Observations of Thick Disks

(Stellar)

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Exponential Disks, Flagstaff, October 7, 2014
What can we learn?

- Thin stellar disks are fragile and can be disturbed by external influences such as companion galaxies and mergers, and internal perturbations such as spiral arms, bars and Giant Molecular Clouds.
  - Stellar systems are collisionless and cannot ‘cool’ once heated, unlike gas.
    - Vertical structure contains imprints of past heating and of star formation during dissipational settling.
  - Radial structure contains imprints of angular momentum distribution/re-arrangement.

- Properties of thin and thick stellar disks constrain:
  - Merger/accretion, infall history.
  - Star formation rate vs dissipation rate.
  - Internal secular processes.
Thick Stellar Disks

- Identified first as third component in surface brightness profile in external S0 galaxies – bulge, thin disk plus an additional exponential vertical fall-off (Burstein 79, Tsikoudi 79)

- Star counts at the Galactic Poles fit by two exponentials

Gilmore & Reid (1983)
see also Yoshii (1982)
Thick Disks in External Galaxies

- Most external (edge-on) disk galaxies have vertical surface brightness profiles better fit by two components - exponentials or isothermal disks (e.g. Comerón et al 2011; 2013) - with the higher scale-height thick disk being old(er) (e.g. Yoachim & Dalcanton 2008; Mould 2005)
  - A few are counter-rotating → external origin?

- Derived thin and thick disks have comparable scale-lengths and scale-heights different by a factor of around 4, each approximately constant with radius (e.g. Comerón et al 2011)

- Mass ratio of thick to thin disk higher at lower circular velocity (Comerón et al 2011; Yoachim & Dalcanton 2006)

- Ratio of mass in thick disk plus ‘bulge’ to mass in thin disk approximately constant (Comerón et al 14 + Salo + Comerón talks)
Decomposition of 2MASS R-band surface brightness for the Milky Way analogue, NGC 891 by Bournaud, Elmegreen, & Martig in 2009. HST star-count analysis gives similar results (Ibata et al 2009).
Milky Way Thick Disk

- Stars studied mostly within few kpc of the Sun
- Kinematics intermediate between thin disk and halo, mean rotation velocity lags thin disk by ~ 50km/s, vertical velocity dispersion ~ 40km/s \( \rightarrow \) thick, with scale height of ~1kpc
  - Higher than extrapolation of thin disk age-velocity dispersion
- Mean metallicity \( \sim -0.6 \) dex (0.25 solar value)
- Elemental abundances ‘alpha-enhanced’ \([\alpha/Fe] > 0\)
- Most thick disk stars are old, \( \sim 10\) Gyr
- Derived mass \( \sim 20\% \) of thin disk mass i.e. \( \sim 10^{10} \) \( M_\odot \)
- Thick disk appears distinct but distributions overlap with those of other stellar components and often non-Gaussian: how best to define the thick disk? [e.g. Wyse 2009]
Milky Way Galaxy Thin Disk

- Local thin disk stars show age-velocity dispersion relationship: older stars are ‘hotter’
- Exact trend difficult to define (age uncertainties, plus substructure in planar velocities – effect of bar plus spirals?)

Casagrande et al 2011, analysis of the Geneva-Copenhagen Survey (Nordstrom et al 2004), F/G stars within ~ 100pc  

‘good’ age $\sigma < 1$Gyr or 25%

\[ \star \text{ thick disk} \]
Elemental Abundances: beyond metallicity

Alpha element and iron

![Graph showing IMF biased to most massive stars, Type II only, Plus Type Ia, Slow enrichment SFR, winds, Fast, Slope of decline depends on SFR.]

Self-enriched star forming region.
This model assumes good mixing so IMF-average yields

Wyse & Gilmore 1993
Very Local Galaxy

- Thick and Thin disks separated by elemental abundance pattern, obtained from high resolution spectra \(\Rightarrow\) distinct star-formation and enrichment histories

Bensby et al 14
Adiekyan et al 13

FG(K) stars within 100pc
Local Thick and Thin Disks

Kinematics-based definition

Age-based definition

Blue: younger  Red: older

Bensby, Feltzing & Oey 2014
Thick disk is old and 'alpha-enhanced'
Formed from gas predominantly enriched by core-collapse SNe
Consistent with old age of turnoff, dominant population (Wyse et al 09)

Haywood et al 2013

Adding ages to the local HARPS sample of Adibekyan et al 2013

Bensby et al 2014
Thick disk has OLD turnoff

8,600 faint F/G dwarfs, several kpc above the plane,
spectroscopic metallicities from AAOmega/AAT data

[Fe/H]

Young stars would be here

Old stars here

12Gyr turn-off points (Girardi et al)

(g-r)_o

Wyse, Gilmore, Norris

Gilmore & Wyse 1985
Carney et al 1989……
Non-Local Samples: SEGUE

**SDSS Segue survey**, ~20,000 G dwarf stars several kpc distant
spectral resolution $R \sim 2,000$

Not ideal for elemental abundances!

Bovy et al 2012

‘The Milky Way has no thick disk’

Observed distribution

After correction for selection function
Non-Local Samples: GES

Gaia-ESO survey, FG dwarf stars several kpc distant ($r < 18$), VLT Flames/Giraffe spectra $R \sim 20,000$

Two sequences separated by low-density region: distinct thick disk.

Recio-Blanco et al (inc RW), 2014

300 VLT nights over 5 years
100,000 stars + clusters
PIs Gilmore & Randich
Started 12/2011

Also Ruchti & Bensby talks
Non-Local Samples: GES

Gaia-ESO survey, FG dwarf stars several kpc distant ($r < 18$), VLT Flames/Giraffe spectra $R \sim 20,000$

Errors increase a) $0.05$ in $[\alpha/\text{Fe}] \rightarrow$ d)

Two sequences separated by low-density region: distinct thick disk.

Recio-Blanco et al (inc RW), 2014

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Opposite rotational velocity gradients for thin and thick disks:

Recio-Blanco et al 2014

Haywood et al 2013

Qualitatively consistent with trends obtained by Bovy et al (2012) of increasing scale-length with increasing [Fe/H] for ‘high-alpha’ stars, and decreasing scale-length with increasing [Fe/H] for ‘low-alpha’ stars: scale-length should increase with increasing rotational velocity (for fixed velocity dispersions).
Non-Local Samples: APOGEE

Thick disk sequence constant
Thin disk sequence changes with R,Z

⇒ Varying star formation efficiency/outflow

Nidever et al 2014
Distinct Galactic Thick Disk

- Selection by kinematics, or age, or distance from the plane, or metallicity, or elemental abundance at given metallicity (best separation) gives broadly similar samples of ‘thick disk’ stars: distinct from thin disc ➔ can talk about ‘the thick disk’

- Metal-weak thick disk has thick-disk kinematics (e.g. Kordopatis et al. inc RW 2013 – data from RAVE; Beers et al 14)
  - Metal-weak thick disk does have enhanced elemental abundances equal to those of stellar halo – invariant IMF (Ruchti, Fulbright, Wyse et al. 2010, 2011 – stars selected from RAVE)

- Similar stellar age distribution as bulge ➔ same event/mechanism? (Wyse, 2001; Comerón et al 2014)
Internal, Secular Evolution

- Heating by in-plane spirals and GMC in present thin disk apparently insufficient to form thick disk, but play major role in thin-disk age-velocity dispersion relation

- Mixing from increased epicyclic excursions insufficient to provide observed scatter in age-metallicity relationship (for realistic metallicity/age gradients)

- **Radial migration** (Sellwood & Binney 2002) can move stars over ~ 2kpc while maintaining orbital circularity: acts at co-rotation resonance, needs many transient spirals of different pattern speeds to affect the entire disk
  - More effective for stars on close to circular orbits, less for populations of significant velocity dispersion, but also depends on spiral pattern (Vera-Ciro et al 2014; Solway et al 2012; Daniel & Wyse, in prep)
  - Be careful of usage of term ‘radial migration’ – heating or not?
Radial Migration to Form Thick Disk?

- Velocity dispersion of thin disk stars increases towards the central regions, as surface density increases; stars migrating outwards expected to reach higher scale-heights than local thin disk i.e. form a thick(er) disk (Schonrich & Binney 2009)

- Inner disk stars are older (inside-out formation?)
  ⇒ old(ish) thick disk, but expect age range to result

- Concept valid, importance not yet established quantitatively
  - Vertical energy not conserved (Solway et al 2012; Minchev et al 2012; Roskar et al 2013) so not so thick
  - Effectiveness of migration decreases with random motions (possible signature detected, decrease in velocity dispersion for highest [Mg/Fe] stars at high [Fe/H], Minchev et al, RAVE, 2014)
  - Chemical evolution model needs development

- Apparently plays important role in simulations but complicated (e.g. Bird et al 2012, 2013; Roskar et al 2012, talks here...)
Upper panels: Chemical evolution with radial migration, Schonrich & Binney 2009
Lower panels: (left) local stars sorted by Kinematics, Bensby et al. 2014; (right) symbol size scaled by age, Fuhrmann 2011
- Trends not well matched
Thick Disks through Minor Mergers

- Initially thin stellar disk; after merging orbital energy is absorbed into internal degrees of freedom of the disk, increasing vertical velocity dispersion and scale-height \( \Rightarrow \) thick stellar disk.
  \[ \Delta \sigma^2 \sim v_{\text{orbit}}^2 \frac{M_{\text{sat}}}{M_{\text{gal}}} \] (Ostriker 1990, Gilmore & Wyse 1985)
- Orbital angular momentum gives tilt.
- Satellite debris spread through galaxy
- Thick disk will be compressed and heated by accretion of gas to re-form thin disk
- Re-start chemical evolution, form second sequence in elemental abundances (?)
  e.g. Snaith et al 2013

Including gas causes less heating/thickening (radiate energy); more mergers cause more heating \( \Rightarrow \) old age limits mergers to early times redshift > 2.
Hierarchical clustering of \( \Lambda \)CDM generically leads to late mergers and broad range of ages in thick disk (and bulges)
Thick Disks without Mergers: Evolution of Clumpy Turbulent Disks at $z \sim 2$?

- Gravitational instabilities form massive clumps, $M \gtrsim 10^8 M_\odot$, rapid star-formation plus scattering creates thick disk (Bournaud, Elmegreen & Martig 09).
- Early thick disks will be compressed and heated by accretion/re-formation of thin disk (Ostriker 1990; Elmegreen & Elmegreen 2006).
- Adiabatic growth would lead to
  \[
  \frac{\Delta H}{H} \sim - \frac{\Delta M_{\text{gas}}}{M_{\text{disk}}} \; ; \; \frac{\Delta \sigma^2}{\sigma^2} \sim -2 \frac{\Delta H}{H}
  \]
- Clumps alternatively/also form bulges.
- Star formation during dissipative settling from thick to thin disk (Burkert et al 92) would form vertical metallicity gradient in thick disk ➔ hints of gradient, e.g. Reico-Blanco et al 14.
- Would subsequent thin disk have separate elemental abundance pattern?
- Mergers would reheat – need very quiescent (Bird’s talk – no significant merger since redshift of 3).
Both Galactic thick disk and Galactic bulge dominated by old population

Mean metallicity of local thick disk lower than that of bulge (factor 1.5 – 2) – need data for inner disks

Changes in stellar metallicity distributions in lines-of-sight to bulge can be modelled as changing mix of populations (Ness et al 2013; Rojas-Arriagada et al, inc RW, 2014)

– what are they?

Elemental abundance patterns merge (Melendez et al 2008; Ness et al 2013)

More data (APOGEE, GES, HERMES..) and modelling (e.g. Immeli et al 2004) are needed!
Conclusions

- Thick disks and their relation to thin disks lie at the core of nature vs nurture, internal vs external influences on galaxy evolution
  - Galactic thick disk appears distinct from thin disk
  - Old, little merging since redshift of > 2
  - Unusual in ΛCDM (few percent only of mass of Milky Way!), but selected for ‘zoom-ins’ of Milky Way analogues
- Ongoing massive spectroscopic surveys should elucidate connections among stellar components
  - How the Milky Way evolved - a typical disk galaxy
- Great complementarity between study of old nearby resolved stars and direct study of systems forming at high redshift: will only improve as new facilities and capabilities become realized