Dynamics of the Milky Way

          II. Fundamentals of Stellar Dynamics
Part 2:  Stellar Orbits and Jeans’ Theorem
Part 3:  The Galactic Bulge and Bar
Part 4:  The Galactic Disk and Halo
Cylindrical Rotation in Galactic Bulge

Kinematics from BRAVA survey show nearly cylindrical rotation between $b=-4^\circ$ and $b=-8^\circ$

Kunder+’12

Confirmed by ARGOS survey . . .

Ness+’13, see K.Freeman’s lectures

Signature of the boxy bulge

(although in principle axisymmetric models with cylindrical rotation can be constructed, Rowley’82)
The BRAVA data for M-giant stars (Howard+’08) show nearly cylindrical rotation which is well fit by a boxy bulge formed from the disk (Shen+’10).

Models from similar simulations with a preexisting classical bulge of 8% (>15%) the disk mass worsen the fit (are considered to be ruled out).

Hence Shen+’10 conclude the MW originated from an essentially pure disk galaxy.
Dynamical (NMAGIC) Models for BRAVA data

Dynamical Model constructed with M2M method
Starting point: disk galaxy simulation
Constraint: BRAVA kinematic data and model density
Martinez-Valpuesta, Portail, OG, in prep.
Metallicity Gradients Can Survive Through Disk Instability

The Galactic bulge is mostly very old (>10 Gyr), therefore the chemical structure of the early disk back then could have been different from that of the Galactic disk today.

In a rapidly evolving disk, radial metallicity gradients are not erased by bar and buckling instabilities:

(Jacobi) binding energies scattered by $\ll$ initial range

Martinez-Valpuesta+OG’13
Metallicity Gradients Through Disk Instability

Final metallicity gradient in the bulge is similar to initial radial gradient in the disk – therefore a pure disk evolution model can be found which approximately reproduces MW bulge metallicities (gradients and longitudinal asymmetrics). Metallicity gradients per se do not imply a classical bulge.

Differences to VVV map hint at additional evolutionary processes

Martinez-Valpuesta+OG’13
Metallicity-Dependent Kinematics

- Near-cylindrical rotation for all metallicities  
  - Ness+’13
- More metal-poor stars have higher dispersions  
  - also Babusiaux+’10
Small classical bulges spun up by the bar can develop cylindrical rotation

Non-rotating classical bulge with 6% disk mass absorbs angular momentum from the bar. Final model has both boxy bulge from disk, and rapidly, cylindrically rotating classical bulge, mass ratio above plane about 3:1 and different shapes. See Saha, Martinez-V. + OG’12, 13

Cylindrical rotation does not rule out classical bulge cmpt
Conclusions

• Star count analysis (RCG from VVV and other surveys) shows that the Galactic bulge is of Box/Peanut-type.
• This agrees with the observed cylindrical rotation which can be reproduced by dynamical models.
• B/P-bulges are the inner parts of bars and are common in other evolved barred galaxies.
• B/P-bulges arise through a buckling instability and are supported by X-shaped, 2:1:2 resonant orbits.
• The long bar may be the in-plane component of the bar, but not much is known yet about its 3D structure and kinematics.
• The buckling instability allows preexisting metallicity gradients (radial, or components) to survive.
Dynamics of the Milky Way

Part 4:
The Galactic Disk and Halo (brief)
Preview

• Stellar disk parameters
• Cold gas (l,v)-diagram, spiral arms
• Terminal velocity curve
• MW inner rotation curve
• Dark halo mass distribution
• Timing argument: the MW and M31
Galactic Disk Structure

- **Scale-length**
  - Optical data: 2.3-2.7 kpc (Zheng+’01, Siegel+’02, Juric+’08 SDSS)
  - NIR: 2.1-2.5 kpc (Freudenreich ‘98, Drimmel+Spergel ‘01, Bissantz+ OG ‘02)
  - Starcounts: 2.0-3.5 kpc (Robin+92, Ortiz+93, Chen+99, Ojha 01, Lopez-Corredoira+02,04)

  Complications: vertical structure, disk breaks, extinction, stellar population

- **Central profile** giant starcounts appear to flatten out inside 4 kpc (Lopez-Corredoira+04, Robin+03, Polido+13)

- **Influence of the bar:** expect such break in profile near bar radius

- **Outer break**
  - Older data gave $R_b=12-15$ kpc (Robin+’92, Ruphy+’96, Freudenreich ’98)
  - Recent data $13\pm0.5$ kpc (Sale+’10 A*), $13.9\pm0.5$ kpc (Minniti+10 RCG). Now seen in many data sets (e.g. Glimpse) over large areas of sky (Benjamin ’13 review)

- **Thin disk and thick disk:** continuity (Bovy+’12) or discrete (Gilmore+Reid ‘83, Juric+’08, Fuhrmann+08)?
Milky Way Spiral Structure - $(l,v)$-Diagram

CO from Dame+’01, plot from Rodriguez-Fernandez+Combes’08

Milky Way Spiral Pattern – Tangent Points

- Four main spiral arm tangent point directions and 3 kpc arm seen in gaseous or young stellar tracers
- HII regions and GMCs overlaid on simulation of bar-driven flow from Englmaier & OG (1999)
- Difficulty: locations of the spiral arms connecting the tangents (e.g., Vallee 2005)

Table 1. Observed spiral arm tangents compared with model predictions.

<table>
<thead>
<tr>
<th>Inner Galaxy spiral arm tangents in longitude</th>
<th>Measurement</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scutum</td>
<td>Hα</td>
<td>Weaver (1970), Burton &amp; Shane (1970)</td>
</tr>
<tr>
<td>Sagittarius</td>
<td>integrated $^{12}$CO</td>
<td>Cohen et al. (1980), Grabelsky et al. (1986)</td>
</tr>
<tr>
<td>Centaurus</td>
<td>$^{12}$CO clouds</td>
<td>Dame et al. (1986)</td>
</tr>
<tr>
<td>Norma</td>
<td>warm CO clouds</td>
<td>Solomon et al. (1985)</td>
</tr>
<tr>
<td></td>
<td>Hα−Regions (H109−α)</td>
<td>Lockman (1989), Downes et al. (1980)</td>
</tr>
<tr>
<td></td>
<td>$^{36}$Al</td>
<td>Chen et al. (1996)</td>
</tr>
<tr>
<td></td>
<td>Radio 408MHz</td>
<td>Beuermann et al. (1985)</td>
</tr>
<tr>
<td></td>
<td>2.4 μm</td>
<td>Hayakawa et al. (1981)</td>
</tr>
<tr>
<td></td>
<td>60 μm</td>
<td>Bloemen et al. (1990)</td>
</tr>
<tr>
<td></td>
<td>adopted mean</td>
<td></td>
</tr>
</tbody>
</table>

Tracing Spiral Arms with HII Regions, Masers, MIR

- Left: pattern deduced from HII regions with approx. distances (Taylor & Cordes ‘93, Russeil ‘03): Perseus, [Sagittarius/Carina], Scutum/Centaurus, [Norma/Outer]

- Right: Artist picture (R.Hunt) and superposed SF regions with accurate parallaxes (Reid et al 2009). Will map out the spiral arms with Masers and with Gaia!

- Frustratingly hard to see tangent point overdensities of old stars in the NIR light or star counts. Mid-IR star counts show overdensities at Scutum and Crux tangent points but not at Sagittarius tangent (Benjamin+’05, Churchwell +’09). Measuring masses of spiral arms requires accurate velocities for suitable tracer stars (e.g., Grosbol in prep.)

Suggests the MW may only have two stellar spiral arms outside bar corotation.
Classic method is to infer rotation curve from terminal velocity curve, assuming circular orbits and a value for $V_0$, here $V_0=250$ km/s. Cannot see $\Omega = \text{const}$ part.

However, orbits are not circular, we live in a barred galaxy!
Gas Morphology and lv-diagrams

From Fux 99, cf. also Englmaier & OG 99, Weiner & Sellwood 99, Bissantz+03
In barred MilkyWay model, gas streamlines are determined by gravity and dissipative forces: approx. follow closed orbits but are not allowed to cross -- shocks modify the gas flow to avoid this crossing.

Terminal velocity curve = observed maximum/minimum radial velocity.
Includes:  
- streaming motion in bar  
- spiral arm perturbations  
- DM halo

Reproducing observed gas velocities with gas flow in barred Milky Way model gives “maximum” mass scaling.

Caveat: Models have uncertainties

**HI data:** Burton & Liszt (1993), Fich et al. (1989)  
**$^{12}$CO data:** Clemens (1985), Alvarez et al. (1990)  
**Model:** Englmaier & OG (1999), Bissantz, Englmaier & OG (2003)
Rotation Curves of Models fitted to NIR Luminosity and Bulge/Gas Kinematics

Left: circular rotation curves of the luminous and dark components in the initial, bar-unstable models of Fux ‘97, ‘99. \( R_0=8 \) kpc, \( V_0=220 \) km/s.

The luminous mass in the COBE model predicts predicts \( v_0 \approx 180 \) km/s at solar radius, 190-200 km/s at 2-4 kpc.

Right: circular rotation curve of the combined bulge+disk contribution derived from the COBE NIR data, with M/L scaled to terminal v’s and bulge dispersions, cf. Englmaier+OG ‘06, ‘99, Bissantz+’03)

Dynamics of the Milky Way --- Part 4:
Galactic Disk and Halo

MW Rotation Curve fitted to Stellar Radial Velocities

Most probably inner Galactic rotation curve from fitting 3365 stellar radial velocities in 14 APOGEE fields, with a kinematic disk model including asymmetric drift, velocity dispersions, solar motion parameters, etc., gives very nearly flat $v_c = 218 \pm 6$ km/s \textit{Bovy+’12}

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### Table 2
Results for Galactic Parameters and Tracer Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Flat Rotation Curve</th>
<th>Power-law $V_c(R) = V_c(R_0) (R/R_0)\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_c(R_0)$ (km s(^{-1}))</td>
<td>218 ± 6</td>
<td>$218^{+4}_{-19}$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>...</td>
<td>$0.01^{+0.01}_{-0.10}$</td>
</tr>
<tr>
<td>$dV_c/dR$ (R(_0)) (km s(^{-1}) kpc(^{-1}))</td>
<td>...</td>
<td>$0.2^{+0.2}_{-2.8}$</td>
</tr>
<tr>
<td>$A$ (km s(^{-1}) kpc(^{-1}))</td>
<td>13.5(^{+0.2}_{-1.7})</td>
<td>$13.5^{+0.2}_{-1.0}$</td>
</tr>
<tr>
<td>$B$ (km s(^{-1}) kpc(^{-1}))</td>
<td>$-13.5^{+1.7}_{-0.2}$</td>
<td>$-13.7^{+3.3}_{-0.1}$</td>
</tr>
<tr>
<td>$(B^2 - A^2)/(2\pi G) (M_\odot pc^{-3})$</td>
<td>...</td>
<td>$0.0002^{+0.0002}_{-0.0025}$</td>
</tr>
<tr>
<td>$\Omega_0$ (km s(^{-1}) kpc(^{-1}))</td>
<td>27.0(^{+0.3}_{-3.5})</td>
<td>$27.3^{+0.4}_{-4.2}$</td>
</tr>
<tr>
<td>$R_0$ (kpc)</td>
<td>8.1(^{+1.2}_{-0.1})</td>
<td>$8.0^{+0.8}_{-1.0}$</td>
</tr>
<tr>
<td>$V_{R,\odot}$ (km s(^{-1}))</td>
<td>$-10.5^{+0.5}_{-0.8}$</td>
<td>$-10.3^{+1.1}_{-0.1}$</td>
</tr>
<tr>
<td>$V_{\phi,\odot}$ (km s(^{-1}))</td>
<td>$242^{+10}_{-3}$</td>
<td>$241^{+5}_{-17}$</td>
</tr>
<tr>
<td>$V_{\phi,\odot} - V_c$ (km s(^{-1}))</td>
<td>$23.9^{+5.1}_{-0.5}$</td>
<td>$23.1^{+3.6}_{-0.5}$</td>
</tr>
<tr>
<td>$\mu_{\text{Sgr}A^*}$ (mas yr(^{-1}))</td>
<td>$6.32^{+0.07}_{-0.70}$</td>
<td>$6.36^{+0.09}_{-0.86}$</td>
</tr>
<tr>
<td>$\sigma_R(R_0)$ (km s(^{-1}))</td>
<td>$31.4^{+0.1}_{-3.2}$</td>
<td>$32.2^{+0.2}_{-2.6}$</td>
</tr>
<tr>
<td>$R_0/h_\sigma$</td>
<td>$0.03^{+0.01}_{-0.27}$</td>
<td>$0.06^{+0.01}_{-0.17}$</td>
</tr>
<tr>
<td>$X^2 \equiv \sigma_\phi^2/\sigma_R^2$</td>
<td>$0.70^{+0.30}_{-0.01}$</td>
<td>$0.64^{+0.18}_{-0.02}$</td>
</tr>
</tbody>
</table>

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Dynamics of the Milky Way Part 4.  
Galactic Disk and Halo  
21
The Galactic Halo
Dark Halo Mass Distribution from Jeans Eqn

Spherical Jeans equation

Three terms in brackets have magnitudes

~4, ~[0.1-0.3], ~[0-1];

thus \( V_c \) depends mostly on \( \sigma_r \) and slope of density profile for the tracer population

e.g., Gnedin+’10

Example: same \( \sigma_r \) similar \( \beta \) correspond to 30% more mass for steeper slope of density profile (\( \alpha=4.6 \) vs \( \alpha=3.5 \))

Deason+’12
Tracer Density and Dispersion Profiles

BHB stars from SDSS-DR6
BHB stars from HVS survey

Outer tracer density steeper ($\gamma = 4 - 4.5$); recent ML analysis of DR8 BHB stars favours two-power law model with $\gamma = 2.3$ -> $\gamma = 4.6$ at $r = 27$ kpc
Deason+’12

RR Lyrae from SDSS Stripe 82
diagrams from Gnedin+’10

Velocity dispersion nearly flat to 80 kpc

**ML-estimated rotation curve for outer halo**

\((x,z)\)- and \(v_{\text{los}}\)-r for 1933 BHB stars from SDSS-DR8

Since \(v_{\text{los}}\)-velocities from Sun are mostly radial, anisotropy can be estimated only for large sample with wide sky coverage.

ML analysis for two-power law density profile favours \(\beta=0.5\) and potential slope \(\gamma=0.4\)

Deason+’12
Blue/hatched: ML power-law halo with density slope $\alpha=4.6$; grey $\alpha=3.5$;
Vertical/horizontal hatched: extra systematic error in slope $\pm 0.2$ dex;
MB10, M11: solar neighbourhood V0/R0 (McMillan+Binney ‘10, McMillan ‘11);
X08, G10: halo BHB stars SDSS-DR6 (Xue+08), HVS (Gnedin+’10)

Results of this analysis:
$M_{DM}=4\times10^{11}M_\odot$ (50 kpc),
$\sim10^{12}M_\odot$ virial
$c=20$ (expected from sim$^s$: $c=10$)
Deason+12
MW-M31 timing argument revisited: the proper motion of M31

HST fields for PM measurement

N-body simulation for analysis

PM measurements by Sohn+'12
Analysis & implications:
vander Marel +'12ab

Dynamics of the Milky Way --- Part 4:
Galactic Disk and Halo

Transverse velocity of M31

- PMs in 3 fields from multiple images per field, time baseline 5-7 yrs. ~5-10’000 reference stars per field, relative to ~200-300 background galaxies. Careful consideration of systematic errors. Final combined accuracy 12 μas yr⁻¹ [Sohn+’12]

- N-body model of M31 to correct PM of individual fields to PM of center-of-mass. Diagram shows Giant Stellar Stream ridge in vlos-proj.radius space, comparing to measured velocities incl. for present field.

- Results consistent with updated constraints from M31 satellites [van der Marel + Guharthakurta ‘08 (blue, app. rotation)] so take weighted average with corrected PMs (red). Weighted average (black) consistent with radial orbit, after taking into account the reflex motion of the Sun with $R_0=8.3$ kpc, $V_0=239$ km/s (black star).

- $V_{\text{tan}}(\text{M31}) = 17$ km/s (1σ CL <34 km/s) [van der Marel+1205.6864]
Timing argument

Planar Keplerian orbit ($M_{\text{tot}}$, a, e, $\eta$) fully constrained by D, $V_{\text{rad,M31}}$, $V_{\text{tan,M31}}$ and $t=13.75$ Gyr. Errors $\rightarrow M_{\text{tot,timing}} = (4.27\pm0.53)\times10^{12} M_{\odot}$ (black). Down from prev. est. due to $\sim$20 km/s larger solar motion towards M31 (lower M31 radial velocity).

Timing mass applied to millenium sim$^n$ galaxy pairs has inaccuracies, ‘cosmic variance’ Li + White 08; for low $V_{\text{tan,M31}}$ $\rightarrow$ broad final pdf.

Bayesian analysis with this and dyn.mass priors for M31, MW halo $\rightarrow$ posterior pdf’s below,

$M_{\text{M31,vir}} = (1.51\pm0.42)\times10^{12} M_{\odot}$

$<M_{\text{MW,vir}} > = 1.63 \times 10^{12} M_{\odot}$

$M_{\text{tot,vir}} = (3.14 \pm 0.58) \times 10^{12} M_{\odot}$

[Virial radii $\sim$300 kpc for M31, MW]

Timing argum’t does not increase $M_{\text{tot,vir}}$ much (cosmic variance!)
The MW in ~7 Gyr

Centaurus A Radio Galaxy (VLT KUEYEN + FORS2)

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