Class #15: Structure of the Milky Way: ISM, rotation, nucleus

Structure and Dynamics of Galaxies, Ay 124, Winter 2009

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Material in this class is taken mostly from Binney & Merrifield §8.2, §9.1, §9.2 & §9.5.

1 The Interstellar Medium of Disk Galaxies

1.1 Radial Density Profiles

We can get a good overall picture of the structure of the ISM in galactic disks by looking at Fig. 1. The left-panel shows the radial distribution of atomic and molecular hydrogen compared with the distribution of starlight. A few points are immediately obvious:

- The molecular hydrogen is significantly more centrally concentrated than the atomic hydrogen;
- Their is a depression in the density of atomic hydrogen in the central regions;
- The ISM is significantly more radially extended than the starlight.

The right-panel shows molecular and atomic hydrogen radial profiles for other galaxies—these show central depressions in both atomic and molecular gas (characteristic of early-type disk galaxies, such as Andromeda).

The large radial extent of HI disks is very useful for probing rotation curves (and therefore dark matter halos) out to large radii. The HI disks of galaxies cut off quite sharply at a surface density of about 10^{24}m-2. The reason for this was predicted by Sunyaev in 1969: the cosmic background of ionizing photons is always trying to ionize HI gas, at higher surface densities the HI gas is able to self-shield (the outer layers become ionized thereby absorbing all of the ionizing photons and allowing the inner HI to remain neutral). Below $10^{24}\mathrm{m}^{-2}$ the HI is unable to self-shield and becomes ionized by the cosmic background radiation. If this explanation is correct, we would expect the HI disks to be enveloped in HII which should radiate in the Hα line. This HII envelope should also extend to larger radii. This is in fact seen in the Milky Way.

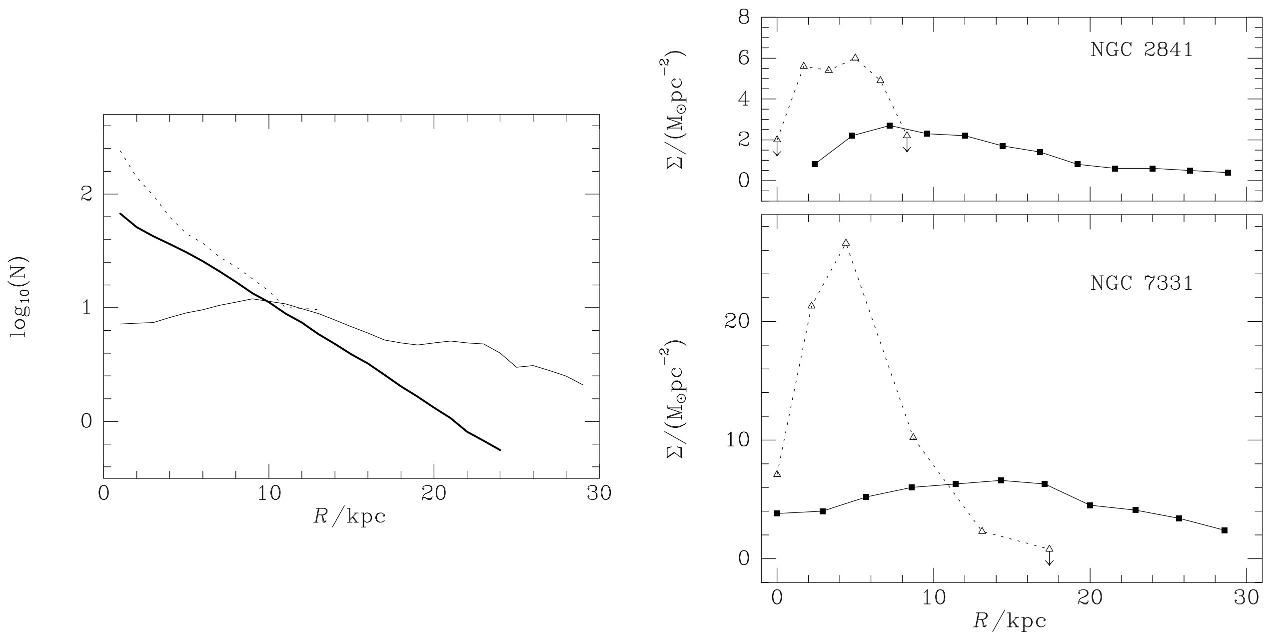

Figure 1: The radial distribution of B-band light (heavy line), H_2 (dashed line) and HI (dotted line) for NGC 6946.

1.2 Azimuthal Density Profiles

1.2.1 Bars and Oval Distortions

The gas (mostly H_2) near the center of a disk often shows a bar structure (even if no bar is visible in the stellar light). When an optical bar is present, the H_2 bar is aligned with the optical one.

The outer disks might be slightly elliptical rather than circular. This hypothesis has to be tested using velocity fields (since an intrinsically elliptical disk is difficult to distinguish from a circular one seen slightly inclined).

1.2.2 Spiral Structure

Spiral structure is readily apparent in the gas content of disks. Figure 2 shows the distribution of CO compared to red light and 21-cm emission in M51 (which shows a very clear, two-armed spiral pattern due to a tidal interaction with a nearby neighbor). The CO distribution peaks on the concave side of the arms. As we learned, the gas is flowing into the arms from the concave side, the the peak in the gas density is just upstream of the arm's crest in the mass distribution. The HI (and Hα) emission peaks slightly downstream from that of the CO and is consistent with arising from molecular gas being heated and dissociated by radiation from hot young stars produced by the dense molecular gas. The HI distribution also shows evidence that the HI is not smoothly arranged, but is instead broken up into blobs containing around $5 \times 10^6 M_\odot$ with diameters of a

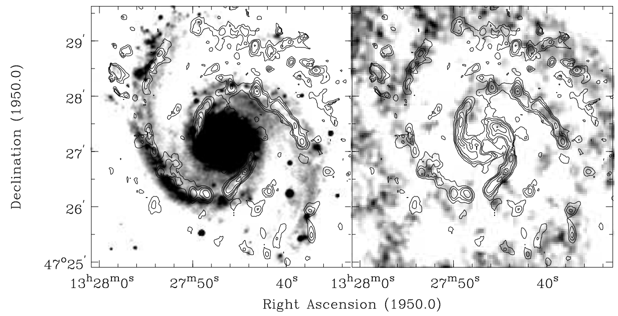

Figure 2: The correlation of CO and HI emission with spiral arms in M51. Contours show CO emission while the grey-scale shows red-continuum light (left) and 21-cm emission (right).

few hundred parsecs.

1.2.3 Lop-sidedness and Warps

Gas beyond the optical radius of galaxies often appears to be lop-sided (see Fig. 3), which would not be expected is the gas disk were axisymmetric and planar. Interestingly, the isodensity contours of the gas are approximately circular at all radii, but are not concentric with the galaxy's nucleus at large radii. However, velocity mapping shows that the gas is on circular orbits around the nucleus even at large radii. The lop-sidedness must arise from the orbits being non-uniformly populated at large radii. What's strange about this is that differential rotation should smear out any such arrangement with a few rotation periods (recall the winding problem argument). Since many galaxies show this phenomenon it suggests that recent additions of gas to the outer regions of galaxies is not uncommon, although the definitive answer to this puzzle remains elusive.

An additional common distortion, seen in edge-on galaxies, is a warp, in which the outer regions of the disk deviate from the plan define by the inner regions. Such a warp corresponds to one of the primary modes of a self-gravitating disk and as such is easily excited by, for example, an interaction with a nearby galaxy.

1.3 Velocity Fields

By observing the frequency of a line (e.g. 21-cm line) of ISM gas we can (via the Doppler effect) infer the velocity of the material in a galaxy disk at any given point. In general, if $\mathbf{r}$ is a vector from the galactic nucleus to some point in the disk, $\hat{\mathbf{n}}$ is a unit vector normal to the annulus of the disk of radius r and $\Omega(r)$ is the angular velocity of that annulus then the velocity of material at $\mathbf{r}$ must be $\mathbf{v} = \Omega(r)\hat{\mathbf{n}} \times \mathbf{r}$ with a line-of-sight component

$$v_{\rm los} = \hat{\mathbf{R}} \cdot \mathbf{v} = \Omega(r)\mathbf{r} \cdot (\hat{\mathbf{R}} \times \hat{\mathbf{n}}), \tag{1}$$

where $\hat{\mathbf{R}}$ is the unit vector from the observer to the galaxy. The velocity field of a galaxy can be modelled by varying $\Omega(r)$ and the polar angles (θ, ϕ) of $\hat{\mathbf{n}}$ until the values of $v_{\rm los}$ predicted by the

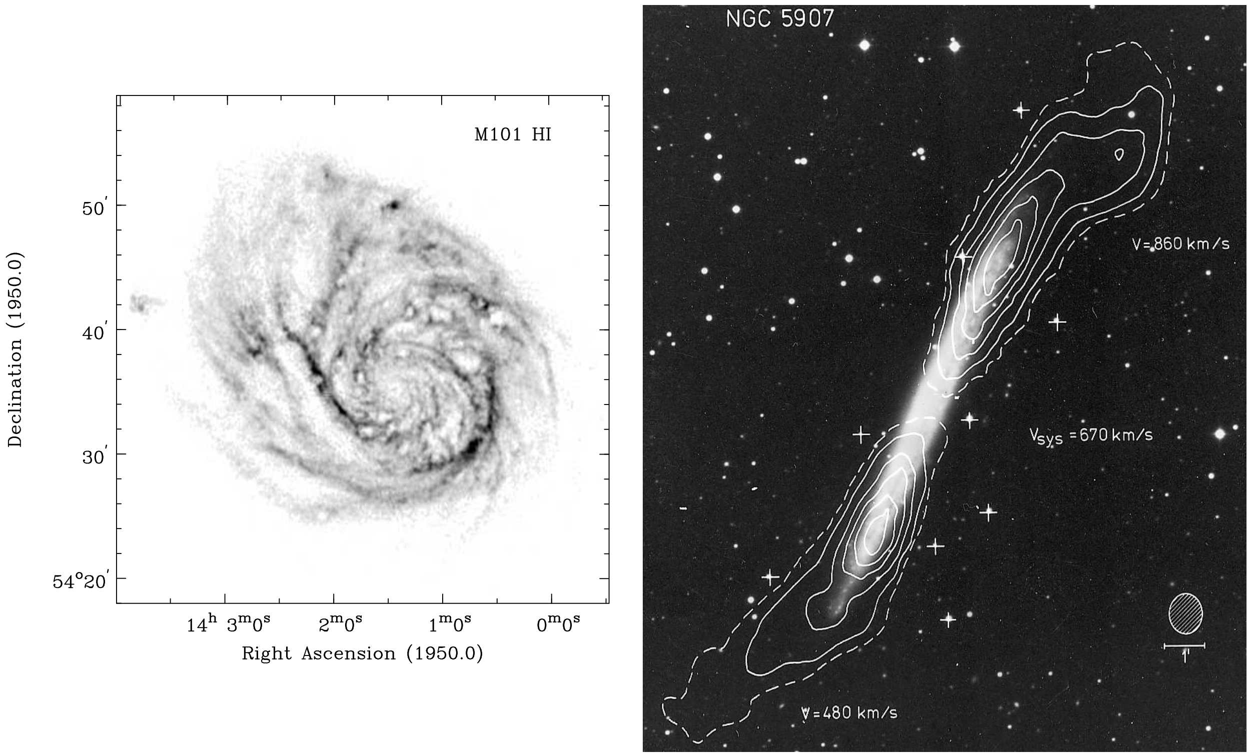

Figure 3: An example of a lop-sided galaxy (left) and a warped galaxy (right).

above match those measured.

In the simple case of a flat disk the vector $\hat{\mathbf{n}}$ is constant and the line of sight velocity reduces to

$$v_{\rm los} = \Omega(r) \sin i \mathbf{r} \cdot \hat{\mathbf{k}}, \tag{2}$$

where i is the galaxy's inclination and

$$\hat{\mathbf{k}} \equiv \hat{\mathbf{R}} \times \hat{\mathbf{n}} / \sin i, \tag{3}$$

is the unit vector perpendicular to both $\hat{\mathbf{R}}$ and $\hat{\mathbf{n}}$ and runs parallel to the galaxy's apparent major axis. Knowing i (which can be inferred from the apparent ellipticity of the disk if we assume it's actually circular) we can infer the rotation speed $v_{\rm c}(r) = \Omega(r) r$ from the line of sight measurements.

Typical circular speed curves (a.k.a. rotation curves) are shown in Fig. 4. These are very important because they can be used to infer the enclosed mass $M(r)$[1]. The shapes of rotation curves differ significantly from one galaxy to the next but often show an inner region of solid-body rotation (i.e. $v_{\rm c} \propto r$) followed by an extended region of constant $v_{\rm c}$. The only clear correlation between the rotation curve and galaxy properties is that more luminous galaxies show higher peak rotation speeds (as quantified by the Tully-Fisher relation).

One could try to predict the rotation curve of a galaxy by using the measured light distribution and a mass-to-light ratio, Υ, to convert this into a mass distribution. Sometimes this gives a good

[1]We often do this by assuming that the mass interior to radius r is spherically distributed such that $M(r) = v_{\rm c}^2 r/{\rm G}$. Treating the disk as a razor thin plane gives a slightly different answer (of order 10–20% different).

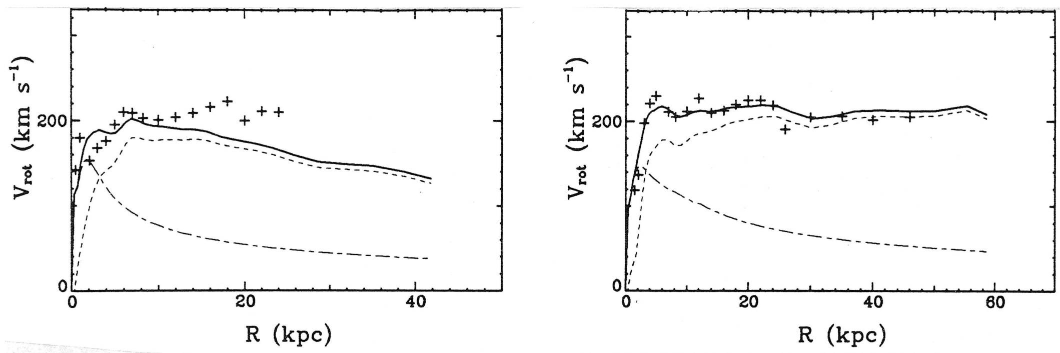

Figure 4: Rotation curves of two galaxies. Measured rotation speeds are shown by crosses. The dashed and dot-dashed lines show the expected rotation speeds from disk and bulge components after assigning appropriate mass-to-light ratios to them. The solid lines shows the net rotation due to the combination of disk and bulge.

match to the measured $v_{\rm c}(r)$ but often it does not (see Fig. 4). The problem is that many rotation curves remain flat to large radii but, at sufficiently large radius, the rotation speed due to a galaxy must always decline as $r^{-1/2}$ (i.e. the galaxy acts as a point mass so we get Keplerian rotation). Even though we often don't know Υ all that well, in many cases there is no vaue of Υ which would result in a good fit to the entire rotation curve.

The interpretation of this is that there is some unobserved matter at large radii which contributes to the rotation. These measurements don't tell us what it is—it could in principle be very faint stars or brown dwarfs, black holes, rocks etc.—but from other reasoning we believe that it is dark matter.

1.4 Metallicities

The metallicity of ISM as can be inferred from the strengths of emission lines in the spectra of HII regions (which are just regions of highly ionized gas around young, hot stars). For our purposes, the metallicity is interesting in so far as it can tell us about the structure and formation of the galaxy.

One interesting observational fact is that the mean metallicity of the ISM is correlated strongly with the peak rotation speed of the disk—higher $v_{\rm c}$ implies higher metallicity. From our simple models of chemical evolution we know that the effective yield (which determines the metallicity of the gas) depends on the degree of mass outflow experienced by the galaxy. If lower $v_{\rm c}$ galaxies experience stronger outflows (which may be expected since the gravitational potential well depth is proportional to $v_{\rm c}^2$) then they shoudl have lower effective yields and so lower metallicities. Recalling the definition $p_{\rm eff} = -Z/\ln f_{\rm gas}$ observations show that $p_{\rm eff}$ varies within a galaxy (ruling out the closed-box model) as well as from galaxy to galaxy: a dwarf galaxy may have $p_{\rm eff} \approx 0.005$ while the inner regions of a luminous disk may have $p_{\rm eff} \approx 0.012$.

1.5 Magnetic Fields

The direction of the magnetic field in galaxy disks can be inferred from polarization measurements (in optical light, scattering from dust grains which tend to align with the magnetic field results in the electric vector of the radiation being aligned with $\mathbf{B}$ while at radio wavelengths synchrotron emission is polarized perpendicular to $\mathbf{B}$). Measurements show that the magnetic field tends to point along spiral arms and, in the Milky Way, that it lies in the plane of the disk.

The magnitude of the magnetic field can be inferred from measurements of the intensity of synchrotron emission $j_{\rm sync} \propto \epsilon B^2$ (where ϵ is the energy density of the electrons causing the synchrotron emission) and the assumption that the magnetic energy density, $B^2/2\mu_0$, is comparable to that of the cosmic ray energy density (i.e. equipartition). This allows B to be solved for and typical values of order a nT (10^{-5} Gauss) are found.

1.6 Star Formation

Observations of Hα emission from galaxy disks trace the presence of young, hot stars. (These stars emit copious numbers of ionizing photons, creating HII regions around them. Recombinations in those HII regions then emit Hα photons. In equilibrium then, the rate of Hα emission is proportional to the rate of ionizing photon production and therefore to the number of young stars.) Since these stars are short lived, their number provides a measure of the star formation rate over the past $\sim$ 10Myr.

Stars probably form through the gravitational instability of the ISM. We might therefore expect that the star formation rate should depend on the surface density of gas (which is what determines that stability). In fact, observationally

$$I(\mathrm{H}\alpha) \propto \Sigma_{\rm gas}^{1.3}, \tag{4}$$

in regions where the gas surface density is sufficiently high. Interestingly, the Hα intensity rapidly falls below this value when the gas density reaches about 0.63 times the critical density of

$$\Sigma_{\rm crit} \equiv \frac{\kappa v_{\rm s}}{\pi \mathrm{G}}, \tag{5}$$

where κ is the epicyclic frequency and $v_{\rm s} \approx$ 6km/s is the sound speed. As we've seen, a gas disk is unstable to axisymmetric disturbances only if its surface density exceeds this value. So, observations suggest that instability is required for star formation. (The reason that star formation shuts off at 0.63 times the critical density instead precisely at the critical density is probably due to the fact that the disk is not purely gaseous—there's a stellar component—and that there are observational uncertainties in the determination of $\Sigma_{\rm crit}$.)

While the gas density rises above $0.63\Sigma_{\rm crit}$ in the star forming regions of the disk, it never exceeds it by a huge amount. This suggests that once the disk becomes unstable, star formtion rapidly depletes it of gas driving the density back down towards $\Sigma_{\rm crit}$.

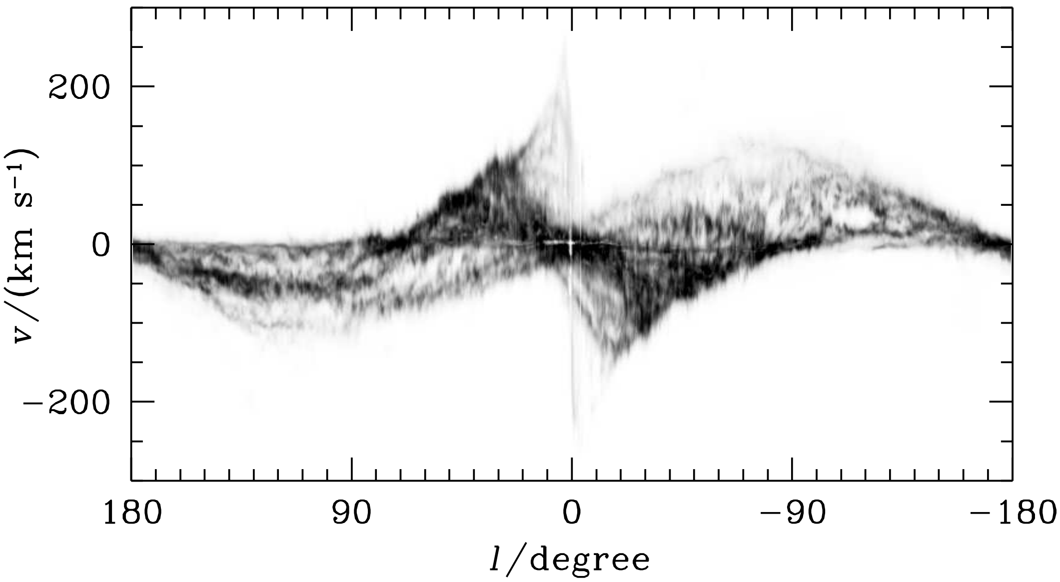

Figure 5: Longitude-velocity plot of the intensity of 21-cm radiation from the Milky Way.

2 Differential Rotation

When trying to map out the stucture of the Milky Way's disk through observations of the ISM the quantity that we can easily obtain is the amount of material (e.g. HI) at each velocity along a particular line of sight. (For example, when observing a line the line is shifted in frequency due to the velocity of the material while its intensity indicates the amount of material present.) For a disk it is useful to average this quantity around a small range of galactic latitudes b close to $b = 0$ (i.e. around the mid-plane). The result is a *longitude-velocity* plot showing the amount of material at each longitude and velocity (see Fig. 5). To simplify matters we'll imagine that the Sun were actually moving with the Local Standard of Rest (it's easy enough to convert these diagrams to the LSR once the Sun's motion relative to it is known).

We can consider what the (l, v) plot would look like for a disk with purely circular rotation. The vector velocity of material at position $\mathbf{R}$ from the galactic center is $\mathbf{v}_{\mathrm{c}} = \mathbf{\Omega}(R) \times \mathbf{R}$, where $\mathbf{\Omega}(R)$ is the (vector) angular velocity. The LSR moves with velocity $\mathbf{v}_0 = \mathbf{\Omega}(R_0) \times \mathbf{R}_0$ where $\mathbf{R}_0$ is the position of the Sun. The line-of-sight velocity seen by an observer in the LSR is then $\mathbf{v}_{\mathrm{c}} - \mathbf{v}_0$ projected onto the vector $(\mathbf{R} - \mathbf{R}_0)$:

$$v_{\mathrm{los}} = \frac{\mathbf{R} - \mathbf{R}_0}{|\mathbf{R} - \mathbf{R}_0|} \cdot [\mathbf{\Omega}(R) \times \mathbf{R} - \mathbf{\Omega}(R_0) \times \mathbf{R}_0]. \tag{6}$$

We can simplify this with some vector algebra to give

$$v_{\mathrm{los}} = \frac{[\mathbf{\Omega}(R) - \mathbf{\Omega}(R_0)] \cdot (\mathbf{R}_0 \times \mathbf{R})}{|\mathbf{R} - \mathbf{R}_0|}. \tag{7}$$

From Fig. 6 we see that $\mathbf{R}_0 \times \mathbf{R} = -R_0 R \sin\alpha \hat{\mathbf{n}}$ where $\hat{\mathbf{n}}$ is a unit vector normal to the disk and $\sin\alpha / |\mathbf{R} - \mathbf{R}_0| = \sin l / R$. Also, $\mathbf{\Omega} = -|\mathbf{\Omega}|\hat{\mathbf{n}}$ (the negative here just arises from the sense of rotation

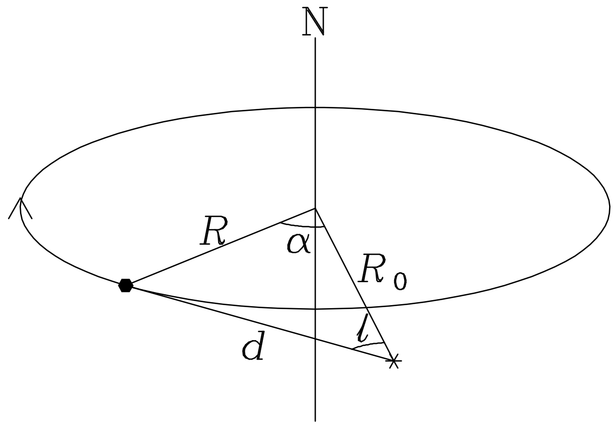

Figure 6: Geometry of a disk of material in circular rotation.

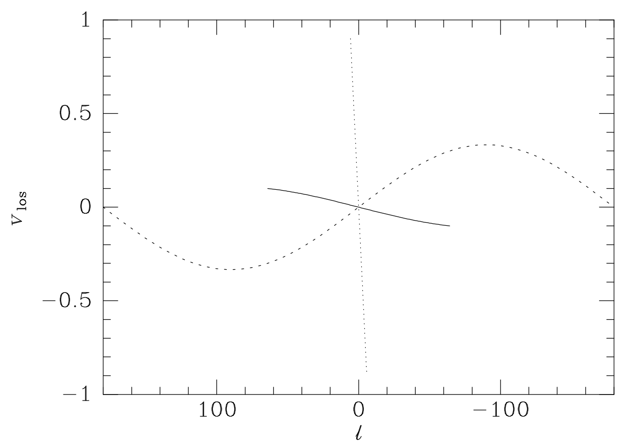

Figure 7: Traces in the (l, v) plane for three rings of radii $r = 0.9R_0$ (solid), $r = 0.1R_0$ (dotted) and $r = 1.5R_0$ (dashed) normalized to unit circular speed at all R.

of the Milky Way). Putting this all together we find

$$v_{\rm los}(l) = [\Omega(R) - \Omega(R_0)]R_0 \sin l. \tag{8}$$

If we considered just a single ring of matter then the above equation shows that along any line of sight we intersect it at just one unique velocity and that velocity is proportional to $\sin l$. In the (l, v) plot the trace of such a ring therefore always looks like a sine wave (Fig. 7). For $r < R_0$ there is a limited range of l that actually intersects the ring ($l = \pm \arcsin(R/R_0)$) so we see only part of the curve. For $r > R_0$ all directions intersect the ring, so we see the full sine wave. The slope at the origin is proportional to $\Omega(R) - \Omega(R_0)$. For any reasonable mass distibution $\Omega(R)$ increases inwards so the slope is largest for the smallest rings and flips signs across $R = R_0$. For $R \to \infty$ the amplitude of the curve tends to $\Omega(R_0)R_0$.

We can think of the Milky Way's disk as being made up from an infinite number of such rings which will therefore populate large regions of the (l, v) plane, but not all regions. From our simple model, material at $l > 0$ must have velocities less than $-R_0\Omega(R_0)\sin l$ so anything beyond this is said to be a *forbidden velocity*.

Along any given line of sight (i.e. fixed l) the largest velocity observed must correspond to the smallest ring intersected (which has the largest $\Omega(R)$). The line of sight must therefore be tangent to this ring (otherwise it would intersect yet smaller rings). Clearly the radius of this ring is just $r_{\rm t} = R_0 \sin l$ and it's easy to show that its circular velocity must be

$$v_{\rm c}(r_{\rm t}) = v_{\rm los}^{(\rm t)}(l) + v_{\rm c}(R_0)\sin l. \tag{9}$$

Since $v_{\rm los}^{(\rm t)}(l)$ is an observable quantity we can use this to determine the rotation curve if we can find some way to measure $v_{\rm c}(R_0)$. In principle $v_{\rm c}(R_0)$ is just the amplitude of the boundary of the occupied region of the (l, v) plane for large R. In practice though, its difficult to measure, as we'll see later.

Once we've determined the rotation curve $v_{\rm c}(R)$ (and, therefore, $\Omega(R)$) we can use the measured line of sight velocity to any object to infer its distance from the Sun. For rings outside the Solar circle there any line of sight intersects the ring only once, allowing for a unique distance to be determined[2]. Inside the Solar circle a line of sight will intersect a ring either twice or not at all. This means that there are two possible solutions for the distance to any given object.

2.1 Spiral Structure

Non-circular motions in the gas will complicate the (l, v) plot. From our study of spiral structure, we know that spiral arms arise when particles move on elliptical orbits with the major axes of those ellipses rotating smoothly as a function of radius as in the left panel of Fig. 8.

This has two effects on the (l, v) plot. Firstly, the density enhancement in the arms causes increased emission at the corresponding point in the (l, v) plot. The right panel of Fig. 8 shows how the points along a spiral arm trace out in the (l, v) plane—the spiral pattern leads to enhanced emission along curves which fan out from the origin. The spiral pattern also affects velocities (since particles are no longer moving on circular orbits) leading each ring of material to form a loop in the (l, v) plane around the circular orbit sine wave. Spiral arms can thus be found by using the (l, v) plane to map regions of enhanced emission into real space coordinates. In principle, to map the (l, v) plane of a spiral pattern back into real space we need to model the arms kinematics (to allow us to convert observed velocities to diatances). Somemwhat fortuitously, modelling the kinematics using circular orbits tends to actually enhance the spiral pattern obtainde in real space making it relatively easy to detect the spiral features!

[2]However, there is a finite range of velocity corresponding to an infinite range in radius outside of the Solar circle. Even small errors in velocity can therefore lead to large errors in distance.

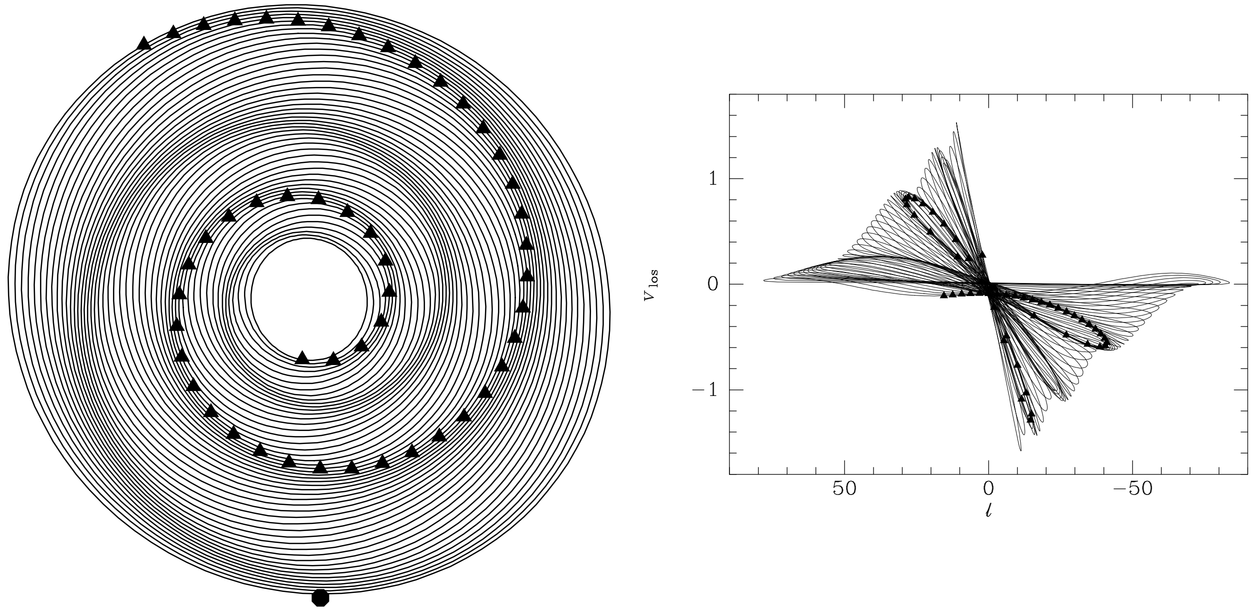

Figure 8: Geometry of a disk of material in circular rotation.

3 The Nucleus

The Galactic nucleus remains one of the most poorly undertsood regions of the Galaxy, mostly because it's i) small, ii) highly obscured and iii) has a lot going on. Recent work is beginning to really constrain the nature of whatever is at the very center though. This is good because active galactic nuclei (accreting supermassive black holes) produce far more energy than all of the stars produced in galaxies and recent work suggests that this energy is actually crucial in shaping the formation and evolution of galaxies. Our own galactic nucleus is not at all active though—it's actually very quiet (surprisingly quiet!). A brief inventory of the contents of the Galatic center looks like this:

Sgr A* This is bright point of non-thermal radio emission which seems to be the dynamical center of the Galaxy.

Mini-spiral This is a spiral-shaped region of Bremsstrahlung emission from ionized gas near Sgr A* and extends over about 8pc. The source of the ionization is known as...

Sgr A West to distinguish it from the more extensive region of non-thermal emission known as...

Sgr A East which most likely arises from a shell of shocked gas being driven out into the ISM by SNe explosions, stellar winds or some other process.

Nuclear molecular ring Observations of molecular lines of HCN show a ring of molecular gas that extends to about 7pc from Sgr A*. The ring clearly doesn't lie in the plane of the Milky Way as we see it clearly as a ring. It has been modeled as being in circular rotation at a velocity of 100km/s inclined at 65°.

The ionization within this nuclear ring comes from an unusual cluster of stars whose center lies within 0.04pc of Sgr A* and has a half-mass radius of about 0.5pc. This cluster seems to contain many young, hot stars suggesting a period of star formation only 10^7yr ago. (Alternatively, these could be older stars which have been significantly modified by mass exhange during collisions with other stars.)

Sgr A* itself is a non-thermal radio source with a size less than 2.5AU. Most likely it is a supermassive black hole. Recently, two groups (led by Reinhard Genzel and Andrea Ghez) have measured the orbits of stars which pass very close to Sgr A*. These orbits constrain the mass of the object to be about 2–3$\times 10^6 M_\odot$. Of course, the Schwarchild radius of a black hole of this mass would be only 2×10^{-7}pc, much smaller than the radii of the orbits which have been measured (which go down to $\sim$ 0.01pc). So, this could in principle be an extended mass distribution and not a black hole.

However, we can actually constrain the mass of Sgr A* dynamically. Due to the high stellar density around Sgr A* relaxation times should be short and Sgr A* and the surrounding star cluster should be in equilibrium and therefore have reached equipartition of energy. Therefore, the velocity of Sgr A* should be drawn from a Maxwellian distribution with dispersion equal to $\sigma_{\rm cl}\sqrt{M_*/M_{A*}}$ where $\sigma_{\rm cl}$ is the velocity dispersion of the star cluster, M_* the mean mass of a star in that cluster and M_{A*} the mass of Sgr A*. While we can't measure the radial velocity of Sgr A* (no lines in its spectrum) its proper motion can be measured and is $v_\perp = -11.6 \pm 8.9$km/s, i.e. vanishingly small. This suggests a mass of at least $10^4 M_\odot$ (since $\sigma_{\rm cl} = 1150$km/s.