Space Telescopes after JWST

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Evolution of our understanding

- Uncover (“discover”) the unseen
  - Catalog the universe
  - Adduce the physical laws
  - Understand the reason for it all

- Local to the distant, minor to major components
  - Solar system - Milky Way - galaxies - recombination
  - Planets - Stars - Galaxies - Structure

- What is next?
  - We have many questions to address with known techniques
  - Traditional exploration is getting increasingly expensive
    - Resolution & sensitivity improvements require large structures
  - Gains available in sky coverage and time domain
    - Surveys with dedicated telescopes
Astrophysics in the New Millennium

- Astronomy & Astrophysics in the New Millenium
  - How did the universe begin and evolve to its present state?
    - Age, amount & distribution of matter and energy, and history
  - How do galaxies form and evolve?
    - Dawn of the modern universe
  - How are black holes created?
  - How do stars form and evolve?
  - How do planets form and evolve?
  - Is there life elsewhere in the universe?

- Quarks to Cosmos:
  - What is the dark matter?
  - What is the nature of the dark energy?
  - How did the universe begin?
  - How do cosmic accelerators work and what are they accelerating?
  - How were the elements from iron to uranium made?
How difficult are these questions?

- **Astronomy & Astrophysics in the New Millenium**
  - The heavy elements from iron to uranium
  - Dark matter: distribution & effects
  - Dark energy: presence, distribution, and evolution
  - Creation and evolution of the universe
  - Galaxy creation: the dawn of the modern universe
  - Stellar birth and evolution
  - Black holes
  - Planetary birth and evolution

- **New technology (interferometers)**
  - Radically new technology: large apertures, enormous baselines

**Hubble-like**

**JWST-like**
Exploration: angular resolution

Courtesy of Martin Harwit (2002)

Schwarzschild radius of 1 Solar mass black hole across the Galaxy

- 1959
- 1979
- 1999

$10^8 M_\odot$ BH

1 km

10 Mpc

Earth @ 10 pc

Jupiter @ 10 pc

HST

JWST

10 m

$1''$

Log [wavelength (cm)]

Angular resolution: log(radians)

Pair production

Absorption limit

Limit to solar system based observations

Interstellar absorption limit

Exploration: angular resolution

Courtesy of Martin Harwit (2002)
Resolution & Collecting Area

Filled apertures

Dark matter
Dark energy
Elements
Galaxies
Stars, SN

Sparse apertures

Baseline (m)

Area^{1/2} (m)

10^4
Kepler: eclipsing exo-planets

Kepler: dedicated telescope to discover eclipsing exo-planets

- 1.4 m telescope (Hubble-like), 903 kg
- 4 years, Earth-trailing heliocentric
- Photometer: $10^8$ pixels, $1\square < 10^{-5}$ noise
- 100,000 stars, one field, 5 Gbits/day
**SuperNovae Acceleration Probe**

SNAP: dedicated telescope to study distant SN & dark energy

- 2 meter telescope, 2 yr mission (minimum),
- Fixed focal plane, essentially no moving parts
- Optical photometry: 1°x1° giga-pixel mosaic camera, 0.35-1\(\mu\)m
- Infrared photometry: 1’x1’ FOV, HgCdTe array (1-1.7 \(\mu\)m)
- Integral field optical & IR spectroscopy: 0.35-1.7 \(\mu\)m, 2”x2” FOV
Proposed surveys with space telescopes

- Galaxy, AGN evolution
  - HST/ACS
- Supernovae Ia, □
  - HST/ACS+NICMOS, SNAP
- Extra-solar planetary systems
  - HST/ACS Galactic bulge
  - Kepler
- Astrometric surveys
  - SIM, GAIA

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Composition of the Cosmos

- Heavy elements: 0.03%
- Ghostly neutrinos: 0.3%
- Stars: 0.5%
- Free hydrogen and helium: 4%
- Dark matter: 30%
- Dark energy: 65%

- □ □ ~ □/D
- B_0 ~ Zodiacal l
- FOV ~ optics l

HST WFPC2 SN SEARCH in HDFS by SNZ

Ingress  Eclipse  Egress
Resolution & Collecting Area

Filled apertures

- Dark matter
- Dark energy
- Elements
- Galaxies
- Stars, SN

Sparse apertures

- Exo-Earth imaging
- Black holes, Cosmic jets

Baseline (m)

Area^{1/2} (m)

- HST
- Exoplanets Vis
- Exoplanets IR
- Exo-Jupiter imaging

Dark matter

8/03/03
Cost of Space Telescopes

http://www.jsc.nasa.gov/bu2/AMCM.html
Mirror Technology Development

At start of conceptual design:

Mirror area density, diameter, cost and schedule were ~10x higher than JWST goals

Manufacturing Time/Unit Area
- HST (2.4 m) ≈ 1 year/m²
- SIRTF (0.9 m) ≈ 3 years/m²
- JWST (6 m) ≈ 1 month/m²

JWST AMSD: ~15 kg/m²
Kodak AMSD Mirror

- 1.4 m Diameter Semi-Rigid ULE Closed-Back Mirror
- Graphite Epoxy (M55J) Reaction Structure by COI.
- Reaction structure complete
  - Thermal cycled to 113°C
- 16 Force Actuators by Moog
  - 7 for wavefront & radius
Technology Development for Optimum Integration of Human and Robotic Roles

Courtesy of Rud Moe, Goddard Space Flight Center, April 2003
Interferometers: TPF, PI

- Baselines: 30m - 30 km
- Element sizes: 4 - 10m
- Required resolution:
  - <0.1 arcsec (IR nulling)
  - <10^{-5} arcsec (Jupiter)
  - <10^{-6} arcsec (Earth)
Beyond JWST

How will we build and maintain large telescopes in space?

- Mirrors will be large
  - Filled apertures $\sim$10 - 100 m or more
  - Interferometer elements: $\sim$3-10 m, separations $\sim$100 - 1000 m

- Goal: 10 kg/m$^2$ for entire telescope (mirror + structure, instruments and spacecraft)
  - Typical cost $2$-$5$ billion
  - Construction: in space, by humans or robots
  - Replacement or upgrade may be difficult

- Return on investment
  - Service the degradable items
  - Upgrade instruments through servicing
    - Humans
    - Robots
Large optical coronagraph contrast $> 10^{10}$

Large optical coronagraph
- Giant exoplanets
- Young exoplanets

CS disks & rings
Exozody clouds

Large optical light bucket
- Census of exoplanets
- Exoplanet atmospheres

Disk chemistry
$\text{H}_2$ spectra of disks
Disk structure, gaps, rings

HST-like: UV spectra
$\Delta I/\Delta D$

Atmospheres of SS planets
Occultation of stars
Composition of bodies
Ring dynamics

Stellar winds
TTS in LMC
Binary stars
Stellar pops
IGM Baryons
Microlensing
$\alpha(z)$ ($e^2/hc$)

Large optical coronagraph

HST-like UV
Large Optical