The Milky Way Galaxy

Marina Rejkuba, ESO, Garching
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Lund Observatory, 1955

The Infrared Milky Way
This map of the infrared sky includes the light of a half billion stars.
Eggen, Lynden-Bell & Sandage 1962: “Evidence from the motions of old stars that the Galaxy collapsed”

- “… the oldest objects were formed at almost any height above the galactic plane, whereas the youngest were formed very near the plane.”
- “The process was very rapid and consumed a time span of not more than a few times $10^8$ yr.”
- metallicity gradient
Lack of metallicity gradient for outer halo globular clusters

Halo built up over an extended period (after the collapse of the central regions of the Galaxy have been completed) from independent protogalactic fragments with masses $\sim 10^8 M_\odot$
Milky Way is a spiral galaxy

- **Disk** → defines the plane and extends to ~15 kpc
  - \( \frac{3}{4} \) of the baryonic mass – \( 5 \times 10^{10} \, M_\odot \)
  - Thin disk Hz~300 pc, Thick disk Hz~900 pc (old, \( \alpha \)-enhanced)
  - Normalization thick/thin disk~2-20%

- **Bulge** → central component extending to ~3kpc
  - Dominated by the bar – peanut shape (COBE/DIRBE)
  - \( \frac{1}{4} \) of the baryonic mass
  - Old, \( \alpha \)-enhanced

- **Halo** → nearly spherical extending to ~100kpc
  - 1% of the baryonic mass; local normalization ~1/1000
  - Old, \( \alpha \)-enhanced, sub-structure

- **Dark matter halo**: \( 1-3 \times 10^{12} \, M_\odot \)
Large area surveys

Stellar counts studies & large surveys

- **UK Schmidt Telescope** → Thick disk (Gilmore & Reid 1983), Sagittarius dwarf (Ibata et al. 1994, 1995)

- Palomar Observatory Sky Survey (POSS) → asymmetries in the disk counts (Larsen & Humphreys 1996, Parker+2003)

- **Hipparcos** → SFH in the solar neighbourhood (Hernandez & Valls-Gabaud ’00)

- Two Micron All Sky Survey (2MASS) → Sgr dwarf (Majewski+2003), streams and sub-structure (Rocha-Pinto et al. 2003, 2006)


- The Radial Velocity Experiment (RAVE) → kinematic groups (Antoja+2012)
Edvardsson et al. 1993

- 189 nearby field F & G dwarf stars selected from Strömgren photometry (Olsen 1977, 1983 – La Silla Danish 50cm, KPNO)

- S/N~200 spectra from ESO 1.4m ESO Coude Auxiliary Telescope (60 usable nights 1983-1986) & 2.7m McDonald Observatory (1982-1988)

- First systematic homogeneous analysis (>1450 citations)
  - Abundances of 13 elements based on new generation of model atmospheres
  - Kinematics → orbital properties
  - Photometric ages
Edvardsson et al. 1993

- [Fe/H] vs age very flat with a large scatter in metallicity at all ages
- Remarkably little scatter in abundance ratio of elements
- Galactic abundance gradient confirmed $\sim 0.1$ dex/kpc
- Galactic chemical evolution requires complex models
Nordström et al. (2004), Holmberg et al. (2007)

- Metallicity, rotation, age, kinematics and Galactic orbits for a complete, magnitude-limited and kinematically unbiased sample
- 16,682 nearby F and G dwarf stars (Strömgren \textit{uvby}_\beta)

CORAVEL: Danish 1.5m in La Silla & Swiss 1m at Observatoire de Haute-Provence:

- “60,476 CORAVEL observations have been made of 12,941 of the programme stars … some 1000 nights’ worth of data.”

Thin disk MDF
Mean [Fe/H] = -0.14, \(\sigma=0.19\) dex
Age Metallicity Relation?

- Holmberg et al. 2007 Fig. 23b
  - Little or no variation in mean metallicity with age
  - Large and real scatter in [Fe/H] at all ages (see also Feltzing et al. 2001)
  - Mean $[\text{Fe/H}] = -0.21$ and standard deviation $\sigma = 0.21$ dex

- da Silva et al. 2012 – large underlying complexity in $[X/\text{Fe}]$ vs. age

Soubiran et al. 2008, Fig. 9
See also Rocha-Pinto et al. 2006
AMR present
Stellar ages are difficult to measure

- Cosmocronometry – age dating from relative abundances of radioactive isotopes
  - Hill et al. 2002: The extreme r-element rich, iron-poor halo giant CS 31082-001 observed with UVES@UT2 (within “First Stars” LP) → age = 14 ± 2.4 Gyr

- From white dwarf mass distribution
  - Kalirai 2012: comparison of inner halo WD masses selected from SPY survey (UVES LP by PI: Napiwotski) with M4 & disk WDs
    - M4 WDs M=0.529±0.012 M☉, age=12.5±0.5 Gyr
    - Inner halo WDs M=0.551±0.005 M☉, age=11.4±0.7 Gyr
    - Disk WDs M=0.613±0.126 M☉ (SDSS)

- Asteroseismology

- Isochrone fitting in the HR diagram
Metallicity gradient steeper in the inner disk

Open clusters:
- “Bologna Open Cluster Chemical Evolution” (BOCCE) project (Carretta+’04, ‘05, ‘07, Bragaglia+2008) – FLAMES@UT2
- Carraro+2007, Sestito+2008, Magrini+2010 – FLAMES@UT2
- Friel et al. 2002 – CTIO+KPNO

Cepheids:
- Pedicelli et al. 2009 (compilation incl. ESO data)

Red clump giants:
- Hill et al. 2012– FLAMES
Thick disk

- Gilmore & Reid 1983:
  Thick disk discovery – star counts from photographic UK Schmidt telescope plates pointing near South Galactic Pole

- Fuhrmann 1998-2011
  Volume complete sample d<25 pc from FOCES at Calar Alto Observatory
  thin vs. thick disk dichotomy
  Thick disk is massive; 20% local stars

Gilmore & Reid 1983, Fig. 6

Fuhrmann 2011, Fig. 15
Thick disk characterisation

- FEROS@1.5m + UVES@UT2 ESO + SOFIN@NOT + MIKE@Magellan high-res spectra of F & G dwarfs
- Stellar parameters and abundances for 14 elements

![Graph showing the relationship between stellar parameters and abundances for 14 elements in the context of thick disk characterisation.](image)
Thick disk characterisation: Bensby et al. 2003-2011

- Thick disk extends to solar [Fe/H] – early and fast enrichment
  - Flat [$\alpha$/Fe]=0.3-0.4 until [Fe/H]=-0.4 dex then decrease (SNIa)
- Average age: thin 4.9±2.8 Gyr, thick 11.2±4.3 Gyr
- Scale length $L_{\text{thick}}=2$ kpc, $L_{\text{thin}}=3.8$ kpc
- Metal-poor bulge – thick disk similar: ages, MDF, flat radial abundance gradient (stellar radial migration)

Bensby et al. 2011, Fig. 2
Two distinct halo populations

- SDSS: kinematics + metallicity distributions (Carollo+2007)
- Schuster & Nissen 1997, 2010, 2011, 2012: \textit{EMMI@NTT, UVES@VLT Archive + FIES@NOT} spectra
  - low-\(\alpha\) halo population accreted \(\rightarrow\) \(\omega\) Cen as progenitor?

Schuster & Nissen 2010, Fig. 3

Schuster & Nissen 2010, Fig. 1
Halo: two populations?

Gratton et al. 2003: 150 field subdwarfs and subgiants with accurate parallaxes (Hipparcos) halo: dissipative vs. accretion component

Be as a cosmochronometer?

- Distinct populations in the halo
- Thick disk – homogeneous population

UVES data

Gratton et al. 2003, Fig 3

Smiljanic et al. 2010, Fig. 17
Metallicity Distributions and the search for metal-poor stars

- **HK survey (Beers et al.)**
  - Objective prism H & K lines of CaII
- **Hamburg/ESO (HES) survey (Christlieb et al.)**
  - ESO 1m Schmidt telescope
  - HERES (Hamburg ESO R-process Enhanced Stars) – UVES LP (PI: Christlieb) + many different 4m telescopes
- **SDSS**
  - Follow-up SEGUE (Carollo et al. 2007, Ivezic et al. 2008)
- **UVES search for extremely metal-poor stars** (Cayrel et al. 2004, Francois et al. 2007 (First Stars UVES LP), Bonifacio et al. 2009, 2012)
- **X-SHOOTER** as the new tool (Caffau et al. 2012; LP)
35 very metal-poor stars with very high quality spectra: **UVES@UT2**

- Precise determination of 33 elemental abundances
- High uniformity for $\alpha$ and Fe-peak elements, larger scatter for n-capture
- Reaching primordial yields and probing early enrichment events

![Graphs showing elemental abundances](image)
Bulge age

- Old bulge:
  From deep CMDs turn-off >10Gyr (Zoccali et al. 2003, Fig 20: SOFI@NTT)

- Bensby et al. (2011, 2012) find evidence for an intermediate age population in a sample of 38 microlensed dwarfs, 16 (40%) are younger than 7 Gyr

- Old bulge:
  Proper motion cleaned deep HST CMD
  Clarkson et al. 2008, Fig 20
Bulge: structure

- Bar: $\sim 25^\circ$, 1:0.35:0.26
- Bissantz & Gerhard '02
- Babusiaux & Gilmore '05
- Cabrera Lavers et al. '08
- ... 

NEW:
- X-shape:
  - red clump splits along minor axis, $|b| > 5^\circ$
- Two overdense regions along the line of sight
- McWilliam & Zoccali 2010
- Nataf et al. 2010
- Saito et al. 2011

Vasquez, Zoccali et al. 2012, submitted
Bulge: populations & origin


- Metal-rich component (low $\alpha$) – disk/bar kinematics
- Metal-poor component ($\alpha$-enhanced) – spheroid kinematics
- Gradient: $[\text{Fe/H}]$ & $[\alpha/\text{Fe}]$ – metal-rich (low $\alpha$) component disappears at higher $b$ (minor axis)
VVV: The VISTA Variables in the Via Láctea

- PIs: D. Minniti, P. Lucas


- 300 deg$^2$ bulge: $-10^\circ < l < +10^\circ$, $-10^\circ < b < +5^\circ$ (Minniti et al. 2010)
- 220 deg$^2$ disk: $295^\circ < l < 350^\circ$, $-2^\circ < b < +2^\circ$

- Y, Z, J, H, Ks filters – ~4mag deeper than 2MASS
- ~100 epochs in Ks – variability campaign started
Large and variable extinction (Gonzalez et al. 2012)


Gonzalez et al. 2012, Fig. 3
VVV: BEAM Calculator

The complete (photometric) metallicity map of the MW bulge


Gonzalez et al. 2012, in prep
Galaxy formation sequence

(Inner) halo collapse $\rightarrow$ thick disk & bulge $\rightarrow$ accretion of the outer halo & thin disk formation

- Inner halo 2-3 Gyr older & higher $\alpha$-enhancement than outer halo (Schuster & Nissen 2012)

- Outer halo substructure (2MASS, SDSS; Belokurov et al. 2006) – early accretion due to higher $\alpha$-element abundances than current dSph (Tolstoy)

- Thick disk is old, $\alpha$-enhanced – fast formation (Bensby et al., Fuhrmann)

- Similarity of inner disk to bulge/bar population (Melendez et al., Bensby et al., Gonzalez et al., Hill et al.)

- Thin disk – long formation time-scale (>6-7Gyr) $\rightarrow$ radial migration, vertical heating; gas infall $\rightarrow$ narrow MDFs (G-dwarf problem)
Gaia data volume and quality of data \(\rightarrow\) revolution

- Large statistically significant samples \(\rightarrow\) surveys
  - dynamical, kinematic and compositional studies

ESO: follow-up & complementarity
- High & medium-resolution spectroscopy
- Multi-object IR spectrograph
- High multiplex optical/blue spectrograph

Improvements in theory, modeling and analysis techniques
ESO contribution to understanding MW galaxy

- **Past:**
  - Major role in high-resolution spectroscopy

- **Recent/Ongoing:**
  - Starting to take lead also in photometric surveys: VISTA & VST
  - VVV → Bulge stellar populations, 3D structure
  - VHS → Halo sub-structure, satellites
  - VST – VPHAS+ → disk and 3D extinction mapping, spiral structure
  - Gaia-ESO survey (Gilmore & Randich) → high-resolution spectroscopy: $10^5$ MW stars in the field and open clusters

- **Future:**
  - 4MOST / MOONS → high-multiplex spectrographs
  - Gaia follow-up