GENERAL ASTROPHYSICAL CONCEPTS

Astronomical length scales and time scales

First principles of cosmology

The universe is: (a) HOMOGENOUS (b) ISOTROPIC

Homogeneity implies isotropy,
but isotropy does NOT imply homogeneity

Kepler’s laws of motion (3)

(1) Orbits of planets follow ELLIPSES with the Sun at one of the two foci

(2) Equal areas are swept out in equal intervals of time

(3) P^2 proportional to R^3 or P^2 = C R^3 / M

where P is the period of the orbit, R is the ‘radius’ of the orbit, and M is the mass of the central object (Sun)

The Milky Way and Other Galaxies Like It

Overview of its constituents

Dynamics (and mass) of a typical spiral galaxy, The Milky Way

Application of Kepler’s third law

Forces

Newton’s Laws of Motion

Inverse square law of forces

Fundamental forces (4)

(1) Gravitational force

(2) Electromagnetic force

(3) Weak nuclear force

(4) Strong nuclear force

ELECTROMAGNETIC RADIATION

Propagation of Energy in the Form of Oscillating Electric

and Magnetic Fields

Speed of propagation (in vacuum): c = 300,000 km/s

Frequency \nu: number of oscillations per second
[Unit of frequency: s^-1 or Hertz (Hz)]

Wavelength \lambda: distance travelled during one oscillation
[Unit of wavelength: meter (m), Angstrom (1 Ang =10^-10 m)]

c = \lambda \nu or \lambda = c / \nu or \nu = c / \lambda

[\nu and \lambda are inversely proportional to each other]

Electromagnetic Spectrum

Progression of frequency or wavelength

Radio, millimeter, sub-millimeter, microwave, infrared,
optical, ultraviolet, X-ray, gamma rays

[Optical/visible white light spectrum (rainbow colors):
Red Orange Yellow Green Blue Indigo Violet]

[Order of decreasing wavelength, increasing frequency]

Atmospheric Windows

Optical, [sub-millimeter], millimeter, and radio wavelengths

[Impact on astronomy (and on human evolution!)]

Black Body Radiation

Perfect emitter of radiation; perfect absorber of radiation

Energy radiated per second depends on temperature:

L = A \sigma T^4 or L = 4 \pi R^2 \sigma T^4
(sphere of radius R)

where: L = luminosity (in erg/s); \sigma = Stefan’s constant;
T = temperature (in Kelvin)

‘Quality’ of radiation (\nu or \lambda or color) depends on the
black body temperature (Wien’s law):

\lambda_peak T = constant

(\lambda_peak is inversely proportional to T)

Wave-Particle Duality

Radiation consists of energy bundles (quanta) called photons

Energy of each photon: E = h \nu

where: h = Planck’s constant; \nu = frequency of radiation

[Energy of each photon depends on ‘color’ (\lambda, \nu) of radiation]

The more luminous a source of radiation, the more photons it emits per second

Atomic Energy Levels

An atom in Quantum Mechanics; discrete energy levels

Transitions between levels: emission & absorption lines

MEASURING DISTANCES IN ASTRONOMY

Basic Principles

Geometric methods

Standard candles

Standard rulers

[the last two methods relate quantities that are independent of distance to quantities that depend on distance]

Parallax and Proper Motion

Angular size: degree [\circ], arcminute [’], arcsecond ["]

\theta [in arcseconds] = 206265 (L/D)

[where: \theta = angular size;
L = linear (or ‘true’) size; D = distance]

Definitions: parallax (p), Astronomical Unit [AU], parsec [pc]

D [in parsec] = 1/p [in arcseconds]

1 pc = 206265 AU = 3.26 light yr

[Parallax can only be used on nearby stars (D < 10 pc)]

[Atmospheric blurring (seeing); Hipparcos satellite; Hubble Space Telescope]

Motion of stars within cluster:

Proper motion [arcsec/s] = change of angular position

Line-of-sight motion [km/s] - measured via Doppler shift

Comparison of average stellar proper motion in cluster with average line-of-sight speed yields distance to cluster

Luminosity and Flux

Inverse square law: f = L / (4 \pi D^2)

where: f = flux [erg/s/cm^2]; L = luminosity [erg/s];
D = distance [cm]

Magnitude scale: brightnesses of astronomical sources

Stars as Standard Candles

Variable stars: Cepheids and RR Lyrae stars

Period-luminosity relation; measure P and infer L

Other standard candles: brightest red giants, HII regions, planetary nebulae, supernovae, globular cluster luminosity

Galaxies as Standard Candles and Rulers

Luminosity correlated with typical speed of stellar motion

[Tully & Fisher; rotation of spiral galaxies]
[Faber & Jackson; random stellar motion in elliptical galaxies]

Size correlated with typical speed of (random) stellar motion
[D_n-\sigma relation for elliptical galaxies]

Redshift as Distance Indicator

Expansion of the Universe

Hubble’s law: v = H_0 D

where: H_0 = Hubble constant [km/s/Mpc]

Doppler shift used to measure recession velocity:

v = c \Delta\lambda / \lambda

where: \Delta\lambda / \lambda = fractional change in wavelength

SPECIAL THEORY OF RELATIVITY (STR)

The Speed of Light

Constancy of the speed of light: Michelson & Morley experiment

Speed of light (in vacuum): c = 300,000 km/s

No signal or object can travel faster than c
[The ultimate speed limit!]

Basic Principles of STR

The speed of light is the same to all observers

The laws of physics are the same to all observers

Observable Consequences of STR

Simultaneity is a relative concept

Length contraction: moving rulers appear to be short

Time dilation: moving clocks appear to run slow

The apparent mass (inertia) of an object increases as its
speed increases (impossible to accelerate it up to c)

Equivalence of mass and energy: $E = m c^2$

Special relativistic effects are important when the
SPEED of an object is CLOSE TO THAT OF LIGHT: $v \sim c$

GENERAL THEORY OF RELATIVITY (GTR)

Principle of Equivalence

All objects experience the same motion in a given
gravitational field, irrespective of their mass

[Galileo’s experiment at the leaning tower of Pisa]

Gravitational field <===> Accelerated reference frame

Gravity can be thought of as a distortion of space-time

Observable Consequences of GTR

Perihelion precession of Mercury

Light bending: solar eclipse experiment

Gravitational lensing: multiple images, image distortion

Gravitational Redshift
[Extreme case: light is ‘trapped’ in a black hole]

General relativistic effects are important
in a STRONG GRAVITATIONAL FIELD

STARS & GAS - BUILDING BLOCKS OF THE GALAXY

Stars as Black Body Radiators

Hertzsprung-Russell diagram: Luminosity vs. Temperature

Radiation over a ‘continuous’ or broad range of frequencies (continuum radiation)

Gas Nebulae

Radiation at specific frequencies (line radiation)

Emission lines: from energetic atoms in gas cloud

Absorption lines: a gas cloud seen against the backdrop of a continuum radiation source

Line radiation from nebulae allows us to probe their physical conditions (composition, temperature, density)

Doppler shift of line radiation due to motion along the line of sight:

If the speed (v) is much smaller than the speed of light (c),

$$\Delta\lambda / \lambda = - \Delta\nu / \nu = v/c$$

where: $\Delta\lambda$ and $\Delta\nu$ are the changes in λ and ν, respectively

INTRODUCTION TO GALAXIES

Basic Structure

How densely packed are stars in a galaxy?

Size (diameter) of a typical star: 10^6 km

Distance between stars: 1 pc = 3 x 10^{13} km

[Analogy: marbles separated by 300 km!]

What fills in the space between stars?

[Interstellar medium: gas, dust]

Different Types of ‘Normal’ Galaxies

Spirals & irregulars (disk galaxies); ellipticals

Morphological (structural) features:

Disk, bulge, bulge+disk, presence/absence of central bar

Nature of kinematics (stellar motion):

Coherent rotation of stars in a disk; differential rotation

Random motion of stars in a bulge or elliptical

Hubble Sequence of Galaxies

Tuning fork diagram: E0-E7, S0, Sa-Sd / SBa-SBd, Irr

Morphological trends along the sequence:

Shape (how flattened?), bulge-to-disk ratio, spiral arms

Kinematical trends along the sequence:

Ellipticals: mostly random motion, hardly any rotation

Spirals: mostly rotation, hardly any random motion

Trends in the stellar mix:

Ellipticals: mostly cool (old) stars

Spirals: dominated by hot (young) stars

The ‘Local Group’ of Galaxies

Two large spirals:

Milky Way & Andromeda (Messier 31 or M31)

Distance between them: D = 700 kpc = 2.3 x 10^6 light yrs

Each has several smaller satellite galaxies around it:

Milky Way: Large Magellanic Cloud (LMC),
Small Magellanic Cloud (SMC), etc

Andromeda: Messier 32 (M32), NGC 205, etc

QUASARS, ACTIVE GALACTIC NUCLEI (AGN), AND BLACK HOLES

What is an ‘active galaxy’ or ‘quasar’ and how is it different from a ‘normal’ galaxy?

1. Much, much more luminous

2. Brightness varies rapidly with time
   [Implication: light emitting region must be small!]

3. Broad emission lines

4. Non-stellar radiation

5. Jets / radio lobes

Models of Active Galaxies (black holes)

- Black holes: Natural explanation of AGNs and quasars

- Definition of event horizon or Schwarzschild radius:

  $$R_{BH} = 2 G M / c^2$$

  [Characteristic size of region over which radiation is emitted is comparable to Schwarzschild radius of the central black hole]

- Rapid motion of material swirling into black hole

  - Large Doppler shifts

  - Efficient energy production

- Synchrotron radiation (mostly at radio wavelengths)

  - Charged particles spiral around magnetic field lines

- Jets and radio lobes

  - Two oppositely-directed rapid streams of material

  - Jets plough into intergalactic medium --> radio lobes

- Hawking radiation from a black hole:

  - Spontaneous pair production near event horizon

  - BH radiates like a black body: T proportional to $1/M$

  - Evaporation of BH: 1 M_{sun} BH lasts 10^{70} yrs!

INTRODUCTION TO COSMOLOGY

Expansion of the Universe

* Natural consequence of GTR field equations

* Einstein’s static solution: arbitrarily introduce cosmological constant Lambda (self-proclaimed "greatest blunder")

* Edwin Hubble’s observations of receding galaxies

* Hubble’s law $v=H_0 d$, H_0 is the Hubble constant ~ 70 km/s/Mpc

* Expansion of Universe is the expansion of space itself

* Observed redshift of distant galaxies --- wavelength of photons "stretched" by the expansion of space

* Not everything is expanding --- if it were, we couldn’t detect the expansion since our rulers would be expanding in proportion

The Big Bang

* Reverse extrapolation of Universal expansion: epoch if infinite density

and temperature

- NOT like an explosion; it happened everywhere!

- Universe has a finite age: t ~ 1/H_0

- Is the expansion slowing down? Gravity is expected to do that.

- Critical density rho_crit ~ 10^-30 g/cm^3. Actual density of the universe rho may or may not be equal to this. Omega def rho/rho_crit

- Determination of Omega a major goal of cosmology. Three methods:
  - Density of galaxies in the distant Universe
  - Measure the local density (via the gravity) of matter
  - Search for candidate dark matter particles

Alternative to the Big Bang: Steady State Cosmology

- Cosmological Principle: Universe is homogenous and isotropic --- the same everywhere in space.

- Perfect Cosmological Principle --- Universe the same at all _times_ also. Universe probably does not obey the Perfect Cosmological Principle

- Steady State theory proposed as alternative to Big Bang by Bondi, Gold, & Hoyle in 1940s. Theory is based on Perfect Cosmological Principle.

- Requires that galaxies constantly be created at the expense of energy out of the so-called C-field.

- Not widely believed; discovery of the Cosmic Microwave Background Radiation is considered definitive evidence against Steady State cosmology.

Olbers’ Paradox: Why is the Night Sky Dark?

- Assume uniform and infinite distribution of stars --- night sky should be infinitely bright, but is observed to be dark.

- Paradox phrased by Olbers in 1823, though already well known for about a hundred years.

- Stars are distributed over a finite volume (our Galaxy, for example) but the argument can be extended to the distribution of individual galaxies.

- Can absorption by dust in galaxies solve the paradox? NO! Dust would heat up and glow as a black body radiator.

- Universe has finite age t --> observable Universe has a horizon of distance ct. Finite size --- the most important factor in solving Olbers’ Paradox.

Cosmic Microwave Background Radiation (CMBR)

- Relic of the Big Bang predicted in late 1940s.

- Discovered by Penzias & Wilson in 1965; they won the Nobel Prize for the discovery.

- CMBR studied in much detail by satellites (COBE, WMAP)

- Radiation comes from era of decoupling of matter and radiation in the early Universe (˜ 10^6 year old) when neutral atoms first formed.

- CMBR very smooth --- photons from different directions have the same properties.

- Earth’s motion with respect to the CMBR is detectable --- one half of sky hotter by one part in 1000.

- Satellite observations detected tiny fluctuations in CMBR (one part in 10^6) that represent seeds of density fluctuations from which galaxies arose.

THE INFANCY OF OUR UNIVERSE

Major Epochs in the Early Universe

- $t<3\times10^5$ years: Universe radiation dominated
- $t<3\times10^5$ years: Univers matter dominated
- Why?
  - Let R be the scale length of the Universe (the separation between your favorite pair of galaxies, say).
  - Energy density of matter propto $1/R^3$ since volume propto R^3
  - Energy density of radiation propto $1/R^4$ since lambda "stretched out propto R. By Wien’s Law, T decreases as 1/R, and by the blackbody eqn. energy density decreases as T^4 propto $1/R^4$

Unification of Forces

- All four fundamental forces of Nature unified at $t<10^{-43}$ sec, the Planck time.
- Gravity ‘froze’ out separate from the other three forces at this time.
- Next the strong nuclear force froze out at $t=10^{-35}$ sec
- Weak and electromagnetic forces unified until $t=10^{-12}$ sec
  - Electroweak unification confirmed in the laboratory during the 1980s at CERN particle accelerator in Europe.

Baryon Asymmetry

- Extremely hot radiation in the few seconds after the Big Bang

- Very energetic photons --> contniuous interchange of radiation into matter and vice versa (via pair production and pair annihilation).

- Observable Universe is made up of mostly matter (as opposed to anti-matter)

- Implies a slight asymmetry between matter and anti-matter in the very early Universe (a little more matter than antimatter)

- This is referred to as the ‘baryon asymmetry’ of the Universe.

Confinement and Recombination

- Quarks are the basic particles that protons and neutrons are thought to be composed of.

- $t = 10^{-6}$ sec ($T = 10^{13}$ K), quarks were able to combine to form protons and neutrons --> the epoch of confinement.

* After t = 10^{13} sec or 3 x 10^5 years the temperature dropped to
T=3000 K

* Protons and electrons (and neutrons) were able to combine to form
neutral atoms.

* Matter and radiation practically ceased to interact with each other (i.e.,
the Universe became transparent to radiation).

* The epoch of decoupling of matter and radiation or the epoch of recombination.
* The Cosmic Microwave Background Radiation (CMBR) we observe today bears the
imprint of whatever fluctuations there were
in the density distribution of matter at the epoch of decoupling.

Big Bang Nucleosynthesis

* Almost all the hydrogen we see in the
present Universe was formed at the epoch of recombination

* Most of the light elements (helium, deuterium, lithium, etc.) were formed
shortly thereafter

* The efficiency with which these light elements were formed depends on what
the density of protons and neutrons was (baryonic matter).

* Studying the abundance of light elements (relative to hydrogen) is a good way
of determining the baryon content of the Universe.

* There is a fairly strong
indication that most of the matter in the Universe is non-baryonic, in
addition to being non-luminous.

The CMBR Horizon Problem

* The CMBR has the same properties in all directions.

* Consider two portions of the Universe from opposite ends of the sky.

* These two portions are within our observable Universe (horizon), but they
are outside each other’s horizons.

* Light has not yet had time to travel from one of these portions to the other.

* If they have never been in communication, how do they know to be at the same
temperature?

Inflation

* Very early phase of extremely rapid expansion (Guth, Linde, 1980s).

* During this inflationary phase, the Universe expands by a factor of
10^{50} in the time span t=10^{-35} sec to t=10^{-24} sec (!!!!).

* Inflationary phase is immediately after the epoch at which the strong
nuclear force froze out, and before the weak nuclear force and
electromagnetic force froze apart from each other.

* All of our observable Universe was an infinitesimally small volume

10^{50} x 10^{50} x 10^{50} = 10^{150} times smaller than we would have guessed from a simple extrapolation of the expansion we observe today.

Solving the Horizon Problem

* Two parts of the Universe on opposite sides of the sky _now_ outside each other’s horizons.

* Prior to inflationary epoch, these two patches would have been within each other’s horizons and therefore ‘known’ to acquire the same temperature.

* Inflation caused them to expand out of each other’s horizon.

* Inflation requires the universe to expand faster than the speed of light.

* Does not violate special relativity --- STR only applies in flat spacetime (i.e., in weak gravitational fields)

* Special relativity is a special case of General relativity; inflation does obey the equations of General relativity.

Inflation (continued)

* Why is the density of the present Universe so close to critical (or why is the geometry of the observable Universe so close to flat)?

* The scale of the observable Universe is much smaller than its ‘radius of curvature’.

* What causes the rapid expansion during the inflationary era?

* Inflation may be thought of as a phase transition in the Universe (as in a transition from a liquid to solid phase).

* The ‘latent heat’ in this phase transition builds up into an extremely high vacuum energy density, and this drives the expansion (analogous to the repulsive effect of Einstein’s cosmological constant \Lambda).

LARGE SCALE STRUCTURE

Galaxy Formation

* Collapse of an overdense region of space (gas and dark matter) under gravity.

* Disks can be produced as the cloud of material spins faster and faster as the collapse progresses.

* To conserve angular momentum, the spin speed must increase inversely proportional to the size of the cloud.

* Spiral galaxies --- contain much raw material (gas) for star formation and a large fraction of newborn stars. Ongoing star formation.

* Elliptical galaxies --- mostly formed their stars early, little or no

current star formation, very little gas or dust.

* Bulges of spiral galaxes are similar to elliptical galaxies.

* Ellipticals and spiral bulges thought to form by merging smaller galaxies; merging process results in disordered stellar orbits.

* Important distinction between stars and gas: gas is dissipative (clump of gas tends to drag surrounding material with it due to viscosity), stars are not.

Observation of Large Scale Structure

* Groups of galaxies: up to ~ 10, typical speeds 100-500 km/s, typical size up to 1 Mpc (i.e. Local Group)

* Clusters: few hundred galaxies, 500-2000 km/s, 10 Mpc (Virgo, Coma)

* Superclusters: few thousand galaxies, not necessarily gravitationally bound together, over 10 Mpc in size (Perseus-Pisces supercluster)

* Peculiar velocities --- velocity not associated with Universal expansion. "Fingers of God" effect.

Distribution and Properties of Stars in Galaxies

Disk Galaxies: Structural Components

* Flattened differentially rotating disk

* Dense centrally concentrated bulge with mostly disordered orbits

* Extended, not centrally concentrated, mostly dark halo.

* Bulge + Halo = Spheroid

Properties

* Bulge stars older on average than disk stars.

* Youngest disk stars lie in very thin plane.

* Older disk stars lie in a thick disk.

* Disk stars, particularly young ones, organized into spiral arms.

* Spiral density waves in the disk is the most successful explanation.

Globular Clusters

* Most galaxies, including our own, contain dense clusters of 10^3 -- 10^6 stars known as globular clusters.

* Observed distribution of globular clusters tells us that the Sun is NOT at the center of the Galaxy.

THE BIRTH AND LIFE-CYCLE OF STARS

A Star is Born!

* Giant molecular clouds: mostly of H_2, small amount of other molecules made of more complex elements

* dense cores can begin to collapse under their own gravitational attraction.

* As a cloud core collapses, the density and temperature of the gas increase --> more blackbody radiation.

* opacity --- the gas is not transparent to the radiation, and the radiation interacts with the gas particles exerting an outward pressure.

* The intense radiation from hot, young stars ionizes the gaseous interstellar medium surrounding it.

* The gravitational collapse is usually accompanied by the formation of an accretion disk and bi-polar jets of outflowing material.

* The remnants of an accretion disk can ultimately give rise to planets --- these disks are often referred to as protoplanetary disks.

* A protostar’s temperature and luminosity can be plotted on a Hertzsprung--Russel diagram or HR diagram.

* Protostars tend to become hotter but less luminous during the process of gravitational contraction; the decrease in luminosity is mostly a result of the protostar becoming smaller.

* The exact track in an HR diagram followed by a contracting protostar depends on its mass.

* These tracks are called Hayashi tracks, after the Japanese astrophysicist who first researched this problem.

The Properties of a Newborn Star

* The Zero Age Main Sequence (ZAMS) represents the onset of nuclear burning (fusion).

* The properties of a star on the ZAMS are primarily determined by its mass, somewhat dependent on composition (He and heavier elements)

* Can measure masses of stars if they happen to be part of a binary system.

* The classification of stars in an HR diagram by their spectral type (OBAFGKM) is a direct measure of their surface temperature.

* A study of the exact shape of the ZAMS in an HR diagram indicates that more massive stars have larger radii than less massive stars.

Evolution (Aging) of a Star

* A star remains on the main sequence as long as it is burning hydrogen (converting it to helium) in its center or core. A main sequence star is also called a dwarf.

* The time spent by a star on the main sequence (i.e., the time it takes to finish burning hydrogen in its core) depends on its mass.

* Stars like the Sun have main sequence lifetimes of several billion years. Less massive stars --- longer lifetimes; more massive stars --- shorter lifetimes (as short as a few million years).

* A given star spends most of its lifetime on the main sequence (main sequence lifetime ˜ total lifetime). Very rapid evolution beyond main sequence.

* Luminosity classes in an HR diagram (I through V) are based on the evolutionary phase of a star---whether it is a dwarf, subgiant, giant, or supergiant.

* Main sequence --> Subgiant/Red giant: From burning hydrogen in the core to burning hydrogen in a shell that surrounds an inert (i.e., non-burning) helium core.

* Red giant --> Horizontal Branch: Helium ignition (or helium flash) occurs at the tip of the red giant branch, after which the star burns helium in its core.

* Subsequent thermal pulses are associated with the burning of successively heavier elements (carbon, oxygen, etc.).

* The loosely bound outer material is ejected by radiation pressure driving a superwind.

* This is known as the planetary nebula phase of a star (actually, this phase has nothing to do with planet formation!).

STELLAR DEATH

White Dwarf Stars

* Low mass stars are unable to reach high enough temperatures to ignite elements heavier than carbon in their core --> become white dwarfs.

* Hot exposed core of an evolved low mass star.

* Supported by electron degeneracy pressure. This is the tendency of atoms to resist compression.

* The more massive a white dwarf, the smaller it is. A solar mass white dwarf is about the size of the Earth.

* As white dwarfs radiate energy, they become cooler and less luminous gradually fading into oblivion.

Neutron Stars & Pulsars

* Neutron stars are stellar cores that are more massive than the Chandrasekhar limit (1.44 M_sun).

* They are held up against their own

intense gravity by the tendency for neutrons to be incompressible (neutron degeneracy pressure).

* Their gravity is too strong to be supported by electron degeneracy pressure.

* The more massive a neutron star, the smaller it is. A 1.44 M_sun neutron star is only about 10 km in radius.

* Neutron stars contain strong magnetic fields.

* Charged particles moving in the neutron stars magnetic field emit synchrotron radiation at radio wavelengths.

* Most neutron stars spin rapidly, slowing down with age. As the radio emission is beamed towards us periodically, we see pulses of radiation. Such objects are called pulsars. Not all neutron stars are observable as pulsars.

* Pulsars were discovered by Anthony Hewish and Jocelyn Bell. Recently, Joe Taylor and Russel Hulse won a Nobel Prize for their study of pulsars.

* These objects act as cosmic clocks are are useful for probing the dynamics of stars.

Black Holes

* Stellar cores that are more massive than about 3 M_sun have too strong a gravitational field to be supported by even neutron degeneracy pressure --> black holes.

* The more massive a black hole, the larger its event horizon.

* Stellar mass black holes are detected via their X-ray radiation.

* A black hole accelerates its surrounding material (often gas from a binary companion) to very high speeds in an accretion disk.

* The heat generated by viscosity (friction) in this high speed gas produces X-rays.

* Some of this gas is ultimately swallowed by the black hole.

Supernovae

* In the process of the core of a massive star collapsing under its own gravity to come a neutron star (or black hole), the material in the outer envelope may be ejected in a spectacular explosion known as a supernova.

* Stars that are more massive than about 5 M_sun explode as supernovae.

* The explosion is associated with the production of neutrinos and with lots of radiation at all wavelengths. A typical supernova is comparable in brightness to an entire galaxy!

* The supernova blast wave results in a tangle of interstellar gas and dust that is called a supernova remnant.

THE INTERSTELLAR MEDIUM IN GALAXIES

Ionized Hydrogen (HII)

- While ionized hydrogen (protons, electrons) forms the majority of the ionized phase of the ISM, it also contains ionized forms of other elements: e.g., OII, OIII, CIV, MgII.

- Highest temperature and lowest density of the three gaseous phases (hot, tenuous phase of the ISM):
  T ~ 10^3 - 10^6 K; n ~ 10^{-5} - 10^{-3} atoms/cm^3

- Weak degree of concentration to the plane of the Galactic disk: scale height z is a few kpc. Also seen in dense knots known as "HII regions" marking areas of intense star formation activity. HII regions tend to lie along spiral arms.

- Radiation from hot, young stars causes the gas to be ionized. The cascade of electrons down atomic energy levels results in an emission line spectrum. Examples of emission lines in the ultraviolet and optical part of the electromagnetic spectrum include: Ly-\alpha (2->1; 1216 Angstrom), H-\alpha (3->2; 6563 Angstrom), H-\beta (4->2; 4861 Angstrom), OII (3727 Angstrom).

Atomic Hydrogen (HI)

- An atom of neutral hydrogen consists of an electron and a proton. The electron and proton can either spin in the same direction or in opposite directions, and the energy of the atom is slightly different in these two states. A transition between these two states is called a "hyperfine" or "spin-flip" transition and leads to the emission of a photon whose wavelength is 21 cm. This is in the radio part of the electromagnetic spectrum.

- Intermediate in temperature and density between the other two gaseous phases (warm, diffuse phase of the ISM):
  T ~ 10 - 100 K; n ~ 1 - 100 atoms/cm^3

- Moderate degree of concentration to the plane of the Galactic disk: scale height z ~ 100 pc - 1 kpc. Complicated spatial distribution consisting of clouds, filaments, bubbles, dense knots, etc.

Molecular Hydrogen (H_2)

- It is difficult (though not impossible) to detect molecular hydrogen directly. There are several other molecules that are usually found in molecular clouds: e.g., CO (carbon monoxide), HCHO (formaldehyde), CH_4 (methane), and even C_2 H_5 OH (ethyl alcohol). These molecules can be in various energy states due to the vibrations of their molecular bonds and due to their rotation. Transitions between vibrational and rotational energy states result in the emission or absorption of photons in the infrared and submillimeter parts of the electromagnetic spectrum, respectively.

- Lowest temperature and highest density of the three gaseous phases (cold, dense phase of the ISM):
  T ~ 10 K; n ~ 10^3 - 10^6 atoms/cm^3

- High degree of concentration to the plane of the Galactic disk: scale height $z < 100$ pc. Primarily confined to large and dense concentrations known as giant molecular clouds.

- Molecules are easily broken up by energetic photons (a process called photodissociation). They form in dense and dusty environments where they can be shielded from the radiation of nearby stars.

Dust Grains

- Solid particles of C (graphite, soot) and Fe & Mg silicates, often with mantles of water or CO_2 ice.

- Grain sizes range from about 1 μm (10^{-4} cm) down to a few tens of Angstroms (10^{-7} cm).

- Dust particles absorb and scatter some fraction of the incident radiation. The shorter the wavelength of the photon, the higher the efficiency of this process (and vice versa): i.e., ultraviolet photons are easily absorbed and scattered by dust, while infrared photons tend to pass right through. Stars appear fainter and redder when viewed through a dust cloud.

- The energy absorbed by dust grains causes them to be heated to $T \sim 15 - 50$ K. They are then capable of emitting black body radiation. Most of this energy comes out in the far infrared part of the electromagnetic spectrum ($\lambda_{peak} \gtrsim 100\ \mu$m).

DARK MATTER

What Do We Mean by the Term ‘‘Dark Matter’’?

- Includes any form of non-luminous or unseen matter - i.e., matter that does not emit any form of electromagnetic radiation.

- Often loosely used to include any matter from which we do not detect electromagnetic radiation.

- A planet reflects light but does not typically emit detectable amounts of radiation; therefore, planets should (and are) included in this category.

- Neutral hydrogen gas in the interstellar medium emits no optical light but does emit radiation at radio frequencies ($\lambda = 21$ cm) so is not considered dark matter.

- Dark matter makes its presence felt through its gravitational field (gravitational force or potential).

- The motion of stars and/or gas in a gravitional field or the effects of light bending in a gravitational field allow us to study the strength of the field, and thereby infer the amount of matter present.

- All forms of matter exert gravitational forces. Thus, the strength of a gravitational field tells us about both luminous and non-luminous forms of matter.

* The luminous form of matter emits radiation, of course, so we can (directly) tell how much of it there is.

* The term ‘missing matter’ was in fairly common use early on, but it is misleading because the matter really is there - it is not missing!

* There were also attempts by some scientists (Milgrom & collaborators) to see if a MOdified theory of Newtonian Dynamics (MOND) might explain the observed motion of stars without requiring dark matter.

* This theory made specific predictions which were not borne out by observation, and now is (almost) universally believed to be wrong.

Dark Matter in Galaxies

* The observed motion of stars near the Sun, specifically their motion along the direction perpendicular to the plane of the Galactic disk, indicates the presence of a certain amount of matter in the Solar neighborhood (or else the stars would no longer be confined to a thin disk).

* The stars that are actually seen in this region provide only a fraction of the required gravity. The required mass-to-light ratio is: M/L ~ 5 - 10 (M/L)_sun.

* This provides a lower limit to the amount of dark matter present in the Galaxy’s disk, and is called the Oort limit after the Dutch astronomer, Jan Oort, who first proposed and carried out this experiment.

* The shape of the rotation curve of spiral galaxies (rotation velocity as a function of radius) is a measure of how the density of matter within the galaxy is distributed as a function of radius.

* Most spirals are observed to have ‘flat’ rotation curves (v ~ constant) in their outer parts, which corresponds to an ‘isothermal’ density profile: \rho proportional to 1/R^2.

* The light distribution in galaxies, however, is observed to fall off more steeply towards increasing radii than this (roughly as 1/R^3).

* The inferred M/L of spiral galaxies is about 10 - 30 (M/L)_sun and the fraction of dark matter increases outwards (i.e., the dark matter is less centrally concentrated than the luminous matter).

* The speed at which stars move (on average) within an elliptical galaxy can be measured by its ‘velocity dispersion’ (or spread in velocity among the different stars relative to us) along the line of sight.

* The indication is that elliptical galaxies too contain dark matter (a somewhat higher proportion than spiral galaxies, in fact), with M/L ratios as high as 100 (M/L)_sun.

* This massive but mostly dark and relatively low central concentration component of galaxies is referred to as their dark halo.

Dark Matter in Groups and Clusters of Galaxies

* The typical speed of galaxies within a group or cluster, as measured by the velocity dispersion, indicates the strength of the gravitational field.

* The line-of-sight velocity dispersion of groups is in the range 100 - 500 km/s, while that of clusters is in the range 500 - 1500 km/s.

* The velocity dispersion and physical size (radius R) of a group or cluster can be used to determine its total matter content:
 M ~ {v^2} R / G.

* Most groups and clusters contain intergalactic (intragroup or intracluster) gas.

* This gas experiences the gravitational potential of the group/cluster, and the atoms comprising the gas are accelerated to very high speeds.

* In fact, the atoms become ionized and the resulting electrons and ions (mostly protons) move at speeds characteristic of a very high temperature gas (T ~ 10^6 K).

* This hot plasma emits black body (or thermal) radiation in the X-ray part of the electromagnetic spectrum. The more massive (and compact) the group or cluster, the higher the temperature of the X-ray radiation: T proportional to (M/R).

* The bending of light in the strong gravitational field of massive galaxy clusters causes distortions in the images of the more distant background galaxies (e.g., arcs, arclets, Einstein ring).

* The amount of distortion can be measured and used to determine the amount of mass present in the cluster.

* The above three methods of measuring the masses of groups and clusters are complementary to one another. They all indicate the presence of copious quantities of dark matter in groups/clusters, with M/L ~ 300 (M/L)_sun.

Dark Matter Candidates and Searches

* Understanding the nature of dark matter is critical since it appears to be the most common type of matter in the Universe.

* Astronomers measure the abundance of various light elements and relate this to the theory of nucleosynthesis in the early Universe in order to infer the amount of baryonic matter (i.e., normal matter consisting of protons, electrons, neutrons) present in the Universe.

* The amount of (baryonic) matter required to explain the products of nucleosynthesis is less than the amount of (total) matter required to explain the gravitational field in clusters of galaxies.

* Some fraction of the dark matter must be non-baryonic.

* The exact form in which non-baryonic dark matter exists is not known.

* Its form and nature determines how it responds to gravity and thus determines the exact way in which density perturbations (fluctuations)

‘grow’ in the early Universe.

* There is a variety of theories suggesting what
the nature of non-baryonic dark matter might be: ‘cold’ (massive and
relatively slow moving: e.g., axions), ‘hot’ (low mass and fast moving:
e.g., neutrinos with finite mass), or a mixture of the two.

* Several extensive searches are underway to look for the dark
matter that makes up the halo of our Galaxy.

* If this matter is in the form
of dense lumps (dubbed MACHOs for MAssive Compact Halo Objects), these lumps
can act as micro gravitational lenses.

* Such lenses should cause the
occasional apparent brightening of a background star for a brief period (days
or months) as the MACHO happens to line up with the background star.

* While
microlensing events have been observed, the number of MACHOs inferred from
such observations falls short of the number required to explain the shape of
the Galaxy’s rotation curve.

* If the dark matter is composed of tiny elementary particles
(e.g. massive neutrinos or Weakly Interacting Massive Particles), there
should be a number of particles rushing about in any given volume of the
Universe.

* There are many ongoing laboratory experiments designed to look
for such elementary particles.

* No definite candidates have been found so far.