Einführung in die Astronomie II

Teil 12

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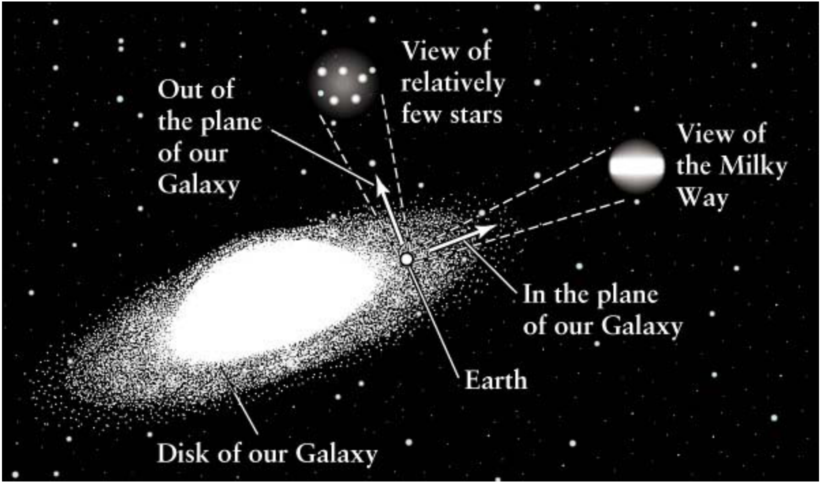
Overview part 12

- The Galaxy
  - Historical Overview
  - Distance determinations
  - star clusters
  - Rotation
  - Structure
  - Populations

Historical Overview

- The Galaxy: 'our' Milky Way
- galaxy, galaxies: 'other' galaxies
- Milky Way appears as bright band across the sky
- Galileo discovered that it is a collection of stars
- Kant and Wright hypothesized that the Milky Way is a stellar disk

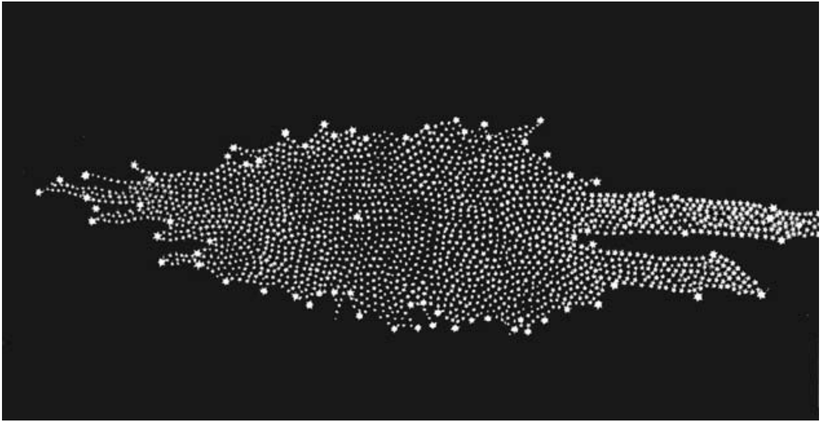
View of the Milky Way !!



Historical Overview

- Herschel counted stars in 633 regions and made a map of the Galaxy under the assumptions:
  1. all stars have the same absolute magnitude
  2. number density of stars is constant
  3. no interstellar extinction

Herschel's Milky Way



Historical Overview

- This was continued by Kapteyn, his more quantitative model looked like a flattened spheroid
    1. Sun is 38 pc north of the mid-plane and 650 pc from the center
    2. in the *plane of the Galaxy*, the stellar density drops to 1/2 at 800 pc distance from the center
    3. perpendicular to the plane, the same drop has occurred after 150 pc
    4. 1% stellar density at 8.5 kpc (plane) and 1.7 kpc (perpendicular)

Historical Overview

- at the same time (1915–1919), Shapley used RR Lyr and W Vir stars to estimate the distances to *globular clusters*.
    1. GCs are *not* uniformly distributed
    2. GC distributed around a center about 15 kpc from the Sun toward Sagittarius
    3. most distant clusters are at $\approx 70\,\text{kpc} \rightarrow$ Galaxy's diameter is about $100\,\text{kpc}$.
- Shapley's Galaxy is 10 times larger than Kapteyn's, & in his model the Sun is much farther from the center.
- *Both* models are wrong, Kapteyn's too small and Shapley's too large!

Historical Overview

- Reason: *both* neglected interstellar extinction!
- Kapteyn (although aware of the possibility) put his "selected regions" most in the plane
  $\rightarrow$ extinction is large
  $\rightarrow$ couldn't see the distant regions of the Galaxy.
- Shapley's GCs are well above/below the plane
  $\rightarrow$ extinction smaller $\rightarrow$ see farther
- in addition, P-L relation calibration was incorrect, *overestimating* the distances systematically.
- *zone of avoidance*: no GC's in $\pm 10^{\circ}$ of the plane $\rightarrow$ strong indication of extinction by dust.

Distance determinations !!

- Trigonometric parallax π

$$\sin \pi = a/d$$

  - a radius of Earth's orbit
  - d distance to the star

Distance determinations !!

- Photometric parallax

$$m - M = 5\,\mathrm{mag}\log(d) - 5\,\mathrm{mag} + A(d)$$

  - d distance in pc
  - $m - M$ distance modulus
  - $A(d)$ interstellar extinction

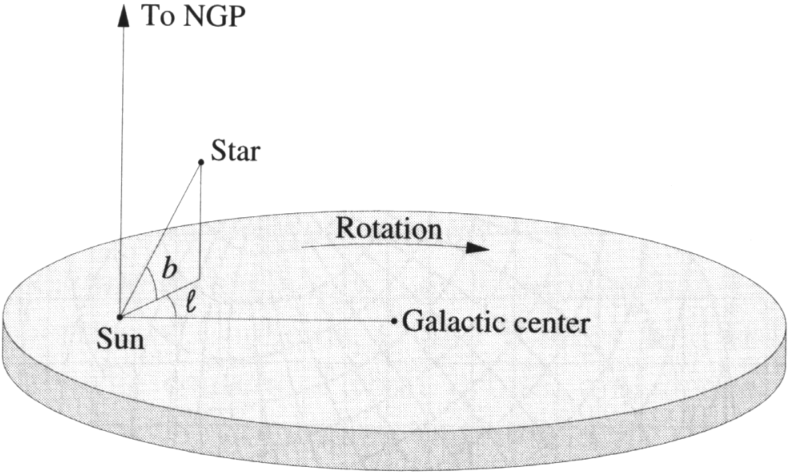
Distance determinations

- Stream parallax
  - group of stars moving in same direction
  - measure radial velocities and proper motions
  - compare true space motion with apparent motion
  - $\rightarrow\approx$ distance to stream
- Dynamic parallax
  - binary stars
  - follow apparent and true orbital motions
  - $\rightarrow$ compute distance

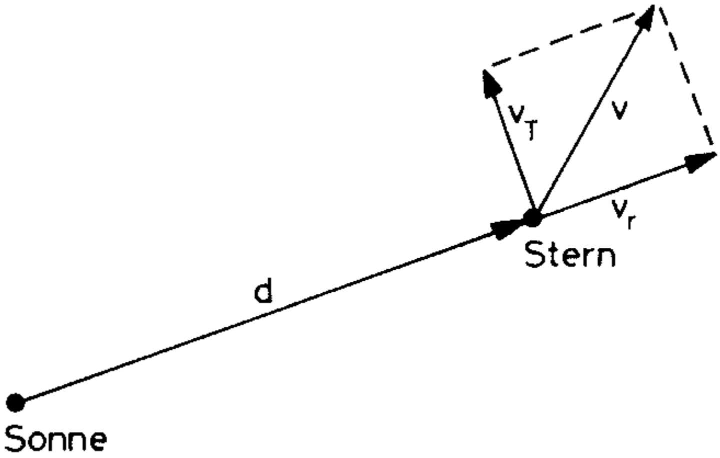
Galactic Coordinates

- Galactic equator
- *Galactic latitude* b and *Galactic longitude* ℓ
  - defined with the Sun as the center!
  - b measured in degrees north and south of the Galactic equator
  - ℓ measured in degrees along the Galactic equator
  - $b = 0^\circ$, $\ell = 0^\circ$ is close to (but not exactly) the Galactic center
  - transformation formulae from (RA, δ) to (ℓ, b) and a transformation chart are given in the literature

Galactic coordinates !!



Stellar motions !!



Kinematics of the Galaxy !!

- from statistics of near-by stellar motions
- solar peculiar velocity: $\approx 20\,\mathrm{km\,s^{-1}}$
- *solar apex*: $\ell = 53^\circ$, $b = 25^\circ$ (toward Hercules)

Oort's constants !!

- Oort constructed kinematic relations to help determine the *differential rotation curve* of the Galaxy
- circular orbits (can be generalized)

Oort's constants

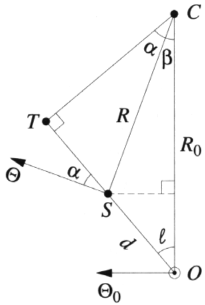


Figure 22.24 The geometry of analyzing differential rotation in the Galactic plane. The Sun is at point O, the center of the Galaxy is located at C, and the star is at S, located a distance d from the Sun. ℓ is the Galactic longitude of the star at S, and α and β are auxiliary angles.

Oort's constants

- "O": location of the Sun
- "S": location of an object (Star, nebula) orbiting the center C
- relative velocity as seen from the Sun must be corrected for solar orbital velocity (incl. vector direction!).
- practice: radial velocity ($O \rightarrow S$) and proper motion (if d is known) converted to true velocity
- radial and transverse velocities:

$$
\begin{aligned}
v_r &= \Theta \cos \alpha - \Theta_0 \sin \ell \\
v_t &= \Theta \sin \alpha - \Theta_0 \cos \ell
\end{aligned}
$$

Oort's constants

- the angular velocity is given by:

$$\Omega(R) = \frac{\Theta(R)}{R}$$

so that

$$\begin{aligned} v_r &= R\Omega \cos\alpha - R_0\Omega_0 \sin\ell \\ v_t &= R\Omega \sin\alpha - R_0\Omega_0 \cos\ell \end{aligned}$$

Oort's constants

- from the triangle OTC (right angle at T!):

$$\begin{aligned} R\cos\alpha &= R_0\sin\ell \\ R\sin\alpha &= R_0\cos\ell - d \end{aligned}$$

so that

$$\begin{aligned} v_r &= (\Omega - \Omega_0)R_0\sin\ell \\ v_t &= (\Omega - \Omega_0)R_0\cos\ell - \Omega d \end{aligned}$$

Oort's constants

- can be used to estimate $\Omega(R)$ if the other parameters are known.
- R_0 and Ω_0 are not well determined
- measuring the distance d is hard
- *interstellar extinction!!*

Oort's constants !!

- Oort derived approximations that are valid near to the Sun:
  - assume that $\Omega(R)$ is smooth and can be expanded in a Taylor series around $\Omega_0(R_0)$:

$$\Omega(R) = \Omega_0(R_0) + \left.\frac{d\Omega}{dR}\right|_{R_0} (R - R_0) + \cdots$$

  - therefore:

$$\Omega - \Omega_0 \approx \left.\frac{d\Omega}{dR}\right|_{R_0} (R - R_0)$$

Oort's constants

- with $\Theta = \Omega R$ we have:

$$\left.\frac{d\Theta}{dR}\right|_{R_0} = \left.\frac{d\Omega}{dR}\right|_{R_0} R_0 + \Omega_0$$

so that

$$\left.\frac{d\Omega}{dR}\right|_{R_0} R_0 = \left.\frac{d\Theta}{dR}\right|_{R_0} - \frac{\Theta_0}{R_0}$$

so that

$$(\Omega - \Omega_0)R_0 \approx \left[\left.\frac{d\Theta}{dR}\right|_{R_0} - \frac{\Theta_0}{R_0}\right](R - R_0)$$

Oort's constants

- with this (and $\Omega d \approx \Omega_0 d$):

$$
\begin{aligned}
v_r &\approx \left[\left.\frac{d\Theta}{dR}\right|_{R_0} - \frac{\Theta_0}{R_0} \right] (R - R_0) \sin \ell \\
v_t &\approx \left[\left.\frac{d\Theta}{dR}\right|_{R_0} - \frac{\Theta_0}{R_0} \right] (R - R_0) \cos \ell - \Omega_0
\end{aligned}
$$

- from the geometry of the figure:

$$R_0 = d \cos \ell + R \cos \beta \approx d \cos \ell + R$$

for $\cos \beta \approx 1$ (small β) due to $d \ll R_0$.

Oort's constants !!

- define *Oort constants*

$$A = -\frac{1}{2}\left[\left.\frac{d\Theta}{dR}\right|_{R_0} - \frac{\Theta_0}{R_0}\right]$$

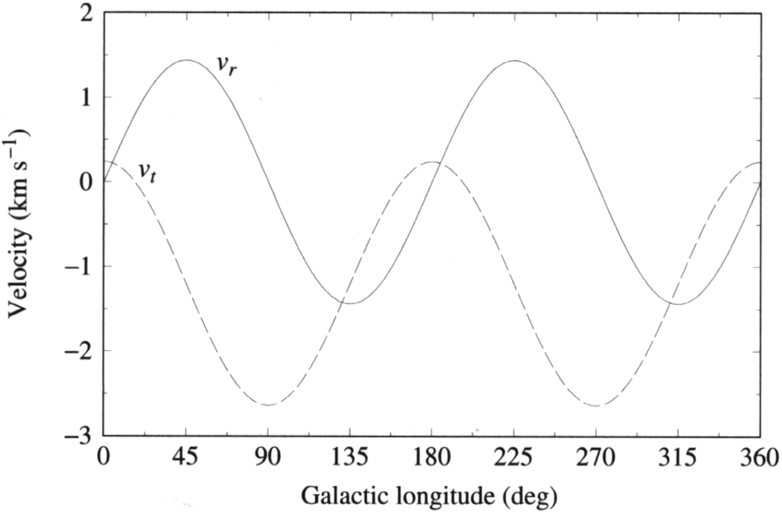
$$B = -\frac{1}{2}\left[\left.\frac{d\Theta}{dR}\right|_{R_0} + \frac{\Theta_0}{R_0}\right]$$

so that (with the trig-formulae for 2ℓ):

$$v_r \approx Ad\sin 2\ell$$

$$v_t \approx Ad\cos 2\ell + Bd$$

Oort's constants



(b)

Oort's constants

- Some useful relations between A, B and the local parameters of the rotation of the Galaxy R_0, Θ_0, Ω_0, $d\Theta/dR|_{R_0}$:
- $\Omega_0 = A - B$
- $\frac{d\Theta}{dR}\Big|_{R_0} = -(A + B)$
- maximum radial velocity at given ℓ: at tangent point T (where $R = R_{\rm min} = R_0 \sin\ell$ is minimal) $\rightarrow$ $\Theta(R)$ will be maximal (if it is monotonically increasing with smaller R) $\rightarrow$

$$v_{r,\rm max} = \Theta(R_{\rm min}) - \Theta_0(R_0)\sin\ell$$

Oort's constants

- for observations *inside* the solar circle
  $\rightarrow d \ll R_0$, $R \approx R_0$
  $\rightarrow$ expand $\Theta(R)$ in Taylor series around Θ_0, inserting this in the above equation but keeping only first order terms:

$$v_{r,\max} \approx 2AR_0(1 - \sin \ell)$$

- these relations help to place constraints on R_0 and Θ_0.

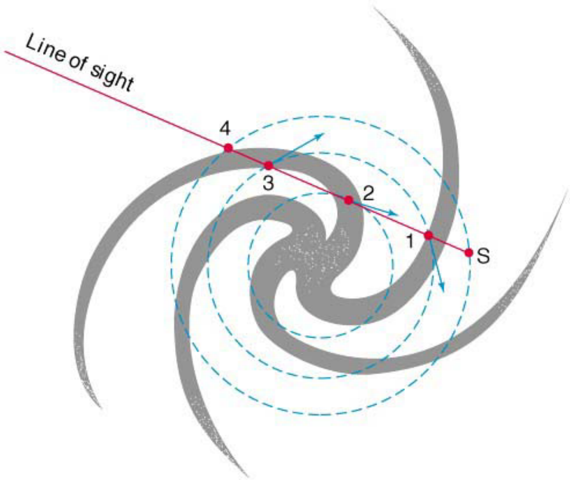
Oort's constants

- "standard" values:

$$A = 14.4 \pm 1.2 \text{ km s}^{-1}\text{ kpc}^{-1}$$
$$B = -12.0 \pm 2.8 \text{ km s}^{-1}\text{ kpc}^{-1}$$

Large scale v-structure !!

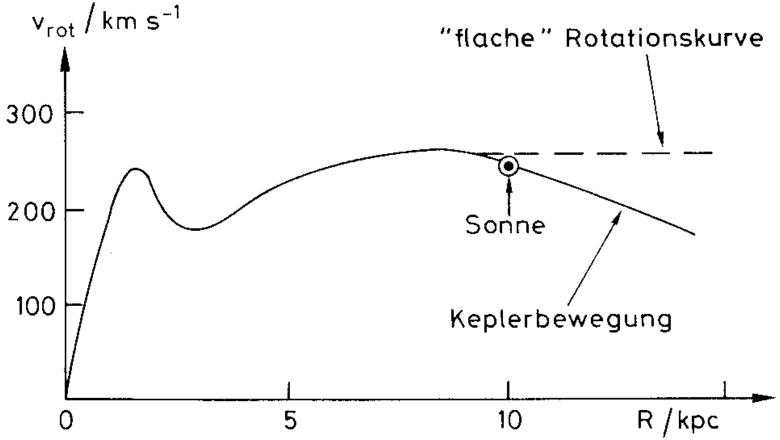
- cannot use Oort's constants
- use 21 cm line of H I to see whole Galaxy!



Large scale v-structure !!

- if distances are known → construct Galactic rotation curve!
- determining d is hard!
- take *largest* radial velocity measured along LOS
  → comes from the region around $R_{\min}$
  → $d = R_0 \cos \ell$
- → measure $v_{r,\max}$ for ℓ's in the "inner" region
  → build up rotation curve!
- to measure the rotation curve for $R > R_0$
  → need d independently
  → use Cepheids etc.

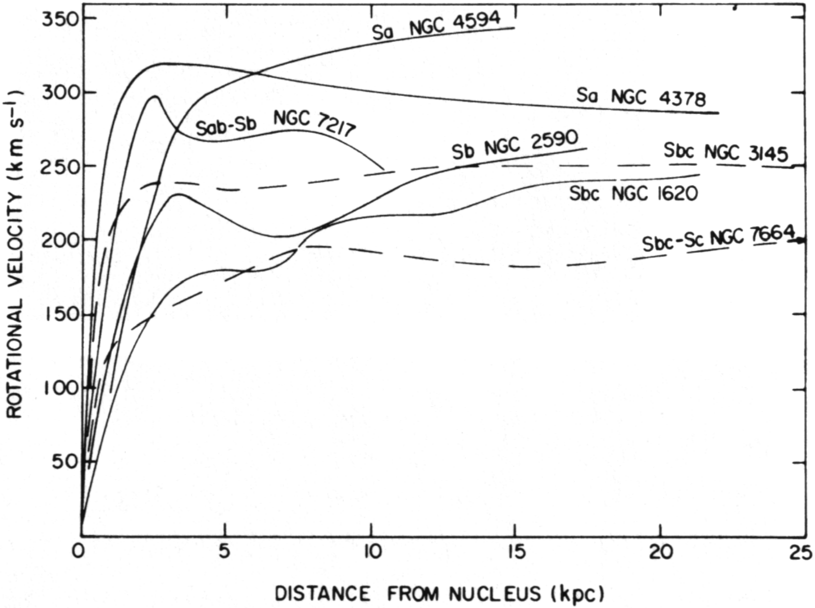
Galactic rotation curve !!



Galactic rotation curve !!

- *flat* beyond R_0
- should drop off $\Theta \propto R^{-1/2}$ (*Keplerian motion*)
- $\rightarrow$ significant mass at $R > R_0$ (dark halo)
- other spiral galaxies show similar result:

rotation curves !!



Galactic rotation curve

- inner part: rapid rise with $\Theta \propto R$ or $\Omega = \mathrm{const.}$
  $\rightarrow$ *rigid-body rotation*
- rotation depends on *distribution of mass*:
- rigid rotation $\rightarrow \rho \approx \mathrm{const.}$ and a spherical mass distribution

Flat rotation curve !!

- $\Theta(R) \equiv V = \mathrm{const.}$
- force balance:
$$\frac{mV^2}{r} = \frac{GM_r m}{r^2}$$
so that
$$M_r = \frac{V^2 r}{G}$$
- differentiating:
$$\frac{dM_r}{dr} = \frac{V^2}{G}$$

Flat rotation curve !!

- put together with mass conservation:

$$\frac{dM_r}{dr} = 4\pi r^2 \rho$$

$\rightarrow$

$$\rho(r) = \frac{V^2}{4\pi G r^2}$$

- $\rightarrow \rho \propto r^{-2}$
- but stellar number density $\propto r^{-3.5}$!
- $\rightarrow$ dark matter!

Flat rotation curve !!

- to "match up" with the inner (rigidly rotating) part of the Galaxy:
$$\rho(r) = \frac{C_0}{a^2 + r^2}$$
- $C_0 \approx 4.6 \times 10^8\ \mathrm{M}_\odot$, $a \approx 2.8$ kpc
- $r \gg a \rightarrow \propto r^{-2}$
- $r \ll a \rightarrow a^{-2} = \mathrm{const.}$
- r^{-2} law cannot be valid for all R (integral unbound $\rightarrow$ infinite mass!)

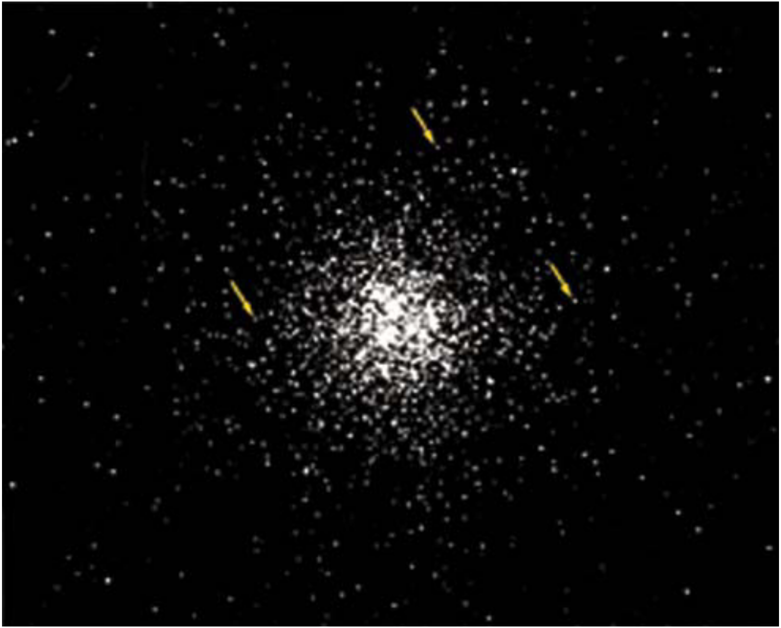
Distance Galactic Center

- recommended “standard” value: $R_0 \approx 8.5\,\mathrm{kpc}$
- *solar circle*: circle with $r = R_0$ centered at the Galactic center
- techniques to find R_0:
- centers of spatial distributions of halo and bulge objects (GCs, RR Lyr, Miras)
- kinematic properties of Cepheids, OB stars, H II regions can be used to find the centers of their orbits (for axisymmetric Galaxy!)

Stellar Clusters

- globular cluster
  - very concentrated to its center
  - $10^{4\dots7}$ stars
  - 15–150 pc diameter
  - $10^{3\dots4}$ times normal stellar density (center)
  - old stars (10^{10} yr)
  - probably several hundred in the Galaxy (125 known)
  - form halo around center of the Galaxy

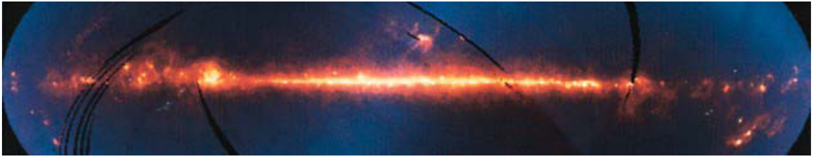
M55



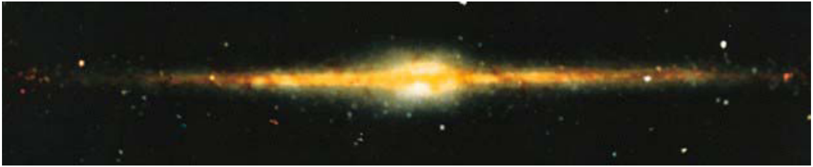
Shape of the Galaxy !!

- nucleus (center) totally obscured by extinction at visible light
- use IR radiation (dust is more transparent!)
- or use radio (effectively no extinction)
- IR can detect the warm dust (10–90K) dust in the Galaxy
- Wien's law $\rightarrow$ dust radiates at about 30–300 μm (*far-infrared*)
- *near-IR* can detect stars (red giants)

far-IR view



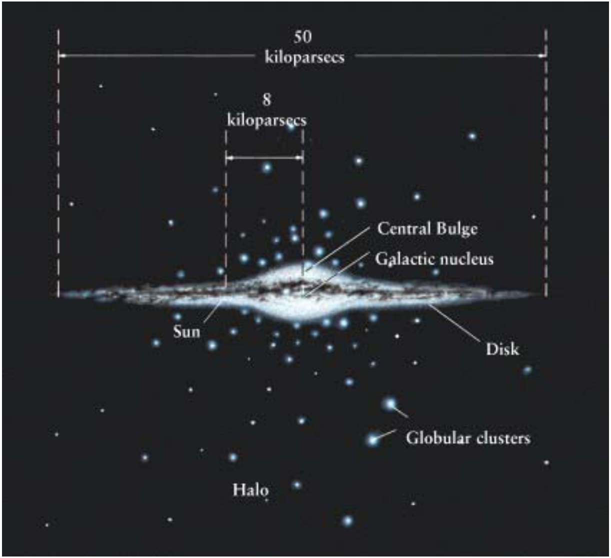
near-IR view



Shape of the Galaxy

- *disk* of the Galaxy
  - 50 kpc diameter
  - 0.6 kpc thick
- *central bulge*
  - peanut-shaped bar
  - about 2 kpc diameter

Schematic view !!



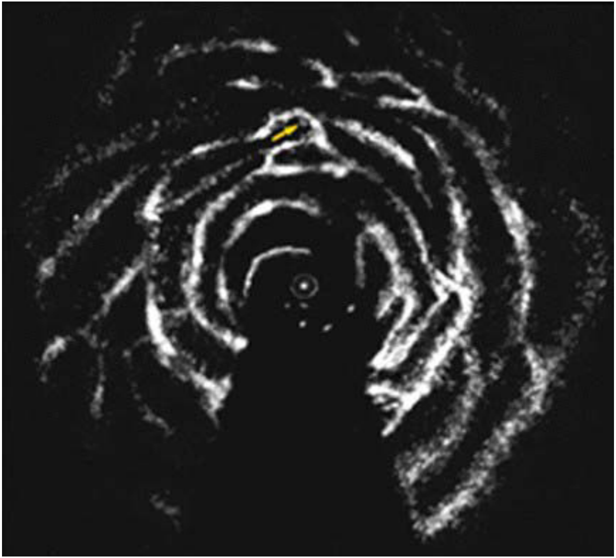
Spiral Structure !!

- radio observations of the Galaxy show its detailed structure
- show that it has *spiral arms*
- observing hydrogen atoms at radio wavelengths
- gas very cold, all H in ground state $\rightarrow$ no optical lines
- $\rightarrow$ *21 cm radio emission* from H I
- can map the whole sky in the 21cm line!

Spiral Structure

- H I prominent in the disk of the Galaxy
- but complex distribution of clouds!
- Doppler shifts of the 21cm line show radial velocities of different clouds!
- makes sorting out different clouds possible
- $\rightarrow$ make a map of the Galaxy!
- H I is concentrated into arched lanes $\rightarrow$ spiral arms

21cm view !!

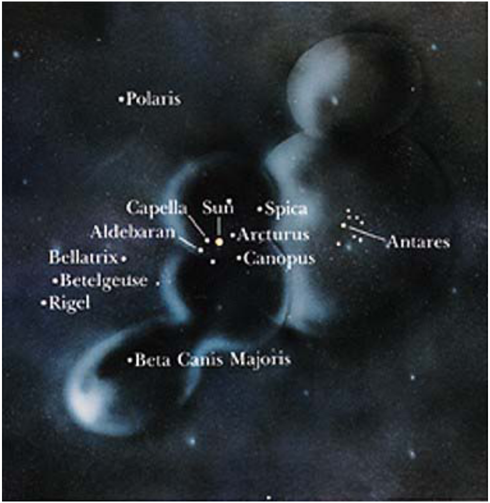


Spiral Structure !!

- also outlined by young stars, emission nebulae!
- note: lots of older stars are between the spiral arms, but the massive young stars in the spiral arms make them stick out!
- mapping star-forming regions in the Galaxy also traces spiral arms
- map CO gas to trace molecular clouds
- Galaxy has 4 major spiral arms
  - Sun located on the Orion arm
  - Sagittarius arm toward the galactic center
  - Perseus arm away from the center

Schematic view !!

Solar neighborhood



Galactic Halo

- globular clusters
- field stars with large v-components $\perp$ to the plane:
  $\rightarrow$ *high-velocity stars*
- two distinct spatial distributions of GCs:
  1. older, metal poor ($[\mathrm{Fe/H}] < -0.8$):
     $\rightarrow$ extended spherical halo
  2. younger GCs ($[\mathrm{Fe/H}] > -0.8$):
     $\rightarrow$ much flatter distribution (thick disk??)

Dark Matter Halo

- roughly spherically distributed
- extends out to > 100 kpc
- gravitational effect on luminous matter $\rightarrow$ density distribution

$$\rho(r) \propto \left(a^2 + r^2\right)^{-1}$$

with $a \approx 2.8$ kpc

Dark Matter Halo !!

- dark halo mass might be 1.9×10^{11} $M_\odot$ for $r < 25$ kpc!
- $\rightarrow$ Galaxy's mass: $M \approx 2.8 \times 10^{11}$ $M_\odot$
  $\rightarrow$ 70% of this would be in the dark matter halo!
- dark matter halo density decreases *slower* than stellar halo
  $\rightarrow$ dark matter may be $>$ 90% of the mass of the galaxy!

Dark Matter Halo !!

- Composition of the dark matter halo:
  - largely unknown: not directly observable!
  - it's not dust (no extinction)
  - it's not gas (absorption lines)

Dark Matter Halo !!

- dark matter halo candidates:
  1. Weakly Interacting Massive Particles (*WIMPs*) (e.g., massive neutrinos)
  2. Massive Compact Halo Objects (*MACHOs*) (e.g., black holes, NS, brown dwarfs)

The Galactic Center

- lots of stars in the bulge region
- at the center of the Galaxy, we could see 1 million stars as bright as Sirius
- center itself cannot be observed in the visible!

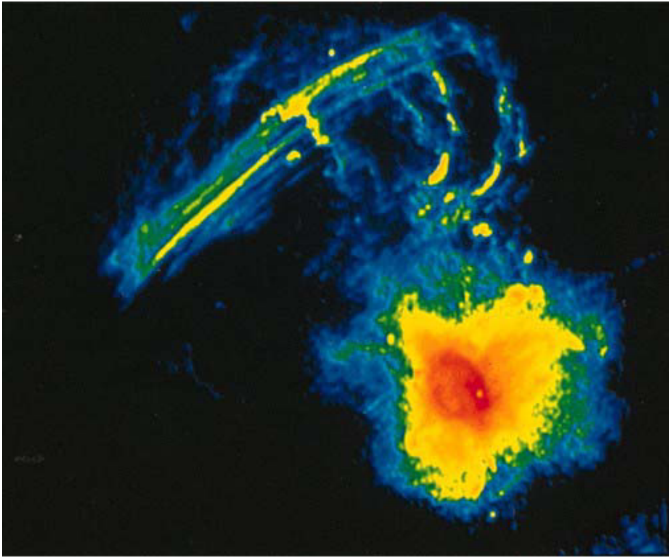
Gal. Center I

Gal. Center II

The Galactic Center

- IR images show arches and streams of dust
- Sagittarius A: radio source at the center itself
- inner 60 pc contain filaments of gas perpendicular to the plane

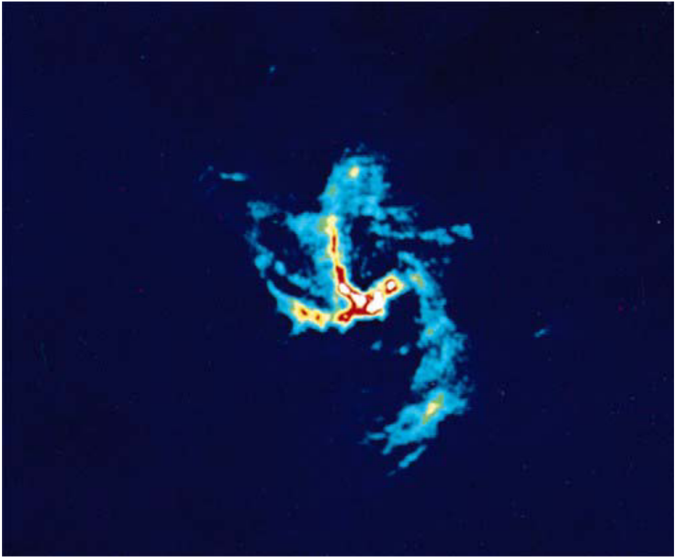
Gal. Center III



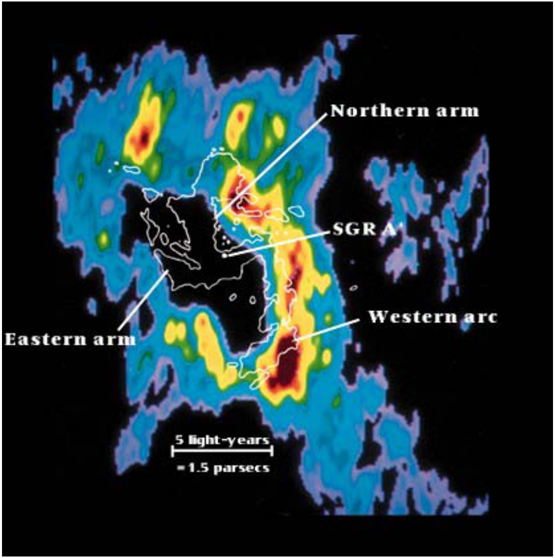
The Galactic Center

- stretch out for 20 pc N-S, then arch abruptly towards Sagittarius A
- inner core of Sagittarius A: about 7pc across
- mini-bar spiral centered around Sagittarius A*

Gal. Center IV



Gal. Center V

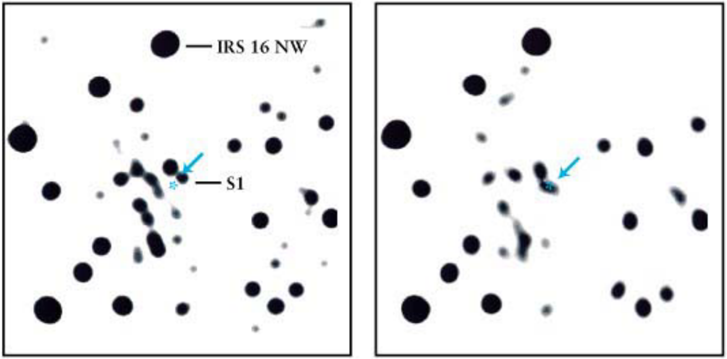


Northern arm
SGR A*
Western arc
Eastern arm
5 light-years
=1.5 parsecs

The Galactic Center !!

- total mass in the structure $\approx 3 \times 10^4\,M_\odot$
- material closer than 2 pc to Sagittarius A^* is fully ionized
- Sagittarius A^* appears to be the true center
- stars close to it orbit at $1500\,\mathrm{km\,s^{-1}}$
- $\rightarrow$ Kepler's 3rd law
  $\rightarrow$ mass of Sagittarius $A^* \approx 2.6 \times 10^6\,M_\odot$
- Sagittarius A^* is likely a *supermassive black hole*

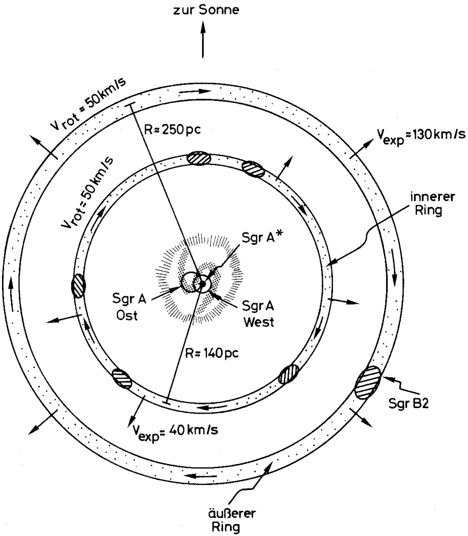
Gal. Center VI



April 1994

April 1996

Gal. Center schematic !!



Stellar Populations !!

- Stellar composition parameterized by the *metallicity*

$$\left[\frac{\mathrm{Fe}}{\mathrm{H}}\right] \equiv \log\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right) - \log\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\odot}$$

Stellar Populations !!

- sometimes (often?) also written as $[\mathrm{M/H}]$
- solar metallicity: $[\mathrm{Fe/H}] = 0.0$
- metal-poor stars: $[\mathrm{Fe/H}] < 0$
- metal-rich stars: $[\mathrm{Fe/H}] > 0$
- typical range:
  - $[\mathrm{Fe/H}] = -4.5 \ldots - 5.5$ for old, extremely metal-poor stars
  - $[\mathrm{Fe/H}] = +1$ for young, extremely metal-rich stars

Stellar Populations !!

- different populations of stars:
  1. Population I: metal-rich: $Z \approx 0.02$
  2. Population II: metal-poor $Z \approx 0.001$
  3. intermediate or disk population
  4. extreme Population I or II

Stellar Populations

- halo: old, metal-poor Pop. II stars
- stars in the disk:
  young, metal-rich Pop. I stars
- disk appears blue due to O-B stars
- $\rightarrow$ young stars
  $\rightarrow$ active star formation in the disk
- halo: no O-B stars $\rightarrow$ no star formation
- bulge: reddish, many giants and supergiants!
- contains both Pop. I and Pop. II stars!