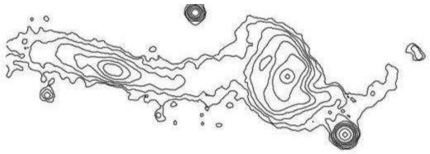

Surface Photometry of Galaxies

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Surface photometry is a technique to measure the surface brightness distribution of extended objects (galaxies, HII regions etc.).

Surface photometry: distribution of light (mass), global structure of galaxies, geometrical characteristics of galaxies, spatial orientation, stellar populations, characteristics of dust...

Surface photometry and **spectroscopic observations** – two major observational methods of extragalactic astronomy.

Plan

Literature

J. Binney, M. Merrifield “Galactic Astronomy”, Princeton University Press, 1998

L.S. Sparke, J.S. Gallagher “Galaxies in the Universe: An Introduction”, Cambridge University Press, 2000

D. Mihalas, J. Binney “Galactic Astronomy”, W.H. Freeman and Company, 1981

S. Okamura “Surface photometry of galaxies”, PASP, v.100, p.524, 1988

B. Milvang-Jensen, I. Jorgensen “Galaxy surface photometry”, Baltic Astronomy, v.8, p.535, 1999

Definitions

Surface brightness – radiative flux per unit solid angle of the image ($I \propto f/\Delta\Omega$).

To a first approximation, the s.b. of an extended object is independent of its distance from us since f and $\Delta\Omega$ are proportional to $1/r^2$ (flat, static Universe).

Optical astronomers measure s.b. in magnitudes per square arcsecond [$^m/arcsec^2$ or $^m/\Box''$]:

$$\mu = -2.5\,\lg I + \mathrm{const.}$$

Definitions

The surface brightness in magnitude units is related to the surface brightness in physical units of solar luminosity per square parsec by

$$I(L_\odot/\mathrm{pc}^2) = (206265)^2 \cdot 10^{0.4(M_\odot-\mu-5)} = 4.255\,10^8 \cdot 10^{0.4(M_\odot-\mu)},$$

where $M_\odot$ is the absolute magnitude of the Sun.

In the B passband $M_{\odot,B} = +5.48 \Longrightarrow$

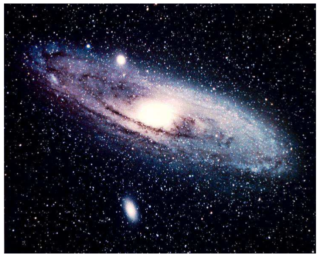
$$\mu(B) = 27.05 - 2.5\,\lg I(B).$$

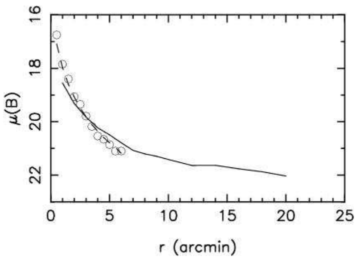
$\mu(B) \approx 27^m/\Box''$ corresponds to $I \approx 1\,L_{\odot,B}/\mathrm{pc}^2$.

Short history

One of the oldest techniques in modern astronomy.
The first attempt at surface photometry of galaxies dates back to Reynolds (1913).

Reynolds (1913) – circles
Walterbos & Kennicutt (1987) – solid line





Short history

Hubble (1930) – first systematic study of the light distribution in ellipticals. Main conclusions: elliptical galaxies
1) have no definite edge,
2) have all the same standard luminosity profile $I(r) = \frac{I_0}{(r+a)^2}$,
3) are relaxed self-gravitating systems in equilibrium.

Redman & Shirley (1936–1938) – first systematic discussion of some of the technical difficulties of the photographic surface photometry. In particular they discussed the effect of the point spread function (PSF) on the apparent luminosity distribution.

Oort (1940) – joint photometric and dynamical analysis of NGC 3115 and NGC 4494.

Short history

Seyfert (1940) – first quantitative study of optical color distribution in the disks of 7 spirals.

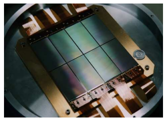
Patterson (1940) – surface brightness in the disk of M 33 decays **exponentially** with distance from the center; first detailed intensity matrix maps of 14 spiral and irregular galaxies.

Lindblad (1941-42) – detailed studies on the luminosity and color distributions in several large spirals; detection of reddening in the dust lanes between spiral arms; luminosity–color asymmetry along the minor axis of the image.

G. de Vaucouleurs (1948) – “de Vaucouleurs law” for elliptical galaxies.

Main steps of surface photometry

Surface photometry is currently done using CCDs (charge-coupled devices).



CCD detectors

When a photon hits the detector, it sets free electrons, generating a current. This current is collected and amplified, and the signal produced should be linearly proportional to the number of incident photons.
The surface of a CCD is divided into individual picture elements, or pixels. It is possible to do photometry (the image recorded is then a portion of the sky/star/galaxy) or spectroscopy (the light is dispersed by using a grating into its colors).

Main steps of surface photometry

There are some common problems with CCDs, which need to be taken into account in every observational program:

– read-out noise (random fluctuations in the count rate: 3–10 e/pixel)
– dark counts (failure to respond to currents, or electrons without an incident signal → cooled down to 100–200 K)
– cosmic rays (energetic particles hit the detector and produce a signal which is not related to the astronomical object under study). They appear as “stars”, but if the same portion of the sky is imaged more than once, it’s unlikely a cosmic-ray will fall in the same pixel. Hence they can be corrected for.

Main steps of surface photometry

- *Flat-fielding.* Pixels do not respond uniformly. Need to measure the individual response of the pixels by observing a diffuse screen or black twilight sky.
- *Sky background subtraction.* The background local sky level $I_S(x, y)$ is determined and subtructed from $I_{G+S}(x, y)$, leaving $I_G(x, y)$, the intensity distribution of only the galaxy. This is the most important step in surface photometry.
- *Stack of frames.*
- *Photometric calibration.* Need to observe some standard stars of known brightness to determine how many counts correspond to a given flux or magnitude.
- *Presentation of surface photometric data.*
- *Detailed interpretation, modelling.*

Sky background subtraction

The brightness of the moonless sky is made up of 4 components:

- Air glow: Photochemical processes in the upper atmosphere. It depends on the position on the sky. Changes by as much as 20% on timescales of tens of minutes.
- Zodiacal light: Sunlight scattered off particles in the solar system. Makes the largest contribution.
- Faint unresolved stars in our Galaxy.
- Diffuse extragalactic light – distant, faint, unresolved galaxies.

Relative importance of these components, and total intensity from them vary from site to site and with position in the sky.

The Earth's atmosphere contributes only about 30% of the ground-based night sky brightness.

Sky background subtraction

Brightness of the moonless night sky:

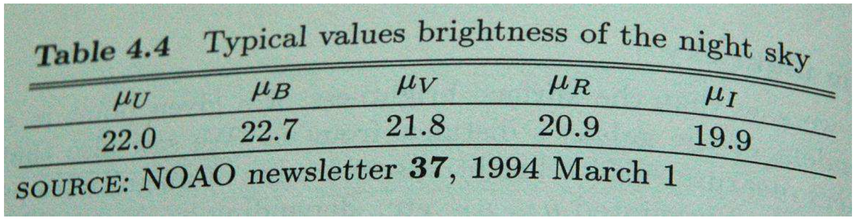


Table 4.4 Typical values brightness of the night sky

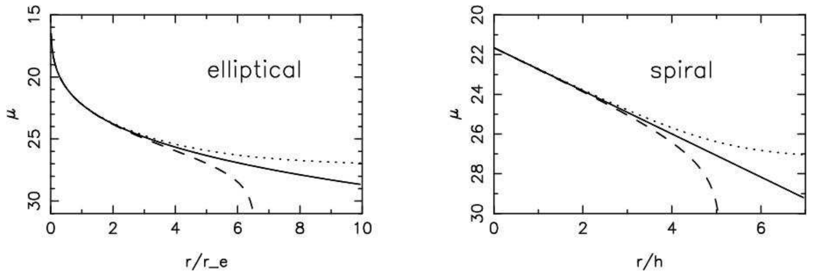
μ_U	μ_B	μ_V	μ_R	μ_I
22.0	22.7	21.8	20.9	19.9

SOURCE: NOAO newsletter **37**, 1994 March 1

The night sky is rather red; it has a color index near B-V = +0.9, similar to that of a fairly red galaxy.

Sky background subtraction

Inaccurate subtraction of the background contribution can mislead the following interpretation.



The effects of errors in the subtracted sky level on the typical profiles of E and S galaxies (*dashed line* – the background was overestimated by 1%, *dotted line* – underestimated by 1%).

Effect of Seeing

One important aspect in the study of the surface brightness of galaxies is the characterization of their surface brightness profiles, that is the dependence of the surface brightness on the projected distance from the center of the galaxy.

However, turbulence in the upper atmosphere degrades the quality of an image since, due to changes in the refractive index, the light-rays from a point-like object that reach the detector have to travel slightly different paths, and hence arrive at slightly different places on the detector. The shape on the detector of an otherwise point-like source is called the **Point Spread Function** (or **PSF**), and depends both on the **seeing** of the site, and on the properties of the telescope-detector assembly.

Seeing

The effect of the seeing is to blur an otherwise sharp image. If in absence of seeing the surface brightness of an object at a position **R**′ is I_t(**R**′), the measured brightness at a location **R** will be:

$$I_{app}(\mathbf{R}) = \int \mathrm{d}^2\mathbf{R}'\, P(\mathbf{R}-\mathbf{R}') I_t(\mathbf{R}'),$$

where P(**d**) is the PSF.
In the simplest case, the PSF can be treated as a circularly symmetric Gaussian

$$P(d) = \frac{1}{2\pi\sigma^2}\,\mathrm{exp}(-\frac{d^2}{2\sigma^2}).$$

Seeing

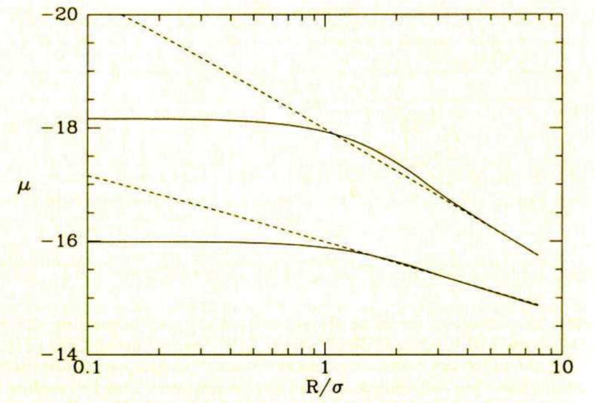
It is possible to show that:

$$I_{app}(R) = \int_0^\infty \mathrm{d}R'\, R'\, I_t(R')\, I_0(\frac{RR'}{\sigma^2}),$$

where I_0 is a modified Bessel function of order zero.

For $R \leq \sigma$ the measured surface brightness is smaller than the true s.b., for $R \geq \sigma$ – is larger than the real s.b. since the light removed from the smallest radii has to emerge at slightly larger radii.
The overall effect of seeing is to introduce into a featureless power-law profile an apparent core, that is, a central region of nearly constant apparent s.b.

Seeing



The dashed curves show the true central surface-brightness profiles of circularly-symmetric galaxies in which $\mu \sim r^{-1}$ and $\mu \sim r^{-0.5}$ at small radii. The full curves show the profiles that would be measured for these galaxies if the PSF were a Gaussian of dispersion σ.

Standard packages

ESO-MIDAS (http://www.eso.org/midas/)
European Southern Observatory - Munich Image Data Analysis System
The MIDAS system provides general tools for image processing and data reductions with emphasis on astronomical applications including special reduction packages for ESO instruments at La Silla and the VLT at Paranal. In addition it contains application packages for stellar and surface photometry, image sharpening and decomposition, statistics and various others.

IRAF (http://iraf.noao.edu/)
Image Reduction and Analysis Facility
IRAF includes a good selection of programs for general image processing and graphics applications, plus a large number of

Standard packages

programs for the reduction and analysis of optical astronomy data. Some packages are also available for the analysis of HST, XRAY and EUV data.

ESO-MIDAS and IRAF are freely available on many platforms (VMS, UNIX...). Both systems include a complete programming environment for scientific applications, which includes a programmable Command Language scripting facility.

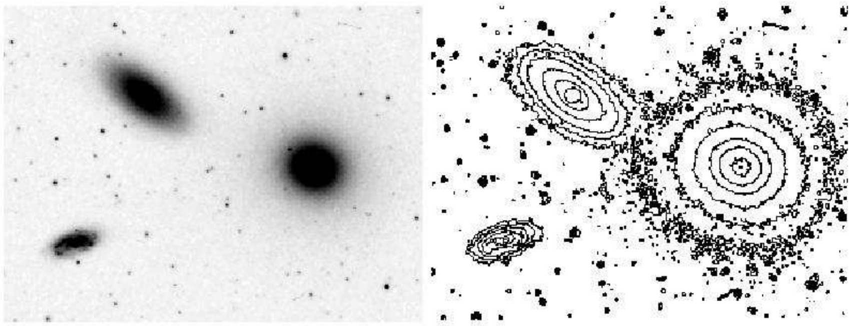
IDL (http://idlastro.gsfc.nasa.gov/)
Interactive Data Language (commercial package)
The IDL Astronomy Users Library – repository for low-level astronomy software written in the commercial language IDL. Not an integrated package, but a collection of procedures from which users can pick and choose for their own use.

Presentation of surface photometric data

Final result of modern digital surface photometry is the calibrated surface brightness distribution, $I(x, y)$, in units of $^m/\square''$, in the form of a digital data array. It consists of a huge amount of numbers ($\sim 10^6 - 10^7$), which do not allow any easy physical interpretation.

The most natural way is to present a gay-scale map or a false-color map. Also, more conventional, way is to plot a map of isophotal contours – isophotes.

Graphic methods



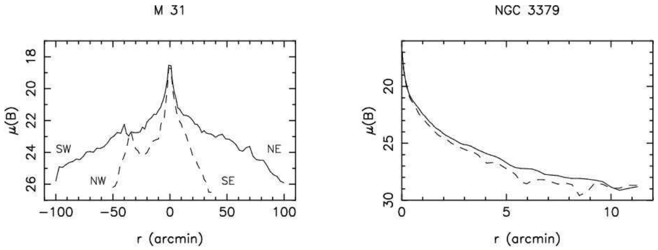
Elliptical galaxy NGC 3379 (right), NGC 3384 (top) and NGC 3389

Graphic methods

2D data are often reduced to a 1D brightness profile – $I(r)$. Widely used profiles are the following:

1. Photometric cuts

Original s.b. distributions along specific P.A. (e.g., major/minor axis) of a galaxy.
Shortcomings: twist of isophotes, non-axisymmetric structures (bars, spiral arms, HII regions...).



Graphic methods

2. Azimutally-averaged profile
is the profile obtained by averaging the brightness distribution $I(r,\theta)$ over θ on an ellipse with semimajor axis r and an axial ratio ϵ. (ϵ is usually defined by the isophotes in the faint outer region.)

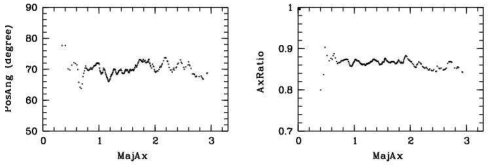
3. Equivalent profile (de Vaucouleurs 1948)
Let S be the area included in an isophote of a s.b. level I. If the isophotes consist of several “islands”, S includes the area of all such islands. The *equivalent radius*, r^*, is defined as the radius of a circle which has the same area as S, that is,

$$r^* = (S/\pi)^{1/2}.$$

Graphic methods

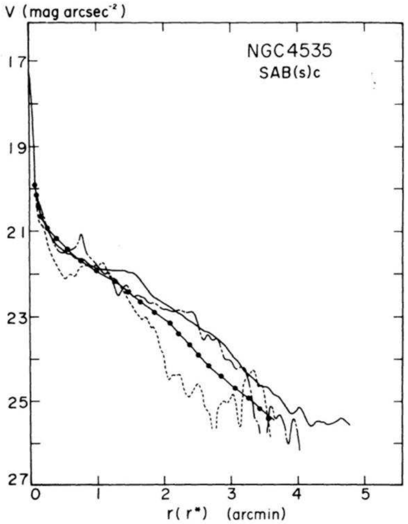
A plot of the s.b. as a function of the equivalent radius r^* is the equivalent profile.
Very smooth profile even for galaxies whose isophotes have considerable irregularities!
But equivalent profile is affected by the change of geometry due to the inclination.

4. Ellipticity and orientation profiles



P.A. and b/a vs. a for NGC 3379

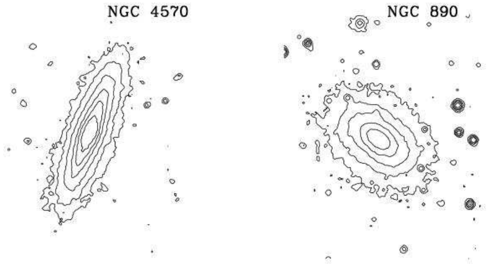
Graphic methods



Dot-dashed and broken curves – mean profiles along the major and minor axes, solid curve – *azimutally-averaged profile*, solid curve with circles – *equivalent profile*.

Graphic methods

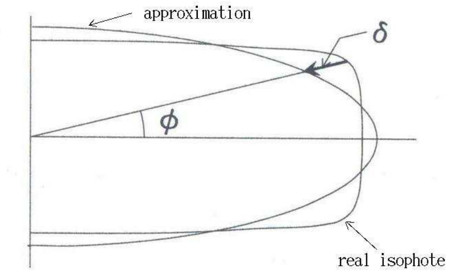
5. Isophotal shapes
Isophotes are not perfect ellipses. There may be an excess of light on the major axis (disky), or on the “corners” of the ellipse (boxy):



Disky (left) and boxy (right) isophotes

Isophotal shapes

The **diskiness**/**boxiness** of an isophote is measured by the difference between the real isophote ($R(\phi)$) and the best-fit elliptical one ($R_{ell}(\phi)$):

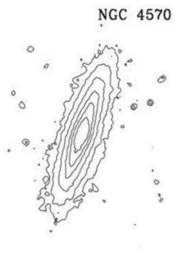


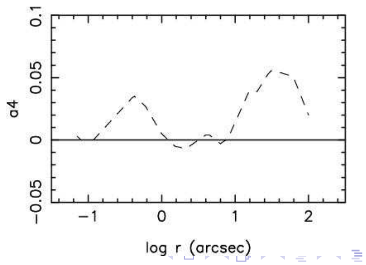
$$\delta(\phi) = R(\phi) - R_{ell}(\phi)$$

Isophotal shapes

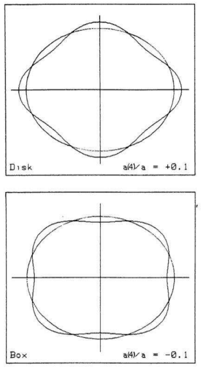
$$\delta(\phi) = \delta_0 \ + \ \Sigma_{n=1}^{\infty}(a_n \cos n\phi \ + \ b_n \sin n\phi),$$

where the terms with $n < 4$ all vanish (by construction), and $a_4 > 0$ is a disky galaxy,
while $a_4 < 0$ corresponds to a boxy isophotes.
Normalized coefficient a_4/a – standard characteristic for the shapes of the isophotes.

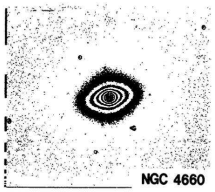




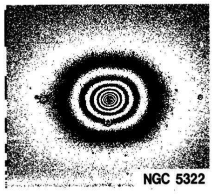
Isophotal shapes



Schematic drawing illustrating isophotes with $a(4)/a = +0.1$ and $a(4)/a = -0.1$.



R-image of NGC 4660, an elliptical galaxy with a disk-component in the isophotes ($a(4)/a \sim +0.03$).



R-image of NGC 5322, an elliptical galaxy with box-shaped isophotes ($a(4)/a \sim -0.01$).

Bender et al. 1988

Isophotal shapes

Disky/boxy shapes for E galaxies correlate with various other galaxy parameters:

– Boxy galaxies are more likely to show isophotal twists (and hence be triaxial)

– Boxy galaxies tend to be more luminous

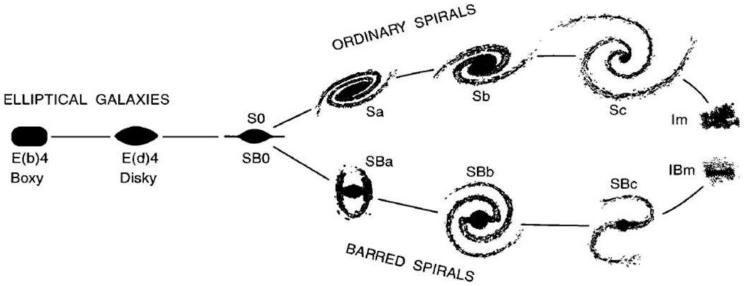
– Boxy galaxies have stronger radio and x-ray emission

– Boxy galaxies are slow rotators

– In contrast, disky galaxies are midsized ellipticals, oblate, faster rotators, less luminous in radio and x-ray

Isophotal shapes

Kormendy & Bender (1996): revision of the Hubble sequence for elliptical galaxies



Ellipticals are illustrated edge-on and at ellipticity $b/a = 0.4$.

System of standard photometric parameters

(G. de Vaucouleurs)

Basic parameter – *total* or *asymptotic* magnitide.

For an ideal object with circular isophotes, the luminosity emitted between r and $r + dr$ is $2\pi I(r)dr$. The integrated luminosity emited between the center and r is

$$L(\leq r) = \int_0^{2\pi} \int_0^r I(r) r d\theta dr = 2\pi \int_0^r I(r) r dr.$$

Total (asymptotic) luminosity is $L_T = 2\pi \int_0^\infty I(r) r dr$.
The fraction of the total luminosity emitted between 0 and r is

$$k(r) = \frac{L(\leq r)}{L_T}.$$

System of standard photometric parameters

$k(r)$ vs. r (or μ) – **relative integrated luminosity curve** or **growth curve**.

Effective radius r_e is determined so that $k(r_e) = \frac{1}{2}$, i.e., half the total luminosity is emitted within the circle of this radius.

If the isophotes are ellipses of semiaxes a, b, we can introduce effective semimajor and semiminor axes a_e and b_e, and the **equivalent effective radius** $r_e^* = \sqrt{a_e b_e}$.

When the isophotes are irregular, it always possible to define an equivalent radius r^* ($r^* = (S/\pi)^{1/2}$ – see previous sect.). Then the equivalent luminosity profile and the relative integrated luminosity curve are $I(r^*)$ and $k(r^*)$, and the equivalent effective radius r_e^* is defined by $k(r_e^*) = \frac{1}{2}$.

System of standard photometric parameters

Effective surface brightness μ_e – surface brightness at r_e or $k(\mu_e) = \frac{1}{2}$.

Mean surface brightness inside μ_e (or r_e):
$\langle I \rangle_e = \frac{L_T}{2\pi r_e^2}$ or $\langle \mu \rangle_e = m_T + 5\,\mathrm{lg} r_e + 1.995$,
where m_T – total magnitude of galaxy.

Concentration indices:
$k(r_1) = 1/4$, $k(r_3) = 3/4$ and $C_{21} = r_e/r_1$, $C_{32} = r_3/r_e$
(or $r \to r^*$).

More popular version: $C = 5 \times \mathrm{lg}(r_{80}/r_{20})$, where r_{80} and r_{20} are the growth curve radii.

Other parameters

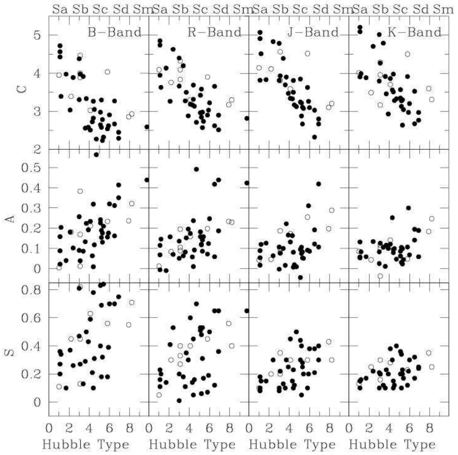
- **Rotational asymmetry parameter**

$$As = \frac{\Sigma_{ij}|I_{ij} - I_{ij}^R|}{\Sigma_{ij} I_{ij}},$$

where I_{ij} – intensity in pixel $(i,\ j)$, and I_{ij}^R – corresponding intensity after image rotation by 180° about image center.
As correlates with morphological type and color index.

- **Clumpiness** (or **smoothness**)
S – the ratio of the amount of light contained in high frequency structures to the total amount of light in the galaxy.
S is similar to Asymmetry but one subtracts a smoothed version of the object from itself.

Other parameters



CAS vs. Hubble type for 44 isolated spirals (Hernandez-Toledo et al. 2007)

Other parameters

- **Lopsidedness**
Global low-order asymmetry:

Quantitative measure of lopsidedness is the average of the $m = 1$ to $m = 0$ azimuthal Fourier amplitudes between 1.5 and 2.5 scale lengths of the disk – $\langle A_1/A_0 \rangle$.
$\sim$30% of field spiral galaxies exhibit significant lopsidedness ($\langle A_1/A_0 \rangle \geq 0.2$) at large radii.

Other parameters

Also:

axial ratio ($q = b/a$)

galaxy inclination ($\cos^2 i = \frac{q^2 - q_0^2}{1 - q_0^2}$)

P.A. or P.A.(r)

diameter (D_{25})

B/D ratio

etc.