Let's Go:
Solar System

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webpage with images and links:

`http://www.astro.uiuc.edu/~bdfields/mste_aims08.html`

- The Big Picture:
  Ptolemy, Copernicus, and our place in cosmos

- The dynamic Solar System:
  gravity and the motion of the planets

- Whirlwind tour of the Solar System
  planets from Mercury to Neptune
  ...and Pluto too!

The Big Picture: Ptolemy, Copernicus, and our place in cosmos

Early Cosmological Models

Scientific Models must:

- explain observations
- predict future observations

> The principle of science, the definition, almost, is the following: *The test of all knowledge is observation.* Experiment is the *sole judge* of scientific "truth."
>
> The first principle is that you must not fool yourself–and you are the easiest person to fool.
>
> —Richard Feynman

want to build scientific models to
explain and predict motion of planets

models change:
- when predictions fail
- when new observations require new explanations

model refined $\rightarrow$ theory!
theory is end product–not mere speculation or offhand/wacky idea

Planets: Naked-eye Data

Known since ancient times:
Mercury, Venus, Mars, Jupiter, Saturn

Discovered later, with telescopes:
Uranus, Neptune, Pluto

daily motion: westward w.r.t. horizon

w.r.t. fixed stars:
always stay close to ecliptic
usually move eastward
`www: SOHO LASCO planet movie`
but sometimes westward: "retrograde motion"
`www: retrograde motion of Mars`
so motion not uniform in angular speed
in fact, not uniform even when in "direct" (non-retro) motion

correlations observed:

Mercury, Venus	Others
always stay close to sun on sky	can move freely along ecliptic
retro when in **conjunction** (i.e., when closest to Sun on sky)	retro when in **opposition** (i.e., opposite Sun on sky)

Greek Cosmology

Pythagoreans

- earth: spherical shape
- stars and planets on spheres

  (Note aesthetic preference for spheres: symmetry!

→ pure geometry

Aristotle (284-322 BC)

Two realms, where different physical principles apply

Realm	**Heavenly** [incorruptible]	**Terrestrial** [corruptible]
location:	above moon	below moon
natural motion:	uniform circular rotation	earth, air, water, fire: toward natural place in universe earth lowest, then water, air, fire
status:	perfect, unchanging	imperfect, changeable

earth stationary, and at center of universe

Earth at center of universe ("geocentric")

$\star$ apparent lack of **stellar parallax**

If earth orbits sun

diagram: Sun, Jan, July, star, lines of sight

star appears in different directions!

not observed until $\sim$ 1830

$\sim 1'' = 1$arc sec; but $\ll$ eye $\sim 1' = 1$ arc min

Aristotle explained data of time–strong evidence **against** Sun-centered picture!

Q: What does the geocentric model (described thus far) explain? what not?

Problems

must explain **Retrograde motion**
cannot do this with circular orbits
(having constant angular velocity)

solution must complicate the orbit:
add deferent and epicycle
diagram: Earth, deferent path, epicycle, motion arrows

Claudius Ptolemy $\sim$ 125 AD

Constructed complete geocentric model
every planet had epicycles—in fact, epicycles on top of epicycles
complicated/elaborate model, but also sophisticated

Ptolemy accounted for
- non-uniform motion
- retrograde motion
- Venus and Mars never in opposition
  center of epicycles always on line
  connecting earth and sun

how good: observations decide!
Errors generally < 5 deg: not bad but observable!
remained in use for $\sim$1400 years!!

Q: is Ptolemy scientific?

A Cosmological Revolution

we fast forward 1.5 millenia → Renaissance Europe
the age of da Vinci, Michelangelo, Elisabeth I, Shakespeare
...and:

Nicolaus Copernicus 1473–1543 Polish
offended by Ptolemy's equants (on aesthetic grounds: "ugly")
adopted *heliocentric* cosmological model

Copernican Model
- Earth spins ⇒ daily motion of celestial objects
- Earth orbits Sun ⇒ apparent Sun motion in zodiac
- Mercury & Venus orbits inside Earth's ⇒ always seen near Sun
- retrograde motion: naturally caused by Earth–planet passing
  `www: animation`
  simply explains retrograde correlations w/ planet location
- lack of stellar parallax ⇒ must assume large distance to stars

Note what Copernicus does and does not say:

- planets still on spheres
- Copernicus sill used epicycles!
- predictions not better than in Ptolemy's model
- $\longrightarrow$ geometrically equivalent
- Copernicus' model not generally accepted
  and Ptolemaic–Copernican disagreement though to be metaphysical, unanswerable question

Galileo Galilei

First to use telescope in Astronomy

`www: Galileo shows scope to Duke`

contributions:

- mountains on the moon
- moons of Juptier
- sunspots
- phases of Venus

`www: Venus phase animation`

obs'ns contradicted Aristotle

supported Copernicus

"paradigm shift" (Kuhn)

radical change in outlook/conceptual framework

Galileo , forced to recant geocentric view
– his work, Copernicus, Kepler banned until 1832
– official semi-apology ("mistakes were made") 1992
complex: crackdown as much political as theological

note:
1. really not at all obvious that sun at center
2. the paradigm shift was a difficult one and challenged outlook

ENOUGH ALREADY–TAKE A BREAK!

The dynamic Solar System: gravity and the motion of the planets

Gravity in a Nutshell

Galileo not only great astronomer
but also a great physicist
paved way for Newton's dynamics by study of
two special cases of motion

1. **"free body"** – *no* external influences
natural motion: coast in straight line, const speed
$\longrightarrow$ retain current state of motion
$\longrightarrow$ bodies have **inertia**

2. **"free fall"** – when only influence is *gravity*
Galileo recognized another key motion
Demo: Tower of Pisa expt
$\longrightarrow$ constant acceleration **indep of mass**!
Q: what's acceleration?
$a = g$, $g = 9.8\,\mathrm{m/s^2}$

Newton's Law of Motion

focus on *acceleration*: change in speed or direction of motion
speed up rate or slow down rate

Newton's 2nd Law of Motion: "$F = ma$"

- a force acting on an object causes it to accelerate
- acceleration is proportional to force
  and inversely proportional to mass
- $a \propto F/m$
- or: $F = ma$

Newton's Universal Law of Gravity

Isaac Newton:
gravity initmately linked to *mass*

- all objects with mass exert force: gravity
- all objects with mass feel gravity forces
  from all other massive objects

in fact: more mass $\longrightarrow$ more gravity
but: gravity forces *decrease* as distance *incresaes*
$\longrightarrow$ *inverse* relationship with distance

General rule: two objecs of mass m_1, m_1
separated by distance d
each feel attractive gravity force F due to the other

- $F \propto m_1$
- $F \propto m_2$
- $F \propto 1/d^2$

together:

$$F_{\text{grav}} \propto \frac{m_1 m_2}{d^2} \tag{1}$$

"inverse square law"
$\rightarrow$ double distance: F_{grav} is 4 times smaller!
$\rightarrow$ to lose weight, go upstairs!

Q: what's direction *of gravity force in this case?*
Q: why doesn't gravity from the massive Sun suck us off Earth?

Newtonian Free Fall

Consider two objects orbiting the Sun
different masses $m_1 \neq m_2$ but same distance d:

$$F_1 = m_1 a_1 = \frac{G M_{\text{sun}} m_1}{d^2} \tag{2}$$

$$F_2 = m_2 a_2 = \frac{G M_{\text{sun}} m_2}{d^2} \tag{3}$$

forces are different! but look at acceleration:

$$a_1 = \frac{G M_{\text{sun}}}{d^2} = a_2 \tag{4}$$

the same! This is Galileo's free fall result!

a big deal!

Q: why?

Newton's laws + Newton gravity:
$\rightarrow$ *all* objects at same distance from Sun
have same acceleration
$\rightarrow$ i.e., gravity accel. depends *only* on distance from Sun

So what?
- accleration = *change* in velocity
- but if know how v changes at all times
- then know position/location at all times

$\Rightarrow$ know full orbit!
$\Rightarrow$ planet *orbits* completely determined by location from Sun
Q: which planet should move fastest (biggest accel)? slowest?

Newton's laws of motion and of gravity
completely explain all solar system motions!

- $a = GM_{\text{sun}}/d^2$: small $d \rightarrow$ big a
  Mercury moves fastest!
  Pluto moves slowest
- orbit *period* P set by distance as well

$$P^2 = d^3 \tag{5}$$

where $P =$ period in years
where $d =$ distance, in AU = Earth-Sun distance
Q: what are P, d for Earth? is equation true?
Q: prove that Mercury must have $P < 1$ yr?

ENOUGH ALREADY–TAKE A BREAK!

Whirlwind tour of the Solar System

The Solar System

`www: Place in the Big Picture`

Why study the Solar System?

▷ it's home!

▷ use present to learn about past

$\longrightarrow$ clues for origins of Earth & Sun

▷ help understand origin of exoplanets: compare/contrast

Sociology: traditionally, astronomy divided into study of solar system vs extrasolar objects

boundary is artificial, and somewhat loosening now...

Basic Organization `www: SS lineup`

Terrestrial (Earth-like) planets: smaller, rocky
Mercury, Venus, Earth/Moon, Mars

Asteroid Belt: rocky debris

Jovian (Jupiter-like) planets: large, gaseous
Jupiter, Saturn, Uranus, Neptune

Kuiper Belt & Oort Cloud: Icy debris

Pluto: in summer 2006, demoted to "dwarf planet"
$\rightarrow$ will discuss what's behind this

Planet Properties

Collected here for reference; discussion follows

Note trends, distinctions between terrestrial/Jovian

Property	Terrestrial	Jovian	Pluto
Members	Merc, Ven, Earth/Moon, Mars	Jup, Sat, Urn, Nep	PL
avg dist. from Sun (a)	$0.4 - 1.5$ AU	$5.2 - 30$ AU	39 AU
size R	$\sim$ earth	4–11 earth	$\sim$ 0.2 earth
mass	$\lesssim$ earth	15–300 earth	$\sim$ 0.002 earth
density	3000–5000 kg/m^3	$\sim$ 1000 kg/m^3	$\sim$ 2000kg/m^3
interior	rocks, metals	gas, ice, metal core	?
spin period	$\gtrsim$ 1 day	$\lesssim$ 1 day	6 days
atmosphere	none, CO_2, O_2, N_2	H_2, He, H-compounds	methane CH_4

Composition

composition = what mix of elements

note: density $\leftrightarrow$ composition connection

denser $\rightarrow$ richer in heavy elements
e.g., water (H_2O): $\rho = 1000\,\mathrm{kg/m^3}$
rocks (O,Si): $\rho \sim 3000\,\mathrm{kg/m^3}$
metals (Ni,Fe): $\rho \sim 6000\,\mathrm{kg/m^3}$

Q: terrestrial/Jovian density comparison? implications?

The Earth

recall: $R = 6.4 \times 10^4$ m $= 6400$ km
get mass from $g = GM/R^2$ (need G!)
$\rightarrow M = 6.0 \times 10^{24}$ kg

Average density:
$\rho_{\text{av}} = 3/4\pi M/R^3 = 5,500\text{kg/m}^3$
between rocks and iron $\rightarrow$ some of both

Interior
sketch
crust: 16–40 km
mantle: ~ 3000 km
outer core: $\sim 2,200$ km
inner core: $\sim 1,200$ km

inner core: solid. Fe, Ni
outer core: liquid. Fe, Ni
mantle: "plastic". Fe, Mg, Si, O
crust: solid. ocean basins—basalt: O, Si, Al, Mg
continental plates–granite: O, Si, Al, Na, K
heaviet elements lowest $\rightarrow$ settling ("differentiation")

Q: how do we know?

How do we know?
"Refraction" of Earthquakes
Demo: slinky

Earthquakes "emit" waves $\rightarrow$ use seismographic info to learn earth structure
diagram

Plate Tectonics

```
www:  plot of earthquake sites
www:  plot of volcano sites
www:  plate locations
```

crust not a sigle rigid solid
but collection of "plates"
motions in mantle (convection) cause plate motion
sketch convection currents

```
www:  satellite laser ranging
www:  VLBI: radio telescopes used to detect motion
www:  drift animation
```

plates collide, slide, buckle
$\Rightarrow$ "plate tectonics"

www: Mountain

www: volcano (Kilauea, HI)

www: San Andreas

ex: San Andreas fault in CA: sliding plates $\rightleftharpoons$

Earth is evolving!

`www: Messenger image`

Q: what's notable about this image?

Mercury

no atmosphere, many craters
$\longrightarrow$ much like our Moon
$\longrightarrow$ no moons of its own

Recently visited: NASA *Messenger*

`www: Mercury`

Venus

Properties

M, R, ρ_{avg} Earth-like, "sister planet"

$\rightarrow$ probably very Earth-like initially

now: hellish!

atmosphere: thick

mostly CO_2; clouds of concentrated sulfuric acid

surface pressure $P_0 = 90\text{atm} = 90\times$ Earth

surface $T = 750\text{K} = 380$ C $= 800$ F; melts lead!

`www: Venera 9 & 10 comparison`

`www: Venera 13 image`

landers lasted for $\sim 1 - 2$ hr, then got cooked

found: flat rocks, basaltic soil $\rightarrow$ volcanic activity

other evidence for "geo"logical activity on Venus:

`www: Guinevere plains---stretching forces from mantle`

`www: Venus craters`

crater counts similar to Earth–a few 100 Myr old

but no plates! Has to be resurfaced some other way, perhaps active volcanism?

`www: radar map: volcano lava flows?`

Note: $T_{\text{Venus,surface}} \approx T_{\text{Mercury,surface}} \approx 750\text{K} = 380\ \text{C} = 800\ \text{F}$

$\rightarrow$ farther from Sun than Mercury, but same surface T?!

$\rightarrow$ i.e., much hotter than you might expect

Q: Why so hot?

Greenhouse Effect

basic idea: atmosphere traps thermal energy
note: important for Earth and Mars too

Consider radiative energy flows
incoming: sunlight–visible wavelengths, atm transparent
  Venus surface not dark!
outgoing: surface thermal (BB) emission: IR
  but CO_2 in atm blocks IR, absorbs energy
$\Rightarrow$ atmosphere acts like blanket

Venus: probably initially cooler, had liquid water(?)

note–early Sun was 30% dimmer

CO_2 dissolved in oceans, rocks

note: CO_2 in Earth rocks, oceans is enough for 70 atm! ...just like Venus!

Now imagine: watery Venus heated a bit

Q: effect on atmosphere? on temperature?

if early water-bearing Venus heated, positive feedback loop:
Heat $\rightarrow$ surface $T \uparrow$
$\rightarrow$ H_20 evap, atm $\rightarrow$ CO_2 released as well
$\rightarrow$ repeat until all H_2O evaporated!

also: H_2O molecules lighter than CO_2
$\rightarrow$ all H_2O evaporated
$\rightarrow$ go to upper atm
UV light from Sun $+ H_2O \rightarrow H + OH$, H escapes
$\Rightarrow$ water lost! $-$ warming irreversible
$\rightarrow$ **runaway greenhouse effect**

Mars

Vital Statistics:
$R \simeq 1/2\ R_{\text{Earth}}$
$M \simeq 10\%\ M_{\text{Earth}}$
$\rho_{\text{avg}} = 3900\ \text{kg/m}^3\ <$ Earth $\rightarrow$ smaller core

atmosphere thin: $P_0 \sim 1/200$ Earth atm
$\rightarrow$ liquid water cannot exist! sublimates, freezes
composition: heavy species–95% CO_2, $\sim 2\%$ N_2, Ar
- smaller mass $\rightarrow$ more escape
- no ocean to absorb CO_2

surface temperature: $T \sim$ 190–240 K
polar caps: frozen water, CO_2; cap sizes vary: seasons!

soil – iron rich (red color $\rightarrow$ iron oxide=rust)

Water on Mars

today: ice–polar caps, permafrost in soil

`www: nuclear reaction cartoon`

`www: epithermal neutron map of Mars`

`www: Phoenix mission to polar cap--ongoing!`

but much evidence for liquid water in past!

`www: outwash ‘‘river delta’’`

- “arroyos” – river-like channels (run downhill, show sandbars!)
- Martian meteorites: were wet when made
- Mars Global Surveyor: flat basin in N. hemisphere w/ “coast-line” features

  channels stop here → ancient ocean?
- gullies–small but uneroded → recent

  2005–new gully created – confirms active flows

Life on Mars?

Water $\rightarrow$ maybe life?
No clear evidence

But: ancient Mars meteorite (discovered on Earth)
Q: how did it get here? how know it's Martian?
claimed to have fossil bacteria
`www: microscopic image--bacteria-like figures?`
$\rightarrow$ perhaps life long ago?

Q: who cares if Mars had bacterial life?

Jupiter

prototype for Jovian planets
mass: $M = 1.9 \times 10^{27}$ kg $= 0.1\% M_\odot \simeq$ sum of rest of planets
radius: about 10 R_{Earth}
$\rho_{\text{avg}} \simeq 1,300$ kg/m$^3 \ll \rho_{\text{rock}}$ for sure isn't rocky!
composition: H 79%, He 20%, 1% other $\rightarrow$ very similar to sun
color: ammonia clouds

spin: rapid, 9hr 50min $\rightarrow$ oblate ("M&M shape") $\rightarrow$ atmospheric circulation!
`www: Jupiter`
high pressure regions: zones
low " ": belts
Great Red Spot: long-lived storm
`www: Red Spot`
`www: red spot animation`

Jupiter Interior

transp: Jupiter cutaway
no solid surface!

gaseous atmosphere becomes incresingly dense
until compressed liquid H_2 (hi pressure)
then liquid H metal, probably rocky core
(differentiation of heavy elements)

Saturn

Rings

not solid! many small icy rocks, dust

each has individual circular Keplerian orbit

$\longrightarrow$ rings have different periods, speeds depending on distance

$\sim$ few $\times$ 100 m thick: razor-thin!

aligned with equator

Cassini-Huygens: ongoing mission

spectacular views of rings

detailed data on ring structure, interaction with moons

`www: Cassini images`

So: why does Saturn have rings?

what gives them their structure?

rings are a result of gravity!

consider "rubble pile" held together by its own gravity
left alone: pile is *stable*
but gravity field of planet: stronger pull on near side, weaker on far
$\rightarrow$ net "stretch" = tidal force
if pile too close to planet: torn apart
"minimum safe distance" = *Roche limit*

Saturn: rings inside Roche limit, moons outside
$\rightarrow$ rings are captured moon?
$\rightarrow$ more likely: "protomoon" that never coalesced

note: **all** Jovian planets have rings!
`www: Jupiter rings (Voyager, IR)`

Debris

in addition to planets
Solar system contains large amount of smller junk
- rocky debris: asteroids
- icy debris: comets

Debris I: Asteroids

Properties

"minor planets" number $\sim 10^5 - 10^6$
masses: total $\sim 10^{-5} M_{\text{Earth}}$
sizes: poorly known, but go up to ~ 300 km
composition: solid (no gasses, ices)
- 5/6 are "C-type" carbon rich
- 1/6 rea "S-type" iron rich

Q: how do we know this?

Asteroid Orbits

asteroids orbit Sun $\rightarrow$ must follow Kepler's laws (of course!)

wide variation in a, e

but average $\bar{a} \simeq 2.8$ AU

$\rightarrow$ between Mars & Jupiter

avg $e < 0.1$: nearly circular

most orbit planes close to ecliptic

`www: Inner Solar System in real time`

`www: Near-Earth objects`

if cross Earth's orbit, enter atmosphere: meteorite

`www: Leonids`

`www: fireball`

Note: meteorites on view in Geology–extraterrestrial matter!

current events: NASA press release last Friday

$\rightarrow$ downsized program for near-Earth object search

what do asteroids look like? From ground, see only largest
but now have visited some (on the way to outer SS)

`www: Gaspara`

`www: Ida & Dactly`

Near Earth Asteroid Rendezvous
intercept near-earth asteroid 433 Eros
S-type: stony-iron
large: 35 km long, 14 km wide–Chicago
"potato shaped"

`www: NEAR image of 433 Eros`

`www: NEAR movie`

hints of stratification–broken from (much) larger object?

Debris II: Comets

`www: Hale-Bopp, Hyakutake, Ikea-Seki`
last month–brightest comet in decades! `www: McNaught`

Comet Structure: "dirty snowball" nucleus: ~ 10 km
solid: ices (H_2O, CO_2, CH_4), embedded dust grains

very elliptical orbits: changing $r \rightarrow$ changing T
far from Sun: completely frozen
as approach: ice $\rightarrow$ vapor (sublimation)
dust, gas released $\rightarrow 10^6$ km **coma**
`www: HST Hale-Bopp: coma & jets, nucleus unresolved`
pressure from sunlight & solar "wind" of particles
$\rightarrow$ **tails**: Ion, dust
Q: where should the tails point?

ion tail: small, low-momentum particles
$\rightarrow$ carried by solar wind
$\rightarrow$ points away from Sun
dust tail: larger, higher-momentum particles
$\rightarrow$ retain $\vec{v}$ component in comet direction
$\rightarrow$ non-radial arc tracing comet path
Transp: *Comet tails*

NASA Mission: Stardust
at 1.86 AU from Sun (2.6 AU from earth)
fly by comet P/Wild 2, collect samples of dust, gas
returned to earth last year: parachute, caught by airplane
"fresh" comet, hasn't lost all of its original material
$\rightarrow$ learn about interstellar dust grains
$\rightarrow$ output of stars and building blocks of planets

Comet Orbits

"Long Period": $P > 10^5$ yr

$\rightarrow a > 2000$ AU!

all orientations $\rightarrow$ not just ecliptic

Oort Cloud

spherical comet "reservoir" at 3000–100,000 AU

not observed directly!

probably did not form there....

ejected by Jovian planets in early SS?

"Short Period": $P < 200$ yr

lie in ecliptic

$\rightarrow$ not from Oort cloud $\rightarrow$ **Kuiper Belt**

$a = 30 - 100$ AU

`www: Outer solar system sketch`

first K.B. object detected in 1992
a.k.a., Trans-Neptunian objects; today, tally is hundreds
typically $\sim$ few% $-$ 10% size of Pluto
probably formed where they are now
estimates: 70,000 KBO's
total mass $\sim 0.1 M_{\text{Earth}}$

also: some comets strongly deflected,
have orbits with very small perihelion
(i.e., very close to Sun).
`www: sun-grazing comets`

Pluto

Orbit

$a = 39.5$ AU, $P = 285$ yr, $e = 0.25$ – largest for planet

Properties

$\rho_{\text{avg}} \simeq 2000$ kg/m^3 $\rightarrow$ ice, rock surface: N_2 ice

atm: very thin, $P = 10^{-5}$ earth

`www: HST image`

Pluto's Moon: Charon – together a "double planet" system
Mass $M_{\mathsf{P}} + M_{\mathsf{C}} = 0.0024 M_{\mathsf{Earth}}$; $M_{\mathsf{C}} \simeq 0.12 M_{\mathsf{P}}$
$R_{\mathsf{P}} = 720$ km, $R_{\mathsf{C}} = 395$ km
both spins, orbit have same period:

- system tidally locked into co-rotation
- each keeps same face to other

similar to comet nucleus, Kuiper Belt object
Pluto: smallest planet or largest KBO?

Pluto: History and Status

Clyde Tombaugh (1930): Pluto discovered in sky scan
totally unlike it's outer planet neighbors

1930's-1950's: Kuiper belt idea proposed
1990's: Kuiper belt objects discovered
2002–present: more large outer solar system objects

- Quaoar ("Kwawar"): $\approx 60\%$ Pluto size
- Sedna: $\approx 70\%$ Pluto size
- "Xena" $\rightarrow$ Eris: $>$ Pluto size!!

all are spherical rocky iceballs
largest of huge population of object beyond Neptune
orbits more elliptical than planets, but still $\approx$ in ecliptic
$\rightarrow$ "transneptunian objects" or Kuiper belt objects
smaller Kuiper belt members sometimes scatterer $\rightarrow$ comets

To Be Or Not To Be

last summer: International Astronomical Union redefines "planet"
Pluto demoted to "dwarf planet"
Q: Vote–planet or no planet?

Q: does it matter?
Q: arguments pro, con?