physics on stellar scales.

The Galactic Neighborhood (GAN) - Mike Shull
- Structure and properties of nearby galaxies including the Milky Way and their stellar populations, interstellar media, star clusters. Evolution of stellar populations.

Galaxies across Cosmic Time (GCT) - Meg Urry
- Formation and evolution of galaxies and galaxy clusters, active galactic nuclei and QSOs, mergers, star formation rate, gas accretion, global properties of galaxies and galaxy clusters, supermassive black holes.

Cosmology and Fundamental Physics (CFP) - David Spergel
- Early universe, microwave background, reionization and galaxy formation up to virialization of protogalaxies. Large scale structure, intergalactic medium, determination of cosmological parameters, dark matter, dark energy. High energy physics using astronomical messengers, tests of gravity, physical constants as determined astronomically.
The Science Frontier
discovery areas and principal questions

Discovery areas:
- Identification and characterization of nearby habitable exoplanets
- Gravitational wave astronomy
- Time-domain astronomy
- Astrometry
- The epoch of reionization

Questions:
- How did the universe begin?
- What were the first objects to light up the universe and when did they do it?
- How do cosmic structures form and evolve?
- What are the connections between dark and luminous matter?
- What is the fossil record of galaxy assembly and evolution from the first stars to the present?
- How do stars and black holes form?
- How do circumstellar disks evolve and form planetary systems?
- How do baryons cycle in and out of galaxies and what do they do while they are there?
- What are the flows of matter and energy in the circumgalactic medium?
- What controls the mass-energy-chemical cycles within galaxies?
- How do black holes work and influence their surroundings?
- How do rotation and magnetic fields affect stars?
- How do massive stars end their lives?
- What are the progenitors of Type Ia supernovae and how do they explode?
- How diverse are planetary systems and can we identify the telltale signs of life on an exoplanet?
- Why is the universe accelerating?
- What is dark matter?
- What are the properties of the neutrinos?
- What controls the masses, spins and radii of compact stellar remnants?
Science Objectives

• Building on the science priorities identified by the survey, the recommended program is organized by three science objectives that represent its scope:
  – Cosmic Dawn
  – New Worlds
  – Physics of the Universe

• Success in attaining these science goals will enable progress on a much broader front

• Also foster unanticipated discoveries
Cosmic Dawn
Searching for the first stars, galaxies, and black holes

- We have learned much about the history of the universe, from the Big Bang to today
- A great mystery now confronts us: when and how the first galaxies formed and the earliest stars started to shine - our cosmic dawn
- JWST, ALMA and radio telescopes already under construction will help point the way
- Approaches:
  - Locating “reionization” – finding the epoch ~0.5 billion years, when light from the first stars split interstellar hydrogen atoms into protons and electrons
  - “Cosmic paleontology” – finding the rare stars with the lowest concentrations of heavy elements
New Worlds
Seeking nearby, habitable planets

- Nearly 500 extrasolar planets now detected - extraordinarily rapid progress
  - Huge range of properties exhibited, surprisingly different from those in our own solar system
  - Many ongoing approaches seek new “Earths” – potentially habitable rocky planets with liquid water and oxygen
  - New techniques being developed
- Kepler data adds over 500 "candidates" to the list, including many less than twice the size of Earth
- Next great step forward: understand frequency of different types of planets and lay scientific and technical groundwork to inform future strategies for detailed study of nearby Earth-like planets
Physics of the Universe
Understanding Scientific Principles

- Determine properties of dark energy, responsible for perplexing acceleration of present-day universe
- Reveal nature of mysterious dark matter, likely composed of new types of elementary particles
- Explore epoch of inflation, earliest instants when seeds of structure in the universe were sown
- Test Einstein’s general theory of relativity in new important ways by observing black hole systems and detecting mergers
Infrastructure Study Groups

Computation, Simulation, & Data Handling (CDH) – Robert Hanisch & Lars Hernquist
- Computational resources and support for analysis and archiving of astronomical data; resources and support available for astrophysical and cosmological simulation; major challenges and changes in computing environments and software; expected availability of computing capability over the next decade.

Demographics (DEM) – James Ulvestad
- Numbers of astronomers and astrophysicists working in different environments and subfields; diversity, geography and student populations; breakdown of resource allocation by field, discipline and cost category where possible; subscription rates for programs; publication rates.

Facilities, Funding and Programs (FFP) – J. Craig Wheeler
- List major operational public and private facilities, their capabilities, ages, and proposal pressure; budgets for all agency programs; infrastructure issues such as support for laboratory astrophysics and technology development and theory.

International and Private Partnerships (IPP) – Robert Dickman
- Lessons learned; scope and current status of relevant major projects in development; summarize lessons learned to promote successful collaborations.

Education & Public Outreach (EPO) – Lucy Fortson & Chris Impey
- Public communication programs; astronomy in K-12 and college education; professional education for astronomers, journalists and science policy experts.

Astronomy & Public Policy (APP) – Daniel Lester
- Benefits to the nation that accrue from federal investment; contributions made to important research of societal importance; current structure of committees and reporting lines that are used to provide advice to the federal government.
International Matters

• Astronomy is more collaborative, international and interdisciplinary than ever. Most major facilities and spacecraft are multi-national and/or public/private

• Principle of open skies is compatible with maximizing scientific output

• RECOMMENDATION: U.S. investors in astronomy and astrophysics, both public and private, should consider a wide range of approaches to realize participation in international projects and to provide access for the U.S. astronomy and astrophysics community to a larger suite of facilities than can be supported within the United States. The long-term goal should be to maximize the scientific output from major astronomical facilities throughout the world, a goal that is best achieved through opening access to all astronomers.
International Matters

• Globalization of astronomy mandates streamlined strategic planning

• The practical step is to formalize the coordination and sharing of regional strategic plans at the highest level

• RECOMMENDATION: Approximately every 5 years the international science community should come together in a forum to share scientific directions and strategic plans, and to look for opportunities for further collaboration and cooperation, especially on large projects.
Stewardship of the Survey

• Several recommendations in this report are conditional upon technical developments, outcomes of scientific observing programs and decisions taken by international and private partners over the next five years.

• It is imperative that the agencies receive the best independent strategic advice in a timely manner to assess progress toward the recommended goals and to make deferred choices.

• RECOMMENDATION: NASA, NSF, and DOE should on a regular basis request advice from an independent standing committee constituted to monitor progress toward reaching the goals recommended in the decadal survey of astronomy and astrophysics, and to provide strategic advice to the agencies over the decade of implementation. Such a Decadal Survey Implementation Advisory Committee (DSIAC) should be charged to produce annual reports to the agencies, the Office of Management and Budget, and the Office of Science and Technology Policy, as well as a mid-decade review of the progress made. The implementation advisory committee should be independent of the agencies and the agency advisory committees in its membership, management, and operation.
Optimizing the Recommended Program

- Prioritizing based on science objectives
- Building upon existing astronomical enterprise
- Evaluating cost risk and technical readiness
- Maximizing scientific return under highly constrained budget guidelines
- Choosing most urgently needed activities from long list of compelling ideas and concepts
- Considering international and private partnerships
Balancing the Program

- Large and small/medium activities
- Existing and new facilities
- Known science objectives and discovery space
- Promise vs. risk
- Ground and Space
- 2020 and 2030
Program Prioritization Panels

Radio, Millimeter and Submillimeter from the Ground (RMS) - Neal Evans
- Observatories and telescopes that observe primarily in these wavebands

Optical and Infrared Astronomy from the Ground (OIR) - Pat Osmer
- Observatories and telescopes that observe primarily in these wavebands

Electromagnetic Observations from Space (EOS) - Alan Dressler
- All space-based astronomical projects observing the electromagnetic spectrum.

Particle Astrophysics and Gravitation (PAG) - Jackie Hewitt
- All projects exploring areas at the interface of physics and astronomy such as gravitational radiation, TeV gamma-ray astronomy, and free-flying space missions testing fundamental gravitational physics.
Cost, Risk, and Technical Evaluation

- Early call for Notices of Intent followed by open Request for Information
  - Activities selected by PPPs and committee for a 2nd Request for Information

- Subset selected by PPPs and committee for CATE review
  - Independent cost appraisals
  - Evaluations of technical readiness schedule and risk assessment
What CATE is and isn’t

• Is:
  • Based on detailed project input
  • Application of uniform and historical data-informed risk analysis
  • Independent appraisal of project budget, schedule and technical risk
  • Considerate of a wide range of maturity in the concepts with respect to total life cycle, including “pre-Phase A” and designed to be fair and neutral
  • Projection through the decade considering potential cost/schedule growth
  • Probabilistic assessment of required reserves and identification of cost/schedule liens and threats
  • Generation of a 70% confidence cost appraisal
  • Input to the committee and program prioritization panels

• Is Not:
  • A bottoms-up costing exercise
  • A traditional non-advocate ICE (Independent Cost Evaluation) or TMC (Technical, Management, Cost) process which generally occur later in project lifecycles.
Large Scale Space Program - Prioritized

1. Wide Field InfraRed Survey Telescope (WFIRST)

1. Explorer Program Augmentation

2. Laser Interferometer Space Antenna (LISA)

3. International X-ray Observatory (IXO)
WFIRST - Science

Near infrared wide-field telescope with a set of key science objectives:

- **Dark energy** (part of a coherent ground-space strategy):
  - Baryon acoustic oscillations
  - Distant supernovae
  - Weak lensing

- **Exoplanet statistics**
  - Gravitational microlensing

- Guest investigator mode enabling survey investigations
WFIRST and Exoplanets

WFIRST open up a new frontier of exoplanet studies by monitoring a large sample of stars in the central bulge of the Milky Way for changes in brightness due to microlensing by intervening solar systems. This census, combined with that made by the Kepler mission will determine how common Earth-like planets are over a wide range of orbital parameters.
WFIRST and Dark Energy

An equally important outcome will be to settle fundamental questions about the nature of dark energy, the discovery of which was one of the greatest achievements of U.S. telescopes in recent years. It will employ three distinct techniques—measurements of weak gravitational lensing, supernova distances, and baryon acoustic oscillations—to determine the effect of dark energy on the evolution of the universe.
WFIRST and Surveys

WFIRST will also, in guest investigator mode, survey our Galaxy and other nearby galaxies to answer key questions about their formation and structure, and the data it obtains will provide fundamental constraints on how galaxies grow.
WFIRST – Program Details

• Recommended by EOS Panel

• Several RFI concepts for dark energy, IR survey, or exoplanet science promoted similar telescope designs

• All 3 WFIRST science goals are possible employing JDEM-Omega hardware:
  – 1.5m; 144MPx HgCdTe detectors, 200mas, grism; L2

• Start 2013, launch 2020; total appraised cost $1.6B, Medium/Low risk

• Key element of the ground & space programs in both dark energy and exoplanets
WFIRST – Program Details

- Discussions between NASA/DOE and ESA about mounting a joint mission could be a positive development if they lead to a timely execution of a program that fully supports all of the key science goals of WFIRST (planet microlensing, dark energy science, general investigations) and leads to savings overall.

- It is expected that the United States will play a leading role in this top-priority mission.

- A minority role in a Euclid dark energy/cosmology mission does not appear among the NWNH recommendations.
WFIRST Implementation

The telescope exploits the important work done by the joint DOE/NASA design team on the Joint Dark Energy Mission—specifically the JDEM Omega concept—and expands its scientific reach. WFIRST is based on mature technologies with technical risk that is medium low and medium cost and schedule risk. The independent cost appraisal is $1.6 billion, not including the guest investigator program. The recommended schedule has a launch data of 2020 with a 5-year baseline mission. An extended ten-year mission could further broaden the science program.
WFIRST Misunderstandings

• “WFIRST is a dark energy mission”
  – It is proposed to achieve important science objectives in dark energy, exoplanet and galaxy surveys and its ranking is predicated upon it doing this.

• “LSST will do the dark energy science”
  – LSST’s major contribution will be to weak lensing and it will need infrared photometry and spectroscopy from space; WFIRST’s main contribution will be to BAO, weak lensing and supernovae and it will need LSST’s photometry.
WFIRST Misunderstandings

• “WFIRST is a larger and more ambitious mission than Euclid”
  – WFIRST only has an infrared focal plane unlike Euclid which also has optical CCDs. It will also be operated in a simple staring mode. However, the WFIRST telescope is slightly larger than the Euclid telescope

• “WFIRST can wait”
  – The results of the exoplanet microlensing survey will be needed as soon as possible to help design an exoplanet flagship
  – There is little motivation for repeating the dark energy measurements
WFIRST Misunderstandings

• “WFIRST is more expensive than JDEM and Euclid”
  – The committee was instructed not to trust project or center-generated costs and generate its own appraisals. WFIRST’s cost of $1.6B, as appraised by Astro2010, is indeed larger than the JDEM-Omega estimate of $1.1B for identical hardware and the (more capable) Euclid cost of 470M Euro plus national contributions. However, a uniform appraisal procedure would have to be used to compare costs.

• “WFIRST is a ten year mission”
  – The recommendation is to design a five year baseline mission and this is assumed in the cost appraisal. A nominal observing plan that could accomplish science objectives in all three science areas in five years is outlined. A ten year goal is reasonable to consider but should not be allowed to increase the cost. This would be covered by a Senior Review.
WFIRST Summary

• WFIRST addresses fundamental and pressing scientific questions and will contribute to a broad range of astrophysics.
• It is an integral part of a coordinated and synergistic ground-space program in fields in which the U.S. has the leading role.
• It presents opportunities for interagency and perhaps international collaboration and coordination that would tap complementary experience and skills.
• It also presents relatively low technical and cost risk, making its completion feasible within the decade, even in a constrained budgetary environment.
• For all these reasons it is the committee’s top priority recommendation for a large space mission this decade.
Explorer Program - Science

- Rapid, targeted, competed investigations
- Versatile program delivers high scientific return
- WMAP, Swift, GALEX, WISE… are extraordinarily successful past examples
- NuSTAR, GEMS, Astro-H very promising
Explorer Augmentation – Program Details

- In past, program reduced to pay for costs of major NASA activities

- **RECOMMEND** Restoration of Explorer line to enable astrophysics launch rates originally envisaged

- Proposed increase from $40M to $100M per year for astrophysics missions -- Low risk

- Support two new MidScale (MIDEX), two new Small (SMEX) Explorers, and at least four Missions of Opportunity (MoO) over decade

- Essential to maintaining breadth and vitality of space astrophysics program
LISA - Science

• Exploiting a new field of astronomy using long wavelength gravitational radiation – ripples in spacetime – to observe:
  – Inspirals and mergers of binary black holes to cosmological distances, back to Cosmic Dawn; measure black hole masses, spins
  – Large numbers of ultra-compact binary stars in our galaxy

• Precision tests of general relativity

• Possible detection of spacetime ripples from the very early universe

• The unexpected
LISA – Program Details

- Three spacecraft 5 million km apart in Earth-trailing orbit
- ESA-NASA partnership:
  - Candidate for ESA L-class launch (with IXO, Laplace)
  - LISA Pathfinder mission scheduled for 2012
- Recommendation conditional on success of Pathfinder and selection by ESA as first L-class mission, in which case risk is Medium
- **RECOMMEND U.S. share of 50%**
- Total appraised mission cost $2.4B
- Projected 2016 start and ~2025 launch
IXO – Science

- Large area, high spectral resolution x-ray observatory to explore hottest regions in the universe
- Clusters of galaxies, intergalactic medium, black hole accretion disks
- IXO would revolutionize X-ray astronomy and address many high priority science objectives in the spirit of Chandra and XMM-Newton
IXO – Program Details

• 3m² aperture, 5 arcsec imaging, microcalorimeter spectrometer

• More ambitious successor to Constellation-X (AANM rec.)

• Joint with ESA, JAXA:
  – Candidate for ESA L-class mission (with LISA, Laplace)
  – Proposed U.S share 50%
  – Current mission appraised at $5.0B, total; Medium-High risk

• If space recommendations 1-3 go ahead, unless there is a substantial budget increase there will be funds only for technology development this decade aimed at reducing the mission cost and risk for next decade

• **RECOMMEND $180M for the decade**
Medium-Scale Space Program - Prioritized

1. **New Worlds** Technology Development Program

2. **Inflation** Technology Development Program
New Worlds Technology Development Program

• To achieve New Worlds objective – studying nearby, habitable exoplanets - need **preliminary observations** before choosing a flagship mission:
  – Planetary demography over wide range of conditions:
    ▪ Kepler, WFIRST, integrated ground-based program
  – Measurement of zodiacal light:
    ▪ Ground-based telescopes.
    ▪ Sub-orbital and explorer mission opportunities.

• In parallel, need **technology development** for competing approaches to make informed choice in second half of decade

• **RECOMMEND $100-200M over decade**

• Planned integrated ground-space exoplanet program
Inflation Technology Development Program

• Ground-based microwave background telescopes seek “B-mode polarization,” sensitive signature of processes from epoch of inflation, thought to have occurred during earliest moments of the universe

• If signal is seen from ground then space-based mission with at least ten times greater sensitivity is warranted and associated technology development is needed

• RECOMMEND $60-200M over decade, conditional on signal detection
Small Category: SPICA

- **US Instrument contribution to JAXA-ESA SPICA mission**
  - Far-infrared telescope; successor to Spitzer
  - Birth of galaxies, stars, planets; cycling of gas through interstellar medium
  - 3.5m aperture
  - Launch date 2018

- **Will address many of this survey’s science priorities, including understanding the birth of galaxies, stars, and planets, as well as the motion of matter through our own interstellar medium.**
Recommended Small Projects - Details

• **Future UV-Optical space capability** is a ~4m diameter successor to HST. Many technology trades to be discussed.

• **Gemini** augmentation is recommended to allow both telescopes to deliver on their scientific promise and address impact of UK withdrawal. Gemini program expected to participate in Senior Review in 5 years.

• **U.S. Instrument contribution to JAXA-ESA SPICA** mission would contribute to understanding the birth of galaxies, stars, and planets, as well as the motion of matter through our own interstellar medium.

• **Theory-Computation Networks** is a new competed program for substantial challenges raised by the science program. All three agencies recommended to issue coordinated calls
Large-scale Ground-based Program - Prioritized

1. Large Synoptic Survey Telescope (LSST)
2. Mid-Scale Innovations Program
3. Giant Segmented Mirror Telescope (GSMT)
4. Atmospheric Cerenkov Telescope Array (ACTA)
LSST - Science

- Efficient, deep optical survey telescope
- Will transform observation of the variable universe and address broad questions:
  - Dark energy using gravitational lensing and supernovae
  - Dark matter
  - Near-Earth, Kuiper-belt objects
  - Solar neighborhood
  - Transient phenomena
    - Gamma-ray bursts, Variable stars, Supernovae...
- Publicly accessible archive – >100 Pbyte
LSST – Program Details

• 8.4 m diameter telescope located in Chile
• 3.5 degree field of view -- Observe half sky every four days using six filters from 0.3-1\(\mu\)m
• NSF-DOE partnership with private and international contributions
• Total appraised cost $465M; Annual operation $42M
• Medium/Low risk excepting data management and archive software
• RECOMMEND entry into MREFC line as soon as possible
• Ten year lifetime, followed by Senior Review
Mid-Scale Innovations Program – Overview

- Large number of exciting and viable projects addressing survey goals are in ~$10-$100M range
- RECOMMEND creation of competed program at NSF that will meet this need, like NASA Explorer program
Mid-Scale Innovations Program - Details

• RECOMMEND annual proposals for:
  – Conceptual and preliminary design activities
  – Detailed design and construction

• ~7 projects funded over decade
  – Possible exemplars include: BigBOSS, CMB, ExoPlanet initiatives, FASR, HAWC, HERA, Adaptive Optics, NanoGRAV

• Funding increase from ~$18M currently to competed $40M per year
## Small-scale Program
(Ground and Space – not prioritized)

<table>
<thead>
<tr>
<th>Program Augmentation</th>
<th>Agency</th>
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<tbody>
<tr>
<td>Advanced Technologies and Instrumentation</td>
<td>NSF</td>
</tr>
<tr>
<td>Astronomy and Astrophysics Grants (including Lab. Astro.)</td>
<td>NSF</td>
</tr>
<tr>
<td>Astrophysics Theory Program</td>
<td>NASA</td>
</tr>
<tr>
<td>Intermediate Technology Development</td>
<td>NASA</td>
</tr>
<tr>
<td>Laboratory Astrophysics</td>
<td>NASA</td>
</tr>
<tr>
<td>Sub-orbital Program</td>
<td>NASA</td>
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<tr>
<td>Telescope System Instrument Program</td>
<td>NSF</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>New Initiatives</th>
<th>Agency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development of future UV-optical space capability</td>
<td>NASA</td>
</tr>
<tr>
<td>Leadership in Gemini international partnership (increment)</td>
<td>NSF</td>
</tr>
<tr>
<td>Participation in JAXA’s SPICA mission</td>
<td>NASA</td>
</tr>
<tr>
<td>Theory and Computation Networks</td>
<td>NASA, NSF, DOE</td>
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Small-scale Investments

- Target work-force development (TSIP, Sub-orbital, AAG, ATP)

- Address changing role of computation and theory (TCN)

- Support current/upcoming facilities (Gemini, Lab Astro, TCN)

- Develop technology for future (NSF ATI, NASA Tech. Dev.)
Budgetary Context

• Agency Guidelines
  – NSF and DOE – constant budgets in fixed dollars ($FY2010)
  – NASA – constant real year dollars (declining budget in $FY2010)

• Survey Budgets (the optimistic scenario)
  – NSF and DOE – “doubling” = 4% per year growth in $FY2010
  – NASA – constant in $FY2010 dollars

• Notional “sand charts”
  – Exhibit possible spending profiles consistent with committee budgets and the recommended program, i.e. phasing
  – Allowed the committee to examine possible programmatic scenarios
  – Provide advice in less optimistic budget scenarios
**NASA**

- **Expectation under survey’s budget scenario:**
  - launch WFIRST
  - augment Explorers
  - start LISA
  - timely contribution to SPICA
  - advance
    - IXO
    - Exoplanet and Inflation technology development
- **Details depend upon ESA negotiations and decisions**

- **If budgets are lower,** SPICA contribution dropped and
  - First priority: WFIRST, Explorer augmentation and small program
  - Second priority: New Worlds (Exoplanet) Technology Development, LISA and IXO Technology Development
  - Third priority: Inflation Technology Development
Other Recommendations & Conclusions

- International Matters: collaboration, coordination; open skies
- Stewardship of the Survey: independent, strategic advisory group
- Benefits to the Nation: STEM literacy; technology spin-offs; citizen science
- Astronomers: career mentoring; demographics; public policy
- Computation and Data: archive and curate data
- Laboratory Astrophysics: support at current or higher levels
- NSF/AST Senior Review: conduct early in decade
- NOAO and Gemini: explore management and operations consolidation
- Solar Astronomy: maintain multidisciplinary ties
- Radio Astronomy: SKA pathfinder opportunities
Summary

- This is an extraordinary time in the study of the cosmos, but also a time of serious constraints on federal discretionary budgets.
- The recommended program is science-driven and will enable progress across a large swath of research and open up more discovery space.
- A balanced program should be maintained throughout the decade. Effective international, public-private and inter-agency collaboration is required for success of the program.
- A serious effort has been made to appraise activity cost, risk and technical readiness.
- Mid-decade decisions should be made based on recommendations from an independent, strategic advisory committee.
- Astro2010 has had unprecedented involvement and support by the astronomical community and immense effort by the committee, panels and consultants, as well as the strong cooperation of the agencies and professional societies.