STRUCTURE OF GALAXIES

Lecture 2. Luminosity distributions and component analysis.

Bulge luminosity laws.

Reynolds* (1913) made the first fit to the M31-bulge.

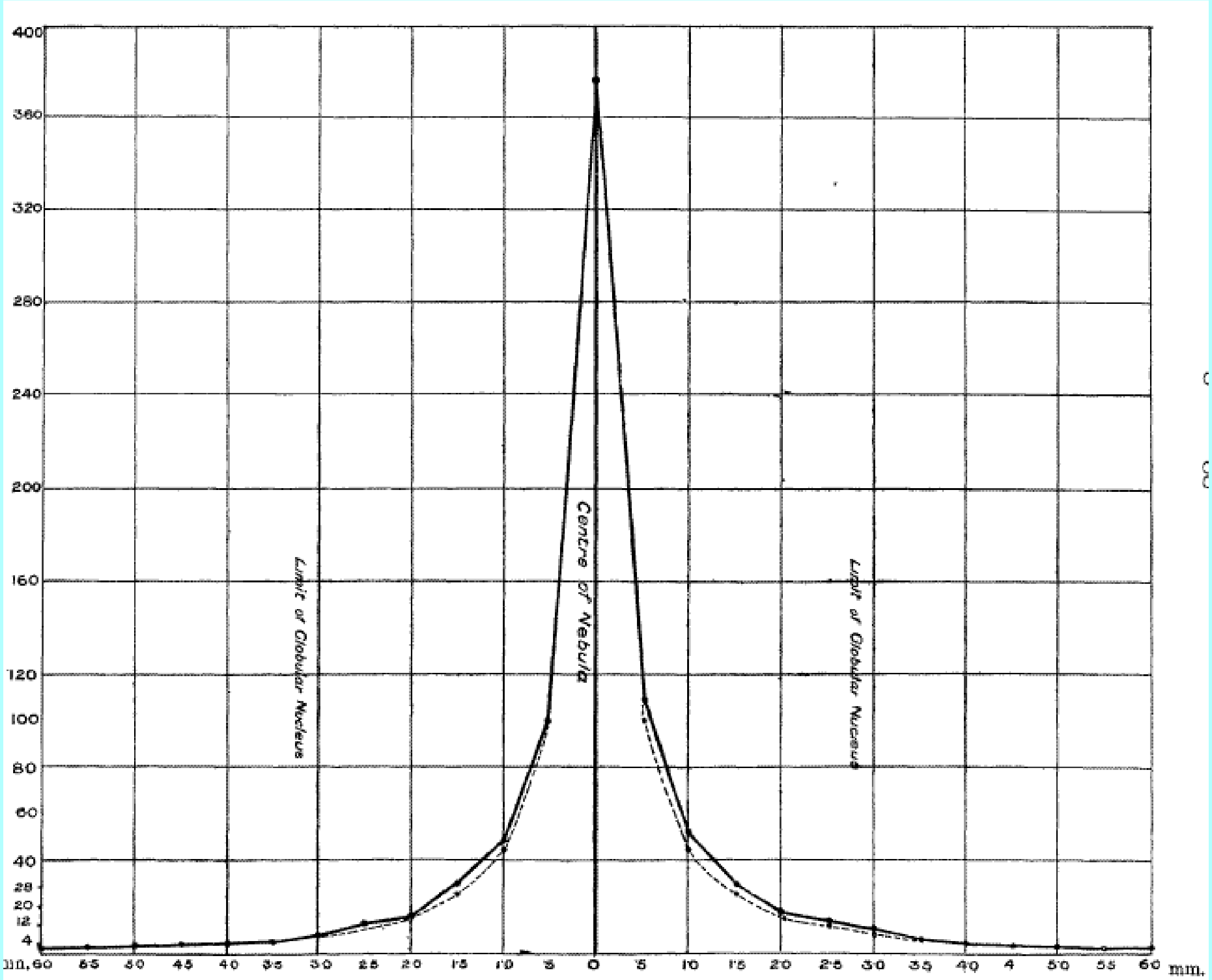
He used the function:

$$(x+1)^2 y = \text{constant}$$

with x the radial distance and y the "light ratio" (relative surface brightness on a linear scale).

He went out to only 6.9 arcmin ($\sim$ 1.4 kpc). At this radius the surface brightness is 21 B-mag arcsec^{-2}).

*Mon.Not.R.A.S. 74, 132



Light Curve of the Andromeda Nebula.

Hubble used this later in the form:

$$I(R) = I_0(R + a)^{-2}$$

The most commonly used fitting function is the so-called $R^{1/4}$-law found empirically by de Vaucouleurs* in 1948.

*Ann. d'Astrophys. 11, 247

$$\log \frac{I(R)}{I_{\mathrm{e}}} = -3.3307 \left[\left(\frac{R}{R_{\mathrm{e}}} \right)^{1/4} - 1 \right]$$

$$R_{\mathrm{e}} = \text{Effective radius}$$

$$\mu(0) = \mu_{\mathrm{e}} + 8.3268$$

$$L = 7.215 \pi I_{\mathrm{e}} R_{\mathrm{e}}^2 (b/a)$$

For this there is a numerical deprojection formula from Young*, which has an approximation for large R (in $\mathrm{L}_\odot\ \mathrm{pc}^{-3}$):

$$\begin{aligned} L(R) &= 52.19 \left(\frac{L}{R_{\mathrm{e}}} \right)^3 \left(\frac{R}{R_{\mathrm{e}}} \right)^{-7/8} . \\ &\qquad \exp \left[-7.67 \left(\frac{R}{R_{\mathrm{e}}} \right)^{1/4} \right] \end{aligned}$$

If flattened $R \to \alpha = \sqrt{R^2 (b/a)^2 + z^2}$.

*1976: A.J. 81, 807

More physical rather than empirical are the King models*, which work best for globular clusters and also better for elliptical galaxies than bulges.

They are based on isothermal distributions with upper limits on the energy of the particles and are therefore isothermal spheres with a tidal radius.

Jarvis & Freeman† introduce also rotation and study the effects of the gravitational effects of the disk.

The starting point is a distribution function, which is a truncated Maxwellian:

$$f(E, J) = \alpha[\exp(-\beta E) - \exp(\beta E_0)] \exp(\gamma J)$$

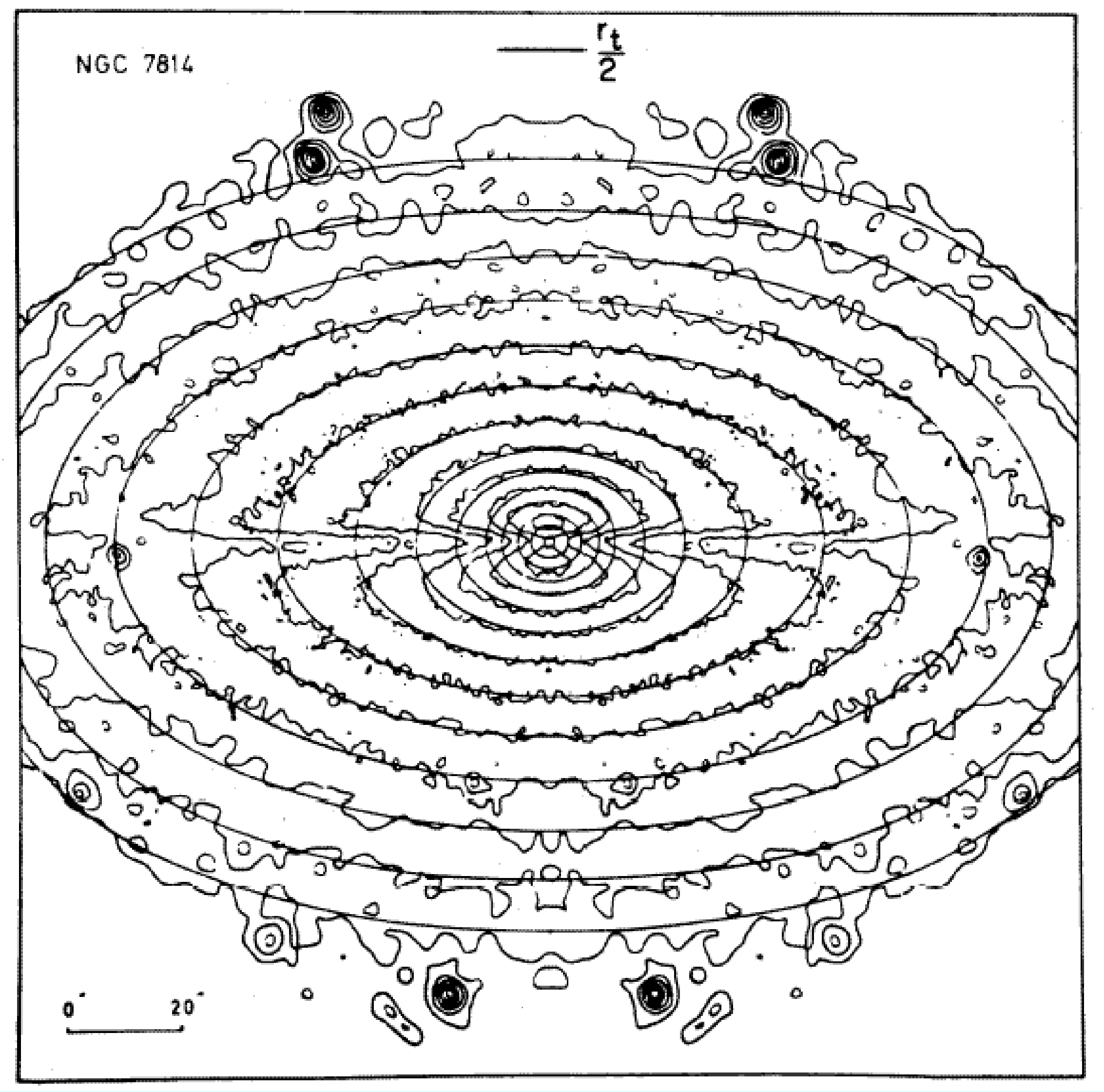
$E \leq E_0$ is the energy per unit mass and J the angular momentum parallel to the symmetry axis.

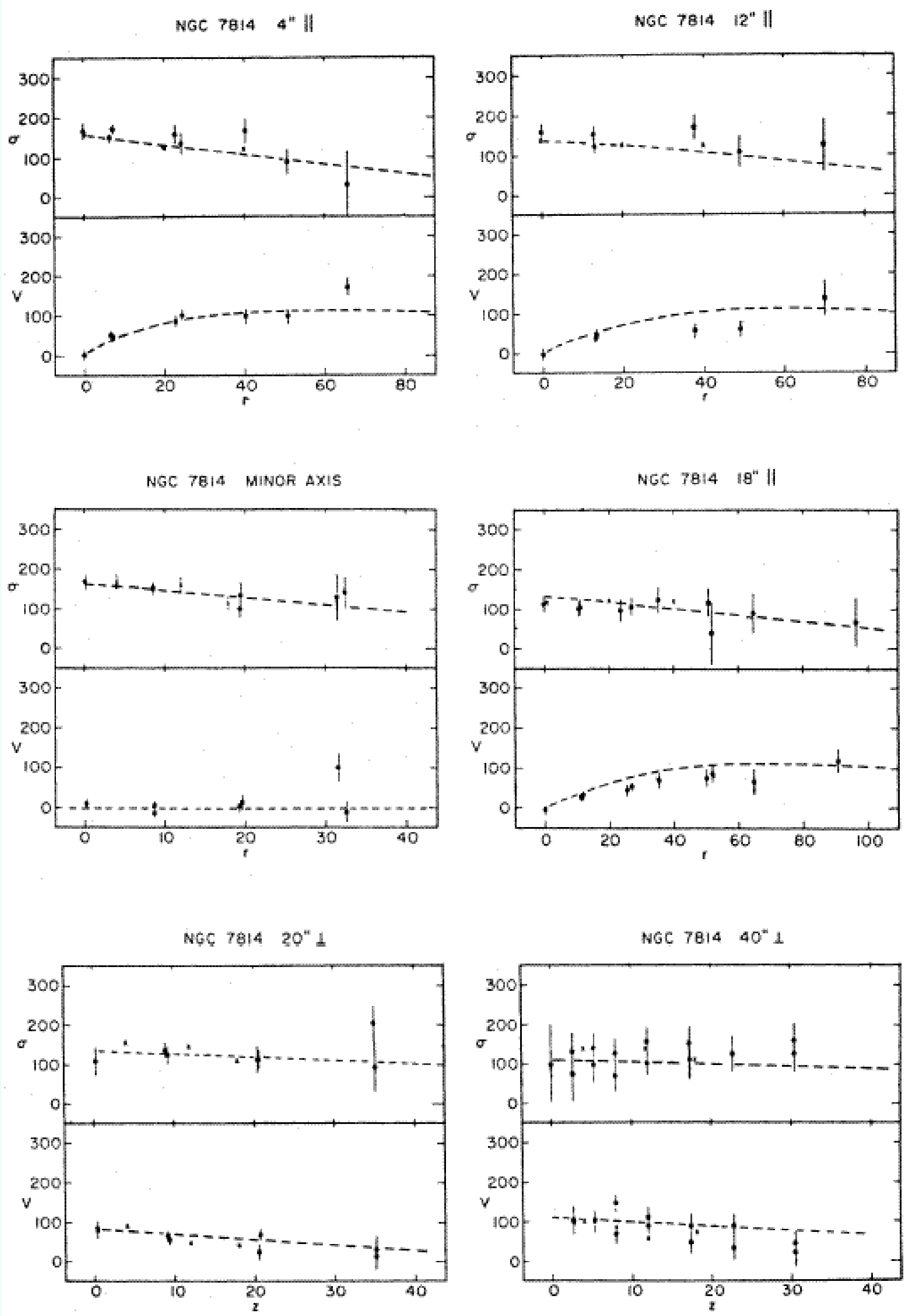
For $\gamma = 0$ we get the King models.

*A.J. 71, 64 (1966)

†Ap.J. 295, 314 and 324 (1986)

Jarvis and Freeman take a constant M/L and include effects of disk potential, and are able to reproduce observations of both isophotes and (stellar) kinematics.

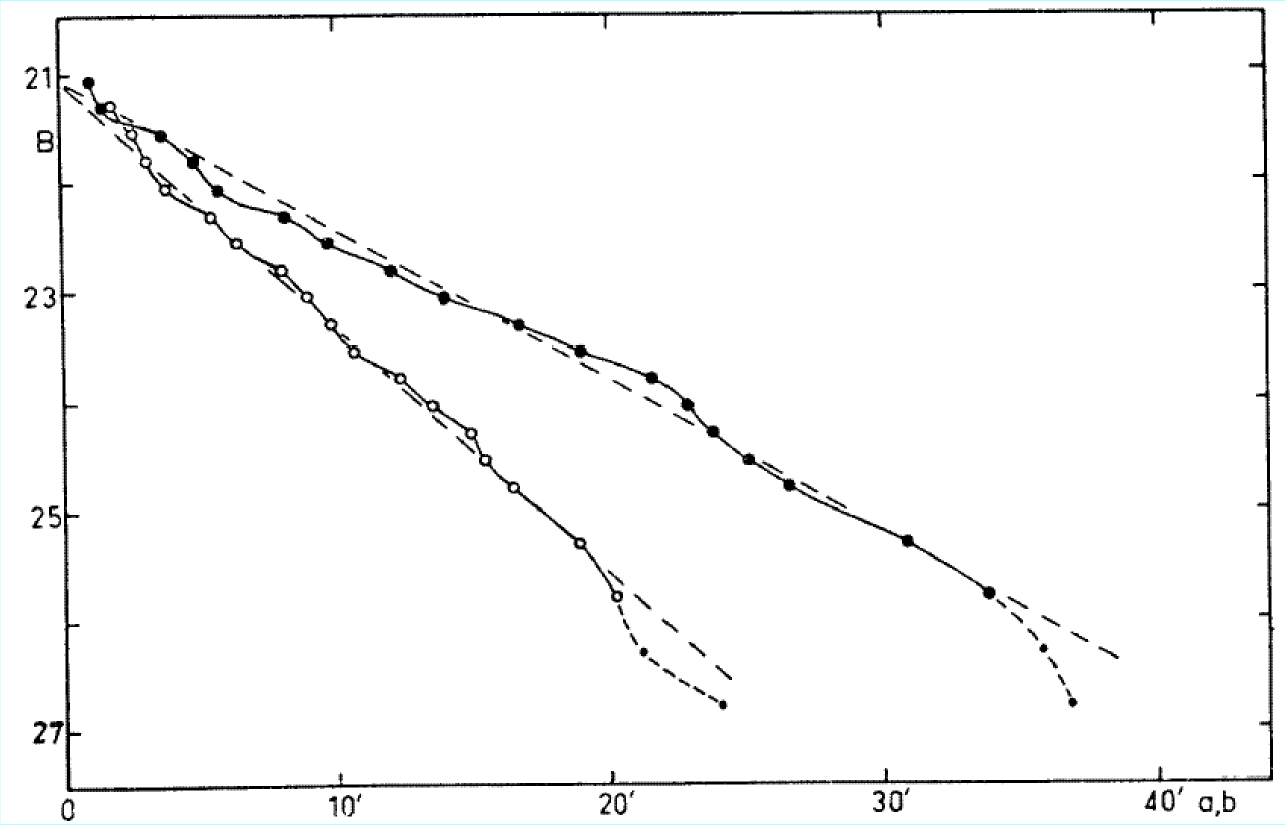




The conclusion is that bulges are consistent with isotropic, oblate spheroids, flattened mostly by rotation.

Luminosity distributions in disks

De Vaucouleurs* discovered that radial surface brightness profiles of disks are exponential.



A famous paper on exponential disks and the corresponding dynamics is by Freeman† (1970).

$$I(R) = I_0 \exp\left(-R/h\right)$$

*Ap.J. 130, 728 (1959)

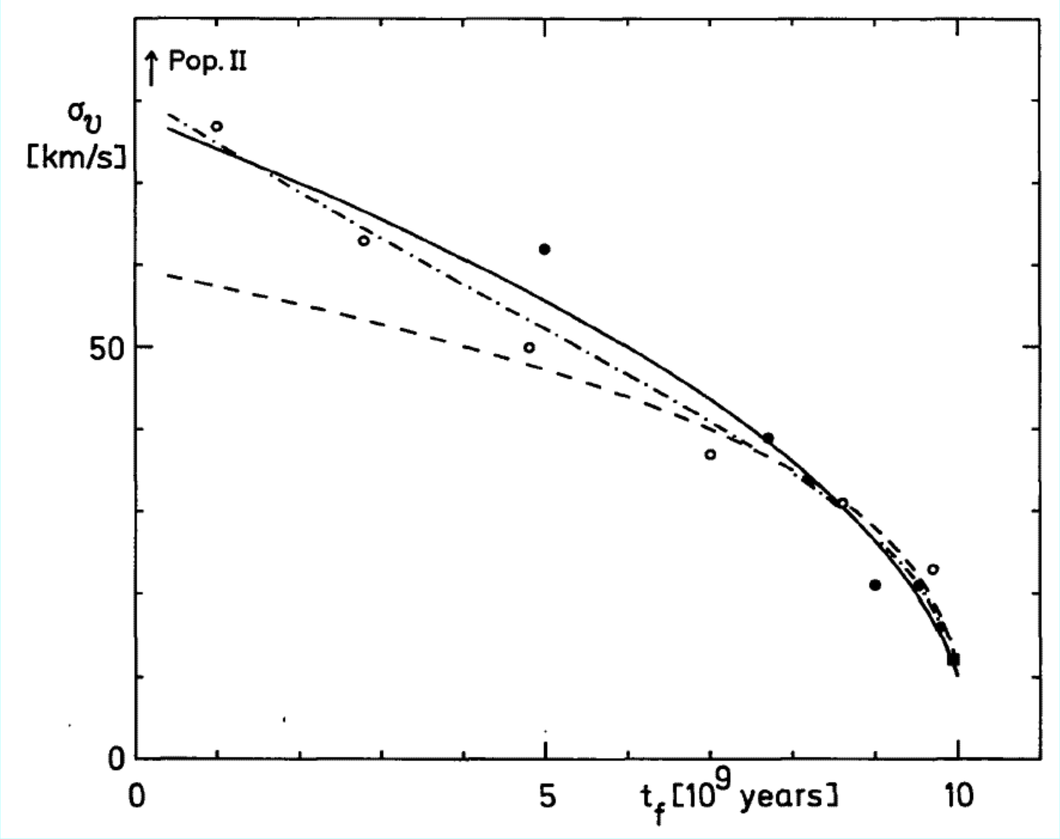
†Ap.J. 160, 811

The total luminosity is

$$L = 2\pi h^2 I_0$$

Vertical distributions can (away from the dust lane) be approximated with an isothermal sheet.

This is not unreasonable in view of the Age - Velocity dispersion relation* of stars in the solar neighborhood.



*Wielen, A.&A. 60, 263 (1977)

The three-dimensional distribution of stars in disks was therefore proposed* as (with the inclusion of a cut-off radius, so that $R < R_{\mathrm{max}}$)

$$L(R,z) = L(0,0)\ \exp\left(-R/h\right)\ \mathrm{sech}^{\,2}(z/z_0)$$

$$I(R) = 2z_0 L(0,0)\ \exp\left(-R/h\right)$$

$$\langle V_z^2\rangle = \pi G I(R) z_0 (M/L)$$

For large z-distances:

$z/z_0 \gg 1$ then $\mathrm{sech}^{\,2}(z/z_0) = 4\ \exp\left(-2z/z_0\right)$

Near the plane:

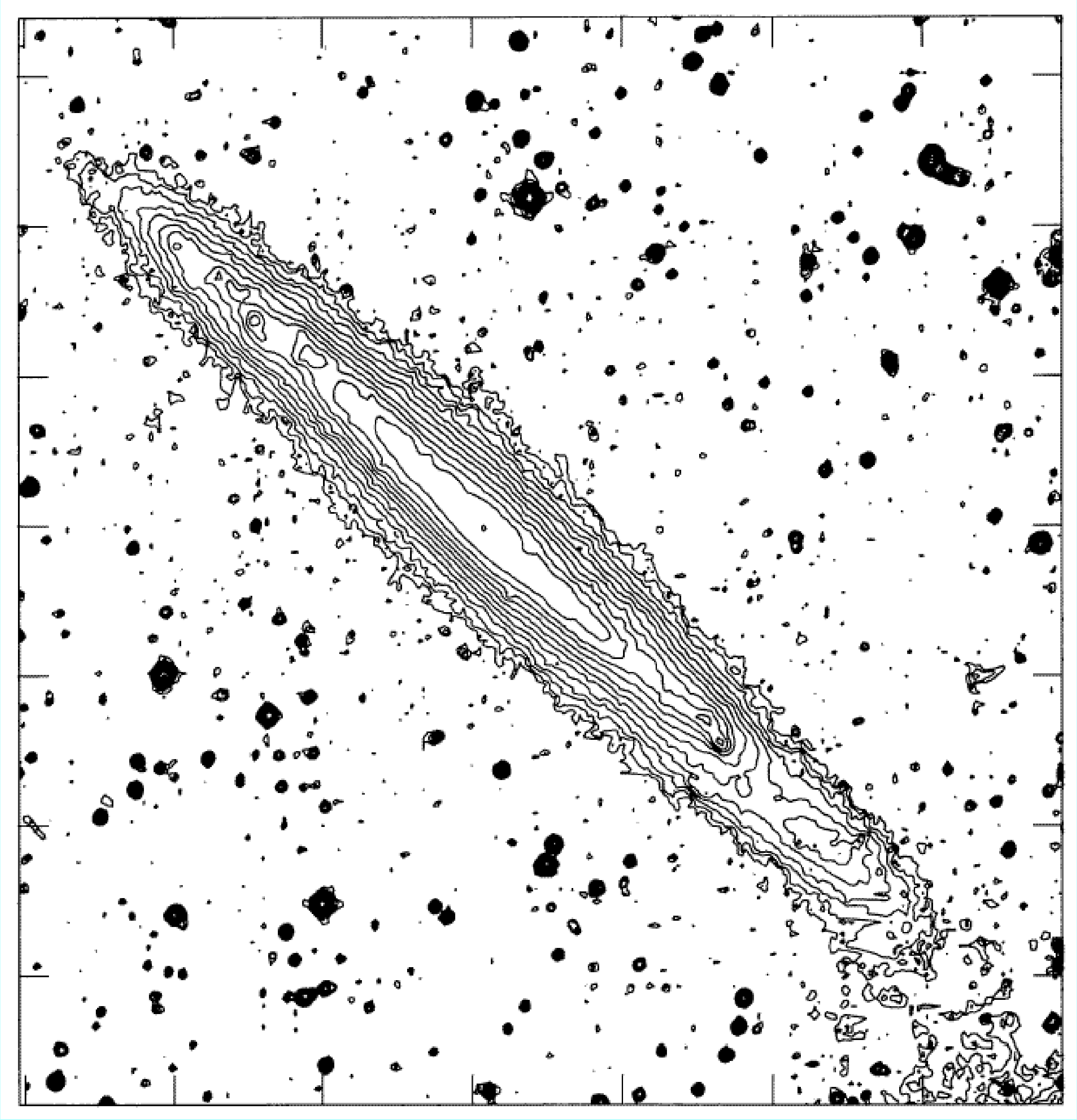
$z/z_0 \ll 1$ then $\mathrm{sech}^{\,2}(z/z_0) = \exp\left(-z^2/z_0^2\right)$

For $R_{\mathrm{max}} \rightarrow \infty$:

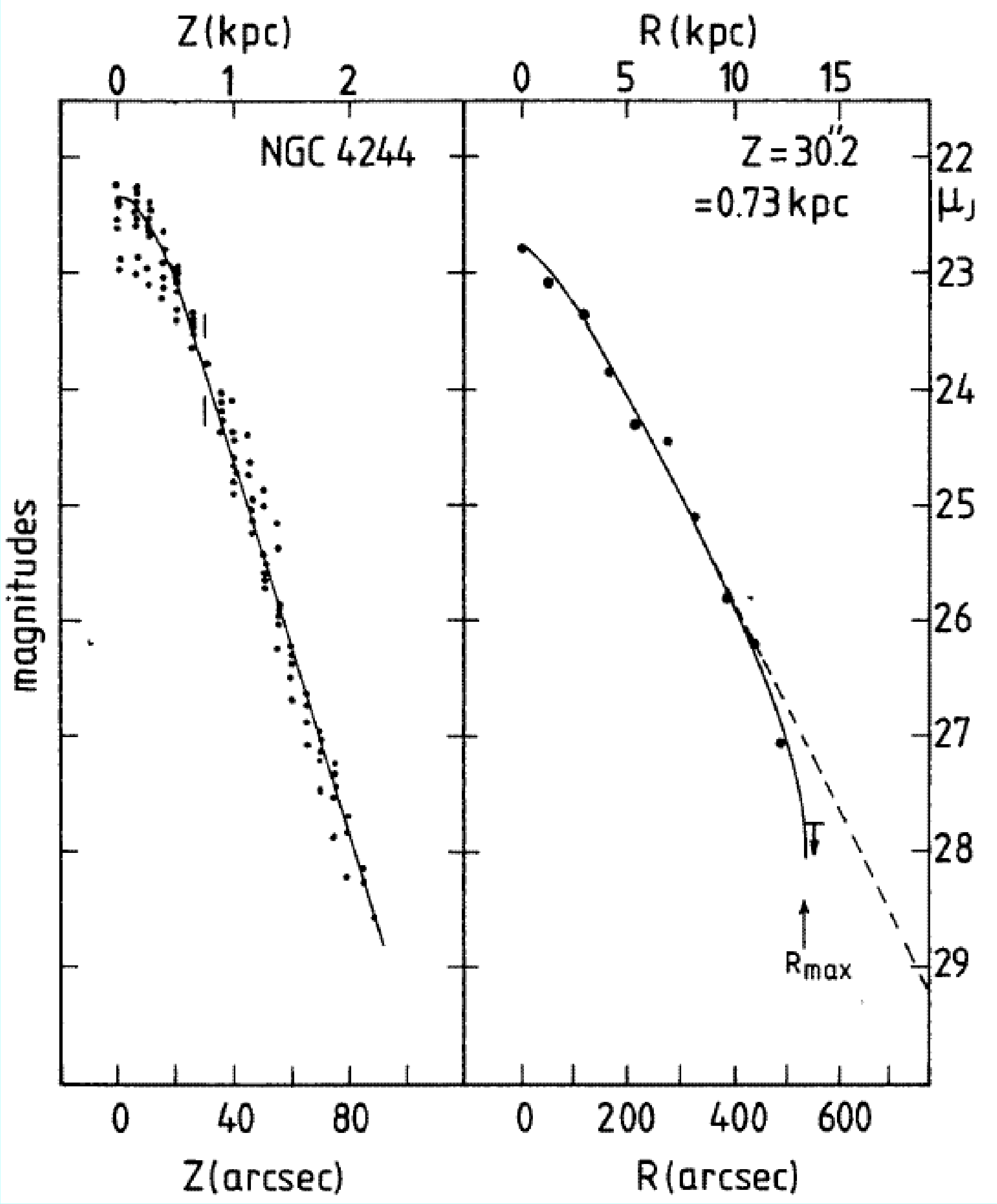
$I(R,z) = 2hL(0,0)(R/h)K_1(R/h)\ \mathrm{sech}^{\,2}(z/z_0)$

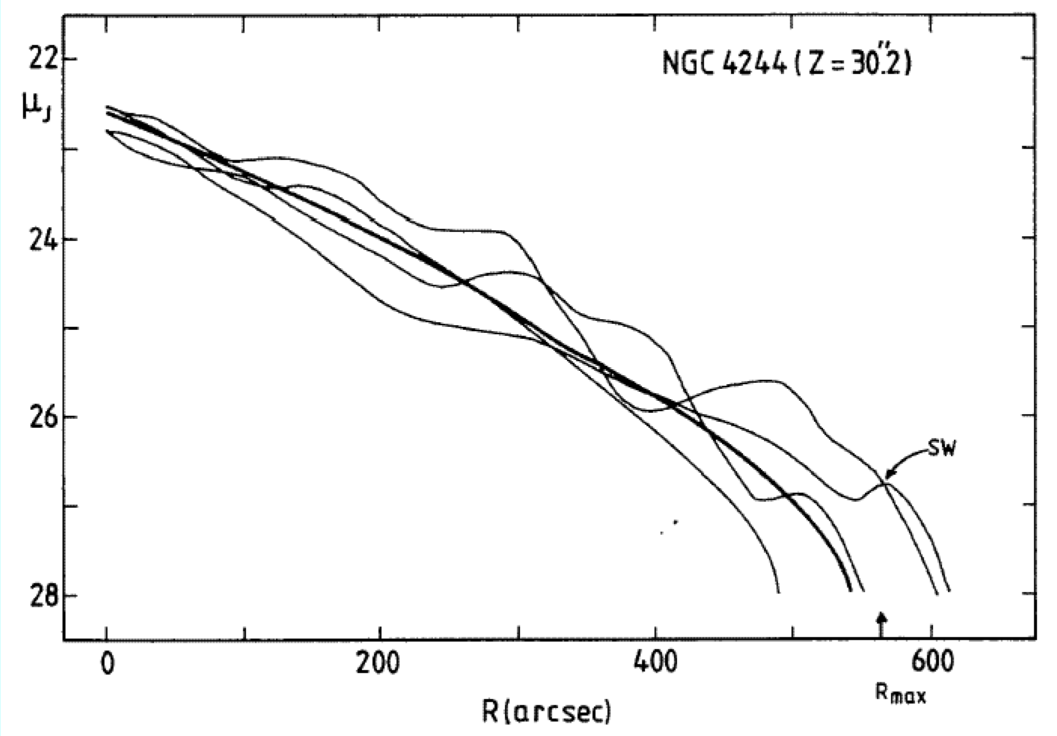
*van der Kruit & Searle, A.&A. 95, 105 (1981)

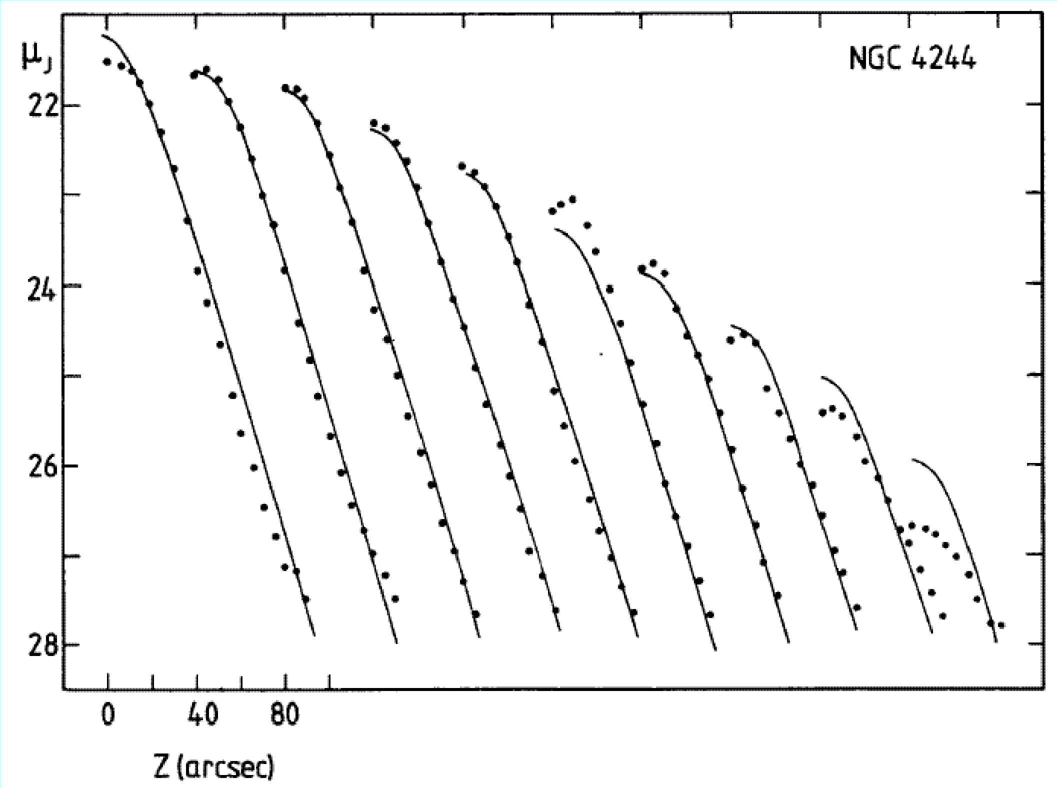
Here is an isophote map of the pure disk, edge-on galaxy NGC 4244.



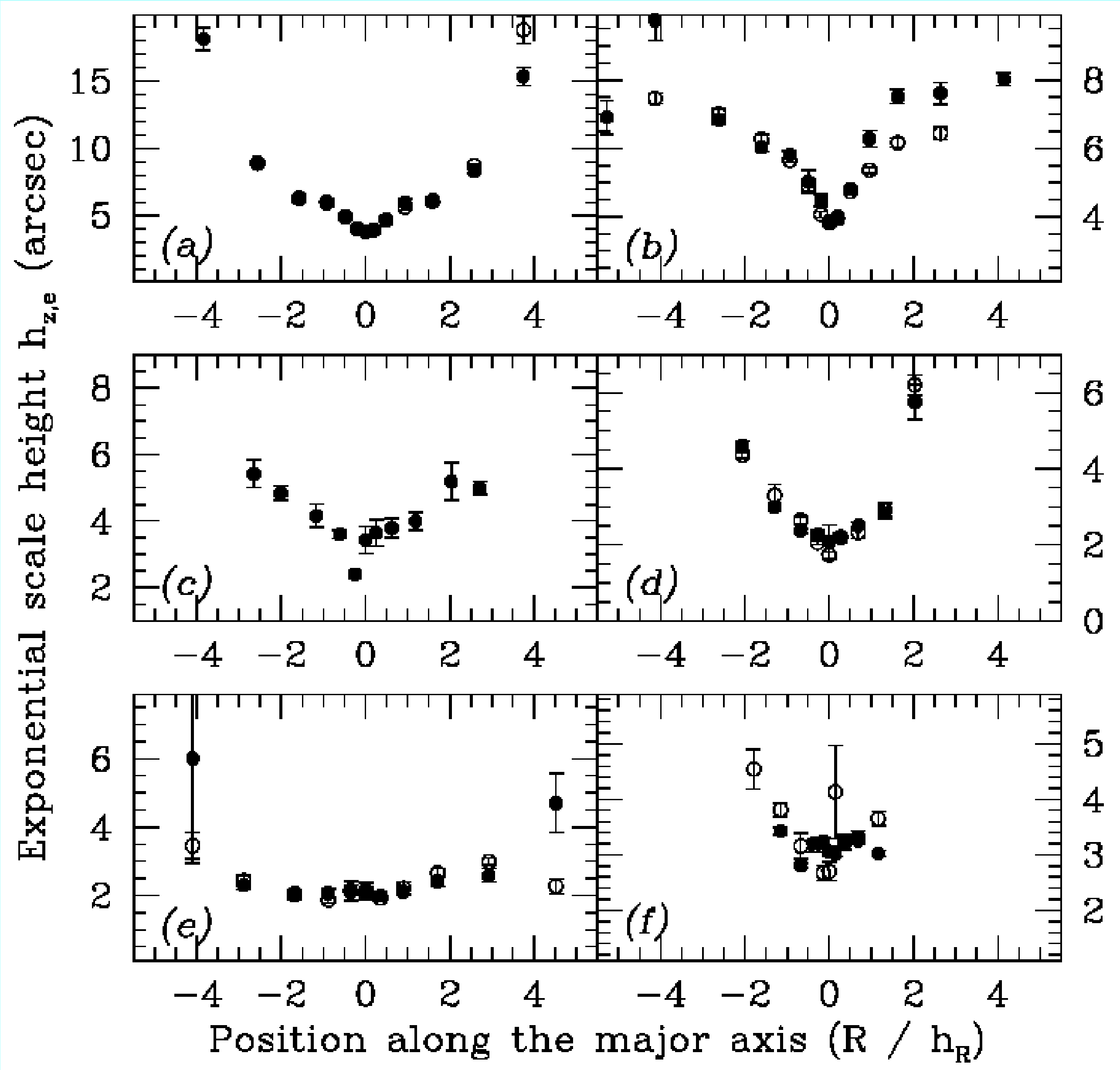
We fit profiles, averaged symmetrically, in z at various R and shifted in coincidence (left) and at a radial profile at a suitable z above the dustlane.



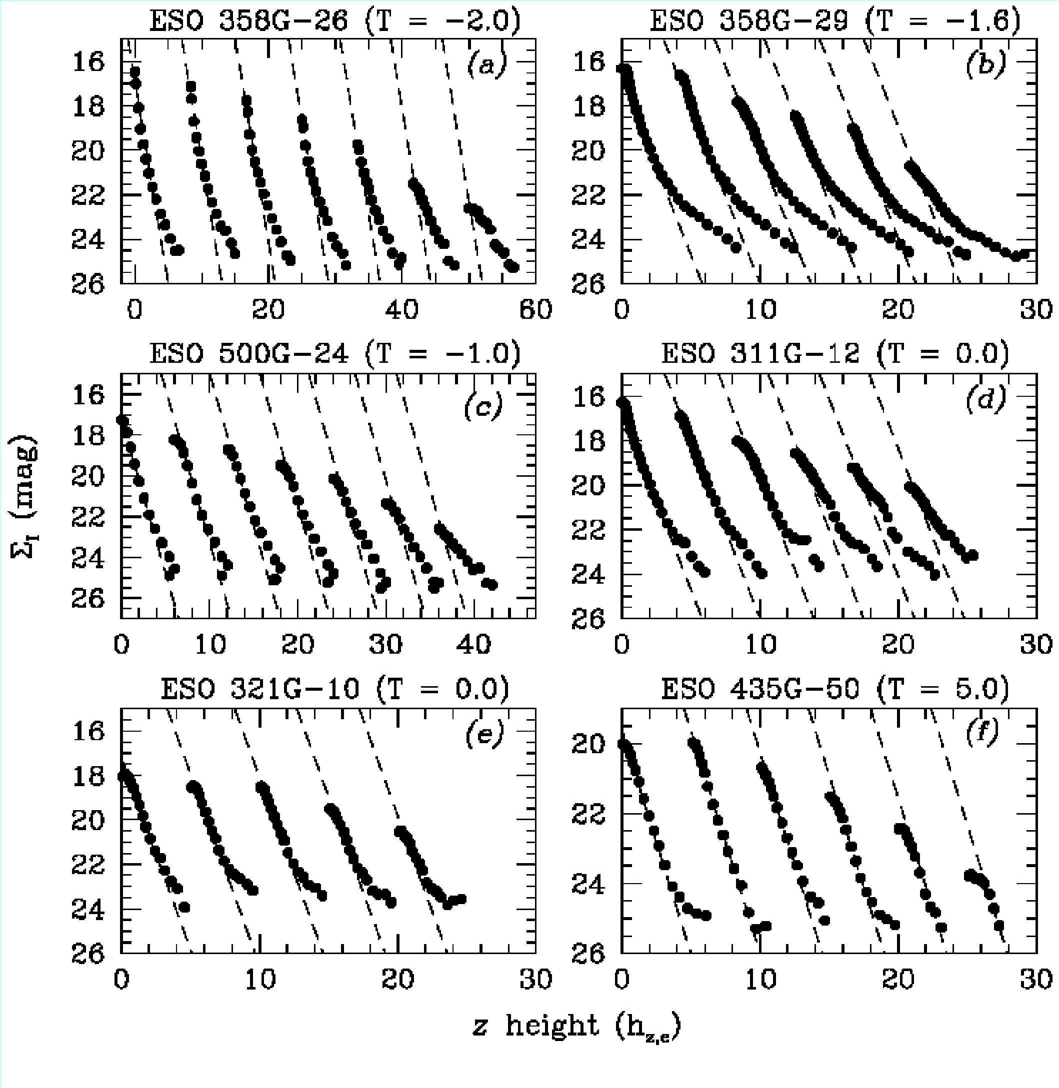

NGC 4244 (Z = 30.″2)
μJ
22
24
26
28
SW
0
200
400
600
Rmax
R (arcsec)


NGC 4244
μJ
22
24
26
28
0
40
80
Z (arcsec)

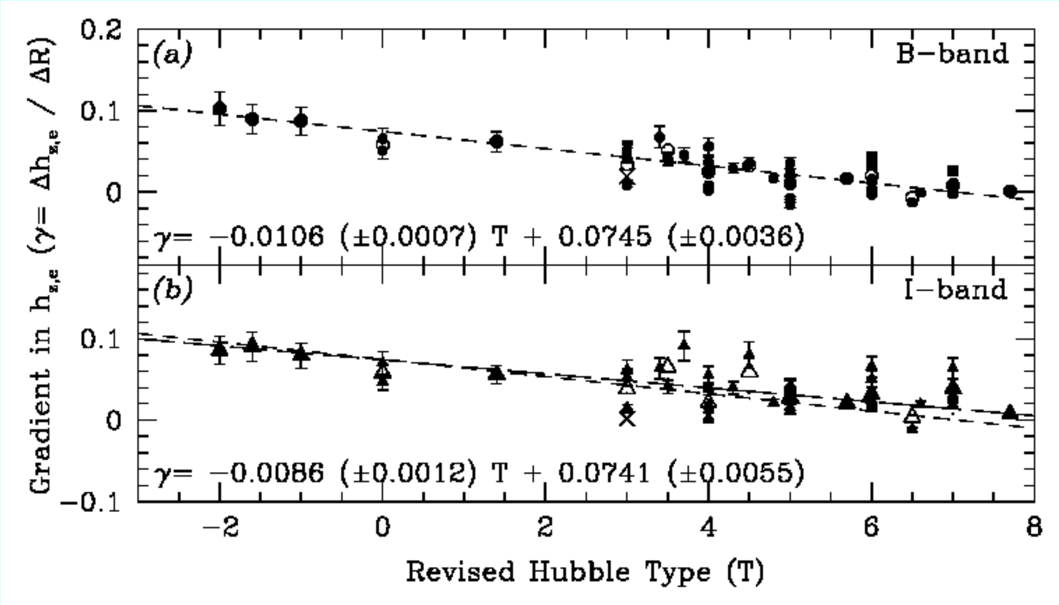
A closer look at a larger set of edge-on galaxies* shows that the constancy of the vertical scale-height $z_\circ$ does not hold for early type galaxies.



*de Grijs & Peletier, A.&A. 320, L21 (1997)



ESO 358G-26 (T = −2.0)
ESO 358G-29 (T = −1.6)
ESO 500G-24 (T = −1.0)
ESO 311G-12 (T = 0.0)
ESO 321G-10 (T = 0.0)
ESO 435G-50 (T = 5.0)
(a)
(b)
(c)
(d)
(e)
(f)
Σ_I (mag)
z height ($h_{z,e}$)



(a)
B−band
$\gamma = -0.0106\ (\pm 0.0007)\ T + 0.0745\ (\pm 0.0036)$
(b)
I−band
$\gamma = -0.0086\ (\pm 0.0012)\ T + 0.0741\ (\pm 0.0055)$
Gradient in $h_{z,e}$ ($\gamma = \Delta h_{z,e} / \Delta R$)
Revised Hubble Type (T)

It is unlikely that at moderate and small distances above the plane the stellar population is isothermal.

Therefore a set of functions was proposed to allow for this*

$$L(z) = L(0)2^{-2/n} \,\mathrm{sech}^{\,2/n}\left(\frac{nz}{2z_\circ}\right)$$

This ranges from the isothermal distribution for $n = 1$ to an exponential for $n = \infty$.

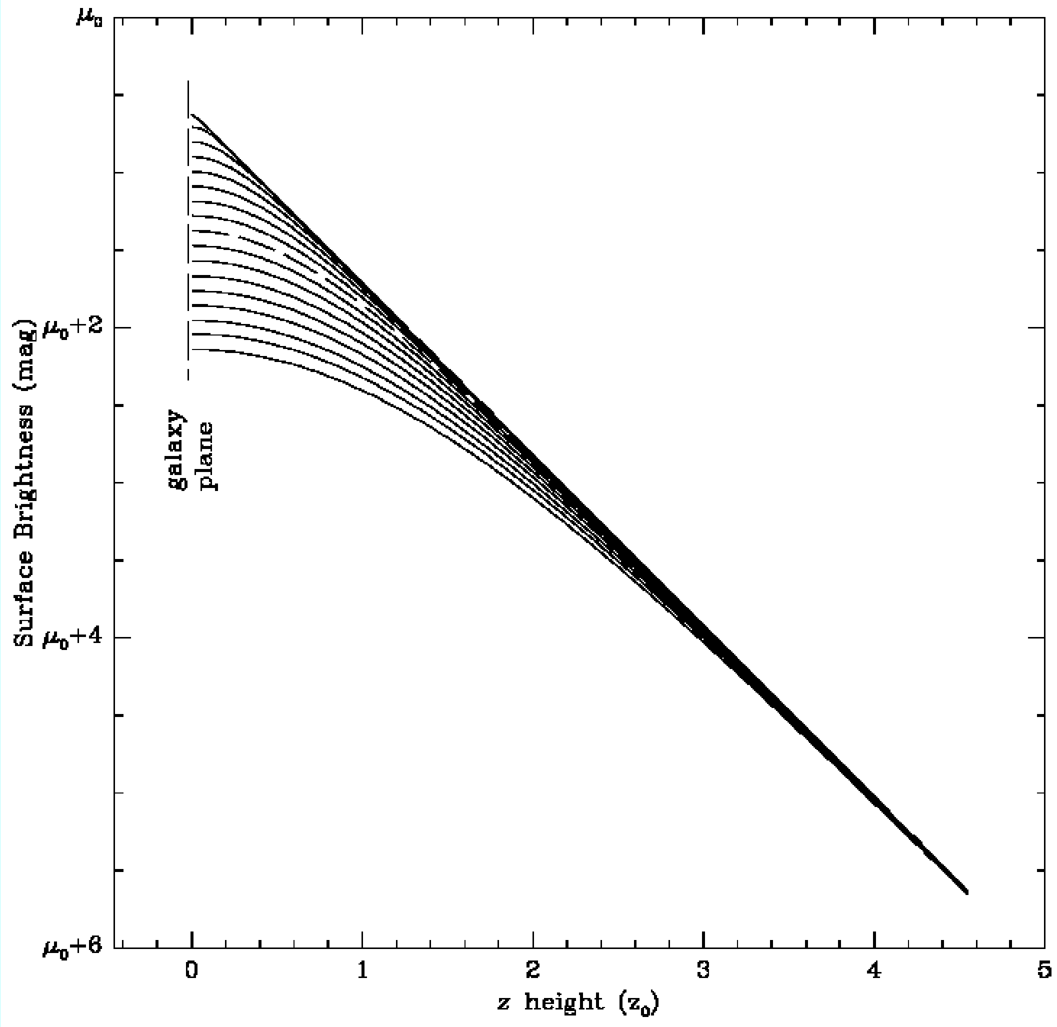
Fits† give

$$2/n = 0.54 \pm 0.20$$

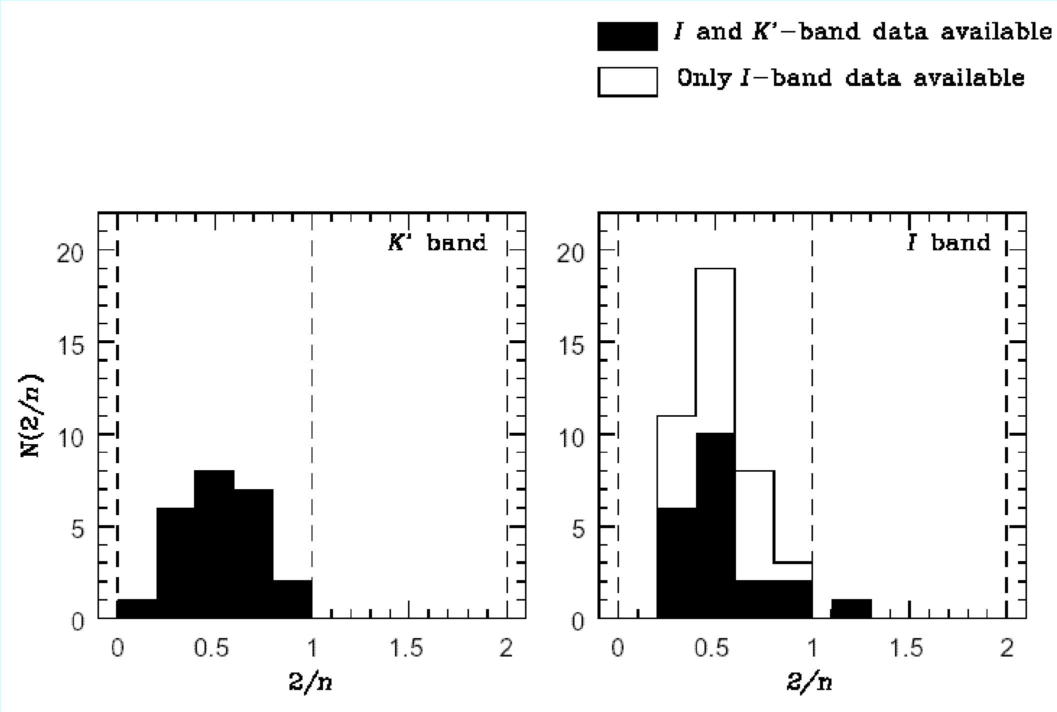
in the K-band (2.2 μ).

*van der Kruit, A.&A. 192, 117 (1988)

†de Grijs, Peletier & van der Kruit, A.&A. 327, 966 (1997)



μ_0
μ_0+2
μ_0+4
μ_0+6
Surface Brightness (mag)
galaxy plane
0
1
2
3
4
5
z height (z_0)



I and K'−band data available
Only I−band data available
K' band
I band
N($2/n$)
0
5
10
15
20
0
0.5
1
1.5
2
$2/n$

Component separation

a. Inclined spirals

The usual assumption is to view the galaxy as built up of an exponential disk and an $R^{1/4}$-bulge.

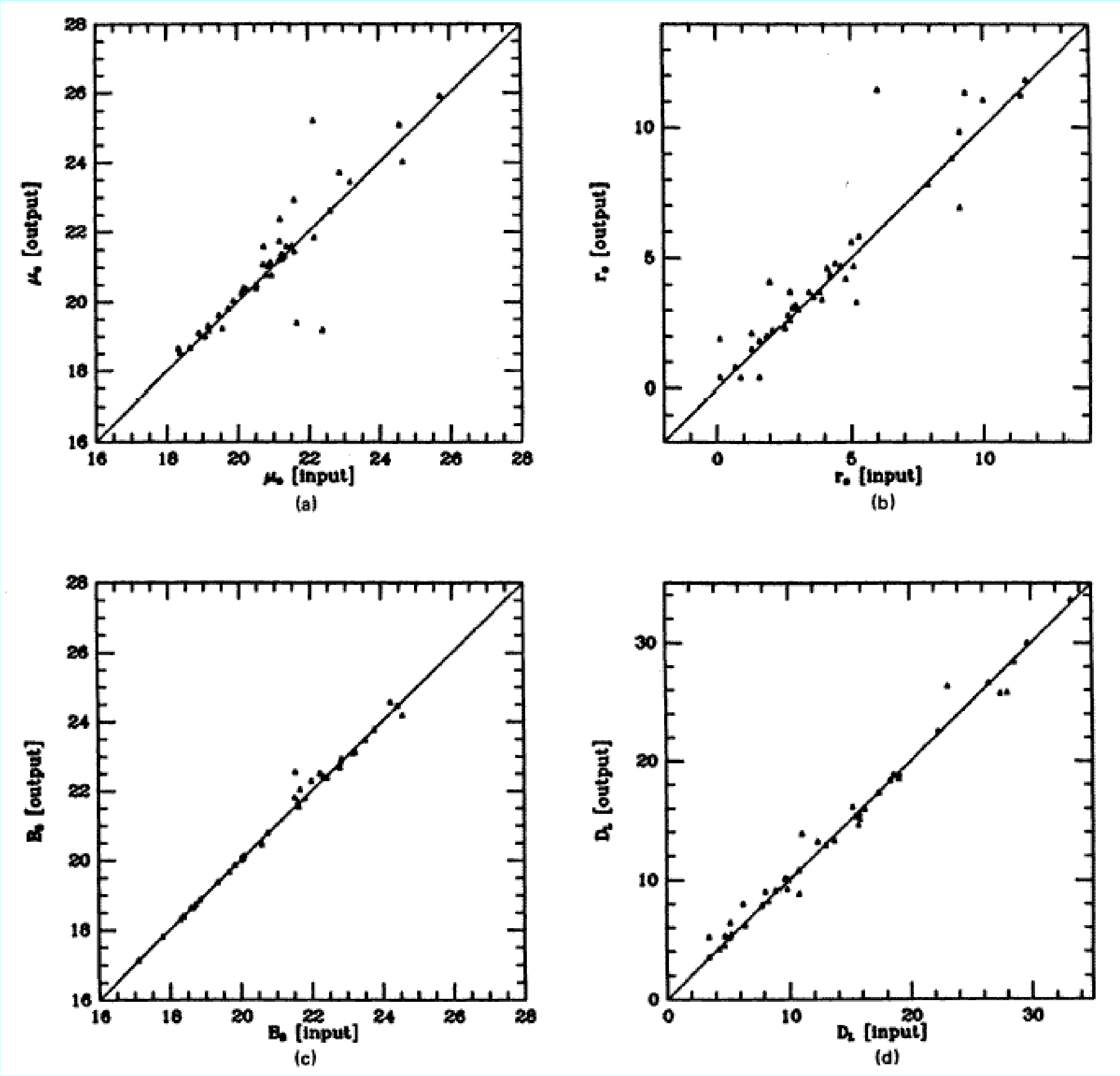
Parameters of the fit then are:

- μ_e and R_e for the bulge
- μ_0 and h for the disk

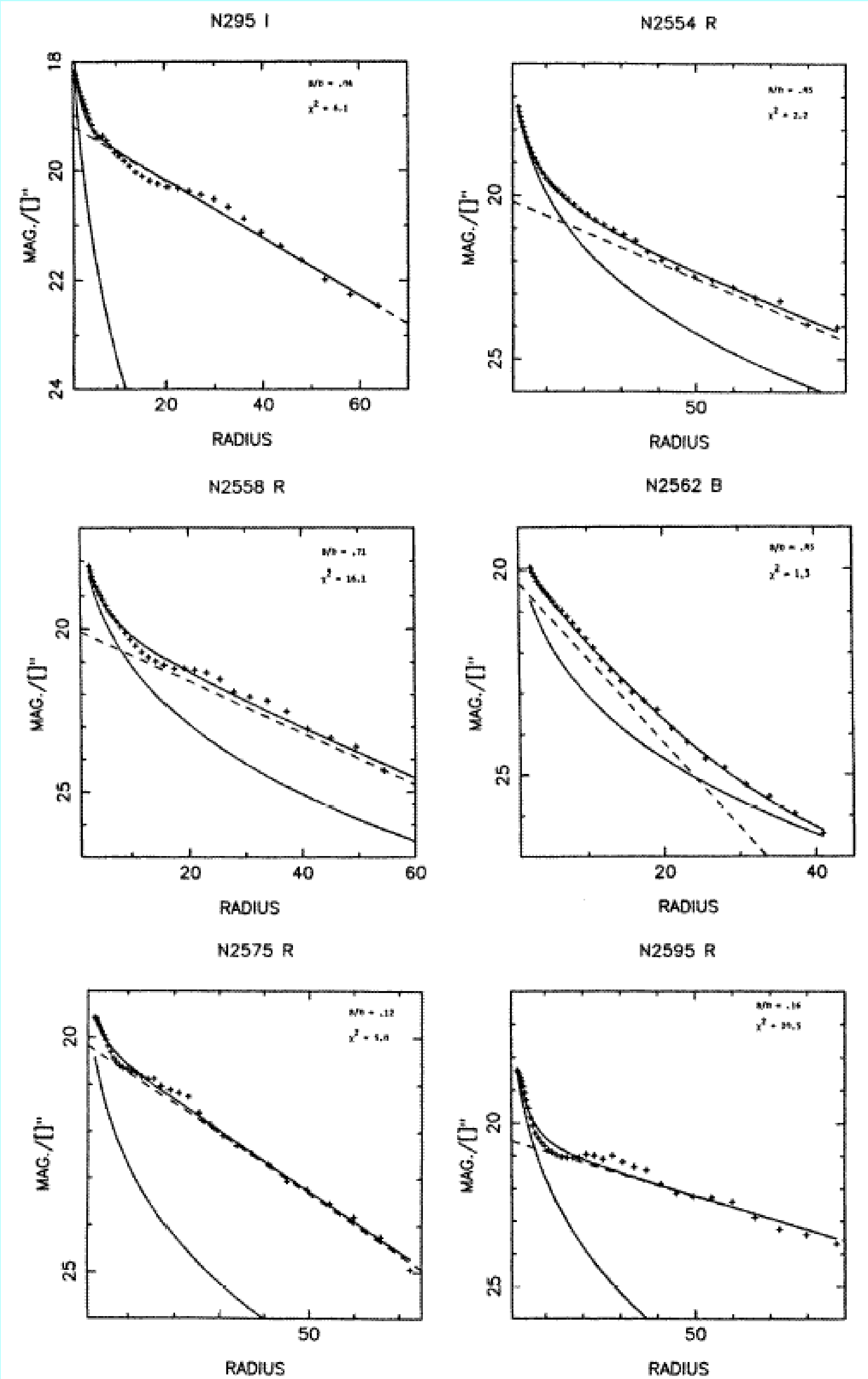
This is usually done with some least-squares procedure after a first guess at parameters for the dominant component.

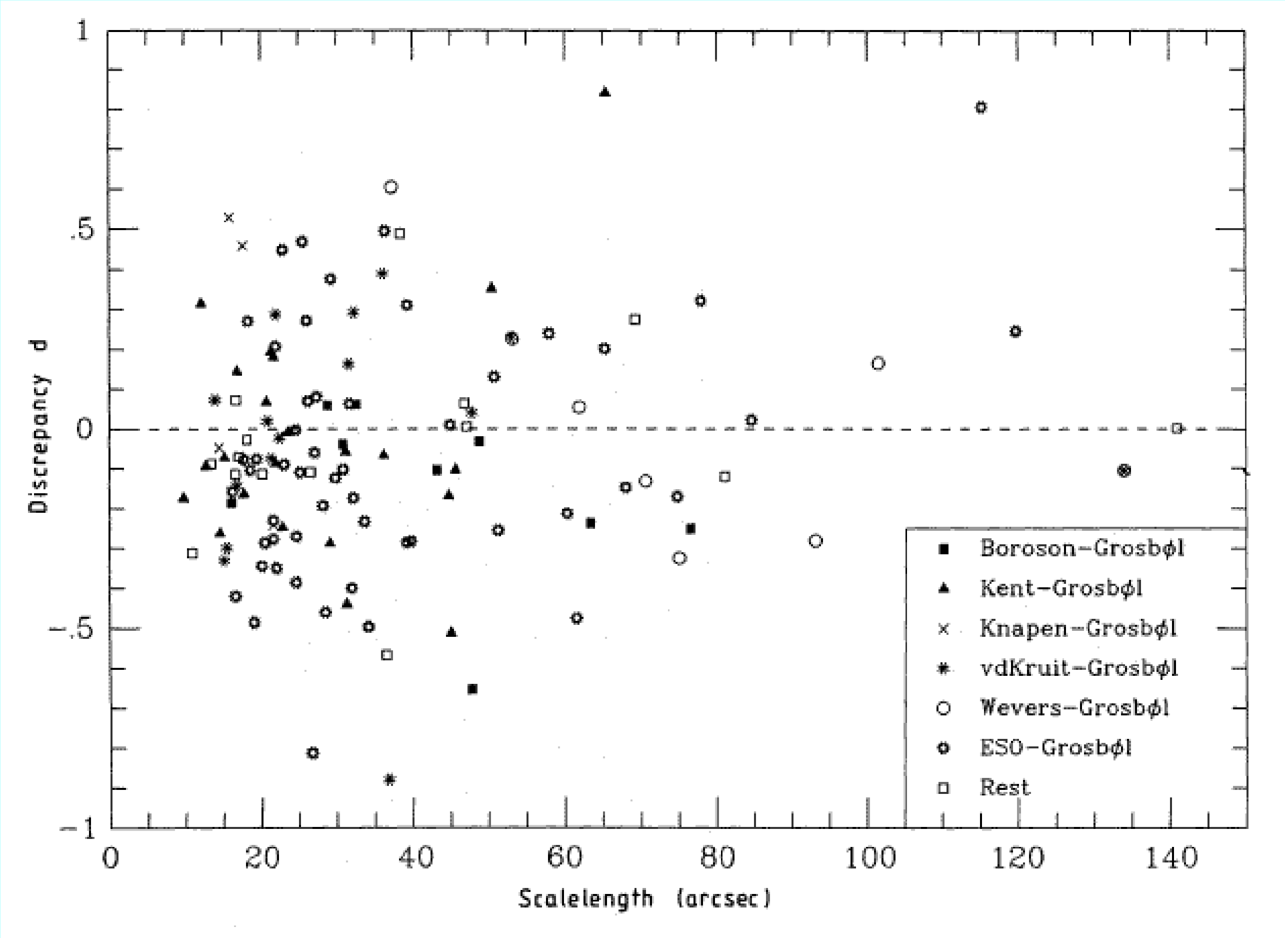
Test on artificial images* show that this usually works well.

*Schombert & Bothun, A.J. 92, 60 (1987)



Each panel has the input parameter on the horizontal axis and the output one vertically. The top panels are for the bulge effective surface brightness and effective radius; the bottom ones are the disk central surface brightness and the scalelength.


N295 I
N2554 R
N2558 R
N2562 B
N2575 R
N2595 R
MAG./[]"
RADIUS



A comparison* of published scalelengths in the literature shows large discrepancies.

The discrepancy $d = (h_1 - h_2)/\langle h \rangle$ is plotted in the figure above as a function of $\langle h \rangle$.

The average absolute discrepancy is 23%.

This is mainly due to differences in fitting algorithms.

*Knapen & van der Kruit, A.&A. 248, 57 (1991)

b. Edge-on spirals

We now fit to a projected exponential, locally isothermal disk and an $R^{1/4}$-bulge.

Parameters of the fit now are:

- μ_0, h and z_0 for the disk

- μ_e, R_e and b/a for the bulge

The fit is made first for the dominant component and this is subtracted from the observed distribution.

We look at two examples:
NGC 891*. This is an Sb in which the disk dominates the light.
NGC 7814†. This is an Sa and the bulge dominates the light.

*van der Kruit & Searle, A.&A. 95, 116 (1981)

†van der Kruit & Searle, A.&A. 110, 79 (1982)

NGC 891 (D = 9.5 Mpc)

DISK (old disk only):

$L_\mathrm{B}(0,0) = 2.4 \times 10^{-2} L_\odot \ \mathrm{pc}^{-3}$

$h = 4.9$ kpc

$z_0 = 0.99$ kpc

$R_\mathrm{max} = 21$ kpc

$L = 6.7 \times 10^9 L_\odot$ (≈**82 %** of total)

$(B-V) \approx 0.8$

$(U-B) \approx 0.1$

BULGE:

$R_\mathrm{e} \approx 2.3$ kpc

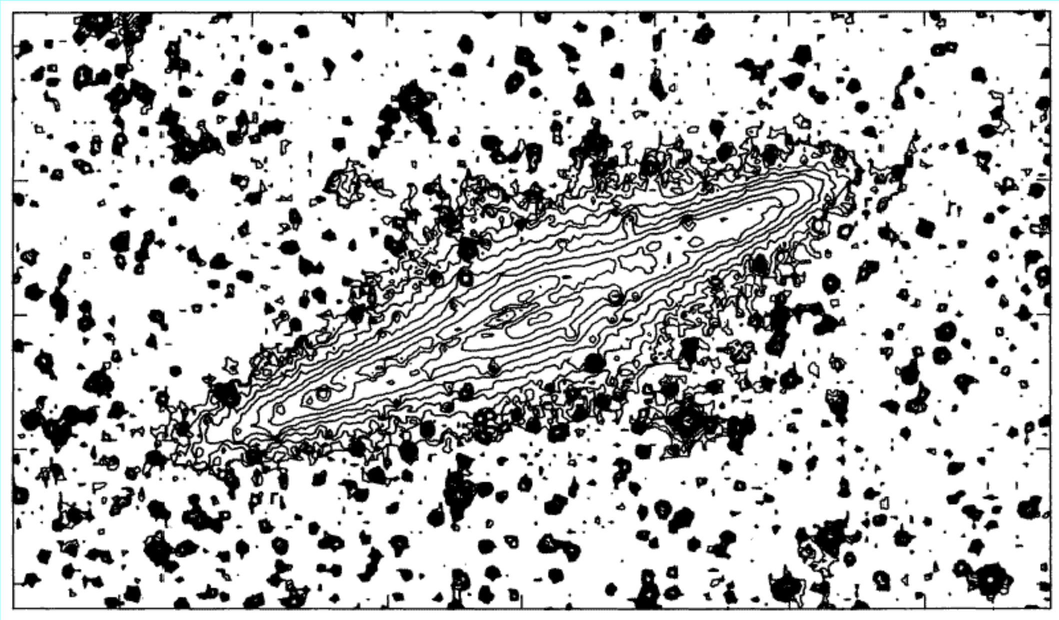
$b/a \approx 0.6$

$L_\mathrm{B} \approx 1.5 \times 10^9 L_\odot$

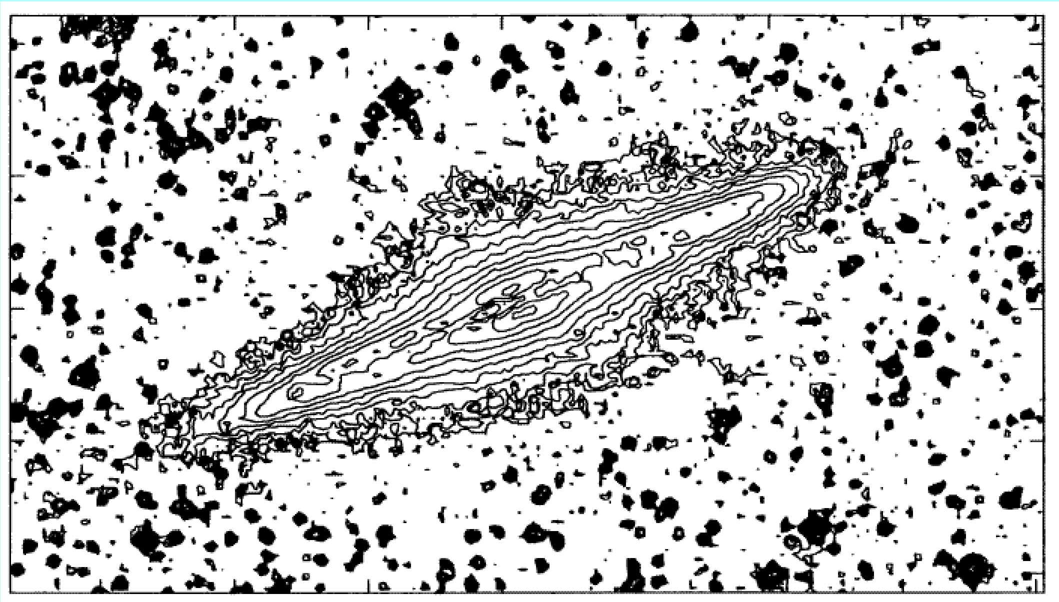
$(B-V) \approx 0.7 \leftrightarrow 1.0$ (6 $\leftrightarrow$ 2 kpc minor axis)

$(U-B) \approx -0.1 \leftrightarrow 0.4$

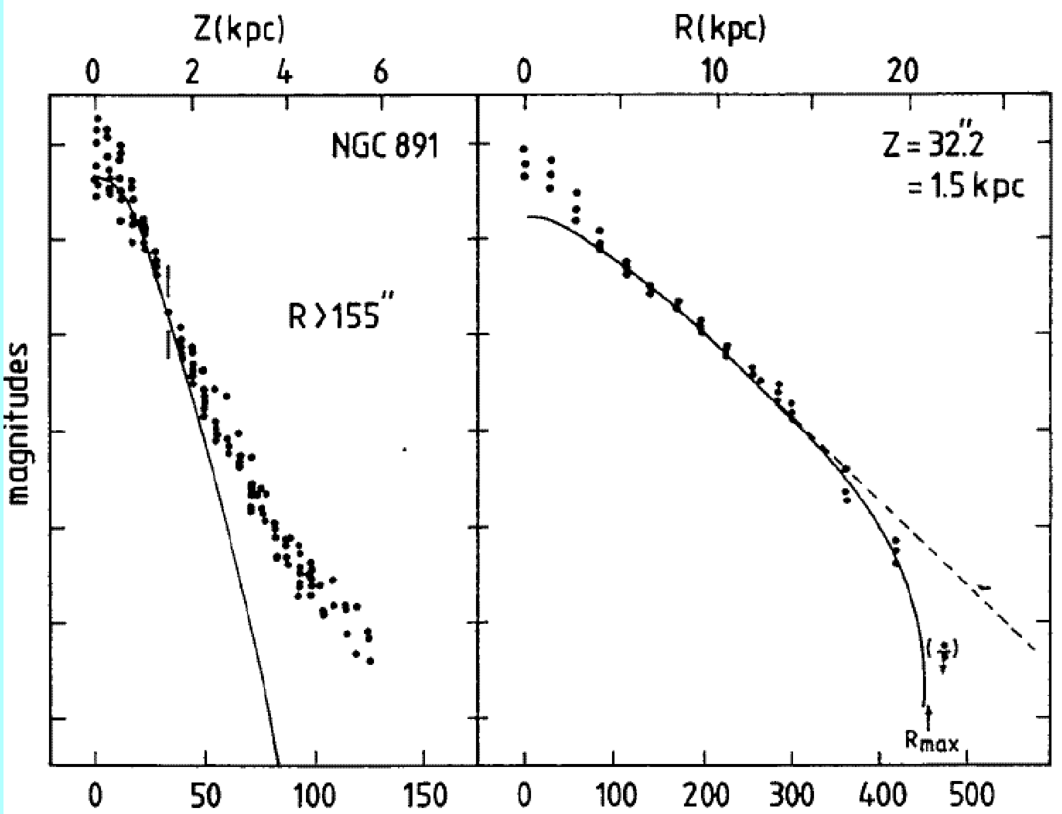
We start with the original image (here the $J \approx B$ band).



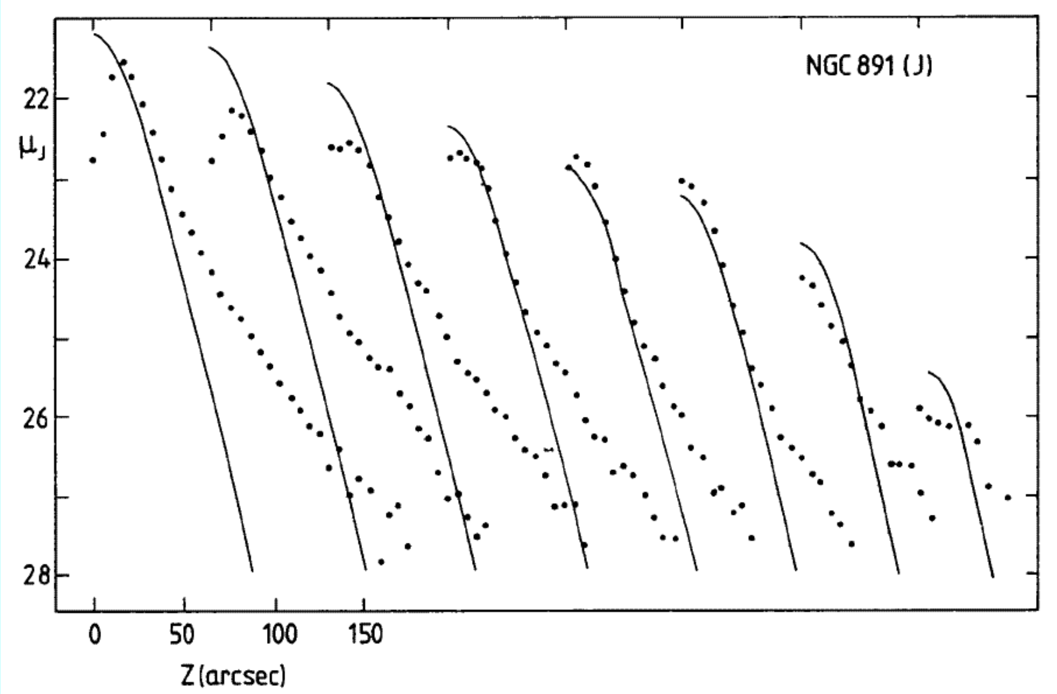
First we need to "subtract" foreground stars by interpolating over their image (or simply block them).

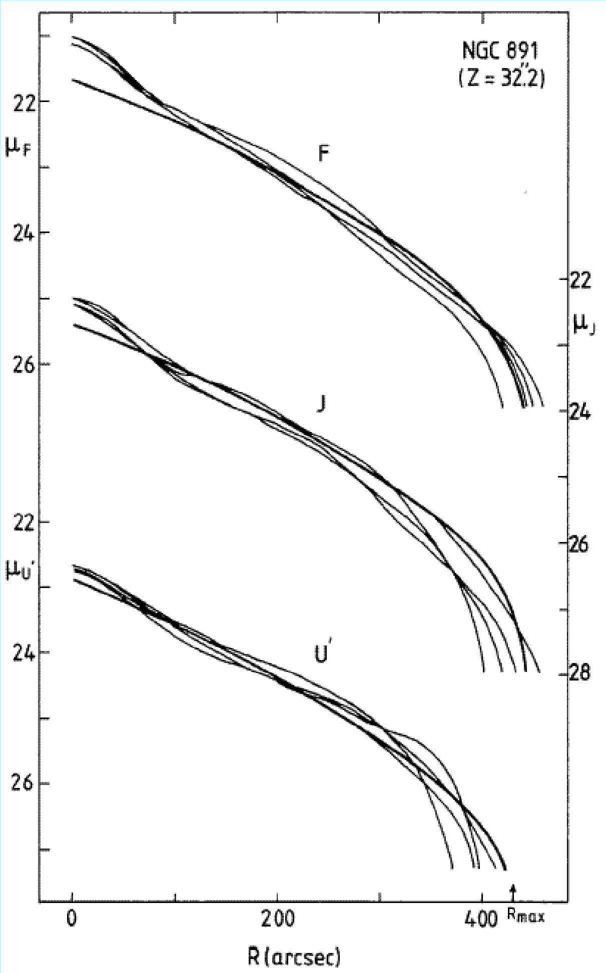


Then we make a fit for the disk from composite R- and z-profiles.

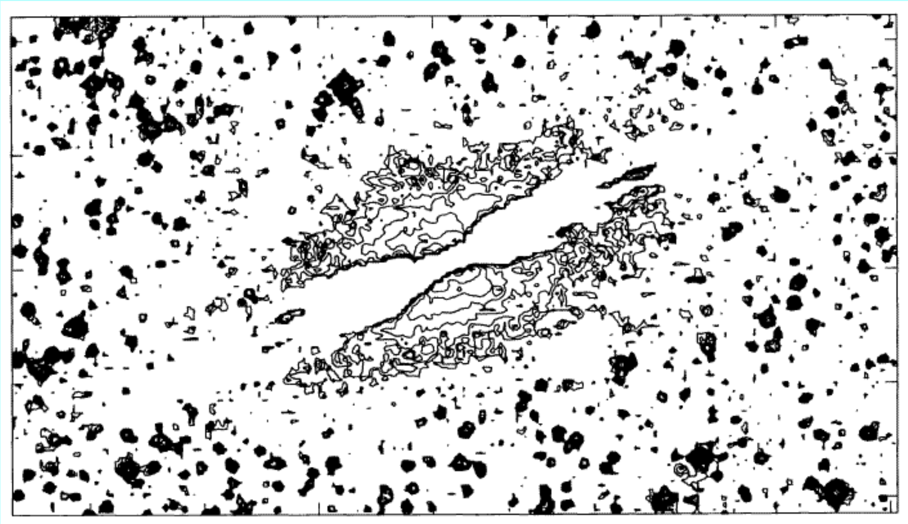


These can be checked against individual profiles. Note that we now can only fit the vertical profiles near the plane (but above the dustlane).

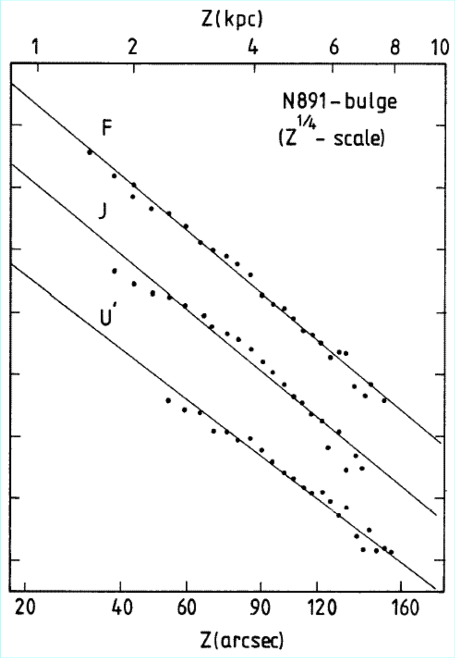

NGC 891 (J)
μJ
22
24
26
28
0
50
100
150
Z (arcsec)


NGC 891
(Z = 32.2″)
μF
22
24
26
F
J
μJ
U′
μU′
R (arcsec)
0
200
400
Rmax

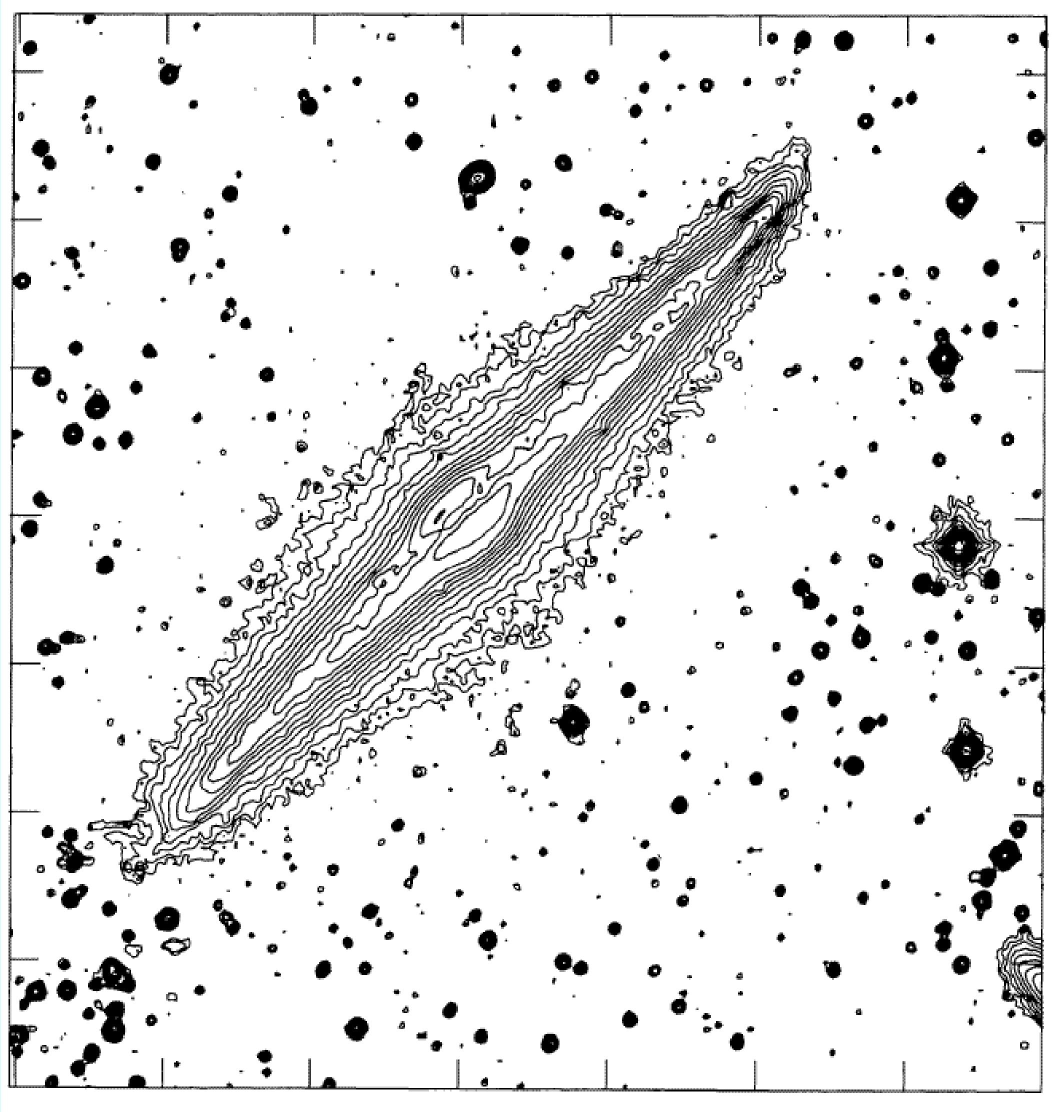
We then subtract the disk model and find the bulge brightness distribution.

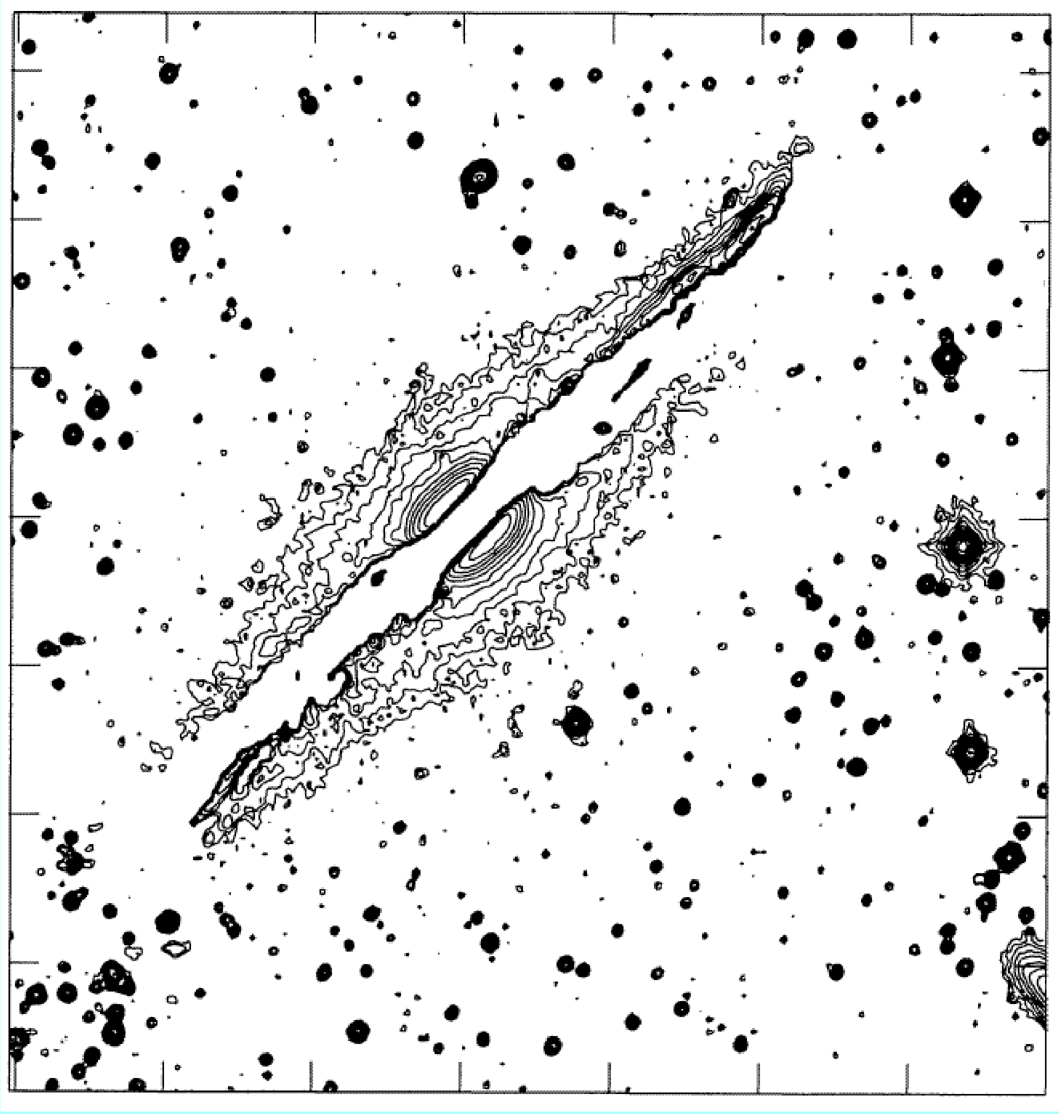


The minor axis profiles can be fitted with $R^{1/4}$ functions. The slopes are different, so there is a color gradient (outer parts are bluer).

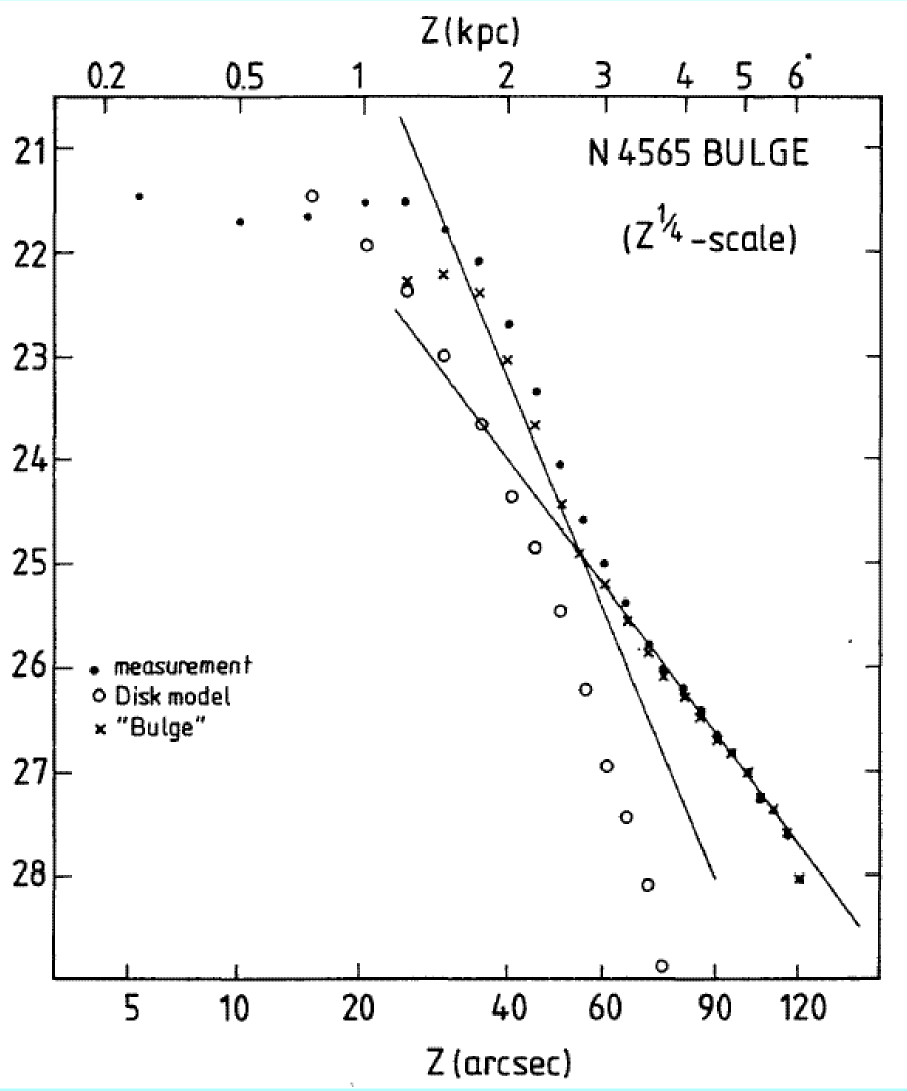


In some galaxies the stellar disks show a warping in the outer parts, such as in NGC 4565.





The minor axis profile cannot be fitted in this case with a single $R^{1/4}$ law.



NGC 7814 (D = 15 Mpc)

BULGE:

$R_{\mathrm{e}} = 2.2$ kpc

$b/a = 0.57$

$L_{\mathrm{B}} = 1.6 \times 10^{10} L_{\odot}$

$(B - V) \approx 0.5 \leftrightarrow 1.3$ (13 $\leftrightarrow$ 2 kpc along minor axis)

$(U - B) \approx 0.3 \leftrightarrow 0.6$

DISK (old disk only):

$L_{\mathrm{B}}(0, 0) \approx 6.6 \times 10^{-4} L_{\odot}$ pc^{-3}

$h \approx 8.4$ kpc

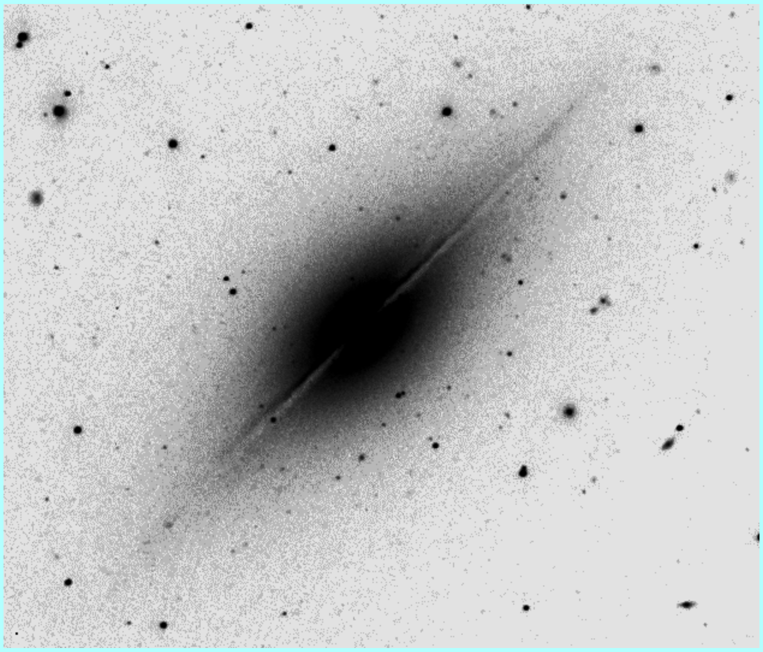
$z_0 \approx 2.0$ kpc

$R_{\mathrm{max}} \approx 18.2$ kpc

$L = 1.2 \times 10^{9} L_{\odot}$ ($\approx$**7 %** of total)

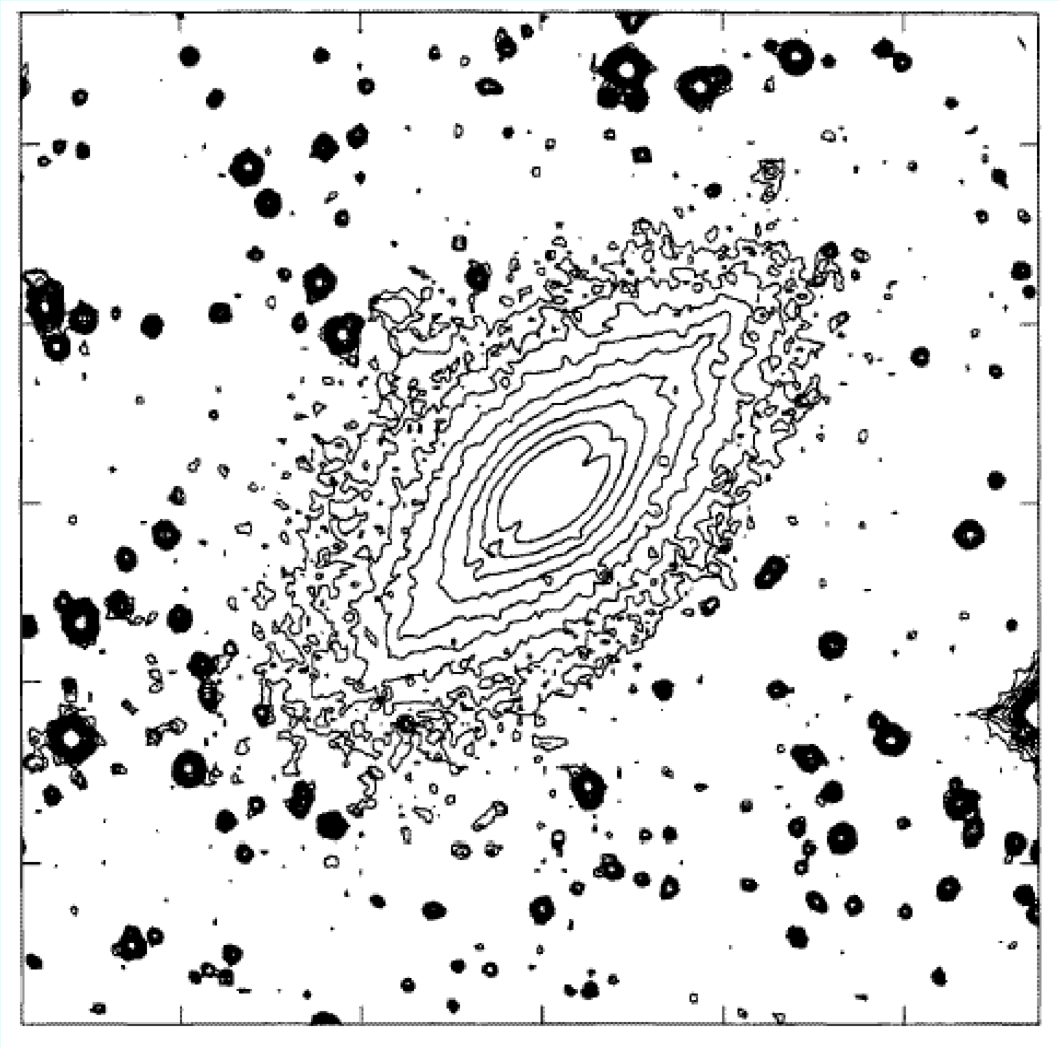
$(B - V) \approx 1.1$

$(U - B) \approx 0.6$

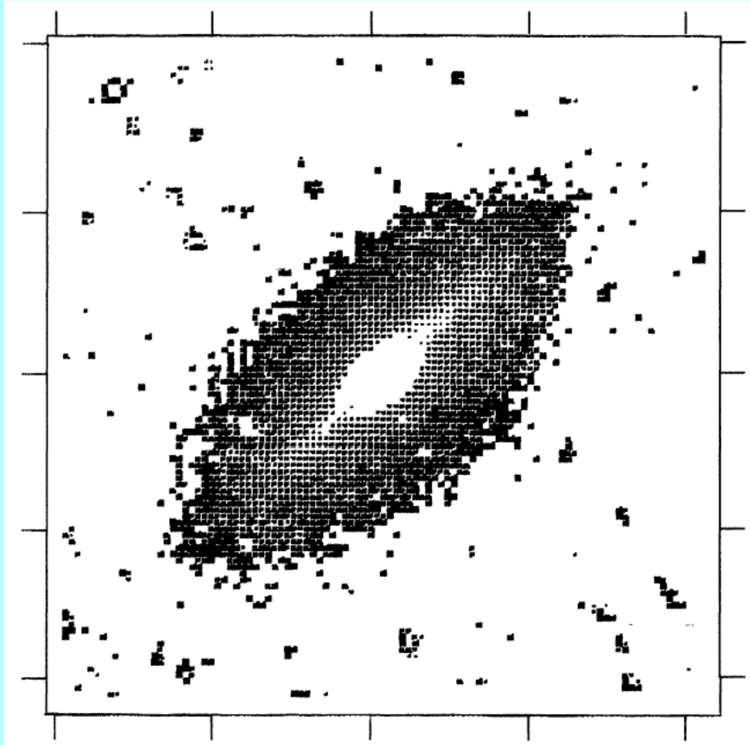


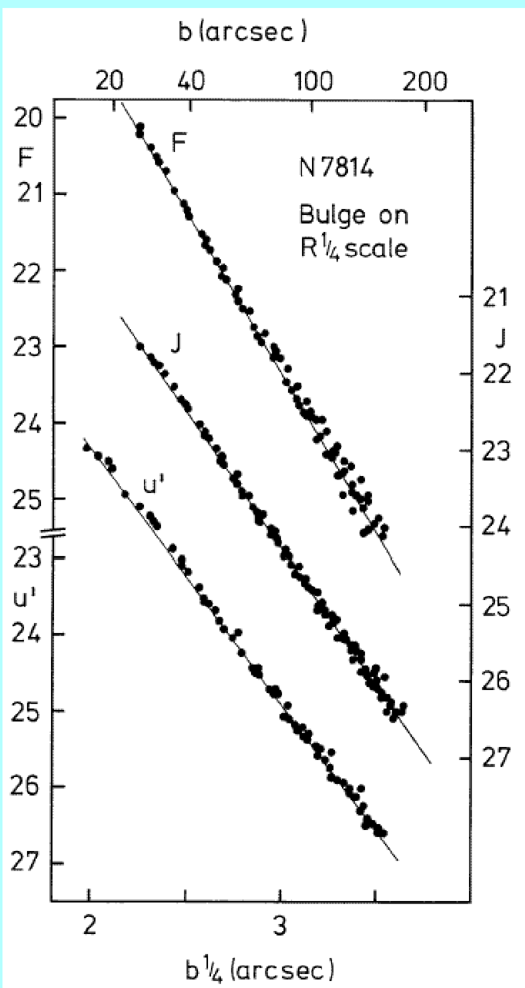
The procedure now is to find a bulge model and subtract that from the observations to reveal the disk.

Note the color change in the bulge (again bluer in the outer parts)* .

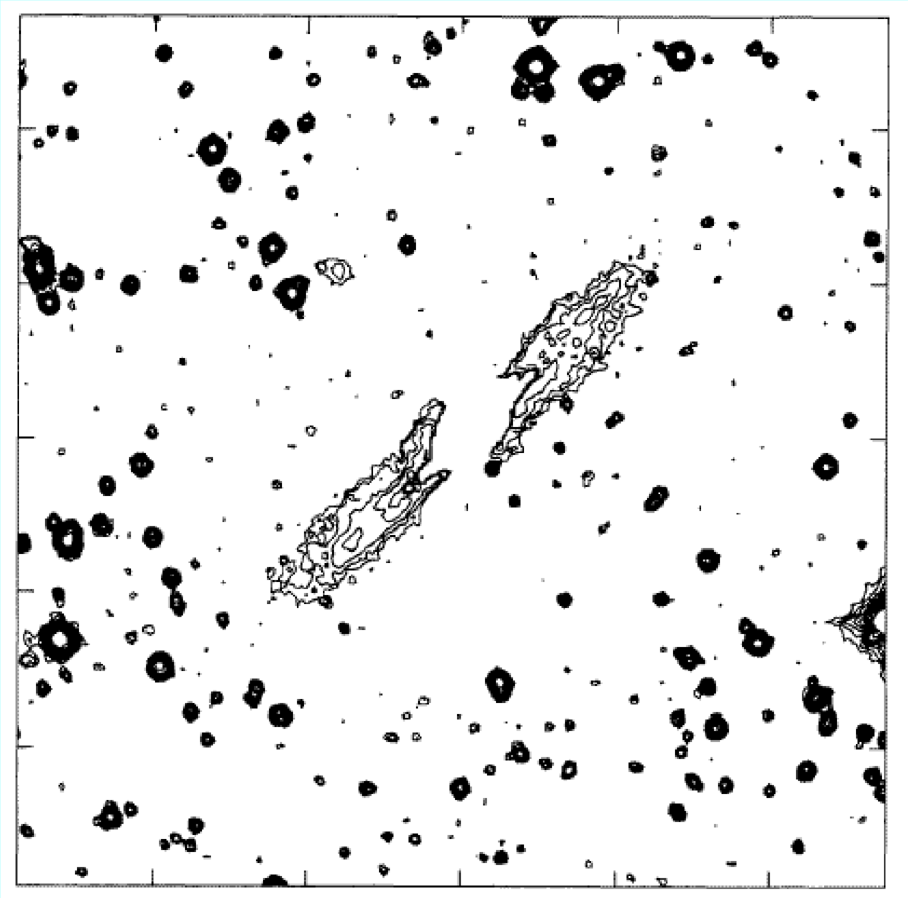


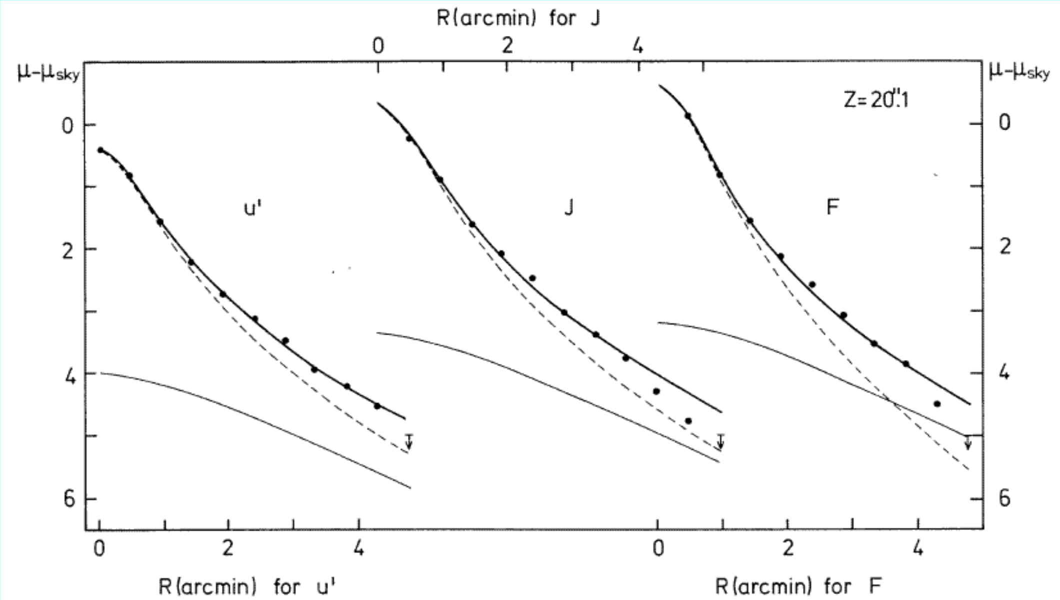
*Wainscoat, Freeman & Hyland, Ap.J. 337, 163 (1989)

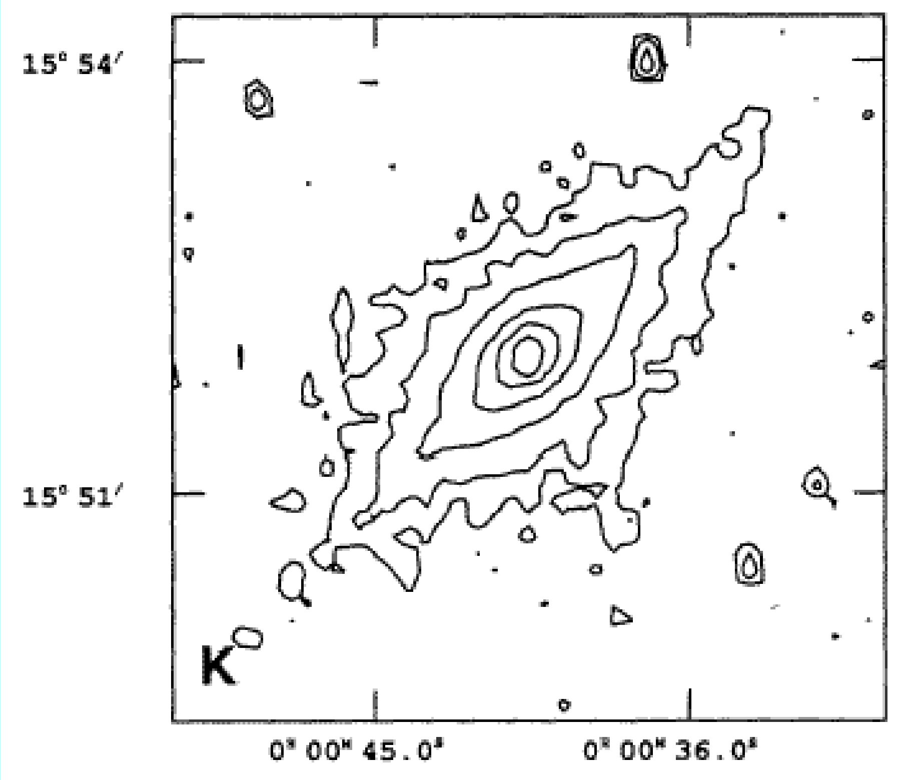


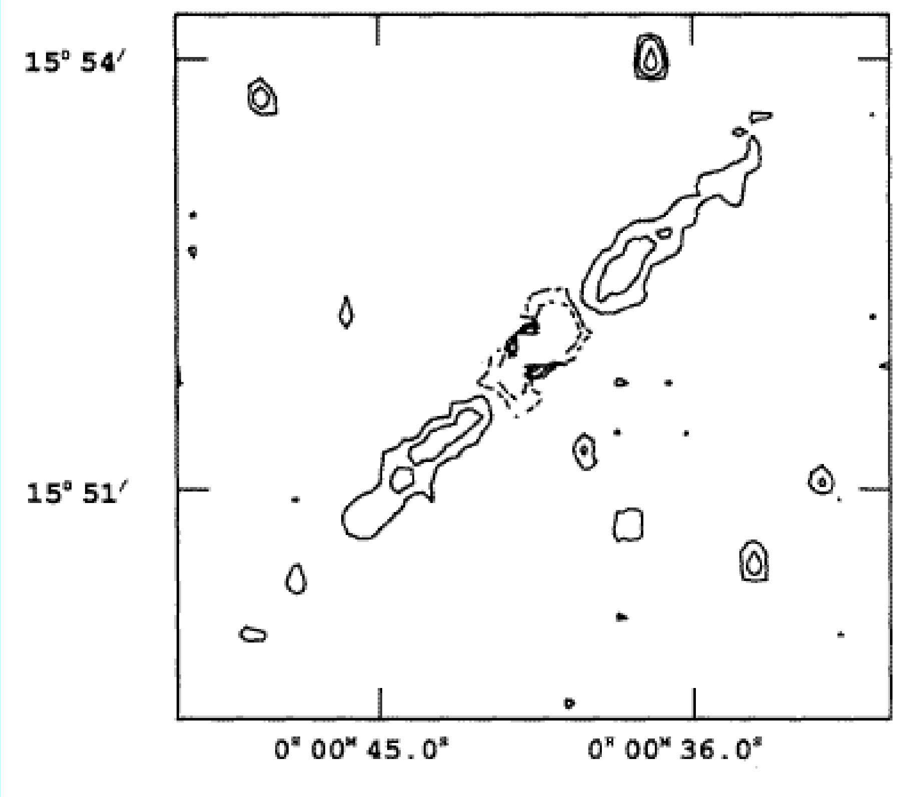


$$\mu_{U'} = 14.87 + 3.32 b^{1/4}$$
$$\mu_{J\,\mathrm{opt}} = 13.72 + 3.55 b^{1/4}$$
$$\mu_{V} = 13.08 + 3.75 b^{1/4}$$
$$\mu_{F} = 10.70 + 4.20 b^{1/4}$$
$$\mu_{J} = 9.19 + 4.36 b^{1/4}$$
$$\mu_{K} = 8.07 + 4.43 b^{1/4}$$




R(arcmin) for J
0
2
4
μ-μsky
Z=20".1
u'
J
F
R(arcmin) for u'
R(arcmin) for F


15° 54′
15° 51′
K
0ʰ 00ᵐ 45.0ˢ
0ʰ 00ᵐ 36.0ˢ

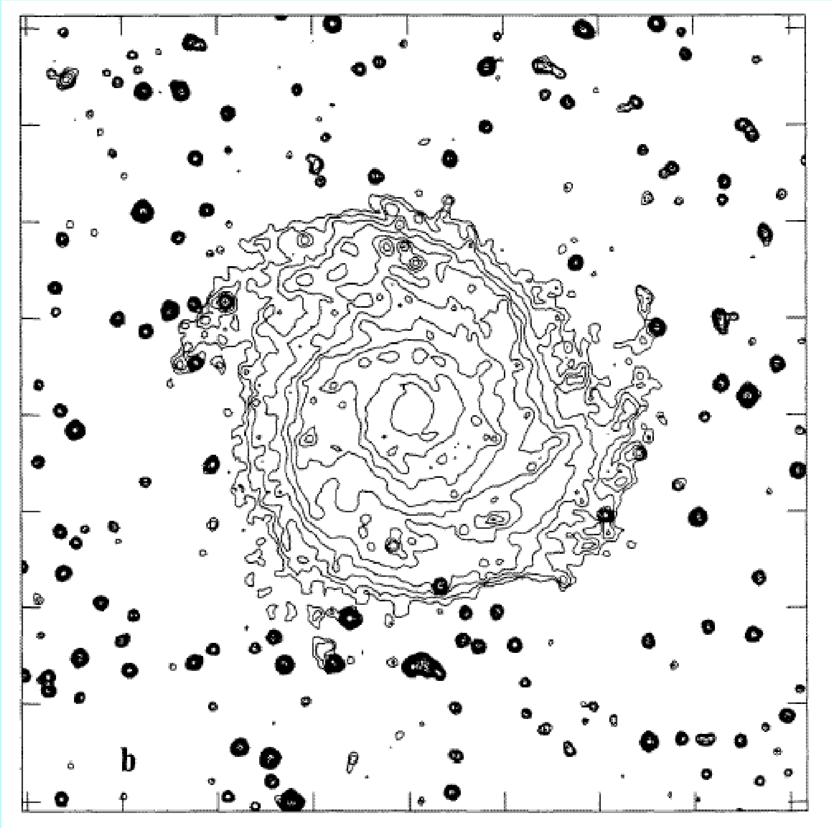

15° 54′
15° 51′
0ʰ 00ᵐ 45.0ˢ
0ʰ 00ᵐ 36.0ˢ

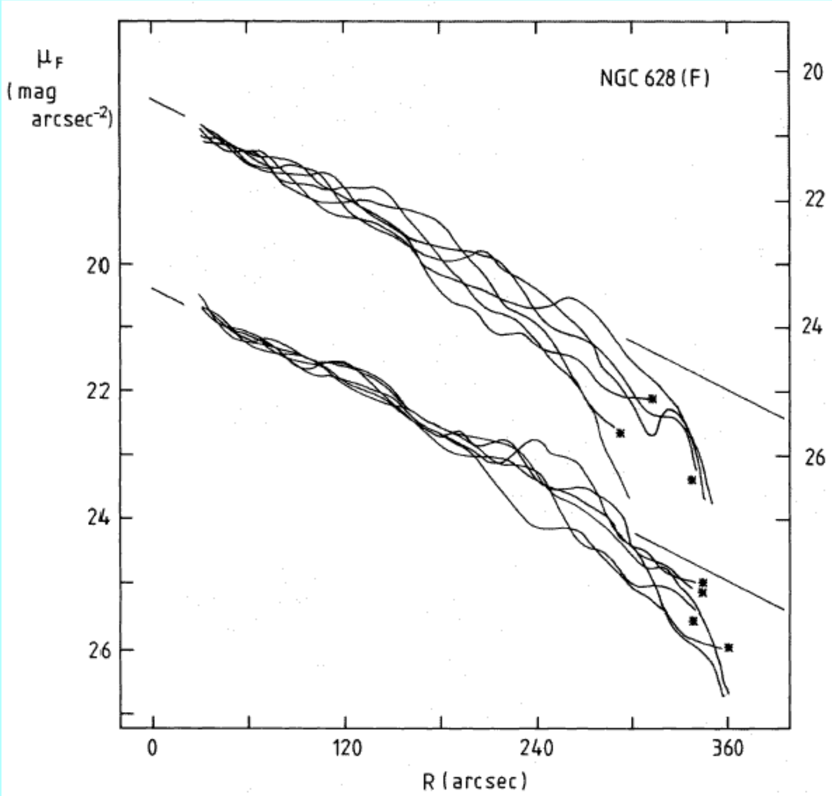
Disk truncations in face-on galaxies

In face-on or moderately inclined galaxies the disk truncations occur at faint levels.

However, they can be seen as a decreasing spacing between the isophotes, as in NGC 628*.

*van der Kruit, A.&A. 192, 117 (1988)


b


μ_F
(mag arcsec^{-2})
NGC 628 (F)
20
22
24
26
20
22
24
26
0
120
240
360
R (arcsec)

Survey of spiral galaxies.

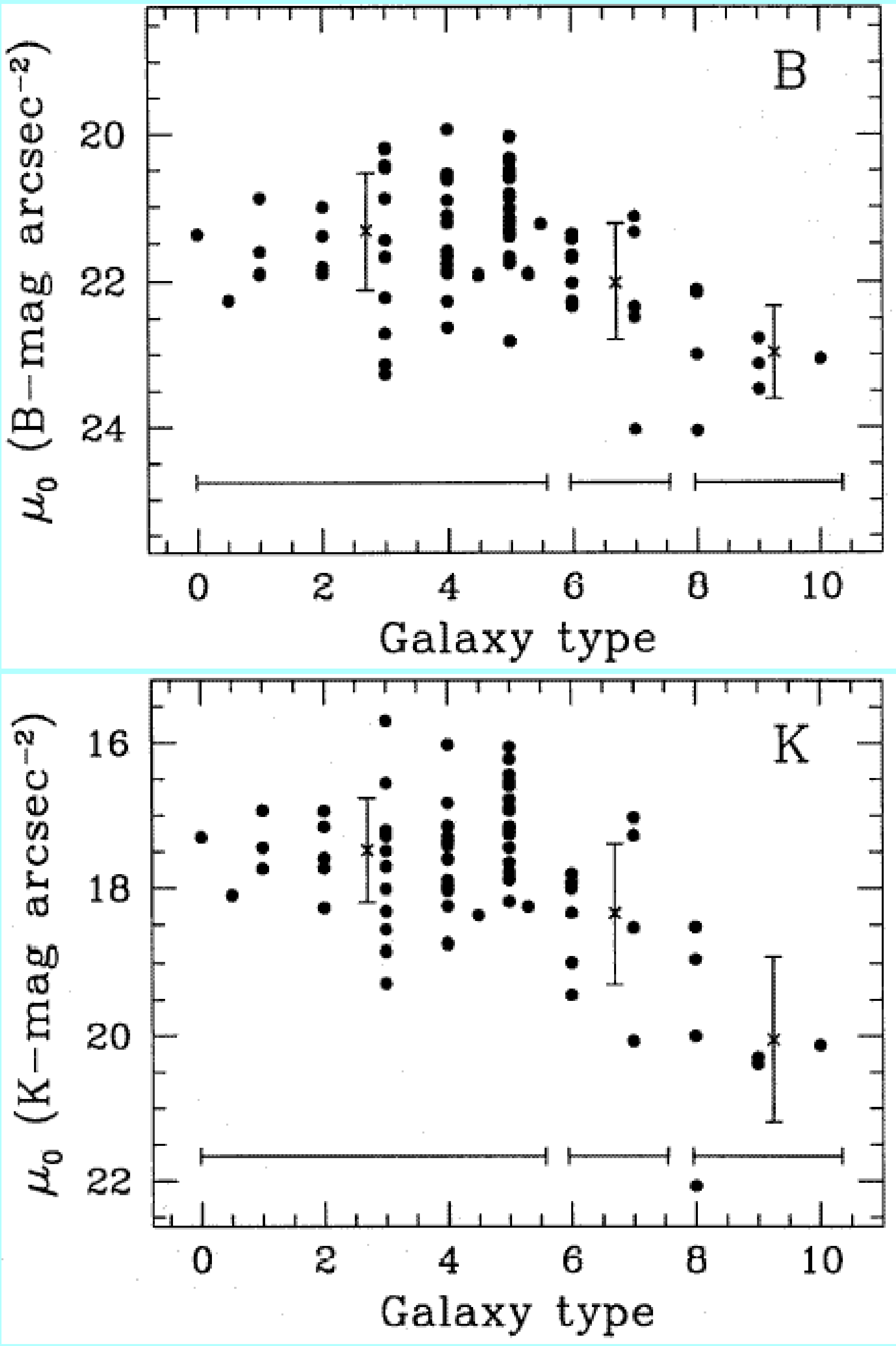
An extensive survey of a sample of 86 spiral galaxies in the optical and near-infrared is in the Ph.D. thesis of Roelof de Jong*

The following figures show some results as funcion of Hubble type (indicated on a scale where 0 = S0, 2 = Sa, 4 = Sb, etc. It shows data in the B (optical) and K (near-IR) bands.

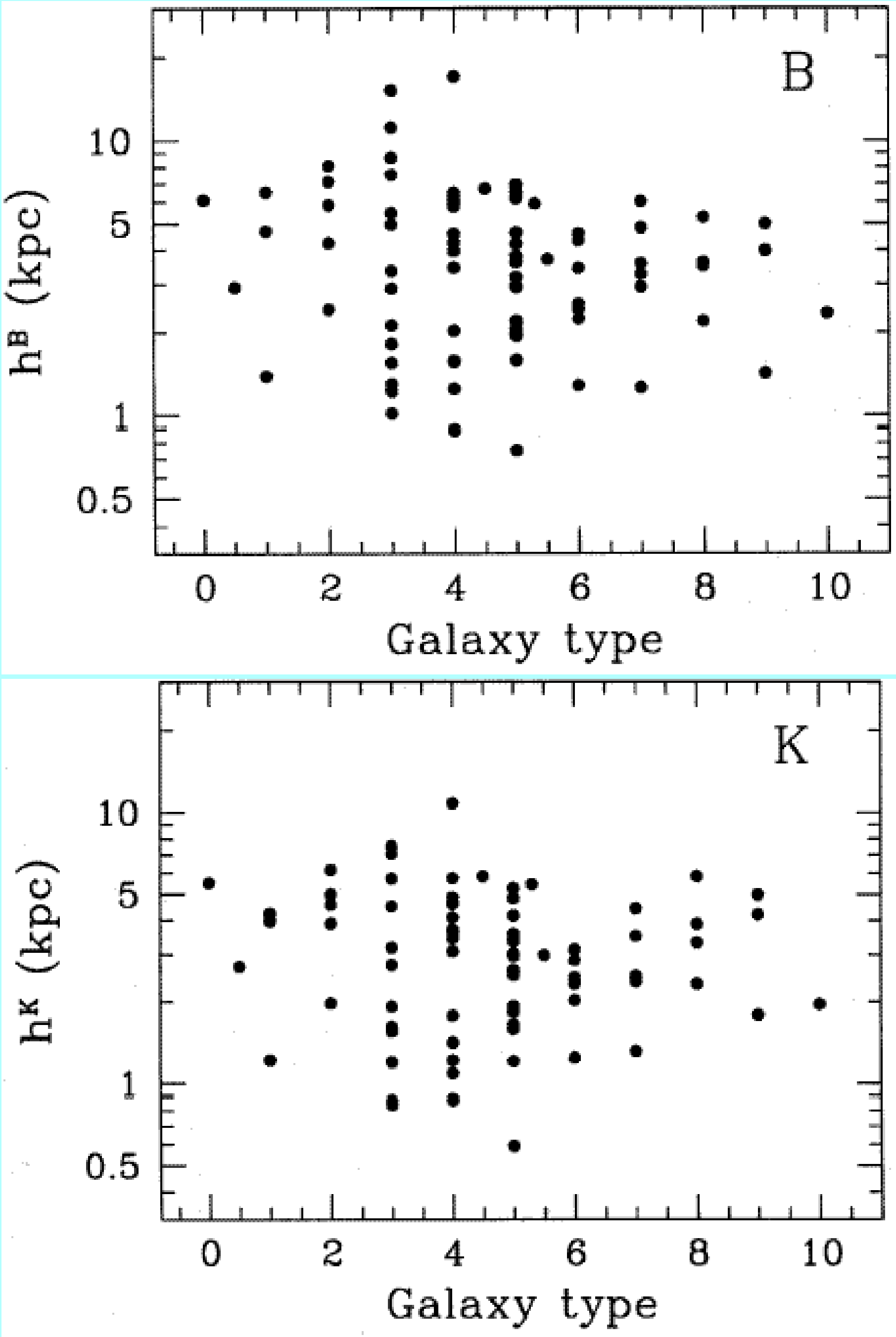
- Disk central surface brightness is fainter for late-type systems.
- Disk scalelength is not a strong function of morphological type.
- Bulge effective surface brightness correlates well with Hubble type, but effective radius much less.
- The bulge-to-disk ratio (a Hubble classification criterion) correlates only weakly with Hubble type and it is mainly due to bulge effective surface brightness.

*1995, see also de Jong & van der Kruit, A.&A.Suppl., 107, 419 (1995), de Jong, A.&A.Suppl. 118, 557, A.&A. 313, 45 and 377 (1996).

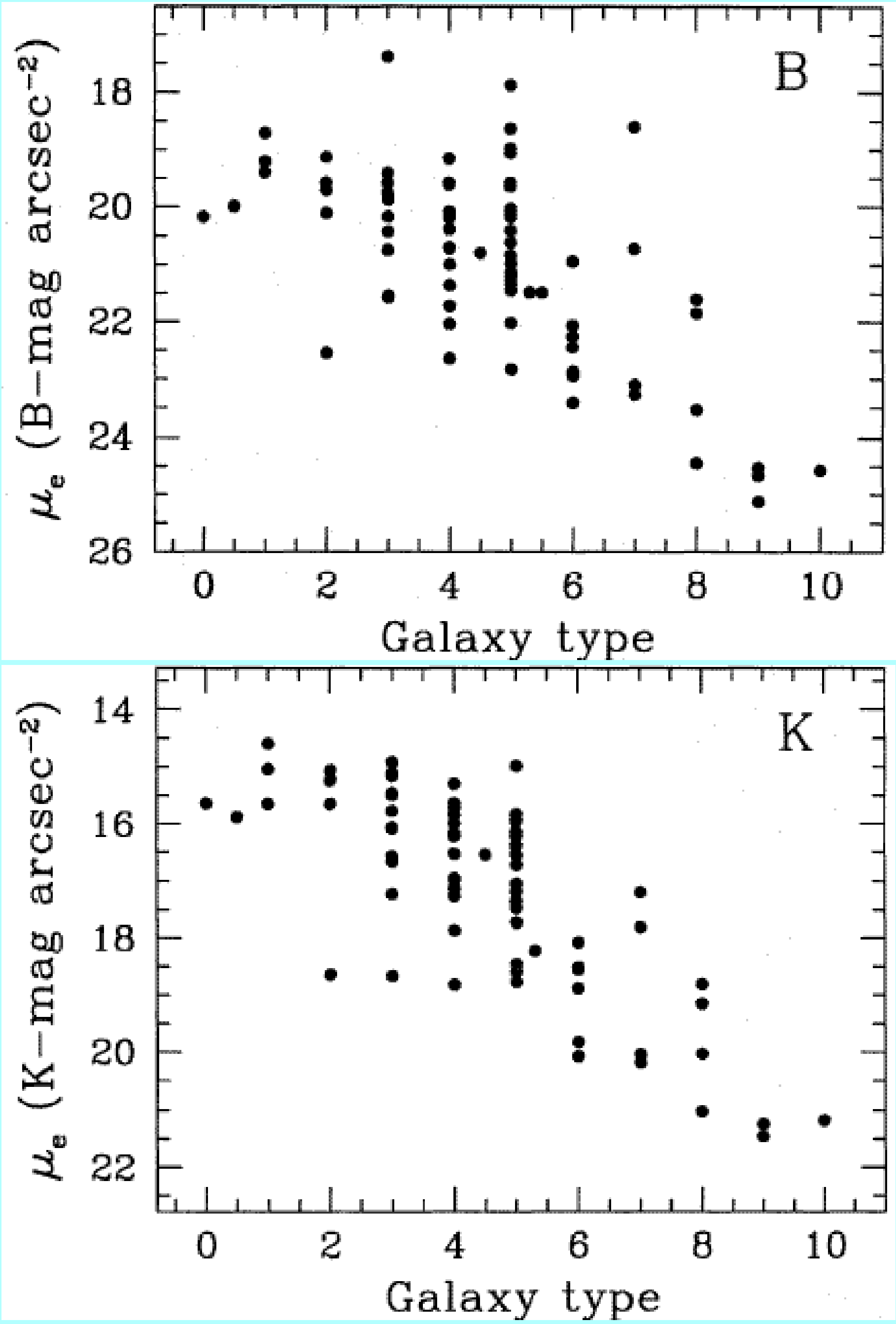
Face-on central disk surface brightness.



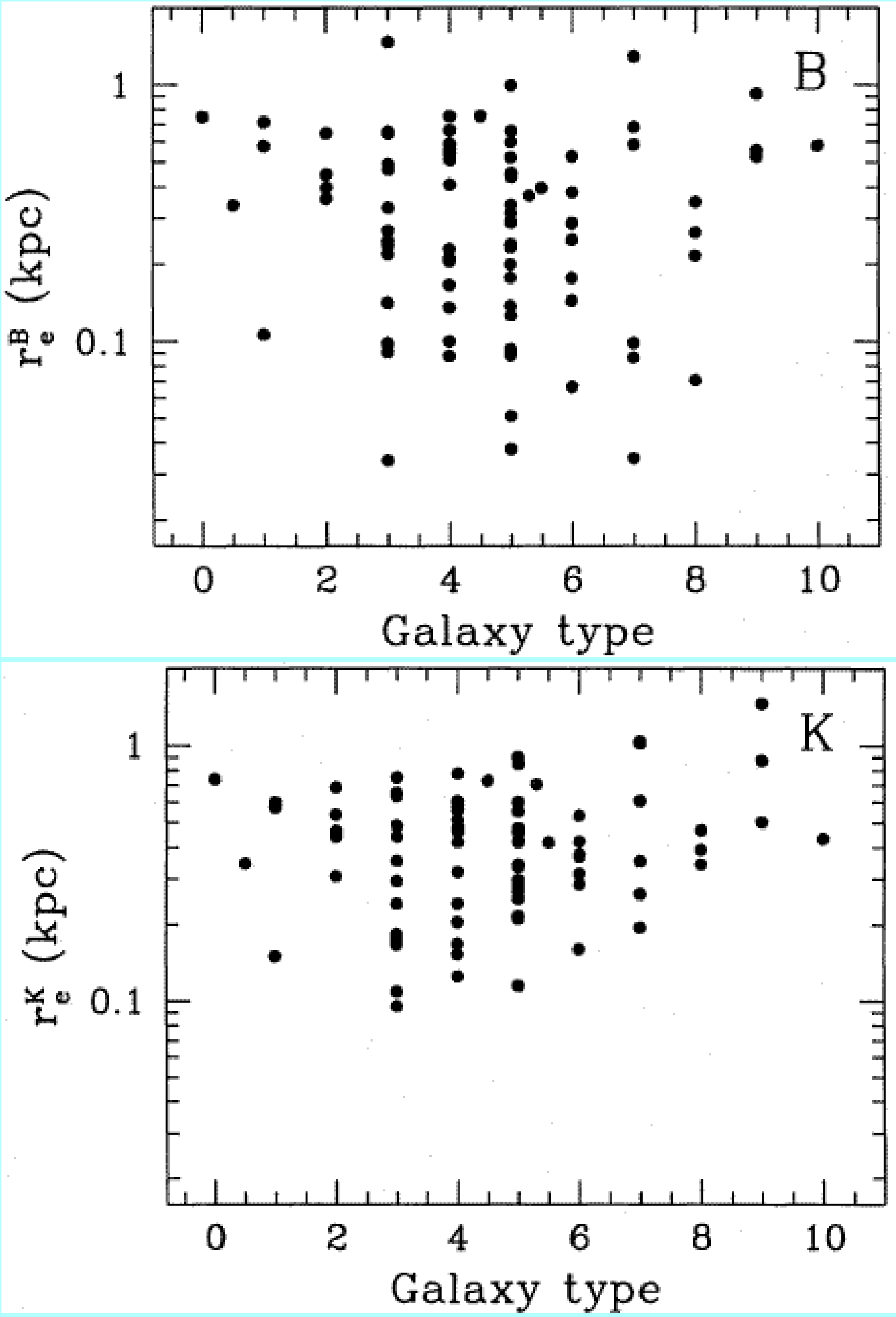
Disk scalelength.



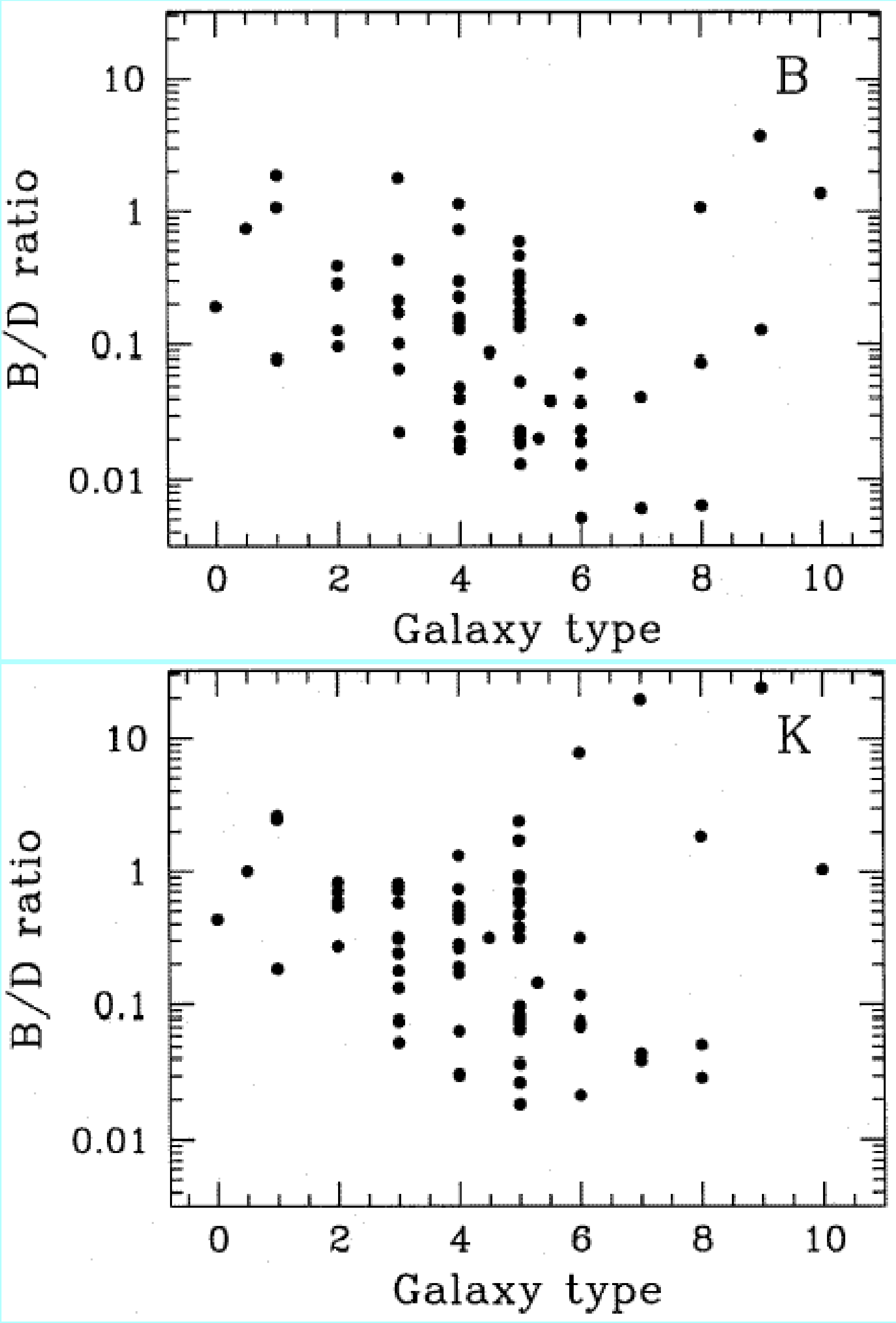
Bulge effective surface brightness.



Bulge effective radius.



Bulge-to-disk ratio (in total luminosity).



Survey of edge-on galaxies.

The Ph.D. thesis of Richard de Grijs* did a survey of edge-on galaxies, also in the optical and near-infrared.

He did one-dimensional fits of the disk parameters to the surface brightness maps. This has recently been improved with two-dimensional fits.†

The following figures show some of his results.

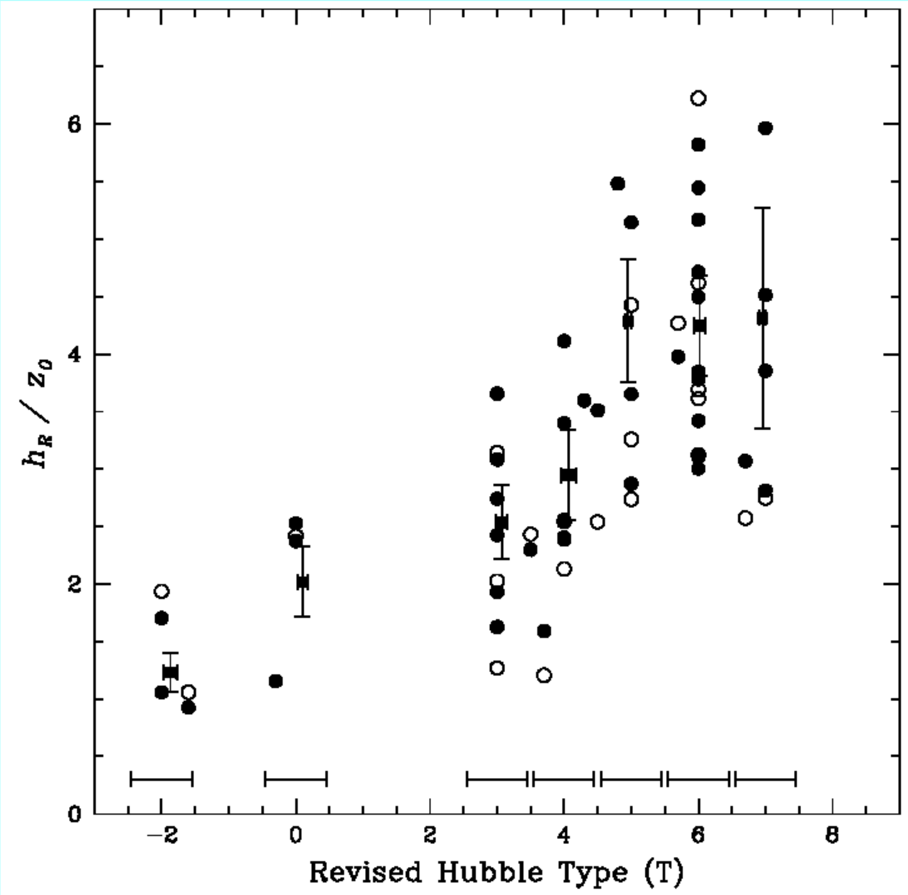
- The thinness of galaxy disks (ratio of scalelength to scaleheight) increases systematically from types S0 to Sc.

- Radial color gradients increase in disks from Sa to Sc.

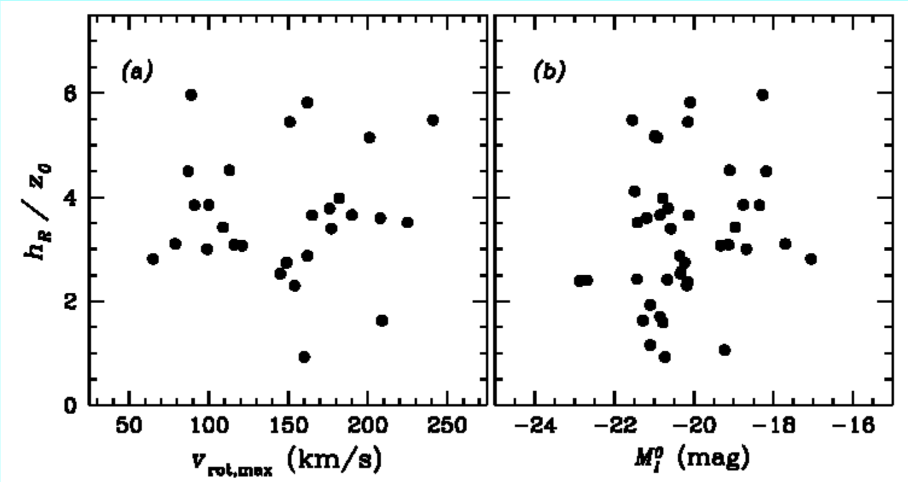
*1997, see also de Grijs & van der Kruit, A.&A.Suppl. 117, 19 (1996), de Grijs, Mon.Not.R.A.S. 229, 595 (1998) and references therein.

†Kregel, van der Kruit & de Grijs, Mon.Not.R.A.S. 334, 646 (2002)

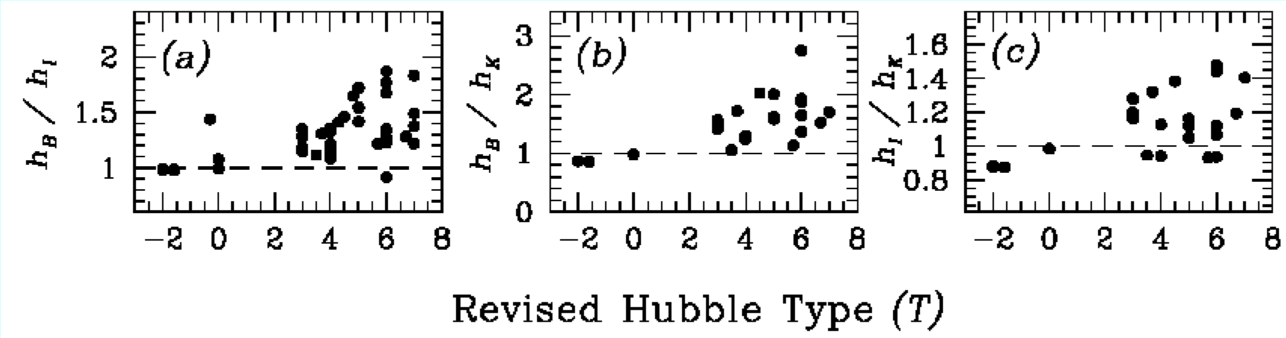
The ratio of the radial scalelength to the vertical scaleheight as a function of morphological type.



Disk flattening does not depend on rotation velocity or integrated luminosity.



Radial color gradients as a function of morphological type.



Luminosity distribution in the Galaxy.

The surface brightness of the Milky Way is that of integrated starlight, which can be derived from deep star counts*.

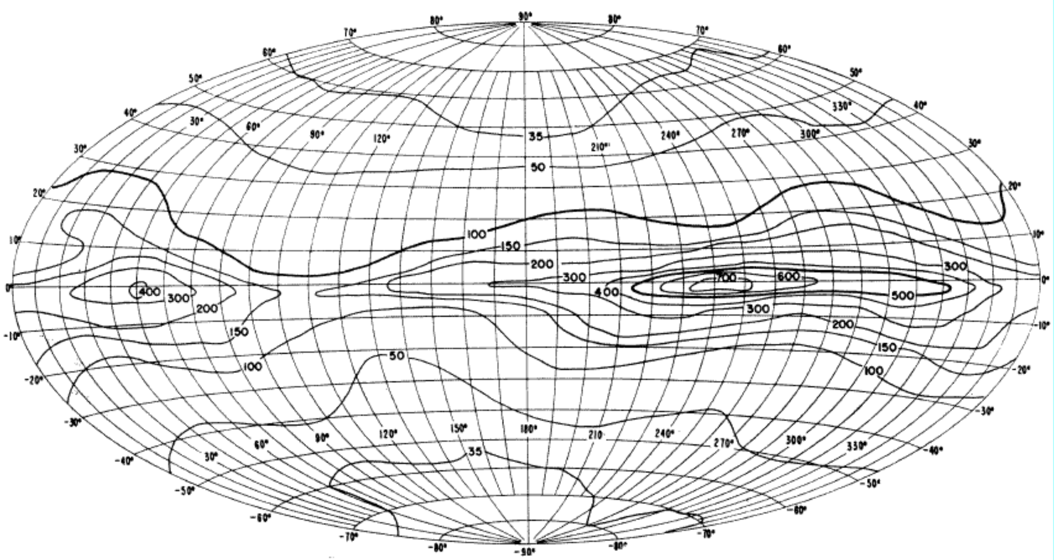


FIG. 6.—Total integrated starlight in number of tenth-magnitude (visual) stars per square degree in galactic co-ordinates

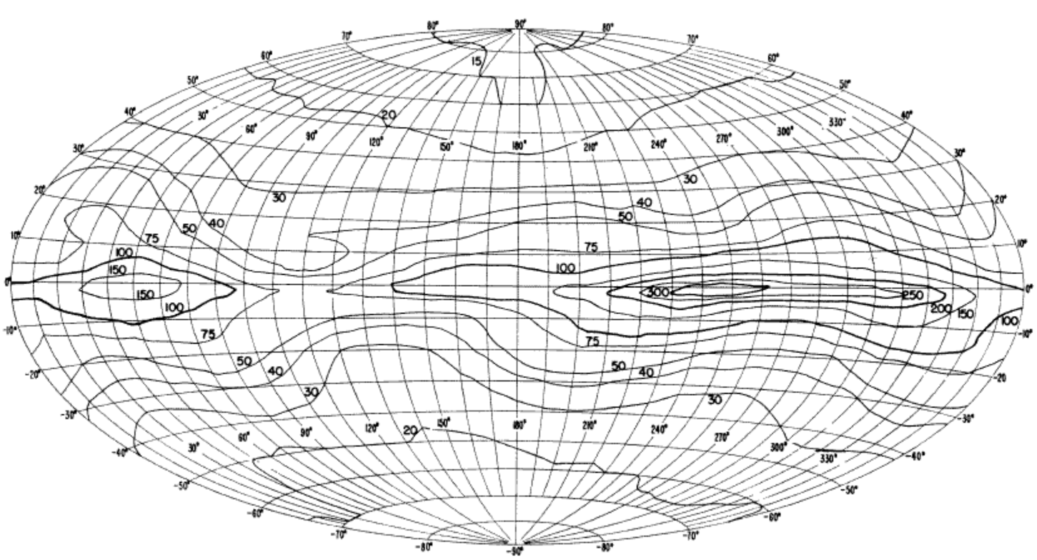


FIG. 5.—Total integrated starlight in number of tenth-magnitude (photographic) stars per square degree in galactic co-ordinates

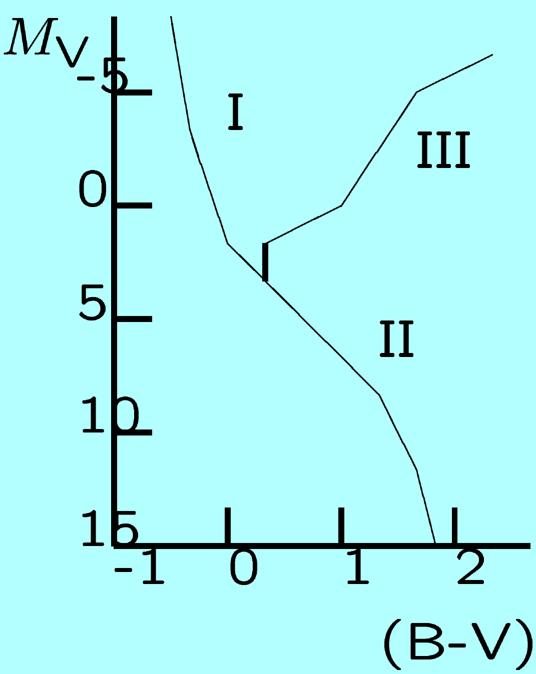
*Roach & Megill, Ap. J. 133, 228 (1961)

Bahcall & Soniera* constructed a model for the Galaxy in order to reproduce star counts.

It consists of an $R^{1/4}$-bulge and a disk with a distribution of stars as

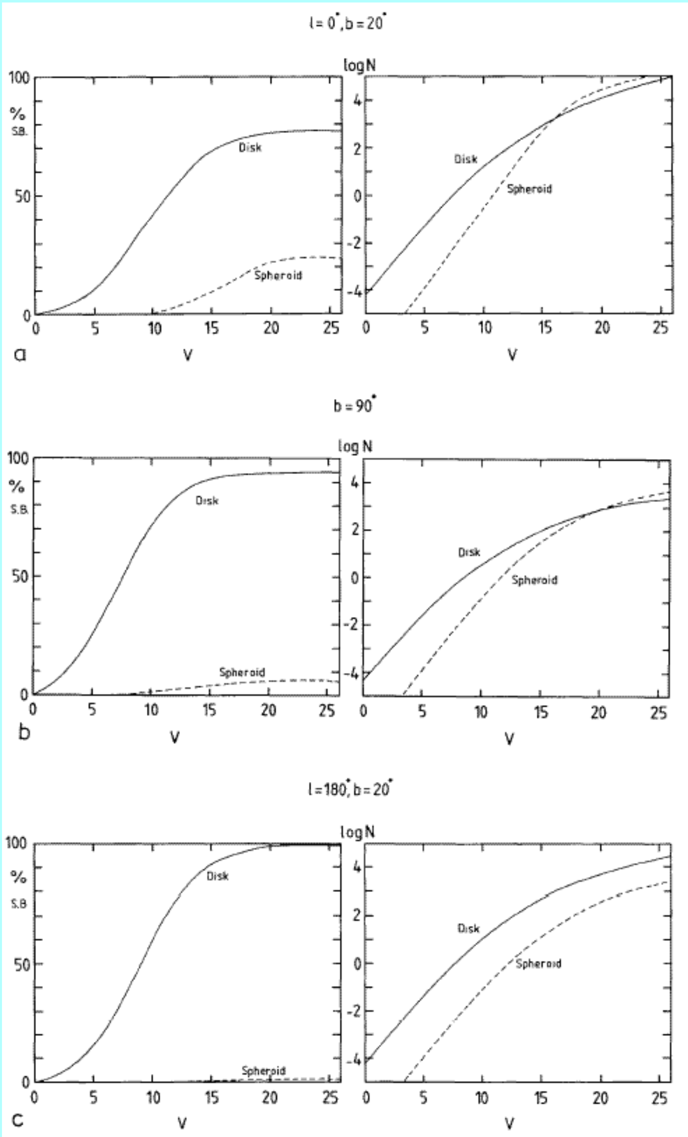
$$n(M_{\rm V}, (B-V), R, z) \propto \text{ exp } -\left(\frac{R}{h_{\rm R}} + \frac{z}{h_{\rm z}}\right)$$

- $h_{\rm R} = 3.5$ kpc from de Vaucouleurs;
- $h_{\rm z} \approx 90$ pc for Population I (region I in HR-diagram);
- $h_{\rm z} = 350 \pm 50$ pc for Old dwarfs (region II);
- $h_{\rm z} = 250 \pm 100$ pc for Disk giants (region III).



*Ap.J.Suppl. 55, 67 (1984)

The figure here compares direct star counts on the right with contributions to the total surface brightness on the left.



It shows that stars of magnitude 20 or so hardly contribute to the total surface brightness, but in the counts give important information on the bulge distribution.

Direct measurements of the surface brightness of the Galaxy are difficult due to other contributions:

The sky contributions in the visual with some comparisons are as follows:

	$S_{10}(V)_{\mathrm{G2V,V}}$	V-mag arcsec^{-2}
Disk of sun	$\sim 10^{17}$	$\sim$ -15
Daylight	$\sim 3 \times 10^{11}$	$\sim$ -1
Full moon	$\sim 10^{11}$	0.5
Airglow	50	23.5
Zodiacal light (ecliptic)	180	22.0
Zodiacal light (pole)	80	23.0
Bright stars ($m_{\mathrm{V}} < 6$)	20	24.5
Integrated starlight (plane)	300	21.5
Integrated starlight (pole)	30	24.0
Diffuse Galactic light (plane)	50	23.5
Diffuse Galactic light (pole)	2	27.0
Cosmic background	~ 1	~ 28.0

The property $S_{10}(V)_{\mathrm{G2V},\lambda}$ denotes the equivalent number of G2V-stars in the λ-band per square degree that have magnitude 10 in the V-band.

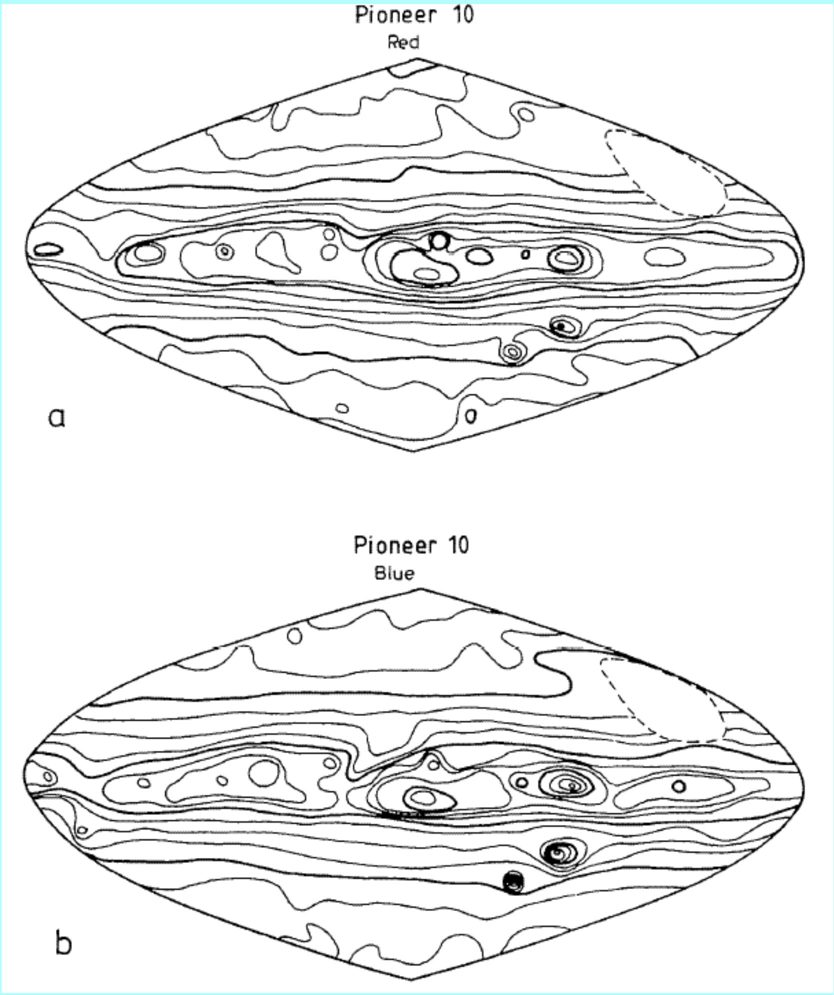
The zodiacal light is the biggest problem when studying the background distribution of starlight.

The problem is the reverse for people interested in studying zodiacal light.

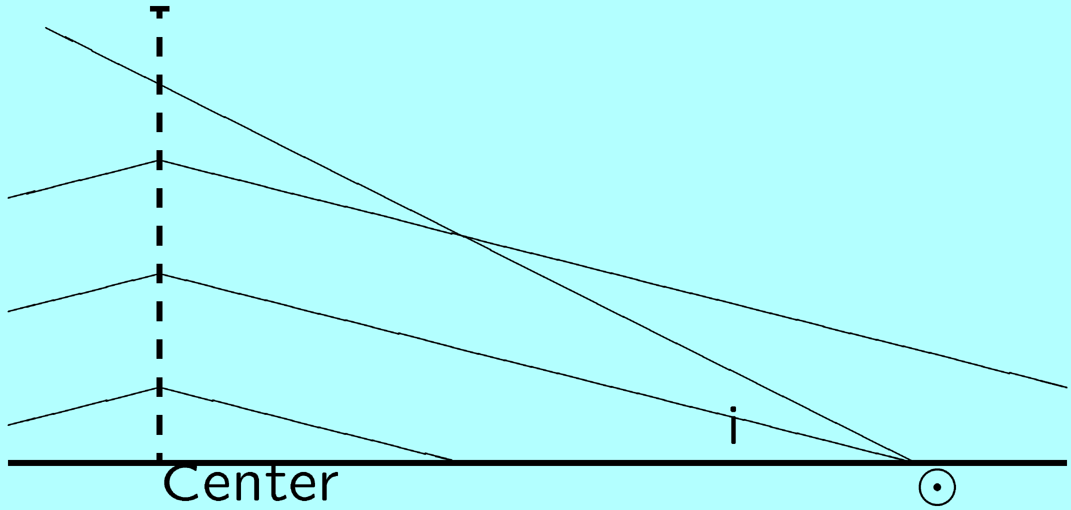
Pioneer 10 photometry

The satellite Pioneer 10 was launched in March 1972 and reached Jupiter in December 1973.

During its trip in the asteroid belt and beyond it swept the skies and made a map of the background starlight free of zodiacal light.



Now consider the following geometry.



With the reasonable range of parameters $h_{\mathsf{R}} =$ 2.5 - 6 kpc, $h_{\mathsf{z}} =$ 300 - 375 pc and $R_{\odot} =$ 7.5 - 9 kpc, we get

$$i = \tan^{-1}(h_{\mathsf{z}}/h_{\mathsf{R}}) = 3^{\circ} - 8.5^{\circ}$$

Due to absorption we can only use data for $b > 20^{\circ}$ in the Pioneer data.

So we can only restrict $h_{\mathsf{R}}/h_{\mathsf{z}}$ and not $h_{\mathsf{R}}/R_{\odot}$.

Analysis of the Pioneer 10 data gives informaton on the photometric parameters of the disk in the Galaxy*.

- $h_{\mathrm{R}}/h_{\mathrm{z}} = 8.5 \pm 1.3$;
- $h_{\mathrm{z}} = 350 \pm 50$ pc;
- $\rightarrow h = 5.5 \pm 1.0$ kpc;
- $h = 5.0 \pm 0.5$ kpc (from various independent arguments);
- $\mu(R_\odot) = 22.1 \pm 0.3$ B-mag arcsec^{-2};
- $(B - V) = 0.84 \pm 0.15$;
- $L_{\mathrm{B}} = (1.8 \pm 1.3) \times 10^{10}\ L_\odot$;
- $L_{\mathrm{B}} \approx 1 \times 10^{10}\ L_\odot$ (old disk);
- $R_{\mathrm{max}} = 20 - 25$ kpc.

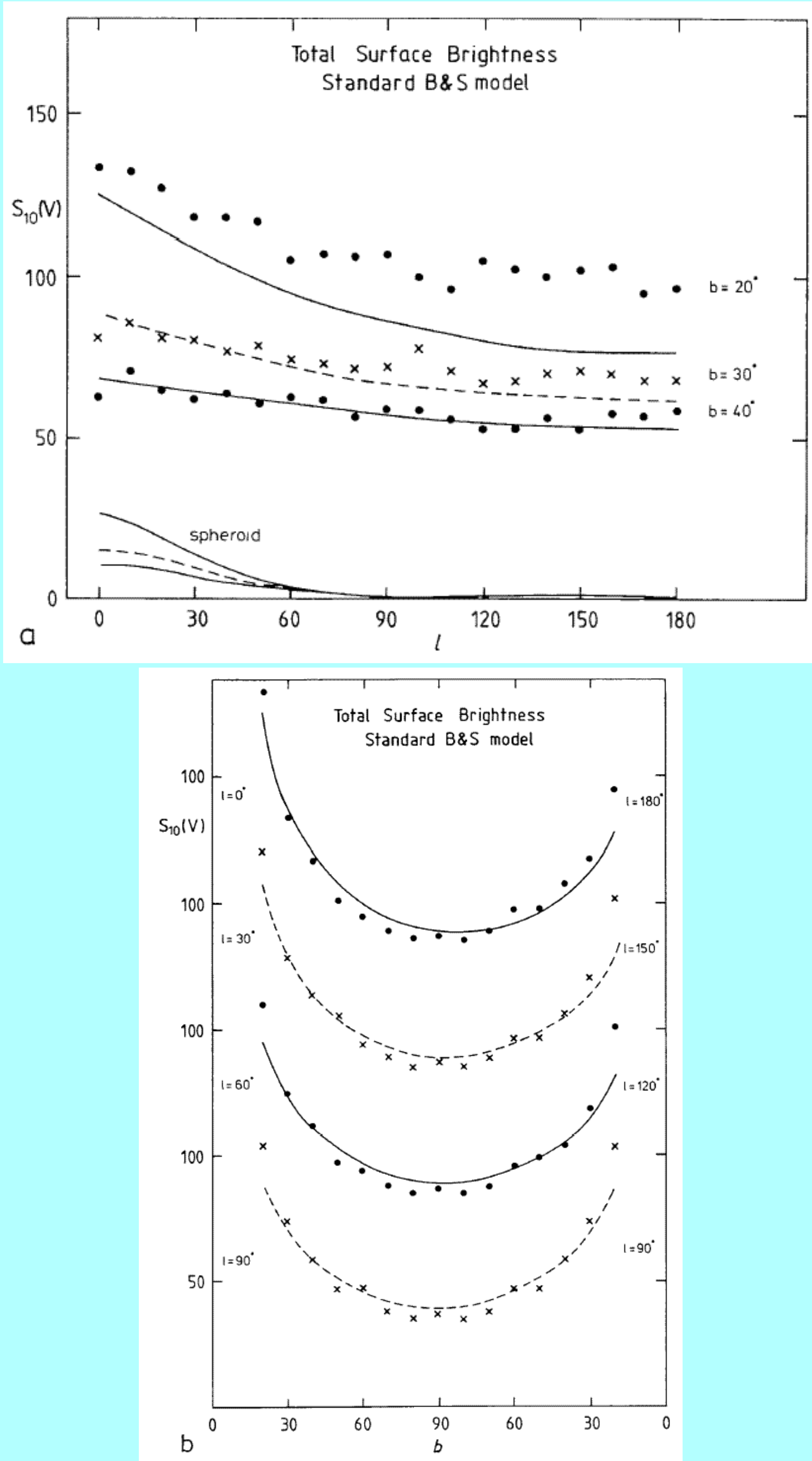
For the bulge we have to take older values†:

- $R_{\mathrm{e}} = 2.7$ kpc;
- $\mu_0 \approx 15.1$ B-mag arcsec^{-2};
- $V_{\mathrm{m}}/\sigma = (60 \pm 30)/(110 \pm 10) \rightarrow b/a = 0.5 \pm 0.15$;
- $L_{\mathrm{B}} = 3 \times 10^9\ L_\odot$.

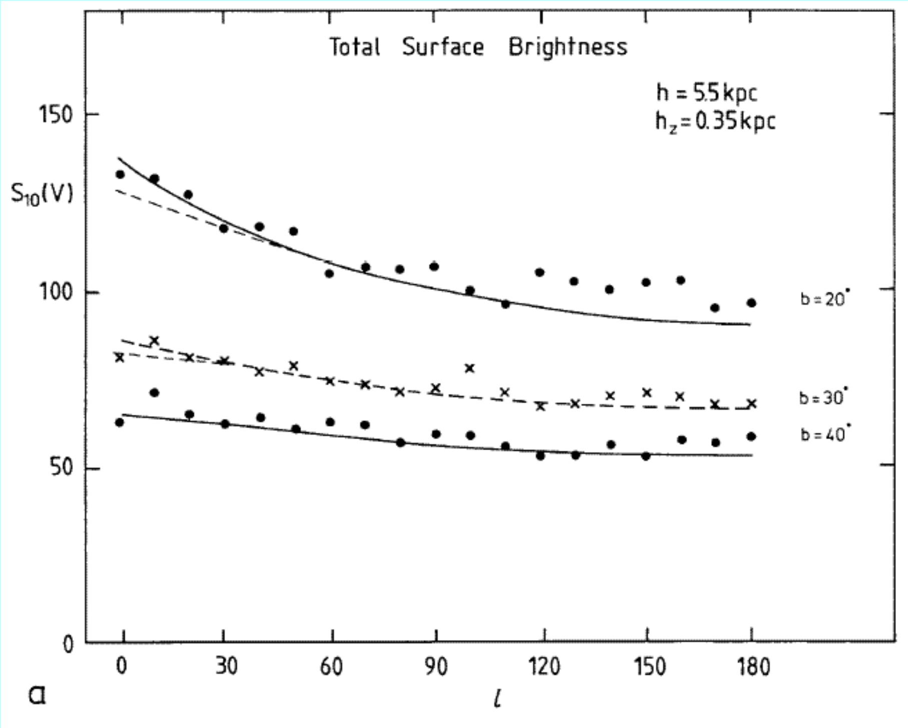
The old disk contains about 80 % of the total light.

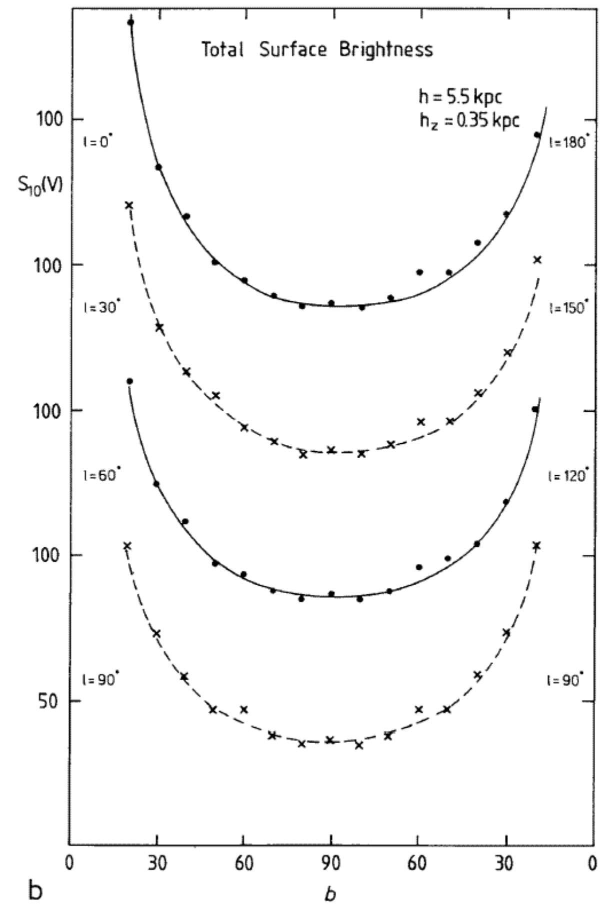
*van der Kruit 1986, A.&A. 157, 230 (1986)

†de Vaucouleurs & Pence A.J. 83, 1163 (1978)

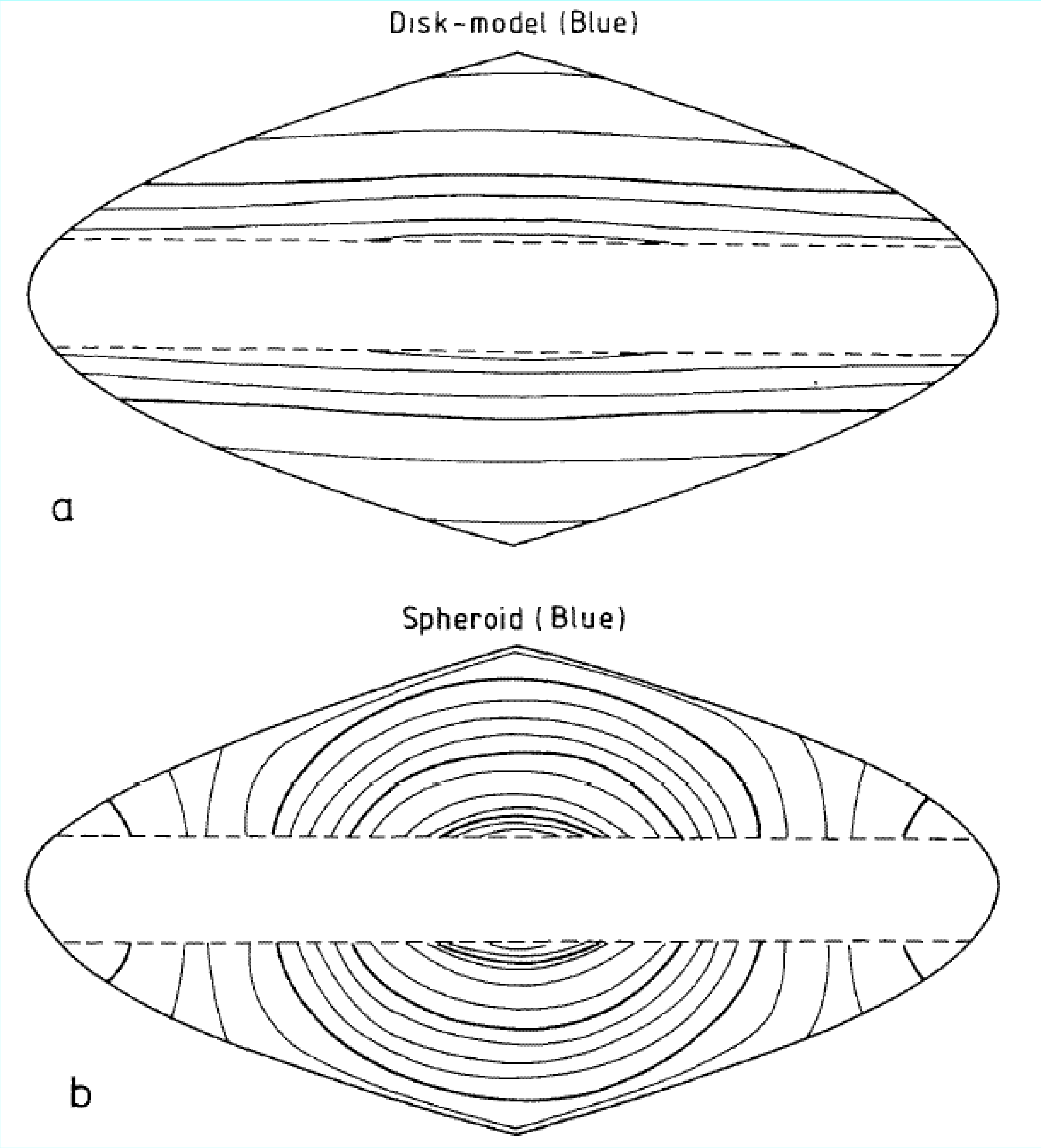


Total Surface Brightness
Standard B&S model
$S_{10}(V)$
b = 20°
b = 30°
b = 40°
spheroid
a
l
Total Surface Brightness
Standard B&S model
$S_{10}(V)$
l = 0°
l = 180°
l = 30°
l = 150°
l = 60°
l = 120°
l = 90°
l = 90°
b
b

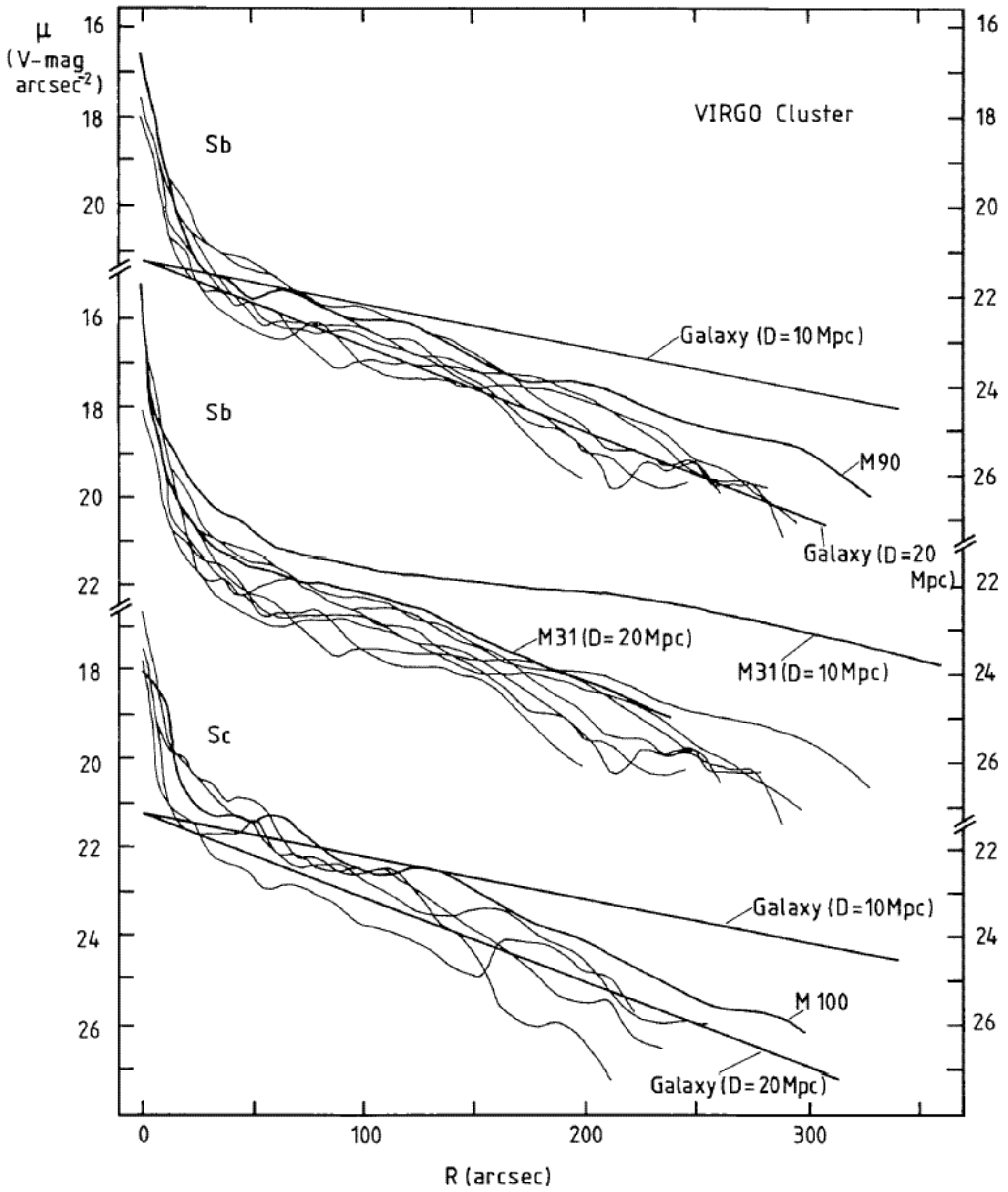

Total Surface Brightness
h = 5.5 kpc
h_z = 0.35 kpc
$S_{10}(V)$
150
100
50
0
b = 20°
b = 30°
b = 40°
0
30
60
90
120
150
180
a
l


Total Surface Brightness
h = 5.5 kpc
h_z = 0.35 kpc
$S_{10}(V)$
100
100
100
100
50
l = 0°
l = 30°
l = 60°
l = 90°
l = 180°
l = 150°
l = 120°
l = 90°
0
30
60
90
60
30
0
b
b

The surface brightness distributions of the disk and the bulge according to the model are as follows.



We can estimate a lower limit to the distance of the Virgo Cluster by assuming that our Galaxy or M31 are comparable in size to the largest spirals in the cluster.



In the Virgo cluster:

- 6 largest Sb-galaxies: $h = 52 \pm 5$ arcsec
- 5 largest Sc-galaxies: $h = 50 \pm 5$ arcsec.

For the Galaxy

- $h = 5.0 \pm 0.5$ kpc, so
- $D_{\mathrm{Virgo}} = 20 \pm 3$ Mpc (if Sc)
- $D_{\mathrm{Virgo}} = 21 \pm 3$ Mpc (if Sb)

For M31

- $h = 6.0 \pm 0.5$ kpc, so
- $D_{\mathrm{Virgo}} = 24 \pm 3$ Mpc.

So

- $D_{\mathrm{Virgo}} = 22 \pm 4$ Mpc.

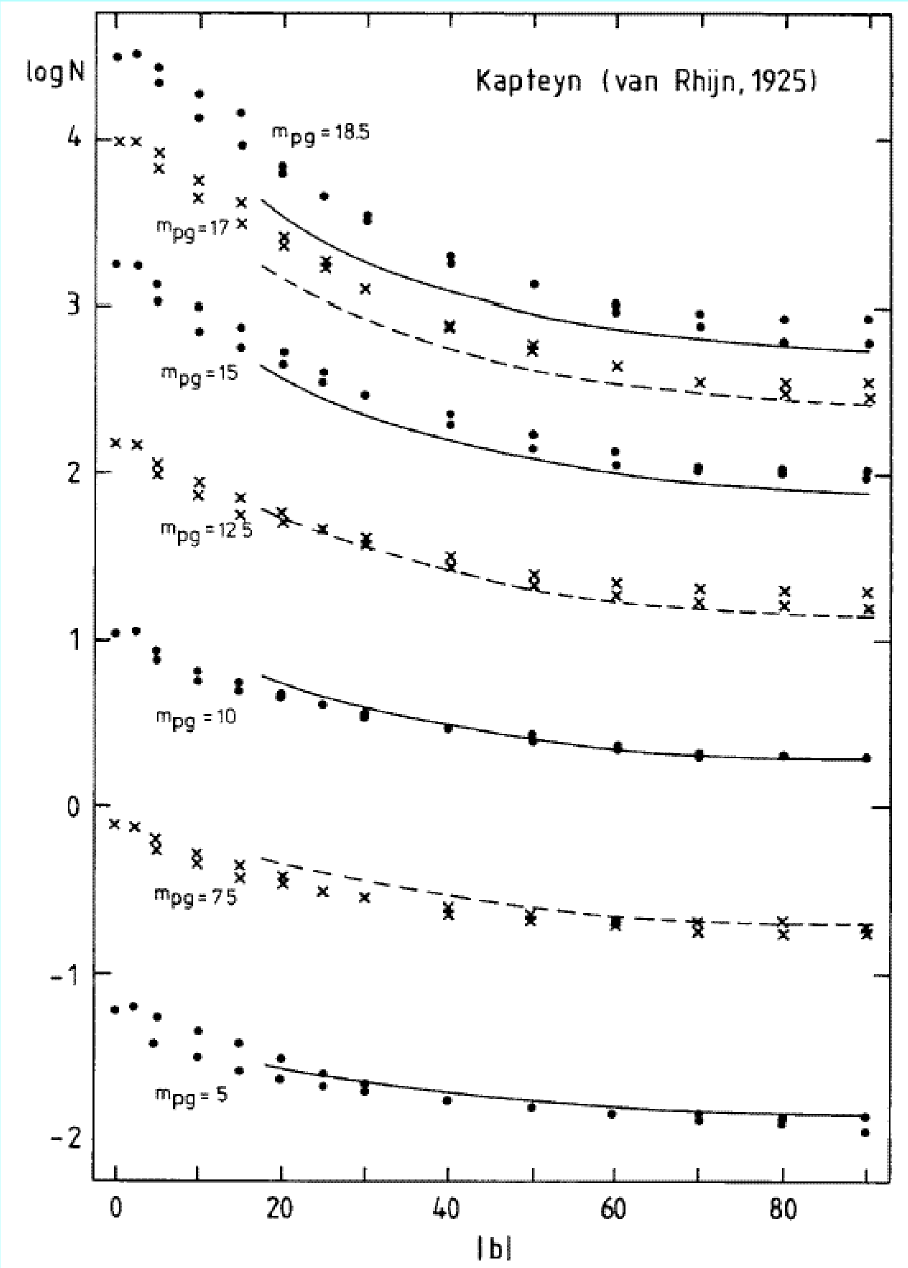
- $V_{\mathrm{rad}}(\mathrm{Virgo}) = 1000 \pm 50$ km s^{-1};
- Local Group infall: $V_{\mathrm{infall}} = 330 \pm 40$ km s^{-1};

so

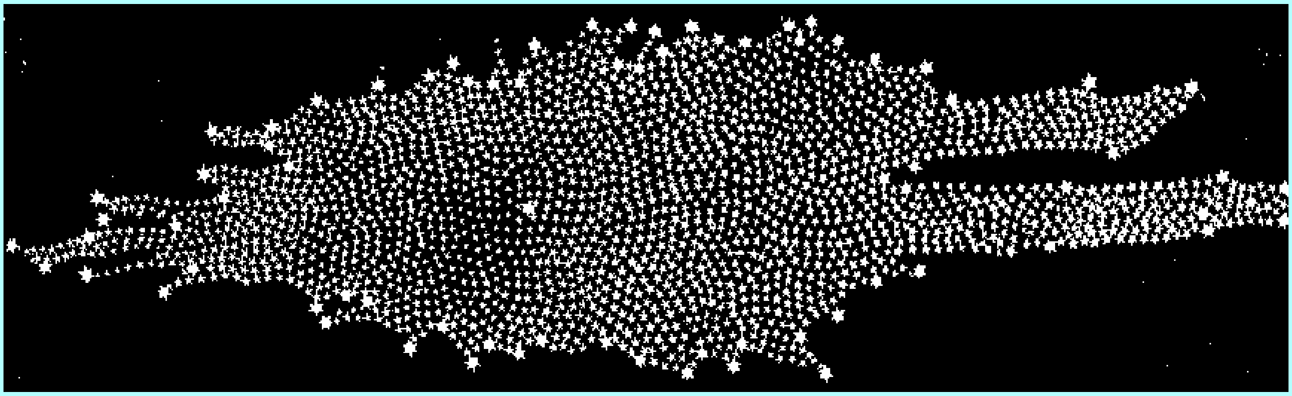
- $H_0 = 65 \pm 10$ km s^{-1} Mpc^{-1}.

Comparison to Kapteyn and van Rhijn (1928).

Comparison of the model counts with published counts show systematic errors in the faint magnitude sacles.



Comparison to William Herschel (1785)

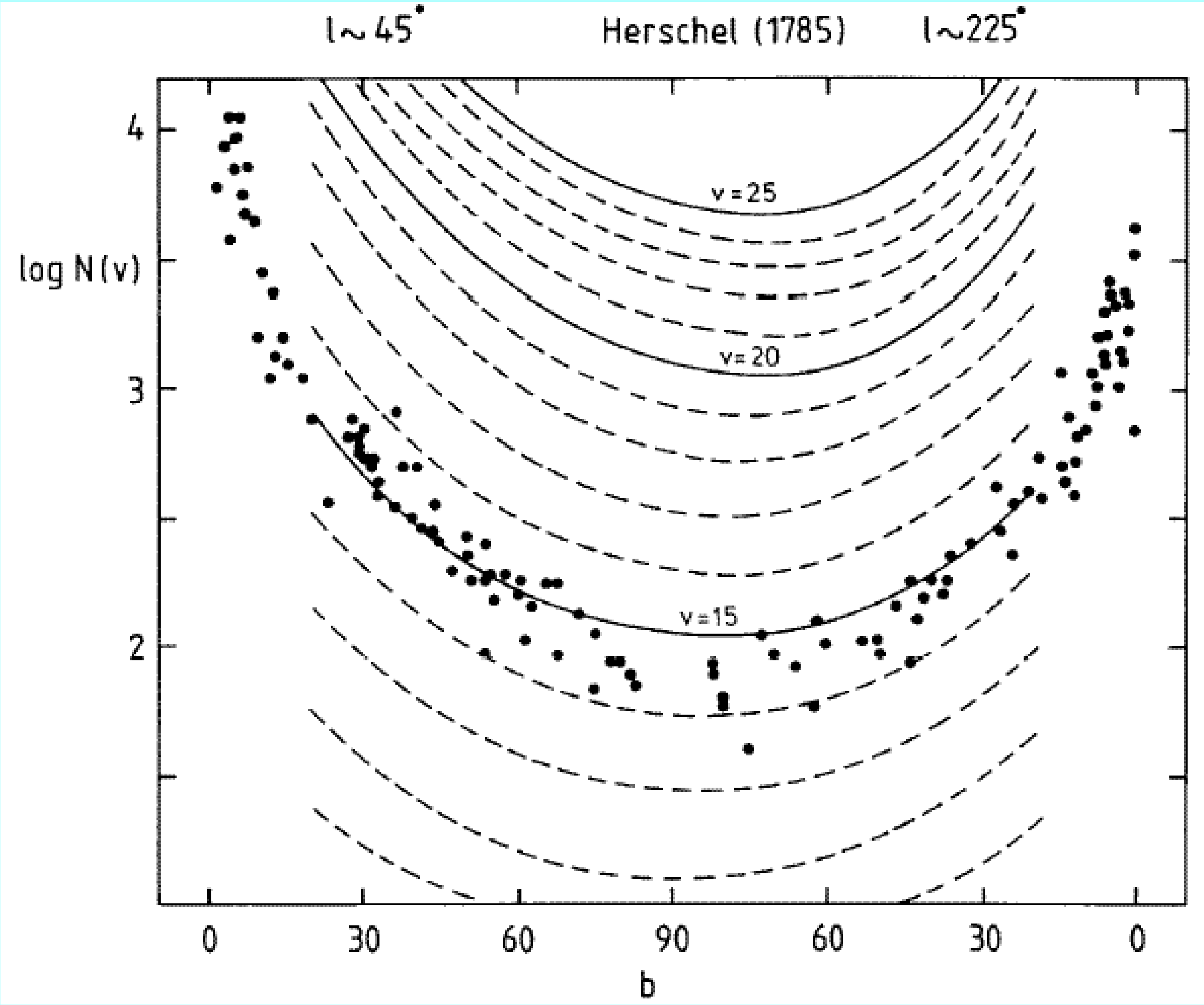


Great circle of his famous cross-cut crosses Galactic plane at $l \approx 45^\circ$ (Aquila) and $l \approx 225^\circ$ (Canis Major) and reaches a maximum latitude $\approx 85^\circ$.

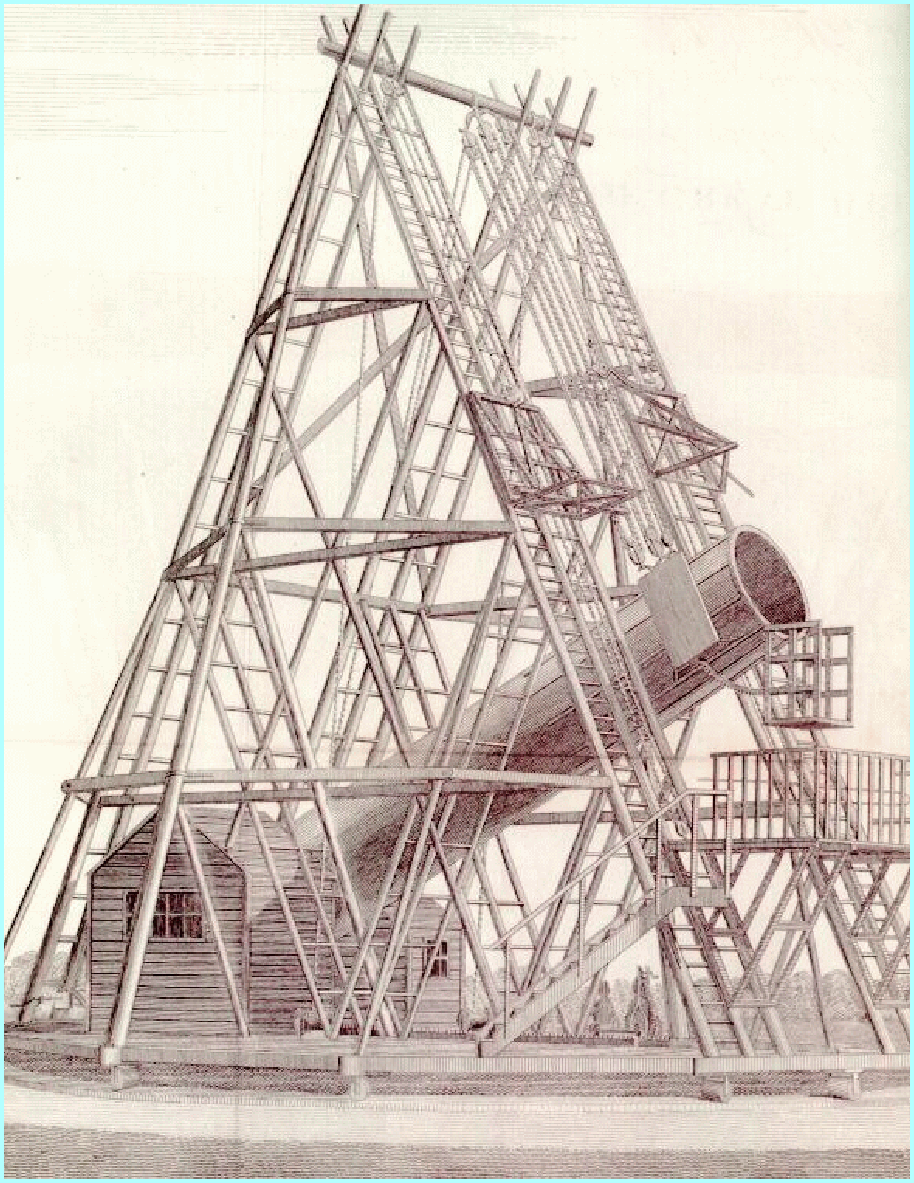
His 20-foot (18.7 inch aperture) telescope has a field of view of 15 arcmin.

Herschel finds dimensions of Sidereal System of 850×200 times the distance to Sirius, by assuming that the distance to the edge of the System $R \propto n^{2/3}$.

So his figure can be translated back to star counts.



⇒ Counted down to ≈ 15 V-mag.



From “Equalisation of starlight”-experiments Herschel estimated his “Space-penetrating powers”:

Unaided eye: 12 times Sirius

20-ft telescope: 75 times unaided eye

$\Rightarrow$ 14.8 mag fainter than brightest stars.