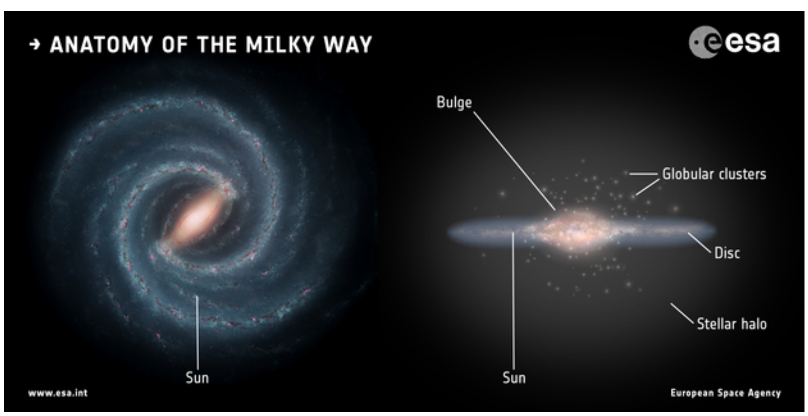
Use all available information to determine answers relating to ***quasars, AGNs, galaxy clusters, and groups of galaxies****, including star formation, massive and* ***supermassive*** *black holes, galactic structure, globular clusters, Type Ia and Type II supernovae, eclipsing binaries and X-ray binaries.*

Contents

1 Galactic Anatomy



1. the **bulge** is the huge, tightly packed group of stars found at the center of a spiral galaxy and as part of lenticular galaxies. there are generally considered to be 2 distinct kinds of bulges.

   (a) **classical bulges** have properties similar to elliptical galaxies.

   - comprised of older, redder, Population II stars.
   - take on a spherical form due to composite stars having orbits which are random in comparison to the plane of the galaxy.
   - no dust or gas → no star formation.

- the distribution of light is described by a Sersic profile.
- thought to be the results of smaller structures colliding, major mergers make gas clouds more likely to convert to stars.
- competing gravitational forces disrupt star orbit paths $\rightarrow$ random orbits.
- 80% of galaxies lack a classical bulge, indicating they have never experienced a major merger.
- $\frac{2}{3}$ of galaxies in dense galaxy clusters possess a classical bulge, which demonstrates the disruptive effect of their crowding.

(b) **disk-like bulges** have properties similar to the central regions of spiral galaxies. often referred to as pseudobulges or disky-bulges.

- the stars orbit in an ordered fashion in the same plane as the stars in the outer disk.
- these bulges have varied structures similar in appearance to spiral galaxies, but 2-100 times smaller.
- the rate at which new stars are formed in these bulges is similar to the rate at which stars form in disc galaxies. bulges may contain nuclear rings that are forming stars at much higher rate (per area) than is typically found in outer disks.
- theories regarding their formation are uncertain.
  - may be the result of gas-rich mergers which happened more recently (last 5 billion years) than classical bulges, but it is difficult for disks to survive mergers, making this doubtful.
  - disk galaxies can rearrange their stars and gas in response to instabilities (secular evolution). this process is believed to send gas and dust to the center of a galaxy, increasing the density and creating a bulge.

(c) most bulges and pseudo-bulges are thought to host a central relativistic compact mass, which is traditionally assumed to be a supermassive black hole.

- masses of the black holes correlate tightly with bulge properties.
- M-sigma relation relates black hole mass to the velocity dispersion of bulge stars
- total stellar mass
- luminosity
- central concentration of stars
- richness of the globular cluster system orbiting in the galaxy's far outskirts
- angle of spiral arms

2. the **disc** is a component of disc galaxies (spiral and lenticular). discs consist of 2 components. they tend to be flat, since the orbits of their components tend to be focused in 1 plane, with little vertical motion.

(a) the **stellar component** is composed of most of the galaxy's stars.

- tends to exhibit little random motions; stars undergo mostly circular orbits around the center.
- this leads to the formation of spiral arms in spiral galaxies.

(b) the **gaseous component** is composed mostly of cool gas and dust.

- majority of the gaseous component is cool atomic hydrogen (HI) and warm atomic hydrogen (HII). hydrogen is distributed fairly uniformly throughout the disc.
- gas serves as fuel for the formation of new stars in the disc.
- 21-cm emission by HI shows that the gaseous component can flare at the outer region of the galaxy.
- clumps or clouds of gas follow approximately circular orbits about the galactic center.
- circular velocity of the gas in the disc is strongly correlated with the luminosity of the galaxy (see Tully-Fisher Relation).

3. the **halo** is an extended, roughly spherical component of a galaxy which extends beyond the main, visible component. The distinction between the halo and the main body of the galaxy is clearest in spiral galaxies, where the spherical shape of the halo contrasts with the flat disc. In an elliptic al galaxy, there is no sharp transition between the other components of the galaxy and the halo.

(a) the **stellar halo** is the component of the halo containing the stars.

- typically contains oldest, most metal stars.
- since they are so faint, studying stellar halos requires very long exposure times.
- data from many galaxies must be combined to derive the average properties of a stellar halo. it is only possible to measure individual stars in the Andromeda and Milky Way galaxies.
- the furthest stellar halos detected are at a redshift distance of 1.
- it is thought that stellar halos consist both of natively created stars and stars obtained from satellite galaxies which merged. this results in streams of stars which are coherent in space or velocity due to being from the same galaxy, as well as variations in properties like metallicity across the halo as a whole.
- it is thought that the Milky Way's stellar halo contains 0.1-1% of its stellar mass.

(b) the **galactic corona** is the hot, ionized, gaseous component of the galactic halo.

- coronal gas may be sustained by the **galactic fountain** — superbubbles of ionized gas from supernova remnants expands vertically through galactic chimneys into the halo.
- as the gas cools, it is eventually pulled back into the disc.

(c) the **dark matter halo** is a hypothetical part of a galaxy which envelops the galactic disc and extends beyond the edge of the visible galaxy.

- the presence of dark matter is inferred from its gravitational effect.
  - w/o large amounts of mass throughout the halo, the rotational velocity of the galaxy would decrease the farther it is from the galactic center
  - however, the rotation curve of most spiral galaxies flattens out.
  - the absence of visible matter to account for this implies that unobserved, i.e. dark, matter causes it (or that general relativity is incomplete).
- dark matter halos are believed to have played a large role in the formation of the early universe.
  - during initial formation, the temperature of the baryonic matter should have still been too high for it to form gravitationally-bound objects alone → dark matter structures must have added additional gravitational force b/c dark matter is cold compared to baryonic matter.
  - hypothesis for CDM structure formation begins with density perturbations in the Universe that grow linearly until they reach a critical density, after which they would stop expanding and collapse to form gravitationally bound dark matter halos. These halos would continue to grow in mass (and size), either through accretion of material from their immediate neighborhood, or by merging with other halos.

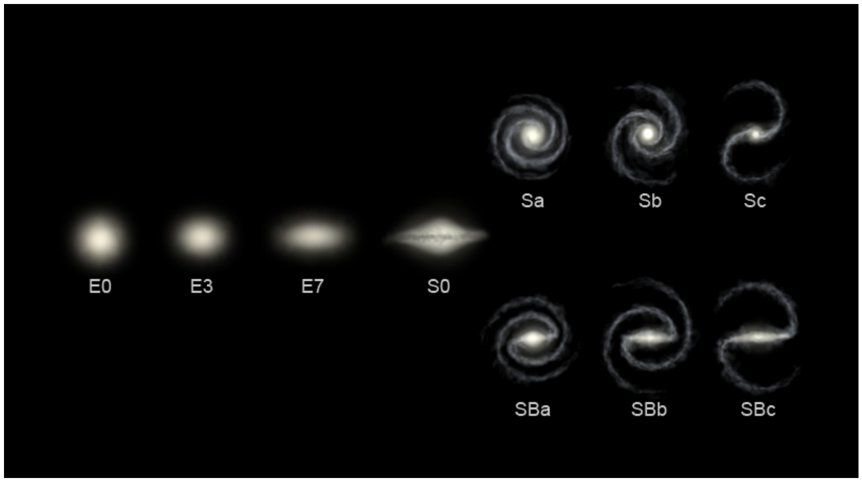
2 Properties of Galaxies

2.1 History

derived from the Greek *galaxias*, meaning milky.

2.2 Galaxy Morphological Classification

astronomers divide galaxies into groups based on their visual appearance. the most often used is the **Hubble sequence**, invented by Edwin Hubble in 1926.



2.2.1 Elliptical Galaxies

General Characteristics	• smooth, featureless image comprised of ovoid masses of stars attached by the gravitational attraction b/w them • no rotational axis — stars show wide range of orbital paths around center, primarily radial motion; slight uniformity is what determines overall shape of the galaxy
Stars	• ellipticals contain mostly **old stars** – more red in color – very little gas and dust hampers formation of new stars
Shapes and Sizes	• highest variability of all galaxy types: – wide range of masses — 10^5 to 10^{13} solar masses – wide range of sizes — observations showing that objects can have diameters of between 1 and 100 kiloparsecs (or 3260 to 326,000 light years) – wide range of brightnesses — some can be up to 10 times brighter than the brightest spirals. At the other end of the scale, the faintest ellipticals can be 1000 times less luminous than the faintest spirals • The Hubble classification of elliptical galaxies contains an integer, n that describes how elongated the galaxy image is. The classification is determined by the ratio of the major (a) to the minor (b) axes of the galaxy's isophotes*: $10 \times (1 - \frac{b}{a})$ • thus, a given elliptical galaxy can be classified as E_n, where an E_0 galaxy is spherical, and an E_7 galaxy is flat. this classification is dependent on the angle from which the galaxy is viewed and thus does not affect its physical properties, but is useful for describing how a galaxy appears through a telescope.

Evolution	• astronomers believe that elliptical galaxies form earlier than spiral galaxies, but they can still have quantities of gas and dust, and can still be very noisy in the radio spectrum. evidence has shown that a reasonable proportion (25%) of early-type (E, ES and S0) galaxies have residual gas reservoirs and low level star-formation. • evolve from the fusion of smaller, gravitationally bound galaxies which are of similar size • more commonly found around clusters and groups of galaxies due to forming from fusion. They are less frequently spotted in the early universe, which supports the idea that they evolved from the collisions that came later in the life of a galaxy. • A supermassive black hole is thought to lie at the center of these ancient galaxies. These gluttonous giants consume gas and dust, and may play a role in the slower growth of elliptical galaxies.

2.2.2 Dwarf Elliptical Galaxy

General Characteristics	elliptical galaxies that are smaller than ordinary elliptical galaxies. They are quite common in galaxy groups and clusters, and are usually companions to other galaxies. Low-luminosity elliptical galaxies are distinguished from late-type galaxies (spirals and irregulars) by their smooth surface-brightness profiles. Despite their name, dwarf ellipticals are not really fainter versions of true elliptical galaxies, but are structurally distinct.
Shapes and Sizes	Dwarf elliptical galaxies have blue absolute magnitudes* within the range $-18\text{mag} < M < -14$ mag, fainter than ordinary elliptical galaxies. Below luminosities of MB approx -18 the smooth-profile galaxies divide into two classes: compact galaxies with high central surface brightnesses (exemplified by M32), and diffuse galaxies with low central surface brightnesses (exemplified by the Local Group dwarf spheroidals). Typical dE's have masses of about one billion solar masses, or about 1/1000th that of a typical giant galaxy. They contain very little or no gas, which makes them different from dwarf irregular galaxies. Three relatively bright dE's are known in the Local Group: NGC 147, 185, and NGC 205, all companions of the Andromeda Galaxy. Hundreds of similar galaxies exist in the relatively nearby Virgo Cluster. **shell galaxy** — A shell galaxy is a type of elliptical galaxy where the stars in the galaxy's halo are arranged in concentric shells. About one-tenth of elliptical galaxies have a shell-like structure, which has never been observed in spiral galaxies. The shell-like structures are thought to develop when a larger galaxy absorbs a smaller companion galaxy. As the two galaxy centers approach, the centers start to oscillate around a center point, the oscillation creates gravitational ripples forming the shells of stars, similar to ripples spreading on water. For example, galaxy NGC 3923 has over twenty shells.

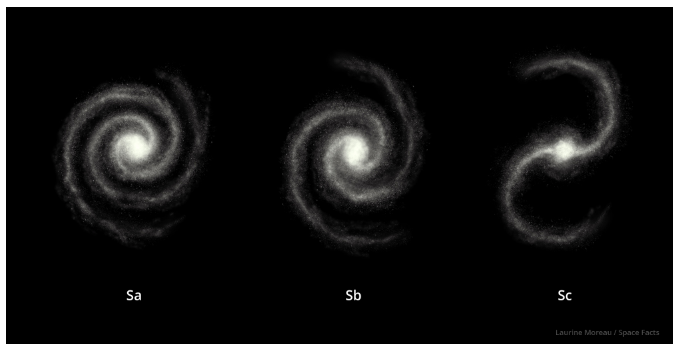
Evolution	• thought to be primordial objects built from the coalescing of dark matter and gas objects to form the building blocks of ordinary galaxies
	• alternately, they could be the remains of low-mass spiral galaxies that were transfigured into a rounder shape through repeated galaxy harassment* from ordinary galaxies within a cluster.
	  – evidence for the hypothesis had been claimed by studying early-type dwarf galaxies in the Virgo Cluster and finding structures, such as disks and spiral arms, which suggest they are former disk systems transformed by the above-mentioned interactions.
	  – however, the existence of similar structures in isolated early-type dwarf galaxies, such as LEDA 2108986, has undermined this hypothesis.

2.2.3 Spiral Galaxies

<table>
<tr>
<td>General Characteristics</td>
<td>Most spiral galaxies consist of a flat, rotating disk containing stars, gas and dust, and a central concentration of stars known as the bulge. These are often surrounded by a much fainter halo of stars, many of which reside in globular clusters*. Together with irregular galaxies, spiral galaxies make up approximately 60% of galaxies in today's universe. They are mostly found in low-density regions and are rare in the centers of galaxy clusters.</td>
</tr>
<tr>
<td>Shapes and Sizes</td>
<td>

Each spiral galaxy is classified with a label which gives some indication of its appearance:

S_a — tightly wound spiral arms w/ large central nuclei.
S_b — looser bound spiral arms w/ smaller central nuclei. the majority of spiral galaxies are of type S_b.
S_c — very open, "untidy" spiral arms and relatively small nuclei. often referred to as the "grand design."



$\frac{2}{3}$ spirals have an additional bar-like elongation of stars extending from the central bulge at the ends of which the spiral arms begin

the proportion of barred galaxies has changed over the history of the universe from 10% to the current amt
these are denoted by the additional label SB

bulge — a huge, tightly packed central group of stars, often defined as the excess of stellar light above the inward extrapolation of the outer (exponential) disk light. Many bulges are thought to host a supermassive black hole at their centers.

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</table>

Celestial Bodies	• The spiral arms are sites of ongoing star formation and are brighter than the surrounding disc because of the young, hot OB stars that inhabit them. Along with fully formed stars, we find sites of stellar formation, with hot glowing clouds of gas and dust forming the "stellar nurseries" which we see as nebulae in our own galaxy.
	  – S_c spirals have the highest proportions of gas and dust, some of which is heated by stars to form nebulae
	• Using the Hubble classification, the bulge of S_a galaxies is usually composed of Population II stars, that are old, red stars with low metal content. Further, the bulge of Sa and SBa galaxies tends to be large. In contrast, the bulges of S_c and SB_c galaxies are much smaller and are composed of young, blue Population I stars. Some bulges have similar properties to those of elliptical galaxies (scaled down to lower mass and luminosity); others simply appear as higher density centers of disks, with properties similar to disk galaxies.
	• most stars are located close to the galactic plane in conventional circular orbit around the center of the galaxy in a spheroidal bulge around the core
	• however, some stars inhabit a **spheroidal halo/galactic spheroid**, a type of galactic halo. The orbital behavior of these stars is disputed, but they may describe retrograde and/or highly inclined orbits, or not move in regular orbits at all. Halo stars may be acquired from small galaxies which fall into and merge with the spiral galaxy.
	  – Unlike the galactic disc, the halo seems to be free of dust, and in further contrast, stars in the galactic halo are of Population II, much older and with much lower metallicity than their Population I cousins in the galactic disc (but similar to those in the galactic bulge). The galactic halo also contains many globular clusters.
	  – The motion of halo stars does bring them through the disc on occasion, and a number of small red dwarfs close to the Sun are thought to belong to the galactic halo, and due to their irregular movement around the center of the galaxy, these stars often display unusually high proper motion.

Evolution	• the most prominent theory regarding the formation of the spiral arms is the **density wave theory** — stars move thru intermittent periods of great density as part of their orbital cycle which form spiral shapes
	  – the density wave rotates slower than the material in the galactic disc, so that stars and gas are able to "overtake" the wave
	  – as interstellar gas passes thru the density wave, it becomes more dense, leading to the formation of new stars
	  – the hottest stars live for a very short time, so they appear bright within the spiral arms during their lifetime, but as they pass out of the spirals and into the galactic disk, they die and become dim, explaining the contrast in brightness
	• the older stars of the bulge and halo are thought to have formed through the primordial collapse of individual gas clouds early in the history of the Universe
	  – bulges, especially those of S_c and S_d type galaxies, sometimes contain younger stars; after the spiral bulges of these galaxies had formed through primordial collapse, they also experienced some form of secular evolution — through accretion processes or the actions of spiral arms or a central bar
	• disks are thought to form after the primordial collapse event responsible for the formation of the spheroidal bulge and halo, possibly through the cooling of the hot gas contained within the halo of the newly formed galaxy. however, spiral galaxies have both thick disks (composed entirely of stars) and thin disks (also containing cold gas).
	  – on average, the thick disk is older than the thin disk but younger than the bulge. It has therefore been suggested that the thick disk may have formed through a significant merger event early in the Galaxy?s history. Both observations and N-body modelling indicate that such an event would disrupt the thin disk and consume a significant fraction of the cold gas in a burst of new star formation, so the proposed merger event must have taken place before the thin disk had time to fully form.
	  – An alternative to this major merger scenario is one in which the thick disk formed relatively slowly through the actions of multiple minor mergers. Once the merger events had formed the thick disk, the stars retained the scale height of the thick disk while the cold gas collapsed back into the galactic plane to form the thin disk.
	  – ongoing star formation takes place in the thin disk. This star formation is usually on the leading edge of the spiral arms where the cold gas of the thin disk is compressed.

2.2.4 Lenticular Galaxies

<table>
<tr><td>General Characteristics</td><td>a type of galaxy intermediate between an elliptical (denoted E) and a spiral galaxy in galaxy morphological classification schemes, they are also known as S_0 galaxies. they contain large discs but do not have large spiral arms; they are disc galaxies that have used up or lost most of their interstellar matter and therefore have very little ongoing star formation. however, they retain significant dust in their disks. As a result, they consist mainly of aging stars (like elliptical galaxies).</td></tr>
<tr><td>Shapes and Sizes</td><td>visible disk component w/ large bulge
much higher bulge-to-disk ratios than typical spirals
may exhibit central bar
lenticular galaxies can be classified according to the $S0_n$ and $SB0_n$ systems
in the $S0_n$ system, n indicates the amount of dust present
in the $SB0_n$ system, n indicates the prominence of the bar. $SB0_1$ galaxies have the least defined bar structure and are only classified as having slightly enhanced surface brightness along opposite sides of the central bulge. The prominence of the bar increases with index number, thus $SB0_3$ galaxies have very well defined bars that can extend through the transition region between the bulge and disk.</td></tr>
<tr><td>Celestial Bodies</td><td>In many respects the composition of lenticular galaxies is like that of ellipticals. For example, they both consist of predominately older, hence redder, stars. All of their stars are thought to be older than about a billion years, in agreement with their offset from the Tully?Fisher relation. In addition to these general stellar attributes, globular clusters* are found more frequently in lenticular galaxies than in spiral galaxies of similar mass and luminosity. They also have little to no molecular gas (hence the lack of star formation) and no significant hydrogen α or 21-cm emission. Finally, unlike ellipticals, they may still possess significant dust.</td></tr>
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<tr>
<td>Evolution</td>
<td>

The absence of gas, presence of dust, lack of recent star formation, and rotational support are all attributes one might expect of a spiral galaxy which had used up all of its gas in the formation of stars
<ol type="a">
anemic* spiral galaxies are similar to lenticular galaxies if the spiral pattern were dispersed
according to the Tully-Fisher relation, spiral galaxies and lenticular galaxies have the same slope on the luminosity/absolute magnitude axis, but are offset by $\Delta I = 1.5$. This implies that lenticular galaxies were once spiral galaxies but are now dominated by old, red stars.

it has also been postulated that lenticular galaxies form from galaxy mergers.
<ol type="a">
lenticular galaxies typically have surface brightness much greater than other spiral classes. It is also thought that lenticular galaxies exhibit a larger bulge-to-disk ratio than spiral galaxies and this may be inconsistent with simple fading from a spiral. they also have an increased frequency of globular clusters*.
Mergers are unable to account for the offset from the Tully?Fisher relation without assuming that the merged galaxies were quite different from those we see today.
advanced models of the central bulge indicate that it is smaller, lessening the inconsistency.

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3 Globular Clusters

3.1 Composition

- a spherical collection of stars orbiting a galactic core as a satellite
- the force of gravity maintains the spherical shape and gives them a high stellar density towards their center
- hundreds of thousands of old, low-metal stars — there is no gas or dust, implying it was all turned into stars
  - Globular clusters can contain a high density of stars; on average about 0.4 stars per cubic parsec, increasing to 100 or 1000 stars per cubic parsec in the core of the cluster. The typical distance between stars in a globular cluster is about 1 light year.
  - normally Population II stars w/ low proportion of elements other than hydrogen or helium (i.e. low metallicity)
  - **Oosterhoff groups** — 2 populations of globular clusters
    - group 1 — "metal-rich," has a slightly stronger metallic spectral line
    - group 2 — "metal-poor," has a slightly weaker metallic spectral line w/ a slightly longer period of RR Lyrae variable stars
    - Many scenarios have been suggested to explain these subpopulations, including violent gas-rich galaxy mergers, the accretion of dwarf galaxies, and multiple phases of star formation in a single galaxy. In the Milky Way, the metal-poor clusters are associated with the halo and the metal-rich clusters with the bulge.
- the high star density leads to close interactions and near-collisions of stars often → exotic classes of stars are very common in globular clusters
  - e.g. blue stragglers, millisecond pulsars and low-mass X-ray binaries
  - searches for black holes in the center of globular clusters have demonstrated evidence for a new kind of black hole intermediate b/w the standard black hole and the supermassive. the mass of these intermediate black holes is proportionate the mass of the clusters.
  - however, this is disputed b/c the heaviest objects in globular clusters will migrate to the center due to the effects mass segregation*. therefore, the sharp increase in mass-to-light ratio toward the center of a cluster may be possible without the presence of a black hole.

3.2 Formation

- it remains uncertain whether the stars in a globular cluster form in a single generation or are spawned across multiple generations over a period of several hundred million years
- In many globular clusters, most of the stars are at approximately the same stage in stellar evolution, suggesting that they formed at about the same time. However, the star formation history varies from cluster to cluster, with some clusters showing distinct populations of stars.
- it is also theorized that globular clusters w/ variation in their star populations formed from the merging of multiple clusters, which is consistent w/ Hubble Telescope Observations of massive clusters of clusters in close proximity
- clusters typically arise in regions of efficient star formation w/ interstellar medium of a higher density than in normal star-forming regions
- Research indicates a correlation between the mass of a central supermassive black holes (SMBH) and the extent of the globular cluster systems of elliptical and lenticular galaxies. The mass of the SMBH in such a galaxy is often close to the combined mass of the galaxy's globular clusters.
- No known globular clusters display active star formation, which is consistent with the view that globular clusters are typically the oldest objects in the Galaxy, and were among the first collections of stars to form. Very large regions of star formation known as super star clusters, such as Westerlund 1 in the Milky Way, may be the precursors of globular clusters.

4 The Tully-Fisher Relation

- an empirical relationship between the mass or intrinsic luminosity of a spiral galaxy and its angular velocity or emission line width, first published in 1977 by astronomers R. Brent Tully and J. Richard Fisher.
- The luminosity is calculated by multiplying the galaxy's apparent brightness/magnitude by $4\pi d^2$, where d is its distance from us, and the spectral-line width is measured using long-slit spectroscopy.
- everal different forms of the TFR exist, depending on which precise measures of mass, luminosity or rotation velocity one takes it to relate. Tully and Fisher used optical luminosity, but subsequent work showed the relation to be tighter when defined using microwave to infrared (K band) radiation (a good proxy for stellar mass), and even tighter when luminosity is replaced by the galaxy's total baryonic mass (the sum of its mass in stars and gas). This latter form of the relation is known as the Baryonic Tully?Fisher relation (BTFR), and states that baryonic mass is proportional to velocity to the power of roughly 3.5?4.
- The TFR can be used to estimate the distance to spiral galaxies by allowing the luminosity of a galaxy to be derived from its directly measurable line width. The distance can then be found by comparing the luminosity to the apparent brightness. Thus the TFR constitutes a rung of the cosmic distance ladder, where it is calibrated using more direct distance measurement techniques and used in turn to calibrate methods extending to larger distance.
- In the dark matter p*aradigm, a galaxy's rotation velocity (and hence line width) is primarily determined by the mass of the dark matter halo in which it lives, making the TFR a manifestation of the connection between visible and dark matter mass. In Modified Newtonian Dynamics (MOND), the BTFR (with power-law index exactly 4) is a direct consequence of the gravitational force law effective at low acceleration.
- The analogues of the TFR for non-rotationally-supported galaxies, such as ellipticals, are known as the Faber-Jackson relation and the Fundamental Plane.

5 Supernovae

- massive stars or white dwarfs are destroyed as part of an explosion occurring during their last evolutionary stages of life
- material is expelled from the star at up to 300,000 km/s, 10% the speed of light
- the explosion creates a shock wave which sweeps up an expanding shell of gas and dust, creating a **supernova remnant**

5.1 Interstellar Impact

5.1.1 Heavy Elements (Supernova Nucleosynthesis)

- supernovae are the major source of elements heavier than nitrogen
  1. **nuclei up to ^{34}S** are produced by nuclear fusion
  2. **nuclei between ^{36}Ar and ^{56}Ni** are produced by silicon photodisintegration rearrangement and quasiequilibrium during silicon burning
  3. **nuclei of elements heavier than iron** are produced by the rapid capture of neutrons during the supernova's collapse
- most likely sites of the **r-process** — rapid capture of neutrons that occurs at high temperature and high density of neutrons, which produces unstable nuclei rich in neutrons which beta decay into more stable forms
  - accounts for half of all heavier isotopes of elements beyond iron

5.1.2 Stellar Evolution

- shockwaves created by the explosion sweep up surrounding interstellar medium during a 2 century phase
- the wave undergoes adiabatic expansion*, mixing w/ the interstellar medium for 10,000 years
- metals created by the supernovae enrich the molecular clouds where stars form → each successive generation of stellar formation has a more metal-rich composition
- kinetic energy from a supernova remnant may also trigger star formation by compressing dense molecular clouds in space

5.2 Supernova Taxonomy

supernovae are classified according to their light curves and absorption lines of the chemical elements appearing in their spectra. if a supernova's spectrum contains lines of hydrogen (the **Balmer series**), it is classified as Type II; otherwise, it is Type I.

5.2.1 Type Ia Supernovae

Type Ia supernovae present a singly ionized silicon (Si II) line at 615.0 nm (nanometers), near peak light. their progenitor stars are considered to be white dwarfs.

2 models for their formation exist:

1. the **single degenerate progenitor** model postulates that Type Ia supernovae form from close binary star systems and account for 20% of Type Ia supernovae
   (a) the larger, primary star evolves into a giant, expanding its envelope
   (b) the primary star spills gas onto the secondary star, engulfing it
   (c) during this shared-envelope phase, the secondary star and the core of the primary spiral toward each other
   (d) the gas forming the common envelope is ejected
   (e) the core of the primary star collapses and becomes a white dwarf
   (f) the companion star, now larger than the remaining core, swells and spills gas onto the white dwarf
   (g) the white dwarf's mass increases until it reaches the Chandrasekhar limit*, at which point the white dwarf's electron degeneracy pressure is unable to prevent collapse, and it explodes, ejecting the companion star
2. the **double degenerate progenitors** postulates that Type Ia supernovae form from the merger of 2 white dwarfs whose combined mass exceeds the Chandrasekhar limit*.
   (a) collisions occur b/w a binary star system or 2 binary systems containing white dwarfs.
   (b) the collision creates a binary system of 2 white dwarfs.
   (c) the orbit of the 2 stars decays and they merge through their shared envelopes.
   (d) the combined white dwarf's electron degeneracy pressure is unable to prevent collapse, and it explodes.
   (e) studies find that white dwarf mergers occur every 100 years in the Milky Way, matching the number of Type Ia supernovae.
   (f) observations from NASA telescopes rule out the possibility of existing supergiant or giant companion stars in the supernovae studied, whose outer shells would emit X-rays had they existed.

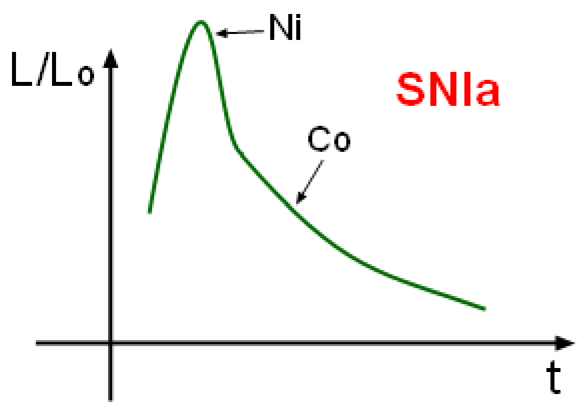
regarding the mechanics of the explosion:

- due to the accretion of material onto the white dwarf, increased pressure and density raise the temperature of the core
- when the star approaches 99% of the Chandrasekhar limit*, a 1,000 year period of convection begins

- a deflagration (layered burning) flame ignites, leading to carbon and oxygen fusion
- since white dwarfs depend on degeneracy pressure, which is independent of temperature, they are vulnerable to runaway fusion reactions → the carbon and oxygen quickly fuses into heavier elements, leading to a massive energy output which unbinds the star

Type Ia supernovae tend to appear in all types of galaxies, whether or not stellar formation is ongoing. this is because a system which has lived long enough to not only form white dwarfs but also transfer enough mass to explode is likely to migrate far from the regions where it formed.

Type Ia supernovae have a characteristic light curve*. near maximal luminosity, the spectrum contains lines of intermediate-mass elements from oxygen to calcium, since these comprise the outer layers of the star. some time afterward, when the outer layers have expanded enough to become transparent, the spectrum consists of heavy elements synthesized from materials near the core of the star. the peak is primarily powered by the decay of nickel, while the later stage is powered by cobalt.



5.2.2 Type II Supernovae

type II supernovae are distinguished from other supernovae by the presence of hydrogen in their spectra. their progenitor stars are much larger, at least 8 times but no more than 40-50 times, larger than the sun of the Milky Way.

the energy to create them is generated through nuclear fusion:

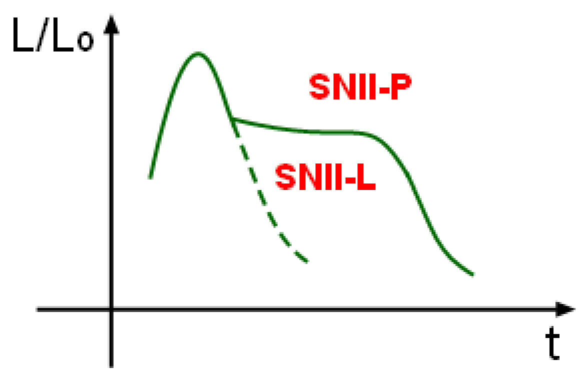
1. stars with great enough mass can fuse elements w/ atomic mass higher than hydrogen and helium (as opposed to our Sun).
2. the energy of the fusion reaction combined with electron degeneracy pressure maintains stellar equilibrium for a time.
3. eventually, fusion produces a core of iron and nickel.
4. fusion of these 2 elements produces no energy output, so the core becomes inert.
5. w/o energy to create thermal pressure, gravity causes the core to contract until it exceeds the Chandrasekhar limit*, leading to implosion of the inner core.
6. lacking the support of the collapsed inner core, gravity causes the outer core to collapse, increasing the temperature up to 100 billion kelvin. as the core's density increases, it becomes energetically favorable for electrosn and protons to merge.
7. neutrons and neutrinos are formed through beta-decay. neutrinos, which rarely interact w/ normal matter, escape from the core, carrying away energy which accelerates the collapse. some neutrino's are absorbed by the star's outer layer, beginning the explosion.
8. the resulting neutron degeneracy (neutron-neutron repulsive interactions) stops the collapse of the inner core, causing the implosion to rebound outward.

9. the shockwave output unbinds the star, leading to an explosion.
10. for a brief time, the high temperature and pressure allows for nucleosynthesis of elements heavier than iron.
11. depending on initial size of the star, the remnants of the core form a neutron star or a black hole.

type II supernovae are usually observed in the spiral arms of galaxies and in H II regions, but not in elliptical galaxies.

the light curve* of type II supernovae demonstrates a characteristic rise to peak luminosity followed by decline. the average decay rate of 0.008 magnitudes per day is much lower than the decay rate of type I supernovae. they can be separated into 2 categories.

1. the light curve* of a **type II-L** supernova shows a linear decline following peak luminosity. the net decay rate is 0.012 magnitudes/day. this is b/c most of the hydrogen envelope in the progenitor star has been expelled.
2. the light curve* of a **Type II-P** supernova shows a distinctive plateau during the decline where luminosity decreases at a slower rate. the net decay rate is 0.0075 magnitudes/day. this is because the progenitor star maintains its hydrogen envelope. when the shockwave oxidizes this hydrogen, it increases the opacity, preventing photons from the inner explosion from escaping. later, when it cools, the hydrogen recombines and becomes transparent once more.



Glossary

absolute magnitude a measure of the luminosity of a celestial object, on a logarithmic astronomical magnitude scale. An object's absolute magnitude is defined to be equal to the apparent magnitude that the object would have if it were viewed from a distance of exactly 10 parsecs (32.6 light-years), with no extinction (or dimming) of its light due to absorption by interstellar dust particles. By hypothetically placing all objects at a standard reference distance from the observer, their luminosities can be directly compared on a magnitude scale. 5, 16

adiabatic expansion a gas expands in the vacuum of outer space. without pressure for it to expand against, the total work done on or by the system is 0. 14, 16

Chandrasekhar limit the maximum mass of a stable white dwarf, above which electron degeneracy pressure in the star's core is insufficient to balance the star's own gravitational self-attraction. consequently, a white dwarf with a mass greater than the limit is subject to further gravitational collapse, evolving into a different type of stellar remnant, such as a neutron star or black hole. the currently accepted value of the Chandrasekhar limit is about 1.4 $M_{\odot}$ (2.765×10^{30} kg). 14–16

galactic plane the plane on which the majority of a disk-shaped galaxy's mass lies. The directions perpendicular to the galactic plane point to the galactic poles. 8, 16

galaxy harassment a type of interaction between a low-luminosity galaxy and a brighter one that takes place within rich galaxy clusters, such as Virgo and Coma, where galaxies are moving at high relative speeds and suffering frequent encounters with other systems of the cluster by the high galactic density of the latter. According to computer simulations, the interactions convert the affected galaxy disks into disturbed barred spiral galaxies and produces starbursts followed by, if more encounters occur, loss of angular momentum and heating of their gas. The result would be the conversion of (late type) low-luminosity spiral galaxies into dwarf spheroidals and dwarf ellipticals. 6, 16

globular cluster a spherical collection of stars that orbits a galactic core as a satellite. Globular clusters are very tightly bound by gravity, which gives them their spherical shapes and relatively high stellar densities toward their centers. they are found in the halo of the galaxy. Every galaxy of sufficient mass in the Local Group has an associated group of globular clusters, and almost every large galaxy surveyed has been found to possess a system of globular clusters. Although it appears that globular clusters contain some of the first stars to be produced in the galaxy, their origins and their role in galactic evolution are still unclear. It does appear clear that globular clusters are significantly different from dwarf elliptical galaxies and were formed as part of the star formation of the parent galaxy rather than as a separate galaxy. 7, 16

isophote a curve on an illuminated surface that connects points of equal brightness. In astronomy, the isophote is commonly used to define two things: the shape of an object, and the amount of light it gives off. The most common use of isophotes in astronomy is in the imaging and classification of galaxies, particularly of elliptical galaxies. The isophotes of elliptical galaxies provide information on a galaxy's shape, and hence upon its structure and dynamical behavior. Isophotes can be used on spiral galaxies, too, particularly to measure their radii, or to map the structures within their spiral arms. Isophotes are also used to measure the size, structure, and brightness of many gaseous or tenuous objects, such as X-ray galaxy clusters, radio jets from quasars, and the distribution of dust in our Galaxy. They have even been used to map the light reflected from the Moon and other planets to understand the properties of their surfaces. 4, 16

light curve the graph of a supernova's luminosity as a function of time after the explosion. 15, 16

mass segregation the process by which heavier members of a gravitationally bound system, such as a star cluster or cluster of galaxies, tend to move toward the center, while lighter members tend to move farther away from the center. 12, 16

open cluster a group of up to a few thousand stars that were formed from the same giant molecular cloud and have roughly the same age, found in the disk of a galaxyThey are loosely bound by mutual gravitational attraction and become disrupted by close encounters with other clusters and clouds of gas as they orbit the galactic center. This can result in a migration to the main body of the galaxy and a loss of cluster members through internal close encounters. Open clusters generally survive for a few hundred million years, with the most massive ones surviving for a few billion years. In contrast, the more massive globular clusters of stars exert a stronger gravitational attraction on their members, and can survive for longer. Open clusters have been found only in spiral and irregular galaxies, in which active star formation is occurring. 16