WELCOME TO ASTR 111!

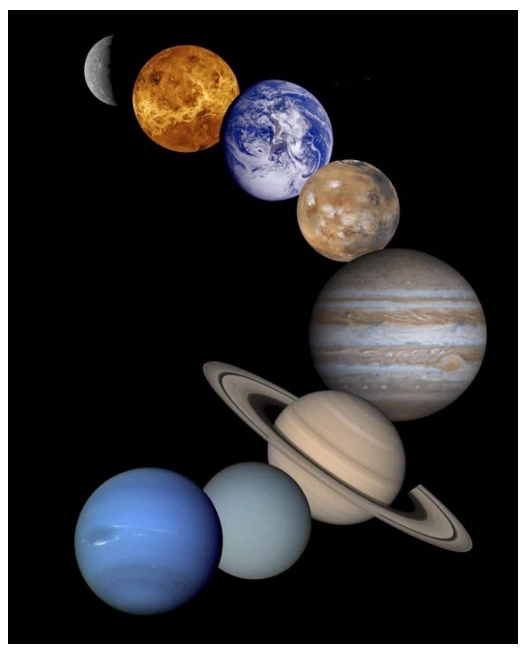
The Solar System and its Origins

OVERVIEW OF THE SOLAR SYSTEM

Contents of the Solar System

What can we measure and what can we infer about its contents?

How do we know? Initial explanations of four of the most important facts about the Solar System



The eight planets, not shown to scale (JPL/NASA)

Familiarize yourself with the definitions of the technical terms which (first) appear in bold.

INVENTORY OF THE SOLAR SYSTEM

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 3.826×10^{33} erg/s = 3.826×10^{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.

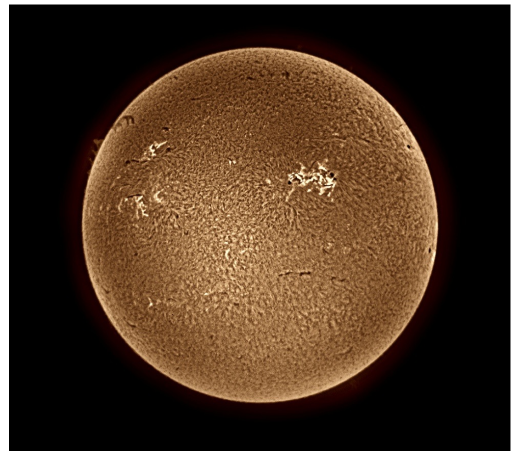


Image by Robert Gendler

ASIDE – OBSERVATIONS OF OTHER PLANETARY SYSTEMS

All planetary systems are like this. Which is why we only gained the ability to see planets in orbit around other stars about three decades ago, even though practically every star has a planetary system.

- This is done by observing the motion of the central star and/or the slight decrease in the star's brightness as the planet eclipses the star, as we will learn later this semester.
- While our understanding of the Solar System has helped us understand the formation and evolution of planetary and stellar systems, what we have found about extrasolar systems has challenged some previous views of solar system formation and evolution.

Artist's conception of AEgir around its star Ran

COMPONENTS OF THE "DEBRIS"

The **Giant** planets: mostly gas and hot, dense 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 (i.e., $10^{-3}\boldsymbol{M}_{\odot}$), or equivalently about 300 times that of the Earth ($300\boldsymbol{M}_{\oplus}$)

Saturn's mass is $3{\times}10^{-4}M_{\odot}$, or $100M_{\oplus}$

Neptune and Uranus are each about $1/6$ the mass of Saturn

The giant planets are 5, 9, 20, and 30 times further from the Sun than Earth ($a =$ 5, 9, 20, 30 **AU**; a is commonly used to denote semi-major axis, covering the possibility of an elliptical orbit)

- AU = semi-major axis of a massless (test) particle whose orbital period around the Sun is *exactly* 1 year

Saturn and Jupiter have roughly Solar-type **composition** – relative abundances of the elements – which means mostly hydrogen and helium.

Neptune and Uranus are only about 20% H and He; instead, they are dominated by heavier elements and have a substantial percentage of their mass in cores with icy or rocky composition.

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

Mercury: $R \sim 2500$ km, $a = 0.4$ AU

Venus and Earth: $R \sim 6000$ km, $a = 0.7, 1.0$ AU, respectively

Mars: $R \sim 3500$ km, $a = 1.5$ AU

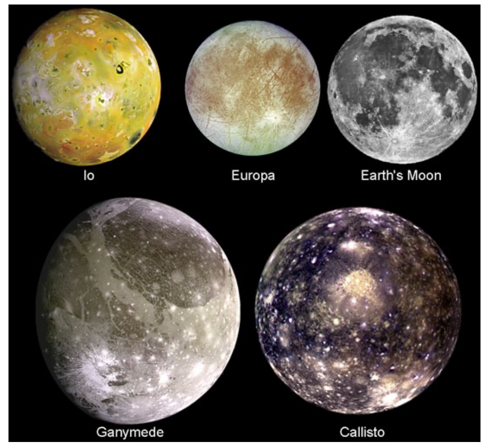
Asteroid belt: $a \sim 2 - 5$ AU

Comet reservoirs:
- Kuiper Belt, including Eris and Pluto, at $a > 30$ AU
- Oort Cloud, including Sedna, at $a \sim 10^4$ AU

Interplanetary dust

Moons of the planets, especially the giant ones

Planetary rings



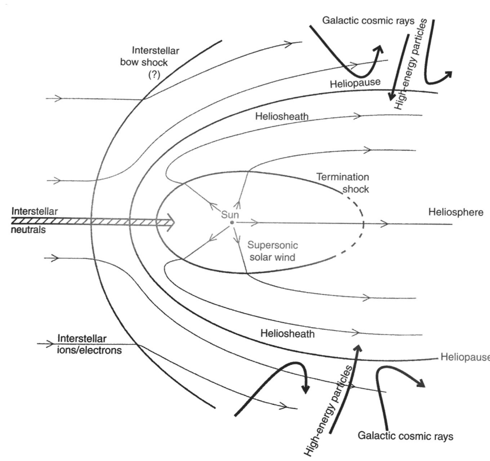
Images from Galileo (NASA-JPL)

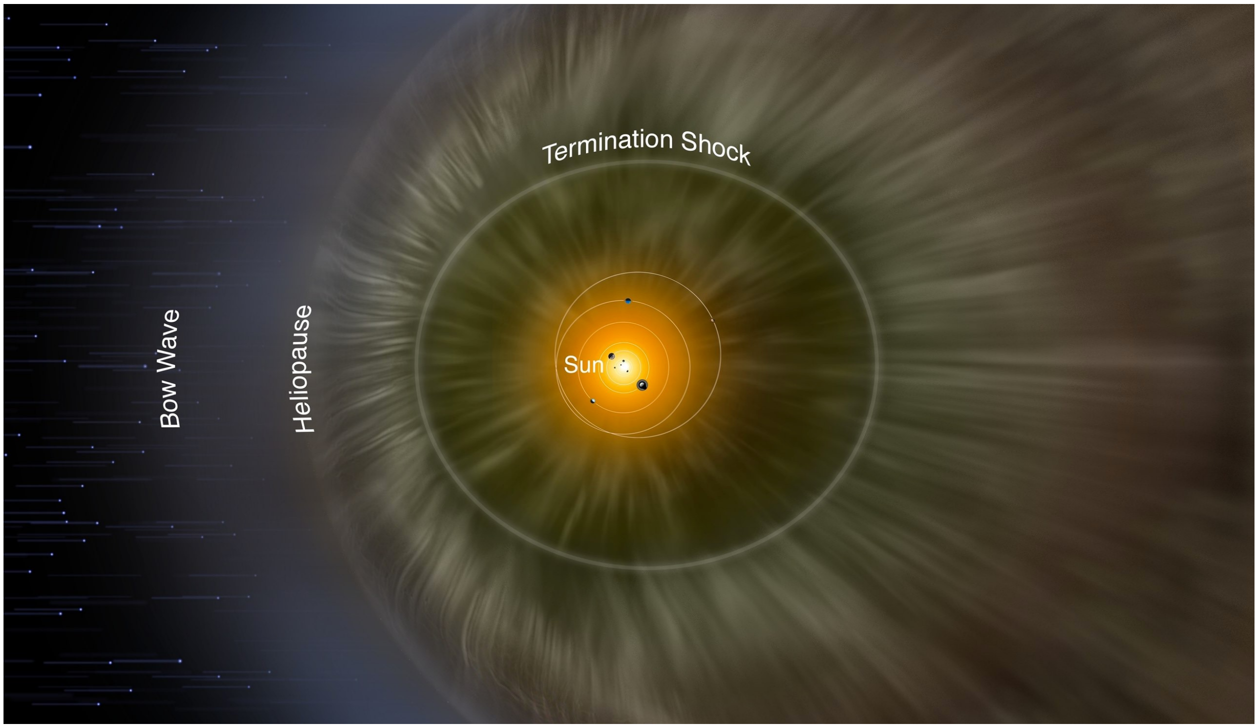
THE HELIOSPHERE

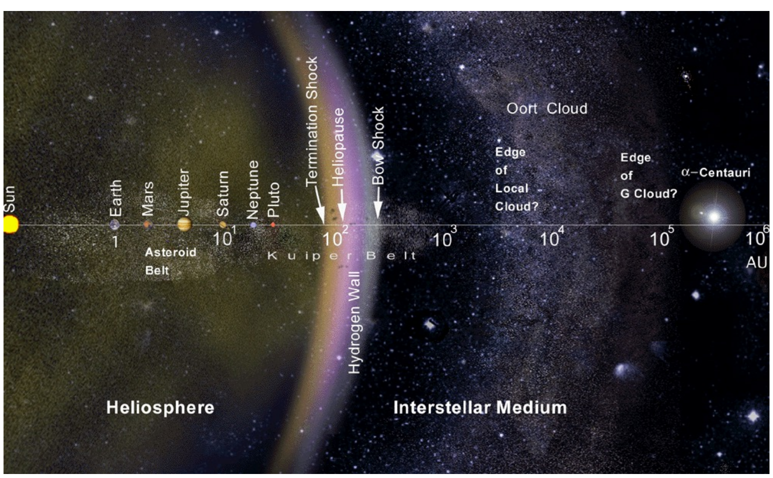
All planets orbit within the **heliosphere**, which contains the supersonic **solar wind** of magnetic fields and plasma.
- **Plasma**: an ionized gas with electrical conductivity and magnetization much larger than an ideal gas.

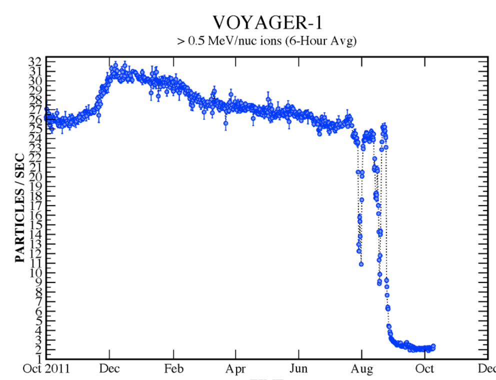
Where the solar wind interacts or merges with the interstellar medium is called the **heliopause**.

Cosmic rays (high energy elementary particles accelerated elsewhere in the Milky Way galaxy) can be diverted by the solar wind.









SIZE OF THE HELIOSPHERE

Both Voyagers have passed through the heliopause and into interstellar space.

JPL

PLANETARY PROPERTIES THAT CAN BE DETERMINED DIRECTLY FROM OBSERVATIONS

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

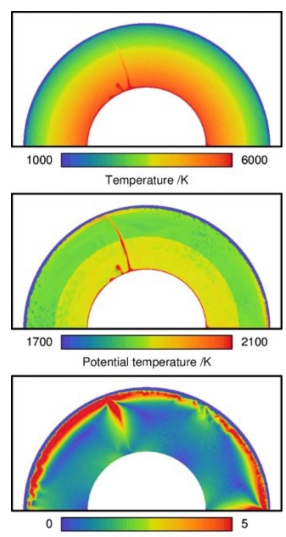
Saturn, Venus, and Mercury, with the European Southern Observatory in the foreground (Stephane Guisard)

OTHER PLANETARY PROPERTIES THAT CAN BE INFERRED OR MODELED FROM OBSERVATIONS

We also have accurate theories founded in basic physics and chemistry, which can take us to places and situations that we cannot see directly, allowing us to study planetary

- Density and temperature of the atmosphere and interior as functions of position
- Formation
- Geological history
- Orbital-dynamical history

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



Model of an $8M_\odot$ superearth exoplanet's mantle, and its convection, by van den Berg et al. (2019)

HOW DO WE KNOW…

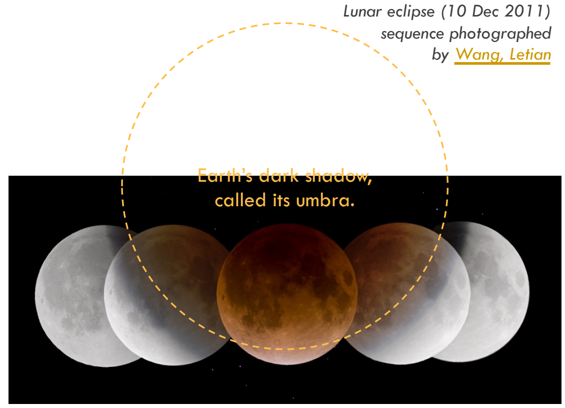
All that we will say about the planets this semester is founded upon empirical facts, many of which are easy to verify. For example:

Lunar eclipse (10 Dec 2011) sequence photographed by Wang, Letian

…that the Earth is approximately spherical?

Direct observation, 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.

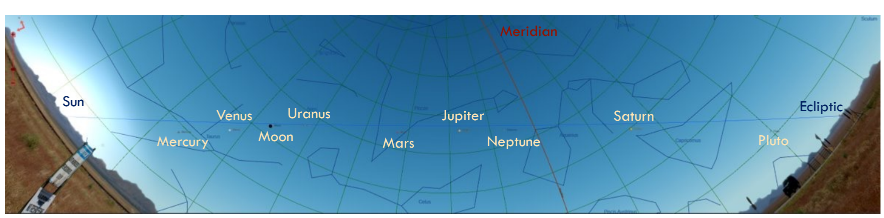


HOW DO WE KNOW…

…that 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**. Astronomers call the mid-line of this band the **ecliptic**. 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.

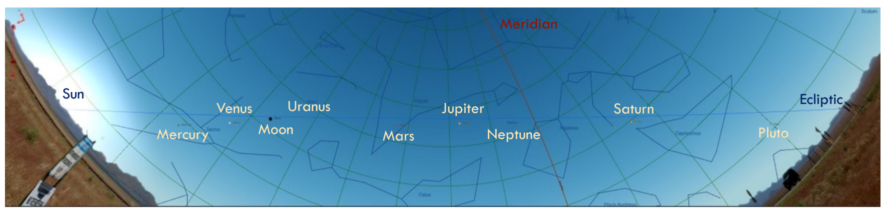


The other seven planets, Pluto, the Moon, and the Sun, at 6:25AM on June 25, 2022.

HOW DO WE KNOW…

- No such shift is seen in the stars toward the perpendicular direction, or in the Sun.
- The shift is a **Doppler effect**, from which a periodic velocity change of Earth with respect to the stars in the zodiac can be inferred of ± 30 km/s.

Thus, the Earth travels in the same plane as the other planets, in an approximately circular path at 30 km/s, centered on the Sun.



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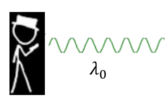
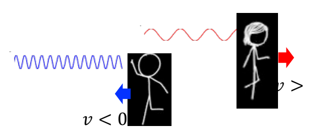
THE DOPPLER EFFECT





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

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

Or

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

> $v > 0$ and $\lambda > \lambda_0$ (a redshift) if the observers recede from one another
>
> $v < 0$ and $\lambda < \lambda_0$ (a blueshift) if they approach one another

where $c = 2.99792458 \times 10^{10}$ cm/s is the speed of light, which is the same for all observers. You will learn why this is in your E&M classes.

ASIDE: GREEK

In physics, and especially in astrophysics, we run out of symbols for our equations way too quickly if we just use the Latin alphabet.

Start getting used to the Greek alphabet…

Upper case, lower case, pronunciation

$\mathrm{A}\ \alpha$	alpha	$\mathrm{I}\ \iota$	iota	$\mathrm{P}\ \rho$	rho
$\mathrm{B}\ \beta$	beta	$\mathrm{K}\ \kappa$	kappa	$\Sigma\ \sigma$	sigma
$\Gamma\ \gamma$	gamma	$\Lambda\ \lambda$	lambda	$\mathrm{T}\ \tau$	tau
$\Delta\ \delta$	delta	$\mathrm{M}\ \mu$	mu	$\Upsilon\ \upsilon$	upsilon
$\mathrm{E}\ \epsilon\ \varepsilon$	epsilon	$\mathrm{N}\ \nu$	nu	$\Phi\ \phi$	phi
$\mathrm{Z}\ \zeta$	zeta	$\Xi\ \xi$	ksi	$\mathrm{X}\ \chi$	chi
$\mathrm{H}\ \eta$	eta	$\mathrm{O}\ o$	omicron	$\Psi\ \psi$	psi
$\Theta\ \theta$	theta	$\Pi\ \pi$	pi	$\Omega\ \omega$	omega

HOW DO WE KNOW…

…that 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 us to measure the sizes of everything else seen in the Solar System.
- Using Venus or Mercury gives the most accurate results, as the Sun itself does not have a very sharp edge at which the radar pulse is reflected. It works with Venus or Mercury as follows:

MEASURING THE ASTRONOMICAL UNIT (AU)

Suppose you were to send a radar pulse at Venus when it appeared to have a first- or third-quarter phase, so that the pulse follows a line perpendicular to the Venus-Sun line. Its reflection arrives back at your location a time Δt later, along the same line. The distance to Venus is then

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

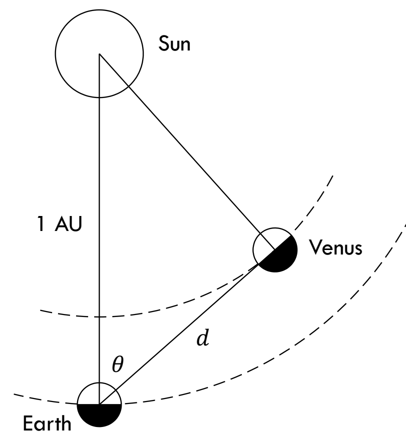
From the geometry, we see that

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

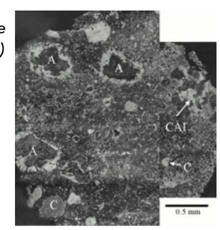
Then

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

(corrected for planet size and averaged over Earth's orbit)



Part of the Tagish Lake meteorite (Brown et al. 2000)



HOW DO WE KNOW…

…that the Solar System is precisely 4.567 billion years old?

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

- When rocks melt, the contents homogenize 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 accurately measured in the lab.
- Thus, the ratio of the amounts of radioactive trace impurities tell how much of that tracer the rock had when it cooled off, and how long ago that was.
- In this fashion, called radiometric age measurement, we find that the oldest rocks in the Solar System are all 4.567 billion years old, independent of where they came from. So that is how long ago the rocky bits of the Solar System solidified.