# Introducing the Universe

**Our place in space:**
- Earth, Moon, Sun
- Solar system
- Stars and interstellar matter
- The Milky Way galaxy
- Galaxies and clusters of galaxies
- Large–scale structure of the Universe

**Our place in time:**
- The early Universe
- Formation of galaxies
- Formation of stars/planets continues, heavy elements

**Four universal forces: gravity, electromagnetic, strong/weak nuclear**

**Space and time are linked in astronomical measurement**

**Distances: may use km, astronomical units, light–years, parsecs (+mega–, giga– for large multiples)**

**Time: astronomical events likewise range from milliseconds to billions of years**

**We are already and always "in space"!**

**Hallmarks of scientific thought:**
**–– principle of uniformity – the Universe is knowable ("playing fair")**
**–– role of quantitative prediction in assessing an idea**
**(Nature is the arbiter)**
**–– roles and meaning of theory, hypothesis, and measurement**
**–– Economy of hypothesis = Occam's razor (the KISS principle)**
**Workings of science**
**Mental pictures versus external reality**
**Interplay of observation and hypothesis**
**The power of mathematics and modeling**

# Powers of 10

| Size | example |
|---|---|
| 1 A | hydrogen atom |
| 10 A | water molecule |
| 0.1 micron | viruses |
| 1 micron | visible light wavelength |
| 10 microns | “smoke” grains; cells |
| 100 microns | largest single cells |
| 1 mm | BB |
| 10 mm | penny |
| 100 mm | finger |
| 1 m | person |
| 10 m | room |
| 100 m | football field |
| 1 km | campus |
| 10 | Tuscaloosa; neutron star |
| 100 | here to Birmingham |
| 1000 | largest asteroids |
| 10000 | Earth |
| 100000 | Jupiter |
| 1000000 km | Sun |
| 10 million km | comet tail; lunar orbit |
| 100 million km | distance to Sun = 1 AU |
| 1 billion km | distance to Saturn |
| 10 billion km | Pioneer/Voyager span |
| 100 billion km | comets in Oort cloud |
| 1 trillion km | outermost part of Oort cloud? |
| 10 trillion km = | 1 light–year (well, actually 1.06) |
| $10^{14}$ = 10 ly | size of star cluster |
| $10^{15}$ = 100 ly | large interstellar gas cloud |
| $10^{16}$ = 1000 ly | width of spiral arm |
| $10^{17}$ = 10 kly | distance to galactic center |
| $10^{18}$ = 100 kly | diameter of largish galaxy |
| $10^{19}$ = 1 Mly | distance to Andromeda Galaxy |
| $10^{20}$ = 10 Mly | size of galaxy cluster |
| $10^{21}$ = 100 Mly | distance to Virgo galaxy cluster |
| $10^{22}$ = 1 Gly | distance to nearby quasar |

# Celestial Patterns – the View from Earth

**Patterns in the sky: CONSTELLATIONS**

**Daily (diurnal) apparent motion due to Earth's rotation**
**Celestial coordinates (right ascension and declination)**
**Solar/sidereal days; time zones and date lines**
**Effects of Earth's rotation: Coriolis forces, Foucault pendulum**

**A model of the sky: the CELESTIAL SPHERE**
**This is useful for some visualizations, but has *no physical reality*.**

**The SUN's apparent motion (from our own orbital movement)**
**On top of daily rise and set the Sun appears to move eastward against the background stars, at one revolution per year.**
**The Sun also changes declination by 23.5$^o$ north and south, due to the angle between Earth's axis and orbit. This – *not the shape of the Earth's orbit*– gives us the SEASONS .**

**The MOON runs its own monthly circle through the sky, for once something due to its own orbital motion. It exhibits PHASES as we view the sunlit half from various directions (thus we see different phases at different locations in the sky).**
***Phases don't come from the Earth's shadow.***

**The bright PLANETS (Mercury, Venus, Mars, Jupiter, Saturn) look like stars, but move around the sky in complex ways. They always appear near the ECLIPTIC, because their orbits go in almost the same direction as the Earth's.**

**Motions of the Earth: daily ROTATION, annual REVOLUTION in its orbit, PRECESSION of the axis, motion with Sun through the galaxy.**

# SOLAR ECLIPSES

**Shadow phenomena – 3D Earth–Sun-Moon layout**
**Observer inside lunar shadow; sees sunlight blocked**

**Varieties:**
**Partial**

**Annular:**

**Total:**

**Visible at totality:** solar atmosphere (corona)
prominences
bright stars and planets

**Other phenomena:** Bailly's beads
Shadow bands

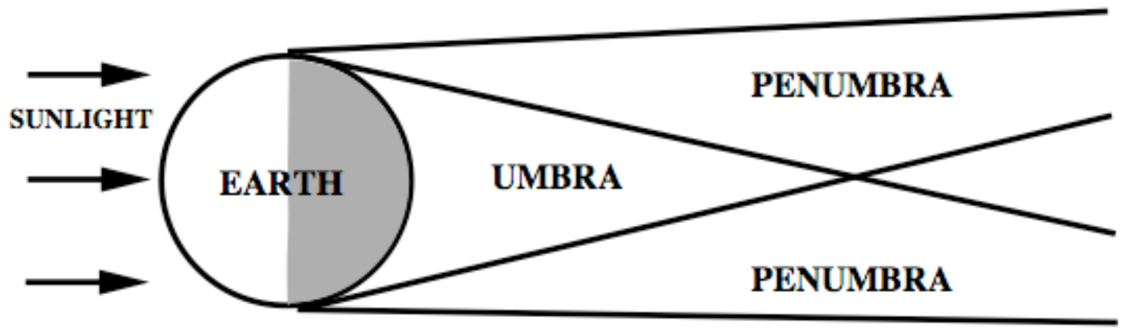
**Limited area of visibility for total eclipses – narrow umbral shadow path**

**Watching eclipses:**

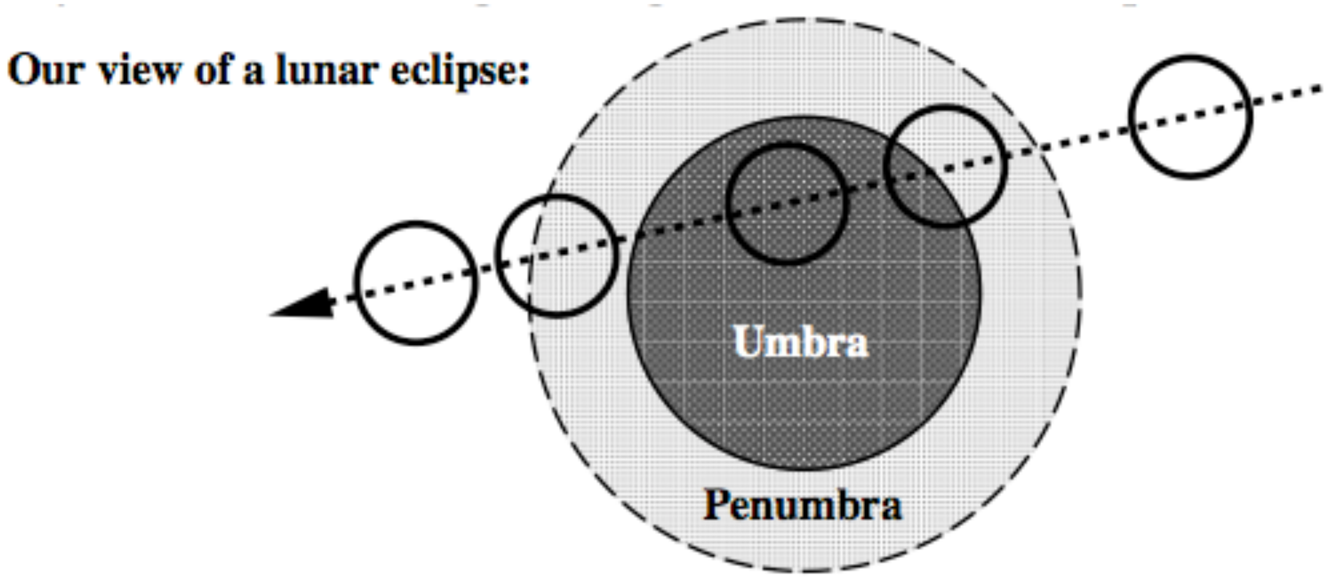
- **DON'T LOOK DIRECTLY AT THE SUN! EVER!**
- **Use of projection from pinhole or telescope**
- **Naked eye okay during totality only**
- **Never miss a total eclipse if you have a chance**

# LUNAR ECLIPSES

**We see Earth's shadow fall on the moon (always at full phase)**
**Umbra and penumbra in shadows of Earth and Moon alike**




**Within the umbra, the whole sun is blocked (total solar eclipse)**
**Within the penumbra, only part of it is blocked (partial solar eclipse)**
**Beyond the umbra, a ring of sunlight remains (annular eclipse)**




**At totality, we see the Moon only by light refracted through our atmosphere**
**Lunar eclipses are visible from nearly half the Earth: we need only be able to see the Moon at the right time**

**History and eclipses:**

**Early hints to Earth's shape, sizes of Sun/Earth/Moon**
**Establishing dates of ancient events**
**History of Earth's rotation from totality tracks**

**Predicting eclipses:**

**Relative tilts of Earth's and Moon's orbits gives eclipse seasons**
**Precession of lunar orbit, driven by Sun's gravity, gives the 18.6–year *Saros cycle***
**Length of eclipse seasons for lunar and solar eclipses**

**Related phenomena:**

***Occultations* of planets, stars by the moon, planets, asteroids**
***Transits* of Mercury, Venus in front of the Sun**
**Eclipses on/by satellites of outer planets**
**Members of double–star systems can eclipse one another.**
**Transits of planets in front of other stars are seen.**

**These have been remarkably enlightening as to both the foreground and background objects – we've learned orbits, sizes, masses of objects, discovered planetary rings, confirmed existence of planets. Terrestrial total eclipses are still unique: the solar surface, but not atmosphere, is blocked.**

**Noteworthy upcoming eclipses:**
**Total lunar eclipse, evening of 27 December 2015**
**Solar eclipse, total in Tennessee/Georgia/S. Carolina, 12 August 2017**
**Solar eclipse, total in Texas/Arkanses/Missouri, 8 April 2024**
**Solar eclipse, total in Tuscaloosa, 12 August 2045**

# Development of Astronomy

**Ancient astronomy**
**Why?**
**Prediction (calendar), ritual (metaphysics), cosmic structure**
**What?**
**Sun and its apparent motion, Moon and phases,**
**planetary motion, stars and their patterns**
**How do we know? –– myth and artifact**
**solar alignment (Stonehenge, pyramids, stone circles)**
**calendars (i.e. Mayan Venus cycle)**
**constellations**

**Astronomy in the Greek era**
**Eratosthenes and the diameter of the Earth**
**Aristotle and the shape of the Earth**
**Aristarchus and the heliocentric picture**
**Precession of Earth's axis discovered**
**Geocentric solar system (codified by Ptolemy)**
**Earth–centered**
**Epicycles and deferents to track observed planetary motions**
**Adequate predictive power for crude naked–eye observations**
**Mediaeval science: largely carried through Arab/Islamic regions**
**Positional astronomy in the Renaissance**

**COPERNICUS (1473–1543) – heliocentric picture of solar system This scheme was widely accepted before form proof was available, mostly on grounds of simplicity and elegance. He had (as yet) no physical basis for these motions.**

**TYCHO BRAHE (1546–1601) – performed the best pre–telescopic measurements of planetary and stellar positions. These data were accurate enough to clearly show inadequacies of the geocentric scheme. Was also a very colorful character.**

**Johannes KEPLER (1571–1630) – used Tycho's observations to derive three laws of planetary motion, allowing their precise mathematical description and prediction.**
**(1) Planetary orbits are ellipses with the Sun at one focus.**
**(2) The orbital speed varies according to the *equal–area formula*.**
**(3) For orbital period P and mean distance from the sun D, different planets have $P^2/A^3$=constant (the Harmonic law).**
**These allow prediction of a planet's future position from its orbit, position, and velocity; the third relates properties of various orbits. These laws apply to *any two bodies* orbiting under only their mutual gravity.**

**GALILEO Galilei (1564–1642) – first reported astronomical observations with a telescope. These opened new vistas in space, confirmed predictions of the heliocentric scheme, and showed that other objects can be centers of motion. His findings included**

**craters on the Moon**
**a complete cycle of phases for Venus**
**the four largest ("Galilean") satellites of Jupiter**
**the Milky Way consists of faint stars**
**sunspots**

**Isaac NEWTON (1642–1727) – formulated basic laws of motion and gravity, which account for Kepler's findings of systematics in planetary motion. Along the way he invented several kinds of calculus and mathematical analysis and did pioneering research on the nature of light.**
**Newton's three laws of motion are:**

***Force = mass X acceleration***
***An action has an equal and opposite reaction***
***Objects at rest remain at rest unless acted upon by an outside force***

**Newtonian gravity is an attractive force that acts between each two particles of matter according to**

$$\text{Force} = G\, M_1\, M_2 / d^2$$

**where two objects with masses $M_1$, $M_2$ are located a distance d apart.**

**Both masses feel the same force*.* This law leads directly to Kepler's laws of planetary motion.**

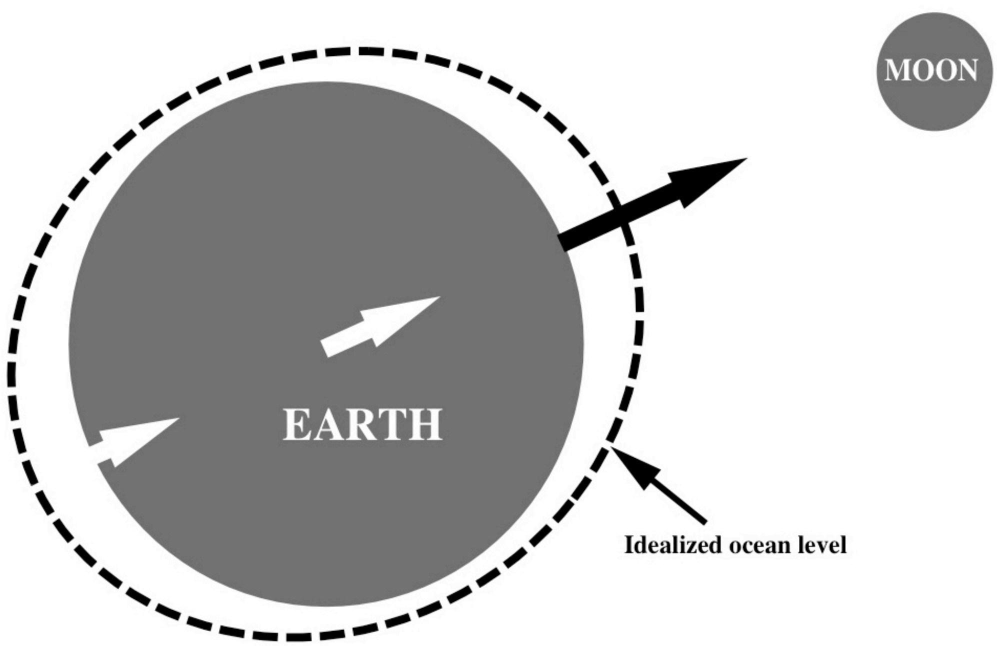
**Orbits: paths of objects freely falling in a gravitational field.**
**Why launches go up.**
**Gravity is a central force –– angular momentum is conserved, which gives Kepler's second law. *The object's spin has nothing to do with it.***
**Orbits are *conic sections*. Bound (returning) orbits must be circular or (more generally) elliptical. An orbit is the path resulting from the object's motion at a given time and the acceleration produced by gravity.**

**Orbital speed declines with increasing orbital radius (as the inverse square root of radius). This has peculiar implications for orbital rendezvous and spaceflight between planets.**
**Cases: geosynchronous orbits, material ejected from spacecraft.**
**Newton's laws aren't so obvious in everyday life because friction and air resistance are important. Lack of these features in the near–vacuum of space makes motions more simple and understandable (celestial mechanics was the first truly exact science).**
**Multiple objects: the same law of gravity now applies simultaneously to each pair of objects. No general analytic solution is possible for 3 or more! Still, numerical techniques can give extremely accurate tracking for long times.**
**Tides: a side effect of gravity. We see these again in stars and galaxies, as well as spacecraft.**
**Symmetry of gravity and the Earth/Moon system. We can use this same principle to search for other planetary systems.**

***Conservation laws*: Certain quantities of isolated systems are conserved under whatever internal changes they undergo. These are powerful tools in understanding their development (orbits, temperature...) and are connected to *symmetries* – ways in which the Universe's properties are consistent with direction, place, or time*.* Examples include momentum, angular momentum, mass+energy, numbers of some kinds of subatomic particles.**

# TIDES

**Gravity becomes weaker at larger distances. Therefore if one object (say the Earth) is affected by the gravity of a nearby one (say the Moon), the gravitational effect will be different on the facing and opposite sides. Material “under” the moon is pulled more strongly. Also, material on the opposite side is pulled less strongly then the center, so appears to be pushed away as seen from the solid Earth. The Earth’s rotation carries the tidal bulges away from this ideal position.**



# Light and Other Radiation

**Still our only tool for exploring beyond the solar system**

**Nature of light: packets of energy propagating electromagnetically**

- **emitted/absorbed by accelerating electrical charges**
- **sometimes acts as particles (*photons*), sometimes as waves.**
- **moves along straightest possible path**
- **always moves at a constant velocity *c* (in vacuum)**
- **falls off with distance following an *inverse–square* law**

**Any radiation has an associated frequency and characteristic energy**
**We perceive this as color for visible light.**

**The electromagnetic spectrum includes:**

| | | |
|---|---|---|
| **Radio waves** | **low energy** | **long wavelength** |
| **Microwave emission** | | |
| **Infrared** | ↑ | ↑ |
| **Visible light (a single octave!)** | ↓ | ↓ |
| **Ultraviolet** | | |
| **X–rays** | | |
| **$\gamma$–rays** | **high energy** | **short wavelength** |

**Each kind of radiation is characteristic of a certain temperature range, and certain physical processes. The sky looks quite different in each of these bands.**

**There is a relationship between the wavelength of a opaque object's most intense radiation and its temperature (Wien's law for blackbody radiation):**

$$\lambda_{max} = \text{constant} / T$$

**so that, for example, mammals emit radiation most strongly in the infrared. Rattlesnakes find this information helpful. So do astronomers, since the Universe contains objects from as cold as 10K to at least 100,000,000 K. (Temperature here is measured in Kelvin or K starting at absolute zero, unlike Fahrenheit).**

**The observed frequency (or wavelength) of radiation can change if the source and observer are in relative motion (the *Doppler shift*). The amount of shift tells the relative velocities *along the line of sight*, so we measure the same shift whether the source, observer, or both contribute to the relative motion.**

**Manipulation of radiation: we can in principle**

- ***reflect* or *scatter***
- ***refract***
- ***absorb***
- ***emit***
- ***disperse***

**each kind of radiation, which lets us form images and measure the radiation very precisely.**

## Optical phenomena in the atmosphere:

**The blue sky and red sunset come from the fact that small particles absorb and scatter shorter wavelengths (i.e. blue and violet) more efficiently than longer wavelengths (yellow, red). Your red sunset is somebody else's blue sky. We see the same thing for dust grains in interstellar space – they redden light from behind them and scatter blue light better.**

**Sun– and moon–sets also show atmospheric refraction – very near the horizon, the lower limb is seen via more strongly refracted rays than is the upper limb, giving sun or moon a flattened appearance.**

**Rainbows: a somewhat complicated combination of internal reflections and dispersion as light enters/leaves spherical water drops. Inner and outer rainbows come from light which was internally reflected once versus twice before leaving the drops.**

**Mirages: a trick of refraction can occur when heated air lies close to the ground, acting as a mirror for certain low–approaching rays (its refractive index changes with temperature).**

# Special Relativity – the Speed of Light

**Observation: the speed of light *c* is independent of observer motion**
**Examples: aberration of starlight**
**Michelson–Morley experiment (did *not* find the ether)**
***plus***
**Postulate: the principle of uniformity, meaning that physical laws must be found to be the same by all observers in uniform motion.**

**led Einstein to derive relations among time, length, and mass as they would be measured by observers in different motions relative to the system in question. Keeping *c* constant means that time must be considered to run at different rates depending on relative motion! Our intuition may rebel at these conclusions, having been forged in a world in which everything happens much slower than *c*.**

**This gives: time dilation (seen in particle decay, GPS, supernovae)**
**corrections to Newton's laws at speeds large compared to *c***
**conversion between mass and energy**

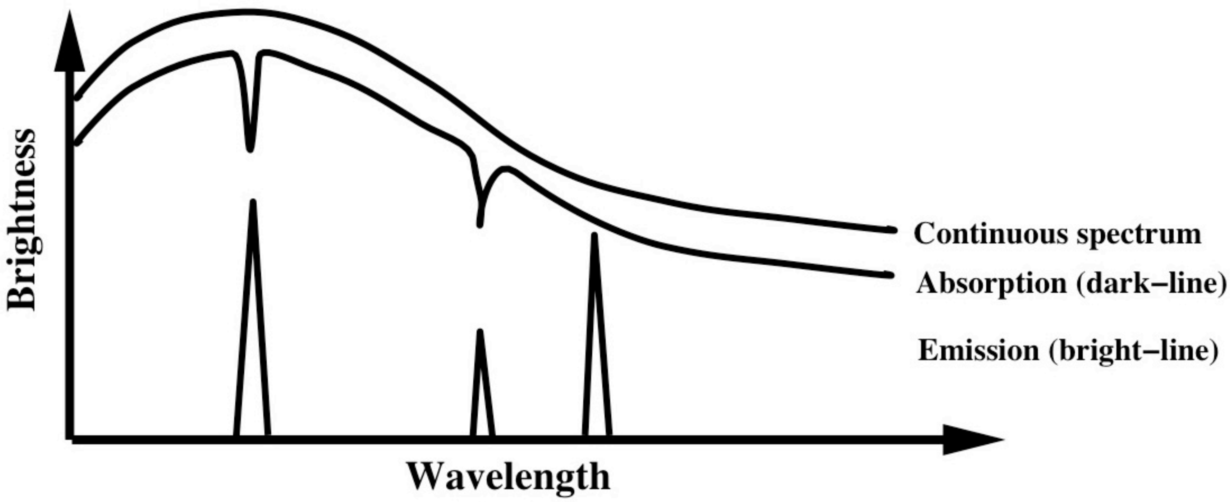
**Time and space can be "mixed" in these measurements, so that *space–time* is the invariant concept. This gives the possibility of mass/energy mixing: the famous equation**

$$E=mc^2$$

# Spectroscopy – Atoms and Light

**Atomic structure: nucleus (protons/neutrons), electron cloud**
**Photons can be: absorbed by electron energy jumps**
**emitted by electron energy jumps**
**The wavelengths emitted in this way are specific to a kind of atom.**

**Diffuse gases produce emission (bright–line) or absorption (dark–line) spectra depending on the viewing arrangement. Dense gases and solids produce continuous spectra.**
**These principles can be applied to any kind of radiation, telling us**




**Chemical and isotopic composition of stars and nebulae**
**Stellar motions from Doppler shift**
**Galaxy rotations, nebula expansions from the Doppler shift**
**Stellar rotation**
**Magnetic fields from line splitting**
**Temperature and density from line spectra**
**(that is, almost everything we know beyond the solar system!)**

# Telescopes – Tools of Astronomy

**What for?**

***Light grasp, image formation, resolution*** **(detail discrimination)**
**Magnification is not always paramount (and defined only for visual use). The aim is to deliver as much radiation from the desired celestial object as possible, to some analytic device (camera, spectrograph, photometer, polarimeter,...).**

**General types for visible light:**

**Refractors (collect light with an objective lens)**
**Reflectors (collect light with a primary mirror), in multiple kinds**
**Each has advantages for particular sizes/applications.**

**Large telescopes**
**–– more light grasp, can work on fainter/more distant objects**
**–– better resolution if atmosphere can be overcome**
**(space instruments, adaptive optics, interferometry)**

**Detectors and instruments**

**Direct cameras, spectrographs, photometers, polarimeters**
**Roles of photography, electronic imaging, image processing**

**Atmospheric limitations from the ground:**

**Turbulent** ***blurring*** **("seeing")**
***Absorption*** **of most kinds of radiation**
***Light pollution***

# Telescopes: Beyond Visible Light

**Spectral regions and atmospheric "windows"**

**Radio telescopes: single antenna, arrays, interferometry**
- **Wavelength–controlled resolution**
- **Results: radio galaxies, quasars, pulsars, interstellar gas, cosmic microwave background radiation, "superluminal" jets**

**Infrared observations: atmospheric difficulties**
- **Space observations – IRAS survey, ISO, Spitzer, Herschel**
- **Results: starburst galaxies, protoplanetary systems, dust, important interstellar gas constituents in far–IR, exoplanets**

**Ultraviolet – satellites (IUE, EUVE, FUSE, GALEX)**
- **Limitations of normal mirrors deep in the UV**
- **Results: hot–star winds, cool–star atmospheres, populations in galaxies, quasar gas clouds**

**X–rays: collimators and grazing–incidence mirrors**
- **Satellites: Uhuru, Einstein, ROSAT, Chandra, XMM–Newton**
- **Results: cataclysmic binary stars, hot gas between galaxies, quasar/active galaxy emission, X–ray background, candidate black holes, coronae of stars**

**Gamma rays: detection problems**
- **Resolution limits; use of multiple spacecraft to locate bursts**
- **Compton Gamma–Ray Observatory (CGRO), BeppoSAX, INTEGRAL**
- **Results: gamma–ray bursts, quasar emission, interstellar medium**

**Recent rise in *multiwavelength astrophysics***
**(how we should have been doing it all along*)***

# The Interstellar Medium

**Different forms of interstellar matter are observed in different ways:**

**Dust: optical reddening/absorption, infrared emission. Grains are ~0.0001 mm in size.**
**produced in red giant atmospheres, nova/supernova outbursts**
**thickest in the galactic plane, blocks our view in visible light**

**Ionized gas: seen as emission nebulae when ionized by starlight produces emission lines as H II regions, typically 10,000 K**
**easy to analyze for abundances**
**usually associated with dust, young stars**

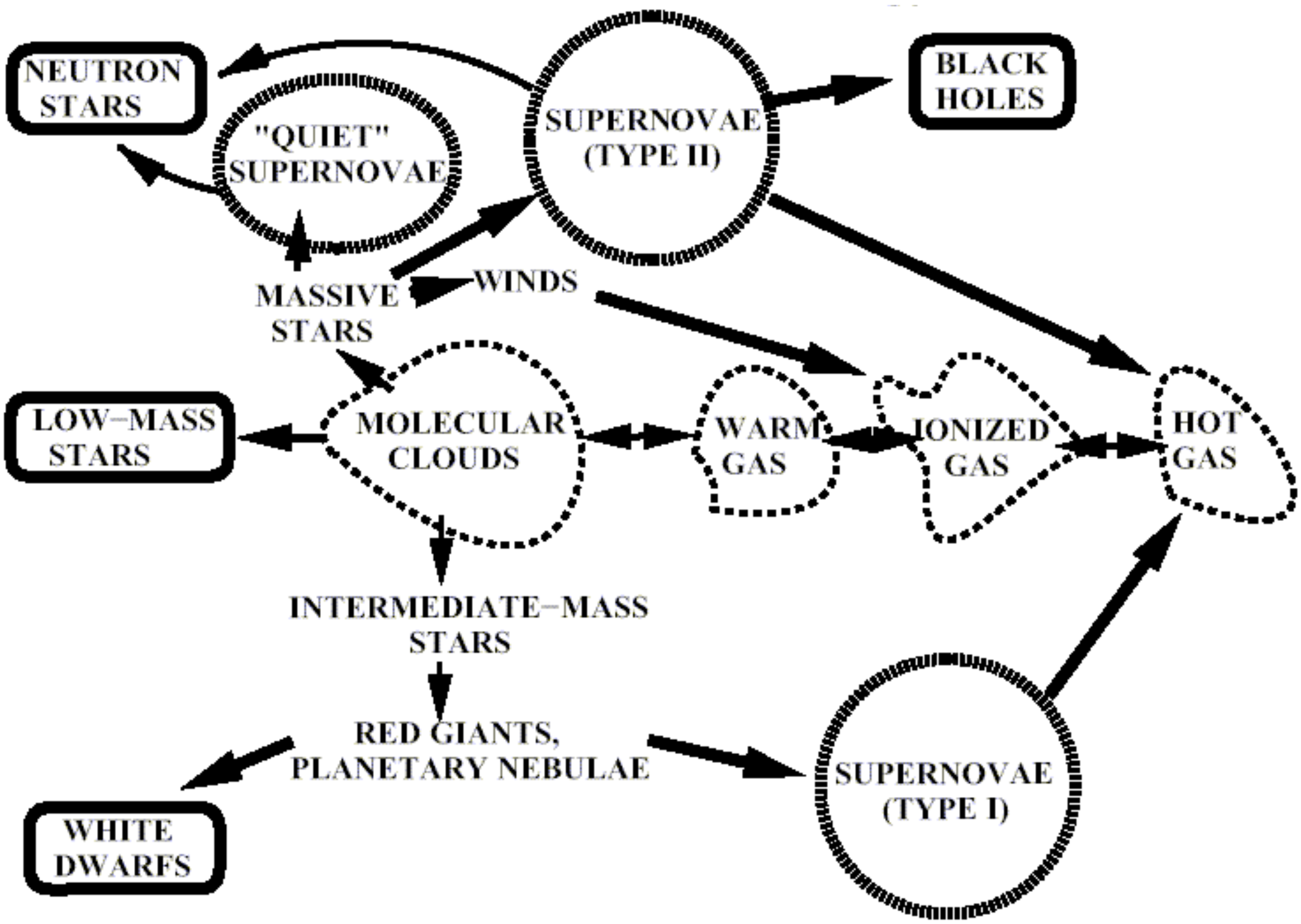
**Atomic hydrogen clouds (H I)**
**Seen only via radiation at 21 cm wavelength from the H I spin–flip transition of cold low–density gas**
**Gas concentrated to galactic disk**
**This measurement is immune to dust absorption**

**Molecular gas: cold, dense, precursor to star formation**
**Molecular hydrogen is dominant but hard to observe**
**Usually measure CO, other asymmetric molecules in mm range**
**Can find dense molecular core, H I surroundings**
**Molecules easiest to form with dust as catalyst**

**Hot gas (millions of degrees) – seen in X–rays and absorption lines**
**Heated by supernova explosions, stellar winds**

**There is an important interplay between stars and gas, from star formation to stars enriching the interstellar medium by exploding. This may be termed a kind of *galactic ecology*.**

# Sketch of "Galactic Ecology"



# Starbirth

**Stars form in interstellar (molecular) clouds**
**Gravity must overcome other supporting agents:**
**Internal heat , spin, magnetic fields (these strengthen during collapse)**

**Collapse of an interstellar cloud:**

- **Fragmentation (perhaps triggered by outside shock waves), cooling of gas**
- **Split into clumps of about stellar masses (most doesn't end up in stars)**
- **Core starts to heat up (now a protostar), initially radiates gravitational energy**

**Finally begins core hydrogen fusion (reaching the main sequence)**

**The observational story**

- **Young stars, molecular clouds, and H II regions**
- **Herbig–Haro objects and protostellar jets**
- **T Tauri stars with strong winds**
- **Disks around young stars, magnetic link to star itself**
- **Accretion can be halted by nearby stars' wind, radiation**

**We deal with long timescales in stellar development**

**Stellar masses: the initial–mass function has many more low– than high–mass stars. Brown dwarfs are too small for H fusion, known to exist, but in uncertain numbers. Largest possible stellar masses are near 150 solar masses – any bigger and the star blows itself apart.**

**Fate of newly formed clusters**
**Sparsest ones are called associations**
**Identity may be lost into general galactic star population**
**Only densest clusters stay recognizable for long times.**

# Solar System – Formation and History

**Joint clues from our own system and observations of other stars.**

- **Planets' orbits nearly circular and coplanar, near Sun's equator**
- **Meteorites show early chemical reactions/agglomeration**
- **The planetary system shows differentiation with distance**
- **Minor planets are old, and show a range of properties**
- **Comets are icy and unevolved; they don't orbit near the ecliptic**
- **Young stars often have disks of orbiting dust and gas**
- **Massive planets (at least) are common around nearby stars**

**Nebular scheme: sun, planets form from a contracting cloud of gas**
**Planets form from material that doesn't make it into sun**
**This makes planets a *normal byproduct of star formation***
**Interstellar cloud collapses (as we observe elsewhere)**
**Central mass will become a star, surrounding material remains in disk**
**Instability in the disk will give denser and more rarefied regions**
**Accretion: particles can stick upon collision; bigger ones can swallow small ones by gravity**

**Largest protoplanets can sweep up gas from surrounding nebulae ––> becoming Jovian planets, in a race among accretion, stellar wind sweeping gas away, and the planets' inward migration in the disk (as happened in some other systems with very close –orbiting massive planets).**

**Fragmentation: rapid collisions among protoplanets break them up. Now seen among asteroids. Last loose fragments give the craters we see**
**Differentiation: temperature and kinds of planets**
**Two reasons inner disk was hot**
**Inner planets lack volatile elements (lower boiling points)**
**Giant planets cold enough to retain hydrogen and helium**
**(dominant elements by far in interstellar gas and the Sun)**
**Cold iceballs farthest from the Sun**
**Early solar wind (T Tauri phase) cleaning out the solar system**

# Terrestrial Worlds

**What do we know?**

- **Ground truth for Earth, Moon, Mars, Venus (in decreasing order)**
- **Role of lunar exploration and robot spacecraft**

**Surface processes: impacts, tectonism, vulcanism, gradation**

**Impact cratering**

- **High velocities - these are explosion craters, not gouges**
- **Features: ejecta blankets, secondary craters, central peaks**
- **Crater counts and surface ages**
- **Finding craters on Earth; the extinction connection**

**Internal structure – heat and its escape**
**Earth: evidence from propagation of earthquake waves**
**Differentiation: evidence for a past molten state**
**Magnetic fields: core production and external effects**
**Moon– small core, fast cooling, possible giant–impact origin**

**Tectonism: large–scale breakage and motion of planetary crust**

- **Plate tectonics on Earth (continental drift)**
- **unique in its development**
- **Origin: mantle convection?**
- **Crustal motion on other worlds**
- **Organizes occurrence of volcanic activity, earthquakes**

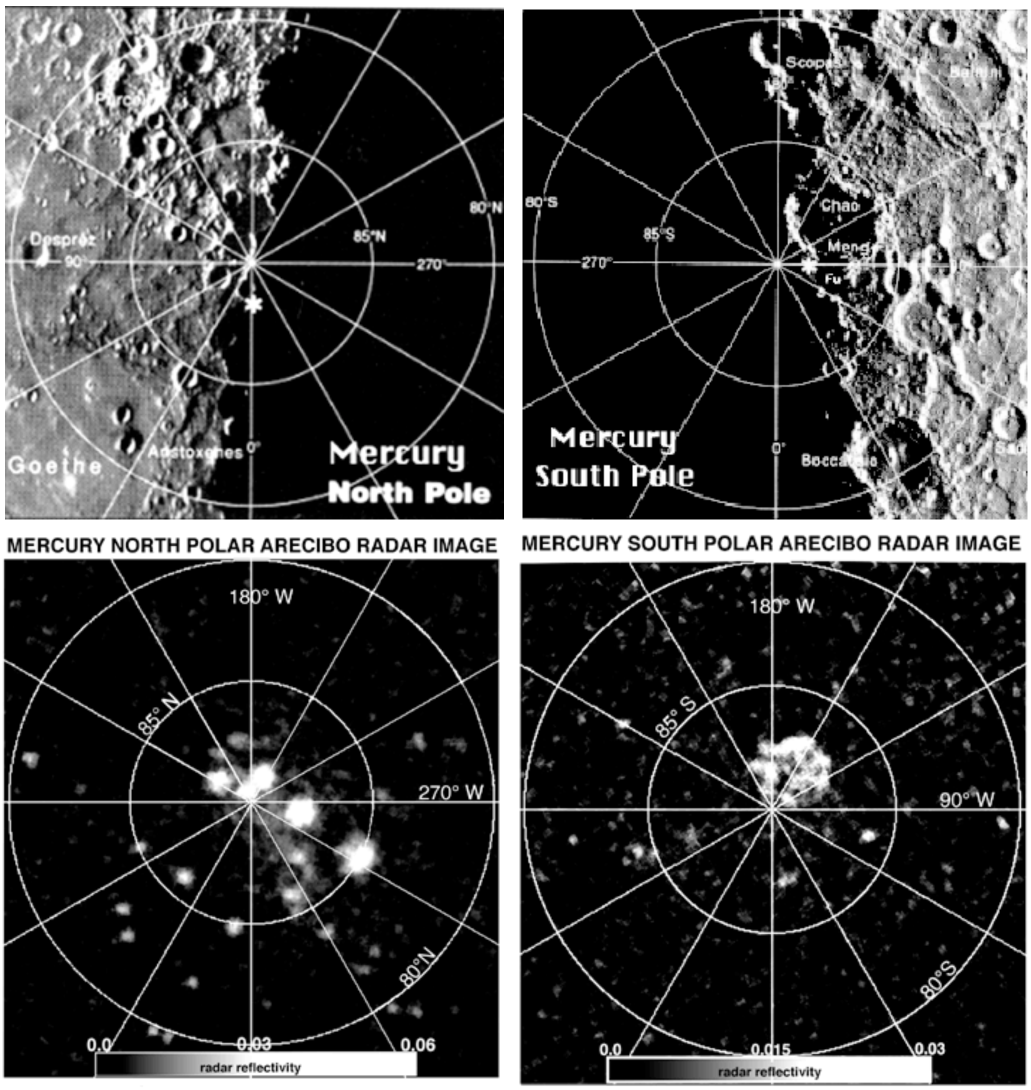
**Vulcanism**

- **Any form of hot material erupted onto surface**
- **Lava floods, cones, shields**
- **Has happened on many worlds**
- **Moon – dark *maria* are lava flows**
- **Jupiter's moon Io – covered with active volcanos**
- **Mars – giant shield volcanos**
- **Venus – planetwide volcanos and lava covering**

**Gradation (erosion)**

**Landscapes are a snapshot in a grand tug–of–war**
**Agents: water, ice, wind, landslides, thermal stress, meteorites**
**Landscape combines present and past kinds of gradation**

**Example: Mars – wind important now, water in the past.**
**Where did the water go? Some in polar caps, more underground?**
**Some ice may be hidden likewise at poles of the Moon and Mercury.**




(Courtesy J. K. Harmon and M. A. Slade)

**Evidence: radar signature of ice at Mercury's poles versus topography – it lies in craters with permanently shadowed floors. Clementine, Lunar Prospector missions suggest similar situation at the Moon's poles as well.**

# Exploration of the Moon and Mars

| | |
|---|---|
| 1959 | Luna photographs of far side |
| 1964–5 | Ranger 7,8,9 closeup photographs before impact |
| 1966 | Luna 9, Surveyor series Soft landings, photos, chemistry. Lunar surface solid, covered with finely churned regolith |
| 1966–7 | Lunar Orbiter (5) – photographed almost entire surface<br>1–3 reconnaissance for landing sites<br>4–5 entire Moon for general science |
| 1968–70 | Zond orbiters – photos, part of Soviet manned program |
| 1969–72 | Apollo: 6 human landings. Sample return, left experiments. Last 3 carried rovers for extended exploration. |
| 1970–73 | Lunokhod – remotely–controlled rovers.<br>Luna – limited automatic sample return |
| 1994 | Clementine – multiband geological mapping of the whole surface (testing sensors for DoD), matching radar altimetry. Publicly available data over Internet. |
| 1998 | Lunar Prospector – surface chemistry. Emphases – water (ice) at poles, overall geological history. |
| 2009 | Lunar Reconnaissance Orbiter, polar ice probe LCROSS |

**So what have we learned?**
**Craters dominated by impacts, but early vulcanism was important.**
**Isotope dating for a timescale of lunar history.**
**Lunar surface composition for comparison with Earth.**
**Measured moonquakes, meteor impacts.**

**Mars:**

| | |
|---|---|
| 1964–9 | Mariner Mars flyby missions |
| 1971 | Mariner 9 orbits mars, maps planet, finds channels |
| 1976 | Viking landers+orbiters, surface, life search |
| 1996 | Martian meteorite ALH84001 and life debate |
| 1997 | Pathfinder lander, surface makeup |
| 1999 | Mars Global Surveyer closeup mapping |
| 2001 | Mars Odyssey thermal/chemical monitoring |
| 2004 | Mars Exploration rovers/Mars Express: ancient water |
| 2006 | Mars Reconnaissance Orbiter high–resolution images |
| 2007 | Phoenix lander near north polar cap |

# Planetary Atmospheres

**Atmosphere: gravitationally bound envelope of gas**
**Structure determined by energy balance, escape of molecules**
**May be *primary* (formed with planet) or *secondary* (acquired later).**
**Primary gases mostly H, He – too light to be kept by terrestrial planets.**
**Secondary sources of heavier gases include internal volcanic release and impact of comets.**
**Comparison: Venus (massive, extremely hot atmosphere)**
**Earth (partially transparent, less massive, warm)**
**Mars (thin, cold)**
**Greenhouse effect: important in differences among Venus/Earth/Mars**
**Sunlight can penetrate atmospheres, while infrared radiation from the surface is absorbed by greenhouse gases and heats the atmosphere. Temperature is controlled by equilibrium between this heating and overall cooling. Greenhouse effect keeps Earth habitable, makes Venus extremely hot. Ineffective on Mars.**
**Greenhouse effect and global warming scenarios**

**Earth's atmosphere**
**Composition: N, O. Importance of living things in this.**
**Layers: Troposphere (near surface, weather, clouds)**
**Stratosphere (ozone layer at its top)**
**Mesosphere**
**Thermosphere (outermost, hot layer)**
**Solar absorption, greenhouse effect control temperature structure.**
**Solar heating drives weather patterns.**

**Aurorae – particles trapped in van Allen belts interacting with atmosphere**

# Giant Planets

**Differences from terrestrial worlds: mass, size, composition, location**
**Discovery of Uranus, Neptune**
**Closeup information: *Voyager 1/2, Galileo, Cassini***

**Makeup: dominated by hydrogen and helium, unlike inner planets but like the Sun.**
**Rapid rotation, equatorial bulges**

**All we see is weather!**
**Visible belts/zones are different cloud layers; several exist at different levels. Storms can be enormous (like Great Red Spot)**

**Interiors:**

- **Hotter and denser going inwards; winds driven from below**
- **Molecular hydrogen upper layers (liquid)**
- **Uranus/Neptune may have deep water layers – "ice giants"**
- **Metallic hydrogen layer**
- **Rocky core (terrestrial planet under pressure?)**
- **Excess radiated energy – gravitational source?**

**Intense magnetic fields: we see aurora, radiation belts**

- **Jupiter/Saturn have fields nearly aligned with rotation**
- **Uranus/Neptune fields are off–center and dramatically misaligned – early impacts?**

**Large magnetospheres, interaction with solar wind**

# Planetary Rings

**All four giant planets in our system have ring systems**
**Jupiter – broad, dark, fine particles**
**Saturn – broad, bright, complex, ice particles**
**Uranus – narrow, dark particles**
**Neptune – uneven, fine particles**

**Why rings?**
**Tidal forces destroy a large solid moon inside the planet's *Roche limit*. Ring systems are always found inside the Roche limit. Collisions make rings the final configuration for swarms of individual particles in orbit; they sap energy but not momentum.**

**How do they stay there?**
**Random motions should make some particles leave the rings and limit their lifetime. External effects can help herd stragglers back.**
**Examples: shepherd moons.**

**Internal structures: rings can be very thin. Radial structure can be produced by gravitational influences (such as tides from nearby moons). Example: the Cassini division. Weaker disturbances can split the ring into many ringlets.**

**Some ring systems are intimately connected to small satellites as sources of particles. (Saturn's outer rings from Enceladus, Jupiter's from several inner moons).**

**Puzzles:**
**Spokes in Saturn's rings**
**How long have rings been there? Are they short–lived, or a perpetual juggling act?**

# Planetary Moons

**Moons are ubiquitous. We know of 168 at last count, from a few miles long to larger than the planet Mercury (plus more around asteroids and dwarf planets). Composition and environment give them surprising variety. A major distinction is whether a moon is or has ever been geologically active (differentiation, vulcanism).**

**Currently active:**
**Io (Jupiter), Enceladus (Saturn) and Triton (Neptune).**
**Tidal heating makes these so active that we have seen volcanic eruptions on their surfaces.**

**Possibly active: Europa (Jupiter) may be the most interesting moon we know of. Tidally heated to some degree, its surface is a layer of ice which shows signs of having melted and refrozen. There may be a substantial subsurface ocean.**
**Titan (Saturn) has a thick nitrogen–rich atmosphere and cloud decks. It hosts methane lakes; the *Huygens* probe may have landed in slush. Some other smaller moons may have once hosted water vulcanism, as well.**

**Formerly active: all the other large moons (including ours).**

**Inactive and always that way: practically all the small moons, many too small to be round. Their only evidence of history is impact cratering onto an inert surface.**

# Minor Planets (Asteroids)

**Nature: small rocky bodies <1000 km in size (often irregular); some are “rubble piles”**
**435,000+ now have catalogued orbits**
**Locations: mostly in so–called asteroid belt (not really that crowded) between Mars, Jupiter. Some are known to pass within Mercury’s orbit, to share Jupiter’s orbit, beyond Uranus.**
**Special groups: Earth–grazers and Earth–crossers**

**Kinds of meteorites: way to analyze tiny stray asteroids**
- **Nickel–iron (once molten, part of differentiated core)**
- **Stony (may be composed of smaller pieces)**
- **Carbonaceous (were never part of a hot object)**

**Chemistry, radioactive dating give clues to early Solar System history**

**Origin: planet breakup versus never forming**
**Gravitational influence of Jupiter; Kirkwood gaps**
**Role of minor planet collisions and fragmentation**
**Asteroid impacts and Earth**
**Potential catastrophic results**
**Searching for potential killer asteroids**
**Asteroid deflection strategies**

**Meteor showers: brief periods of intense meteor activity**
- **Appear to all come from a radiant due to perspective**
- **Linked to comet orbits; these are comet debris!**
- **Occasionally produce meteor storms (Leonids 1966, 2001)**
- **Only non–shower (sporadic) meteors are large enough to reach the ground through atmosphere.**

# Comets

**Comets in history – long considered evil omens**
**Halley and his comet**

**Origin**
**Very elongated, long–period orbits; no strongly preferred direction**
**Oort and Kuiper clouds – relics of early solar system**
**Gravitational "eggbeater" of Jupiter and Saturn and comet location**

**Physical nature:**
**Solid nucleus – "dirty snowball" (frozen gases, tiny dust particles)**
**Coma of material boiled off nucleus**
**Dust and gas tails of escaping material (pointing away from Sun)**
**Deep Impact probe and structure of comet nuclei**
**Rosetta/Philae rendezvous/landing w/comet nucleus in 2014**

**Sungrazing comets, Jupiter's family of comets**
**Comet Shoemaker–Levy 9 and its impact on Jupiter in July 1994**

**Comets and meteor showers**

**Zodiacal light and solar–system dust**

**Trans-Neptune objects**
**Pluto: now termed a dwarf planet**
**Discovery – chance favors the prepared**
**Small size, orbit, single moon Charon, synchronous rotation**
**Methane atmosphere, often frozen to the ground**
**Origin, relation to other trans–Neptune objects**
**Many more large comet–like objects known in the Kuiper–Edgeworth belt, at 1.5 times Neptune's period (like Pluto, closest stable orbit) and beyond. Recently–discovered Eris is more massive than Pluto and brought about debate about how to define planets. These objects may add clues to solar–system history.**
**New Horizons Pluto flyby, July 2015**

# Measuring the Stars

**Distances: measured using either *geometry* or *light propagation***
**Parallax: for nearby stars, triangulation with Earth's orbit as baseline**
**HIPPARCOS satellite data give distances out to 500+ parsecs**
**Star separations: in our neighborhood, typically 1 parsec ~ 3 light–years**

**Brightness (apparent) versus luminosity (intrinsic)**
**The brightness of a distant source follows the *inverse–square law*.**
**If we know a star's luminosity) we can determine its distance, or if we know its distance we can calculate its luminosity**

**Sizes of stars: All but one look tiny. We can measure by**
- **Interferometry (and Hubble imaging for a few close giants)**
- **Lunar occultation**
- **Blackbody physics: luminosity = constant x $R^2$ x $T^4$**

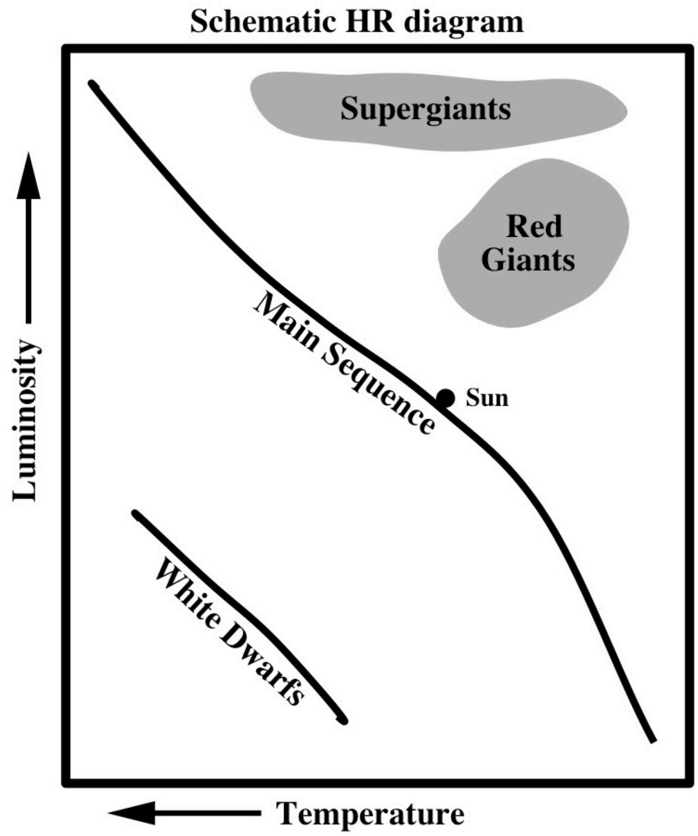
**These lead us to *distinguish giant/supergiant/dwarf* stars**

**Colors and temperatures of stars**
**Blackbody laws and spectra ––> hotter stars are bluer**
**Measurement of colors via multiple filters and spectra**
**Majority of stars have surface temperatures from 3000 K (distinctly orange–red) to 30,000 K (bluish–white).**

**Spectra of stars:**
**The spectra of stars mostly tell of a temperature sequence as various spectral lines come and go. The spectral classes are OBAFGKMLT (in order hot–cool), defined by spectral features and thus unaffected by any interstellar reddening or other color effects.**

**Masses of stars:**
- **Binary stars and Kepler's laws**
- **Relations of mass to radius, luminosity, lifetime of stars**

**The *HERTZSPRUNG–RUSSELL DIAGRAM***
**Stars arrange themselves naturally by temperature and luminosity in the H–R diagram.**




**Major types are:**

**Main sequence (like the Sun) : core hydrogen fusion**
**Red giants (Betelgeuse, Arcturus) : more evolved stars**
**White dwarfs: simply cooling**

***The most important single fact about a star is given by its place in the HR diagram.* Any theory of stellar structure and evolution must fit what we see in the HR diagrams of various sets of stars.**

# Our Sun

**What's inside? We can only see the outer layers**
**Physical modelling (pressure/gravity equilibrium)**
**Helioseismology**
**Results: an energy–producing core (half the mass, 1.6% of volume), diffuse edges, outward energy transport beyond this (0.71 radius) by *radiation* and *convection***

**Solar energy: how can it shine so brightly for so long?**
**Energy from fusion: can trade binding energy of atomic nuclei for other kinds of energy. Conservation of mass+energy operates (more general than conservation of either alone)**

**Proton–proton (p–p) cycle: dominates in the Sun's core**
**Net result: 4 protons –> 1 He nucleus plus 0.7% of their mass into energy ($E=mc^2$)**
**Reviewing nuclear particles, the steps involved are:**
**$^1H+^1H$ ––> $^2D$ + positron + neutrino (D = deuterium)**
**$^2D + ^1H$ ––> $^3He$ + gamma ray ($^3He$ or light helium)**
**$^3He + ^3He$ ––> $^4He + ^1H + ^1H$ + kinetic energy**
**The energy emerges largely as visible light.**

**Observable aspects: neutrinos**
**Neutrino properties: barely interact with matter**
**emerge directly from solar core**
**Measurements: we see solar neutrinos (nuclear processes are at work) but fewer than initially expected (something was not quite right with our predictions). Recent experiments indicate this happens because neutrinos change forms (oscillate) on the way here, and some experiments don't show some forms.**

# The Sun up close

**The solar surface: going upwards we find**

**Photosphere: visible surface. This is where sunspots occur.**
- **Granulation: convective pattern at surface**
- **Limb darkening: tells us the temperature increases inward**
- **Differential (latitude–dependent) rotation (in outer 2/3 of Sun)**

**Chromosphere: easily observed only during total eclipses/from space**
- **Active regions; spicules**

**Corona: outer faint atmosphere, well seen in X–rays**
- **Extremely high temperatures (1–2 million K) – what heats it?**
- **Controlled by solar magnetic field**
- **Begins solar wind**

**Solar composition: from spectroscopy, H and He dominate, everything else together ~1% of mass.**

**Solar activity: seen in sunspots, flares, prominences, corona, auroras**
**Magnetic phenomena (the field suppresses convection, cools sunspots)**
**Solar cycle, approximate 11–year period**
**Butterfly diagram for sunspot variations in position, number, and size**
**Long–lasting solar minima (Maunder minimum in 1645–1715)**
**– weather records suggest a link to Earth's climate.**
**Analogous cycles have been observed for some other stars.**

# Lives of Low–Mass Stars

**On the main sequence: energy is released from core hydrogen fusion How long? Until most core hydrogen is exhausted.**
**Example: for the Sun, if we take the core as 10% of the total mass, it can release a total of $2x10^{33}$ grams x 10% x 0.7% x $c^2$ over its main–sequence lifetime. This gives $1.3 \times 10^{51}$ ergs over its lifetime. At the current rate of $4 \times 10^{33}$ ergs/second, it can shine in this way for $3.15 \times 10^{17}$ seconds or (almost exactly) 10 billion years.**
**For other masses, this lifetime varies as the ratio of mass/luminosity, roughly as $(\text{mass})^{-3}$.**

**What next? Core hydrogen is depleted at the expense of helium "ash". Eventually the core starts to lose the tug–of–war between gravity and internal energy production. The core contracts and heats, until the helium–carbon (triple–$\alpha$) process begins producing energy. The outside result is expansion of the outer atmosphere and corresponding cooling of the surface. In these phases we see a *red giant* – with high luminosity and lower temperature.**
**As the star reaches a balance between He fusion and gravity, it stabilizes in a helium–burning state on the so–called horizontal branch of the H–R diagram. This may be preceded by a *helium flash*, if the core has gotten dense enough to become degenerate. Red giants and related stars may have multiple nuclear reactions in concentric shells. These stars blow substantial winds, losing large fractions of their mass. An unhealthy time for Earthlike planets.**

**Eventually there are no more reactions that generate energy. The envelope becomes unstable and floats away as a *planetary nebula*, shining by absorption of UV light from the central star, formerly the hot red–giant core. They have spiral or barrel symmetry, perhaps due to colliding stellar winds of different ages and speeds.**

**The core now generates no energy, and cools slowly through radiation. It becomes a degenerate *white dwarf* with extreme density**

**and size – about the size of the Earth. Their gravity is balanced by pressure due to electrons.**

# Complications: Lives of Binary Stars

**Most stars are in binary systems. If the stars are close enough together, they can interfere with one another's "normal" development.**

**The crucial distance: the *Roche lobes* in a binary system.**
**A binary member may fill its Roche lobe while expanding as a red giant. Some of its mass is lost to the companion, slowing its evolution and speeding the other's. This process may even reverse as the companion becomes more massive.**

**Cataclysmic variable stars: mass–gaining member is a white dwarf.**
**Accretion disks around compact objects**
**Mass buildup on white dwarfs**

***Nova outbursts* – a star–wide surface nuclear explosion**
**These may repeat as more fresh, H–rich surface layer accumulates**

***Type I (white-dwarf) supernovae*: the white dwarf is finally pushed over the *Chandrasekhar limit* at 1.4 solar masses, beyond which it is unstable. This may happen as two white dwarfs spiral together or as matter is accreted from a larger companion star.**
**The star blows up, releasing as much energy as in the Sun's whole lifetime. These are important sources of energy and heavy processed elements.**

# Massive Stars – Live Fast, Die Young

**Main sequence energy production – CNO cycle dominates the p–p chain. Even small amounts of carbon catalyze H fusion very efficiently at high temperatures.**

**After core hydrogen exhaustion:**
**Smooth transition to helium fusion (the triple–$\alpha$ process), without the red–giant dance. Star loops across HR diagram at nearly constant luminosity passes through unstable, pulsating phases (i.e. Cepheid variable stars)**
**Multiple shells of fusion; we see results in abundances of chemical elements even on Earth.**
**Strong stellar winds throughout their lifetimes**

**The end: when the core is rich in iron, which can yield no nuclear energy, it collapses. The core collapse creates a neutron core and releases $10^{53}$ ergs in *neutrinos* (detected from SN 1987A at 150,000 l.y.). These neutrinos plus a shock wave blow the star apart in a *Type II (core-collapse) supernova*. Some leave behind a neutron star, as well as hot, expanding bubbles of ejected gas.**
**Much of this picture directly confirmed in SN 1987A.**
**Smoking gun for supernova remnants: the Crab Nebula**
**Explosion seen in East Asia, 4 July 1054.**

**Discovery of pulsars, location of fast pulsar in the Crab**
**Stellar debris, plasma powered by the pulsar contribute today**
**Pulsars: a subset of *neutron stars*, which are neutron–degenerate matter (up to about 3 solar masses). They are typically 15–20 km in diameter, the last known stop before collapse to a black hole. Strong magnetic fields and rapid rotation make some neutron stars give off strong 'searchlight beams" of radiation; if we're properly placed, we see these as pulsars.**

# Star Clusters and Stellar Life Cycles

**Stars are mostly formed in groups and clusters. These clusters are thus excellent laboratories for watching stellar evolution, since all their stars have nearly the same age.**

***Open clusters* – still being formed. Few dozen – few thousand stars. We see them at all ages from about 5 billion years to still being formed. Some clusters disperse with time as they orbit through the galaxy.**

**Dating clusters from HR diagrams; main–sequence turnoff.**

***Globular clusters* – all these are very old. Our galaxy doesn't make them any more (though some others may). Very rich, typically a million stars. HR diagram shows red giants and old main–sequence stars, no massive ones. Location: globular clusters form a round halo around the galaxy, ignoring the disk and spiral arms (unlike open clusters). Our galaxy has about 200.**

# General Relativity and Black Holes

**General relativity –– begin with Einstein's equivalence principle Adding accelerations and gravitational fields, this theory (not as logically required as the special theory, but holding up well under experiment) says that:**
**–– *Gravity can be viewed as a curvature of space by mass*, and the "force" is the object going as straight as possible through it. This motion differs measurably from Newton's prediction only for very strong fields (Mercury's orbit, neutron–star binaries).**

**What do we mean by "curved space"?**
**If all the lengths across a cube are equal, we deal with flat space (the familiar Euclidean kind). If the central lengths are longer, we speak of a positive curvature; if shorter, of a negative curvature. This can be seen by the deviations of light rays around a mass (the Sun or a distant galaxy). In extreme cases this gives us *gravitational lensing.* This can also introduce time dilation and redshifting of photons. In the most extreme case, we have a *black hole*. This is a region from which no radiation can escape, as from a collapsed massive star. Its boundary is the *event horizon*. At the center is the singularity itself, approaching a mathematical point mass of infinite density. Using the curvature of space in general relativity, its "walls" are infinitely steep.**

**Formation of black holes:**
- **collapse of massive stars**
- **early universe**
- **galactic nuclei**

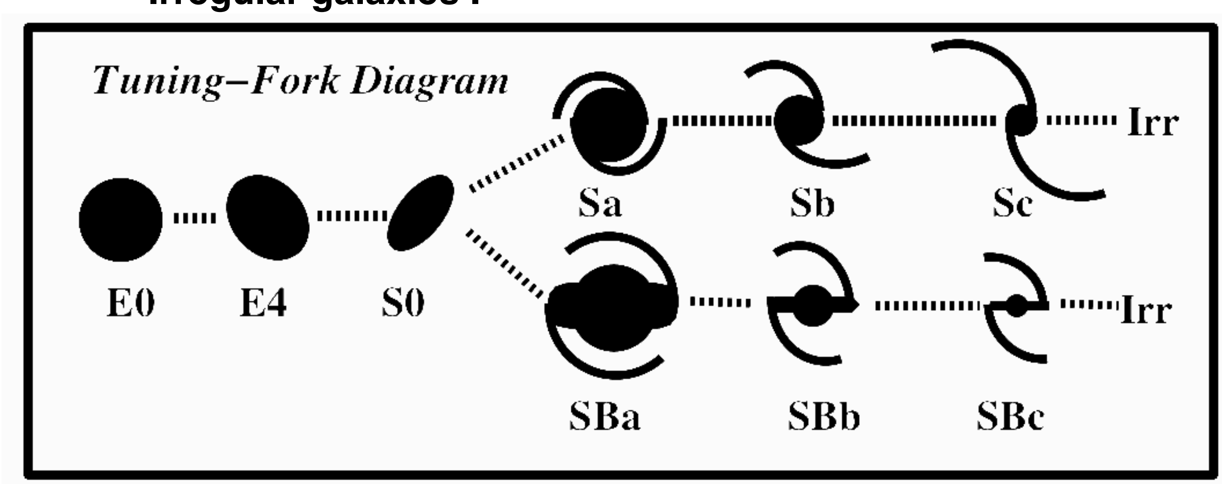
**Looking for black holes: indirect techniques relying on its gravity Remember: black holes are very small, and act gravitationally like any similar mass. They are *not* cruising the universe gobbling things up – it takes work to fall in.**

**Hawking radiation and decay of black holes**

# Galaxies

**Spiral and "formless" nebulae seen away from plane of the Milky Way, by the thousands. Spectra generally did not show emission.**
**Basic theories were: external distant systems like Milky Way or nearby protoplanetary systems**
**Crucial tests: Cepheids in nearby galaxies (Hubble)**
**search for rotation (van Maanen)**
**Cepheid distances: Andromeda spiral about 2 million ly distant a few smaller galaxies closer to us**

**Types of galaxies: we still generally use the Hubble classification:**
- **Ellipticals E0–E7 for increasing ellipticity**
- **Spirals Sa–Sb–Sc**
- **Barred spirals SBa–SBb–Sbc**
- **Irregular galaxies I**




**usually arranged in the tuning–fork diagram without necessarily implying any time sequence:**

**Rates of star formation, stellar and gas content vary systematically along the sequence. Spiral types are determined by the intensity of the central bulge and structure of the arms. We might have come up**

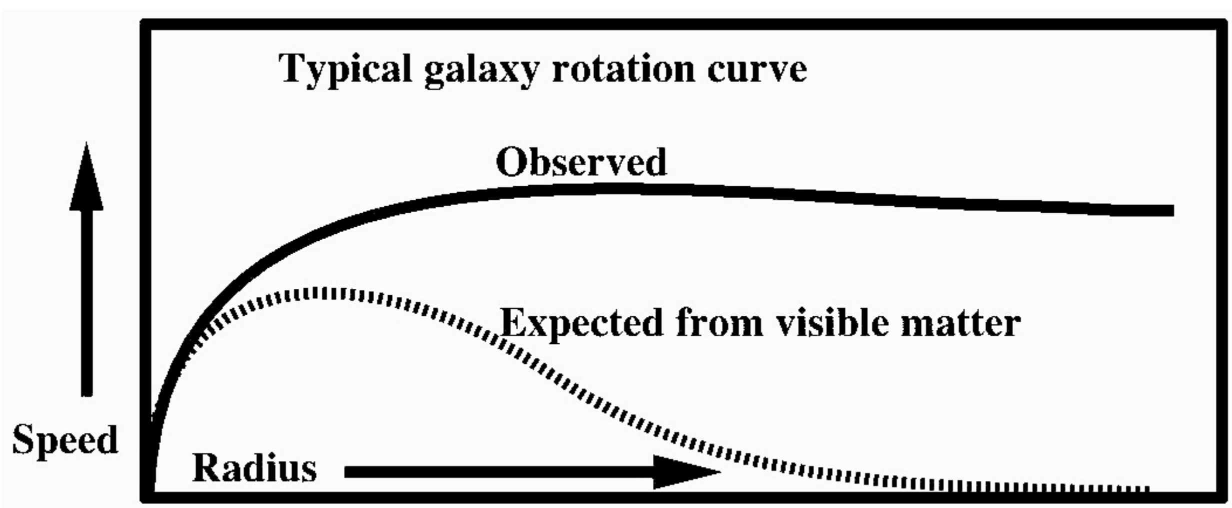
**with a different system had we first seen them in the infrared or ultraviolet.**

**Spiral structure:**
**The arms are not physical features, but wave patterns of bunched stars and gas – much like a traffic jam. The arms may move past a given star in either direction at different places. We do see that star formation is strongest in the arms, perhaps due to the extra crowding and compression there. To some extent, these are optical illusions – the clumping of the brightest young stars make them appear more dramatic than the actual distribution of stars.**

# Dark matter in galaxies

**We can measure galaxy masses using gravity and internal motions (from Doppler shifts)**
**Rotation curves (spirals)**
**Doppler widths (ellipticals)**
**Velocities in galaxy clusters**
**Gravitational lensing**

**Stars and gas are in gravitationally bound orbits, so the orbital speed measures how strongly the galaxy's interior mass is attracting at each point. This allows us to "weigh" different parts of a galaxy, or all the matter in a cluster of galaxies. All four techniques show vast amounts of dark matter – which emits no detectable radiation, and**




**whose existence is shown only by its gravitational effects. This dark matter must be more extended than the starlight, dominating a huge invisible halo around each galaxy.**

**Possible forms for this dark matter include:**
**Brown dwarfs or orphan giant planets**
**Primordial black holes**
**Exotic elementary particles (if I had to bet right now, this would be it)**

# Active Galactic Nuclei

**Violent, energetic events from tiny regions in the cores of galaxies.**
**Major varieties:**

**Quasars (Quasistellar radio sources) and QSOs (quasistellar object)**

- **Look like stars in ordinary telescopes**
- **Broad emission lines**
- **High redshifts ––> very luminous**
- **Variable brightness ––> very small from light–time arguments**

**Seyfert galaxies: discovery from spectra**

- **Rapid gas motions from Doppler linewidths**
- **Broad and narrow emission lines, ratio: two major types**
- **Bright starlike nuclei, usually in spiral galaxies**
- **Links to interactions, maybe mergers**
- **Strong X–ray sources, also seen in IR, radio**

**Radio galaxies: discovery via interferometry**

- **Twin lobes of radio emission**
- **Jets tracing to nucleus**
- **Usually in elliptical galaxies**
- **Lifetime, directional arguments for jets**

**What is the central engine?**
**Clues: rapid gas motions –> deep gravitational well**
**jets –––––––––––––> directional memory, symmetry of core**
**variability ––––––––> smaller than the solar system**
**So what's very small, has very strong gravity, and can produce rapid motions nearby? This leads to the standard picture of a supermassive black hole with surrounding accretion disk.**

**The unified scheme for AGN**
**Many data fit nicely if, for example, radio galaxies are quasars seen "sideways" to an obscuring torus. Similarly, the two kinds of Seyfert galaxy are connected in this way by seeing reflected light and cones of illumination seen sideways.**

**Superluminal jets**
**Some quasars and radio galaxies (along with neutron and black–hole binaries in our own Galaxy) show apparent motions in their radio jets that exceed the speed of light. Relativity tells us that no material object can do this, so something interesting is afoot. This is an optical illusion due to material moving very rapidly (close to the speed of light) and almost directly at us. Such jets pointed at us should also produce the brightest and easiest–studied radio sources. Both effects have to do with the transformations in rate at which we measure time to pass in differently moving reference frames.**

**Quasars and galaxies**
**Host galaxies and problems seeing them**
**Kinds of host galaxies and their companions – many have very small close companions**

**Did all galaxies once host a quasar? Many have quiescent central black holes today. There were once many more active galaxies (quasars) than now.**

**Growth of black holes and galaxy formation**
**There is a relation between the mass of stars in a galaxy's central bulge and the central black hole, suggesting that they had linked formations and that most bright galaxies today have such a black hole.**

**Gravitational interactions: can draw out long tails of stars and gas**
**can trigger "bursts" of star formation**
**can trigger active galactic nuclei**

**These can be important episodes in galaxy evolution (especially galaxy mergers).**

# The Milky Way Galaxy

**Observable guise: the Milky Way, a band stretching around the sky. Shown from Galileo's time to be light of large numbers of faint stars. First try at its form: star counts in different directions, infer extent of star distribution (Herschel, Kapteyn). This shows a flattened system centered near the Sun. Discovery of absorption by interstellar dust demonstrated that this is only our local piece of the galaxy. The true form was uncovered starting with the distribution of globular clusters, which clump around a small region in the constellation Sagittarius.**

**Distances across the galaxy: bright stars and variables (esp. Cepheids, with P–L relationship=Leavitt law)**
**Size of the galaxy: we are about 24,000 ly from the center, stars to 50,000+; it contains (roughly) 400,000,000,000 stars (400 billion)**

**Galactic structure: other galaxies suggest ours might be a spiral with rotating disk. Dust limits our view too much to check this easily, but we can use radio observations of interstellar clouds. These give crude maps of a spiral pattern. We find that ours is a spiral with arms in a thin disk, central bulge containing a barlike pattern, and extended halo. The rotation pattern suggests that much of the mass in the outer parts is in some completely invisible form.**

**Stellar populations: Baade found these in Andromeda, after which they were recognized in our own galaxy. Various properties of stars are related in ways that suggest a specific history to the galaxy.**

| Population: | I | II |
|---|---|---|
| Ages: | Wide range | Old |
| Motions seen | Small | Wide range |
| Heavy elements | Wide range | Small |
| Associated ISM | Yes | No |

| | | |
|---|---|---|
| **Clusters** | **Open** | **Globular** |
| **Shape of system** | **Disk** | **Bulge plus halo** |

**This all suggests that the galaxy collapsed from a spherical shape, as its first stars formed. Stars' orbits are "frozen"; gas clouds can have theirs changed by collisions. The gas settled into a thin disk, for subsequent star formation and chemical enrichment. This happened piecemeal; some former dwarf galaxies are threaded like spaghetti through the Milky Way's halo.**

**Cosmic rays**
**High–energy particles (electrons, nuclei) in galactic magnetic field**
**Origin: supernovae plus ???**
**Detected directly and via synchrotron radiation to large distances**

# The galactic center

**The galactic center lies in Sagittarius, but the view in ordinary light is blocked by intervening dust clouds. Infrared, radio, X–ray, and gamma–ray data show unusual and energetic events at the galactic center – perhaps a minor version of what we see in active galaxies and quasars.**

**Dense central star cluster (expected)**
**Young stars (not quite expected)**
**Filaments aligned along probable magnetic field**
**Violent gas motions**
**Compact radio source (smaller than our solar system)**

**The case for a central black hole has been strengthened by measurement of stars' orbital motions near the galactic center, better tracers than diffuse gas clouds which can be moved in nongravitational ways. Stars very close to the central object can be traced over large arcs of their orbits, for a good estimate of the central mass – a few million solar masses.**

# Galaxy Clusters

**Most galaxies are found in groups of 5–10, or clusters with up to thousands of members, and the clusters themselves are often grouped into superclusters spanning tens of millions of light–years. These in turn form the largest–scale textures seen in the universe (a bubbly or weblike form).**

**The Local Group contains 3 large spirals (Andromeda, Milky Way, Triangulum) plus numerous fainter irregular and elliptical galaxies. Here we see (as usual) many more faint galaxies than bright ones – don't be misled by flashy but rare specimens. The local volume of space is dominated by the Virgo Cluster, containing several hundred (luminous) galaxies of all types. It is surrounded by further parts of the Local Supercluster, of which we are on the outskirts slowly falling in.**

**Galaxies in clusters differ in their types and gas content from those in sparser areas. Elliptical and S0 galaxies dominate in rich clusters, while spirals are more common elsewhere. We can see this change with redshift, so something has changed in clusters. Was their gas removed by galaxy collisions or swept out by gas between the galaxies? Here we see direct signs that galaxies and clusters have evolved with cosmic time.**

***Intracluster gas* was found with X–ray detectors. This has been heated to several million degrees, and fills the space between cluster members. It has been enriched by star formation and isn't just "leftover material". This could play a role in stripping gas from spirals, and perhaps in slowly growing giant galaxies in the centers of clusters. This gas has a mass comparable to that in the galaxies' stars. This is the densest and brightest component of the intergalactic medium, which still traces a web spanning all of space. Some of it was also chemically enriched by the earliest stars.**

# Cosmology

**Study of the Universe itself – its origin, history, and fate.**

**What observations can possibly bear on these grandiose aims?**

**Olbers' paradox – an infinite and infinitely old Universe would contradict the observed darkness of the night sky. One of these assumptions (at least) must be wrong.**

**The Hubble expansion – a uniform expansion, with no unique center required. This may be modified locally by clumps of matter. The expansion rate (Hubble constant) gives a characteristic measure of the age of the expansion.**

**Cosmic microwave background – a uniform radiation field at a blackbody temperature of 2.735 K coming from everywhere. The Universe was once very uniform and hot (the radiation cools over time due to the expansion).**

**Finite ages of oldest stars and radioactive atoms – "age" for the Universe has physical meaning**

**Relative amounts of H,He, Li... in pristine material – a distinct process formed these elements**

**Constancy of physical laws – we see the same chemistry and physics from spectra of distant galaxies. This includes distant QSOs that can never have had mutual contact. This is evidence for homogeneity of physical law and causal connection.**

**Burned by the triple Copernican revolutions – solar system, galaxy, Universe – most cosmological thinking incorporates the "Cosmological Principle":**
**The overall structure of the Universe is the same viewed from anywhere at a given time.**

# The Big Bang Picture

**BIG BANG – an initial state of high density and temperature started an expansion and consequent cooling, galaxy formation, nucleosynthesis, people...**
**Some version of the big bang is now favored by the observations. What exactly does the model say?**
**It is space itself which expands, taking galaxies along for the ride (rubber–sheet analogy)**
**The Big Bang happened everywhere (not an explosion in existing space)**
**The Universe is not required to be either finite or infinite, though the observable portion is finite (light–travel time) – we can deal only with local quantities (density, expansion)**
**An expanding universe may be open or closed depending on whether gravity plus other forces are strong enough to stop the expansion; if closed, we can picture an oscillating universe. Just as the rate of expansion is given by the Hubble constant $H_0$, the curvature (open/closed) is described by the deceleration parameter $q_0$. New evidence from distant supernovae indicates that the expansion is accelerating for some ill–understood reason (the cosmological constant) , so gravity isn't the whole story on a cosmic scale.**
**The expansion gives the redshift of distant objects – the change in scale of space between its time of start and the time we receive the light. It is not exactly a familiar Doppler shift.**

**This picture is consistent with light–element abundances and the temperature and detailed structure of the microwave background. It also fits with ages of the oldest stars, and with observations of the evolution of galaxies and quasars. The current age of the Universe is estimated at 13.7 billion years.**

**Puzzles: cosmic flatness (why is the Universe so close to critical density, expansion rate?)**
**how did everything know to start with the same physical laws? (causality)**
**Possible answer: an early epoch of inflation.**

# History of Cosmic Structure

**Putting the whole scheme together - a sketch history of the Universe:**
**Big Bang (hot, dense) – meaning of space and time in these conditions; both appeared together.**
**Whence did it arise? – quantum foam and fluctuations**
**Planck era, quark soup, matter–energy equilibrium, unification, before $10^{-43}$ seconds**
**Inflationary era – false vacuum, causal connection/separation, set expansion to give exactly the critical density.**
**Are there other disconnected "universes"?**
**Nucleosynthesis (formation of deuterium, helium, and lithium, in race among expansion, fusion, and neutron decay) 3–11 minutes**
**Recombination: the universe becomes transparent. Escaping radiation becomes microwave background. (300,000 years)**
**Gradual collapse of matter following gravity**
**First (massive, hot, short–lived) stars form, explode – heavy elements**
**Galaxy formation, clustering. Role of dark matter in this. (less than one billion years)**
**Matter follows gravity, which follows matter...**
**Normal stars form in galaxies, enrich material, seed ISM, more stars form...**
**Planets can eventually form when enough heavy elements are present**
**Life**
**Animals**
**Vertebrates**
**Mammals**
**Universities**

**Mapping between redshift, distance and time in watching this happen.**

# Life in the Universe

**So how widespread or important is this most complex cosmic structure?**

**Our view of the Universe is conditioned by the anthropic principle: the properties of the Universe must so conspire as to allow intelligent life to exist, for these questions to be asked. Is this logically necessary, as implied by some interpretations of quantum mechanics? The weak anthropic principle is mildly interesting and clearly true (atomic properties, age of Universe, early fusion). Strong anthropic principle is very interesting and very controversial.**

**History of thought on extraterrestrials:**
**Plurality of worlds**
**Early speculations, Locke's moon hoax**
**Mars: canals, Lowell, H.G. Wells, Mariner/Viking results.**
**Gas chromatograph, labelled release, gas exchange – inconclusive results. Meteorite chemistry.**
**UFOs – standards of proof, strangeness vs. reliability**
**Ancient astronauts – old idea (i.e. Sagan and Shklovskii), nothing strong enough (ex.: Dogon)**
**Projects Ozma, etc.; Pioneer/Voyager messages.**

**Intelligent life (still confined to as–we–know–it)**
**Physiological prerequisites: complexity, senses, manipulation**
**Don't know how common these might be!**

**This is seen in the Drake or Green Bank equation for the number of communicating civilizations in the galaxy:**

$$N = N_* \, f_p \, n_{pm} \, f_l \, f_c \, L$$

**$N_*$ Number of stars in the galaxy**
**$f_p$ Fraction of stars with planets**
**$f_{pm}$ Average # of planets/moons**
**$f_l$ Fraction with life**
**$f_c$ Fraction with civilizations**
**L Likelihood of overlap in time**

**We now know something about the occurrence of planets around sunlike stars, but retain profound ignorance of the further factors in the Drake equation.**

**So what might ETs look/think/be like?**
**not just like us only (smaller, greener, with antennae) – parallel development goes only so far**
**Many features of vertebrates are common to all –> ancestral (4 legs, spine, tail, endoskeleton)**
**May have recognizable parts from function (motion, senses)**
**Some species might be intelligent and noncommunicative (dophins?)**
**Some common ground for technological/communicative species**

**So what ought we to look for?**
**Noncommunicative: cosmic engineering (Kardashev, Dyson spheres)**
**planetary engineering (city lights)**
**radiation leakage (TV, radar)**
**patterns in natural habitats (Earth from space)**
**but what about sentient rocks?**
**might only find fossils or ruins (need TIME overlap)**

**Communicative: wait for them.**
**Look/listen for transmissions**
**What wavelength?**
**Reverse cryptography. Our trials: Arecibo, Voyager records (what would we want to transmit)**
**How to recognize a signal? Previous searches.**

**Look for local probes.**

**The future of life in the Universe**
**How long will the Earth remain habitable?**
**How long will there be stars or other sources of energy for life?**
**What should our fundamental definition of "life" include?**