THE NEW BULGE

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The Cabal…

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The Hubble Type of the Milky Way

- Our Galaxy is a relatively late-type multi-armed spiral galaxy
- Like all spirals it contains an inner bulge/spheroid component
The Importance of the Bulge

- It is the only spheroidal-like population that we can resolve into stars to the level of the main sequence turnoff
- Models show bulges to be connected to the early phases of galaxy formation via mergers

Robertson+ 2003
Bulges as small ellipticals

- Fundamental plane seems to indicate that bulges are like small ellipticals living in a disk.
However...

- There seems to be a fundamental difference between actual spheroids and bulges, with spiral bulges being more similar to disks and pseudobulges.
BULGE TYPES

CLASSICAL VS. PSEUDOBULGES

DE VAUCOULEURS vs. EXPONENTIALS
COBE
BOXY/PEANUT BULGE
HIGH EXTINCTION  INFRARED IMAGING
GALACTIC BAR
FROM GAS MOTIONS AND LATER STELLAR COUNTS IN THE IR, THE MILKY WAY IS KNOWN TO CONTAIN A STELLAR BAR AS WELL
RED CLUMP STARS

USED AS DISTANCE INDICATORS

MEAN LUMINOSITY OF RED CLUMP BRIGHTER AT $L=+5$ THAN AT $L=-5$
X-SHAPED STRUCTURE
ORIGINALLY FROM DOUBLE RED CLUMP
X-SHAPES
SEEN IN EXTERNAL GALAXIES

MOST COMMONLY ASSOCIATED WITH PSEUDOBULGES
OUR GALAXY HAS A BAR AND X-SHAPE AND B/P BULGE LIKELY TO CONTAIN A PSEUDOBULGE. HOW IS EVERYTHING RELATED?
The Bulge Radial Velocity Assay

- Is there a bar?
- Is there a classical bulge?
- Are there any cold substructures (dwarfs, mergers)?
- Radial velocity survey of the Galactic bulge
BRAVA

- 9500 M giants ~100 per field
- Spectra from CTIO with Hydra multi-fiber spectrograph
BRAVA STARS
SELECTED FROM 2MASS
WITH COLOURS AND
LUMINOSITIES CONSISTENT
WITH BULGE MEMBERSHIP
No stellar streams

- No evidence of significant deviations from Gaussian mean in any of the BRAVA fields
- Suggests that there is no evidence of substructure in the Bulge and therefore no recent mergers large enough to detect
BRAVA

THE MAIN OUTCOME OF THE SURVEY IS A ROTATION CURVE AND A VELOCITY DISPERSION PROFILE FOR THE GALACTIC BULGE
A pure bar

- The rotation speed of the bulge is consistent with pure cylindrical rotation and no evidence of cold disk components or a pressure supported bulge.
CYLINDRICAL ROTATION CONSISTENT WITH THE VELOCITY FIELD OF A PURE STELLAR BAR
A simple model accounts for all observations.

It consists of a single massive bar comprising the entirety of the bulge.
LIMITS TO CLASSICAL COMPONENT
< 8% OF THE DISK MASS
AGE OF BULGE STARS
OLD AND METAL-RICH Z~3
FIREHOSE INSTABILITY

BULGE FORMS FROM BAR-LIKE INSTABILITY OF MASSIVE EARLY DISK

OLD AGE SO NO MERGERS SINCE Z~3
METALLICITY GRADIENT IN BULGE STARS

LIKE SMALL ELLIPTICAL?
α-elements are enhanced among bulge stars

SUGGESTS RAPID STAR FORMATION AND QUENCHING AT HIGH REDSHIFT
The bulge appears to be a stellar bar formed from the instability of a massive disk at very early times.

Old stellar ages and $\alpha$-enhanced abundances imply rapid early star formation and quiescent evolution.

Difficult to explain the abundance gradients in this fashion.

Unless bulge evolves from an early thick disk.
HEATED DISK

LEADS TO AGE AND METALLICITY GRADIENTS IN BULGE
PSEUDO BULGES

NGC 4565 CAN BE MODELLED WITH A DOUBLE SERSIC PROFILE OF INDEX $\sim 1.3$
PSEUDOBULGE OF NGC4565

LIKELY A COUNTERPART OF OUR GALAXY, BULGE IS ACTUALLY A PROMINENT BAR WITH NO CLASSICAL COMPONENT
DOES THE MILKY WAY LOOK LIKE THIS?
In 11Mpc sample 3/4 of all spirals are bulgeless or have B/P bulges.

BARLENSES IN FACE ON GALAXIES
ARE LIKELY TO BE BOXY/PEANUT BULGES OR BARS AS WELL
OTHER BULGES

CYLINDRICAL ROTATION IS COMMON AMONG B/P BULGES SUGGESTING THEY ARE ALL BARS

Moleainezhad et al. 2016
This poses an interesting problem for theoretical models.

Milky Way sized halos in cosmological simulations tend to form classical bulges via mergers.

While the Galaxy seems to have had a quiet merging history this cannot be true of all galaxies.

Yet most local bulges seem to originate from buckled disks and therefore no mergers since high z.
OUR BULGE
NORMAL PARAMETERS SO ALL BULGES MAY BE BARS
RR Lyrae can be isolated as a true bulge component (distance indicators) and as the oldest stars (core helium-burning low mass).
OGLE SURVEY

40,000 RR LYRAE IN SOUTHERN BULGE
PIETRUKOWICZ ET AL. 2015
CLAIM TO HAVE DETECTED THE BAR IN OGLE RR LYRAE
VVV SURVEY

NO DETECTION OF BAR BUT Spheroidal-like DISTRIBUTION EITHER OLD BULGE OR INNER HALO REGIONS
A BULGE RR LYRA WITH A HALO-LIKE ORBIT
BRAVA RR Lyrae survey

- Radial velocity survey of OGLE RR Lyrae
- Colours and luminosities and periods are typical of what expected from a bulge population
947 RR LYRAE

4 FIELDS OBSERVED FROM THE CAT WITH THE AAΩ MULTI-FIBER SPECTROGRAPH
BRAVA RR

• Our RR Lyrae do not trace a rotating component
• They appear to lie within an approximately spheroidal component supported by pressure
• About 1% of the mass in the bulge
BRAVA RR LYRAE
HALO MEMBERS

UNLIKELY GIVEN THE VELOCITY DISPERSION

HOWEVER MODELS INDICATE THAT THE INNER HALO MAY ONLY BE SPUN UP AT LARGE RADII
KINEMATICS OF RR LYRAE IN MODEL

PEREZ-VILLEGAS ET AL. 2017
A residual bulge

- 1% of the mass of the bar
- It is predicted that the earliest epoch of star formation may take place in the bulge but not be of the bulge
- Relics of the oldest star formation episode in the galaxy should be found in the centre
Conclusions

• The Milky Way is a bulgeless spiral dominated by a massive stellar bar

• There is no significant pressure-supported component

• Bar is very old and implies no significant merging for the Milky Way since z~3
Nearly all bulges in the nearby universe also seem to be pseudo bulges and stellar bars. This is in very severe contrast to models of galaxy formation in CDM where a bulge must always form. A small residual bulge may be present in the inner kpc.