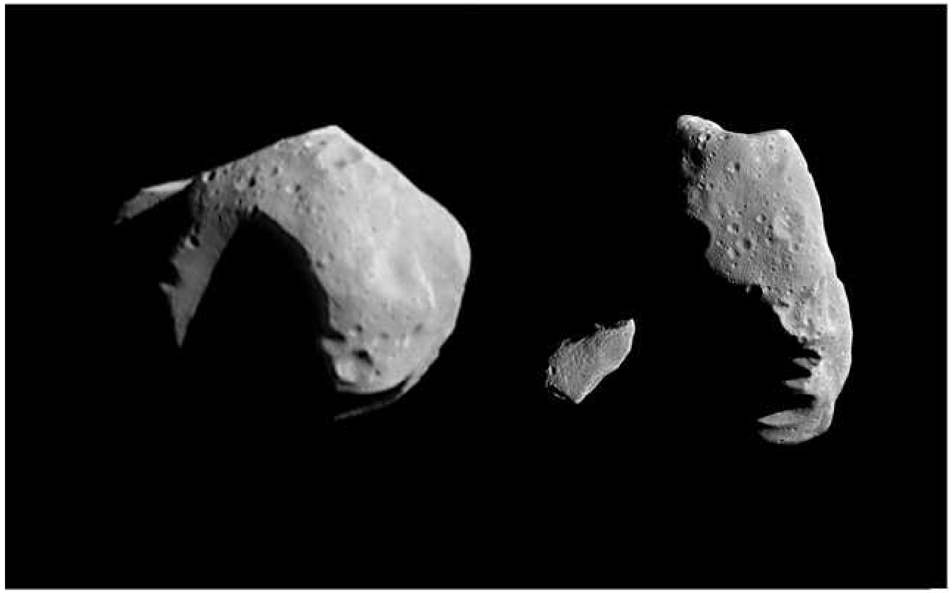
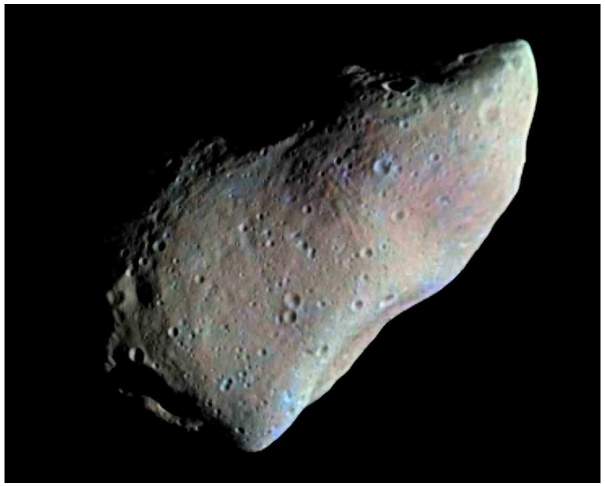
Small Solar System Bodies: Asteroids, Comets, and Transneptunians



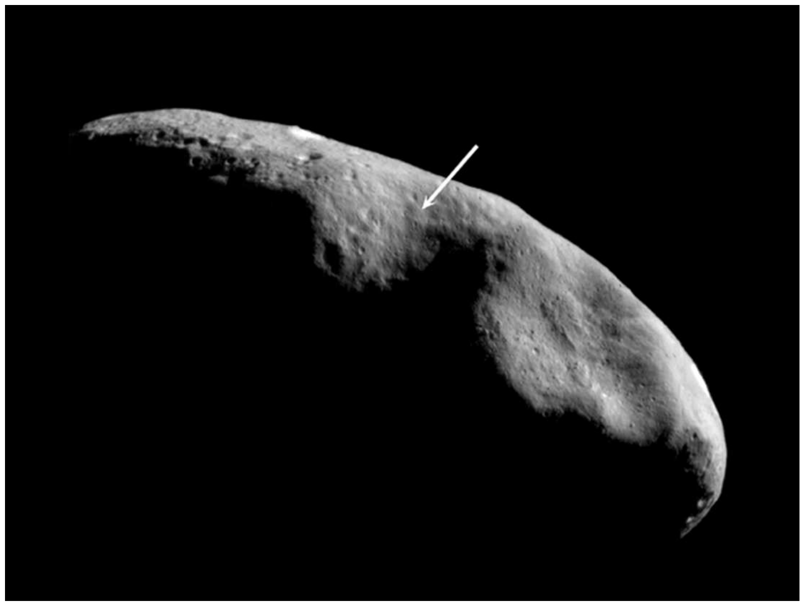
Several asteroids surveyed by interplanetary probes (Mathilde, Eros by NEAR Shoemaker; Gaspra [19 × 12 × 11 km], Ida [58×23 km] by Galileo)



951 Gaspra (NASA)

Asteroids: Minor planets mostly between Mars and Jupiter (main belt), diameters <1000 km

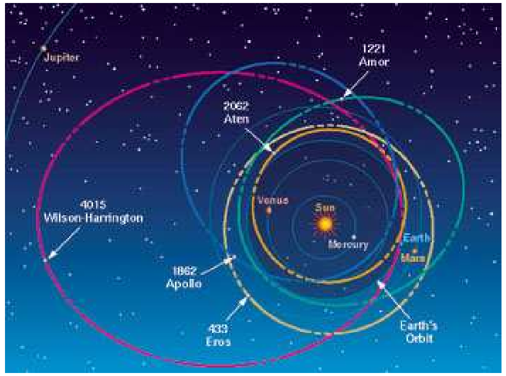
First discovery in 1801 (Piazzi: Ceres, diam. 1000 km)
Today >100000 known, only 7 with diameters >300 km
Total mass ~0.5% of Earth (40% of moon), of which ~30% in Ceres, 75% are C-type (carbonaceous), 17% S-type (silicaceous), and 8% M-type (metallic) asteroids.



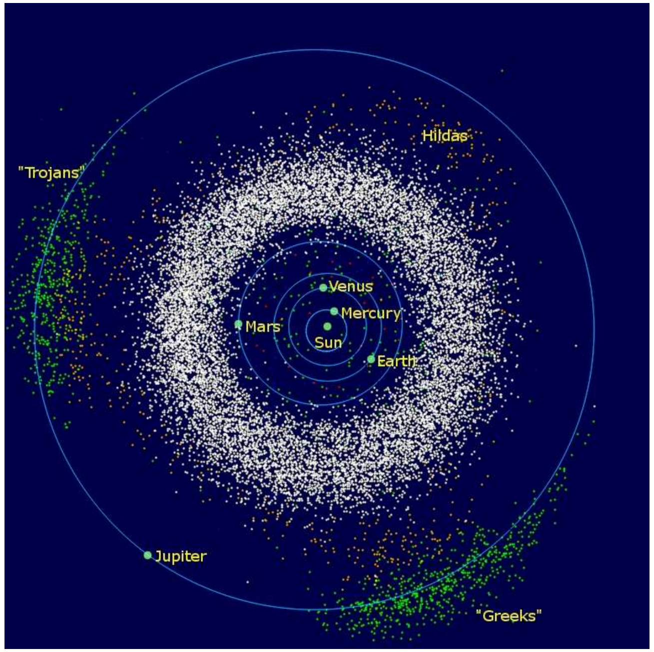
2001 Feb 12: NEAR lands on Eros

MOVIE TIME:

- http://near.jhuapl.edu/iod/20010205/index.html: Rotation of Eros [2000 Dec 3/4]
- http://near.jhuapl.edu/iod/20010731/index.html: descent onto Eros

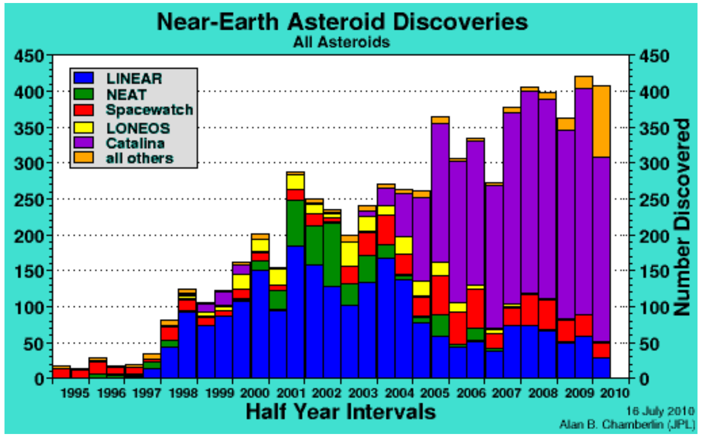


NEAs: Near Earth Asteroids:
Earth path crossing (Atens, Apollos),
Earth approaching (Amors).



Wikipedia

Orbit dynamics leads to structuring of the asteroid belt: asteroid families.



PHA: Potential hazardous Asteroids: >150m, <0.05 AU: ~1000 known, see http://neo.jpl.nasa.gov/index.html

Estimate: there are >1000000 Earth orbit crossing asteroids

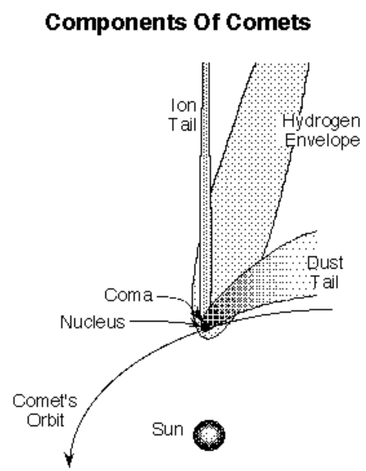
Comets

153P/Ikeya-Zhang (©M. Jäger)

Comet Hale Bopp, March 30, 1997

Comet Hale Bopp over Bamberg, 1997 spring

Structure



NASA

Major components of a comet:

- Nucleus: "Dusty Snowball" (Whipple, 1951), 1–50 km

  dominated by water ice, plus up to 15–20% CO_2 and CO

- Coma: 10^4–10^5 km, evaporated gas surrounding nucleus

  includes H_2O, CO_2, CO, but also H_2S, CH_3OH, H_2CO, NH_3, HCN, CH_4, S_2

- Ion tail: Ionized gas, typical extent up to 10^8 km, often bluish
- Dust tail: Dust evaporated away from nucleus, typical size $\sim 10^6$–10^7 km.

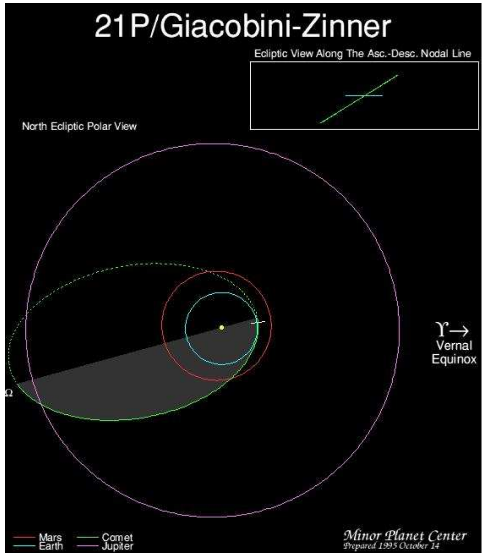
High volatility species indicate origin in cool regions of solar system and "storage" out there until recently.

Structure

Bust of Apian (Ruhmeshalle, Munich)

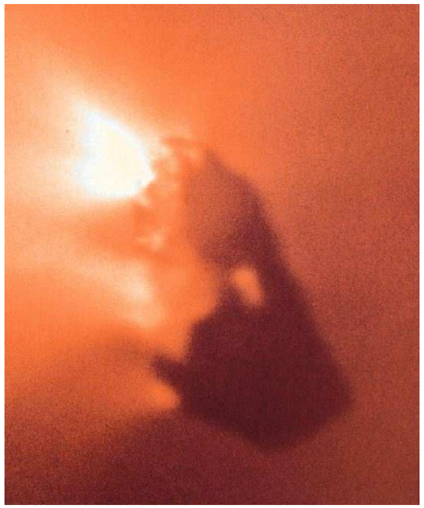
How do cometary tails form?

- tails always point away from the Sun (Apianus, 1531) $\Longrightarrow$ Sun causes the phenomenon
- Dust tail: scattered Sun light.
- Dust particles are accelerated by radiation pressure
- Gas tail: ionised plasma, ions emit light by fluorescence
- Wurm (1943): plasma can not be acccelerated by radiation pressure
- Biermann (1951): There must be a solar wind of particles



siderial period: 6yr 227d, perihel: 1.037 AU, aphel: 6.015 AU
rediscoverd by Zinner, Assistent at Bamberg observatory (later its second director)
first comet oberved by a space probe: 1985: ICE (International Comet Explorer)
flys through tail in 7800 km distance from core

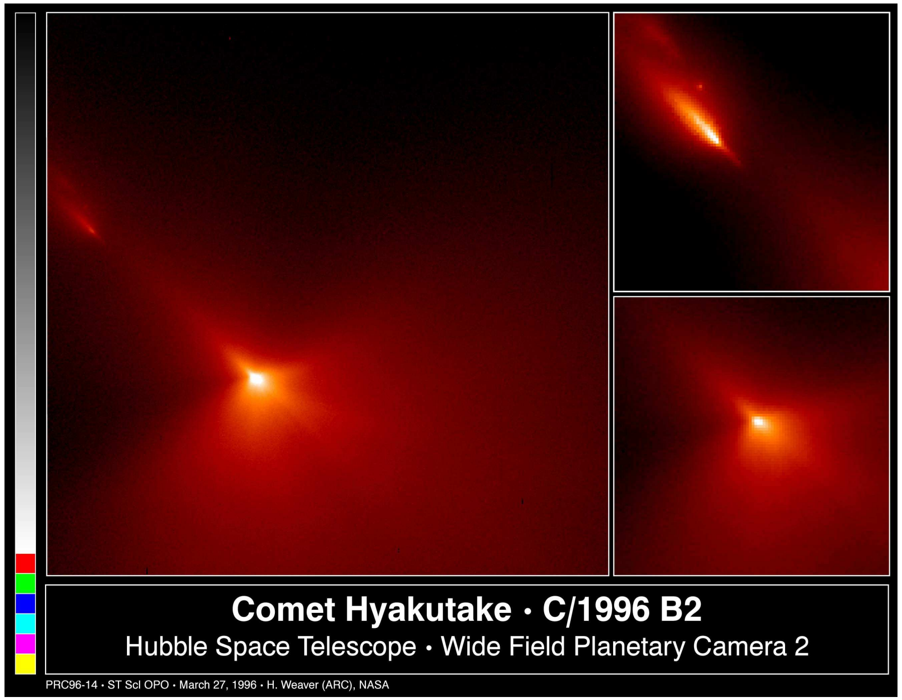
Halley

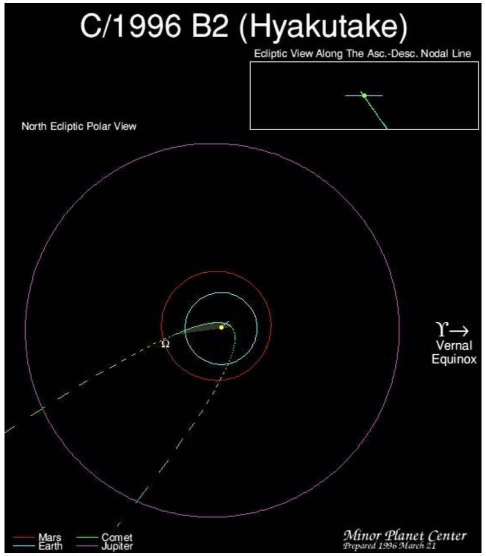


ESA

1P/Halley:

- Orbital period: 76–79.3 year orbit (earliest recorded appearence: 239 B.C, famous: 1066, Tapestry of Bayeux).
- Analyzed in detail during 1986 return, flyby of ESA's Giotto spacecraft close to nucleus, further analysis by Russian Vega 1 and 2 probes, Japanese Suisei and Sakigake, and NASA's International Cometary Explorer.
- "International Halley Watch" with strong contributions from Bamberg observatory.





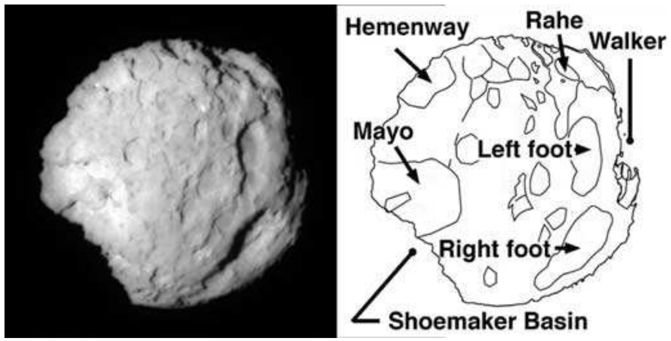
Original Semi-major axis: ~400 AU, closest approach to Earth: 0.1 AU

$i = 125°$; $e > 0.999784$

Pre-perihelion Orbital period: ~8000 years

Post-perihelion Orbital period: ~14000 years

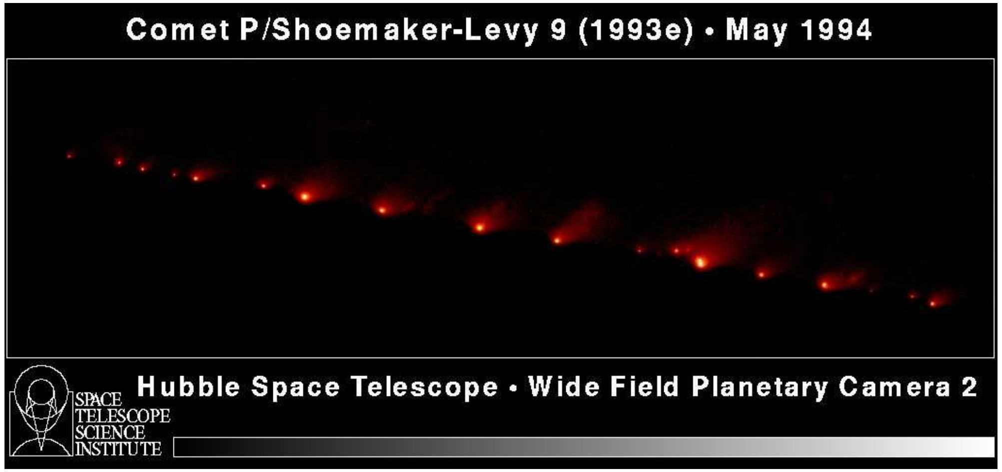
Comet Wild 2



NASA, stardust mission, size ~5 km

NASA's Stardust mission: flyby at comet Wild 2 on 2004 January 2, collection of particles from vicinity of comet's nucleus (closest approach: 240 km), impacted with samples in Utah on 2006 January 15

P/Wild 2: large semi-major axis, perihelion outside Mars after Jupiter encounter in 1974 (~ Jupiter before that) ⟹ Material has not been processed by Sun before sample return.



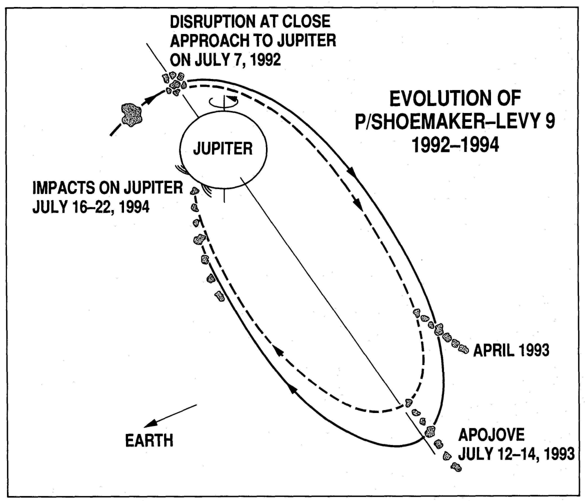
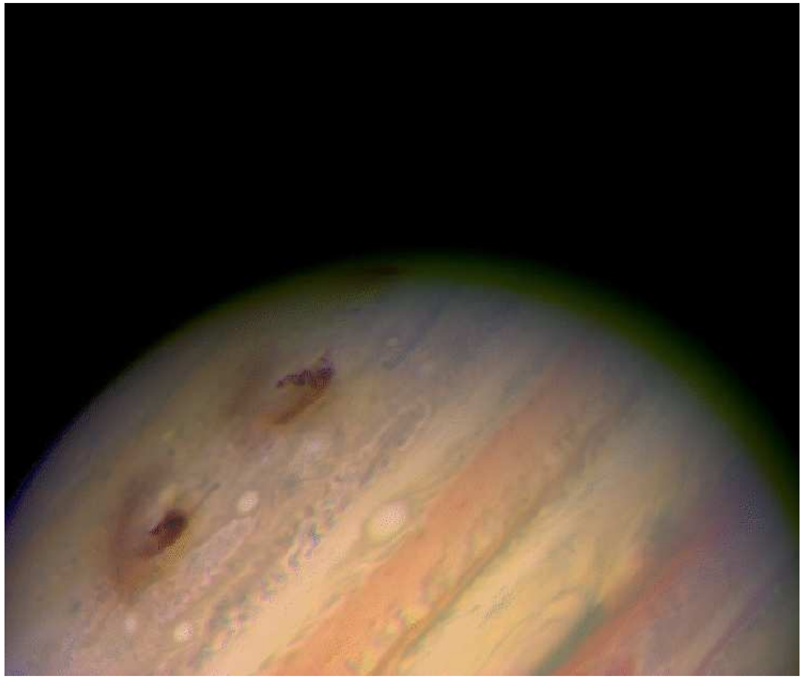
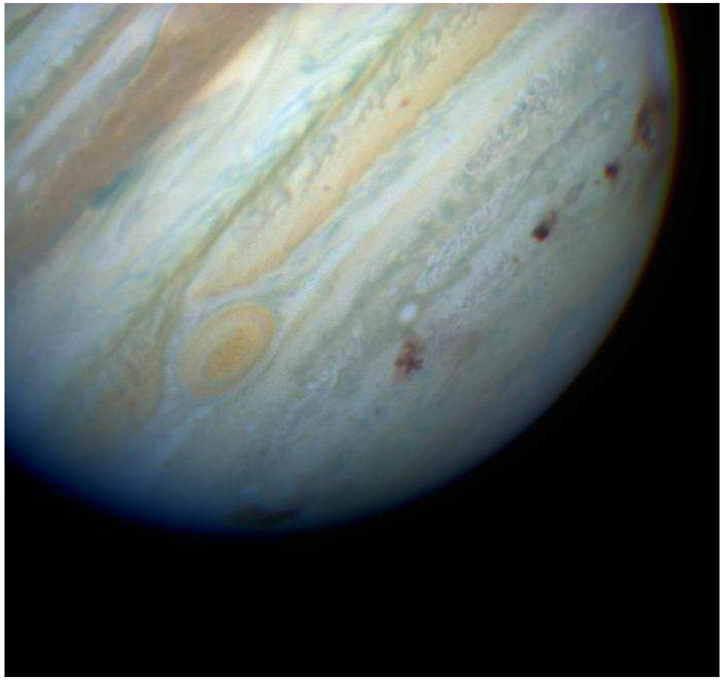


Fig. 9. Schematic representation of the tidal breakup of the parent nucleus of P/Shoemaker–Levy 9 in July 1992, the orbital evolution of its fragments, and their collision with Jupiter in July 1994. It should be remembered that the orbital dimensions and the sizes of Jupiter and the fragment chain are not drawn to scale. The apojove distance in July 1993 was in reality ~520 times the perijove distance in July 1992

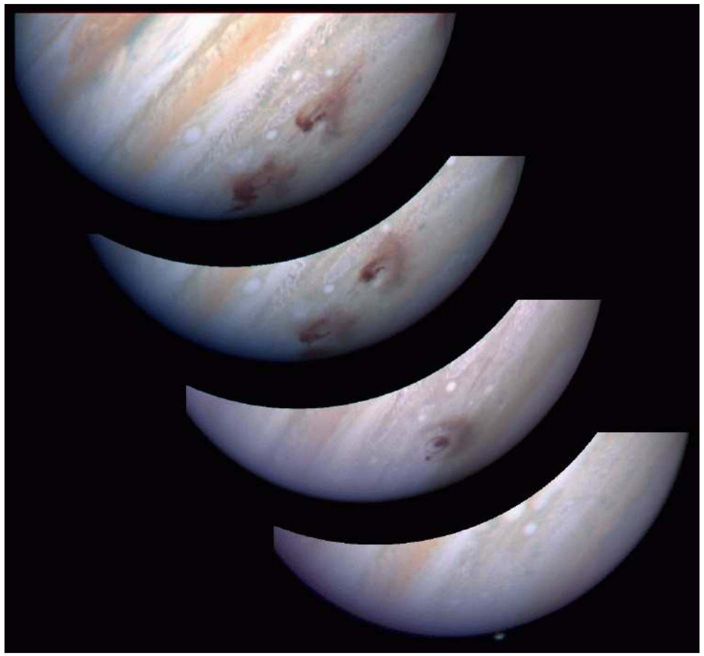
Sekanina et al. (1994, A&A 289, 607)



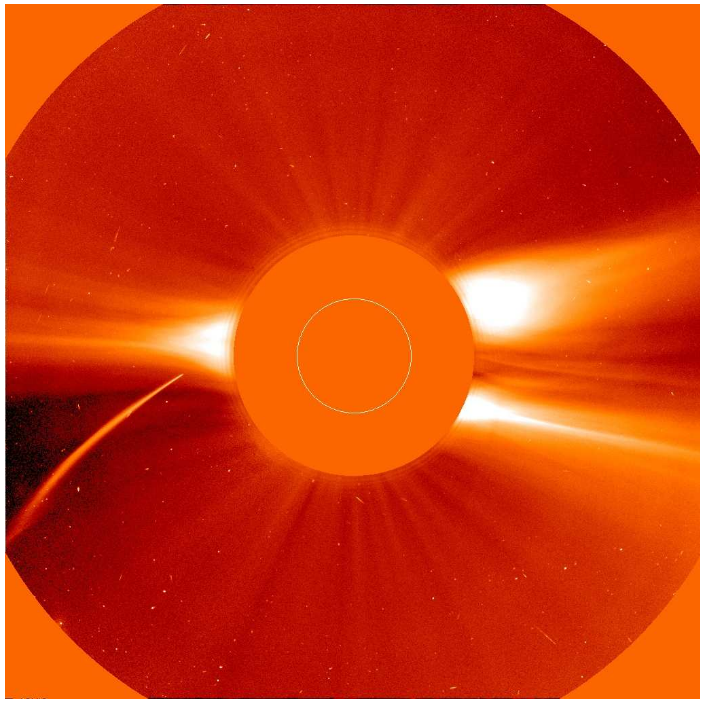
HST: Impact of fragments D and G. Outer ring: $d \sim 12000$ km (Earth!).



HST image of Jupiter after the impacts



Evolution of impact G: bottom to top: 18 July 1994, 5' after impact of fragment (plume!), until 5 days after the impact).



Sungrazers

Sungrazing comets: . . . the unlucky ones, members of the Kreutz group of comets, which come within $\sim$50000 km of the Sun.

Named after Heinrich Kreutz, who discovered these comets in the late 1800s.

Until 1979: 9 comets known.

Since then: solar observations from satellites, more comets found.

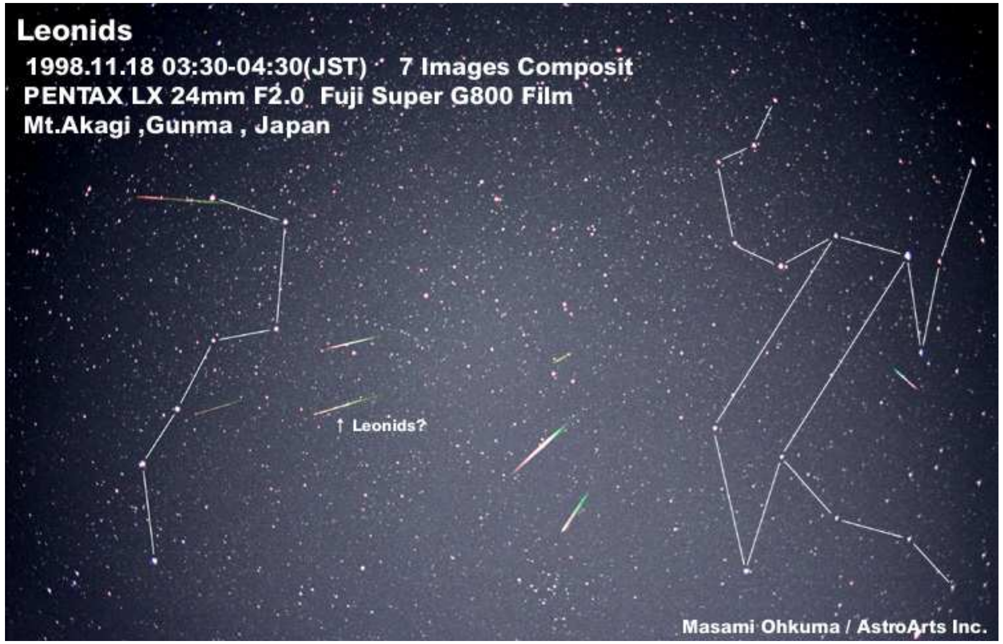
Since 1996: >1800 sungrazers discovered with instruments onboard ESA's SOHO spacecraft.

Sungrazers

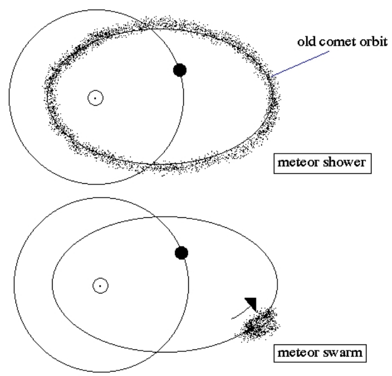
MOVIE TIME:

- `Hyakutake.mpg`: Perihelion passage of P/Hyakutake. Note dust tail and plasma tail!
- `cometM.mpg`: perihelion passage of comet P/Macholz
- `c2002v1.mpg`: perihelion passage of another comet in 2002
- `C3_2comets_CME.mpg`: two comets hitting the sun, followed by an (unrelated!) coronal mass ejection

Meteors

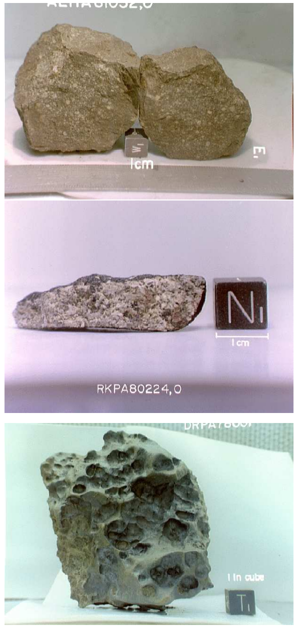


Origin of meteor swarms



- $\approx$25 Mio./day hit Earth's atmosphere.
- most burn up
- $\approx$1 Mio. kg/day to Earth's surface.
- large ones break into pieces, are ablated, but reach the surface as meteorites
- origin: debris of comets: dust tails
- showers/swarms when earth crosses a comet's orbit named after constellation of radiant
- e.g., Leonids due to 55P/Tempel-Tuttle (mid of November).

Meteorites



three major types:

- Chondrites: most common, stone, radiometric dating: age=4.55 billion years
- Pallasites: stone with metals
- iron meteorites: 13 subclasses: iron-nickel allows

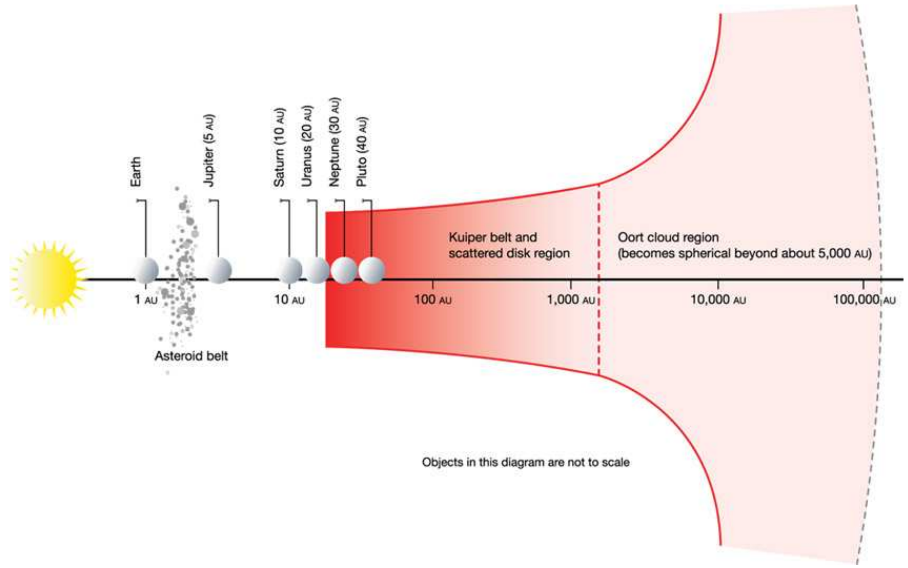
Origin of Comets

Long period comets: $P \geq 200$ years, have very eccentric orbits with huge semi-major axes, all angular momenta and inclinations observed.

Jan Oort (1950) suggested the presence of a large cloud of comets at *huge* distances around the Sun (Oort cloud).

Formal definition: Oort cloud is ensemble of all comets with semi-major axis $a \geq 10^4$ AU; estimated content $\sim 10^{11}$ to 10^{12} objects, total mass 1–50 Earth masses, temperature 5–10 K.

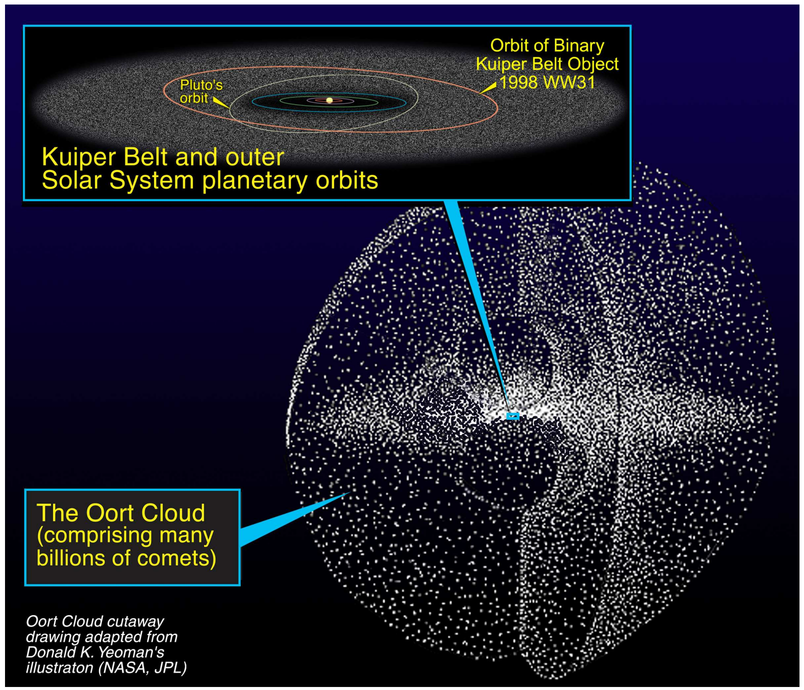
Long period comets originate in Oort cloud, orbits are disturbed by passing stars or Giant Molecular Clouds.



S.A. Stern (2003, Nature 424, 639–642)

short period comets: $P < 200$ years: show angular momenta similar to planets, mainly found in plane of solar system.

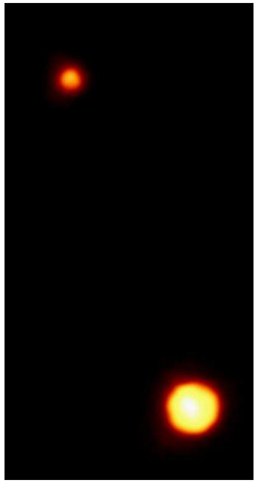
$\Longrightarrow$ probably from Kuiper belt, high collision rates there fragment objects, leading to cometary debris.



NASA/ A. Feild(STScI)

Transneptunians

Pluto - the dwarf planet

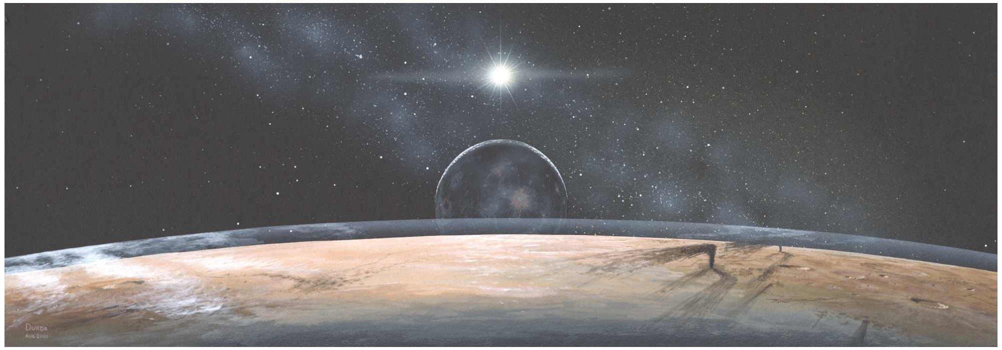


NASA/ESA HST

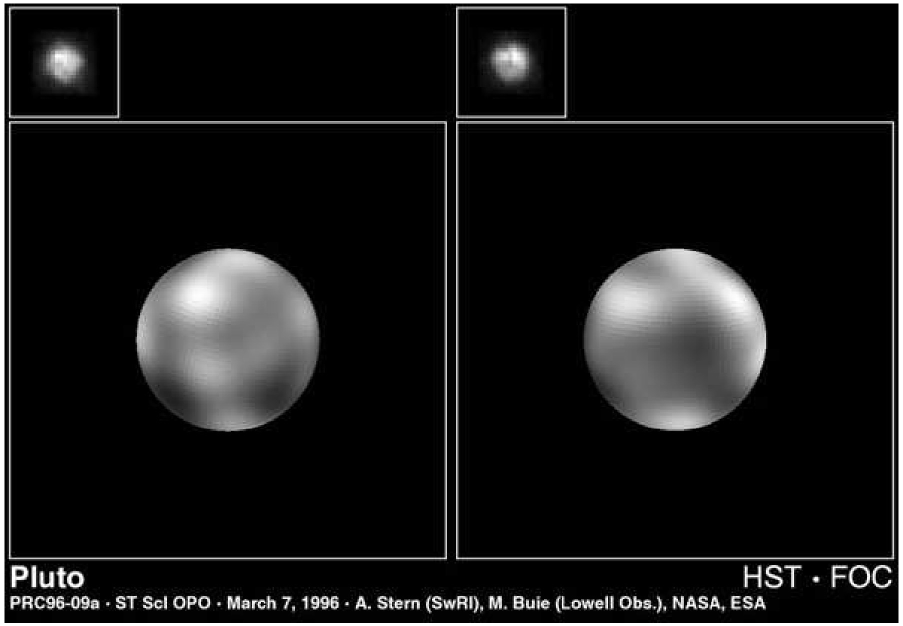
Pluto/Charon:

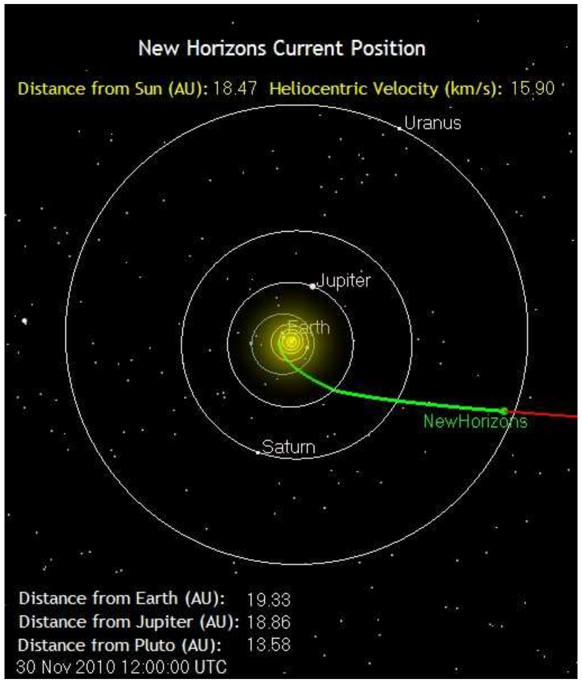
- discovered 1930/1978
- double system (Pluto: $D = 2320$ km, Charon: $D = 1270$ km)
- icy surface, probably cratered
- one of the largest transneptunian objects, member of the Kuiper belt

Kuiper belt: similar to asteroid belt, >70000 objects outside Neptune in 30–50 AU region

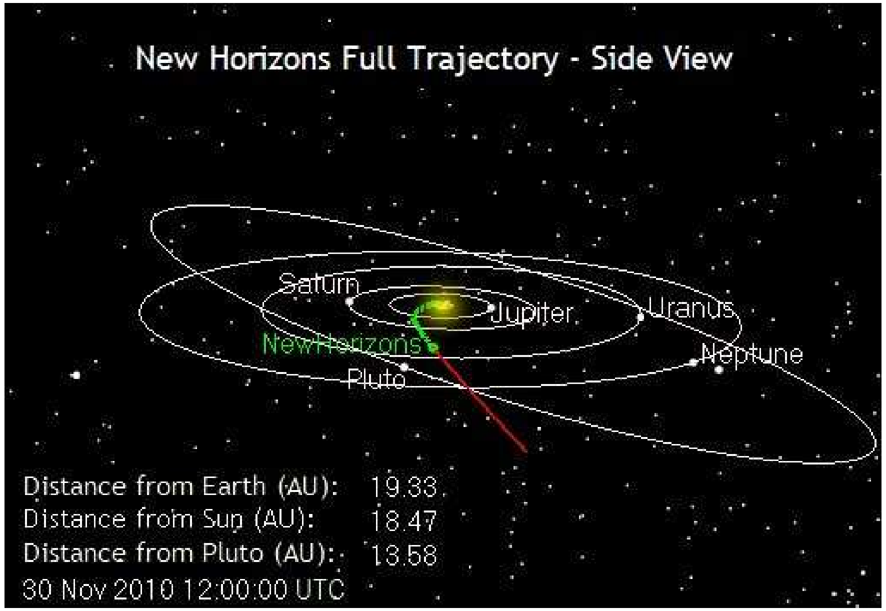


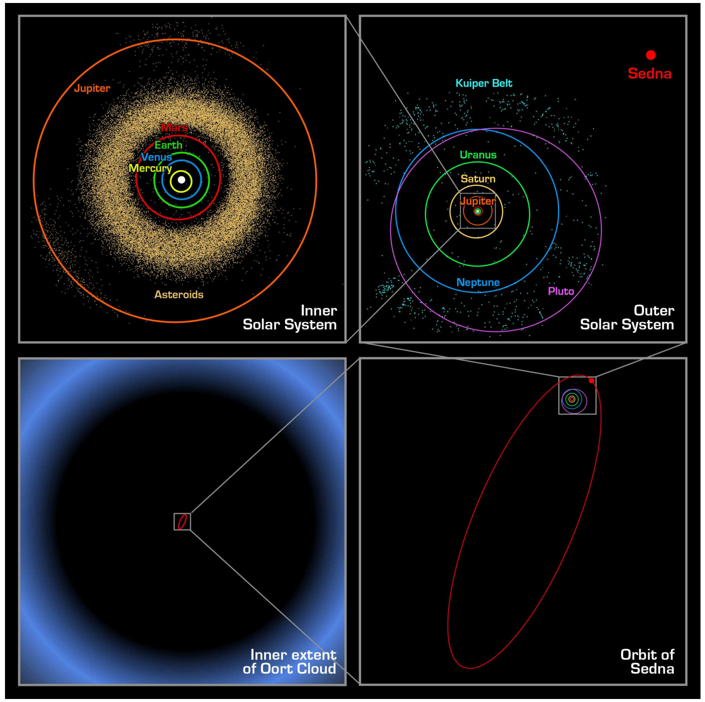
Artist's impression of Pluto and Charon (D. Durda, SWRI)

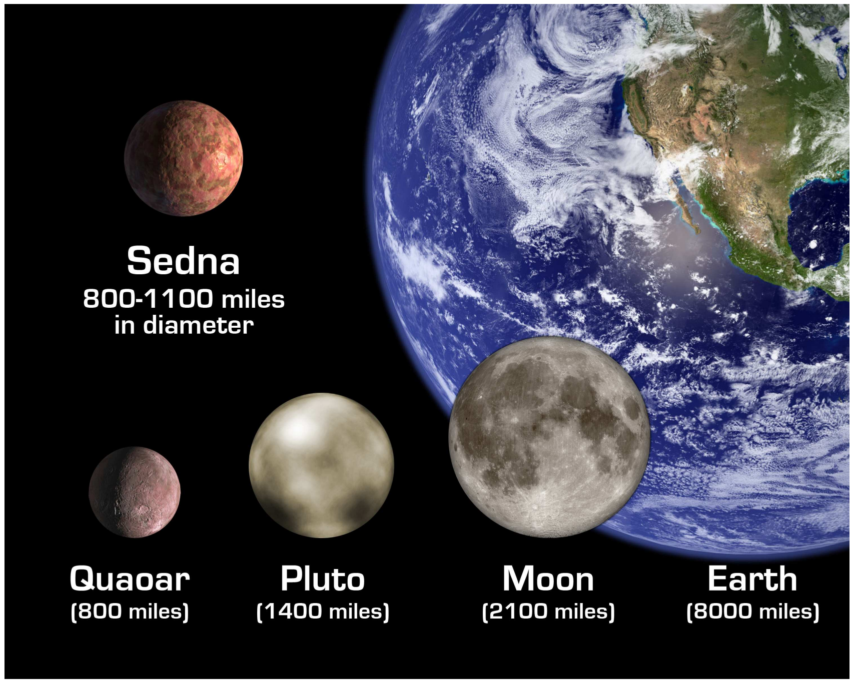




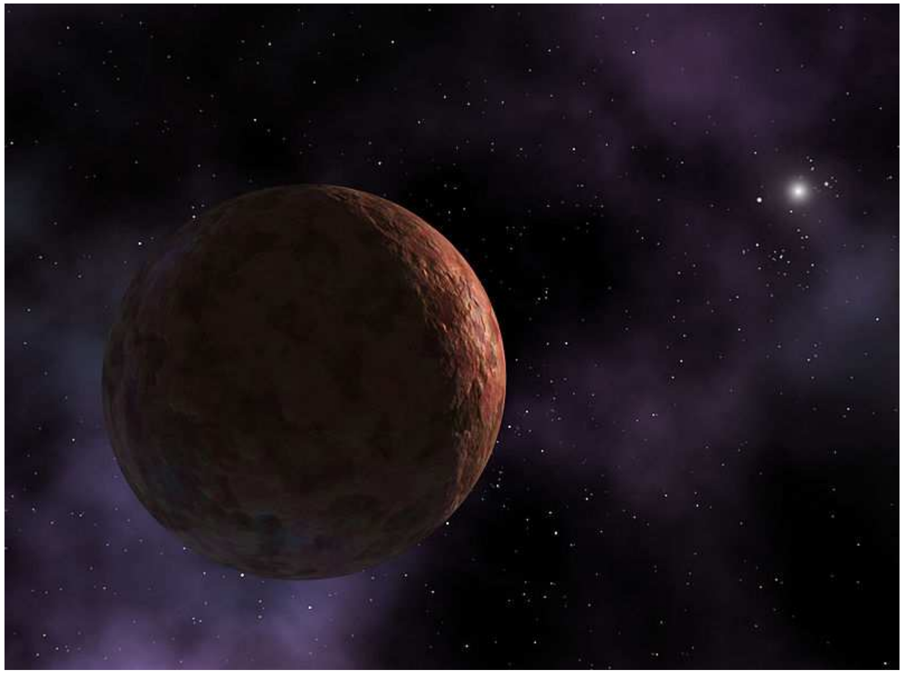
New Horizons: NASA Mission to Pluto and beyond launched 2006 January 19,
2007 February: Jupiter gravity assist,
2015 July: Flyby at Pluto and Charon,
Kuiper Belt mission until 2020



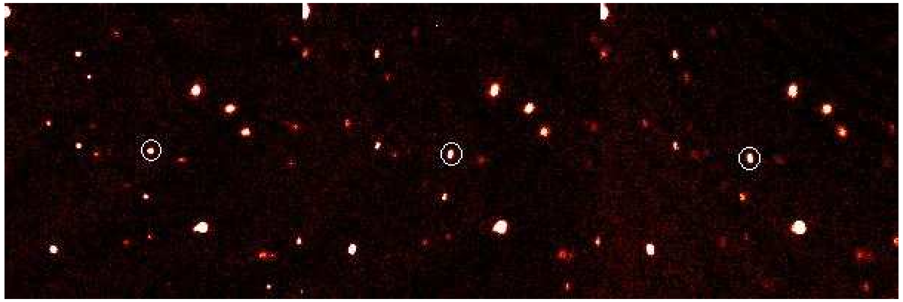




R. Hurt (SSC-Caltech)



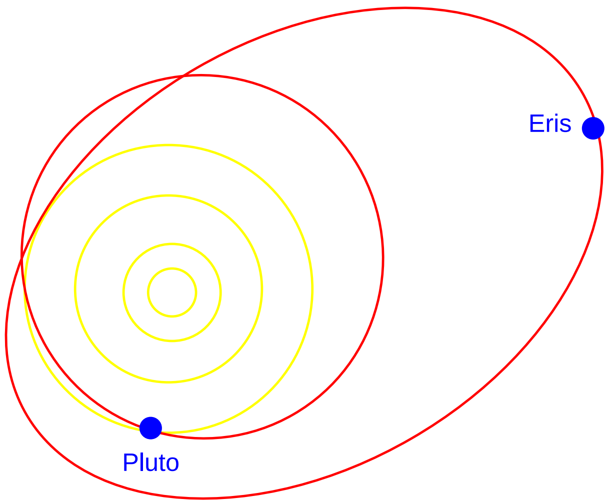
Viewing inwards from Sedna (NASA/JPL)



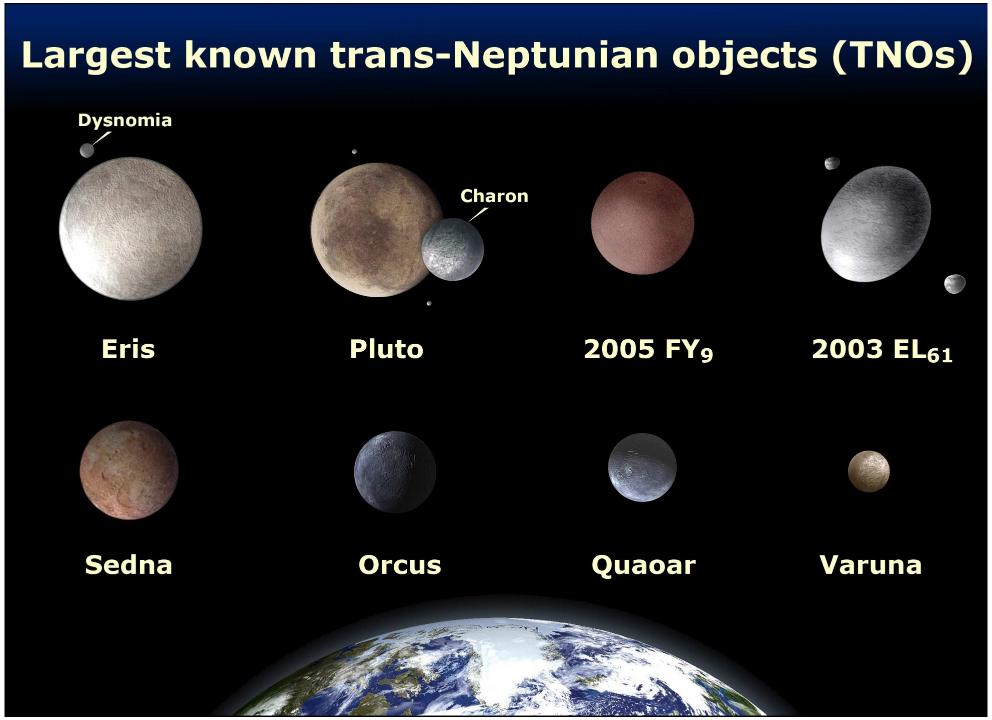
Discovery images of the dwarf planet Eris. The three images were taken 1 1/2 hours apart on the night of 2003 October 21st. Eris can be seen to move very slowly across the sky over the course of 3 hours. (M. Brown et al. Caltech)

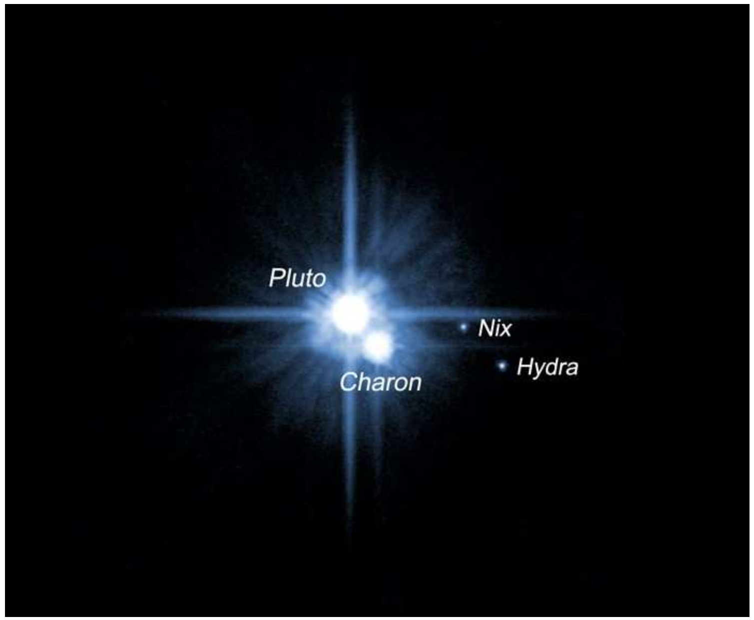
Eris (2003 UB_{313}): discovered 2005: distance $\sim$100 AU, brightness similar to Pluto

$\Longrightarrow$ larger than Pluto, unless it is 100% reflective (unlikely)!

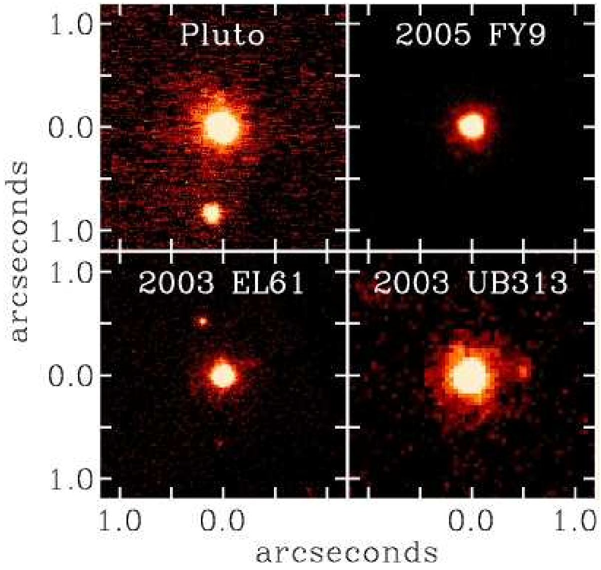


after M. Brown et al. (Caltech)

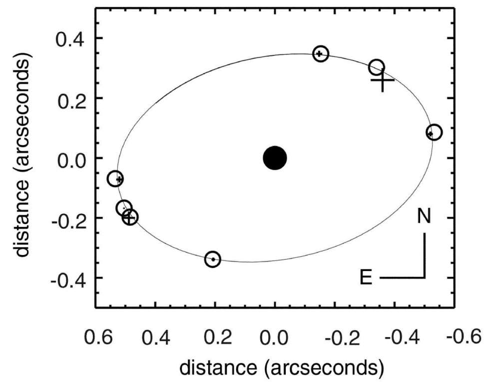




3 moons of Pluto:
http://antwrp.gsfc.nasa.gov/apod/ap060624.html

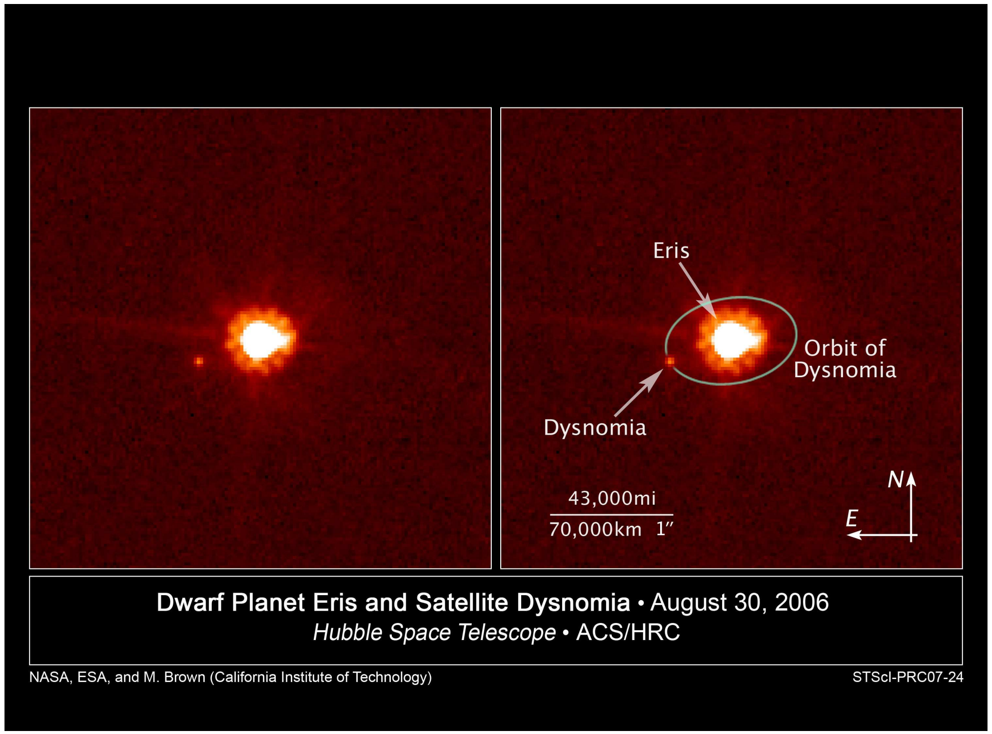


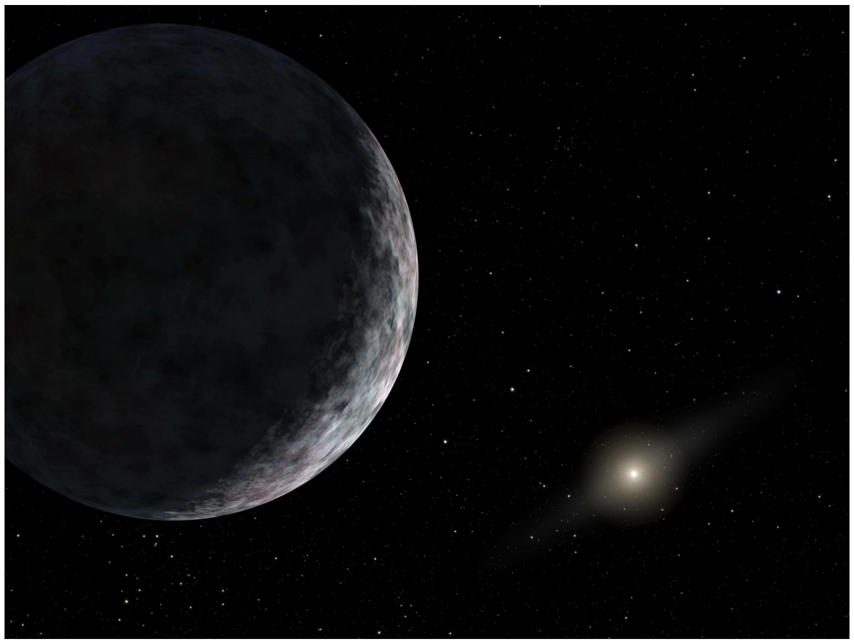
The orbit of Dysnomia around Eris:



- circular orbit
- Period $P = 15.773$ days
- Orbital radius: $R = 37400$ km

(Brown & Schaller, Science Vol 316, 15 June 2007)





Eris: View of the Solar System

(drawing courtesy M. Brown et al./NSF/NASA)

Cosmogony: Formation of the solar system

Formation of the solar system

Facts to be explained:

- planetary orbits all lie almost in the same plane, parallel to the Sun's equator, almost circular
- all planets orbit counterclockwise, in the same direction as the solar rotation
- prograde rotation (except Venus & Neptune)
- planets have 0.15% of the total mass, but 98% of the total angular momentum of the solar system
- (planetary distances obey the empirical Titius-Bode law:

$$a_n = 0.4 + 0.32^n \tag{8.1}$$

for $n = -\infty, 0, 1, \ldots$, $n = 3$: asteroid belt (Ceres))
- terrestrial and giant planets are physically and chemically different
- satellite systems resemble miniature solar systems in structure

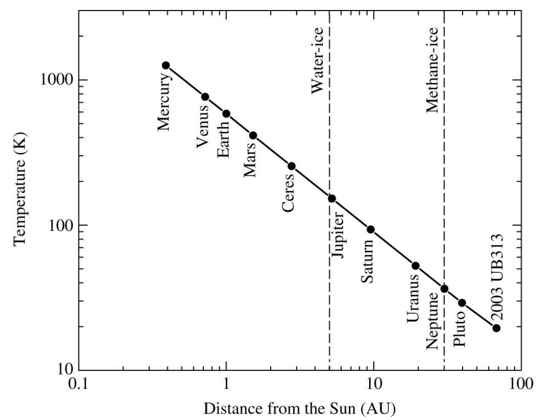
Nebula Hypothesis

- A cloud of interstellar gas and/or dust collapses under its own gravity.
- During collapse gas heats up and compresses in the center.
- A protostar is formed and the rest of the gas orbits/flows around it.
  $\Longrightarrow$ accretion disk
- Metal, rock and ice (only far from star) condense as gas cools.
- The dust particles collide with each other and form larger particles.
- Once the larger of these particles get big enough to have a nontrivial gravity, their growth accelerates $\Longrightarrow$ Run away growth.
- $\approx$1 Myrs after the nebula cooled, star generates a very strong solar wind and sweeps away the gas left in the protoplanetary nebula.
- The "planetesimals" would slowly collide with each other and become more massive.
- Eventually, after 10 to 100 Myrs planets are in stable orbits
  $\Longrightarrow$ solar system formed.

First discussed by I. Kant in 1755

Nebula Hypothesis

Condensation of dust and ices

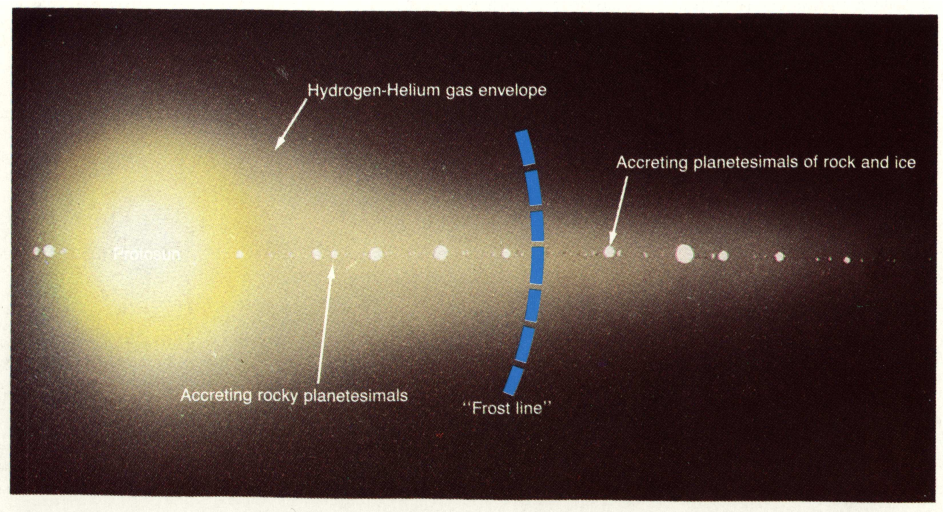


Temperature gradient in the early solar nebula (Carroll & Ostlie)

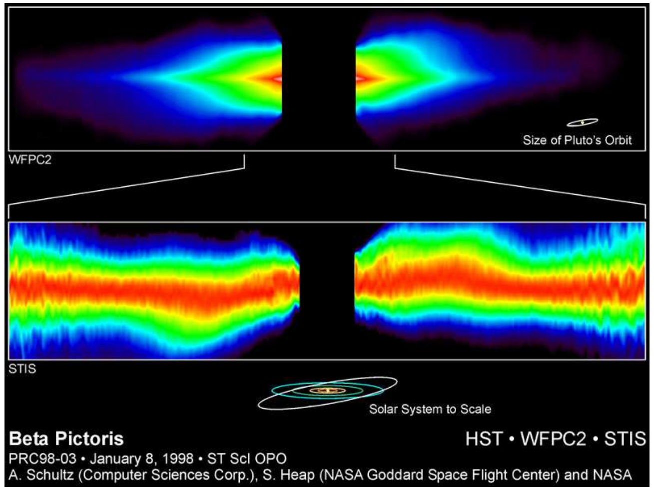
Chemical differentiation according to temperature:

- $T > 1500$ K:
  Fe, Ni, CaO, AlO condense
- $1500\,\text{K} > T > 1000$ K:
  Silicates (e.g. feldspar)
- $1000\,\text{K} > T > 800$ K:
  FeS
- $800\,\text{K} > T > 500$ K:
  Metallic Oxides
- $T < 150$ K: Water ice

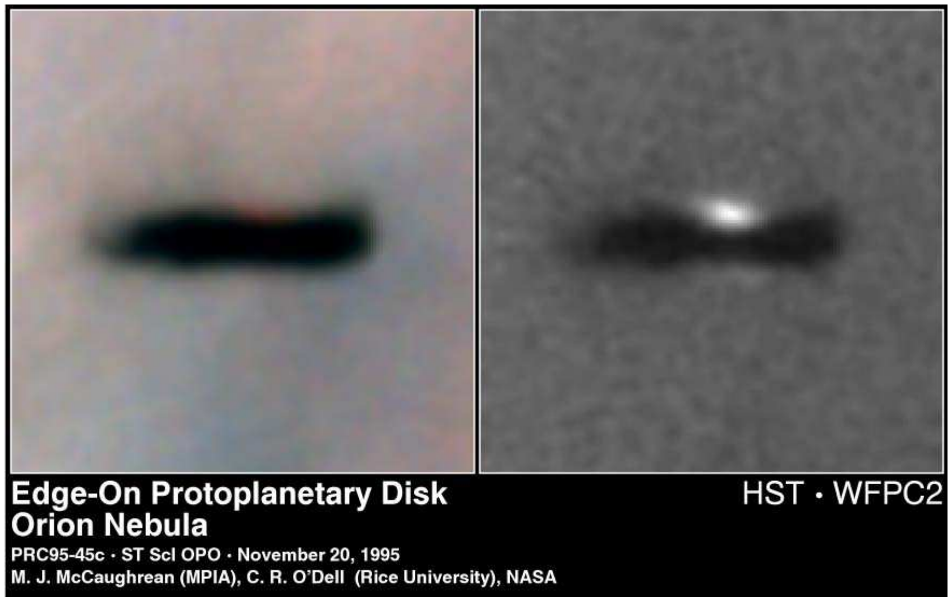
The frostline



Disk around the young star β Pic



"False color" image shows gradations in the brightness of the disk, which scatters the starlight. Warps in the disk might be caused by the gravitational pull of one or more unseen planets.



Coordinates and Measurement Methods

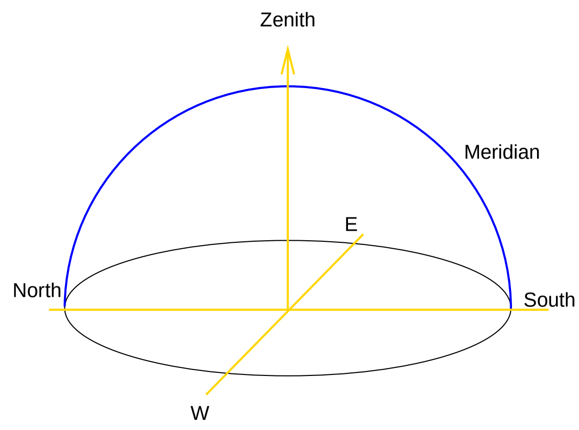
Introduction

We now move away from solar system

$\Longrightarrow$ before we can continue with science, we need to understand

- where astronomical objects are $\Longrightarrow$ coordinate systems
- how astronomical measurements are made $\Longrightarrow$ telescopes

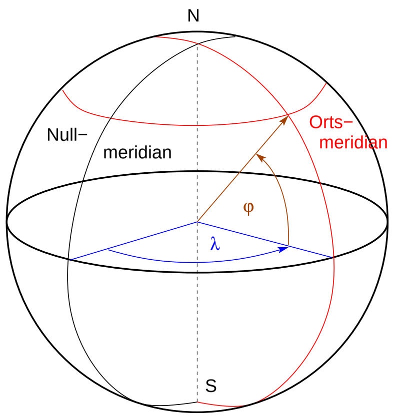
Horizon System



after Giese

Position on sky:

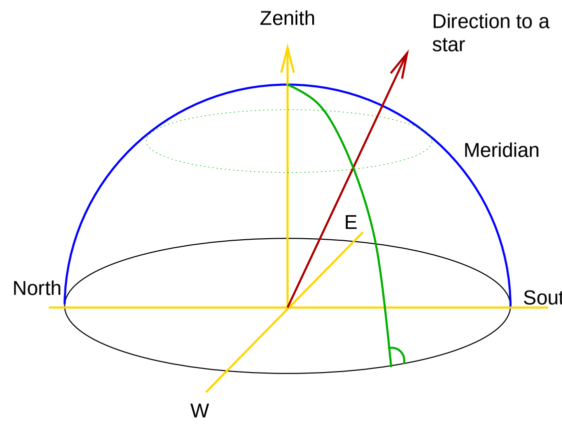
Positions on Earth



λ: geographic longitude (deg),
φ: geographic latitude (deg)

$\lambda = 0^\circ$ defined by position of a meridian circle in Greenwich (London)

Horizon System

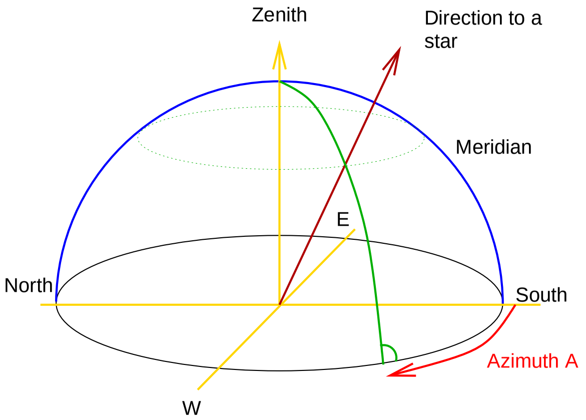


after Giese

Position on sky:

- Define position by giving direction to star.

Horizon System

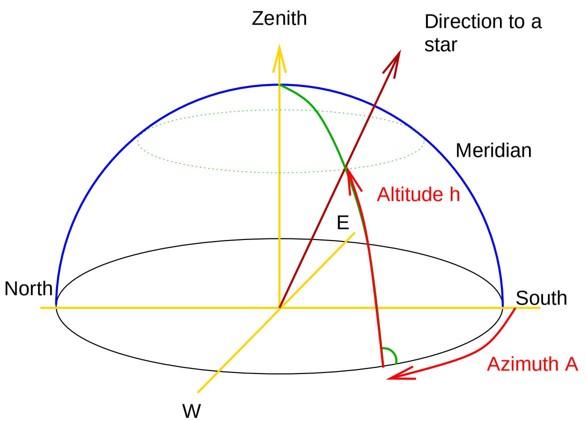


after Giese

Position on sky:

- Define position by giving direction to star.
- Azimuth A: angle in horizontal S-W-N-E

Horizon System

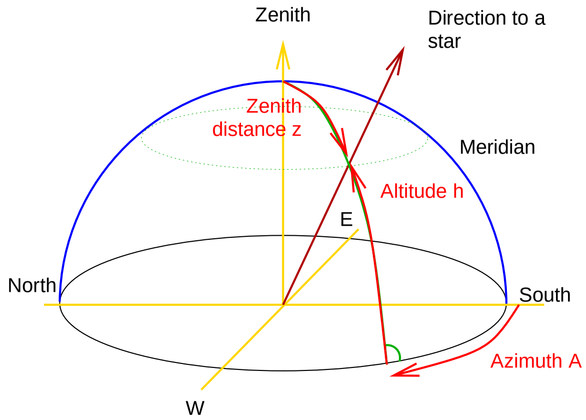


after Giese

Position on sky:

- Define position by giving direction to star.
- Azimuth A: angle in horizontal S-W-N-E
- Altitude h: angle from horizon towards zenith

Horizon System



after Giese

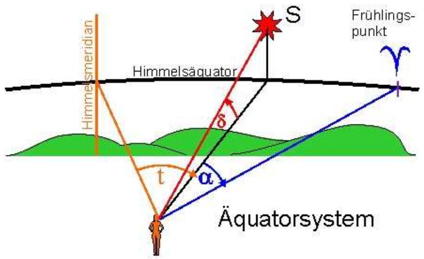
Position on sky:

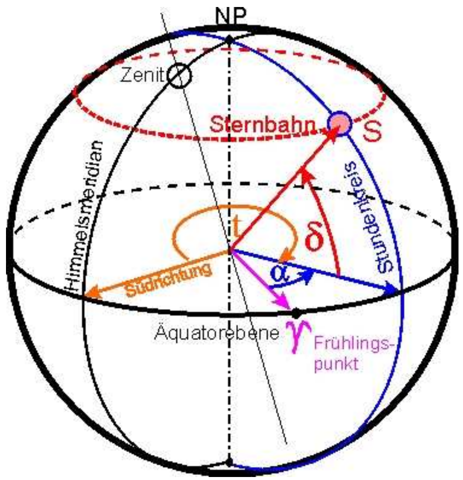
- Define position by giving direction to star.
- Azimuth A: angle in horizontal S-W-N-E
- Altitude h: angle from horizon towards zenith
- Zenith distance z: $z = 90^\circ - h$

http://joeorman.shutterace.com/Trails/Trails_021227_5.html

Earth rotates: A, h do not define position of stars at any time

Equatorial System





Moving:

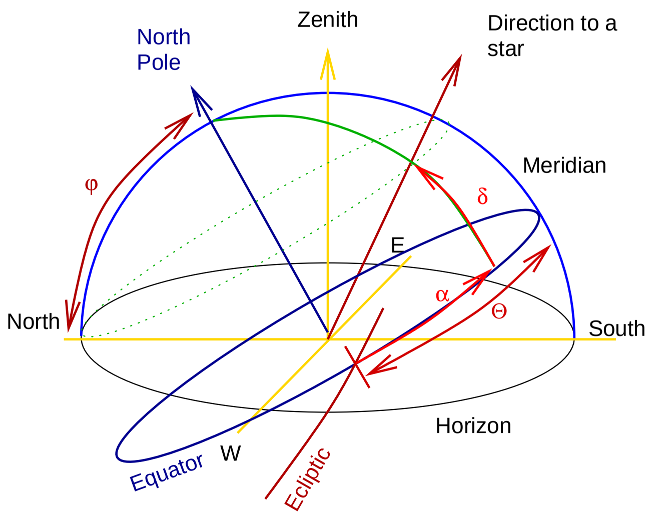
t = hour angle (h, m, s), changes constantly with time

δ = declination ($\circ, ', ''$), constant with time

Fixed: replace t by

α: right ascension (h, m, s), angle measured along equator from vernal equinox

Siderial Time



Define siderial time: 24 h correspond one rotation of the celestial sphere.

0 h siderial time = time when vernal equinox passes through meridian.

$\Longrightarrow$ Local siderial time: Right ascension of stars passing through meridian.

Right Ascension is measured in hours, minutes, and seconds

1 h corresponds to 15°.
α increases towards East.

Siderial Time

Note: Siderial time $\neq$ common time

Common time: 24 h between culminations of the Sun (i.e., passes of Sun through meridian).

BUT

Sun moves on sky towards east

$\Longrightarrow$ one "solar day" takes slightly longer than one rotation of the Earth

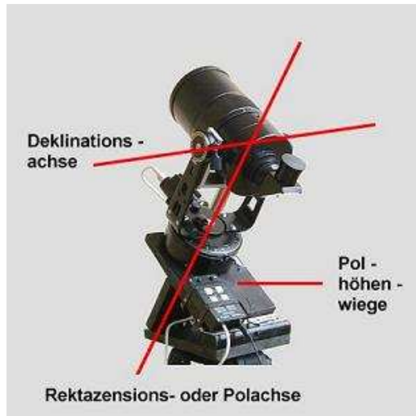
Angular speed of Sun: 360° degrees in 365.25 days, i.e., $0.9856^\circ\,\mathrm{d}^{-1}$.

$\Longrightarrow$ During 365.25 days the Earth rotates 366.25 times

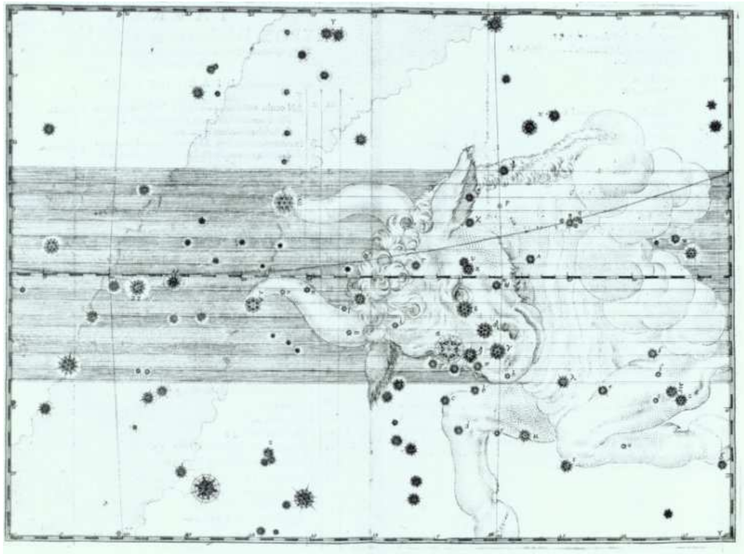
$\Longrightarrow$ Earth's rotation takes $24\,\mathrm{h} \times 365.25/366.25 = 23\,\mathrm{h}\ 56$ minutes.

Telescope Mountings

azimuthal mounting: horizontal axis and vertical axis



equatorial mounting: declination axis and polar axis

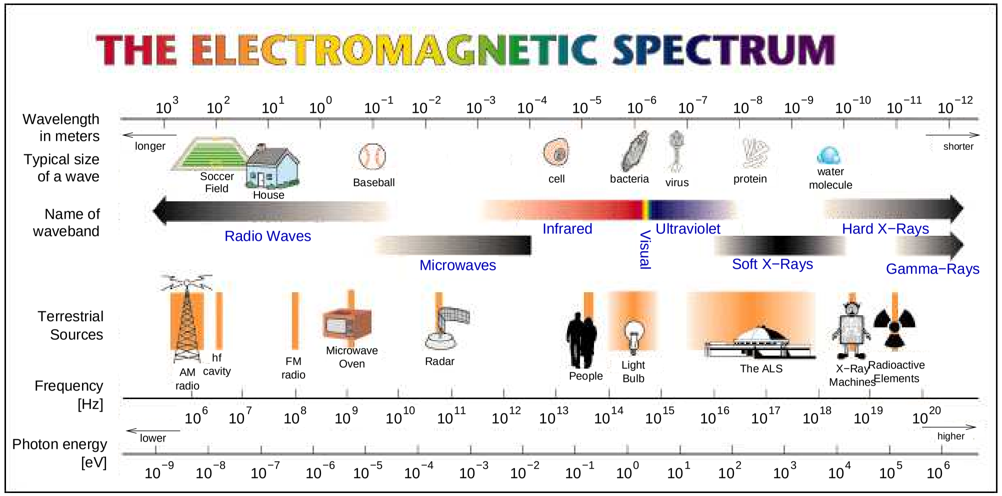


Bayer's Uranometria (1603; University of Illinois collections)

Because of precession and nutation: need to state epoch of coordinate!

Aldebaran = α Tau: $\alpha_{\mathrm{J2000.0}} = 04^{\mathrm{h}}35^{\mathrm{m}}55.2387^{\mathrm{s}}$, $\delta_{\mathrm{J2000.0}} = +16^\circ30'33.485''$

corresponding to $\alpha_{\mathrm{B1950.0}} = 04^{\mathrm{h}}33^{\mathrm{m}}02.9^{\mathrm{s}}$, $\delta_{\mathrm{B1950.0}} = +16^\circ24'37.6''$



Electromagnetic Spectrum

As we all know, light can be characterized by

Wavelength: λ, measured in m, mm, cm, nm, Å.

Frequency: ν, measured in Hz, MHz.

Energy: E, measured in J, erg, Rydbergs, eV, keV, MeV, GeV.

Temperature: T, measured in K.

These quantities are related:

$$\lambda\nu = c \qquad E = h\nu \qquad T = E/k \tag{9.1}$$

where

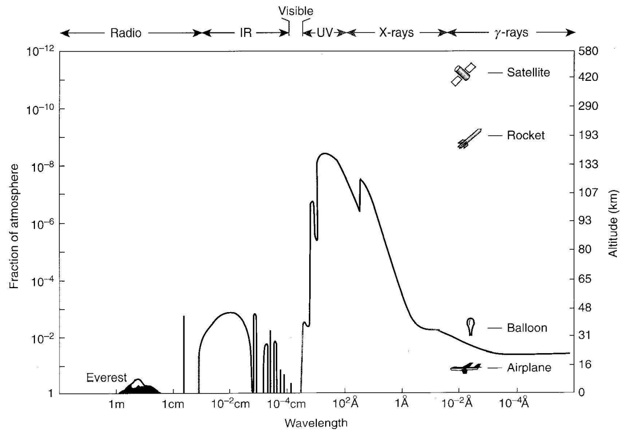
$$c = 299792458\,\mathrm{m\,s^{-1}} \tag{9.2}$$

$$h = 6.6260693(11) \times 10^{-34}\,\mathrm{J\,s} \tag{9.3}$$

$$k = 1.3806505(24) \times 10^{-23}\,\mathrm{J\,K^{-1}} \tag{9.4}$$

Constants are 2002 CODATA values, `http://physics.nist.gov/cuu/Constants/index.html` uncertainty is 1σ in units of last digit shown.

Earth's Atmosphere



Earth's atmosphere is opaque for all types of EM radiation except for optical light and radio.

$\Longrightarrow$ Astronomy is today multi-wavelength astronomy, although optical studies are still very important

Charles & Seward, Fig. 1.12

$\Longrightarrow$ For time reasons only optical telescopes will be discussed.

Introduction

Scientific purposes of a telescope:

1. Collect light, lots of light, to show faint objects ("Light bucket")
2. Resolve small features

Instrumentation used...

1. to make images
   $\Longrightarrow$ Imaging (with Charge Coupled Devices [CCDs], earlier also with film)
2. to measure spectra
   $\Longrightarrow$ Spectrographs
3. to measure stellar brightness
   $\Longrightarrow$ Photometers (often CCDs, there are also dedicated photometers for msec-resolution photometry)

For physics of instrumentation $\longrightarrow$ Astronomy Laboratory

Types of Telescopes

To collect light, we have two possibilities:

1. Lenses: Refractors

   Disadvantage: lens cannot be supported from the back

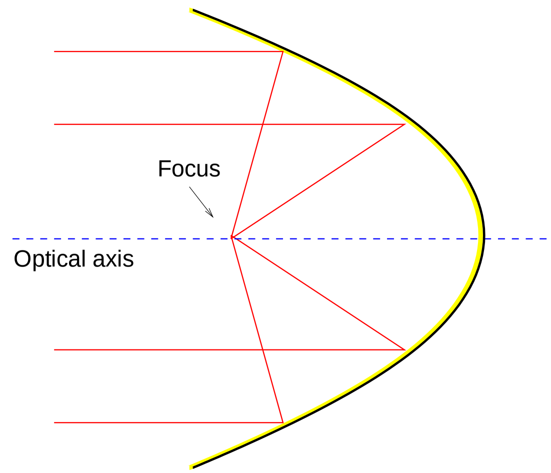
   $\Longrightarrow$ limits max. diameter to $\lesssim$ 1 m

   largest refractor at Yerkes Observatory (University of Chicago): $d = 1.02$ m

   $\Longrightarrow$ not of interest for science
2. Mirrors: Reflectors

   Mirrors can be supported, instrument of choice for today, with diameters up to 11 m

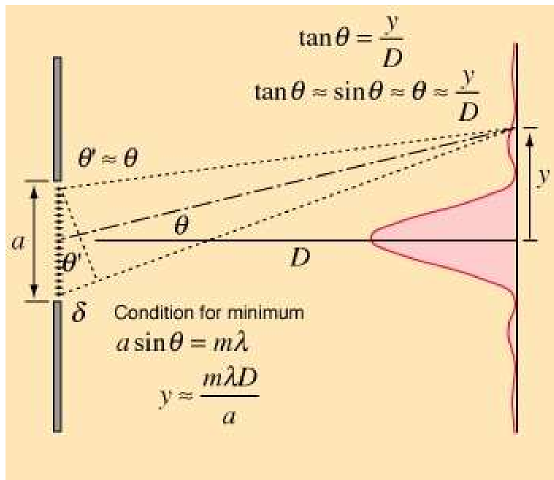
Types of Telescopes



To form image: focus light with a parabolic mirror

Spherical mirrors show spherical aberration $\Longrightarrow$ *not* suited for astronomical telescopes (at least not without correction).

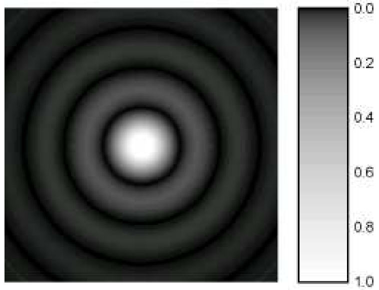
Resolution



GSU

Wave nature of light results in interference pattern caused by diffraction on optical elements in telescope (mainly aperture).

Resolution



Diffraction pattern on telescope aperture: Airy pattern
For a circular aperture with radius r:

$$I(\theta) \propto \pi^2 r^4 \left[\sum_{n=0}^{\infty} (-1)^n \frac{1}{n+1} \left(\frac{m^n}{n!} \right)^2 \right]^2 \propto \frac{\pi^2 r^4}{m^2} (J_1(2m))^2 \quad (9.5)$$

where $m = \pi(r/\lambda)\sin\theta$ and where $J_1(x)$ s the Bessel function of the first kind of order unity.

$I(\theta)$ has minima for $m =$ 1.916, 3.508, 5.087,..., or

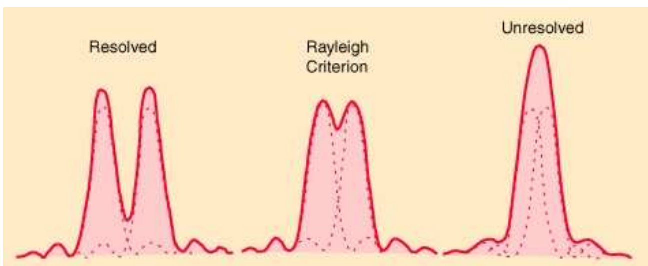
$$\sin\theta = \frac{1.916\lambda}{\pi r}, \frac{3.508\lambda}{\pi r}, \frac{5.087\lambda}{\pi r}, \dots \quad (9.6)$$

or for θ small ($\sin\theta \sim \theta$) minima are found at:

$$\theta = \frac{1.220\lambda}{d}, \dots \quad (9.7)$$

where d: diameter.

Resolution



Resolution of telescope: ability to separate two (point-like) light sources

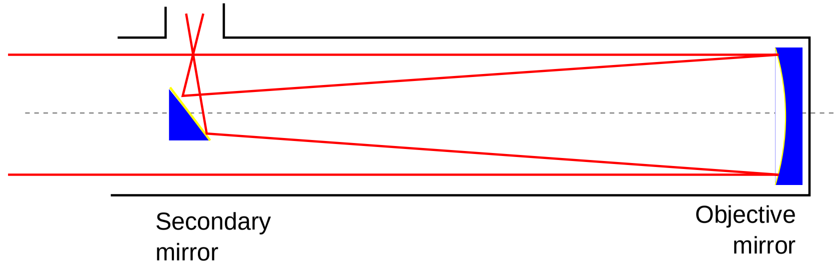
Rayleigh criterion for resolution: maximum of diffraction pattern of one source must fall into minimum of diffraction pattern of other source.

Therefore the diffraction limited resolution is

$$\alpha = \frac{1.220\lambda}{d} = \frac{12''}{D/1\,\text{cm}} \quad \text{for optical light} \quad (9.8)$$

Note: Rayleigh criterion is a criterion, *not* a law. Detailed object separability depends on ratio of intensities of two objects, in practice resolutions up to 3× smaller are achievable.

Newtonian Telescope

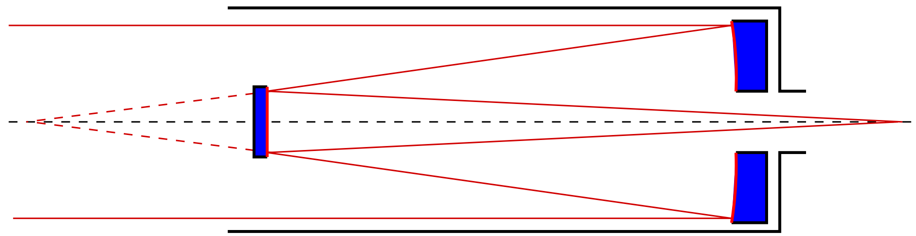


Newtonian telescope: reflector with parabolic mirror.

Common in cheaper telescopes.

Disadvantage: large size ($\sim$ focal length)

Cassegrain Telescope



Cassegrain telescope, after Wikipedia

Cassegrain telescope: reflector with “folded optical path”

(M1: paraboloid, M2: hyperboloid)

$\Longrightarrow$ Much shorter than Newtonian

$\Longrightarrow$ Telescope of choice for modern instruments

Schmidt Telescope

Bernhard Schmidt (Hamburg)
http://www.sky-win.de/

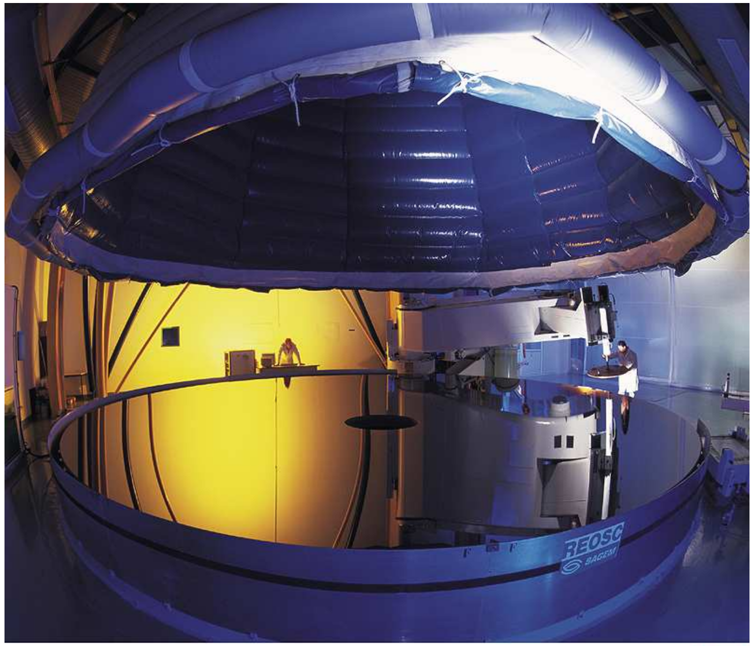
2m Schmidt telescope at the Landesternwarte Thüringen in Tautenburg near Jena: largest Schmidt telescope in the world.

Uses spherical mirror for larger field view, correction plate used to correct for spherical aberration.

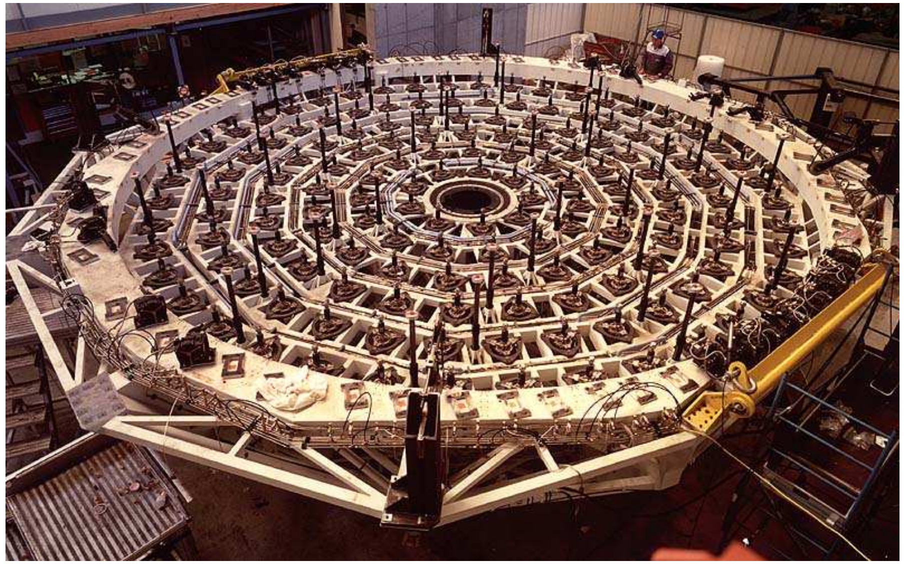
Many amateur telescopes are combination of Schmidt telescope and Cassegrain telescope
$\Longrightarrow$ Schmidt-Cassegrain telescopes.

Example: Building of the European Southern Observatory's Very Large Telescope

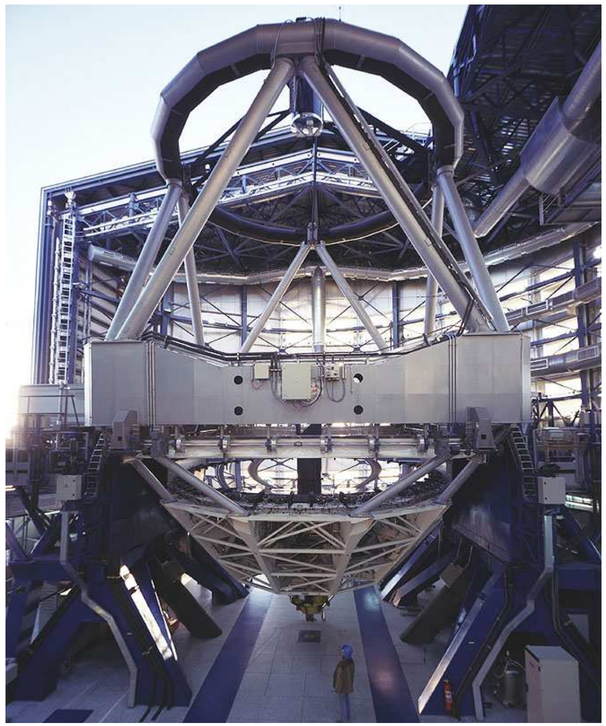
ESO



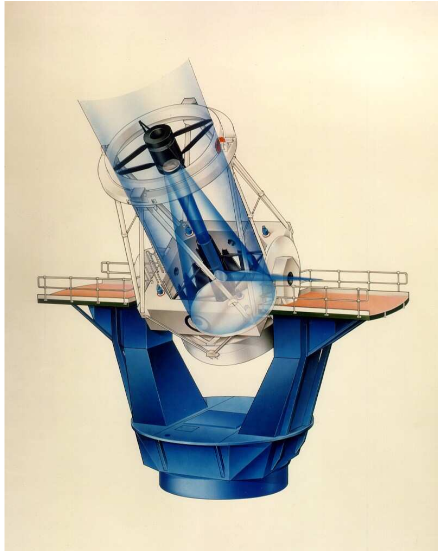
The Polished Fourth VLT 8.2-m Mirror at REOSC
Photo: SAGEM
ESO PR Photo 44/99 (14 December 1999)
European Southern Observatory



Mirror cell supporting the mirror, actuators keep mirror in shape ("active optics", correcting all possible deformations of the mirror).



Building the VLT



Nasmyth Focus:
light reflected through axis

- ideal for modern azimutal mountings
  e.g., European Southern Observatory's Very Large Telescope
- two stationary platforms
- can host large instruments
- very stable

William Herschel Telescope, La Palma

VLT at Paranal

ESO PR Photo 43a/99 (8 December 1999) © European Southern Observatory

Adaptive Optics

From Eq. 9.8, the resolution of a telescope of diameter d is

$$\alpha = \frac{1.220\lambda}{d} = \frac{12''}{D/1\,\text{cm}} \tag{9.8}$$

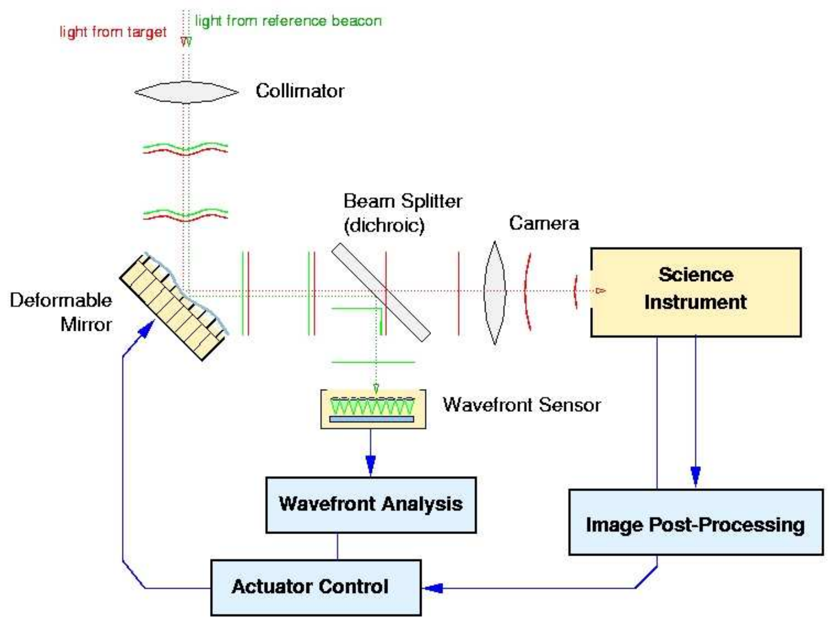
Problem: astronomical seeing

$\Longrightarrow$ turbulence in atmosphere smears pictures of stars to disks with $\theta \gtrsim 0.3''$

$\Longrightarrow$ Increasing telescope diameter to $\gtrsim$40 cm does *not* result in increase in resolution!

Solution to seeing problem: adaptive optics

. . . which only works in the IR so far, need to go to space for optical and UV



Scheme of an adaptive optics system (Lick observatory)

The AO system of Mt. Hopkins observatory, a 30 W laser (©G. Furesz).

The AO system of Mt. Hopkins observatory, a 30 W laser (©G. Furesz).

Adaptive Optics

Gemini North/AURA

Picture of the galactic center in the IR taken with the Gemini North

Adaptive Optics

Gemini North/AURA

Picture of the galactic center in the IR taken with the Gemini North
. . . and corrected with adaptive optics
$\Longrightarrow$ Resolution: diffraction limited!

$$\theta = 1.22\,\text{rad} \cdot \lambda/d \sim 70\,\text{mas} \quad (9.9)$$

(for $d = 8$ m, $\lambda = 2.2\,\mu$m)