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.*

1 Properties of Galaxies

1.1 History

derived from the Greek *galaxias*, meaning milky.

1.2 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.

1.2.1 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.

1.2.2 Dwarf Elliptical Galaxy

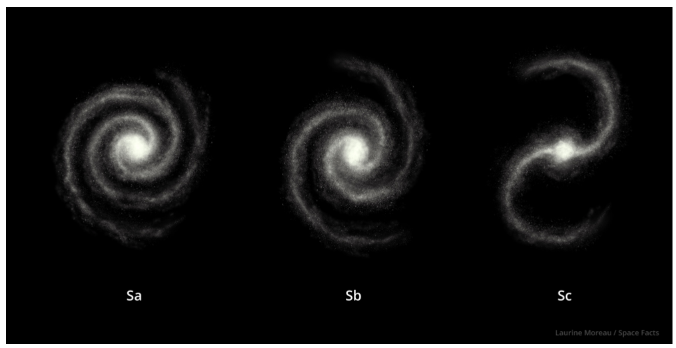
General Characteristics	elliptical galaxies that are smaller than ordinary elliptical galaxies. They are quite common in galaxy groups and clusters, and are usually companions to other galaxies. Low-luminosity elliptical galaxies are distinguished from late-type galaxies (spirals and irregulars) by their 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.

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.

1.2.3 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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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.

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. 2, 5

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. 4, 5

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. 2, 5

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. 3, 5

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. 1, 5

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. 5