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Remaining lectures:

Milky Way I Structure: (today)
Milky Way II Chemical Evolution (Thursday)
The Local Group (Tuesday May 1st)
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Lecture 21:

The Milky Way I

Structure:
Why study the Milky Way?

- Its a highly typical spiral galaxy which can be studied in great detail
Outline

- Components of the Galaxy
- The dark halo (already discussed)
- Globular clusters
- The bulge/bar
- The thick disk
- The thin disk
The Milky Way galaxy

Optical view of the Milky Way is restricted by absorption due to dust. Clearest view is obtained in infra-red:

map from the DIRBE instrument on COBE

At these wavelengths, primarily see emission from cool (hence low mass, typically old) stars. Maps presented in **Galactic co-ordinates**: at the center is the Galactic center, with the disk oriented along the `equator`. 
Clear from the infra-red view that we live in a disk galaxy, very similar to local spiral galaxies.

Several different components in such systems.

1) The bulge: central spheroidal stellar component

Milky Way bulge:

\[
\begin{align*}
L_{\text{bulge}} & \approx 5 \times 10^9 L_{\text{sun}} \\
M_{\text{bulge}} & \approx 2 \times 10^{10} M_{\text{sun}}
\end{align*}
\]

\((L_{\text{sun}} = 3.86 \times 10^{33} \text{ erg s}^{-1}; M_{\text{sun}} = 1.989 \times 10^{33} \text{ g})\)

Galactic center is about 8 kpc from the Sun, the bulge is a few kpc in radius.
2) **The disk**: thin, roughly circular disk of stars with organized sense of rotation about the Galactic center.

\[
L_{\text{disk}} \gg 15 - 20 \times 10^9 L_{\text{sun}} \\
M_{\text{disk}} \gg 6 \times 10^{10} M_{\text{sun}}
\]

Milky Way disk:

Disk extends to at least 15 kpc from the Galactic center, and is centrally concentrated. Density of stars in the disk falls off exponentially:

\[
n(R) \propto e^{-R/h_R} \quad \text{h}_R \text{ is the } \text{disk scale length}, \text{ which is about } 2-4 \text{ kpc for the Milky Way.}
\]

Most of the stars (95%) lie in a **thin disk** - vertical scale height 300 - 400 pc. Rest form a **thick disk**.

Also a gas disk, which is thinner than either of the stellar disks.
3) The halo: the bulk of the Galaxy that is outside the bulge and well above the plane of the disk. Made up of:

(i) Stars - total mass in visible stars $\sim 10^9 M_{\text{sun}}$. Stars are all old, and have random motions. Very low density.
(ii) Globular clusters - dense compact clusters distributed in the Galactic halo.

Hubble image of the globular cluster M80. In the Milky Way, globular clusters are made up of old stars only.
Globular Clusters

M3

100,000 stars
Distribution of Milky Way globular clusters
Halo & Disk Clusters

Halo

Disk
• Disk clusters more metal-rich
• Also a population of field stars traced by blue horizontal branch stars & RR Lyrae stars
• many from destroyed globular clusters
The Bulge:
Our bar-bulge is $\sim 3.5$ kpc long, axial ratio $\sim 1:0.3:0.3$
The Galactic Bulge

small exponential bulge - typical of later-type galaxies.

Unlike the large $r^{1/4}$ bulge of M31
The galactic bulge is rotating, like most other bulges:

Rotation
K giants
and planetary nebulae (+)

Velocity dispersion of inner
disk and bulge are fairly similar
- not easy to separate inner disk
and bulge kinematically

Bulge ends at $|l| \sim 12^\circ$
Age and metallicity of the bulge

Old population $> 10$ Gyr.
No trace of younger population.

Extended metallicity distribution,
from $[\text{Fe/H}] = -1.8$ to $+0.2$
Inhomogeneous collection of photometric (□ ★) and spectroscopic (▲) mean abundances - evidence for abundance gradient along minor axis of the bulge.
The bulge globular clusters

3D kinematics of 7 globular clusters in the bar/bulge

Their velocities show:
- all of them are confined to the bulge region
- the metal-poor clusters (o) are part of the inner halo
- the metal-rich clusters include
  - a bar cluster
  - clusters belonging to a rotationally supported system
Later type galaxies like the Milky Way mostly have small near-exponential boxy bulges, rather than $r^{1/4}$ bulges.

These small bulges are probably not merger products: more likely generated by disk instability

Boxy bulges, as in our Galaxy, are associated with bars, believed to come from bar-buckling instability of disk.
The stars of the bulge are old and enhanced in $\alpha$-elements $\Rightarrow$ rapid star formation history

In the bar-buckling instability scenario, the bulge structure may be younger than its stars, which were originally part of the inner disk
The Galactic Bulge - summary

The bulge is not a dominant feature of our Galaxy - only about 25% of the light.

The bulge is probably an evolutionary structure of the disk, rather than a feature of galaxy formation in the early universe. Structure and kinematics are well represented by the product of disk instability.

The $\alpha$-enhancement indicates that star formation in this inner disk/bulge region proceeded rapidly. The bulge structure may be younger than its stars.
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The Thick and Thin Disks:
The Galactic Thick Disk

*Most spirals (including our Galaxy) have a second thicker disk component, believed to be the early thin disk heated by an accretion event. In some galaxies, it is easily seen:*

*NGC 4762 - a disk galaxy with a bright thick disk*
Surface photometry (BRK) of late-type edge-on galaxies:

Find that all are embedded in a flattened low surface brightness red envelope or thick disk

Age > 6 Gyr, not very metal-poor, like thick disk of the Milky Way

Formation of the thick disk is a nearly universal feature of formation of disk galaxies
However, there are spirals which do not have a thick disk
e.g. NGC 4244 ($M_B = -18.4$) appears to be a pure thin disk: just a single exponential component, no thick disk
The existence of such a pure disk galaxy is interesting because, for at least some late-type disks

- the star formation did not start until the gas had settled to the disk plane

- since the onset of star formation in the disk, the disk has suffered no significant dynamical disturbance from internal or external sources

(pure disk galaxies are not readily produced in $\Lambda$CDM simulations: too much merger activity)
The Galactic thick disk is detected in star counts.

Near the sun, the galactic thick disk is defined mainly by stars with $[\text{Fe/H}]$ in the range $-0.5$ to $-1.0$, though its MDF has a tail extending to very low $[\text{Fe/H}] \sim -2.2$.

The thick disk appears to be a discrete component, distinct from the thin disk.
The thick disk is a very significant component for studying galaxy formation, because it presents a kinematically recognizable ‘snap-frozen’ relic of the early galaxy.

Secular heating is unlikely to affect its dynamics significantly, because its stars spend most of their time away from the galactic plane.
Kinematics and structure of the thick disk

rotational lag $\sim 30 \text{ km/s}$ near the sun and increases by about $30 \text{ km s}^{-1} \text{kpc}^{-1}$ with height above the plane

velocity dispersion in $(U,V,W) = (46, 50, 35) \text{ km/s}$

radial scale length $= 3.5$ to $4.5 \text{ kpc}$ : uncertain

scale height from star counts $= 800$ to $1200 \text{ pc}$ (thin disk $\sim 300 \text{ pc}$)
density $= 4$ to $10\%$ of the local thin disk
The Galactic thick disk is old (> 12 Gyr) and significantly more metal poor than the thin disk: mean [Fe/H] \sim -0.7 and \alpha-enhanced \Rightarrow rapid chemical evolution

P. E. Nissen

\begin{itemize}
\item thick disk
\item thin disk
\end{itemize}

higher \[\alpha/Fe\] \Rightarrow more rapid formation
The age distribution for the thick disk stars indicates a time delay between formation of thick disk stars and the onset of star formation in the current thin disk.
How did the thick disk form?

- a normal part of disk settling
- accretion debris
- early thin disk, heated by accretion events
Most probably:

Thin disk formation begins early, at $z = 2$ to $3$

Partly disrupted during merger epoch which heats it into thick disk observed now

The rest of the gas then gradually settles to form the present thin disk

Not much is known about the radial extent of the thick disk. This is important, if the thick disk really is the heated early thin disk. Disks form from inside out, so the extent of the thick disk now would reflect the extent of the thin disk at the time of heating.
**Formation of disk stars outside the disk**

**ΛCDM simulations of formation of early-type disk galaxies show that not all disk stars form in the disk**

Many of the oldest stars in the disk are debris from accreted satellites which ends up in the thin and thick disk.

Satellite orbit is dragged into disk plane by dynamical friction - acts like dissipation, although system is collisionless.
Why is this interesting?

Because we see thick disk stars in the solar neighborhood with [Fe/H] abundances as low as the most metal-poor globular clusters.

Did these stars form as part of early disk formation, or were they acquired?
Summary of thick disks

The thick disk forms rapidly and early (12 Gyr ago in the Galaxy)

Appears to be distinct from the thin disk

Formed by heating of the early thin disk in an epoch of merging which ended ~ 12 Gyr ago
or
from early accretion of satellites, probably in mainly gaseous form
The Thin Disk
The thin disk

exponential in $R$ and $z$: scaleheight $\sim 300$ pc, scalelength 3-4 kpc

velocity dispersion decreases from $\sim 100$ km/s near the center (similar to bulge) to $\sim 15$ km/s at 18 kpc
star formation history in galactic thin disk: roughly uniform, with episodic star bursts for ages < 10 Gyr, but lower for ages > 10 Gyr
No significant chemical evolution in the nearby old disk for ages 2-10 Gyr
The outer disk of the Galaxy

The galactic disk shows an abundance gradient.
Velocity dispersions of nearby F stars

Old disk

Thick disk appears at age ~ 10 Gyr

Disk heating saturates at 2-3 Gyr

Freeman 1991; Edvardsson et al 1993; Quillen & Garnett 2000
Like the halo, the galactic disk also shows kinematical substructure: usually called moving stellar groups.

Not all of these moving groups are fossils

- Some are associated with dynamical resonances (bar)

- Some are debris of star-forming aggregates in the disk.

- Others may be debris of infalling objects, as seen in ΛCDM simulations
We would like to reconstruct the ancient star-forming aggregates of the disk: phase mixing has dispersed them azimuthally right around the Galaxy.

Structurally invisible - may see them in velocity space (disk moving groups) and integral space (as for halo) and in their chemical properties.

May be able to detect evolution of the cluster mass function, the star formation rate, and epochs of satellite infall and star-bursts during the formation of the disk.
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Nearby stars:
How do we derive the IMF?

• The current mass distribution of local MS stars per unit area, \( n(m) \), is called Present Day Mass Function (PDMF).

• For stars in the range 0.1-1 Msun, with lifetimes > the age of the Galaxy, \( t_G \), we can write:

\[
n(m) = \int_0^{t_G} \varphi(m) \psi(t) \, dt
\]
How do we derive the IMF?

• If the IMF is assumed to be constant in time, we can write:

\[ n(m) = \varphi(m) \langle \psi \rangle t_G \]

where \( \langle \psi \rangle \) is the average SFR in the past.
How do we derive the IMF?

- For stars with lifetimes $\ll t_G (m > 2 \text{ M}_{\odot})$ we can see only the stars born after $\text{Tau}_m$
- Therefore, we can write:

$$t = t_G - \tau_m$$

$$n(m) = \int_{t_G - \tau_m}^{t_G} \varphi(m) \psi(t) dt$$
How do we derive the IMF?

- If we assume the IMF is constant in time we can write:

\[ n(m) = \varphi(m) \psi(t_G) \tau_m \]

- Having assumed that the SFR did not change during the time interval corresponding to stellar lifetimes
How do we derive the IMF?

- We cannot apply the previous approximations to stars in the range 1-2 Msun
- Therefore, the IMF is this mass range will depend on $b(t_G)$:

$$b(t_G) = \frac{\psi(t_G)}{\left< \psi_G \right>}$$
Salpeter Mass Function

The Initial Mass Function for stars in the Solar neighborhood was determined by Salpeter in 1955. He obtained:

\[ x(M) = x_0 M^{-2.35} \]

Salpeter IMF

constant which sets the local stellar density

Using the definition of the IMF, the number of stars that form with masses between \( M \) and \( M + \Delta M \) is:

\[ x(M) \, dM \]

To determine the total number of stars formed with masses between \( M_1 \) and \( M_2 \), integrate the IMF between these limits:

\[
N = \int_{M_1}^{M_2} x(M) \, dM = x_0 \int_{M_1}^{M_2} M^{-2.35} \, dM
\]

\[
= x_0 \left[ \frac{M^{-1.35}}{-1.35} \right]_{M_1}^{M_2} = \frac{x_0}{1.35} \left[ M_2^{-1.35} - M_1^{-1.35} \right]
\]
Can similarly work out the total **mass** in stars born with mass $M_1 < M < M_2$:

$$\dot{M} = \int_{M_1}^{M_2} M x(M) \, dM$$

**Properties of the Salpeter IMF:**

- most of the stars (by number) are low mass stars
- most of the **mass** in stars resides in low mass stars
- following a burst of star formation, most of the **luminosity** comes from high mass stars

Salpeter IMF must fail at low masses, since if we extrapolate to arbitrarily low masses the total mass in stars tends to infinity!

Observations suggest that the Salpeter form is valid for roughly $M > 0.5 \, M_{\odot}$, and that the IMF `flattens’ at lower masses. The exact form of the low mass IMF remains uncertain.
Comments on the Salpeter IMF

What is the origin of the IMF?

Most important unsolved problem in star formation. Many theories but no consensus.

Observationally, known that dense cores in molecular clouds have a power-law mass function rather similar to the IMF. So the IMF may be determined in part by how such cores form from turbulent molecular gas.

Is the IMF `universal’?

i.e. is $\xi(M)$ the same function everywhere?

Most theorists say no. Predict that fragmentation is easier if the gas can cool, so primordial gas without any metals should form more massive stars.

Observationally, little or no evidence for variations in the IMF in our galaxy or nearby galaxies.
Constraints on the SFH from the IMF

- In order to obtain a good fit of the two branches of the IMF in the solar vicinity one needs to assume (Scalo 1986):

\[ 0.5 \leq b(t_G) \leq 1.5 \]
The IMF

- Lower panel: normalization of the multi-slope IMFs to the Salpeter IMF
- Upper panel: different IMFs
How to derive the local SFR

- An IMF should be assumed and then one should integrate the PDMF in time

- Timmes et al. (1995), by adopting the Miller & Scalo (1979) IMF, obtained:

\[ \psi(t_G) \sim 2 - 10M_\odot pc^{-2} Gyr^{-1} \]
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END