Astr 511: Galaxies as galaxies

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Lecture 10:

Dynamics IV: Dynamics of Disks, Spiral Structure, and Bars

Disk Dynamics and Spiral Structure

So far, we've studied the dynamics that helps explain morphology and kinematics of early type galaxies. In these explorations, we've modeled galaxies as spheroids or somewhat flattened axisymmetric, collisionless, systems. This has worked wonderfully in explaining the phenomenology of ETGs and providing some insight of the physics that underpins them.

However, we know that not all galaxies can be modeled as spheroids. A significant fraction (including the Milky Way) are characterized by (thin) disks and asymmetric features such as **spirals** and **bars**.

In this lecture, we'll examine the phenomoenology of these, mostly late type, galaxies and introduce the dynamical framework that allows us to understand them.

- Binney & Tremaine, §6.

Phenomenology of Spiral Structure

Messier 100 (Sbc)

– *European Southern Observatory*

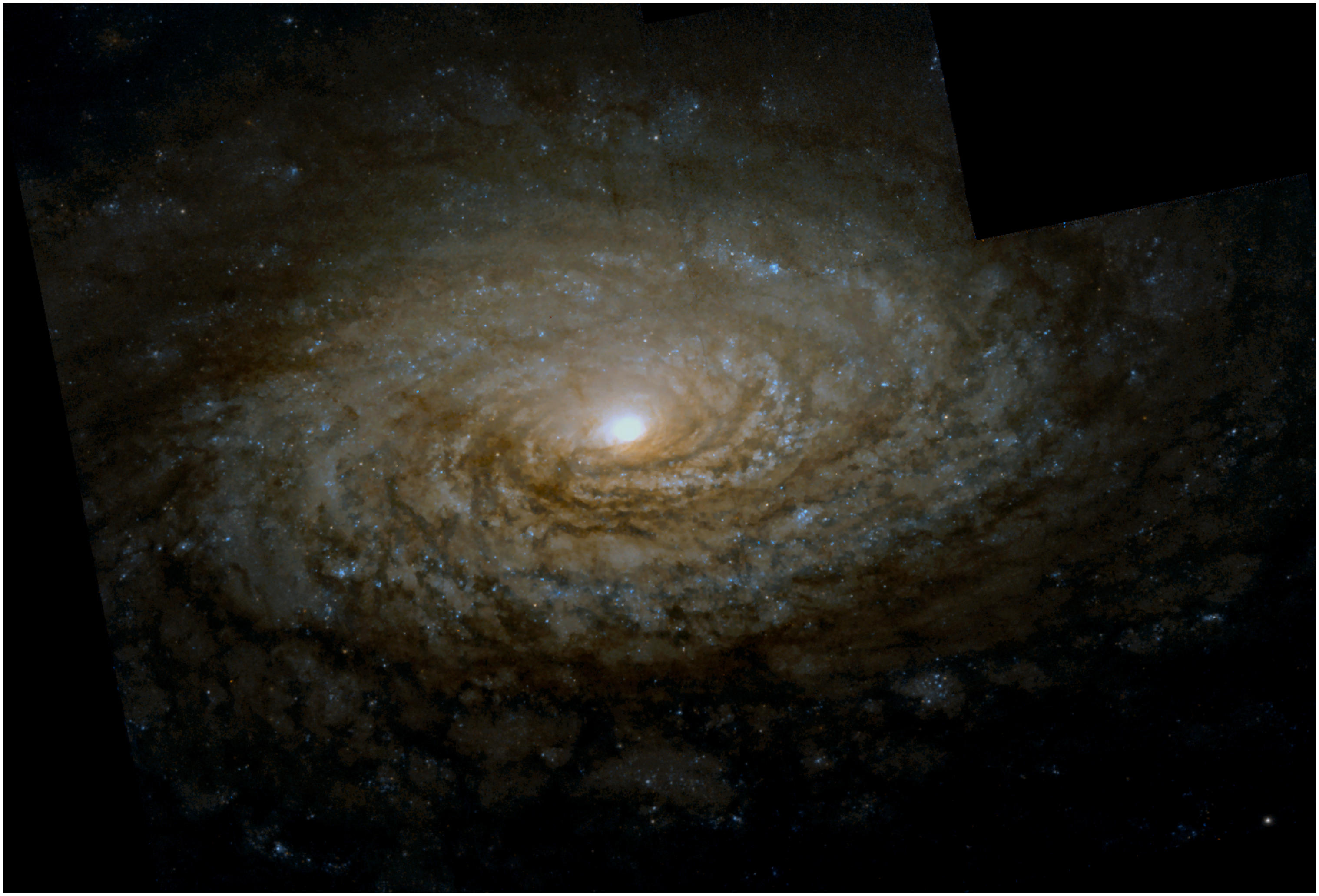
Messier 101 (Sc)

– *HST/STScI/NASA*

Messier 33 (Scd)

– *(c) Alexander Meleg*

Messier 63 (Scb)



– *HST/STScI/NASA*

NGC 1300 (Sb)

– HST/STScI/NASA

NGC 6745 (Irregular)

– *HST/STScI/NASA*

Grand-Design Spirals (M100, M51, M81, ...)

- Example: M100. Observed features: two major **spiral arms**, each of which can be traced nearly a full revolution. Thin dark stripes are *dust lanes*, that generally follow the spiral arms.

- This is an example of a **grand-design spiral** galaxy. **Their defining features are long, continous, symmetric, spiral arms**. Presumably, they have been formed by some large-scale process that involves the whole galaxy. Grand design spirals almost always have two main arms (two-fold symmetry).

- Note: grand-design spirals are actually *a minority* of all spiral galaxies ($\sim 10\%$); they are, however, very overrepresented in textbooks.

Intermediate-scale Spirals (M101, M33, MW, ...)

- Example: M101. Spiral arms still prominent and well-defined, but less regular than in grand design spirals. Arms can be traced by $\sim$half a revolution. Prominent dust lanes still present, with bright "knots" of star formation along the spiral arms.

- This is an example of **intermediate-scale spiral** structure. **The defining property is spiral structure that's still coherent over scales comparable to the galaxy size, but not over the whole galaxy**. In contrast to grand-design spirals, these don't give an impresson of being long lived.

- Another example: M33. The arms are less regular than in M101, but still satisfies the criteria for an intermediate-scale spiral. One of the nearest spiral galaxies.

Flocculent (fluffy) spirals (M63, NGC 4414, ...)

- Example: M63. Each spiral arm can be followed over only a small angle and the overall spiral pattern is composed of many patchy arms segments.

- This is an example of a **flocculent spiral galaxy**. **Their spiral structure is locallized, with many short, poorly defined, arms.**

- In galaxies like these, there's probably no (or very little) causal connection between the arms on the opposite sides of the galaxy. Their origin is likely to be *local*, rather than global.

- Note: the classification of spiral arms is independent of the Huble type. E.g., both M51 and M63 are classified as Sbc, though they significantly differ in appearance (Elmegreen & Elmegreen 1987)

Galaxies with bars (NGC 1300, NGC 1073, ...)

- Example: NGC 1300. The most striking feature is the **bar**, spanning almost the diameter of the galaxy. Two spiral arms are very symmetrical. They can be followed almost for a full circle (on deep images). This particular galaxy is a *grand-design spiral*.

- Note that there are sharp, straight, dust lanes spanning the length of the bar. The spiral arms start at the tips of the bar. At the start of each spiral arm, there is a cluster of HII regions (i.e., rapid star formation is occuring). **These are all common features in barred spiral galaxies.**

Irregulars (NGC 6745, ...)

- In the framework of Hubble classification, an *irregular* galaxy is a bit of a catch-all bin for anything that doesn't fit. In some cases we can still guess what is going on.

- Example: NGC 6745. This galaxy is lopsided and warped, exhibiting a tail of young, blue stars to the lower right. That said, the main body still shows some semblance of spiral structure.

- These features are likely a result of a recent encounter with a smaller galaxy (hiding in the bottom right). The tides inflicted by the small galaxy have compressed and shocked the ISM in NGC 6745, leading to a burst of star formation (including in the tail of stars pointing toward the "intruder").

Star formation in spiral arms

- In all the examples we've looked so far, the light in spirals is dominated by luminous, young, stars and HII regions.

- These massive stars typically live less than $\sim$ 10Myr (compared to typical orbital periods of $\sim$ 100Myr); i.e., they we can't be observing them far from where they were created.

- Therefore, **the star-formation rate (SFR) in the spiral arms must be much higher than in the rest of the disk**.

- This brings up an interesting question: **are spiral arms just areas of increased star formation** (as opposed to increase of overall stellar number density)?

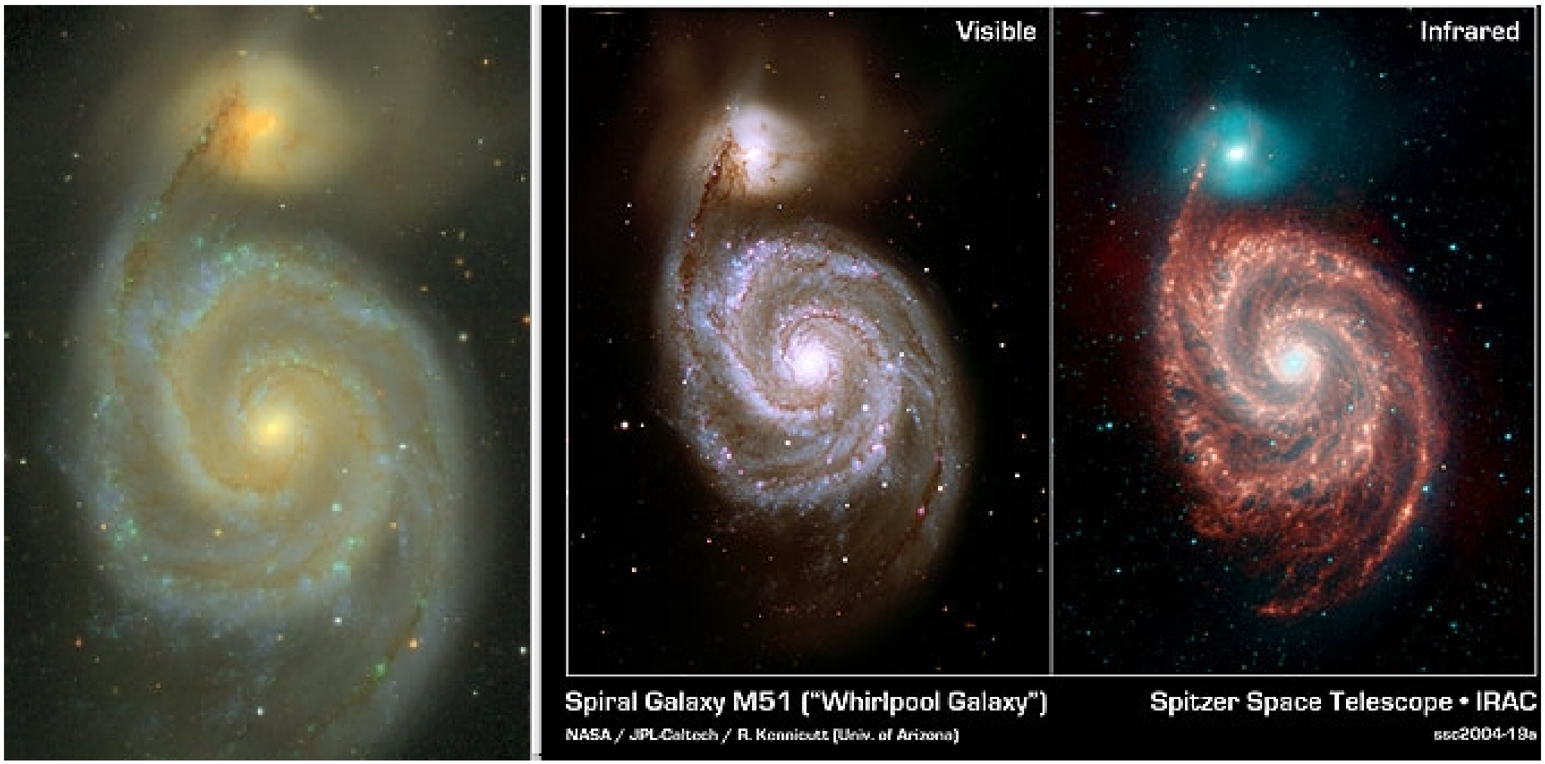
Multi-wavelength Observations of Spiral Arms

- Multi-wavelength observations give us further insight into the nature of spiral structure.

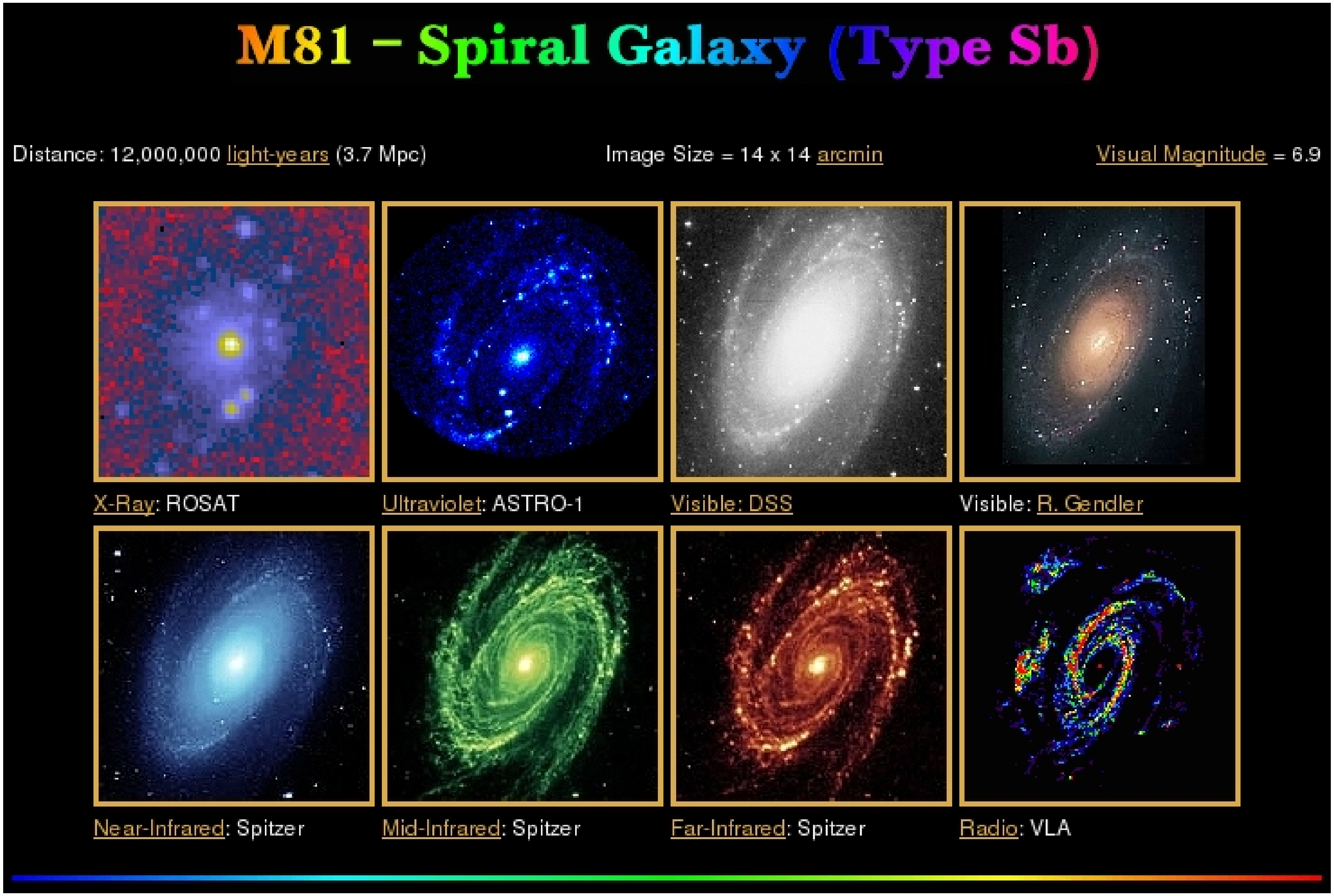
- **Visible** (blue) light is **dominated by young stars**, and it traces **star formation**. **Near-IR** light is **dominated by older populations** (giants), and it's a tracer of **mass**.

- Let's take a look...

M51 in the Visible and Near-IR



– *Spitzer/JPL Caltech/NASA*



– *Spitzer/IPAC/NASA*

Multi-wavelength Observations of Spiral Arms

- We find that **nearly all grand-design spirals are detectable in the near-IR** (e.g., Eskridge et al. 2002) as are galaxies with intermediate-scale spiral structure.

- This leads us to conclude that **the spiral pattern exists both in the surface density – the mass – as well as the star formation rate**. This is the strongest piece of evidence that spiral structure is a **density wave**.

- Also: Typically, the arm traced by the young stars is displaced slightly inside the old-star arm.

Floculent Spirals: Sheared patches of SFR

- What about floculent spirals? They do not exhibit equally noticable spiral structure in near-IR.

- This strongly points to their structure more likely to be **due to a local process**. The observations are consistent with **the floculent spiral structure arising due to patches of star formation, that have been sheared into a spiral on timescales comparable to lifetimes of the young stars** (Elmegreen & Elmegreen 1984; Thornley 1996).

- This would imply these spirals are **transient**, surviving on timescales of ~ 10Myr.

- These perturbations do not change the overall mass distribution within the disk of the galaxy.

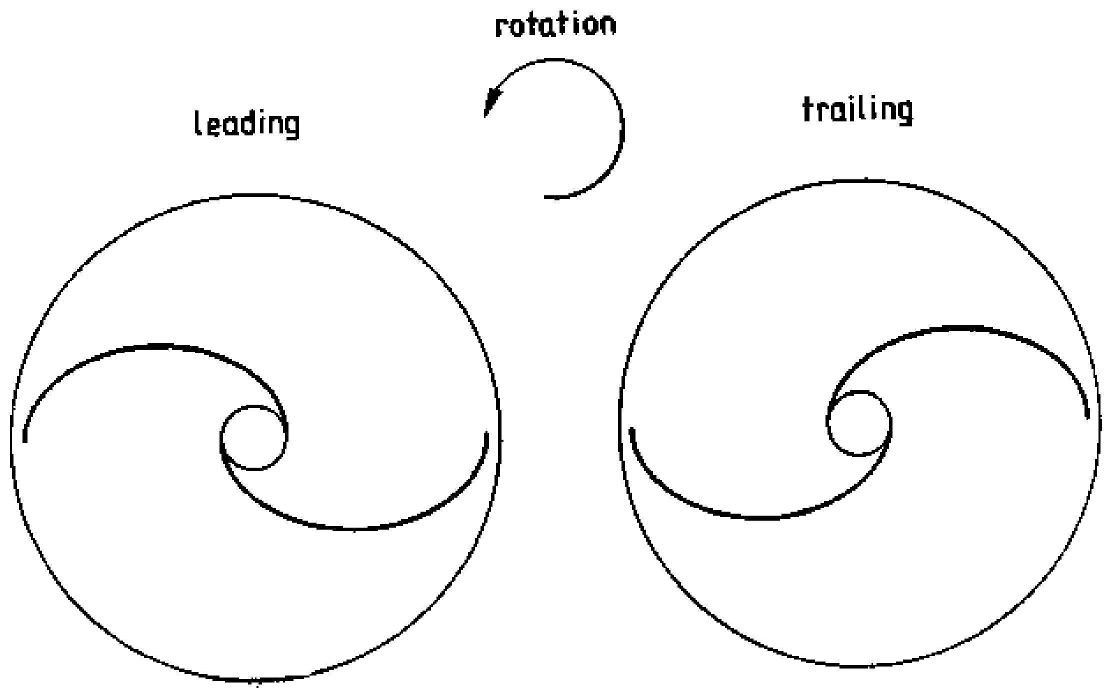
Spiral Structure with Other Tracers

- **Relativistic electrons** trace the spirals (inside the bright-star arm)
- **Molecular gas** (CO) traces the gas/dust arm
- **Neutral atomic gas** coincides with the spiral arms
- **HII regions** trace the bright-star spiral arms

Important observation: it's an observational fact that **spiral structure is present only in galaxies where there's gas**. So even though we see the spiral structure in overall (old-star) stellar density, **gas is somehow required for it to persist**.

Quantifying Spiral Structure

The Geometry of Spiral Structure



Definitions: an arm is **leading** if its outer tip points in the direction of rotation, and **trailing** otherwise.

It's not easy to tell a leading from a trailing arm; it's degenerate with galaxy inclination (see BT Fig 6.5). It's possible to break the degeneracy by observing dust-induced dimming; these kinds of observations reveal **nearly all spiral arms are trailing**.

Characterization of Spiral Structure

- The measures of symmetry (m) and amplitude (A_m) of spiral structure:

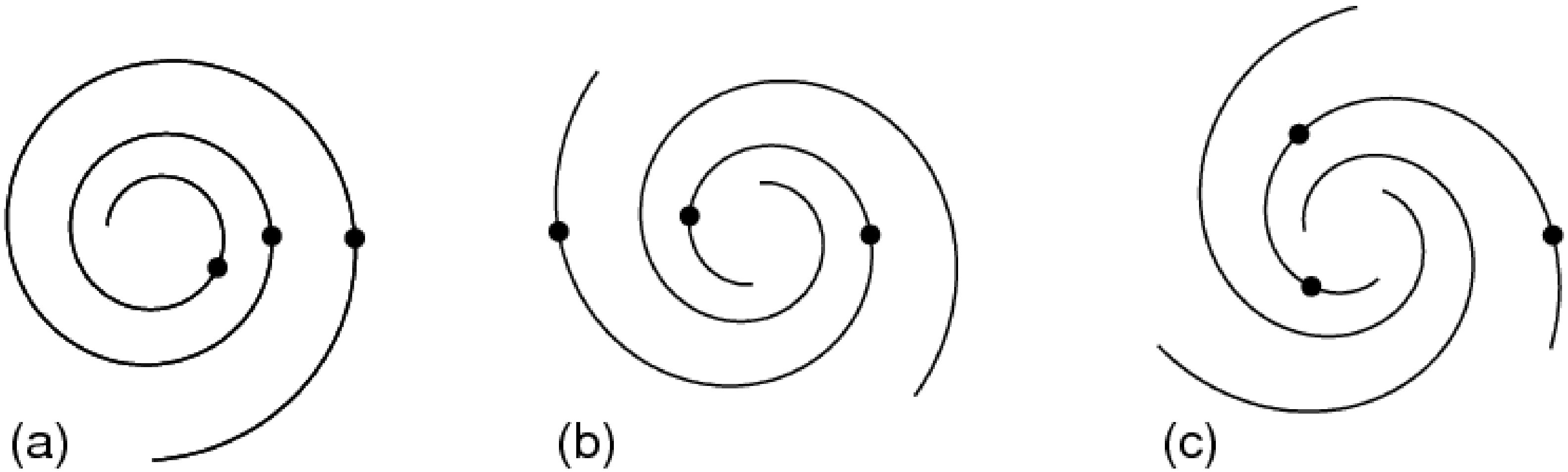
$$\frac{I(R,\phi)}{\bar{I}(R)} = 1 + \sum_{m=1}^{\infty} A_m(R) cos m[\phi - \phi_m(R)]; \quad A_m(R) > 0 \quad (1)$$

  where $\bar{I}(R)$ is the azimuthally averaged surface brightness at radius R and A_m and ϕ_m are the amplitude and phase of the mth Fourier component. If a particular mode m strongly dominates, the spiral is said to have m-fold rotational symmetry; m is **the number of arms**.

- If a single Fourier component m dominates, the **strength** of the spiral can be quantified as the arm-interarm surface-brightness ratio:

$$K = \frac{1 + A_m}{1 - A_m} \quad (2)$$

The Symmetry of Spiral Structure



Density waves with $m = 1$, $m = 2$ and $m = 3$ symmetry. Reproduced from Griv & Gedalin (2010).

Characterization of Spiral Structure

- The **pitch angle**, α, at any radius is the angle between the tangent to the arm, and the circle $R = constant$; by definition, $0 < \alpha < 90^\circ$.

  Related to the pitch angle is the **shape function** of a spiral wave:

  $$m\phi + f(R,t) = \text{constant} \pmod{2\pi} \tag{3}$$

  in a galaxy with m-fold symmetry. The pitch angle is then given by $\cot\alpha = |R\partial\phi/\partial R|$.

- It's also useful to introduce the **radial wavenumber**, k,

  $$k(R,t) \equiv \frac{\partial f(R,t)}{\partial R} \tag{4}$$

  Note that the sign of k determines whether the arms are leading ($k < 0$) or trailing ($k > 0$). With this definition, the pich angle is $\cot\alpha = |kR/m|$.

Characteristic Scales (Observational Facts)

- In grand-design spirals, we find $\mathbf{0.15 \lesssim A_2 \lesssim 0.6}$ (Rix & Zaritsky 1995),
- This corresponds to arm-interarm ratios of $\mathbf{1.4 \lesssim K \lesssim 4}$;
- In most grand-design spirals $m = 2$ **mode dominates** (though some show $m = 3$). $m = 2$ domination is an observational fact requiring a theoretical explanation;
- Significant fraction of galaxies is lopsided in the outer parts $\mathbf{A_1 \gtrsim 0.2}$ (Rix & Zaritsky 1995);
- Large majority of arms are **trailing**, and
- Characteristic pitch angles are in $\mathbf{10^\circ \lesssim \alpha \lesssim 15^\circ}$ range.

The Winding Problem

Let's conduct a thought experiment where we start a spiral arm that is a straight line at $t = 0$, and that rotates together with the disk:

$$\phi(R, t) = \phi_0 + \Omega(R)t \tag{5}$$

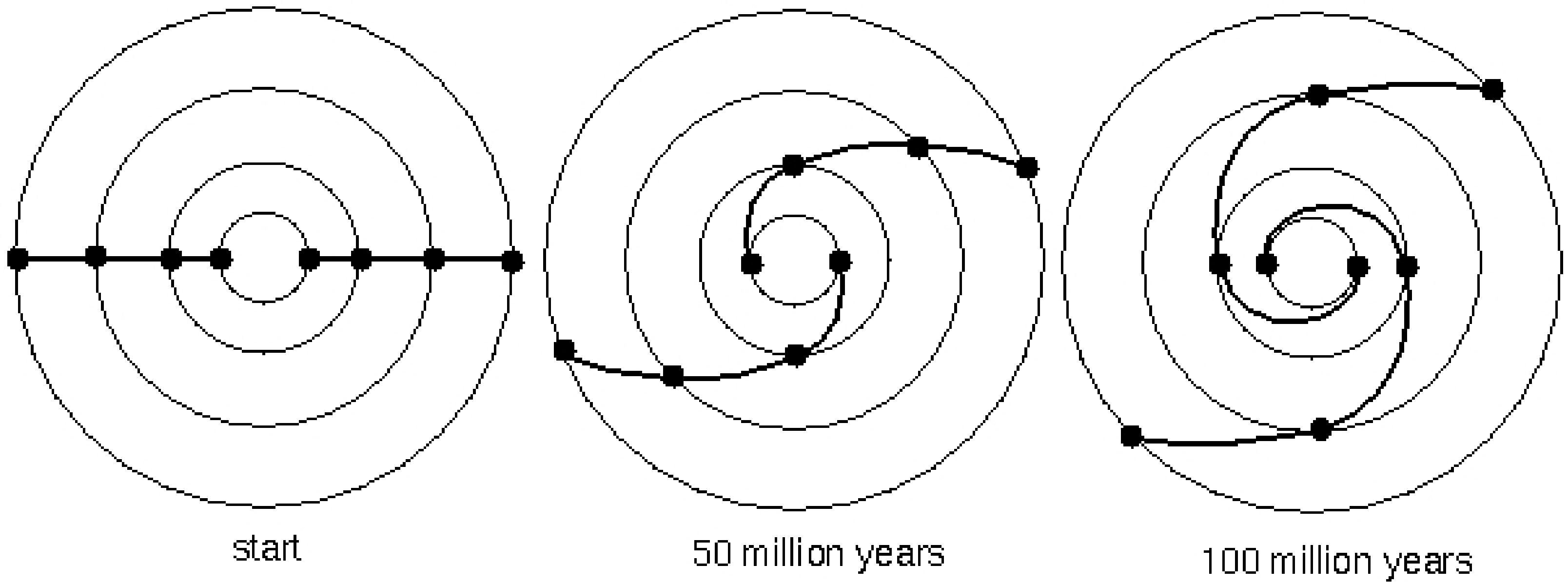
I.e., you can imagine we've "drawn" a line of O stars embedded in an otherwise FGKM-dominated disk. We let these revolve around the center.

The pitch angle will then evolve as:

$$\cot \alpha = Rt \left|\frac{d\Omega}{dR}\right| \tag{6}$$

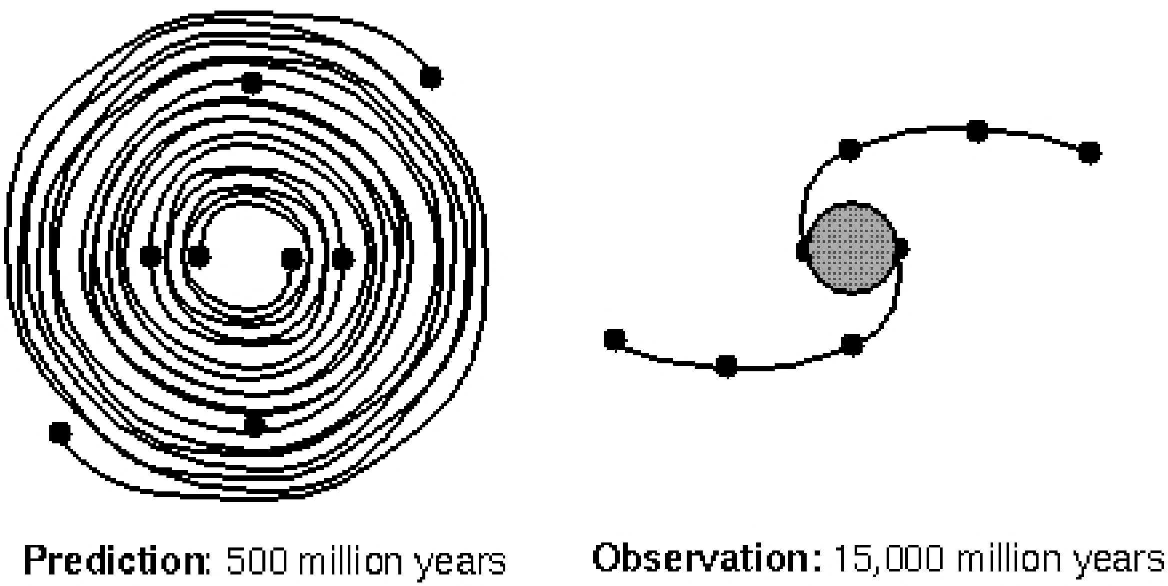
Taking a galaxy with a flat circular-speed curve, $R\Omega(R) = v_c =$ 200km/s, at $R = 5$kpc and $t = 10$Gyr, we find $\alpha = 0.14^\circ$, *far smaller than the observed pitch angles of* $\sim 10^\circ - 15^\circ$. This is the **winding problem** (Linblad 1925).

The Winding Problem



Differential rotation: stars near the center take less time to orbit the center than those farther from the center. Differential rotation can create a spiral pattern in the disk in a short time.

The Winding Problem



The Winding Problem: most spiral galaxies would be tightly wound by now, which is inconsistent with observations.

Implication: Spiral arms **cannot be a static structure** (i.e. **at different times, arms must be made of different stars**). If that's so, what are they?

Theories of Spiral Structure

Theories of Spiral Structure

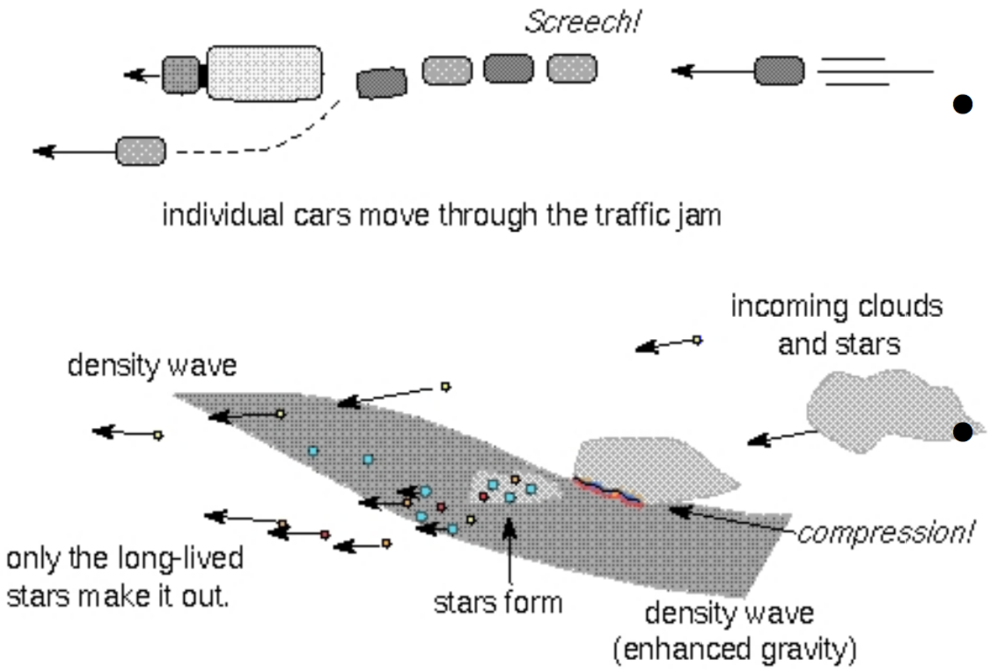
Despite 50 years of work, spirals are not fully understood. It seems clear now that the spiral structure of galaxies is a complex problem where details do not have a unique or tidy answer.

Differential rotation clearly plays a central role, as well as global instabilities, stochastic spirals, and the shocks patterns that can arise in shearing gas disks when forced by bars.

Despite that, the general picture is reasonably clear: the grand design and intermediate-scale spirals are explained by **density waves in stellar density and potential** (either stationary or transient, e.g., perhaps from a recent close encounter with a nearby galaxy), while **flocculent spirals arise due to shearing of localized patches of star formation**.

Density Wave theory

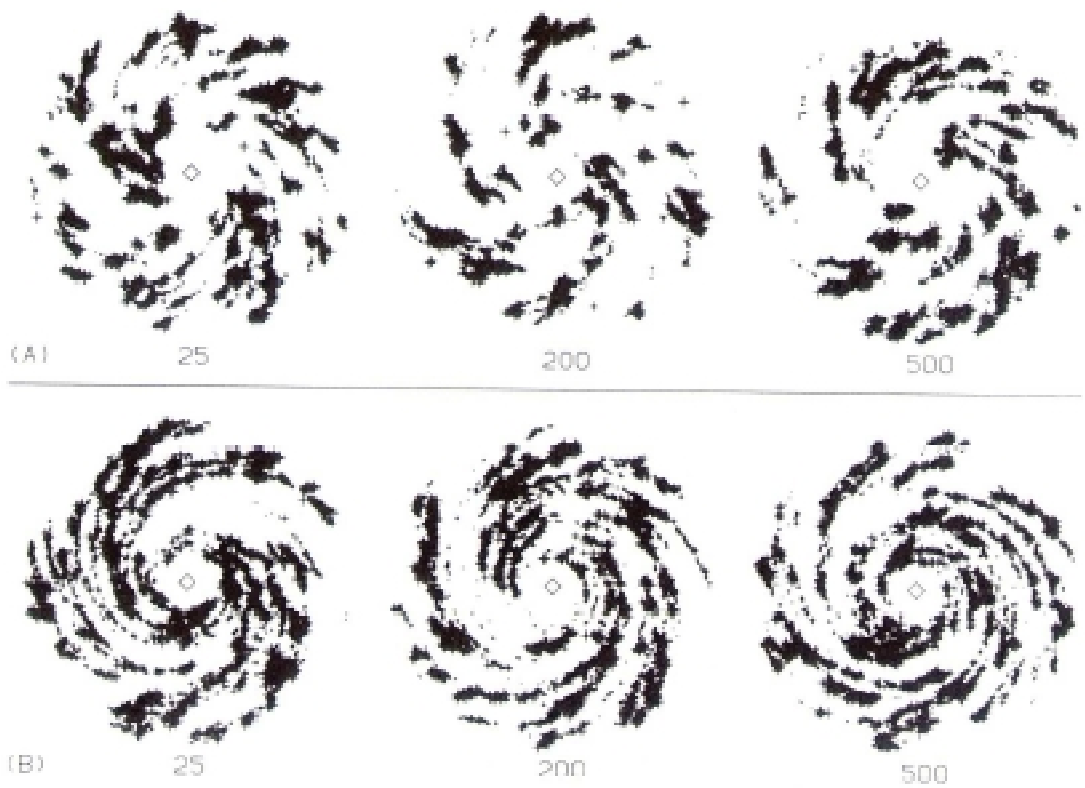
C.C. Lin & F. Shu (1964-66)



Spiral density waves are like traffic jams. Clouds and stars speed up to the density wave (are accelerated toward it) and are tugged backward as they leave, so they accumulate in the density wave (like cars bunching up behind a slower-moving vehicle). Clouds compress and form stars in the density wave, but only the fainter stars live long enough to make it out of the wave.

- This is the preferred model for grand design spirals.
- The spiral arms are over-dense regions which move around at a different speed than star: stars thus move in and out of the spiral arm
- How these density waves are set up is unclear, but it may have to do with interactions. Once they are set up, they must last for a long enough time to be consistent with the observed number of spiral galaxies

Stochastic Self-Propagating Star Formation



Numerical simulations of stochastic self-propagating star formation in spirals (Gerola & Seiden 1978, ApJ 223, 129). Originally roundish star formation regions get stretched out in differential rotation. Numbers give the time in units of 15 Mio. years, the upper panel is for the rotation curve of M101, the lower for M81.

Understanding Density Wave Theory

Let's develop a better understanding of how density waves come about:

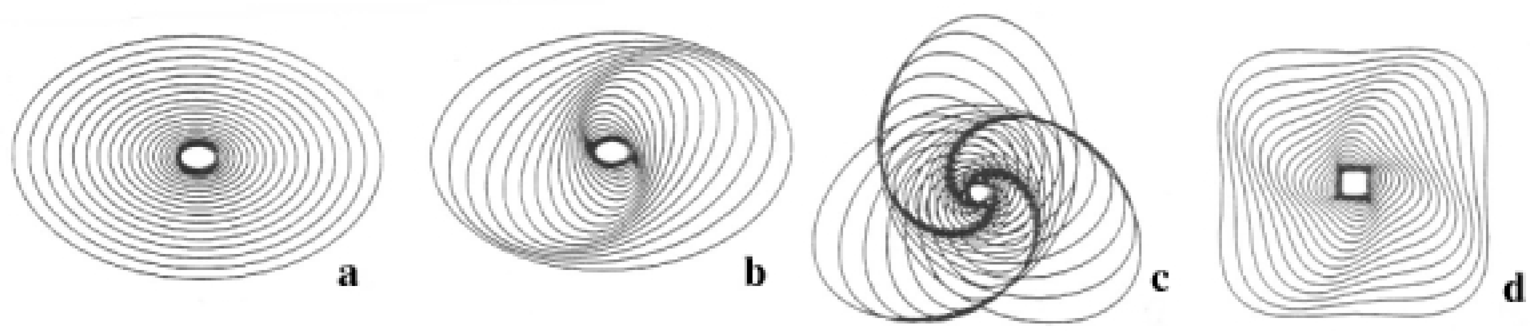
- Let's observe a galaxy from a rotating coordinate system which revolves at some speed, say Ω_p. *(we'll later identify this with the pattern speed of the spiral arms.)*

- For an axisymmetric disk with a flat rotation curve (a good first order approximation to the disk of a spiral galaxy), this rotation speed will match up with the rotation speed at some radius R. This is the corotation radius for pattern speed Ω_p.

- Particles inside this radius will appear to revolve in the direction of the frame rotation (prograde). Outside this corotation radius, they will be retrograde.

Kinematic Density Waves

If orbits in a galaxy are cleverly oriented, they can **generate spiral- and bar-like patterns**:



a) a bar can be produced by aligning a series of concentric elliptical orbits **b)** if each ellipse is given an azimuthal offset proportional to $\sqrt{R}$, the effect is a two-armed spiral **c)** a set of 3/2 orbits produces a three armed spiral **d)** a set of 4/1 orbits produces a four armed pattern

Kinematic density waves

- The above result shows how we can set up arrangements of orbits in a disk galaxy that results in bar- or spiral-like **density waves**. We call these **kinematic** because they only involve the kinematics of orbits in an axisymmetric potential.

- When the majority of the stars are arranged in these patterns, the mass asymmetry will begin to affect the overall potential. The stars will begin to deviate from these orbits.

- A **major goal of spiral-structure theory** is to **determine whether the non-axisymmetric potential due to to the spiral itself can** "coordinate" the orientations and drift rates of orbits in such a way as to **produce long-lived, self-sustaining, spiral patterns**

- Question: can perturbations generate/sustain spiral density waves?

Stability of Differentially Rotating Disks

This is not an easy question to answer in general. It's an impossible one to answer analytically, without resorting to approximations.

One approximation where a solution can be found analytically is one where the (spiral) density waves are tightly wound (their radial wavelength is much less than the radius; $\Delta R \ll R$).

When that's the case, the long-range coupling is shown to be negligible, therefore the response is determined locally, and the relevant solutions turn out to be analytic.

This is called **tight-winding, short-wavelength, approximation**. It's also known as the WKB approximation, by analogy with a mathematically similar procedure in quantum mechanics.

You can follow the details in Binney & Tremaine, §6; here, we will only confine ourselves to final results and qualitative comments.

Stability of Differentially Rotating Disks

BT show how to derive the dispersion relation for **spiral density waves in gaseous disks** (i.e., disks possessing an equation of state) in the tight-winding limit:

$$(m\Omega - \omega)^2 = \kappa^2 - 2\pi G\Sigma|k| + k^2 v_s^2 \tag{7}$$

.

An **analogous relation for stellar disks is**:

$$(m\Omega - \omega)^2 = \kappa^2 - 2\pi G\Sigma|k|F[(m\Omega - \omega)/\kappa, k\sigma_R/\kappa] \tag{8}$$

where function F is defined in BT (eq.6-63).

Stability of Differentially Rotating Disks

What does this mean? Remember that the dispersion relation tells us about the response of a system to plane wave perturbations of the form:

$$\Sigma(R,\phi,t) \propto e^{i[m\phi+f(R,t)]} \tag{9}$$

For a given wavenumber k, ω is **the frequency at which the plane wave will oscillate**. However, if $\omega^2 < 1$, the resulting frequency is *imaginary*, "oscillations" are exponential, and **the system unstable to perturbations at that k.**

This gives us a way to explore the stability of galactic disks to density perturbations.

Stability Criterion (Toomre's Q)

Consider an axially symmetric perturbation in a uniformly rotating ($\kappa = 2\Omega$) gaseous disk ($m = 0$). The dispersion relation reduces to:

$$\omega^2 = 4\Omega^2 - 2\pi G\Sigma|k| + k^2 v_s^2 \tag{10}$$

This will be unstable if $\omega < 0$. If also $\Omega = 0$ (non-rotating potential), then disk is unstable if

$$|k| < k_J \equiv \frac{2\pi G\Sigma}{v_s^2} \tag{11}$$

k_J can be though of as the *Jeans wavenumber* for the gaseous sheet; it defines the wavelength – the scale – at which the sheet will fragment and collapse. Note how rotation helps to keep disk stable.

Stability Criterion (Toomre's Q)

The equivalent in stellar disks results in a relation first derived by (Alar) Toomre (1964). Toomre's local stability criterion for stellar disks is:

$$Q \equiv \frac{\sigma_R \kappa}{3.36 G \Sigma} > 1 \tag{12}$$

When $Q > 1$, the stellar disk is resillient to perturbations (it will "bounce back"). When $Q < 1$, the disk will collapse and fragment when perturbed.

It's interesting to note that MW disk is marginally stable.

Toomre's Q

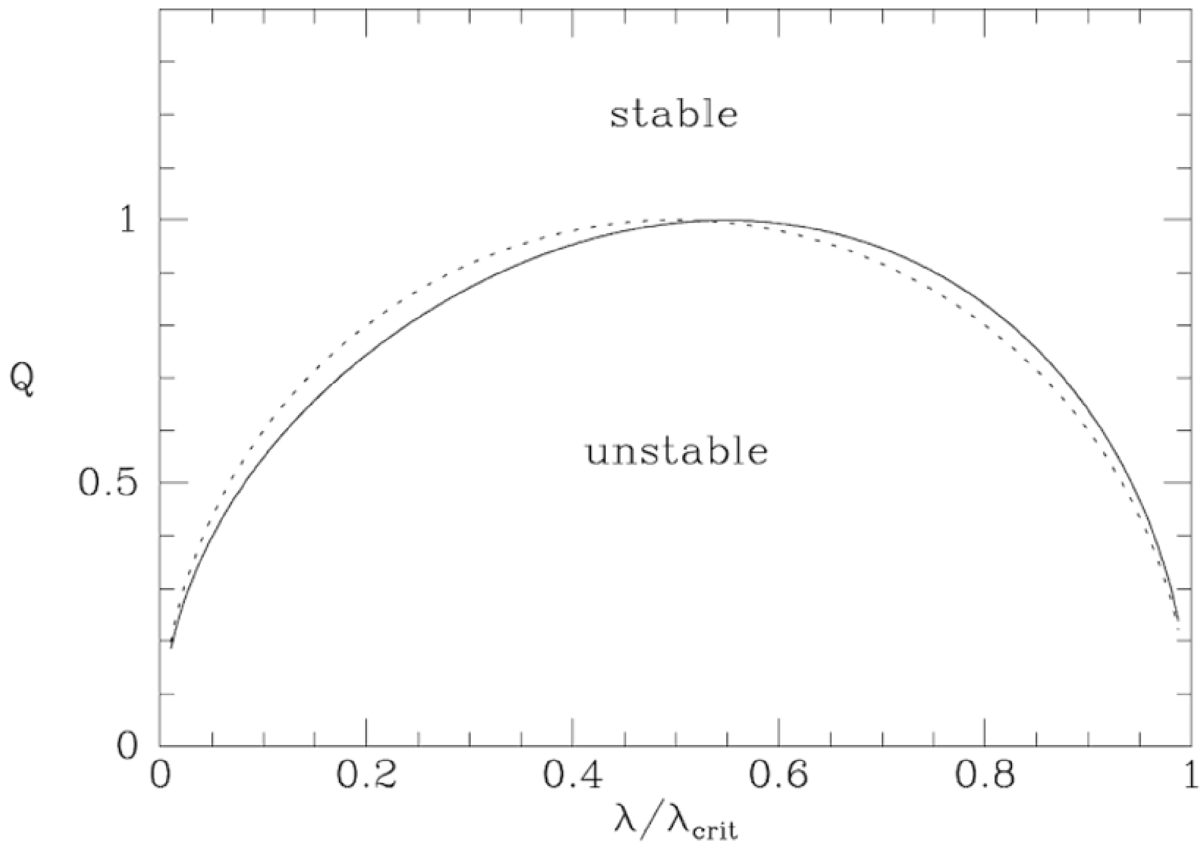


Figure 6.13 Neutral stability curves for tightly wound axisymmetric perturbations in a fluid disk (dashed line, from eq. 6.67) and a stellar disk (solid line, from eq. 6.70).

Stability of Differentially Rotating Disks

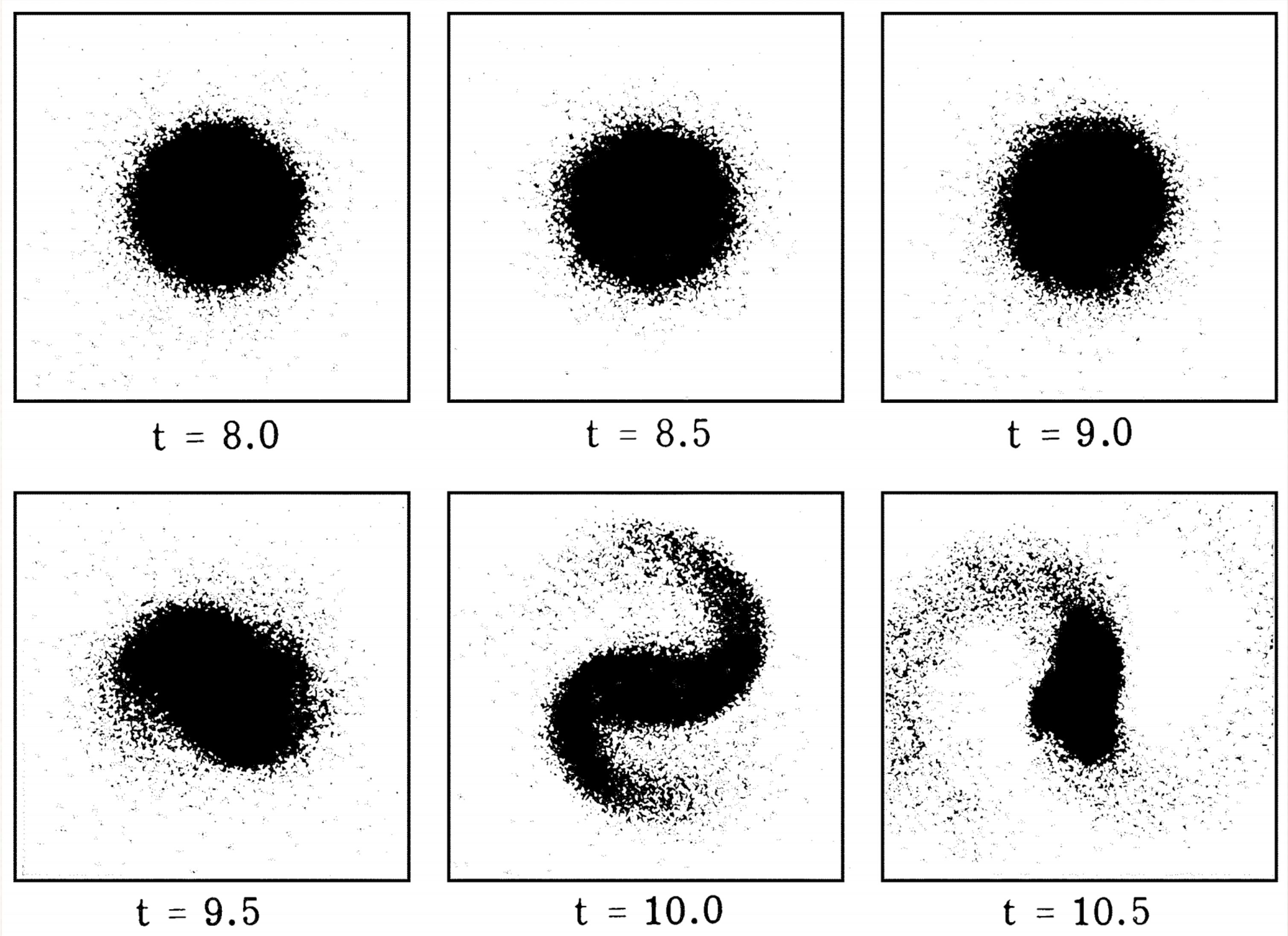
What if tight-winding limit is not applicable? There are no analytic methods – one must perform numerical experiments (N-body or other).

These experiments reveal that Toomre's $Q > 1$ criterion is a fairly accurate predictor of stability to axisymmetric modes of all wavelenghts.

But also, they bring some worrisome results, namely that if most of the kinetic energy of the disk is in rotational motion, then the disk is usually strongly unstable to large-scale bar-like modes (i.e., the creation of a bar).

This raises an important questions: why are disk galaxies stable? Ostriker and Peebles (1973) were the first one ask it, and also point to a solution: that disks of galaxies are embedded in massive dark-matter halos. Under those conditions, the disk of a galaxy will be stable as long as $T/|\Phi| < 0.14$ (the **Ostriker-Peebles criterion**).

Bar Instability



Barred Galaxies (a very brief overview)

NGC 1300 (Sb)

– *HST/STScI/NASA*

Barred Galaxies (NGC 1300, NGC 1073, ...)

- Example: NGC 1300. The most striking feature is the **bar**, spanning almost the diameter of the galaxy. Two spiral arms are very symmetrical. They can be followed almost for a full circle (on deep images). This particular galaxy is a *grand-design spiral*.

- Note that there are sharp, straight, dust lanes spanning the length of the bar. The spiral arms start at the tips of the bar. At the start of each spiral arm, there is a cluster of HII regions (i.e., rapid star formation is occuring). **These are all common features in barred spiral galaxies.**

- Bars are a source of strong, asymmetric, perturbations. The disk responds to these by creating spiral arms.

Barred Galaxies

Bars show up in a variety of sizes. They vary from dominating the appearance of the disk, to weak oval distortions that are only visible in careful Fourier decompositions of the light distribution.

They're typically quite elongated ($\sim 2:1$ ratios are seen in the equatorial plane for SB galaxies).

The global fraction of disk galaxies varies on the exact criteria used; classification by eye shows that 30% to 50% of spiral galaxies are strongly barred in the optical*.

The Milky Way, LMC and SMC are all barred.

*Where the size of the bar is at least 30% of the galaxy's diameter

Barred Galaxies

Bars are more prominent in Near-IR (Eskridge et al. 2000). As we've discussed earlier, this implies they're a true density distortion. They show typical bar-interbar ratios of $K \approx 3 - 6$.

Prominent dust lanes are found in bars, slightly offset in the direction of rotation. There's observational evidence the gas and dust in these lanes is highly compressed and shocked.

But apart from the presence of the bar (and the effects it causes), there are few systemtic differences between barred and unbarred disk galaxies.

Dynamics of Bars

The bar pattern speed Ω_b is usually parametrized by the ratio

$$\mathcal{R} = \frac{R_{CR}}{a_0} \tag{13}$$

of the corotation radius to the bar semi-major axis. Dynamical arguments show that weak bars must have $\mathcal{R} > 1$ (should not extend beyond corotation).

Bars are often called "fast" if $\mathcal{R} \approx 1$ and "slow" if $\mathcal{R} \gg 1$. Observational evidence shows that, within the error bars, all bars have $0.9 \lesssim \mathcal{R} \lesssim 1.3$ and **are therefore considered fast**. This is consistent with results from numerical modeling.

This result has physical significance, as galaxies whose mass within the disk radius is dominated by a dark halo are expected to have *slow* bars. $\Rightarrow$ disk galaxies are baryion-dominated in their centers.