

Vincent van Gogh Starry Night Painting

Hvězdná noc, 1889

# *Struktura a kinematika galaxií (F7567)* *Dynamika a vývoj galaxií (F8567)*

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***F7567/F8567, PŘF MU Brno, 2018/2019***

## *Program přednášky:*

- I. Klasifikace galaxií  
Hmotnostní, prostorové a časové škály
- II. Složky galaxií: bulge, disk, halo, spirální ramena, příčky, hvězdokupy  
Hvězdy, plyn, temná hmota
- III. Profily svítivosti  
Luminozitní funkce
- IV. Gravitační potenciál  
Dvojice potenciál-hustota

V. Dráhy v galaxiích

VI. Rovnováha bezsrážkových systémů

Rozdělovací funkce

Boltzmannova rovnice

Jeansovy rovnice

VII. Gravitační nestabilita

Teorie spirálních hustotních vln

Příčky, dvojříčky

## VIII. Interakce galaxií

Slapové síly, dynamický tlak

Dynamické tření

Galaktický kanibalismus

## IX. N-částicové simulace

X. Vznik hvězd, aktivní galaktická jádra,  
koevoluce galaxií a centrálních černých děr

## IX. Vznik galaxií

Expanze vesmíru

# KAPITOLA I

*1.1. Základní klasifikace galaxií  
(Hubble, de Vaucouleurs)*

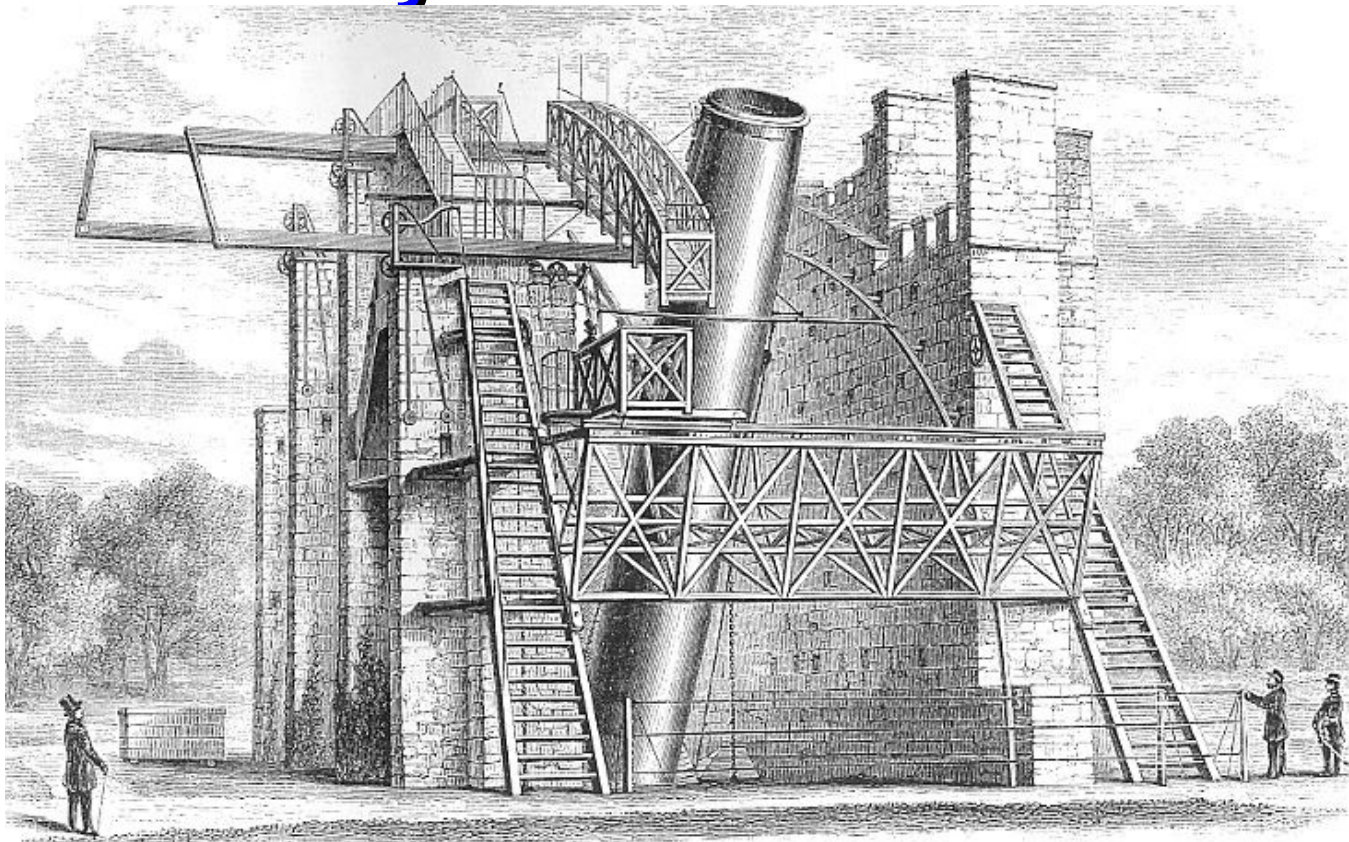
*1.2. Bulge, příčky, dvojpříčky, prstence,  
nukleární spirály*

*1.3. Radiální profily plošné jasnosti  
(Hubble-Reynolds,  
modifikovaný Hubbleův profil,  
de Vaucouleurs, Sérsic, Freeman)*

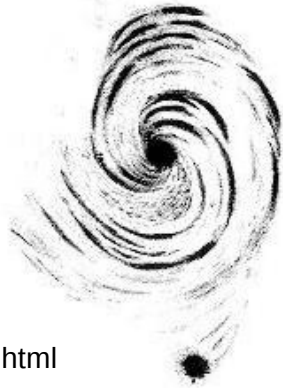
Obrázky a vzorce, u nichž není uveden zdroj, jsou převzaty z učebnice Galactic Dynamic (Binney & Tremaine 1987)

# Leviathan Telescope (1,8m-mirror), Parsonstown, Ireland (1845):

spiral nebulae discovered  
by lord Rosse



# Lord Rosse's drawings of M51, his "Question Mark" "Spiral Nebula"

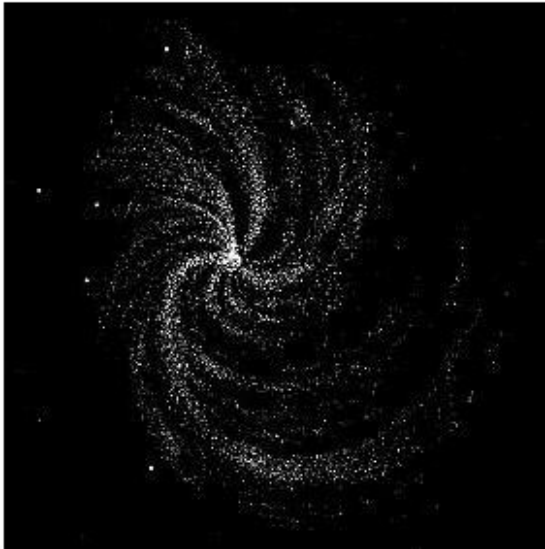


[http://messier.seds.org/more/m051\\_rosse.html](http://messier.seds.org/more/m051_rosse.html)



left:  
Rosse's drawing (1846) -  
the first "spiral nebula"  
right:  
a modern photo of the  
same galaxy (called  
M51 or "Whirlpool Galaxy"  
(see also its *HST* image –  
2 slides back)

## Lord Rosse's drawing of M99



William Parsons (Lord Rosse):

M51 (1846)

M99 (1848)

But ***the true nature of spiral nebulae***, now called spiral galaxies (large systems composed of stars and lying outside our own Galaxy, as independent stellar islands), ***remains unknown until 1924.***

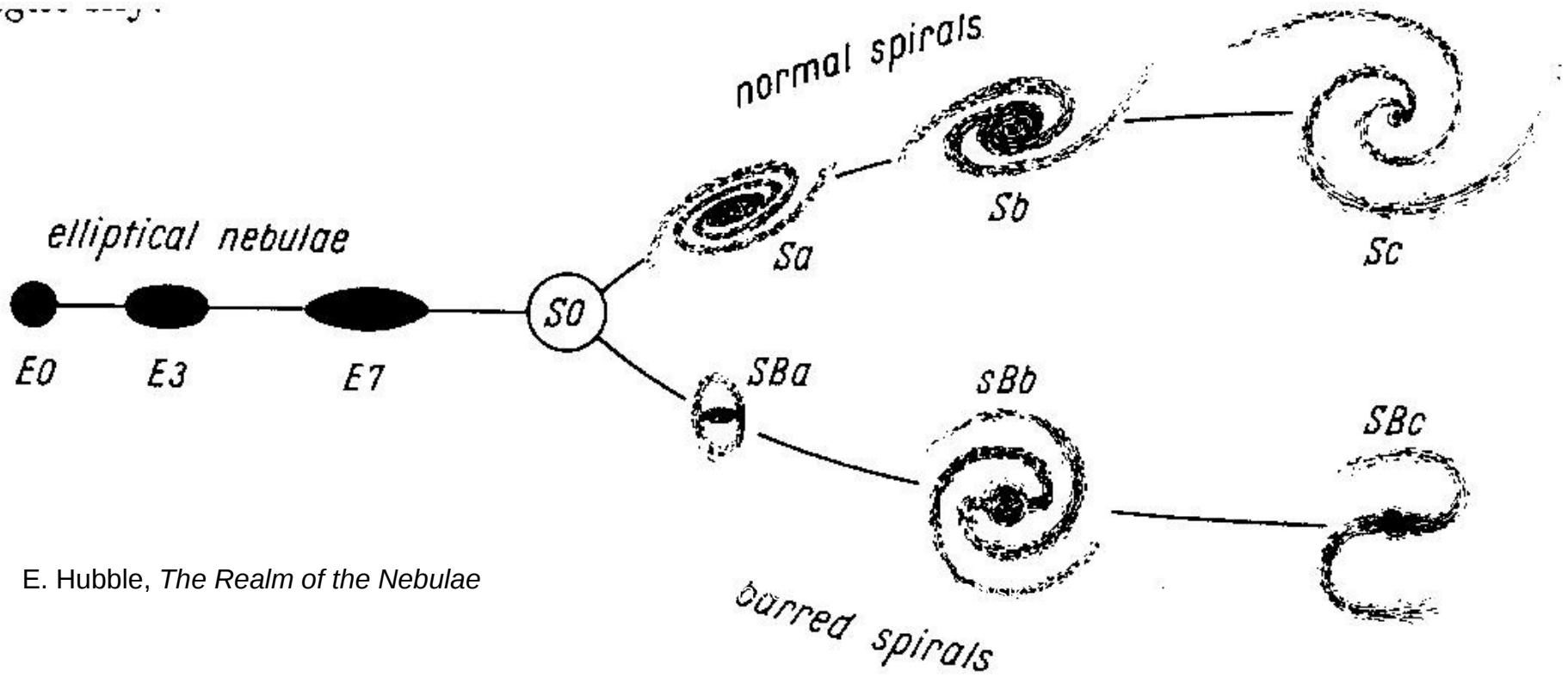
[http://messier.seds.org/more/m099\\_rosse.html](http://messier.seds.org/more/m099_rosse.html)

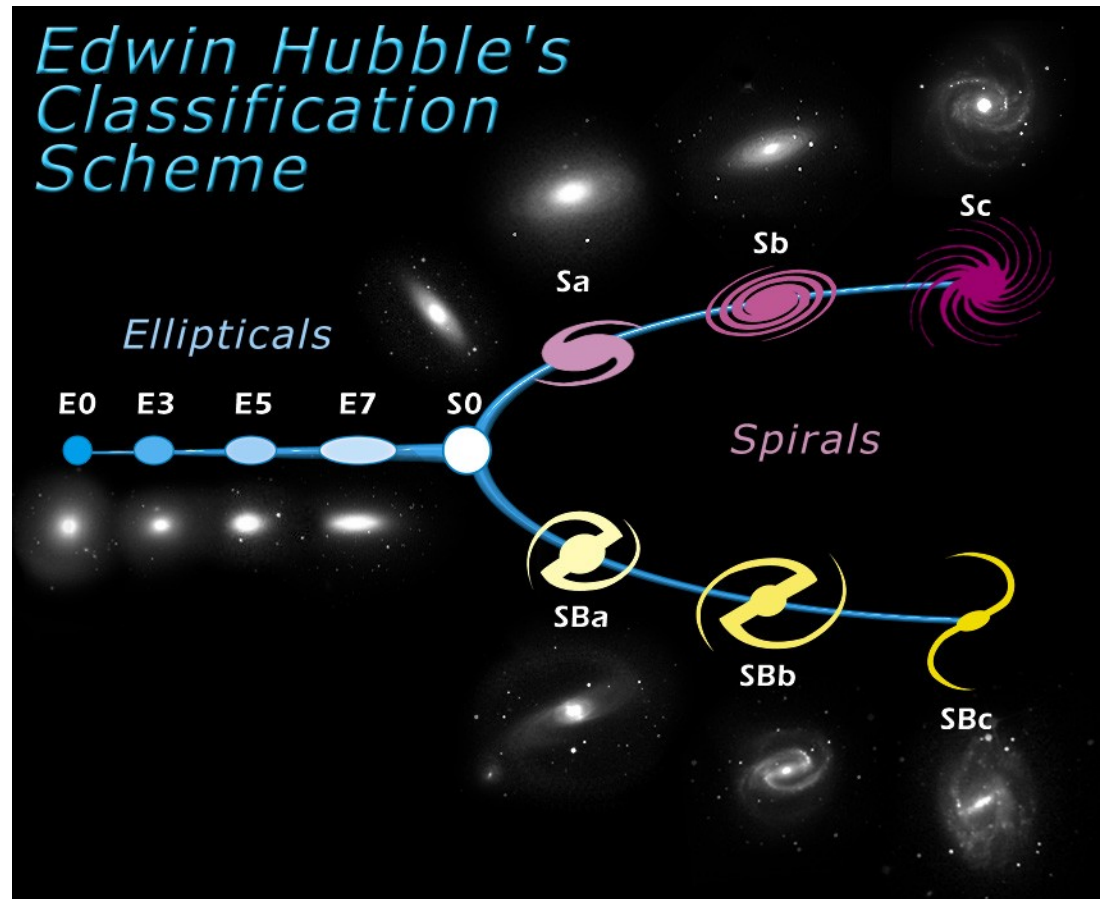


## 1924, Galaxies and the „Great Debate”

1925, **The Hubble Sequence** (The Hubble classification of galaxies)  
Edwin P. Hubble, Mt. Wilson, California

elliptical galaxies (E), lenticular galaxies (S0),  
normal spirals (S), barred spirals (SB),  
irregular galaxies (I)





## Edwin P. Hubble (1889 - 1953)

Classification of galaxies (1925)

Measuring speeds of galaxies → expansion of the Universe discovered (1929)



## Hooker telescope (100-inch mirror) Mt. Wilson, California

### Fundamental discoveries:

- nature of spiral nebulae: **galaxies**
- speeds of galaxies: **expansion of the Universe**

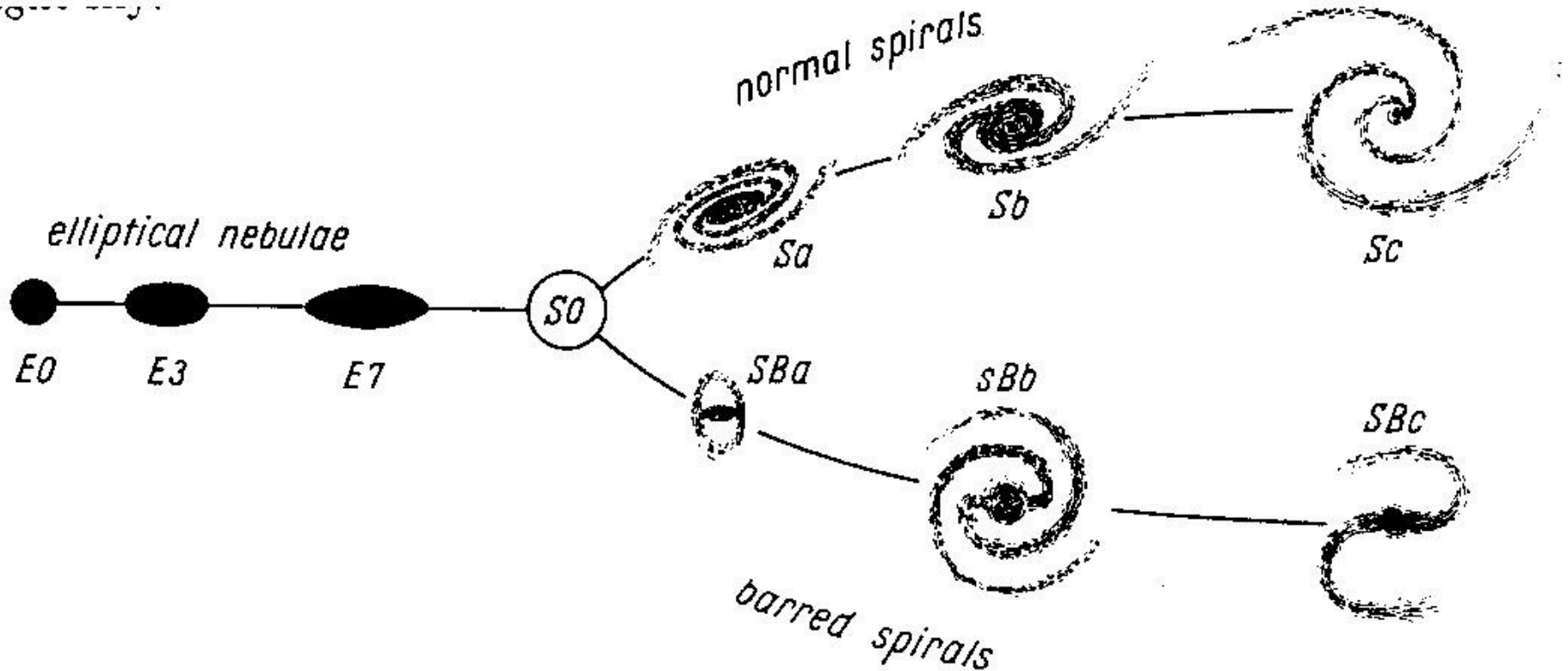


## The Hubble tuning fork (1925, Mt. Wilson)

Elliptical (E), lenticular (S0), normal spiral (S), barred spiral (SB) and irregular galaxies (I)

E sub-types: E0 – E7,  $n = 10(1 - b/a)$

S and SB sub-types: Sa, Sb, Sc and SBa, SBb, SBc





AAT 60

Spiral Galaxy Messier 83  
(FORS / VLT)

Spiral Galaxy NGC 4565  
(FORS / VLT)

ESO PR Photo 24b/05 (August 10, 2005)



ESO PR Photo 24a/05 (August 10, 2005)



elliptical galaxies,  
normal spiral galaxies,  
barred spiral galaxies

face-on views  
edge-views



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AAT 55

The Sombrero Galaxy (VLT ANTU + FORS1)

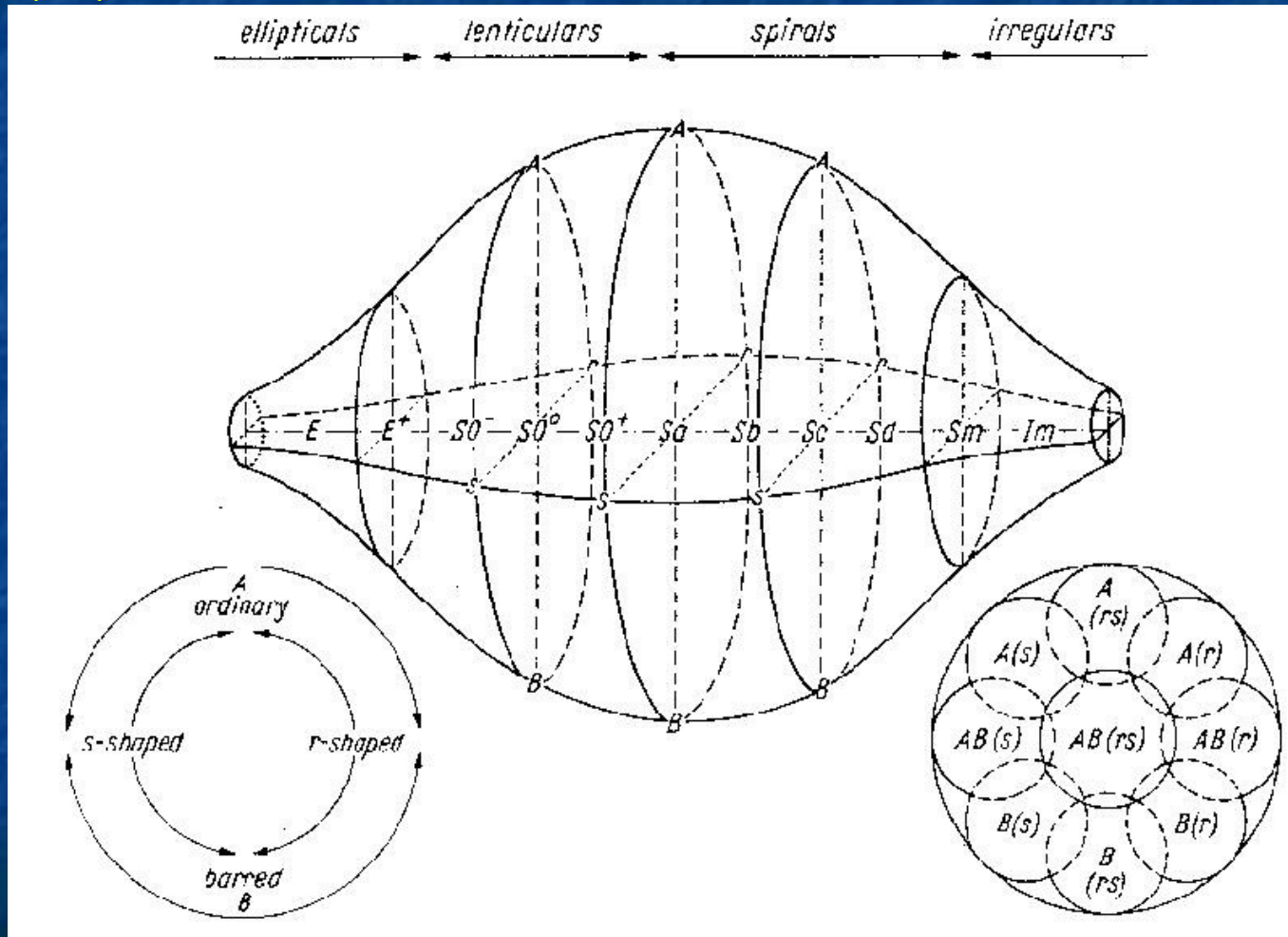
ESO PR Photo 07a/00 (22 February 2009)

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# The de Vaucouleurs classification (1959, 1964)

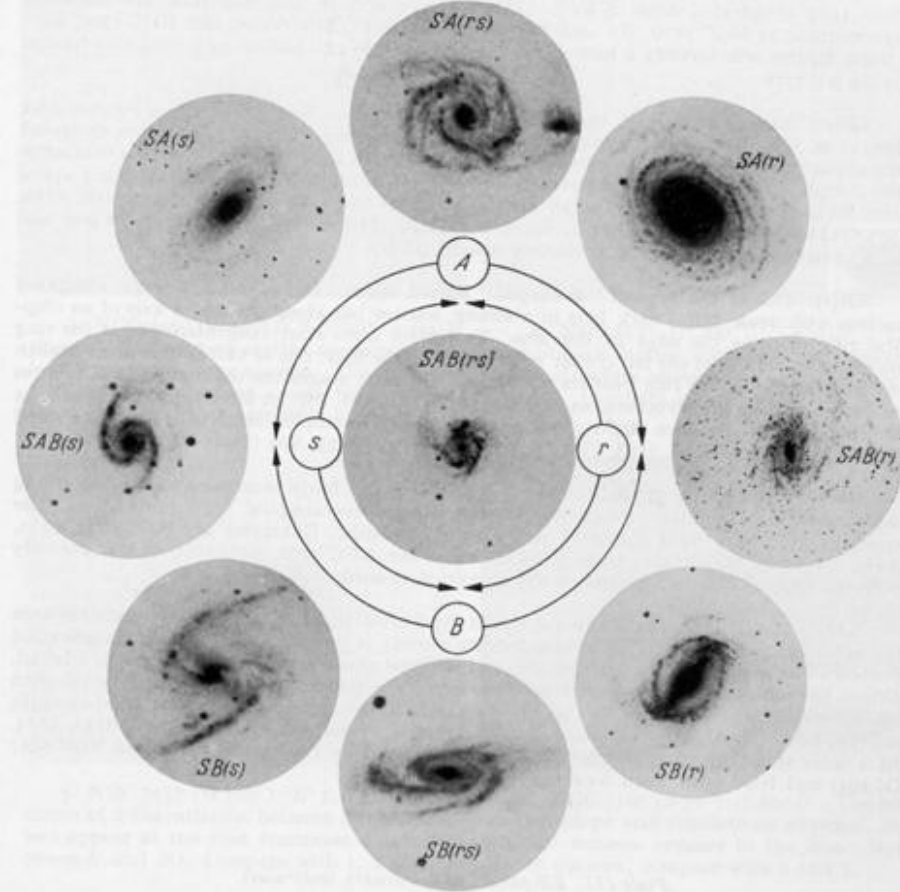
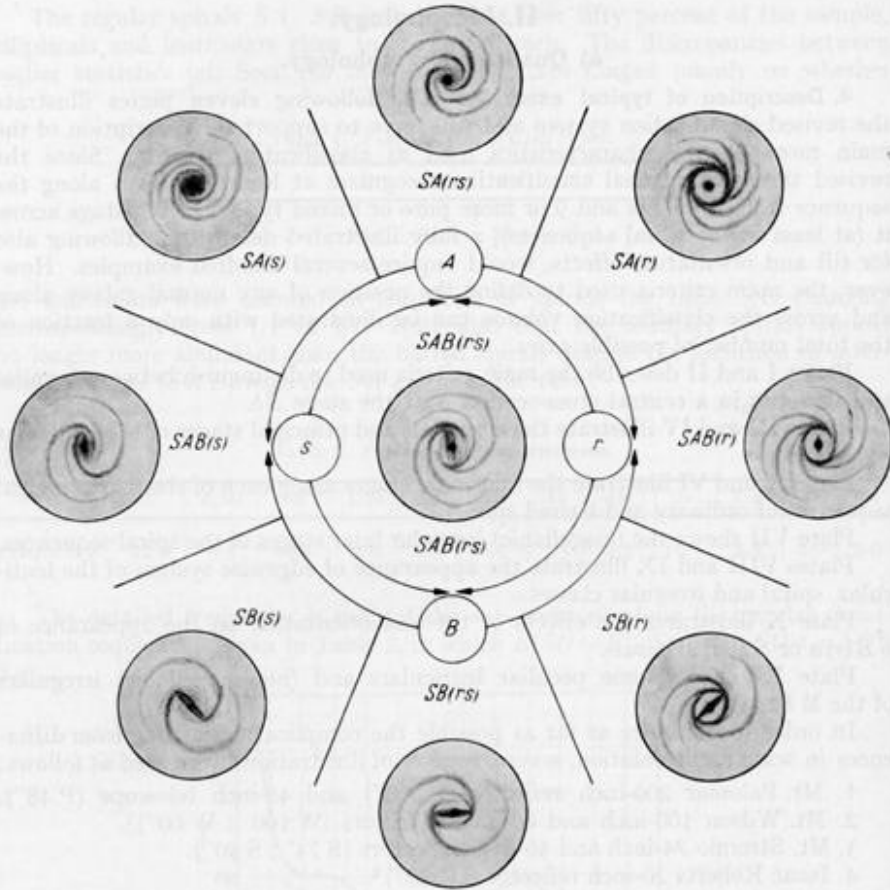
- classes E, S0, S, Im
- families A, AB, B
- varieties s, rs, r



from: G. de Vaucouleurs, Classification and Morphology of External Galaxies, Handbuch der Physik, 1959, Vol. 53, pp. 275-310

<http://nedwww.ipac.caltech.edu/level5/Dev/frames.html>

# De Vaucouleurs (1959)



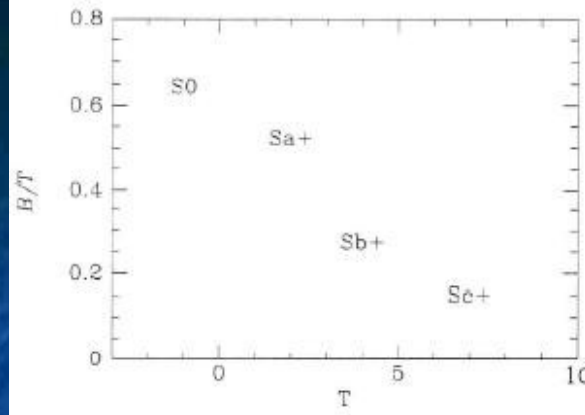
from: G. de Vaucouleurs, Classification and Morphology of External Galaxies, Handbuch der Physik, 1959, Vol. 53, pp. 275-310

<http://nedwww.ipac.caltech.edu/level5/Dev/frames.html>

# Bulges

M 104      SA(s)a  
 NGC 4565      SA(s)b?

**B/D** – bulge-to-disk ratio  
**B/T = B/(B+D)** – bulge-to-total  
 luminosity ratio



(zdroj: Binney & Merrifield, Galactic Astronomy, kapitola IV)

**Figure 4.51** The later the Hubble stage  $T$  of a disk galaxy, the smaller is its bulge fraction  $B/T$ . The plotted values are means. Individual values scatter significantly about these means. [From data published in Kent (1985)]

SA(s)a



The Sombrero Galaxy (VLT ANTU + FORS1)



SA(s)b



Spiral Galaxy NGC 4565 (FORS / VLT)





# Bars (příčky)

> 2/3 diskových galaxií mají příčku viditelnou v optickém oboru

typ SA: galaxie bez příčky ~1/3

typ SAB: galaxie se „slabou“ příčkou ~1/3

typ SB: galaxie se „silnou“ příčkou ~1/3

v blízké infračervené oblasti je frekvence příček > 80%

SAB(s)c



Spiral Galaxy Messier 83  
(FORS / VLT)

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SAB(rs)cd



Spiral Galaxy NGC 7424  
(VLT MELIPAL + VIMOS)

ESO PR Photo 33c/04 (1 December 2004)

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SB(r'l)b



Spiral Galaxy NGC 1097  
(VLT MELIPAL + VIMOS)

ESO PR Photo 35d/04 (22 December 2004)

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Dvojpríčky (double bars, bars-in-bars)  
Nukleární příčky (nuclear bars, baby bars)

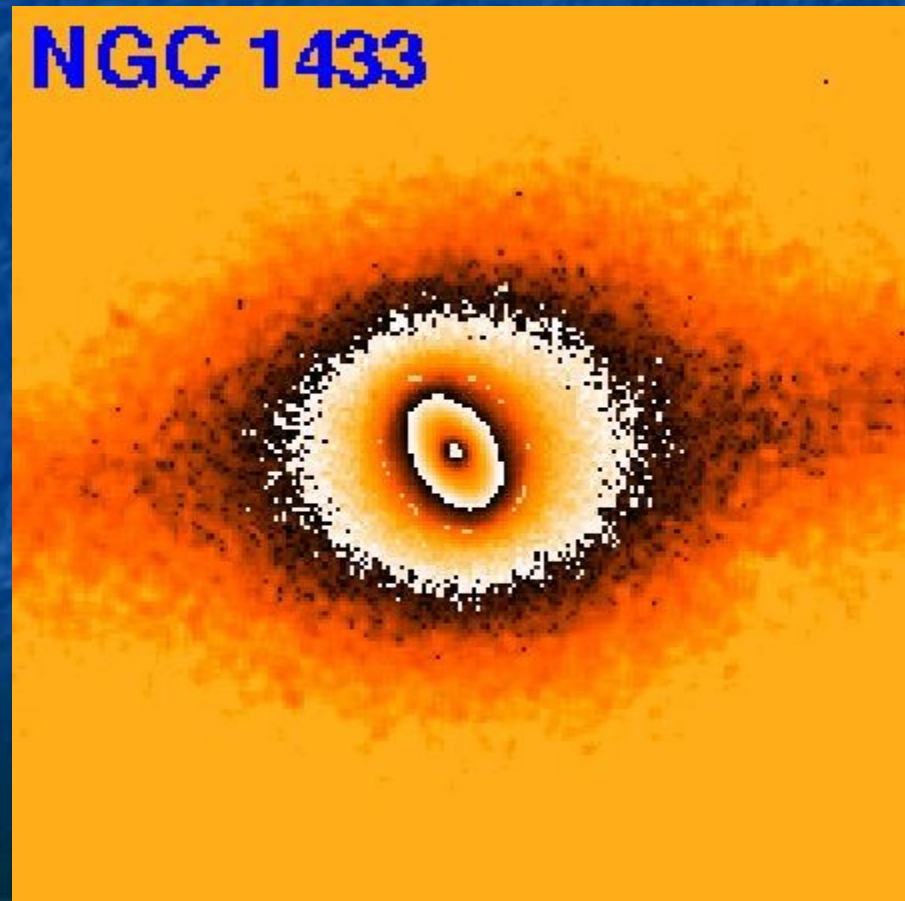
Double bar in NGC 1433 (R<sub>1</sub> SB(rs)ab)

(B band, Buta & Combes 1996)

(H band, JCA, 1997)



NGC 1433



# Prstence (rings) a pseudo-prstence (pseudo-rings) v diskových galaxiích

označení:

prstence      pseudo-prstence

- vnější (outer):  $R, R_1, R_2$        $R', R'_1, R'_2$
- vnitřní (inner):  $r$        $rs$  (nebo  $r'$ )
- nukleární:  $nr$        $nr'$

# Příklady vnějších a vnitřních prstenců

NGC 7020 (Buta & Combes 1996)  
(R)SA(r)0<sup>+</sup>



The Colossal Cosmic Eye NGC 1350  
(FORS/VLT)

ESO PR Photo 31a/05 (September 27, 2005)

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(R'<sub>1</sub>)SB(r)ab (Sy)

(R'<sub>2</sub>)SAB(r)b



Spiral Galaxy ESO 269-57  
(VLT ANTU + FORS1)

ESO PR Photo 20c/99 (30 April 1999)

© European Southern Observatory



# Nukleární prstenec v NGC 1097

SB(r'l, nr)b



Spiral Galaxy NGC 1097  
(VLT MELIPAL + VIMOS)



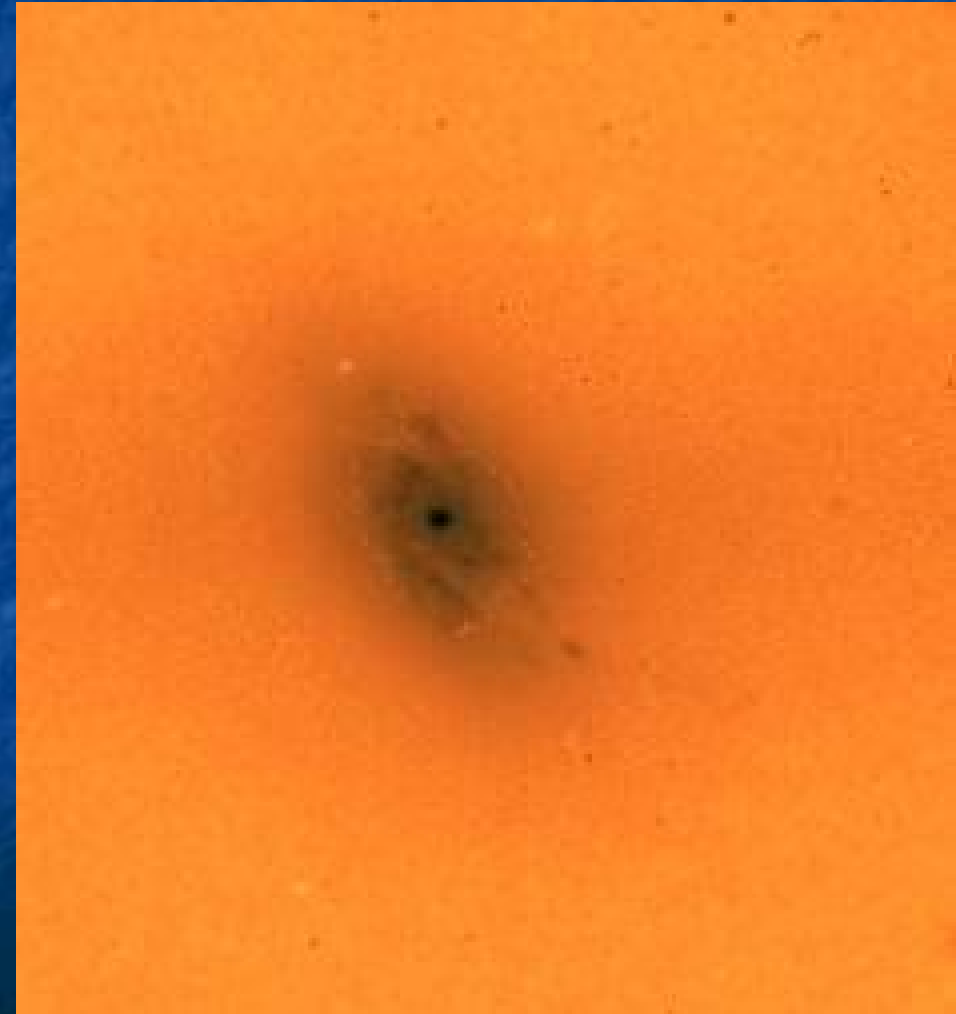
The Centre of the Active Galaxy NGC 1097  
(NACO/VLT)

# Nukleární spirály

NGC 1365, SB(s)b  
optical image



near-IR image (H-band)  
(different scale; from JCA, 1997)



# Frekvence typů (tříd) a podtypů galaxií:

## Hubble (1926)

Type:	<b>E</b>	<b>Sa/SBa</b>	<b>Sb/SBb</b>	<b>Sc/SBc</b>	<b>I</b>
	17%	19%	25%	36%	2.5%

## Shapley and Ames (1926) – Coma-Virgo region

<b>E</b>	<b>S</b>	<b>I</b>
47%	48%	5%

-> environmental dependence

## de Vaucouleurs (1959)

Frequency of revised types:

Type:	<b>E</b>	<b>S0</b>	<b>SA</b>	<b>SB</b>	<b>I</b>	<b>Pec</b>
	23%	21%	24%	26%	3.4%	1.5%

Frequency (%) of subdivisions:

Type:	<b>E</b>	<b>E/S0</b>	<b>S0</b>	<b>S0/a</b>	<b>Sa</b>	<b>Sab</b>	<b>Sb</b>	<b>Sbc</b>	<b>Sc</b>	<b>Scd</b>	<b>Sd</b>	<b>Sm</b>
	22	9.5	10.5	9	4.5	6.5	7.5	7.5	10.5	8.5	2.0	2.0%

# Grand-design spirals vs. flocculent (stochastic) spirals

M 81

SA(s)ab



NGC 2841

SA(r)b



Credit: M81:  
NGC 2841:

Stefan Seip/Adam Block/NOAO/AURA/NSF, <http://www.noao.edu/outreach/aop/observers/m81.html>  
Peter Kukol/Adam Block/NOAO/AURA/NSF, <http://www.noao.edu/outreach/aop/observers/n2841.html>





M 101

SAB(rs)cd

NGC 7217

SAab



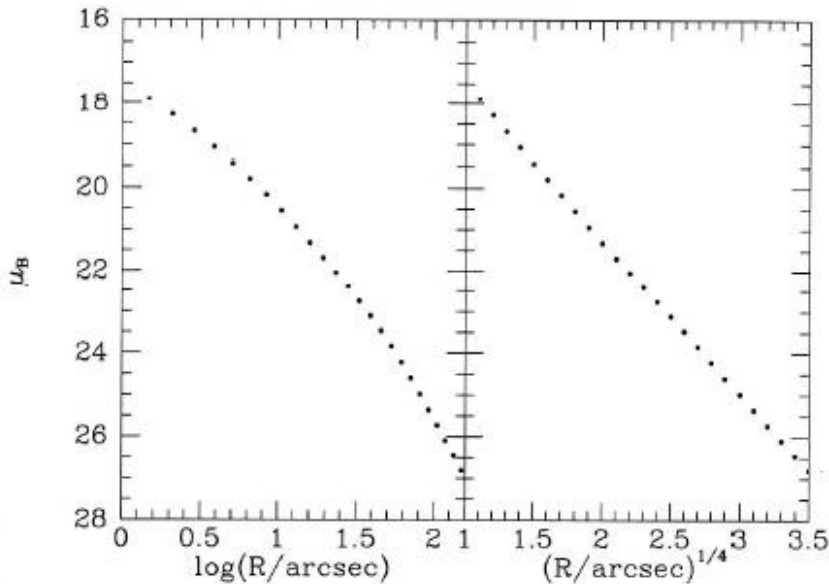
NGC 488

SA(r)b

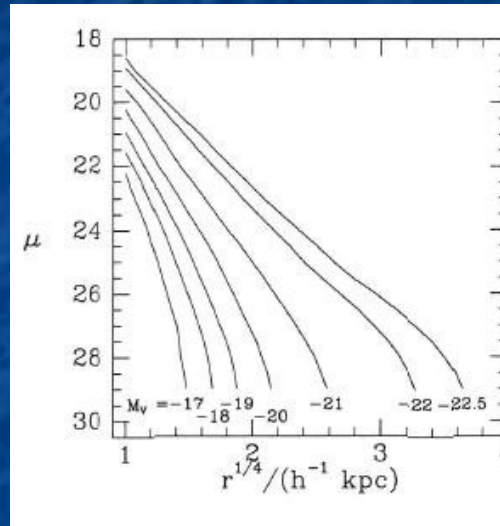


# Surface brightness profiles (profilo plošné jasnosti)

## 1) Elliptical galaxies



**Figure 4.25** The major-axis brightness profile of NGC 1700 plotted against (a)  $\log r$  and (b)  $R^{1/4}$ . [From data published in Capaccioli, Piotto & Rampazzo (1988)]



**Figure 4.26** Characteristic surface-brightness profiles for elliptical galaxies of different luminosities. The luminosities are expressed in terms of absolute  $V$ -band magnitudes and correspond to the portion of the galaxy that lies in projection interior to a circle of radius 16 kpc. These profiles are based on photometry of 261 elliptical galaxies. [After Schombert (1986) from data kindly provided by J. Schombert]

## de Vaucouleurs profile (1948), $R^{1/4}$ -law

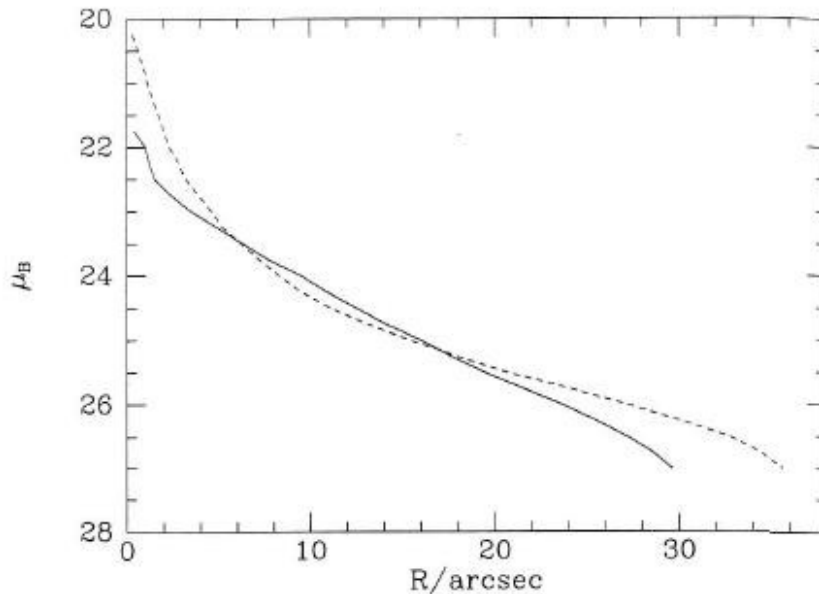
$$I(R) = I_e 10^{\{-3.33[(R/R_e)^{1/4} - 1]\}}$$

$$= I_e \exp\{-7.67[(R/R_e)^{1/4} - 1]\}$$

$$2 \int_0^{R_e} dR I(R) 2\pi R = \int_0^{\infty} dR I(R) 2\pi R$$

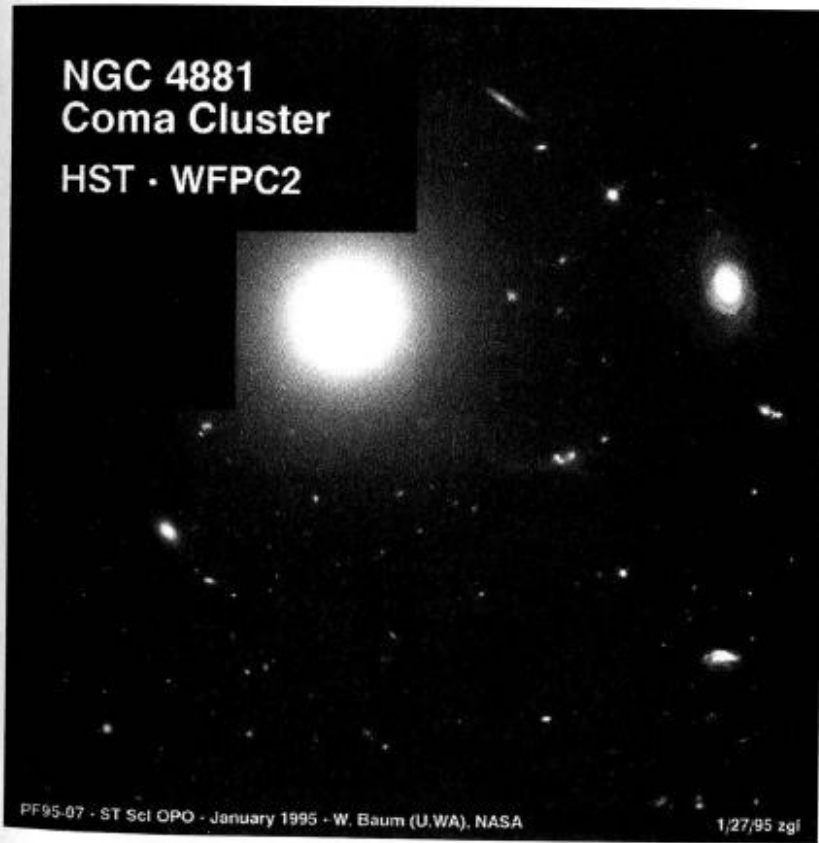
$$= \frac{8! \exp(7.67)}{(7.67)^8} (\pi R_e^2 I_e) = 7.22 \pi R_e^2 I_e$$

## Diffuse dwarf elliptical galaxies: exponential profiles

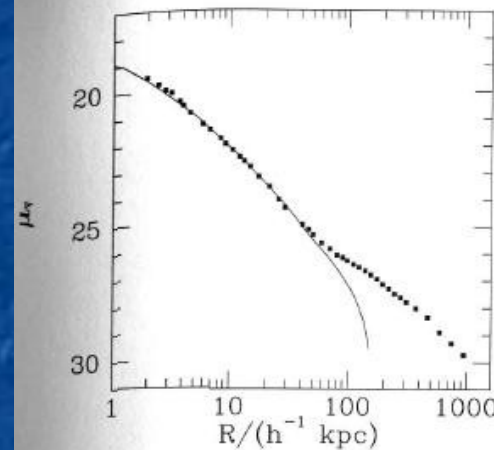


**Figure 4.30** The full curve shows the surface-brightness profile of a typical dE galaxy in the Virgo cluster from the photographic photometry of Ichikawa, Wakamatsu & Okamura (1986). Note that the profile is nearly straight in this log-linear plot because it is well fitted by the exponential law (4.20). The dashed curve shows the surface brightness profile of another galaxy from the same study. This galaxy approximately obeys the  $R^{1/4}$  and is thought to be a background giant elliptical galaxy.

# cD galaxies



**Figure 4.29** The cD NGC 4881 is located near the center of the Coma cluster and is surrounded by a swarm of much less luminous galaxies. [Figure courtesy of STScI]



**Figure 4.28** The surface-brightness profile of the cD galaxy that lies at the center of the cluster Abell 1413 (points). The line shows the  $R^{1/4}$ -law that best fits the inner points. [From data kindly provided by J. Schombert based on the work of Oemler (1976).]

## Other profiles for ellipticals

- Hubble (or Hubble-Reynolds) profile (1913)

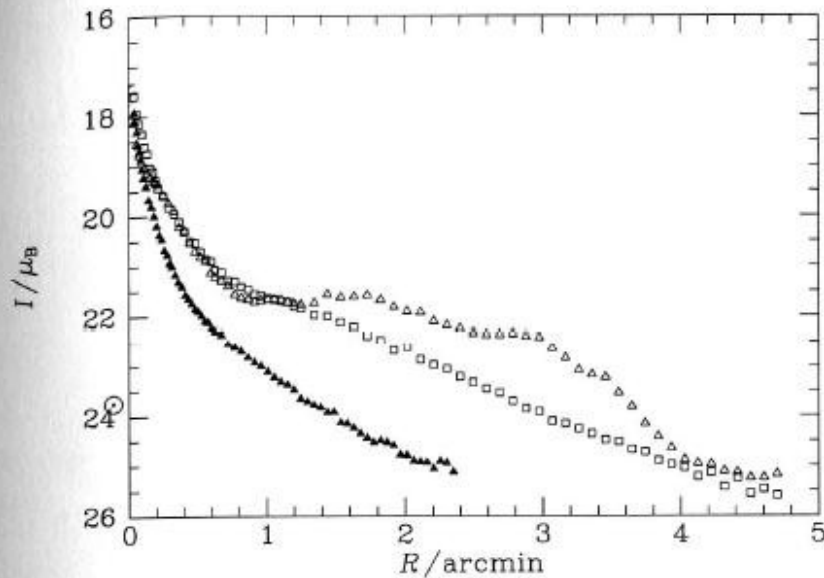
$$I(R) = \frac{I_0}{(1 + R/r_0)^2}$$

- modified Hubble profile: slide 32
- Sersic profile (1968)

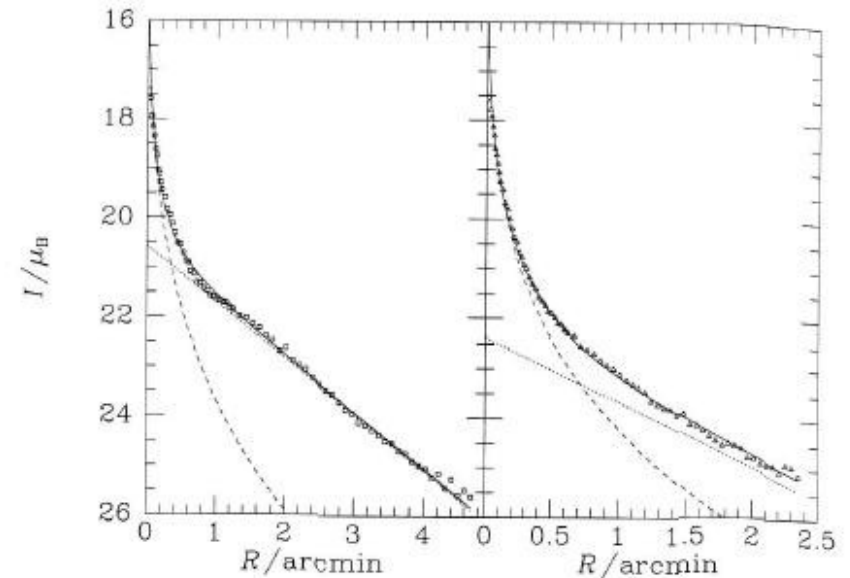
$$I(R) = I_e 10^{\{-b_n [(R/R_e)^{1/n} - 1]\}}$$

## 2) Lenticular and spiral galaxies

bulge + exponential disk (Freeman, 1970)

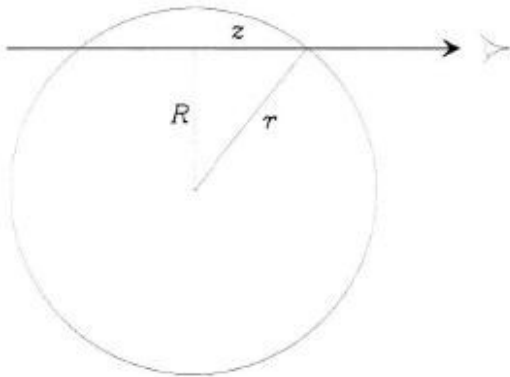


**Figure 4.47** Blue surface brightness versus elliptical radius for three spiral galaxies: NGC 2841 (open squares); NGC 3898 (filled triangles); NGC 5194 (open triangles). The solar symbol  $\odot$  indicates the estimated surface brightness of the Milky Way near the Sun. The outer parts of two of the profiles are fairly straight in accord with equation (4.20). [From data published in Boroson (1981)]



**Figure 4.48** Fits to the surface-brightness profiles of NGC 2841 (left) and NGC 3898 (right). The dotted curves show the exponential fits to the disks and the dashed curves show the  $R^{1/4}$  fits to the bulges; the full curves show the sums of these components. [From data published in Boroson (1981)]

# From 2D to 3D: from surface brightness to volume density



**Figure 4.22** Projecting a spherical luminosity density along the line of sight.

$$I(R) = \int_{-\infty}^{\infty} dz j(r) = 2 \int_R^{\infty} \frac{j(r) r dr}{\sqrt{r^2 - R^2}}.$$

$$j(r) = -\frac{1}{\pi} \int_r^{\infty} \frac{dI}{dR} \frac{dR}{\sqrt{R^2 - r^2}}.$$

## Example: modified Hubble profile

$$I(R) = \frac{I_0}{1 + (R/r_0)^2} \quad \leftrightarrow \quad j(r) = \frac{j_0}{[1 + (r/r_0)^2]^{3/2}},$$

$$L(R) \equiv 2\pi \int_0^R I(R') R' dR' = \pi r_0^2 \ln [1 + (R/r_0)^2].$$



# KAPITOLA II

## *Gravitační pole, Poissonova rovnice*

*Jednoduché modely galaxií:  
dvojice potenciál-hustota, kruhová rychlost-  
rotační křivka, úniková rychlost*

*a) sféricky symetrické systémy  
(logaritmický potenciál, Plummerova sféra,  
modifikovaný Hubbleův profil, homogenní  
sféra, singulární izotermální sféra*

*b) osově symetrické disky  
Toomre-Kuzmin, Mestel, Miyamoto-Nagai,  
exponenciální disk*

# Gravitační pole, Poissonova rovnice

Dvojice potenciál-hustota: jednoduché modely galaxií

a) sféricky symetrické systémy  
(Logaritmický potenciál, Plummerova sféra, modifikovaný Hubbleův profil, homogenní sféra, singulární izotermální sféra)

b) osově symetrické disky  
Toomre-Kuzmin, Mestel, Miyamoto-Nagai, exponenciální disk

Kruhová a úniková rychlost

## Poisson equation, potential-density pairs

$$\nabla^2 \Phi = 4\pi G \rho.$$

$$\Phi(\mathbf{x}) = -G \int \frac{\rho(\mathbf{x}')}{|\mathbf{x}' - \mathbf{x}|} d^3 \mathbf{x}',$$

$$\mathbf{F}(\mathbf{x}) = G \int \frac{\mathbf{x}' - \mathbf{x}}{|\mathbf{x}' - \mathbf{x}|^3} \rho(\mathbf{x}') d^3 \mathbf{x}'.$$

# Spherical systems

## Newton's first theorem

*A body that is inside a spherical shell of matter experiences no net gravitational force from that shell.*

## Newton's second theorem

*The gravitational force on a body that lies outside a spherical shell of matter is the same as it would be if all the shell's matter were concentrated into a point at its center.*

$$\Phi(r) = -4\pi G \left[ \frac{1}{r} \int_0^r \rho(r') r'^2 dr' + \int_r^\infty \rho(r') r' dr' \right]$$

$$\mathbf{F}(r) = -\frac{d\Phi}{dr} \hat{\mathbf{e}}_r = -\frac{GM(r)}{r^2} \hat{\mathbf{e}}_r,$$

$$M(r) = 4\pi \int_0^r \rho(r') r'^2 dr'.$$

$$v_c^2 = r \frac{d\Phi}{dr} = r |\mathbf{F}| = \frac{GM(r)}{r}.$$

$$v_e(r) = \sqrt{2|\Phi(r)|}.$$

## Homogeneous sphere, dynamical time

$$v_c = \sqrt{\frac{4\pi G\rho}{3}} r.$$

$$T = \frac{2\pi r}{v_c} = \sqrt{\frac{3\pi}{G\rho}},$$

$$\frac{d^2 r}{dt^2} = -\frac{GM(r)}{r^2} = -\frac{4\pi G\rho}{3} r,$$

$$t_{\text{dyn}} = \frac{T}{4} = \sqrt{\frac{3\pi}{16G\rho}}.$$

# Simple potentials for galaxies

- Plummer potential (1911)

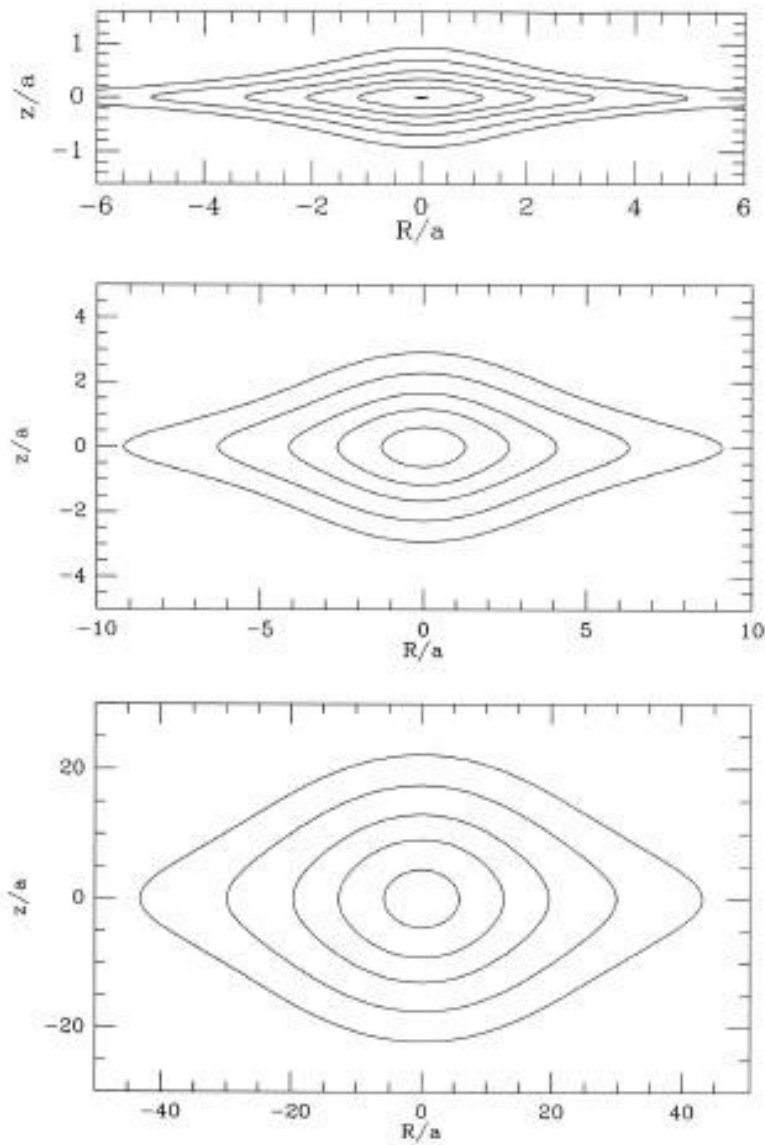
$$\Phi_P = -\frac{GM}{\sqrt{r^2 + b^2}}.$$

- Toomre-Kuzmin potential (1956, 1962)

$$\Phi_K(R, z) = -\frac{GM}{\sqrt{R^2 + (a + |z|)^2}}.$$

- Miyamoto-Nagai (1975) potential

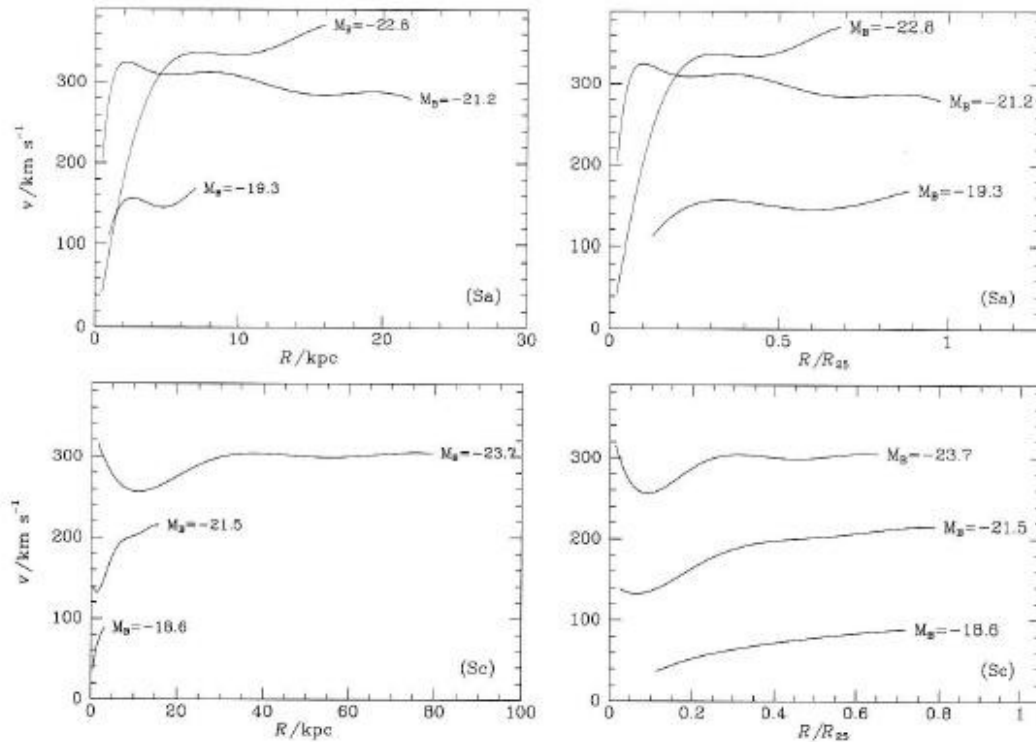
$$\Phi_M(R, z) = -\frac{GM}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}}.$$



**Figure 2-6.** Contours of equal density in the  $(R, z)$  plane for the Miyamoto-Nagai density distribution (2-50b) when:  $b/a = 0.2$  (top);  $b/a = 1$  (middle);  $b/a = 10$  (bottom). Contour levels are  $f \times (1, 0.3, 0.1, 0.03, \dots)$ , where:  $f = M/a^3$  (top);  $f = 0.1M/a^3$  (middle);  $f = 0.0001M/a^3$  (bottom).



# Rotation curves of spiral galaxies



**Figure 8.33** The upper panels show the rotation curves of three Sa galaxies of very different luminosities from the sample of Rubin *et al.* (1985) plotted both on the same linear scale (left) and rescaled by their optical radii,  $R_{25}$  (right). The lower panels show similar plots for three Sc galaxies from the sample of Burstein *et al.* (1982).

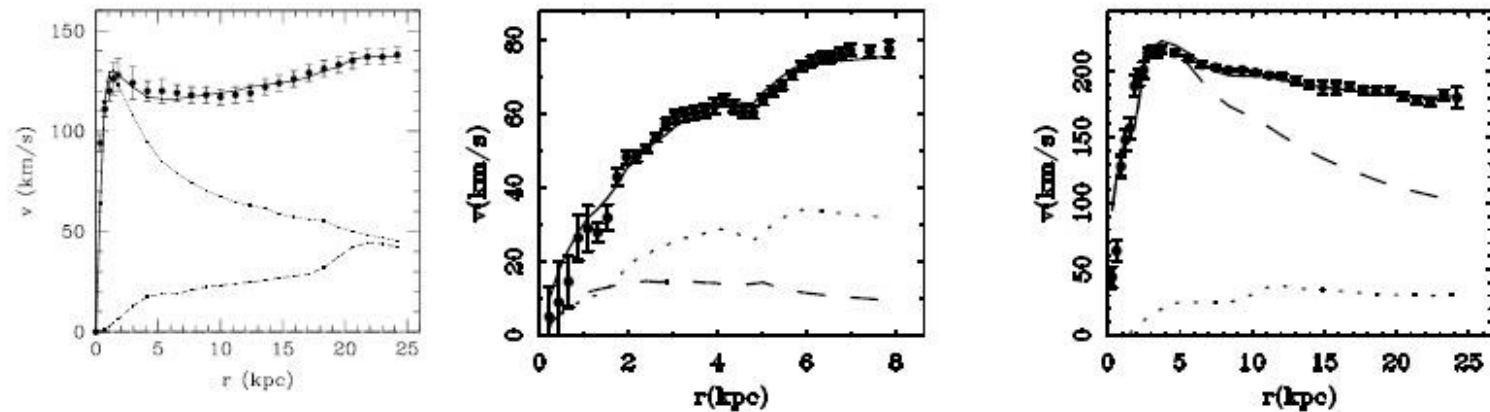


Fig. 2. The observed and MOND rotation curves (in solid lines) for NGC 3657 (left), NGC 1560 (center), and NGC 2903 (right). The first from Sanders (2006), the last two from Sanders and McGaugh (2002). Points are data, dashed and dotted lines for the last two galaxies are the Newtonian curves calculated for the stars and gas alone; the reverse for the first (they add in quadrature to give the full Newtonian curve).

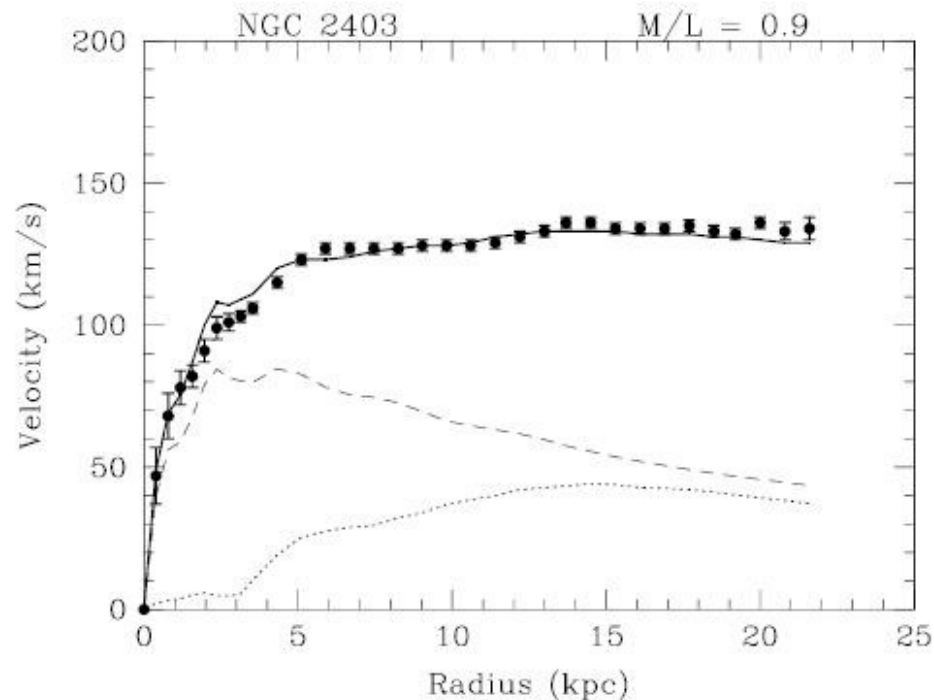


Figure 1: The points show the rotation curve of NGC 2403 as deduced from 21 cm line observations [6]. The dashed curve is the Newtonian rotation curve of the stellar component as deduced from the observed surface brightness distribution with  $M/L=0.9$ , and the dotted curve is the Newtonian rotation curve deduced from the observed HI surface density distribution. The solid curve is that calculated from Milgrom's formula. Here  $a_0 = 10^{-8} \text{ cm s}^{-2}$ .

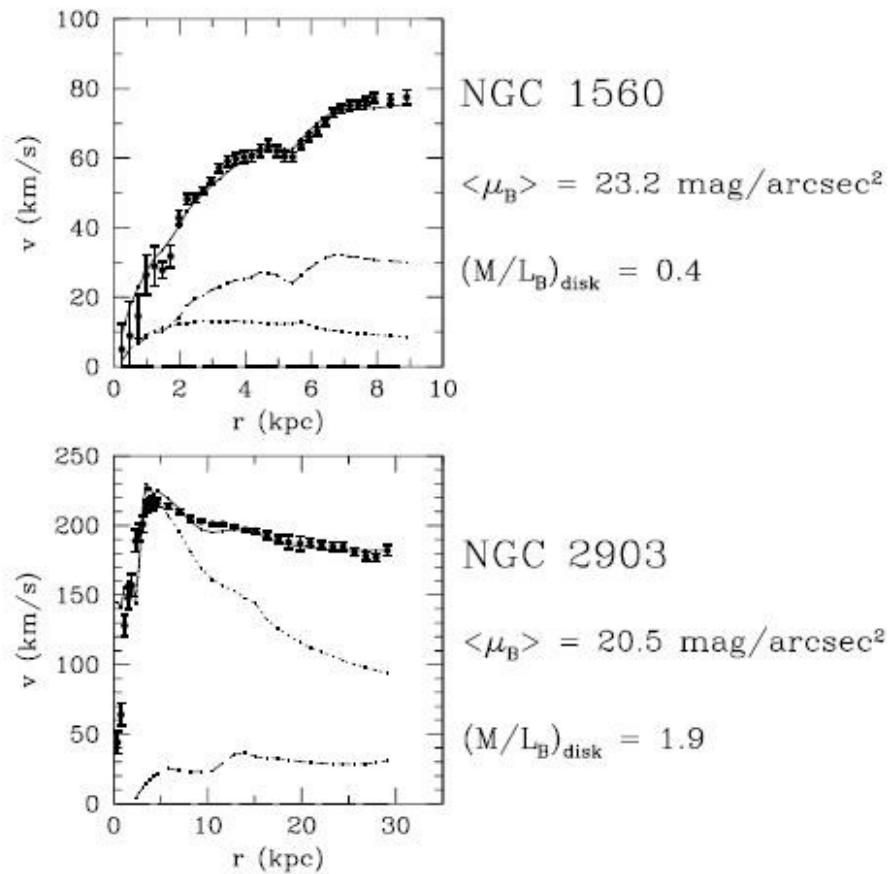
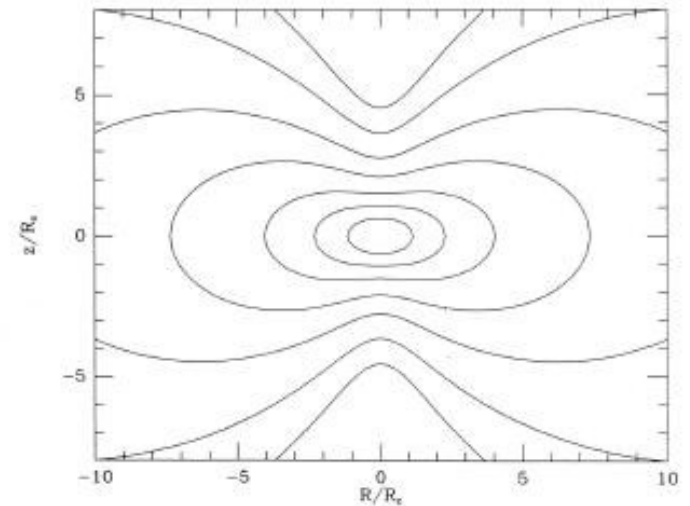
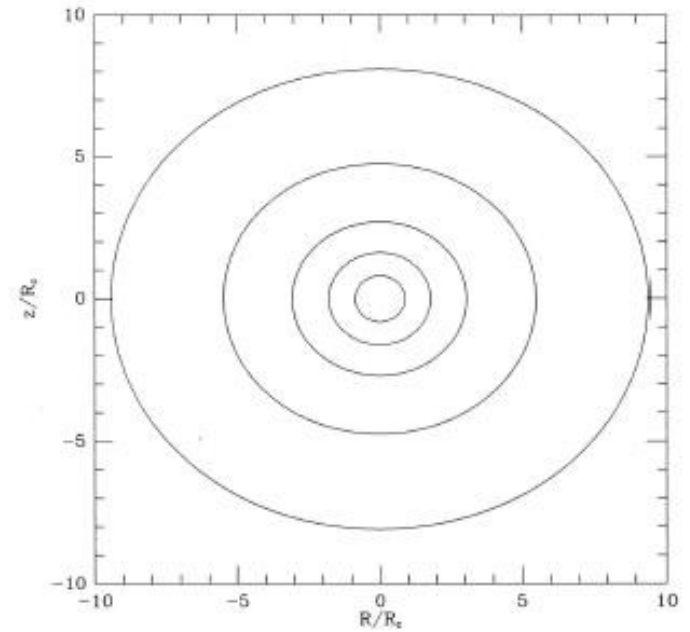


Figure 3: Observed rotation curves of a low surface brightness (Broeils [15]) and a high surface brightness galaxy (Begeman [6]). Here the dotted curve is the Newtonian rotation curve of the stellar component and the dashed curve for the gas. The solid curve is the MOND rotation curve. The mean surface brightness and the implied mass-to-light ratios are indicated.

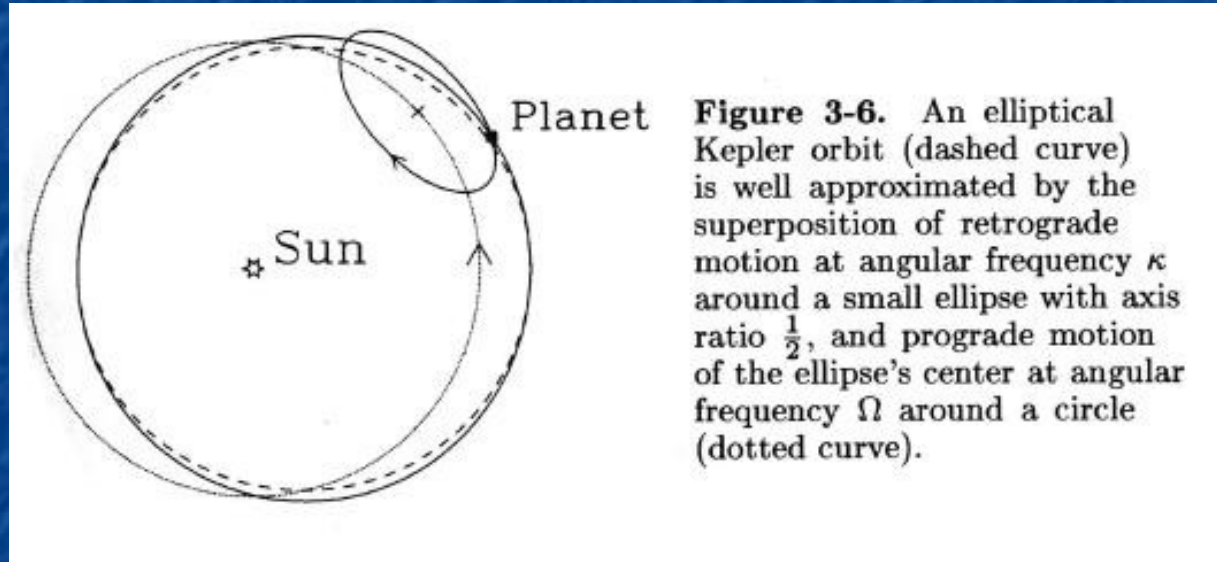
# Logarithmic potential

$$\Phi_L = \frac{1}{2} v_0^2 \ln \left( R_c^2 + R^2 + \frac{z^2}{q_\Phi^2} \right) + \text{constant}$$

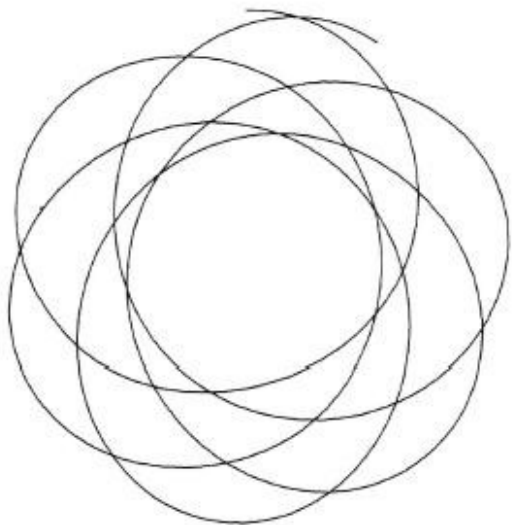


**Figure 2-8.** Contours of equal density in the  $(R, z)$  plane for  $\rho_L$  [eq. (2-54b)] when:  $q_\Phi = 0.95$  (top);  $q_\Phi = 0.7$  (bottom). In each case the contour levels are  $0.1v_0^2/(GR_c^2) \times (1, 0.3, 0.1, \dots)$ . When  $q_\Phi = 0.7$  the density is negative near the  $z$ -axis for  $|z| \gtrsim 7R_c$ .

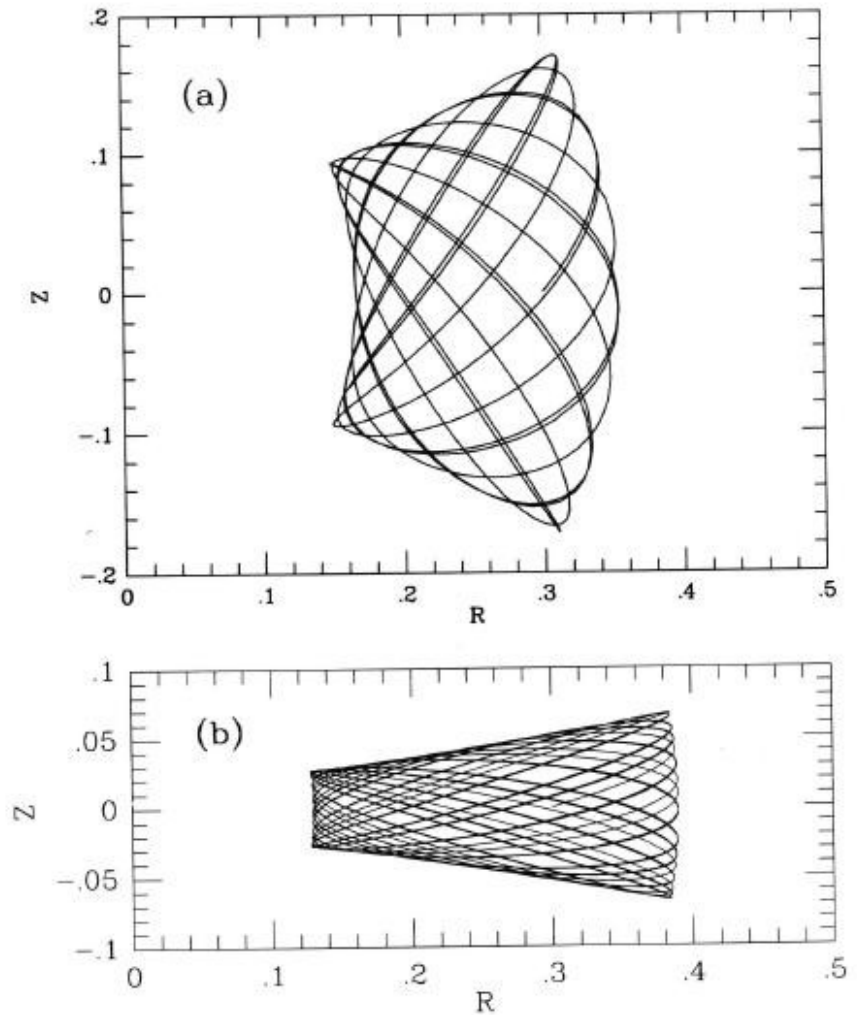
# Epicyclic approximation for Keplerian orbits



from Binney and Tremaine 1987



**Figure 3-1.** A typical orbit in a spherical potential forms a rosette.



**Figure 3-3.** Two orbits in the potential of equation (3-50) with  $q = 0.9$ . Both orbits are at energy  $E = -0.8$  and angular momentum  $L_z = 0.2$ , and we assume  $v_0 = 1$ .

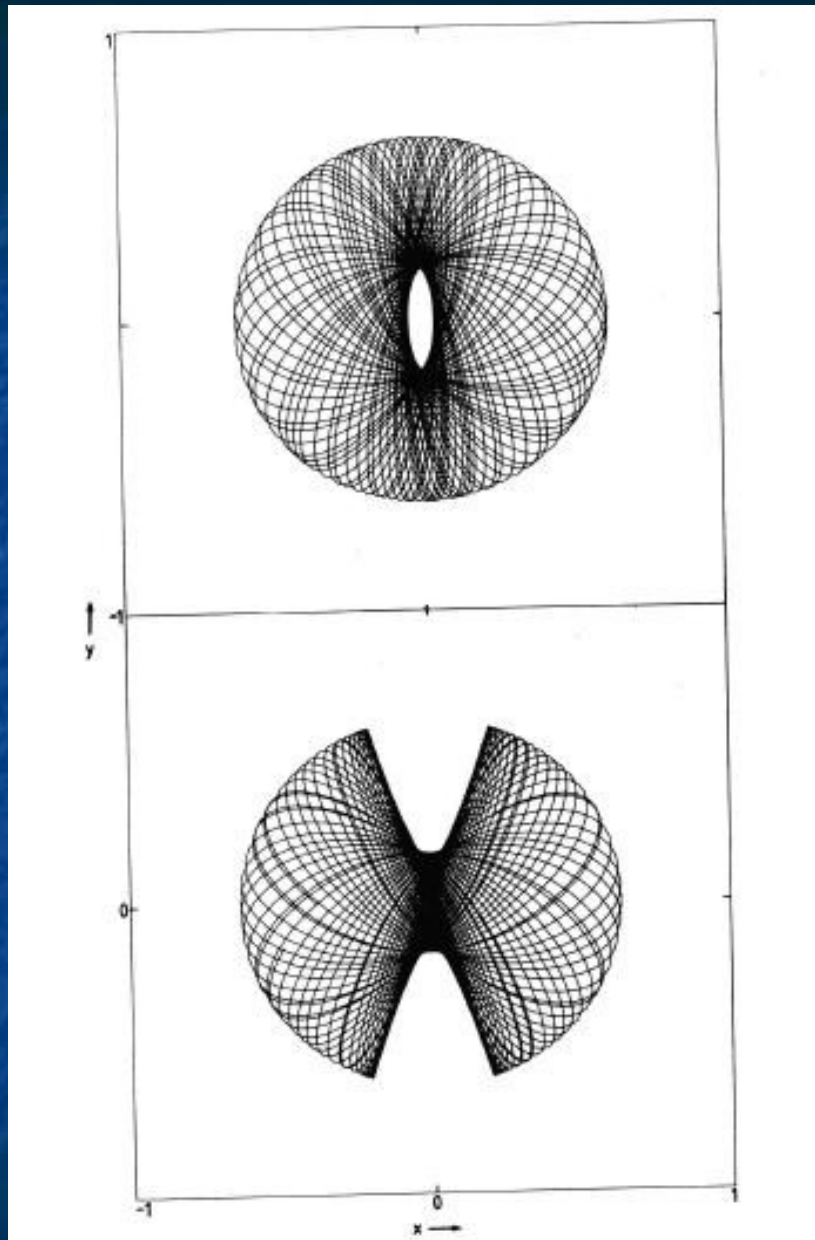
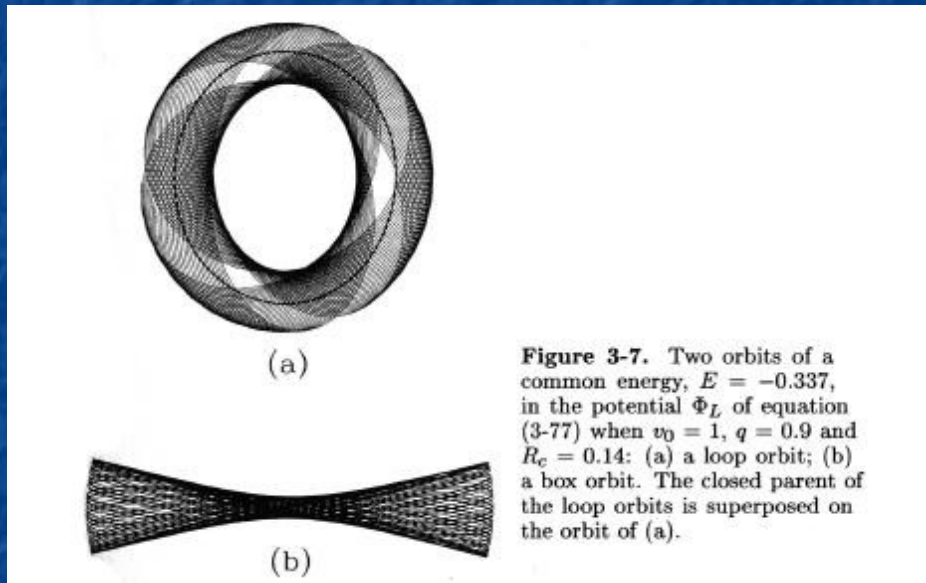
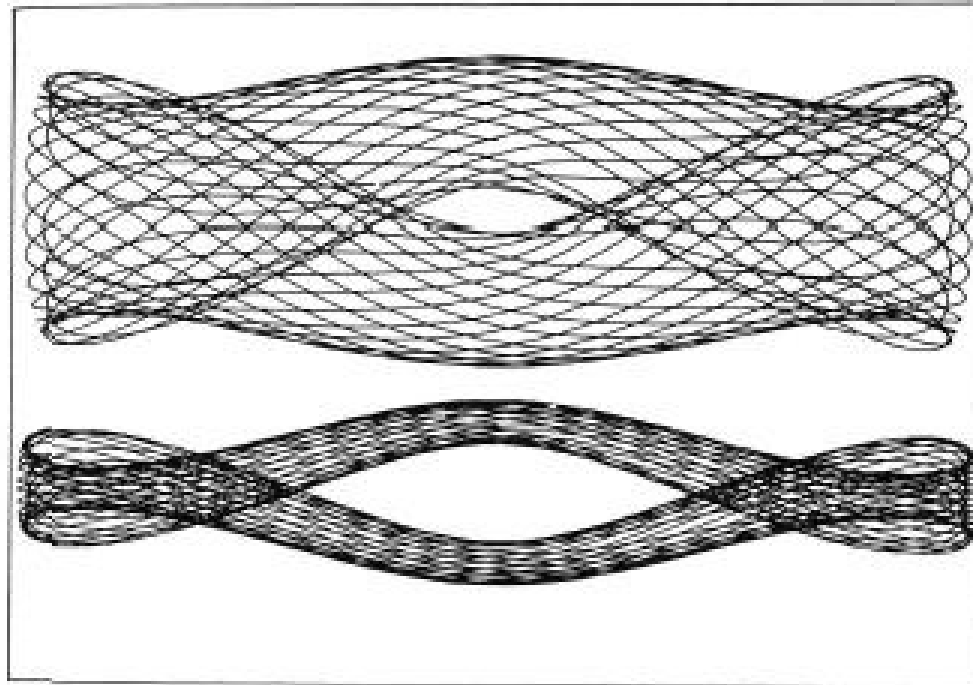
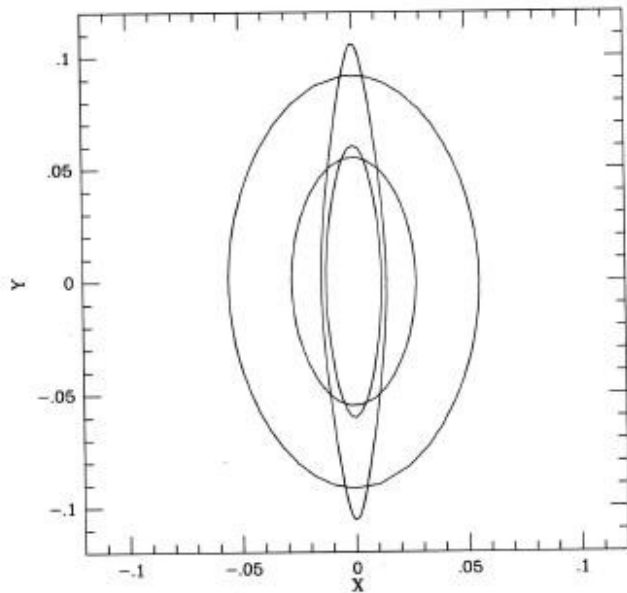


Figure 3-9. One of the most eccentric loop orbits and one of the least elongated box orbits in the potential  $\Phi_L$  ( $q = 0.9, R_c = 0.14$ ) at the energy of Figures 3-7 and 3-8.

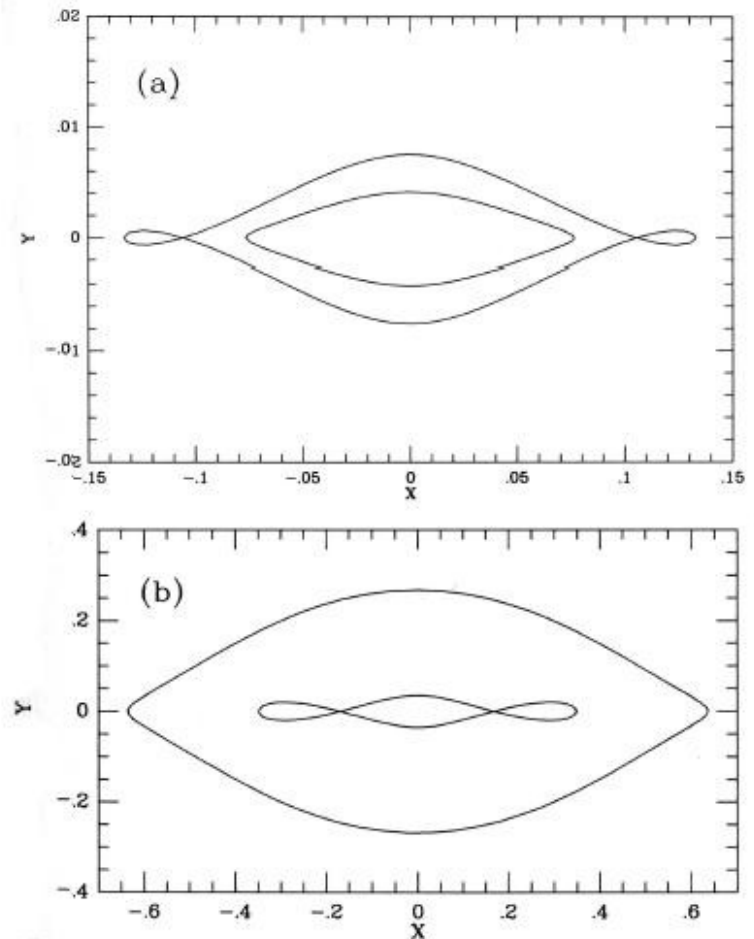




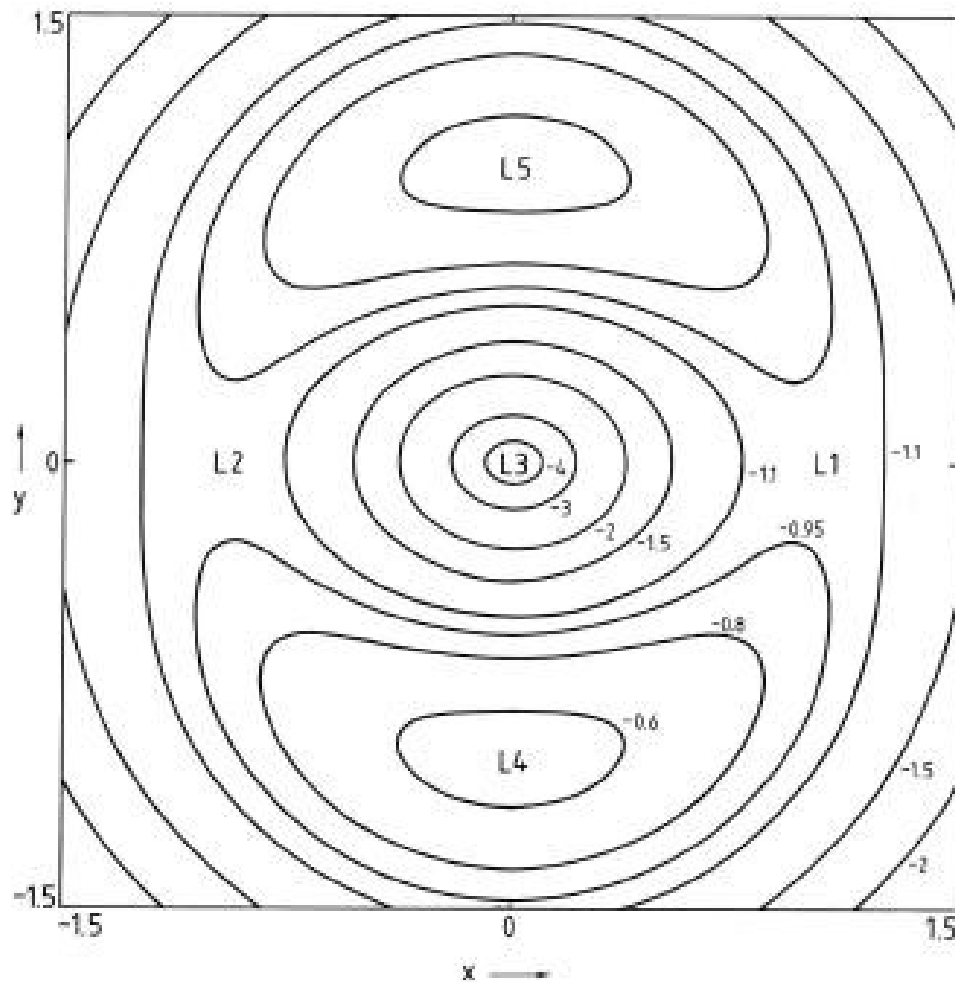
**Figure 3-18.** Two nonclosed orbits of a common energy in the rotating potential  $\Phi_L$ .



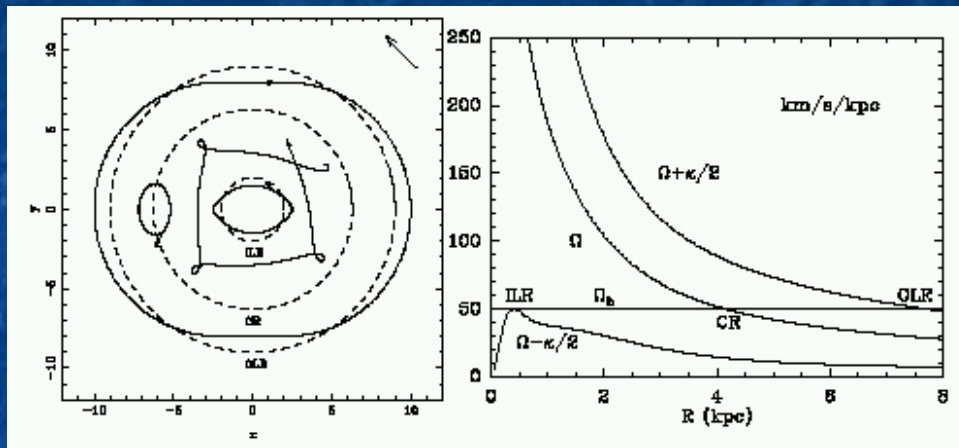
**Figure 3-15.** Closed orbits at two energies higher than those shown in 3-14. Just outside the potential's near-harmonic core there are at each energy two prograde closed orbits aligned parallel to the potential's short axis. One of these orbits (the less elongated) is stable, while the other is unstable.



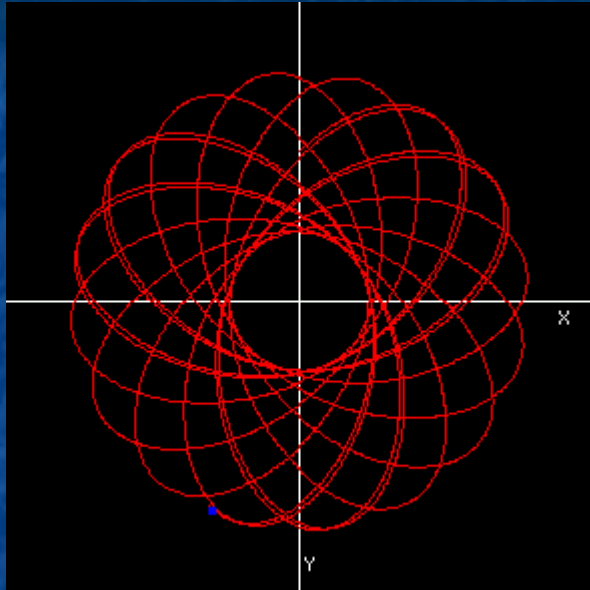
**Figure 3-16.** Near the energy at which the orbit pairs shown in Figure 3-15 appear, the closed long-axis orbits develop loops (a). At higher energies these expand, until the orbits open out into roughly elliptical figures (b). Notice that in (a) the  $x$ - and  $y$ -scales are different. In each diagram, two orbits at two different energies are shown.



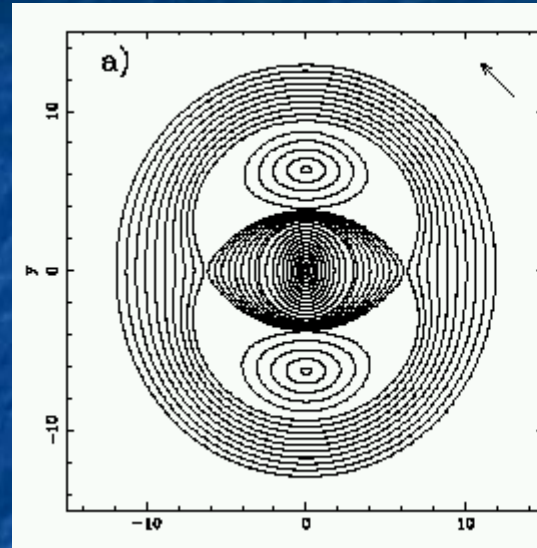
**Figure 3-13.** Contours of constant effective potential  $\Phi_{\text{eff}}$  when the potential is given by equation (3-77) with  $v_0 = 1$ ,  $q = 0.8$ ,  $R_c = 0.1$ , and  $\Omega_b = 1$ . The point marked  $L_3$  is a minimum of  $\Phi_{\text{eff}}$ , while those marked  $L_4$  and  $L_5$  are maxima.  $\Phi_{\text{eff}}$  has saddle points at  $L_1$  and  $L_2$ .



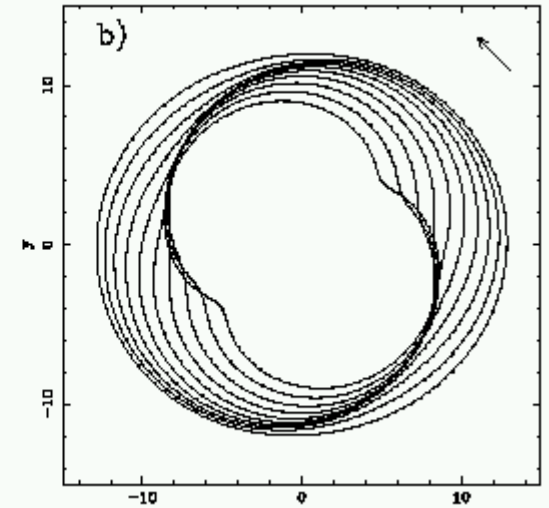
# Orbits in axisymmetric and barred potentials



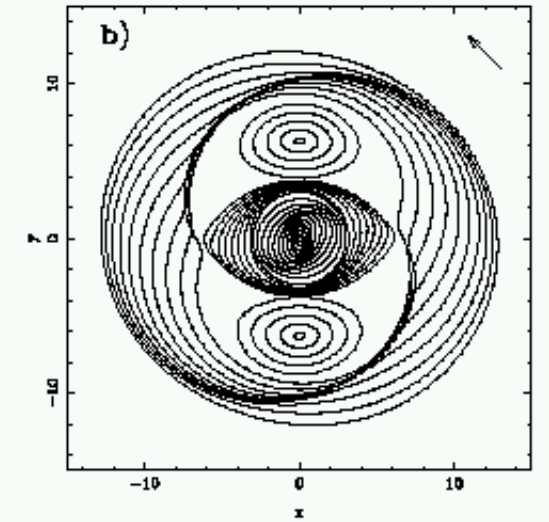
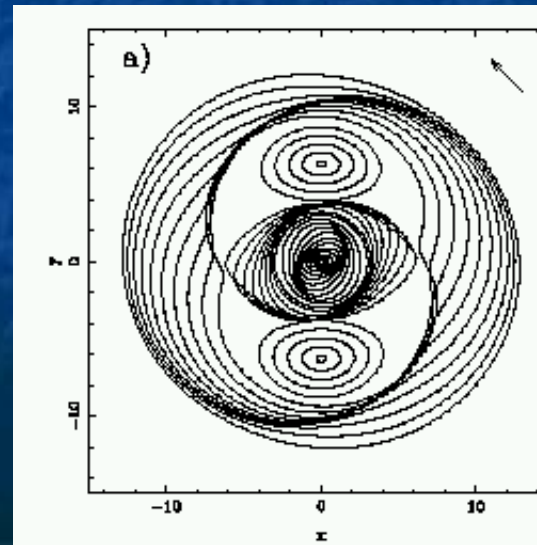
Stars



Gas



Gas



(from Combes 2003)

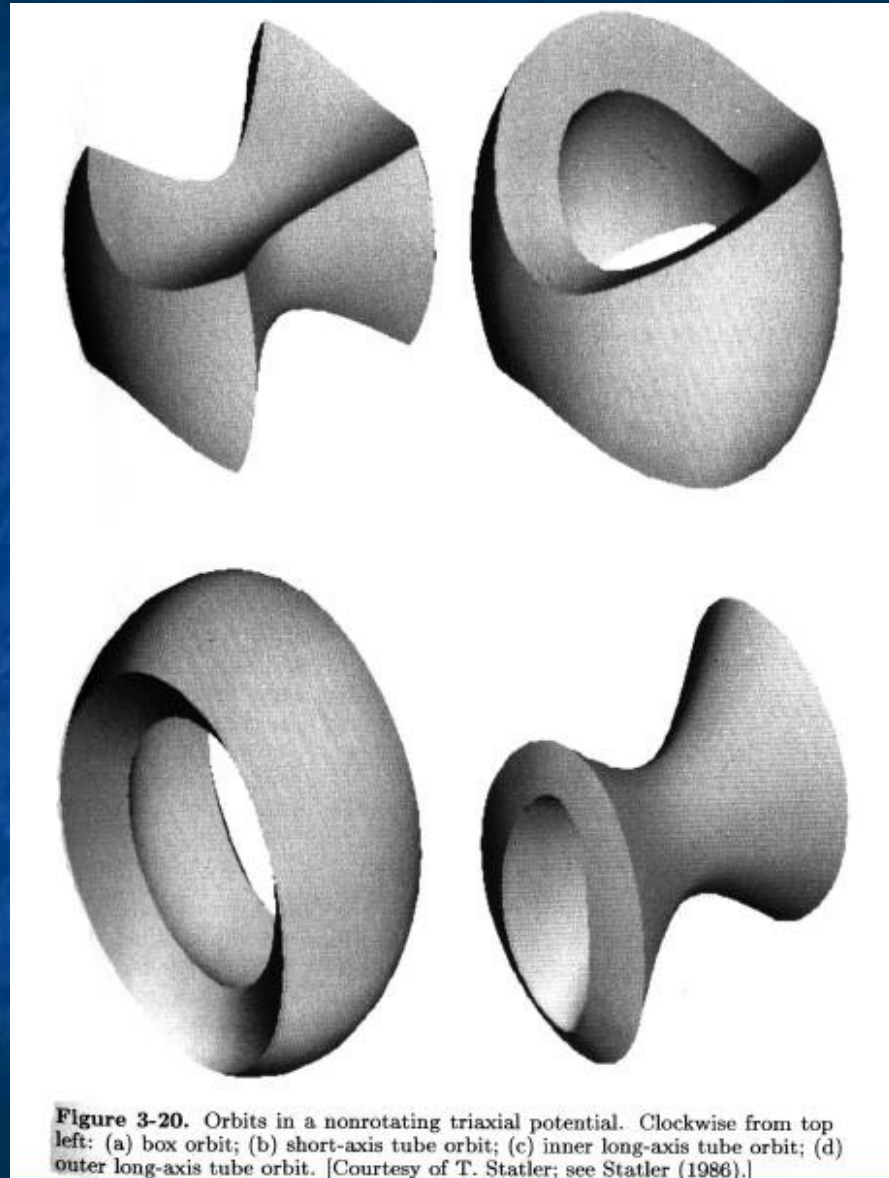


Figure 3-20. Orbits in a nonrotating triaxial potential. Clockwise from top left: (a) box orbit; (b) short-axis tube orbit; (c) inner long-axis tube orbit; (d) outer long-axis tube orbit. [Courtesy of T. Statler; see Statler (1986).]