Lecture 3: MW Rotation and sources of mass

- Our galaxy and spiral structure
- MW Rotation
  - Stars and Oorts constants
  - Mapping rotation via HI
- The case for Dark Matter
- Galaxy components other than stars and DM
  - HI
  - HII, CO
  - ISM (HIM, WIM)
  - DUST
  - SMBHs

overall structure of our Galaxy

- plan view:
  - stars are in: thin disk, thick disk, halo (a few), globular clusters, bulge
  - gas is in: disk plane, halo, beyond halo
• ‘top’ view
  – are we a grand design spiral?
  – probably an Sb to Sc type
  – more than just a pair of arms
  – we’re in a ‘spur’ off an arm

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Spiral arms of Milky Way

• Spiral pattern controls the formation rate of stars
  – the spiral pattern is a pressure wave, not physically made up of the same stars all the time
  – clouds are created where the wave sweeps up diffuse gas (HI)
  – hence arms are the site of most star formation
    • dense cores can fragment out and collapse

• Estimate 100 Myr for a star to travel between arms and 10 Myr to pass through one (mass extinctions ?)
  – this may dictate the timescale for clouds to form stars
Mapping our Galaxy’s arms

• difficult because the Sun lies in the thin disk
• need to use velocity information:
  – tangential velocity $v_t$ and radial velocity $v_r$
  – hence $v = (v_t^2 + v_r^2)^{1/2}$
• radial velocity from spectrum of stars or gas:
  – precision for stars a few km/s
  – precision < 1 km/s for gas (narrower lines)
• tangential velocity from proper motion:
  – need milli-arcsec accuracy (difficult)

• proper motion defined as angle travelled per unit time, so from $\theta = r / d$ we get
  $\frac{dr}{dt} = v_t = d \times \frac{d\theta}{dt} = \frac{d \times \text{p.m.}}{d}$
• which works out at
  $v_t (\text{km/s}) = 4.74 \times d (\text{kpc}) \times \text{p.m.} (0.001'' / \text{year})$
• e.g. distance to the Galactic Centre (Sagittarius star complex)
  – measure p.m. of maser spots and $v_r$ from their spectra
  – masers are moving outwards: $v_x \sim v_y \sim v_z$ (which is $v_r$)
  – write this as $v_z^2 = 1/2 (2v_x^2) = 1/2 (v_x^2 + v_y^2) = 1/2 v_t^2$
  – hence $2 v_r^2 = v_t^2 = d^2 \times \text{p.m.}^2$
  – so from $v_r$ and p.m. can work out $d$
    • about 7.1+/−1.5 kpc to Galactic Centre (correct value 8.5kpc)
Mapping the Galaxy plane

• often only have radial speed of stars or clouds to work with, \( v_t \) measurements are rare
• make assumption that to first order stars and clouds move on circular orbits in a flat plane about the centre

- star is at \( d \) from us but \( R \) from Galactic Centre, also at longitude \( l \) in our co-ordinate frame
• we measure \( v_r \) of star at \( P \)
  \[
v_r = v \cos \alpha - v_0 \sin l
  \]
  and by the sine rule
  \[
  \sin l / R = \sin (90^\circ + \alpha) / R_0
  \]
  \[
  \sin l / R = \cos \alpha / R_0
  \]
  \[
  \Rightarrow v_r = R_0 \sin l ( v / R - v_0 / R_0 )
  \]
Note, if rotation was solid body \( v_r \) would always be zero
Nearby stars with \( 0 < l < 90 \) appear to move away from us
More distant stars with \( 0 < l < 90 \) appear to move towards us
Stars with \( 90 < l < 180 \) appear to move towards us
Stars with \( 180 < l < 270 \) appear to move away from us
Distant stars with \( 270 < l < 360 \) appear to move away from us
Nearby stars with \( 270 < l < 360 \) appear to move towards us

Oort’s constants

• useful for understanding the Galactic rotation curve \( v(R) \)
  \[
v_r = R_0 \sin l ( v / R - v_0 / R_0 )
  \]
  and as we find later, \( v / R \) decreases for larger \( R \)
results from Columbia CO survey
Measuring $V(R)$ of our Galaxy

In principle, $l$ and $d$ measurements would yield $V(R)$ but dust extinction in the ISM makes this difficult. However nearby dust is not an issue (i.e., when $d \ll R_0$).

From: $v_r = R_0 \sin l \left( \frac{v}{R} - \frac{v_0}{R_0} \right)$

• now treat (...) as a small change $\delta(V/R)$

$\rightarrow v_r = R_0 \sin l \delta(V/R)$

or as a differential,

\[
\frac{d(V/R)}{dR} = \frac{\delta(V/R)}{R-R_0}
\]

$\rightarrow v_r = R_0 \sin l (R - R_0) \frac{d(V/R)}{dr}$

• for $P$ close to the Sun, $d \ll R$, and the cosine rule for triangle Sun-P-GC gives

$R_0 = R + d \cos l$ or $R - R_0 = -d \cos l$

hence

$v_r = R_0 \sin l (R - R_0) \frac{d(V/R)}{dr}$

becomes

$v_r = -R_0 \ d \ sin l / \ cos l / d(V/R)/dr$

NB: $2\sin 2\theta = \sin \theta \cos \theta \Rightarrow$

$\sim -1/2 \ R_0 \ d \sin 2l / d(V/R)/dr$

$v_r = d \sin 2l / [- (R/2) d(V/R)/dr]_{R_0}$

$= d A \sin 2l$

where $A$ is defined as the first Oort constant = A measure of the gradient of the rotation curve near the Sun and observationally has a value of $\sim 14 \text{ km/s/kpc per kpc}$
• similarly in the tangential direction
  \[ v_t = d \cos 2l \left[ \frac{-R}{2} \frac{d(V/R)}{dr} \right]_{R_0} - \frac{d}{2} \left[ \frac{1}{R} \frac{d(Rv)}{dR} \right]_{R_0} \]
  and we define
  \[ v_t = d \left[ A \cos 2l + B \right] \]
  where B is the second Oort constant, approx -12 km/s/kpc
  (see 2nd year notes for details)
• Oort constants A and B represent:
  (A) local shear (deviation from solid body rotation)
  (B) local vorticity (angular momentum gradient)
  \[ A + B = -\left[ \frac{dV}{dR} \right]_{R_0} \quad A - B = \frac{V_0}{R_0} \]
  The values of A and B imply that the V is decreasing in the vicinity of the Sun and for \( R_0 = 8.5 \text{kpc}, V_0 = 220 \text{km/s} \)

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**Mapping the rotation curve via HI**

• Oorts constants are useful for nearby stars, but less useful for the Galaxy as a whole
  – \( d_{\text{star}} \) is hard to measure because of extinction
• using gas lines probes much further across our Galaxy
  – HI or CO emission from clouds doesn’t suffer extinction
  – but we still don’t know \( d \)!
  – in fact for a random line of sight, there are two solutions for \( d \) with the same \( v_r \)
Mapping $v(R)$

- so we use the tangent point method... at point $T$, $v_R$ has its greatest value
  
  $R = R_0 \sin l$
  
  $v(R) = v_r + v_0 \sin l$

  so if there is a gas cloud at every point in the disk, we can map $v(R)$ from the tangent points at every $l$

See Handout
the rotation curve of Galaxy rises steeply near the centre but is then rather flat, out to about 20 kpc - which is beyond most of the stars we see.
Mass of the Galaxy?

- Newton’s law tells us that
  \[ F = - \frac{G M m}{R^2} \]
- and the force needed to keep a body moving in a circle is
  \[ F = m \ a = - \frac{m v^2}{R} \]
- hence
  \[ M(<R) = \frac{R v^2}{G} \quad (~\text{Virial Theorem}) \]
- so if orbits really are circular in a flat disk, we can calculate mass \( M \) within radius \( R \) from the rotation curve

Dark matter?

- if for example there are few stars beyond \( R = 10 \) kpc, then the rotation curve should decline beyond this
  \[ V = \sqrt{\left( \frac{G M(<R)}{R} \right)} \]
  so if \( M \) is constant beyond 10 kpc, \( v \) should fall as \( R^{-1/2} \)
  whereas it’s still flat or rising at 20 kpc!
- other galaxy rotation curves show similar patterns
  - can only explain this if there is matter we can’t see at large \( R \)
- even beyond any stars, we can derive the rotation curve from velocities of satellite galaxies
  - even more dark matter at 100’s kpc in clusters of galaxies
Galaxy contents:

- Dark Matter – 90% of total mass from rot. Curves.
- Stars – 5-10% from optical/near-IR surveys
- Neutral Gas (HI) – 0-5% from 21cm observations
- Molecular Gas (HII, CO) – 0-1% from line observations
- Ionised Gas (H⁺)
  - Hot interstellar medium
  - Warm interstellar medium
- Dust - <0.1% - From FAR BB Peak
- SMBHs < 1% - From core velocity dispersion studies
- WDs and BHs < 1% - stellar population synthesis
- Planets < 0.001% - Solar system
Giant Gas discs (UGC5288, NRA, USA)

Purple = HI
White = stars

Other gas phases

• gas distribution can be very complex, as a diffuse gas phase may fill 'holes' in a denser one (e.g. HI in H₂)

• gas ranges from cold molecular clouds through cold neutral medium, warm neutral medium, warm ionized medium up to hot ionized gas phase
  – powered by massive stars and supernovae
  – from ~ 10 K in molecular gas up to ~10⁶ degrees in plasma
  – hotter phases form thick layers, because thermal velocities of particles are higher,
Substructure: chimneys and holes

- because density drops off away from Galactic Plane, gas blows out easily
- the Sun lies in a bubble perhaps blown out by a supernova

Gas in other spirals

- much easier to map in other galaxies, e.g. M31, the nearest spiral
  - differs from MW in the location of the molecular gas clouds that will form the next generation of stars
    - in the Galaxy, these form a ring at 5 kpc, whereas in M31 the equivalent is the ‘ring of fire’ at 10 kpc
Clouds in Andromeda

- star formation only happens in the dense parts of the clouds as stars can only form from HII which MUST be shielded:
  - contours show CO emission while image is star light
  - the stars travel between arms but the clouds disperse

Cold material in galaxies

- some galaxies may have a reservoir of very cold gas and dust (much more non-stellar material than suspected)
  - e.g. the IRAS satellite observed cold dust emission out to 100 microns wavelength
- Wien’s law tells us
  \[ T(\text{dust}) \times \lambda_{\text{peak}} (\text{mm}) = 3 \]
  for blackbody emission, so IRAS was not sensitive to material at less than \( \sim 30 \) K
  - measurements of the flux at 1 mm are needed to detect any very cold dust that was missed by IRAS
Cloud masses

- for blackbody emission from dust particles:
  \[ M = \frac{F_\nu d^2}{B_\nu(T) \kappa_\nu} \]  
  (standard thermodynamics)
  where \( F_\nu \) is the flux, \( d \) the distance, \( B_\nu(T) \) is the Planck function and \( \kappa_\nu \) is the opacity
  - \( B_\nu(T) = \frac{(2h\nu^3/c^2)}{(\exp(h\nu/kT)-1)^{-1}} \) and \( \kappa_\nu \) is in \( \text{m}^2/\text{kg} \)
  - at long wavelengths, \( B_\nu(T) \) simplifies to: \( 2kT (\nu^2/c^2) \) because \( h\nu \ll kT \)
  - hence in the Rayleigh-Jeans (long-wavelength) tail, a 10x colder temperature implies 10x more mass for the same incident flux.
  - however typically \( M[\text{stars}] \gg M[\text{clouds}] \)

Cold dust mass

- NGC 3079, nearby spiral
  - 90% of dust is at a temperature of only about 12 K
  - mass goes up \( \sim 10x \)
  - but not enough for dark matter
    - 99% in some galaxies
    - \( M[\text{stars}] \) is usually \( \gg M[\text{clouds}] \)

Stevens & Gear (2000)
Black holes

• most galactic centres possess a black hole
• in the Milky Way, it’s about $3 \times 10^6 \, M_{\text{solar}}$
  – orbits can be deduced for stars very close to the black hole
  – then use central mass $\sim \sqrt{GM/r}$, with corrections for non-circular orbits

![Graph](proper motion of star close to Galactic Centre black hole, Schoedel et al (2003)](image)

Black holes in other galaxies

• most black holes deduced to be much more massive
  – up to billions of $M_{\text{solar}}$ in active galactic nuclei (AGN)
  – fundamental product of early time in galactic evolution? …masses of black holes correlate with amount of star formation
  • perhaps a fraction of the stars in dense young galaxies always falls onto a central black hole

![Graph](image)
Magnetic field

- in our Galaxy, field follows arms but reverses between arms
- Galaxy acts like a dynamo: differential rotation of partially ionized gas provides a current
- similar patterns in other nearby galaxies

Vallee (1996)