L12 – The Milky Way: Phenomenology

Historical

We see the MW as a band (of stars) mottled with dark patches, what we now know as dust lanes.

> W Herschel (1780s) – produced first map of MW. Assumed all stars have identical L_* and that the number density (n_*) is constant. Found that the Sun is at the center & that the plane was 5X the size of the height Δz.

> J. Kapteyn (1922) – more careful counting, down to a selected magnitude, in 200 regions. The "Kapteyn Universe" was a spheroid, $r = 8.5$ kpc, $\Delta z =$ 1.7 kpc, Sun was in the plane, 600 pc from the center.

> H. Shapley (1919) – Found that globular clusters are centered not on the Sun, but in a region toward Sagittarius. He found distance to the g. clusters using the period–luminosity relation of Cepheid variables (15 $M_\odot$) and RR Lyrae variables (3 $M_\odot$) post-ms stars. Center of the g. cluster system was 15 kpc from the sun (TOO FAR). Most distance g clusters are 50 kpc from the center (there are some there, but his average distance was TOO GREAT).

Kapteyn's Universe was too small } Both errors caused by neglecting dust!
Shapley's MW was too large }

Kapteyn's regions are in the plane, where stars are severely attenuated by dust

Shapley's g cluster's are above the plane, but his period-luminosity relation was wrong, due to neglect of dust in the ~~calibration~~ calibration.
Shapley noted the "zone of avoidance" in the MW plane – thought that g clusters are destroyed there.

Modern Basic Parameters

Diameter of Disk – 50 kpc
Solar distance to G. Center – 8 kpc
Within the plane $I(R) \propto e^{-R/R_0}$, where $R_0 = 2$ kpc
Local total mass density: 0.05 $M_\odot/pc^3$

$L_{bol} = 4 \times 10^{10} L_\odot$
M (~~...~~ visible) $= 9 \times 10^{10} M_\odot$

The precise distance to the G center (R_0) is established by motion of stars near the central black hole. [among other methods]

For example, R_0 is one parameter used to model the elliptical orbit of the S0-star S0-2.

[Show figure from Ghez et al 2008]

Thickness of Disk

[SF here began 9 Gyr ago + is continuing] * "thin disk" $\Delta z \simeq 300$ pc varies from 250 pc $\tau < 3$ Gyr

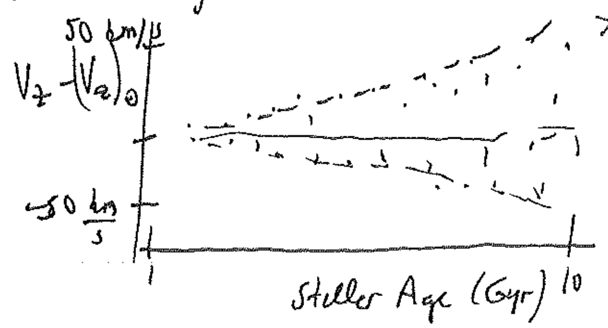
[ages from, eg, white-dwarf distribution + cooling times] ← CO p577 — 300 pc $3 < \tau < 6$ Gyr; 350 pc $6 < \tau < 10$ Gyr

"thick disk" $\Delta z \approx 1$ kpc consists of older stars, and also (perhaps) of the youngest subset of globular clusters [SF here was from 11 to 10 Gyr ago]

The older stars within the thin disk have a greater V_z.

More quantitatively, their velocity dispersion increases:

$$\sigma_z^2 \equiv \left\langle \left(V_z - \langle V_z \rangle\right)^2 \right\rangle$$



main-sequ. F stars

Metallicity

A common measure is

$$[Fe/H] \equiv \log \left[\frac{(N_{Fe}/N_H)_{star}}{(N_{Fe}/N_H)_\odot} \right]$$

Thin disk: $-0.5 < [Fe/H] < +0.3$

Thick disk: $-2.2 < [Fe/H] < -0.5$

Stellar halo: $-5.4 < [Fe/H] < -0.5$

The most metal rich stars have $[Fe/H] \simeq +0.6$

↖ Here, the more metal-rich stars are younger, as seen by turnoff pts in HRD of g. clusters

* Established by Reid & Gilmore (1983) through "photometric parallax" ←
— from broadband colors, found spectral type + hence M_V. Comparing to m_V gives distance

Mass to Light Ratio

L_B for thin disk is $1.8 \times 10^{10}\, L_\odot$ (in comparison, L_B (thick disk) $= 2 \times 10^{8}\, L_\odot$)
(L_{bol} for whole MW is $4 \times 10^{10}\, L_\odot$)

M_{tot} in thin disk stars is $6 \times 10^{10}\, L_\odot$

So the mass-to-light ratio in the thin disk is $\left\langle \frac{M}{L_B} \right\rangle = 3\ M_\odot/L_\odot$

Now, along the main sequence, $\frac{L}{L_\odot} = \left(\frac{M}{M_\odot}\right)^{\alpha}$ $\quad \alpha \simeq 4 \quad > 0.5\, M_\odot$
$\quad \alpha \simeq 2 \quad < 0.5\, M_\odot$

$$\frac{1}{3} = \frac{\langle L/L_\odot \rangle}{\langle M/M_\odot \rangle} = \left\langle \frac{M}{M_\odot} \right\rangle^{\alpha - 1}$$ [crude argument! $\left\langle \frac{L}{L_\odot} \right\rangle \neq \left\langle \frac{M}{M_\odot} \right\rangle^{\alpha}$]

$$3 = \left\langle \frac{M}{M_\odot} \right\rangle^{1-\alpha} \longrightarrow \left\langle \frac{M}{M_\odot} \right\rangle = 3^{\frac{1}{1-\alpha}}$$

for $\alpha = 4$,

$$\boxed{\left\langle \frac{M}{M_\odot} \right\rangle = 3^{-1/3} = 0.7}$$

Spiral Structure

Our own spiral arms are poorly mapped out. (mostly in HI) (also HII regions)
Those in external galaxies show up in optical, & CO, & HI.
In optical, the arms are especially pronounced in blue light
more diffuse in red light
[see my Fig 1.20] handout

External Gas

There is HI gas at high latitudes, most of it is moving toward the plane (but some is moving away).

This could represent a "galactic fountain" created by multiple supernovae

The portion moving toward us could be gas raining down from the inter-galactic medium. This phenomenon has long been invoked to explain the persistence of star formation in the disk, despite the relatively low reservoir of gas there now.

Galactic Bulge + Bar

The thickness of the disk increases dramatically toward the center.
Our disk has a bulge. Dominated by old giants (+ so red), but also has some younger stars.

The surface brightness (in $L_\odot\, pc^{-2}$) is

$$\log\left(\frac{I(r)}{I_e}\right) = -3.3\left[\left(\frac{r}{r_e}\right)^{1/4} - 1\right]$$

de Vaucouleurs profile

r_e = effective radius, within which ½ the total luminosity is emitted.
For our bulge, $r_e = 0.7$ kpc

> This is a general surface brightness profile for spheroidal systems of stars, including elliptical galaxies.

Our galaxy has a short bar of stars, with a radius (half-length) of 4 kpc. Probably not by coincidence, the end of the bar coincides with the molecular ring.

Stellar Halo

Composed of globular clusters (in a spherical distribution) + high-velocity field stars

Total mass in halo is $1\times10^9\ M_\odot$, of which only 1% is in g. clusters (~ 100 clusters × $10^5\ M_\odot$ each)

g cluster — Ages of g clusters: 13 – 11 Gyr
The younger, higher-metallicity globular clusters ($[Fe/H] > -0.8$) are in a flatter distribution that may be coincident with the thick disk.

There are 150 known globular clusters. Closest is 500 pc, farthest is 120 kpc!!

The number density of <u>both</u> the metal-poor globular cluster <u>and</u> the field stars follows

$$n(r) = n_0 \left(\frac{r}{a}\right)^{-3.5} \qquad a = 2\ \text{kpc}$$

The total <u>halo</u> mass density in the solar neighborhood is ~~[illegible]~~ $1 \times 10^{-4}\ M_\odot/pc^3$
This is only 0.2% of the total mass density.

The <u>total mass</u> in the stellar halo is $1 \times 10^9\ M_\odot$ (again)

<u>Dark Matter Halo</u>

This is spheroid, with a radius $R \gtrsim 230$ kpc!

NFW profile

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{a}\right)\left(1 + \frac{r}{a}\right)^2} \qquad \rho(r) \sim r^{-1} \quad r \ll a$$

$$\rho(r) \sim r^{-3} \quad r \gg a$$

$a = 20$ kpc *

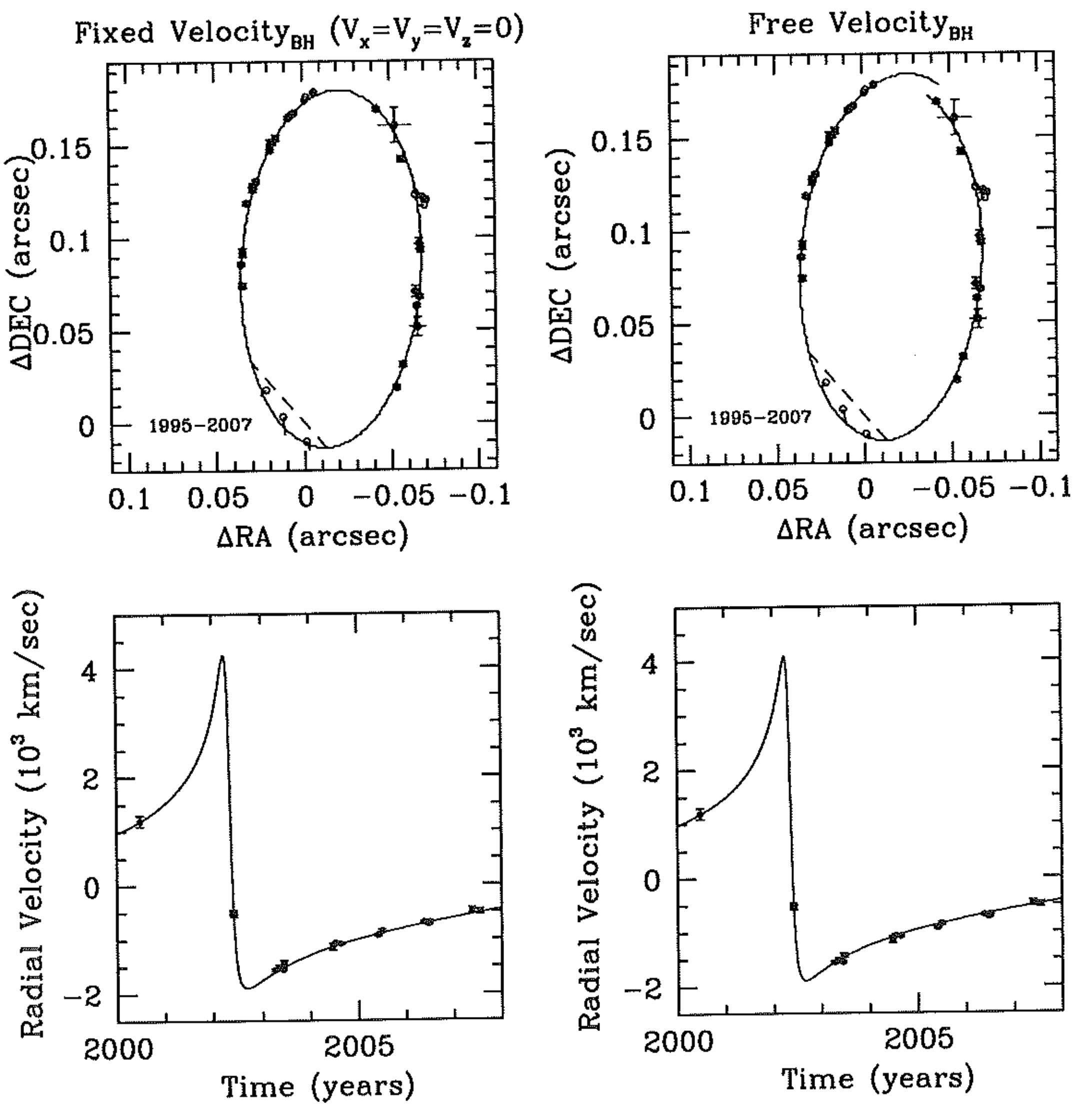
Total mass out to 230 kpc is $\sim 2 \times 10^{12}\ M_\odot$, constituting 95% of total Galactic mass

<u>Possible constituents</u>

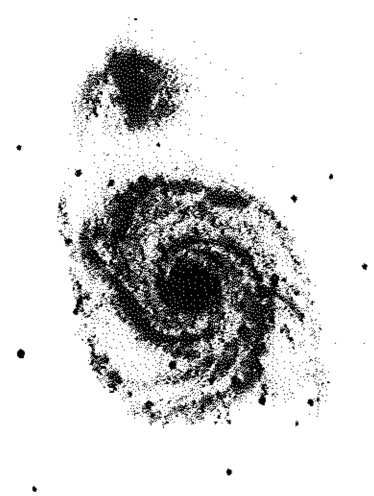
<u>WIMPS</u> – weakly interacting massive particles
cosmology suggests non-baryonic matter
could be super-symmetric particles

<u>MACHOs</u> – massive, compact halo objects
dead stars (brown dwarfs, red dwarfs, white dwarfs, n stars)
From gravitational lensing toward the LMC, there seem to be too few of them to give mass of halo. HST has searched for white dwarfs & red dwarfs – could be 15% of halo mass.

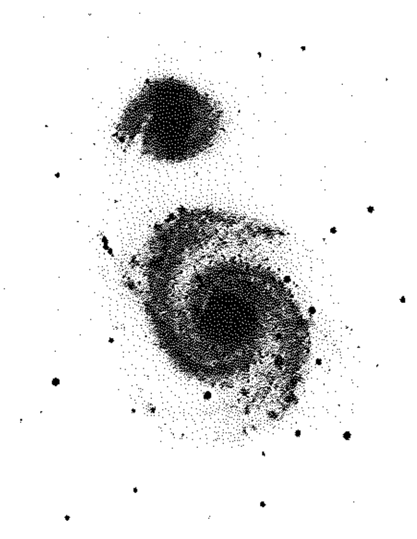
* This figure is from Klypin, Zhao & Somerville 2002, ApJ, <u>573</u>, 597
(theory model)


Fixed Velocity$_{BH}$ ($V_x=V_y=V_z=0$)
Free Velocity$_{BH}$
ΔDEC (arcsec)
ΔRA (arcsec)
1995–2007
0.15
0.1
0.05
0
0.1
0.05
−0.05
−0.1
Radial Velocity (10^3 km/sec)
Time (years)
4
2
−2
2000
2005

M51 Galaxy



Blue



Near Infrared