Bars and boxy bulges in the Milky Way and other galaxies

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Bars form spontaneously in disc galaxies

Bars rotate!
Angular momentum redistribution within the galaxy

Emitters : (material at near-resonance in the) inner disc
Absorbers : (material at near-resonance in the) outer disc and halo

(Lynden-Bell & Kalnajs 72, Tremaine & Weinberg 85, Weinberg 85, 04, Athanassoula 03, Fuchs 04, etc)

More angular momentum redistribution should lead to stronger bars and to stronger decrease of their pattern speed

Indeed simulations show that the strength of the bar correlates well with the amount of angular momentum exchanged

Both for the disc and the halo, there is more angular momentum gained/lost at a given resonance if:
- the density is higher there
- the resonant material is colder

Athanassoula 2013 = EA03
Angular momentum lost by bar: How?

- orbits become thinner
- bar traps stars which where on near-circular orbits around it, into its outer parts
- bar rotates slower
Barred galaxies cannot be stationary!! They have to evolve.
Pattern speed decreases with time

In order to lose angular momentum, the bar can slow down.

The means that the pattern speed will decrease.

The resonances will move further out (to larger radii).

The length of the bar will increase.

Corotation radius $R_{CR}$: the radius at which a star on a circular orbit will corotate with the bar.
Bar growth
Secular evolution
Bar formation
Bar evolution
Effect of halo mass on bar formation and evolution: duality

Haloes slow down bar formation

EA02

But haloes make bars strong (secular, nonlinear evolution)

EA & Sellwood 86

EA03
A series of haloes with different mass in the regions of the main resonance

More concentrated haloes have more mass at resonances and thus can absorb more angular momentum. The bar will emit more angular momentum and grow stronger.

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Stronger bars
Longer, thinner and more massive
Often ansae
Flat radial density profiles (Elmegreen & Elmegreen 1985)

Less strong bars
Fatter
Never ansae

Elliptical-like isodensity contours

Boxy edge-on shape

Rectangular-like isodensity contours

Peanuts or Xs when seen edge-on

\[ \gamma = 5. \]
\[ \gamma = 0.5 \]
Influence of the disc velocity dispersion

Bar formation phase

Bars form later in hot discs

EA & Sellwood 1986

Secular evolution phase

Bars in hotter discs slow down less and they are weaker (oval-like)

Figure 4. Mean eccentricity of the bar isodensities as a function of the mean mass averaged Q.
A classical bulge

In the secular evolution regime they help bars grow stronger.

As a result:

Classical bulges flatten (become triaxial) and start spinning.

(EA & Misiriotis 02, Saha et al 12, Saha & Gerhard 12, 13)
A gaseous component

Athanassoula. Machado & Rodionov 2013 (=AMR13)
Gas slows down bar formation in two ways:

Bars are stronger in gas poor than in gas rich cases

Black line: 0% gas
Blue line: Initially 50% of disc mass in gas, drop with time to 5%

AMR13
Bar formation stage

Relatively heavy haloes ($M_h/M_t$) slows down
Hot discs slows down
Halo triaxiality speeds up
Increased gas fraction slows down
Presence of a thick disc component slows down

What makes bars stronger (secular evolution part)

Maximum angular momentum redistribution, i.e:

Considerable halo and/or bulge contribution stronger
Cold discs stronger
Velocity distribution function in halo stronger/weaker
Halo triaxiality weaker
Gas poor discs stronger
Absence of a CMC stronger

Note: This list is NOT complete
Some of these can not be applied concurrently
What is a bulge?

Three definitions have been used so far:

Morphological: A smooth light distribution that swells out of the central part of a disc seen edge-on.

Photometrical (from radial photometric profiles): The extra light in the central part of the disc, above the exponential profile fitting the remaining (non-central) part.

Bulges
Bulge definitions

Definition 2:
From photometric profiles

The bulge is identified as the extra light in the central part of the disc, above the extrapolated exponential fitting the remaining (non-central) part.

Sersic profile:
effective radius, effective central surface density and, in particular, the Sersic index $n$
Kinematical definitions: V/σ plots

Open symbols: Classical bulges
Filled symbols: Pseudo bulges
x: ellipticals

Binney 1978, 2005

Kormendy 1993
Kormendy & Kennicutt 2004
Classical bulges, boxy/peanut bulges and discy bulges

Kormendy: galaxies are not a homogeneous class of objects (Kormendy 1993, Kormendy & Kennicutt 2004)

Distinction: Classical bulges and pseudo-bulges

Classical bulges

Box/peanut bulges are PARTS of bars and form from a vertical instability. Disc material that has moved out of the plane

Disc-like bulges form from inflow of (mainly) gas material to the centre of the galaxy and subsequent star formation
Bulges
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Classical bulges: $n$ of the order of 3 or 4
Discy-bulges: $n$ of the order of 1
Boxy/peanut bulges: $n$ between 0 and 1
Box/peanut bulges are PARTS of bars and form from a vertical instability. Disc material that has moved out of the plane

Disc-like bulges form from inflow of (mainly) gas material to the centre of the galaxy and subsequent star formation.
Sersic index = 1
in general Sersic Index < 2

Face-on it often has an oval shape or includes a bar (inner bar)

Athanassoula 08
Bars and Boxy/Peanut/X bulges

Movie gtr101

Bars rotate!
Peanuts form AFTER bars

Combes, Debbash, Friedli, Pfenniger 1990
Athanassoula 2005, 2008
Martizez-Valpuesta and Shlosman 2005
Peanuts form AFTER bars

movie
Unsharp masking simulations from different viewing angles

Athanassoula 2005
Observations (unsharp masking)

Bureau, Aronica, Athanassoula, Dettmar, Bosma, Freeman (2006)
Figure 12. Some periodic orbits of the $x_1$ family for model 06. The outline of the bar is plotted with a dotted line.
Orbital structure in bars
Peanut should have a shape compatible with that of the orbits in the vertical families.

Periodic orbits in 3D
Peanuts should be SHORTER than bars

edge-on

face-on
Simulations:

Athanassoula and Misiriotis 2002
Athanassoula 05
Athanassoula and Beaton 2006

Lutticke, Dettmar and Pohlen, 2000
Bureau, Aronica, Athanassoula et al 2006
For a full movie see
http://lam.oamp.fr/research/dynamique-des-galaxies/
scientific-results/milky-way/bar-bulge/how-many-bars-in-mw
Apply to the Milky Way

Signal for 2 bars:

- The COBE/DIRBE bar
  Bar semimajor axis 3.1 – 3.5 kpc
  Axial ratio 10:4:3
  Direction 15 – 30 degrees from the Sun-GC line

- The Long bar
  Bar semimajor axis 4 – 4.5 kpc
  Axial ratio 10:1.54:0.25
  Direction 40 degrees from Sun - GC

Hammersley et al 2000, Benjamin et al 2005

So what is the structure of the bar/bulge system in our Galaxy?

Summarise arguments from Romero-Gomez, EA et al 2011
The bar lengths of the COBE/DIRBE bar and the Long bar show clearly that these two together do not form a double bar system.

Also there are limits to these length ratios from resonant interaction driven chaos and morphology in simulations (Maciejewski and Sparke 2000, Maciejewski and Athanassoula 2008, Shen and Debattista 2009, Heller et al 2009)

(but the MW may well have a double bar Alard 01)

Romero-Gomez et al 2011
How are the COBE/DIRBE bar and the Long bar related?

Clue 1: Long bar is vertically very thin, COBE/DIRBE bar is very thick.
Clue 2: Long bar is longer than the COBE/DIRBE bar

Athanassoula (2006): There is a single bar of which the COBE/DIRBE bar is the boxy/peanut part and the Long bar is the thin outer parts. Tested by Cabrera-Lavers et al (2007).

See also Romero-Gomez et al (2011) and Martinez-Valpuesta and Gerhard (2011)

For a full movie see http://lam.oamp.fr/research/dynamique-des-galaxies/scientific-results/milky-way/bar-bulge/how-many-bars-in-mw
The long bar is at 25 – 35 degrees

Face-on view of the bar: The B/P part is thicker than the outer part. This can contribute to the angle difference between the Long 'bar' and the COBE/DIRBE 'bar'

But:

The difference in position angles? (15 - 30 degrees for COBE/DIRBE bar and 40 degrees for the long bar)

See also Martinez-Valpuesta and Gerhard (2011). Good agreement

Zasowski, Benjamin and Majewski (2011)
A leading extension in the ring: This may be the reason that we see the long bar at a larger angle than the COBE/DIRBE bar (or may contribute substantially to it).

Feature found in: Athanassoula and Misiriotis 02

Use for the MW: Romero-Gomez, EA et al 2011
Martinez-Valpuesta & Gerhard 2011
ARGOS: Ness et al 2012, 2013a, 2013b

McWilliam & Zoccali 2010
Nataf et al 2010
etc
The end