Dynamical modeling of the Milky Way Bulge

Juntai Shen (Shanghai Astro. Obs.)

沈俊太 (上海天文台)
Milky Way's Boxy bulge

- Obscured by dust; asymmetric about minor axis
- Most bulge stars are old (>5 Gyr, Clarkson et al. 2008)
Dynamical modeling of the MW Bulge

- Classical picture: bulges are formed in the dynamical violence of major mergers

**BRAVA survey results as model constraints**

**Build a simple fully-evolutionary N-body model of the MW bulge**

**Infer the formation history of the MW; and examine the classical picture**
Modeling the Milky Way Bulge

- The very simple model can match the BRAVA data extremely well in almost all aspects:

- **Physical mechanism: a tale of two instabilities!**
  - [Bar-forming instability (in-plane)](vertical) → [buckling instability (vertical)](vertical) → saturation → boxy bulge
  
- Boxy bulge = edge-on bar

Shen, J., et al. 2010
Other dynamical properties of the bar (pattern speed, bar angle, axial ratio, bar length) are also consistent with previous independent studies.
Modeling the Milky Way Bulge ---

Match stellar kinematics in all strips strikingly well

- Cylindrical rotation: rotation independent of height
- Hard to reproduce with a classical bulge


See also ARGOS results (Ness et al. 2013a,b)
Can a significant classical bulge be hidden?

- The data excludes a pre-existing classical bulge with mass $\gtrsim 10\% M_{\text{disk}}$; the MW is nearly a pure-disk galaxy!
- Avoided major mergers?
A vertical metallicity gradient can still be generated even after the violent buckling!

Inma’s talk

Martinez-Valpuesta & Gerhard (2013)
Similar simple bar model to Shen et al. (2010)
The recently discovered X-shaped structure in the MW bulge region
Intriguing X-shaped structure in MW Bulge

- Red clumps: a good standard candle
- Along different lines of sight toward the Galactic bulge, red clumps split into two groups
  - A major obs. discovery

Credit: Zhao-Yu Li

Stars are distributed in a vertical X-shape?

McWilliam & Zoccali (2010)
Nataf et al. (2010)
Intriguing X-Structure in the MW?

- The full length of the structure is ~2.3 kpc in the radial direction.
- It tilts away from the Sun-GC line by ~ 20°.
- “The double peaked RC is inconsistent with the tilted bar morphology.” (McWilliam & Zoccali 2010)
X-structure in our model

- The same model matches observations reasonably well
- The X must have formed at least a few Gyrs ago
- Further evidence that **MW bulge formation is shaped mainly by internal dynamical instabilities**, instead of mergers
- Major orbital families supporting the X-shape?
  - Banana? Brezel? Others? (Qin et al. 2015b; Valluri et al., in prep)

Li & Shen (2012); also Ness et al. (2012)
3D structure of the X-shape

- A buckled bar = outer thin part + peanut + inner box
- A reflection of the central peanut?

Li & Shen (2015, in prep)
Predictions of kinematics of X-shape?

- Make model predictions on the kinematic properties of the X-shape
  - R.V. and proper motion
  - Consistent with most of recent obs.
  - Will be further cross-checked by upcoming large surveys like *Gaia* etc.

- Test using the stars’ spatial distribution to determine $R_{\text{GC}}$ (Gardner et al. 2014)

Virtues of the simple bar model

- Simplicity, few parameters to tweak
- Physical processes are well understood
- Despite its simplicity, it ties together several isolated results in a coherent picture, cemented by a fully-evolutionary N-body model in which the bar evolves naturally and without much fine-tuning
  - Beautiful match to full kinematics (cylindrical rotation)
  - Photometric/kinematic bar angle
  - Bar length & bar pattern speed
  - X-shaped structure
  - Vertical metallicity gradient (Martinez-Valpuesta’s talk)
- A physically-motivated starting point
  - To incorporate more complexities (Ness’s talk)
  - Full evolution history of disk+halo+bulge?
    - It is hard, but don’t screw up the bulge/bar when you fit the halo!
Recent review on the MW bulge

- Summarized recent progresses and outstanding problems
- Working on an article for the A&A Review on “the Galactic Bar” (with S. Mao)

Theoretical Models of the Galactic Bulge

Juntai Shen, Zhao-Yu Li (Shanghai Astronomical Observatory)
(Submitted on 20 Apr 2015)

Near infrared images from the COBE satellite presented the first clear evidence that our Milky Way galaxy contains a boxy shaped bulge. Recent years have witnessed a gradual paradigm shift in the formation and evolution of the Galactic bulge. Bulges were commonly believed to form in the dynamical violence of galaxy mergers. However, it has become increasingly clear that the main body of the Milky Way bulge is not a classical bulge made by previous major mergers, instead it appears to be a bar seen somewhat end-on. The Milky Way bar can form naturally from a precursor disk and thicken vertically by the internal firehose/buckling instability, giving rise to the boxy appearance. This picture is supported by many lines of evidence, including the asymmetric parallelogram shape, the strong cylindrical rotation (i.e., nearly constant rotation regardless of the height above the disk plane), the existence of an intriguing X-shaped structure in the bulge, and perhaps the metallicity gradients. We review the major theoretical models and techniques to understand the Milky Way bulge. Despite the progresses in recent theoretical attempts, a complete bulge formation model that explains the full kinematics and metallicity distribution is still not fully understood. Upcoming large surveys are expected to shed new light on the formation history of the Galactic bulge.
Take home message

- Disk buckles to make boxy / peanut-shaped bulges — main driver shaping the MW bulge
- It is a “pseudo-bulge” made by internal dynamical instabilities, not a classical bulge made by mergers
- There is an “X” in the MW bulge! Its properties qualitatively match obs.; it formed at least a few Gyrs ago
- Further evidence that MW bulge formation is shaped mainly by internal dynamical instabilities

That’s where I am gonna put the big black hole!

Credit: Zhao-Yu Li
Thank you!