Lecture 8: Spiral Structure
Spiral structure from stars and gas

- 1949 spiral structure first traced in Andromeda galaxy, M31 using OB stars and HII nebulae
- 1951 spiral structure first demonstrated in the Galaxy by Morgan, Osterbrock and Sharpless (Yerkes Observ.) using OB stars and young associations, and showing parts of three spiral arms
- The arms are:
  (a) the Perseus arm (~2 kpc out from Sun)
  (b) the Local or Orion arm (passing near Sun)
  (c) the Sagittarius arm (~2 kpc towards centre)
Young Population I objects define the location of the galactic spiral arms

The pitch angle is about 25° (angle between arm and a circle through the arm, centred on the galactic centre, G.C.)

Fig. 3.26. Above: Distribution of young open star clusters. (From Vogt and Moffat, 1975). Below: Distribution of associations. (From Humphreys, 1976)
• Our Galactic disk does not appear solid.
  • It has spiral arms, much like we see in other galaxies like M51
• These arms are not fixed strings of stars which revolve like the fins of a fan.
• They are caused by compression waves which propagate around the disk.
  • such waves increase the density of matter at their crests
  • we call them density waves
• They revolve at a different speed than individual star orbit the Galactic center
• Note how the spiral arms appear bluer compared to the bulge or the gaps between the arms.
Spiral Galaxy M83 observed in both visible light and radio wavelengths.
Spiral Arms

- The compression caused by density waves triggers star formation.
  - molecular clouds are concentrated in arms...plenty of source matter for stars
  - short-lived O & B stars delineate the arms and make them blue & bright
  - long-lived low-mass stars pass through several spiral arms in their orbits around the disk
Spiral structure

1- Spiral tracers
- Spiral tracers are objects that are commonly found in spiral arms and so are used to trace spiral structure.
- Photos in blue taken of nearby spiral galaxies such as M31 (Andromeda galaxy) show the bluish spiral arms distinctly. This appearance results from bluish supergiants, H II regions, and population I cepheids that lie in the spiral arms.
- How to apply these tracers to our Galaxy to determine the layout of its spiral arms near the sun? It’s not a simple operation!
- First, it requires an accurate and reliable technique for measuring the distance to each of the tracers.
- Second, the dust obscuration restricts optical observation of starlight.
- Third, the sun’s location in the plane gives us a poor vantage point for seeing the Galaxy’s spiral structure because we are forced to observe it edge-on rather than face-on.
• How cepheid variables have been used to delineate spiral features? The cepheids have the advantage that their distances are easy to determine by the period-luminosity relationship. This technique is so important that you should know how it works.

• A variable star is one whose luminosity changes with time. A light curve is a graph of the change in a star’s flux with time. A star whose light varies in a regular fashion is known as a periodic variable.

• In 1912 Henrietta S. Leavitt noted a number of cepheid variable stars in the Small Magellanic Cloud. At the time, the distance to this galaxy was not known, so Leavitt could not find out the luminosities of these stars. She did recognize that their periods were related to their average fluxes. Because these stars all lie at the same distance from the earth, their luminosities must be related to their periods. For the cepheid variable, Leavitt found that a special relationship, the period-luminosity relationship, connects the luminosity of a cepheid variable to its period. Basically, it states that the longer the period of light variation of a cepheid, the more luminous it is.
How to use the relationship to find distances to cepheids?

1- Find a cepheid (identifying it by its light curve)
2- Measure its period of light variation from peak to peak.
3- Find the star’s average luminosity from the period-luminosity relationship
4- Measure the star’s flux by telescopic observations.
5- Calculate its distance from the inverse-square law for light. You have the flux and luminosity, so you can find its distance.

![A Cepheid Variable](image)
السطوع (Luminosity)

يشم علماء الفلك مقدار الطاقة التي يطلقها جرم ما في الثانية بالسطوع ويرمز له بالرمز $L$.

لكي ندرك كيف يستطيع الفلكيين إجراء تلك القياسات يتعين أن ندرس أولًا العلاقة بين السطوع الظاهري $B$، ونرمز له بالرمز $(brightness)$، للجرم وبعده والذي تعرف بقانون التربيع العكسي.

قانون التربيع العكسي وقياس سطوع نجم

ينص قانون التربيع العكسي على أن السطوعية الظاهرية لجرم تتغير متناسبة عكسياً مع مربع بعده. الفوتونات التي تغادر منبع ضوئي كالنجوم تنتشر بالتساوي في جميع الاتجاهات. فإن عدد الفوتونات التي تمر عبر منطقة معينة يصبح أصغر كلما ازداد بعد المنبع ضوئي، تنتشر الفوتونات التي تصل إليه بصورة أوسع وبذلك يصل القليل منها إلى عينه، فييدوا المنبع أقل سطوعاً. إذا يبدو المنبع خافتاً لأن معظم ضوئه قد انتشر في اتجاهات لا تصل أبداً إلى عين الرأصد.

عند مسافة $d$ من منبع ضوئي ينتشر سطوع المنبع على كرة نصف قطرها $d$. يعطى سطح الكرة بالعلاقة $(4\pi d^2)$، وبذلك يكون اللمعان الظاهري $B$ الذي نرصده

$$B = \frac{L}{4\pi d^2}$$
A certain amount of light passes through 1 square.

Each square transmits $\frac{1}{4}$ of the light passed through the 1st square.

Each square transmits $\frac{1}{9}$ of the light passed through the 1st square.

3 light years

2 light years

1 light year

Light from a star spreads out following the inverse square law.
2- Optical map of spiral structure

The optical maps of spiral structure must be viewed with caution because interstellar dust restricts where and how far we can look from the sun and how well we can estimate distances to optical tracers. Dust decreases the measured flux, and we would estimate a larger distance than actual distance. It’s futile to draw a master map from optical data alone, which works out to distances of only some 15000 ly. Despite discord about details, most optical astronomers concur on at least three major arm segments spaced about 7000ly apart.

![Diagram of spiral structure with Sun's orbit and concentration of O and B stars](image)

The Galaxy appears to have a spiral structure with much irregularity in the general pattern, which may consist of two or four spiral arms – but we cannot tell for certain yet which is correct.
Young O,B Stars: delineate spiral arms

- most luminous stars around
- dust blocks more distant ones
- we live in the “Orion Arm”
3-Spiral structure from radio observations

- The prime drawback to optical mapping of the Galaxy is obscuration from interstellar dust. Radio observations do not have this handicap because dust does not stop radio waves.
- The 21-cm line from hydrogen, which comes from the concentrations of neutral hydrogen (H I) clouds in the spiral arms, is useful as a spiral tracer.
- The best radio tracer seems to be the carbon monoxide millimeter-line emission from giant molecular clouds (GMCs).
Radio observations of CO in dense molecular clouds provide an excellent tracer of the arms, and show an extension of the Sagittarius arm at about $l = 300^\circ$.

Radio observations can also be made of HII clouds, and this enables their locations to be mapped well beyond the limit of optical visibility.
Densities of HI and CO gas as function of distance from galactic centre. Note that HI extends out to ~16 kpc, but CO only to about 9 kpc, the distance of the Sun from centre.
Radio observations help map the galactic disk

- Looking for 21-cm wavelengths of light …

- emitted by interstellar hydrogen

- as we look along the disk of the Milky Way (from inside), we see 21-cm photons Doppler shifted varying amounts

- this allows the interstellar hydrogen to be mapped
Measuring Radial Velocity

- We can measure the Doppler shift of emission or absorption lines in the spectrum of an astronomical object.
- We can then calculate the velocity of the object in the direction either towards or away from Earth. (radial velocity)
Measuring Rotational Velocity

A spectral line from star A:
- Narrow spectral lines indicate that star A rotates slowly.

A spectral line from star B:
- Wide spectral lines indicate that star B rotates rapidly.

Slow rotation for star A:
- This light is slightly blueshifted.
- Approaching side.

Fast rotation for star B:
- This light is greatly blueshifted.
- Receding side.

This light is greatly redshifted.
- To Earth.
4- 21-cm Data and the spiral structure

- The transition from neutral hydrogen at 21 cm, combined with radial velocity variations from differential galactic rotation, allows us to deduce the spiral-arm-structure in the galactic plane.
- From the galactic rotation curve, the distance to concentrations of neutral hydrogen may be found from the observed Doppler-shifted 21 cm line profiles.
- The distance estimation by this method is based on two assumptions: (1) differential galactic rotation and (2) circular galactic orbits for the gas near the galactic plane.
This is one 21cm profile corresponds to the line of sight at l=48°, and it consists of three peaks at radial velocities of 55, 15 and -55 km/s. Clouds A, B, and C are moving away from the “recession” (R < R-sun), while cloud D is moving to the sun “approaching” (R > R-sun). Cloud A has the greatest angular speed and is moving fastest away from the Sun. A has higher density of hydrogen, so appears with the highest intensity. Clouds B and C are moving at about the same angular speed, greater than the Sun's angular speed. Cloud D is outside the solar distance, so has slower angular speed, and also has the lowest hydrogen density.
HI spiral arms in the outer Galaxy (and elsewhere)
A galactic plane 21-cm HI map is based on the Doppler shift of the HI clouds and the intensity of the emission from the clouds to locate the HI in the Galaxy.
A Map of the Milky Way Based on 21-cm wavelength light mapping

By combining 21cm data from both the northern and southern hemispheres, we can construct a schematic picture of the neutral hydrogen distribution in the spiral arms of our galaxy.

The spiral structure is poorly determined near $l = 0^\circ$ and $l = 180^\circ$, toward the galactic center and anti-center respectively.

Circularly orbiting hydrogen clouds in those directions should exhibit no radial velocity; hence, we cannot determine the distances to such clouds.
5- H II regions, OB associations and GMCs tracers

- The spiral arms include in addition to neutral hydrogen (H I), ionized hydrogen (H II).
- How H II regions form? Massive stars evolve very fast and may be seen as main sequence OB stars. The ultraviolet radiation from such stars ionizes the surrounding gas to form H II regions.
- H II regions and OB associations exciting them are population I objects and are tracers of spiral structure. The radio recombination lines from H II regions allow us to determine their radial velocities and also their distances. Such velocities can then be used in the same manner as the 21cm line velocities to delineate the spiral structure, making possible a more complete comparison (see Figure 20-7A).
- The spiral arm patterns delineated by H I and H II are roughly similar. On the large scale distribution, H II attains its greatest concentration closer to the galactic center than does H I.
- The best current tracers of spiral arms are the Giant Molecular Clouds (GMCs), from which massive stars are born. Their millimeter-line emission is Doppler shifted by radial motions, and so their locations can be determined in a way similar to that of H I (see Figure 20-7B).
We easily see these spiral arms because they contain numerous bright O and B stars which illuminate dust in the arms.

However, stars in total seem to be evenly distributed throughout the disk.
6- The evolution of spiral structure

- For years astronomers supposed that the spiral arms in our galaxy and others were material arms, a coherent bunch of objects (stars, nebulae, gas dust) somehow physically held together.
- Such a viewpoint faced hard two questions: What holds the material together? How does an arm persist for a long time? The answers proved the idea wrong!
- The windup problem: The persistence of an arm is a puzzle, because it should wind up. Why? Some parts of the arm rotate more slowly than others. After a few rotations of the Galaxy, the arms should have disappeared.
- Currently, there are two competing theories to explain the nature of galaxies: the density wave theory and the self-propagating star formation theory.

*Stars that start out in a straight line from the Galaxy’s center (a) would begin to show a spiral pattern (b) and (c), but after a few revolutions, the pattern would be lost (d).*
Self-propagating star formation and *spiral density waves* produce spiral arms
Density wave theory of spiral structure

- Differential rotation means spiral arms should be wound up tight and cease to exist in a few times $10^8$ years
- This fundamental problem can be overcome by the density wave theory of Lin and Shu (1969)
- The spiral arm pattern rotates as a solid body, i.e. $\omega_p = \text{constant}$, and at an angular velocity less than the stars and gas
  \[ \omega_p < \omega(R) \]
- The spiral arms are a wave travelling backwards through the disk material
The wind-up problem for differentially rotating spiral arms.

After a few rotations, the arms should be so tightly wound that in effect they can no longer be seen in spiral galaxies.

In practice they must therefore rotate as a solid body.

**FIGURE 14–9** The wind-up problem. Here are two hypothetical "spiral arms" made of six stars following Keplerian orbits. After two cycles, the arm configuration has disappeared into a tightly wound pattern.
• In the density-wave theory, gas and dust fall into the trailing edges of the arms, giving a high density there of gas and dust and dense molecular clouds, where star formation takes place. Young stellar objects, including OB stars emerge from the leading edges of the arms. This model is confirmed by observation.

• Pattern speed corresponds to one rotation of spiral arms in $400 \times 10^6$ years

• Lin-Shu density wave theory explains long stability and maintenance of spiral arms, but not their origin or formation
The Density-Wave model (theory)
- This model pictures spiral arms not as material arms at all but rather as the result of density waves moving through the Galaxy’s disk.
- The spiral structure of a galaxy is regarded as a wave pattern resulting from gravitational instabilities. The density wave moves through the stellar and interstellar material as a configuration whose shape stays fixed. It rotates at a speed less than that of the material speed of galactic rotation. This approach is called the density-wave model of spiral structure.
- These waves produce all the features of a spiral arm (young stars, H II regions, lanes of dust). None of these objects leave very long. As they die and the density wave moves on, new spiral-arm tracers are born from the interstellar medium at the new location of the wave.
- Individual objects revolve at the speed determined by their distance from the center, the wave pattern rotates with a constant angular speed and does not wind up.
- The density wave is a self-sustained phenomenon and is stable. The spiral pattern produced by the density wave is not tied to the matter but instead moves through it.
Suppose cars traveling on a long highway at a speed exceeding the speed limit. Also traveling along the road, at less than the speed limit, is a police car (car x) with its radar on. Observing from a helicopter high in the sky, we see the cars fairly evenly distributed along the highway except around the police car. For a short distance behind and in front on the police vehicle, the cars are bunched up. As a given car approaches the police car from behind, the car slows down, slowly passing the police car. Then when the driver feels that his car is safely in front of the police car, it again speeds up. As a result, there is constantly a high density of cars around the police car, even through the cars making up that group change all the time. The police car moves along, seeming to carry its high-density group along with it, in what we see from helicopter to a density wave.
• The theory holds that stars revolve around the Galaxy independent of the spiral arms and that the arms are simply areas where the density of gas is greater than other places. According to this theory, there are almost as many stars per unit volume between the arms as in the arms, but the arms contain more of the brightest stars and a higher density of gas and dust. The areas of denser gas move around the Galaxy in density waves, causing the formation of new stars and glowing emission nebulae.

• Density waves are common here on Earth, for every sound wave is a density wave, with regions of high and low density making up the wave. In a galaxy, the density wave consists of a region of gas and dust that is denser than normal, perhaps by 10% to 20%. The major difference between sound wave and density waves of a spiral galaxy is that in the atmosphere of Earth, a sound wave travels faster than the particles of the gas itself. However, in the near-vacuum of a galaxy, the wave travels more slowly than the particles. The gas and dust particles—as well as stars—catch the wave from behind and pass through it in much the same wave that cars in analogy passed through the density pulse around the police car.
Now recall that new stars are formed when interstellar clouds of gas collapses. The density wave theory holds that the trigger for this collapse is the wave. As interstellar clouds approach the density wave from behind, they are compresses and stars are formed. Although stars of all masses are formed along the edge of the density wave, the brightest, most massive stars have ended their lives before they pass far from this edge. This means that when we look at a spiral galaxy, the spiral arms are obvious to us because they are areas containing the bright stars.
• The buildup pressure and density heats up the gas suddenly so that a shock wave forms along the front of the density wave. This shock may initiate the collapse of the clouds to form giant molecular clouds complexes, which in turn form young stars and H II regions. Such squeezing also helps to make dust out of the gas, and a thin dust lane forms along the shock front. The compression of the interstellar medium by the density wave forms the features associated with a spiral arm.

• How well does the density-wave model describe the observed spiral structure? First, it outlines the grand scheme of two- and four armed spiral patterns that we observe in other galaxies and probably in our own. Second, it explains the persistence of the spiral arms in the face of galactic rotation. Third, it predicts the general features of a spiral arm. So the density-wave model succeeds fairly well in explaining the prominent features of number of points. It does not explain the origin of the density waves. Nor does it clearly work out what keeps them going (how the density wave is sustained through the life of the galaxy). As the density ripple through the interstellar medium, they lose energy and should dissipate in about $10^9$ years (computer simulations indicate that it would die out). As evidenced by the abundance of spiral galaxies, however, they must last longer than this. Some mechanism must keep supplying energy to maintain them.
Diagram of rotation curve and pattern speed
Arms move at circular velocity $\Theta_p = \omega_p R$
Material (stars and ISM) move at $\Theta(R)=\omega(R).R$
$\omega_p = \text{constant}; \omega(R) > \omega_p$
The self-propagating star formation theory

• According to the **self-propagating star formation** theory of galactic spiral arms, the triggers that start the collapse of the interstellar clouds are nearby supernovae explosions. Then, as the more massive stars finish their lives and become supernovae, they trigger more star formation, and so on. A simple analogy is a forest fire, with the flames jumping from one tree to the next. Thus, the formation of new stars is confined to areas where this process is taking place. Now differential rotation enters this picture. Computer analysis shows that at the rate at which massive stars would be formed, differential rotation would cause spiral arms to be formed and sustained.

• The self-propagating star formation model is able to explain how a spiral arm would begin, since the process stars with a single supernova. Computer simulations based on this model can reproduce the spiral structure of galaxies with poorly defined arms, but it is not successful in reproducing the structure observed in spiral galaxies with well-defined arms.

• The two theories we presented for the formation of spiral arms are very different. In the density wave theory the spiral arms cause star formation, while the opposite is true in the self-propagating star formation theory. It is probable that we need a combination of these two theories in order to explain the observations.