A short history of telescopes and astronomy: Galileo to the TMT
Telescopes in the last 400 years
Galileo

- 1608 Hans Lippershey applied for a patent for “seeing things far away as if they were nearby”
- 1609 Galileo built a 1” diameter refracting telescope with 3x magnification and made observations of celestial objects
Galileo’s Observations

- With his telescopes Galileo could see **fainter** objects and with **higher spatial resolution**
- Observed four faint objects that over time were shown to orbit Jupiter
• Galileo observed imperfections on the surface of the moon and the Sun
• Perhaps most importantly, with the improved spatial resolution of his telescopes, Galileo observed that Venus showed different phases
Galileo and Venus

• The key observation that demonstrated at least one object in the Solar System orbited the Sun was observing Venus go through different phases.
A New World View

- The technological advancement of a simple combination of two lenses to make a telescopes led to a profound discovery.

- The Earth was not the center of the Universe!
• This story of discovery following the invention of new and better tools has been repeated many times since Galileo’s time.
Telescopes 1609-1888

- Refracting telescopes grew in size (diameter of the lens) through the end of the 1800s
- 1888 the 36” refractor was completed at Lick Observatory: largest steerable telescope in the world
Lick Observatory

- First mountaintop observatory in the world in 1888
- First observatory to completely embrace photography
- Visit by King Kalakaua in 1881
The Milky Way Galaxy

- First photographic mapping of the Milky Way and source of much debate about the nature of the dark regions
- Many comets and asteroids
- Measured motions of stars
- Binary star orbits and masses of stars
Reflecting Telescopes

• Newton proposed telescopes using mirrors rather than lenses
• no chromatic aberrations, “faster” optics and possibilities of building larger and larger mirrors (can support mirrors from behind)
The Rise of the Reflectors

- 1896 the 36” Crossley Reflecting Telescope arrived at Lick Observatory
- Using a complicated hand-guiding mechanism, exposures could be made that lasted hours
James Keeler

• “With exposures of four hours, the Crossley photographs show stars and nebulae far beyond the range of any visual telescopes…the number of new nebulae would be about 120,000”

• 3rd Lick Director
Legacy of 36” Telescopes and Photographic Plates: 1910

- Understood the vast size of the Galaxy
- Recognized a magnificently vaster Universe of Galaxies
Short History of Astronomy cont.

- 1900s: Next generation reflecting telescopes were built in the 1908 (1.5m) and 1917 (2.5m) at Mt Wilson
- Led to Hubble’s discovery of the expansion of the Universe
The End of an Era

- The Palomar 5m was completed in 1949
- Established the extragalactic distance scale, discovered stellar populations, discovered quasars and led to the birth of observational cosmology
The Trouble with Big Telescopes

- 5m Pyrex Mirror weighted 14.5 tons and the support structure almost the same
- Surface is polished to \( \sim 1/10 \) micron \((1/200,000\)”) over 11 years of grinding
- Very difficult to maintain that exquisite figure for different orientations
Evolution of Telescopes

In the 1980s, two University of California physicists, Jerry Nelson and Terry Mast, proposed a new approach to building giant mirrors using segments that fit together and are controlled very (very) precisely.

Not obvious that this would work

• Control system/precision
• Manufacturing segments
Keck Observatory

• Nelson/Mast concept became an observatory via gift from the Keck Foundation to Caltech and partnership between Caltech and the University of California
• “prototype” Keck 1 was a spectacular success
• One attractive aspect to segmented approach was scalability of the concept to even larger primary mirrors
For its first decade, the Keck Observatory was the undisputed world-leading facility in optical/IR astronomy:
• Acceleration of the expansion of the Universe
• Majority of the known extra-solar planets
• Nature of gamma-ray bursts
• The determination of the history of star formation over cosmic time
• The abundance of D/H in the early Universe and verification of hot Big Bang nucleosynthesis
The Space Age

- Hubble Space Telescope produced spectacular images limited only by the diameter of the primary mirror
- Gave access to wavelengths that do not penetrate the Earth’s atmosphere
The 3rd Revolution in Astronomy: Adaptive Optics

- Theoretical resolution is set by mirror diameter and a property of light called diffraction
- For telescopes at the surface of the Earth, resolution is set by blurring of the atmosphere to $\sim 1$ arcsecond, equivalent to a 6-inch telescope
Adaptive Optics

Feedback loop:
next cycle corrects the (small) errors of the last cycle.
AO works!
• Correction is easier and better for wavelengths > 1µ
• At most sites, need to correct at 50Hz or faster
• For 10m, diffraction limit is 0.02" @ 1µ
• Need a bright guide star (<13m)
Scattered light from low in atmosphere

Guide star in sodium layer at ~ 90 km

Scattered light from low in atmosphere
• First AO system used for astronomy purposes was completed at Lick Observatory 1994
• First Laser Guide star implemented at Lick Observatory in 1996
• Both systems are the basis for the systems at Keck Observatory
Thirty-Meter Telescope: the next generation

The first Keck Telescope has now been in operation for 16 years

- The Keck community (UC and Caltech) have had access to 10m telescopes for more than 15 years and pushed to observational limits in several areas
- In 2000 started to think about taking the Keck concept to the next level
- Partnership evolved between UC, Caltech and ACURA
- Japan, China, India, Brazil all interested in partnership
- $80M spent in design development phase
Thirty Meter Telescope (TMT)

- Keck style segmented primary 30m in diameter: 492 1.45m segments
- **Nine times** the light collecting area of a Keck Telescope, **Twelve times** higher spatial resolution than the Hubble Space Telescope
TMT Science

- the first epoch of star formation in the Universe
- the assembly and evolution of galaxies
- the discovery and characterization of extra solar planets
- fundamental physics of dark matter and dark energy
Galactic Center Black Hole

- The spatial resolution of the TMT will allow a dramatic advance in the work in the Galactic Center
- Will be able to probe the “strong regime” of General Relativity near the surface of the Black Hole
Extra-Solar Planets

- This became an interesting new scientific field in 1995
- Now more than 400 known ESP
- Multiple systems now seen
- Goals are simple: earth-like, habitable
Characterizing Extrasolar Planets

[Graph showing contrast vs. radius with various categories marked such as Taurus planets, Self-luminous jovians, Terrestrial planets, and reflection light.]
Characterization of Extrasolar Planets
- Atmospheres of massive planets

- With 30m telescope will have the light grasp and contrast to obtain spectra of extra-solar planets
The Thirty-Meter Telescope

• The TMT will easily provide the data to address the forefront problems in astronomy and astrophysics today

• History would suggest that with an advance of this magnitude in capabilities, the more important contributions to knowledge will be in unexpected discoveries

• TMT will be one of the few most important scientific facilities of the 21st century
TMT in a Less Visible Location
• Because of the “fast” primary mirror and large cost of the enclosure, the TMT is surprisingly compact compared to the Keck or Subaru
Why Astronomy?

- The drive to understand the Universe is profound
- Intellect and ingenuity to be able to do so is a tremendous credit to humankind
- Gateway science
- spinoffs
Who are these Observatory people