Today in Astronomy 111: overview of the Solar system

- Contents of the solar system
- What we can measure and what we can infer about the contents
- How do we know? Initial explanations of four of the most important facts about the solar system
- The basic collection of solar-system facts

The eight planets, and a moon (NASA, Palomar Observatory, Lowell Observatory)

Inventory of the Solar System

Image by Robert Gendler

Q: What would an outside observer see if they were looking at our Solar system?

A: The Sun.
And that's pretty much it.

- The **luminosity** (total power output in the form of light) of the Sun, is 3.8×10^{26} watts – 4×10^{8} times as luminous as the second brightest object, Jupiter.
- The mass of the Sun is about 10^{27} metric tons – about 500 times the total mass of everything else in the Solar system.

The solar system is the Sun, plus a little debris.

Aside: observations of other planetary systems

In most other stellar (**extrasolar**) systems, all we know about are the stars, because they are overwhelmingly bright.

- But, planets have been detected around other stars recently, with surprising properties (high eccentricity, small radii from star). This is mostly done by observing the motion of the central star, as we will learn this semester.
- Our understanding of the Solar system has helped us understand the formation and evolution of planetary and stellar systems.
- However, what we are finding about extrasolar systems is challenging previous views of solar system formation and evolution.

Astronomer-artist's conception of HD 209458 and its largest planet (Robert Hurt, SSC/Caltech)

Components of the "debris"

- The Giant planets: mostly gas and liquid.
- The **Terrestrial** (earthlike) planets and other **planetesimals**, some quite small: mostly rock and ice
- The Heliosphere: widespread, very diffuse **plasma**.

Io and Jupiter, seen from Cassini (NASA-JPL)

Giant planets

- Jupiter dominates with a mass of 10^{-3} times that of the Sun $(10^{-3} M_{\odot})$, or 300 times that of the Earth $(300 M_{\oplus})$.
- Saturn's mass is $3\times10^{-4} M_{\odot}$, or $100 M_{\oplus}$.
- Neptune and Uranus are about 1/6 the mass of Saturn.
- Giant planets at 5, 9, 20, and 30 times further from the Sun than Earth is (a = 5, 9, 20, 30AU; a is commonly used to denote semi-major axis, covering the possibility of an elliptical orbit).
- Saturn and Jupiter have roughly Solar type abundances (composition) which means mostly hydrogen and helium. Saturn probably has a rocky core; Jupiter might not.
- Neptune and Uranus are dominated by water (H_2O) and ammonia (NH_3) and have a larger percentage of their mass in rocky/icy cores.
- Jupiter and Saturn are called **gas giants**.
- Neptune and Uranus are called **ice giants**.

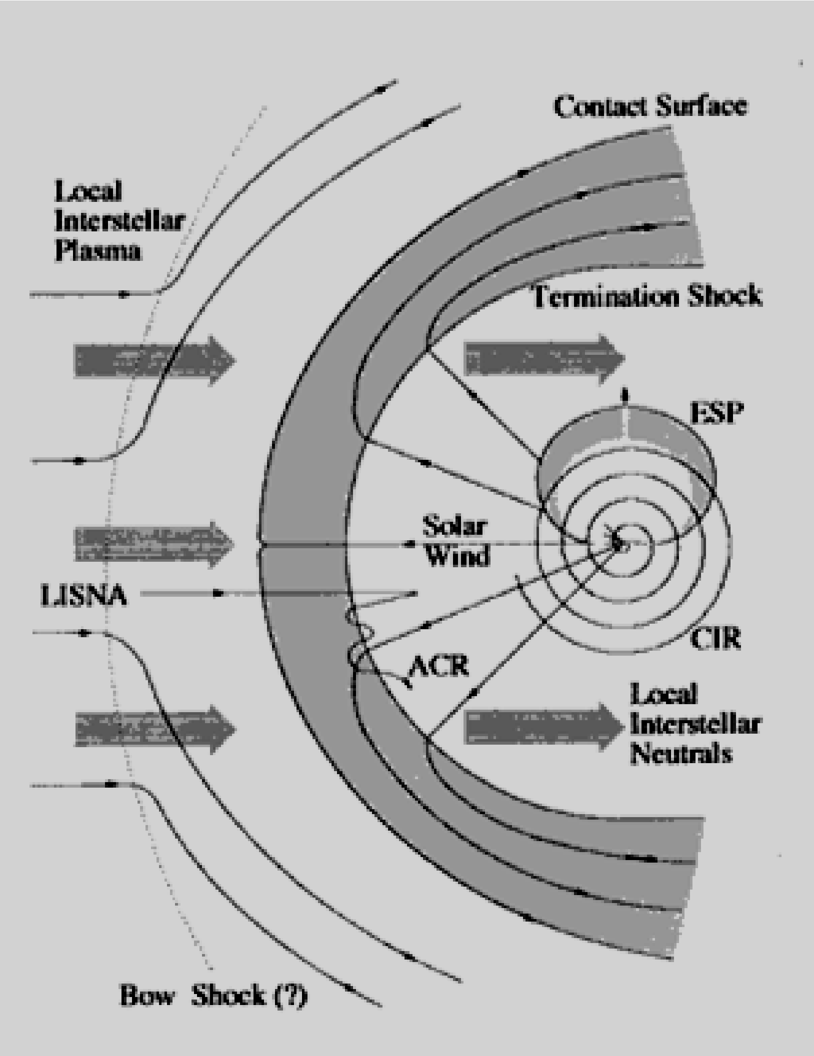
Jupiter, seen from Cassini (NASA-JPL)

Terrestrial planets and other rocky debris

- Earth and Venus, radius R~6000 km, a = 1.0, 0.7 AU respectively
- Mars, R ~ 3500km, a = 1.5 AU
- Mercury, R ~ 2500km, a = 0.4 AU
- Asteroid belt, a ~ 2-5 AU
- Moons and satellites
- Kuiper Belt, including Pluto, at a > 30AU
- Oort Cloud, including Sedna, at $a \sim 10^4$ AU
- Planetary rings
- Interplanetary dust

Images from Galileo (NASA-JPL)

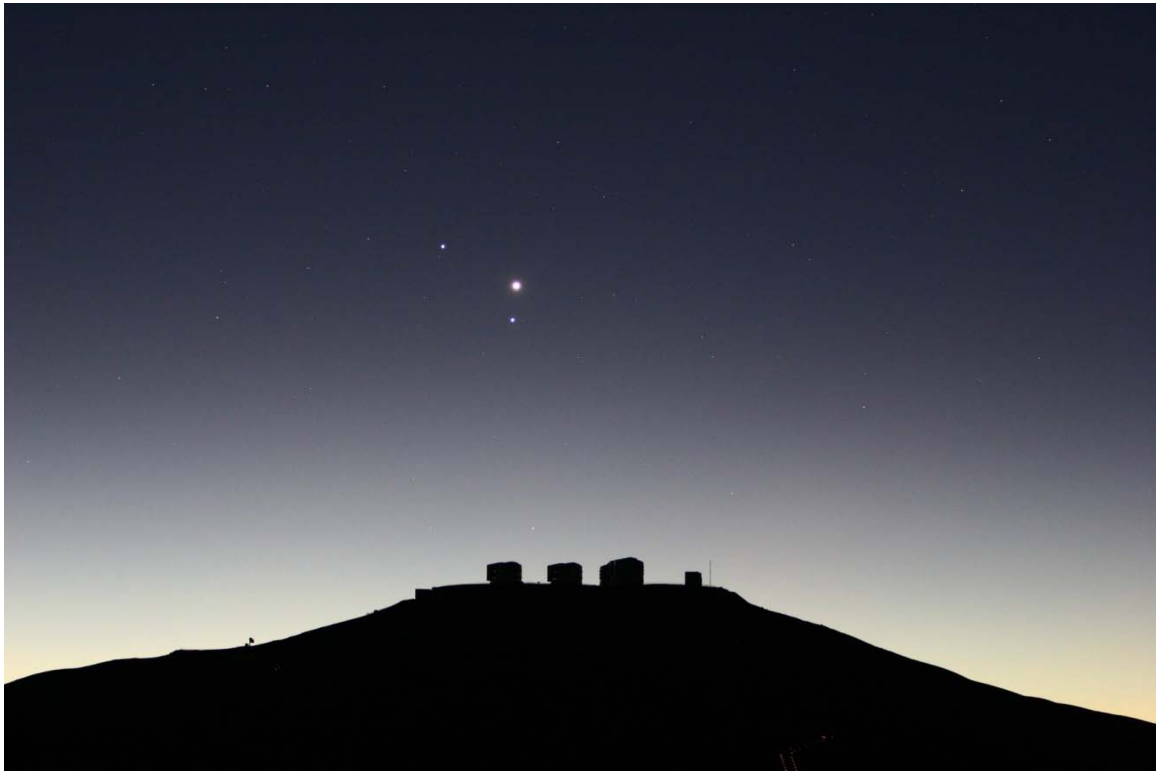
The Heliosphere



- All planets orbit within the heliosphere, which contains magnetic fields and plasma primarily of solar origin. (**Plasma**: an ionized gas with electrical conductivity and magnetization much larger than an ideal gas.)
- The solar wind is a plasma traveling at supersonic speeds.
- Where it interacts or merges with the interstellar medium is called the heliopause.
- Cosmic rays (high energy particles) are affected by the magnetic fields in the heliosphere.

Planetary properties that can be determined directly from observations

- Orbit
- Age
- Mass, mass distribution
- Size
- Rotation rate and spin axis
- Shape
- Temperature
- Magnetic field
- Surface composition
- Surface structure
- Atmospheric structure and composition

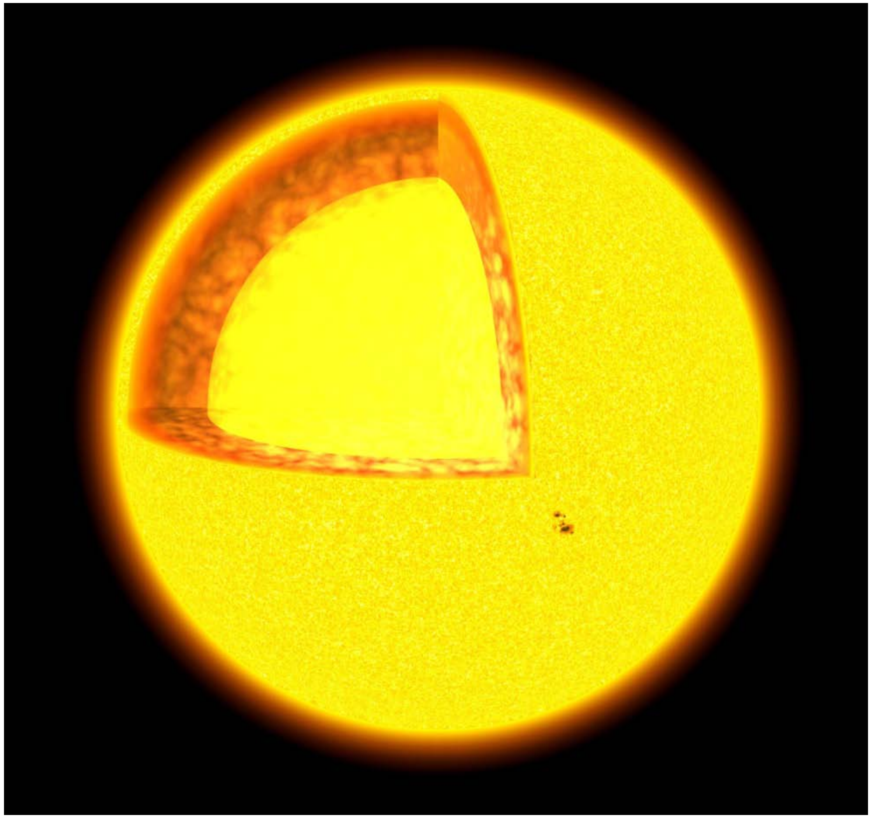


Saturn, Venus, and Mercury, with the European Southern Observatory in the foreground (Stephane Guisard).

Other planetary properties that can be inferred or modeled from the observations

- ❑ Density and temperature as functions of position, of the atmosphere and interior
- ❑ Formation
- ❑ Geological history
- ❑ Dynamical history

These will be discussed in context with the observations and astrophysical processes as part of this course.



Cut-away view of the Sun's convection zone (Elmo Schreder, Aarhus University, Denmark).

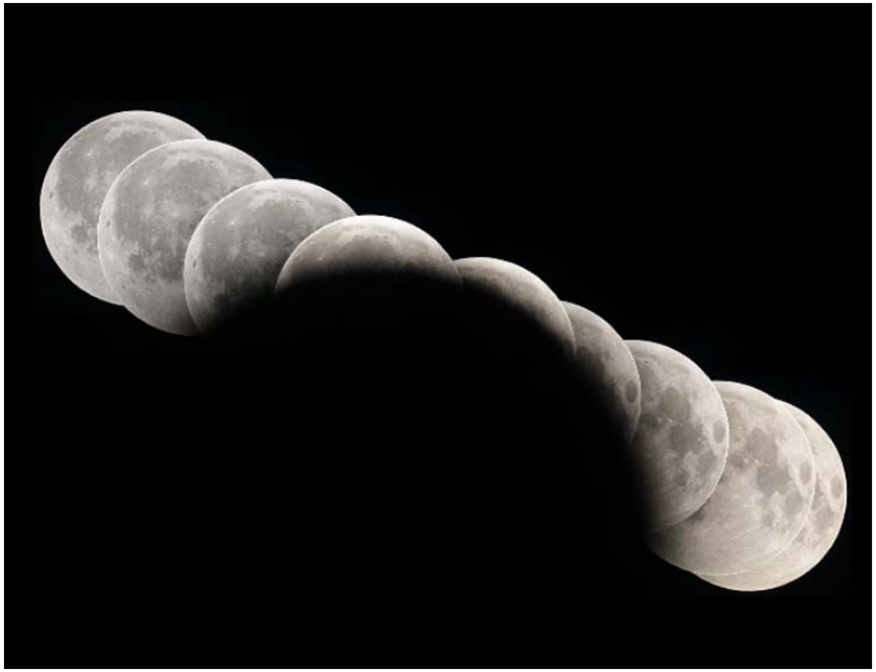
How do we know?

Note that most of what we will say about the planets this semester is founded upon a lot of very direct evidence, rather than theory or reason-aided handwaving. For example:

1. The Earth is approximately spherical.

Direct observation, of course, and known since about 500 BC:

- Lunar phases indicate that it shines by reflected sunlight.
- Therefore the full moon is nearly on the opposite side of the sky from the Sun.
- Therefore lunar eclipses are the Earth's shadow cast on the moon.
- The edge of this shadow is always circular; thus the Earth must be a sphere.



Lunar eclipse (16 Aug 2008) sequence photographed by Anthony Ayiomamitis

How do we know? (continued)

2. The planets orbit the Sun, nearly all in the same plane.

Also direct observation.

- The planets and the Sun always lie in a narrow band across the sky: the **zodiac.** This is a plane, seen edge on.
- Distant stars that lie in the direction of the zodiac exhibit narrow features in their spectrum that shift back and forth in wavelength by ±0.01% with periods of one year. No such shift is seen in stars toward the perpendicular directions, or in the Sun. The shift is a **Doppler effect,** from which one can infer a periodic velocity change of Earth with respect to the stars in the zodiac by ±30 km/sec. Thus the Earth travels in an approximately circular path at 30 km/sec, centered on the Sun.

How do we know? (continued)

The Doppler effect:

Suppose two observers had light emitters and detectors that can measure wavelength very accurately, and move with respect to each other at speed v along the direction between them. Then if one emits light with pre-arranged wavelength λ_0, the other one will detect the light at wavelength

$$\lambda = \lambda_0 \left(1 + \frac{v}{c} \right) \quad ;$$

that is,

$$v = c \frac{\lambda - \lambda_0}{\lambda_0} \quad ,$$

where $c = 2.99792458 \times 10^{10}$ cm sec^{-1} is the speed of light. **You will learn why this is, in your E&M classes.**

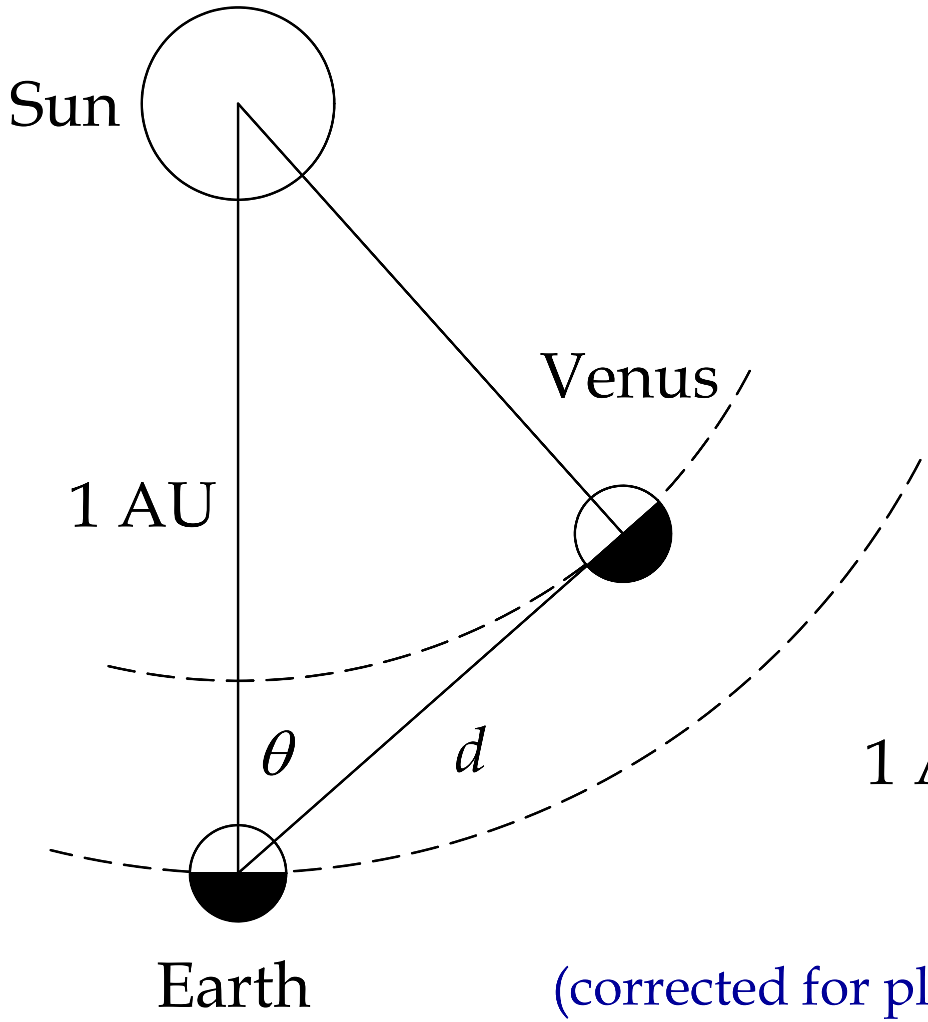
How do we know? (continued)

3. The Sun lies precisely 1.50×10^{13} cm (1 AU) from Earth.

Direct observation: it follows from the previous example, but we can measure the same thing more precisely these days by reflecting radar pulses off the Sun or the inner planets, measuring the time between sending the pulse and receiving the reflection, and multiplying by the speed of light.

- Note that knowing the AU enables one to measure the sizes of everything else one can see in the Solar system.
- Using Venus or Mercury gives the most accurate results, as the Sun itself doesn't have a very sharp edge at which the radar pulse is reflected. It works with Venus or Mercury as follows:

How do we know? (continued)



Suppose you were to send a radar pulse at Venus when it appeared to have a first-or third-quarter phase, so that the line of sight is perpendicular to the Venus-Sun line. Then

$$d = \frac{c\Delta t}{2}$$

$$1\ \mathrm{AU} = \frac{d}{\cos\theta}$$

$$= 1.4959787069(3) \times 10^{13}\ \mathrm{cm}$$

(corrected for planet size and averaged over the orbit)

How do we know? (continued)

4. The solar system is precisely 4.6 billion years old.

Direct observation, again, on terrestrial and lunar rocks, and on meteorites, nearly all of which originate in the asteroid belt. We will study this in great detail:

- When rocks melt, the contents homogenize pretty thoroughly.
- When they cool off, they usually recrystallize into a mixture of several minerals. Each different mineral will incorporate a certain fraction of trace impurities.
- Those trace impurities that are radioactive will vanish, in times that are measured accurately in the lab.
- Thus the ratio of amounts of radioactive trace impurities tell how much of the tracer the rock had when it cooled off, and how long ago that was.
- The oldest rocks in the Solar system are all 4.567 billion years old, independent of where they came from, so that's how long ago the Solar system solidified.

The Basic Facts

Gravitational constant	$G = 6.67390\times10^{-8}$ cm^3 gm^{-1}sec^{-2} $= 6.67390\times10^{-11}$ m^3 kg^{-1}sec^{-2}
Boltzmann's constant	$k = 1.380658\times10^{-16}$ erg K^{-1} $= 1.380658\times10^{-23}$ J K^{-1}
Stefan-Boltzmann constant	$\sigma = 5.67051\times10^{-5}$ erg s^{-1} cm^{-2} K^{-4} $= 5.67051\times10^{-8}$ joule s^{-1} m^{-2} K^{-4}
Planck's constant	$h = 6.6260755\times10^{-27}$ erg sec $= 6.6260755\times10^{-34}$ joule sec
Speed of light	$c = 2.99792458\times10^{10}$ cm sec^{-1} $= 2.99792458\times10^{8}$ m sec^{-1}
Earth mass	$M_\oplus = 5.97223\times10^{27}$ gm
Earth radius	$R_\oplus = 6.378\times10^{8}$cm
Solar day	Day = 86400 sec
Sidereal year	$P_\oplus$ = yr = 3.155815×10^{7} sec
Astronomical unit	$AU = 1.4960\times10^{13}$ cm
Solar mass	$M_\odot = 1.98843\times10^{33}$gm
Solar radius	$R_\odot = 6.9599\times10^{10}$ cm
Solar temperature	$T_\odot = 5800$ K
Solar luminosity	$L_\odot = 3.826\times10^{33}$ erg sec^{-1}
Solar apparent magnitude	$m_S = -26.72$
Light year	ly = 9.4605×10^{17} cm
Parsec	pc = 3.0857×10^{18}cm = 3.2616 ly
Densities (in gm cm^{-3})	Water ice: 0.94 Water: 1.0000000 Carbonaceous minerals: ~2.5 Silicate minerals: ~3.5 Iron sulfide: 4.8 Iron: 7.9

The Basic Facts (continued)

Object	Orbital semimajor axis (AU)	Orbital semimajor axis (cm)	Sidereal revolution period (years)	Sidereal revolution period (days)	Orbital eccentricity	Sidereal rotation period (days)	Radius (km)	Mass (gm)	Visual albedo
Sun						25.4	695990	1.99E+33	
Mercury	0.387	5.791E+12	0.241		0.206	58.650	2436	3.30E+26	0.12
Venus	0.723	1.082E+13	0.615		0.007	-243.01	6053	4.87E+27	0.59
Earth	1.000	1.496E+13	1.000		0.017	0.997	6378	5.98E+27	0.39
Moon		*3.844E+10*		*27.322*	*0.055*	*27.322*	*1738*	*7.35E+25*	*0.11*
Mars	1.524	2.279E+13	1.881		0.093	1.026	3399	6.42E+26	0.15
Phobos		*9.380E+08*		*0.319*	*0.018*	*0.319*	*14x10*	*9.60E+18*	*0.05*
Deimos		*2.350E+09*		*1.262*	*0.002*	*1.262*	*8x6*	*2.00E+18*	*0.05*
Jupiter	5.203	7.783E+13	11.862		0.048	0.414	71370	1.90E+30	0.44
Metis		*1.280E+10*		*0.295*	*0.000*	*0.300*	*20*	*?*	*0.04*
Adrastea		*1.290E+10*		*0.298*	*0.000*	*0.290*	*12x8*	*?*	*0.05*
Amalthea		*1.815E+10*		*0.498*	*0.003*	*0.498*	*135x78*	*?*	*0.05*
Thebe		*2.220E+10*		*0.674*	*0.010*	*0.674*	*50*	*?*	*0.10*
Io		*4.216E+10*		*1.769*	*0.004*	*1.769*	*1815*	*8.89E+25*	*0.63*
Europa		*6.709E+10*		*3.551*	*0.010*	*3.551*	*1569*	*4.79E+25*	*0.64*
Ganymede		*1.070E+11*		*7.155*	*0.002*	*7.155*	*2631*	*1.48E+26*	*0.43*
Callisto		*1.880E+11*		*16.689*	*0.008*	*16.689*	*2400*	*1.08E+26*	*0.17*
Saturn	9.539	1.427E+14	29.458		0.056	0.444	60336	5.69E+29	0.46
Titan		*1.222E+11*		*15.94*	*0.029*	*15.900*	*2575*	*1.35E+26*	*0.60*
Uranus	19.191	2.871E+14	84.014		0.046	0.718	25576	8.68E+28	0.56
Neptune	30.061	4.497E+14	164.793		0.010	0.671	24300	1.02E+29	0.51
Triton		*3.548E+10*		*5.877*	*0.000*	*5.877*	*1355*	*2.14E+25*	*0.75*
Pluto	39.529	5.914E+14	248.540		0.248	6.387	1161	1.29E+25	0.50
Charon		*1.960E+09*		*6.387*	*0.000*	*6.387*	*595*	*1.77E+24*	*0.40*