Measuring gravitational redshift in galaxies in the WHISP database

Stefan Wijnholds

May 16, 2001

Contents

Chapter 1

Introduction

1.1 About the project

As light travels from the center of a galaxy it loses energy, so that by the time it escapes it has been redshifted and appears as if Doppler shifted by a velocity of $-\Phi/c$ (assuming that the potential Φ is defined with its zero point at infinity). Thus, even after the galaxy's light has been projected along the line of sight, it will still display a small velocity shift which increases towards the center.

Clearly this effect is quite small; one needs to determine the mean velocity to about 1% of the velocity dispersion. Some evidence for this effect was demonstrated on a statistical basis by Stiavelli and Setti (1993), who took long-slit data for 24 objects from the literature and found evidence for redshifted cores in 12 of them, while only one core appeared blueshifted. Although this numerical asymmetry is suggestive, the data are not good enough to give information on any one case.

In this project an attempt will be made to see the gravitational redshift signature in archival radio data such as the WHISP database. Radio data has the advantage of inherently good velocity resolution. The spatial resolution, however, is only moderate (about 13 arcsec).

In both radio and optical approaches it is assumed that the kinematics far outside the center of the galaxy are dominated by the global dynamics and that those parts are sufficiently "well-behaved" to determine the systemic velocity. Material close to the center will exhibit a small additional redshift. Unfortunately, this is also where rapidly rotating disks, black holes and other unpleasant features (in view of this project) are likely to be found.

If there is the opportunity to do so, the radio data and the results obtained by them will be compared to archival optical data.

1.2 Acknowledgements

First of all I wish to thank Nigel Douglas for the useful discussions, nice cooperation and being my supervisor during this project. I also wish to thank Thijs van der Hulst for his suggestions, Rense Boomsma for helping me getting started with GIPSY and Martin Vogelaar for providing me some in depth knowledge of GIPSY and for removing an old restriction on the amount of data the program could handle.

Chapter 2

Theory

2.1 Gravitational redshift

When a photon escapes from a gravitational potential, it loses energy causing it to be redshifted. This redshift z can be calculated using

$$z(\vec{x}) = -\Phi(\vec{x})/c^2 \tag{2.1}$$

where $\Phi(\vec{x})$ is the gravitational potential at the point $\vec{x}$ where the photon is emitted and c denotes the speed of light. This formula assumes $\Phi(\infty) = 0$.

2.1.1 Gravitational potential in spiral galaxies

Binney and Tremaine (1988) describe two different models for spiral galaxies. The first is the Plummer-Kuzmin model, which can be described by

$$\Phi(R,z) = -\frac{GM}{\sqrt{R^2 + (a + \sqrt{z^2+b^2})^2}} \tag{2.2}$$

where a and b are free parameters. For cylindrical and spherical coordinates I will use the convention introduced by Binney and Tremaine. The radial coordinate in cylindrical coordinates will be denoted by R, while the radial coordinate in spherical coordinates will be denoted by r. When using cylindrical coordinates I will use z for the height. The central potential is

$$\Phi(R=0, z=0) = -\frac{GM}{\sqrt{(a+|b|)^2}} \tag{2.3}$$

The second case described by Binney and Tremaine is the logarithmic potential

$$\Phi(R,z) = \frac{1}{2}v_0^2 \ln{(R_c^2 + R^2 + \frac{z^2}{q^2})} + constant \tag{2.4}$$

where R_c and v_0 are constants and $q <= 1$ is the axial ratio of the galaxy. In this case the central potential is

$$\Phi(R=0, z=0) = \frac{1}{2}v_0^2 \ln R_c^2 + constant \tag{2.5}$$

2.1.2 Gravitational potential in elliptical galaxies

Walter Dehnen (1993) has described a family of density profiles for elliptical galaxies:

$$\rho(r) = \frac{(3-\gamma)M_{tot}}{4\pi}\frac{a}{r^{\gamma}(r+a)^{4-\gamma}} \tag{2.6}$$

In (2.6) a is a scaling constant which is equal to the effective radius multiplied by a factor which has different values for different models. The models by Jaffe (1983) and Hernquist (1990) take $\gamma = 2$ and $\gamma = 1$ respectively.
In the model by Hernquist, the potential is given by

$$\Phi(r) = -\int_r^{\infty} \frac{GM(r')}{r'^2}dr' = -\frac{GM_{tot}}{a+r} \tag{2.7}$$

where a is taken as

$$a = \frac{r_e}{1+\sqrt{2}} \tag{2.8}$$

In this case the central potential is therefore given by

$$\Phi(r=0) = -\frac{GM_{tot}}{a} = -\frac{(1+\sqrt{2})GM_{tot}}{r_e} \tag{2.9}$$

When assuming a Jaffe model, one finds

$$\Phi(r) = \frac{GM_{tot}}{a}\ln\frac{r}{r+a} \tag{2.10}$$

for the potential where $a = \frac{r_e}{0.763}$. In this case the central potential is

$$\Phi(r=0) = -\infty \tag{2.11}$$

2.2 Integration along LOS

In most cases however one will not measure the true central potential because one is integrating along a line of sight. The extent of this effect can be estimated by taking the intensity weighted mean redshift along a line of sight:

$$z = \frac{\int z(\vec{r})I(\vec{r})d\vec{r}}{\int I(\vec{r})d\vec{r}} = \frac{\int z(\vec{r})\rho(\vec{r})d\vec{r}}{\int \rho(\vec{r})d\vec{r}} \tag{2.12}$$

where it is assumed that the mass-to-light-ratio is constant and $\vec{r}$ is a position vector which describes the line of sight. The integral can be calculated for different models using the geometry shown in figure 2.1.
From the figure it can be seen that $r(x,\theta) = x/\cos\theta$, where x is the distance from the center of the galaxy to the line of sight. The integral can now be evaluated using

$$z_{meas}(x) = \frac{\int_{-\pi/2}^{\pi/2} z(x/\cos\theta)\rho(x/\cos\theta)d\theta}{\int_{-\pi/2}^{\pi/2}\rho(x/\cos\theta)d\theta} \tag{2.13}$$

Figure 2.2 shows the results of this calculation for galaxies obeying the various models described above. All galaxies have a mass of $10^{11}M_{\odot}$. From these plots it can be seen that as a result of the concentration of mass towards the center the integration along the line of sight only makes a small difference.

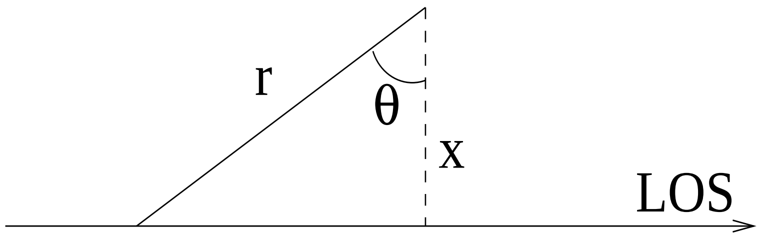

Figure 2.1: Geometry used for calculation of redshift integrated along the line-of-sight.

2.3 Beams of various diameter

Another possible source of problems is the finite resolution of the data. This means that the beam has a certain extent. Therefore the data contained in a beam is not coming from a point, but from a projected area. Integrating over a cylinder with radius r_{beam} and the line-of-sight $\vec{x_0}$ along its axis gives

$$z_{beam}(x_0, r_{beam}) = \frac{\int_0^{2\pi} \int_0^{r_{beam}} \int_{-\pi/2}^{\pi/2} z(\vec{x}/\cos\theta)\rho(\vec{x}/\cos\theta)d\theta dr d\phi}{\int_0^{2\pi} \int_0^{r_{beam}} \int_{-\pi/2}^{\pi/2} \rho(\vec{x}/cos\theta)d\theta dr d\phi} \tag{2.14}$$

where $\vec{x} = \vec{x_0} - \vec{r}$ and $\vec{r}$ is a function of ϕ and r, the distance from x_0. Since the gravitational redshift is most likely to be measured along a line-of-sight close to the center of the galaxy, $\vec{x_0} = 0$ was assumed. Even then the calculation turned out to be very tedious. Therefore a first approximation to (2.14) was made by assuming axial symmetry around the line of sight. Together with $\vec{x_0} = 0$ one obtains

$$z_{beam}(r_{beam}) = \frac{\int_0^{r_{beam}} \int_{-\pi/2}^{\pi/2} z(x/\cos\theta)\rho(x/\cos\theta)2\pi x d\theta dx}{\int_0^{r_{beam}} \int_{-\pi/2}^{\pi/2} \rho(x/\cos\theta)2\pi x d\theta dx} \tag{2.15}$$

where x and θ should be interpreted as shown in figure 2.1.
The results obtained by the resulting calculations are shown in figure 2.3. From this plot it can be seen that the beamwidth causes a reduction by only a minor fraction when looking at a line-of-sight through the center of the galaxy.

2.4 Detectability of the effect

The theoretical values of the gravitational redshift effect are displayed by the red lines in figure 2.2. If the effect is as small as shown in these plots, it will be undetectable. However, if the distribution of mass in stronger concentrated towards the center i.e. the scale length is shorter, the effect gets much stronger, as is illustrated by the extreme case of the Jaffe model. Furthermore the effect is linearly dependent on the total mass of the galaxy.
In view of these considerations the effect may be detectable after all. For example UGC 6132 has $M_B = -22.41$ giving $M_{tot} = 1.4\ 10^{11}$ $M_\odot$ assuming $M/L = 1$, but M/L might be as high as 50 (Shaya e.a. (2000), Bahcall e.a. (2000)). It also has $R_s = 2.18$ kpc instead of about 3 kpc. Therefore gravitational redshifts in the order of 50 km/s are not unreasonable even when one takes the beamsize effects discussed in the previous section into account, but in

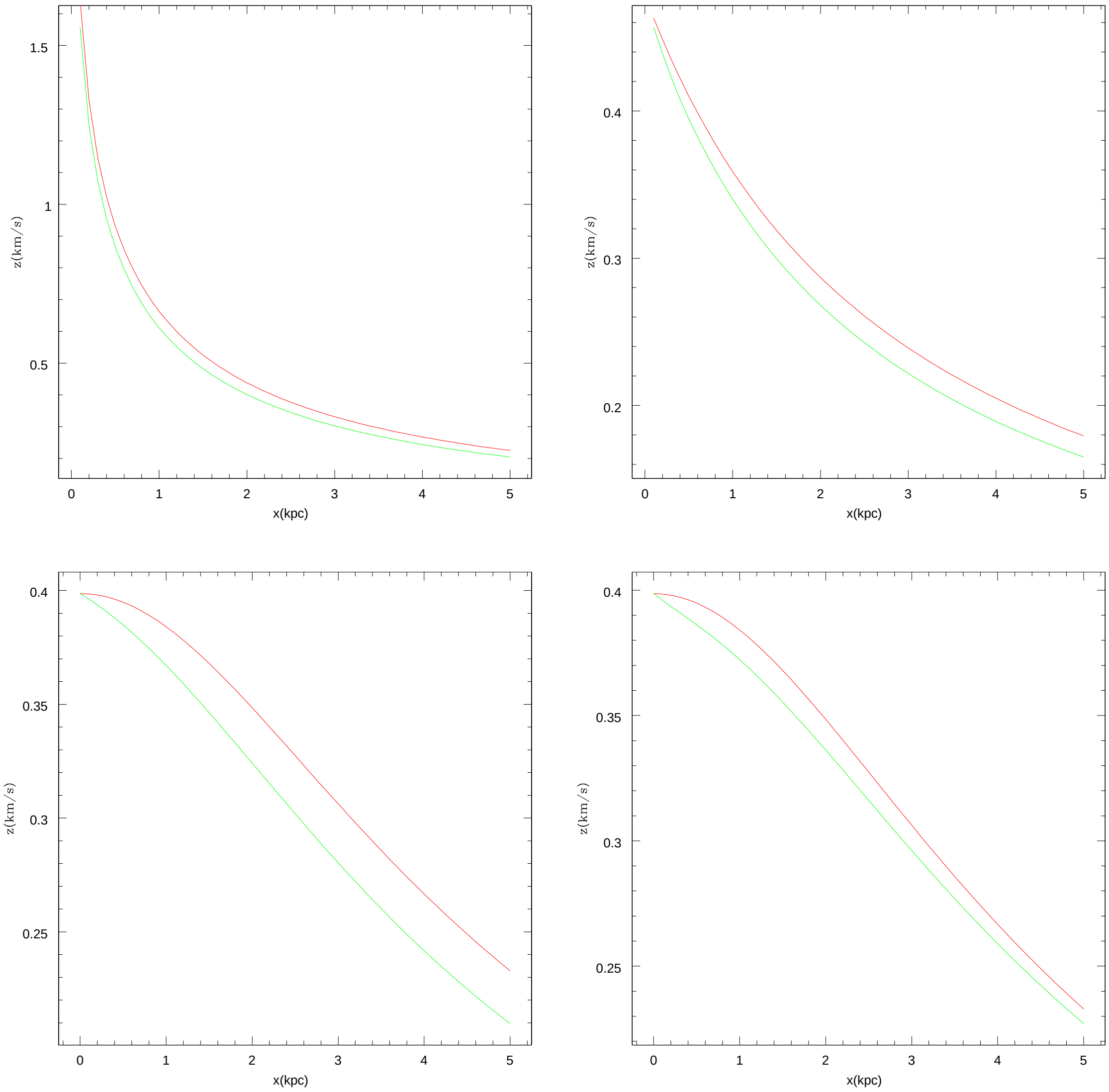

Figure 2.2: These plots show the effect of integration along the line of sight by showing the gravitational redshift (z) against projected distance from the line of sight to the center of the galaxy (x) . The upper left plot shows the result for the Jaffe model with $a = 3$kpc, the upper right plot is based on the Hernquist model for $a = 3$kpc, the lower left plot shows the result for a spiral galaxy conform a Plummer-Kuzmin model for $a = 3$kpc and $b = a/5$ seen edge-on and the lower right plot shows the result for the same spiral galaxy seen face on. All galaxies have a total mass of $10^{11}\mathrm{M}_\odot$. The red lines show the theoretical values, while the green lines represent the values obtained after integration along the line-of-sight.

most cases the effect will be in the order of 10 km/s. This is hard to detect, but might be found on a statistical basis.

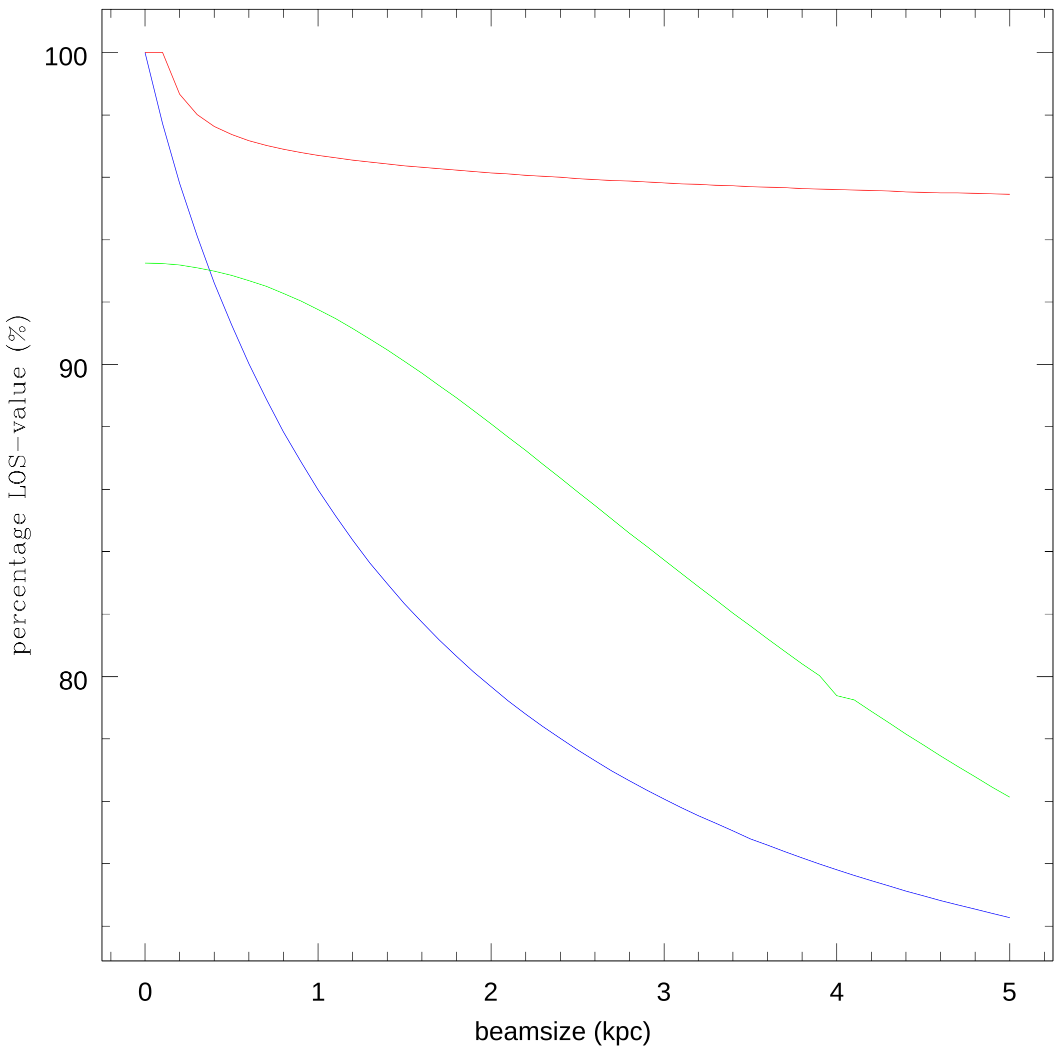

Figure 2.3: Plot showing the effect of beamsize for a Jaffe model (red line), a Hernquist model (blue line) and a face-on spiral following a Plummer-Kuzmin model (green line). All models use a scale length of 3 kpc and a mass of 10^{11} $M_\odot$. The Jaffe model has been cut off at 0.1 kpc because it has a singularity in the center.

Chapter 3

Analysis of WHISP data

3.1 Introduction

The aim was to see the effects of gravitational redshift statistically. This effect is very small as pointed out in the previous chapter. Therefore data with a good velocity resolution was necessary. This was the main reason for using data from the WHISP database in spite of its poor spatial resolution. Another advantage of this data was its availability at the Kapteyn Institute.

While I was working through the data of the galaxies in the sample given below, Nigel Douglas tried to find and analyze some optical data of these galaxies. A proposal to obtain observing time for gathering optical data for a few promising candidates at the VLT was not successful, and observing strategies are being reconsidered.

This chapter describes how candidates were selected from the WHISP database and how the reduction from the radio data was done. The results obtained from the radio data as well as from the optical data are given in the next chapter.

3.2 Selection of candidates

First a selection had to be made from the WHISP database[1]. A first selection was made based on total HI mass, since a high signal-to-noise ratio was necessary to be able to use the highest possible spatial resolution. Furthermore the gravitational redshift is most likely to be detected in the more massive galaxies which are in turn likely to have a high HI mass, although there isn't a one-on-one correspondence between a high total mass and a high HI mass. The WHISP database contains 11 galaxies with a total HI mass over 2×10^{10} solar masses. These are listed below.

[1] See *http://www.astro.rug.nl/˜whisp/cgi-bin/make_xy_list.cgi* for a complete listing of the WHISP database

name	type	HI mass ($10^8 M_\odot$)
UGC 1810	SAb	400.8
UGC 1886	SABbc	243.8
UGC 2855	SABc	289.0
UGC 3334	SABc	367.0
UGC 5253	SAab	475.0
UGC 5316	SBd	224.0
UGC 5931	SABcd	349.4
UGC 5935	IBm	349.4
UGC 6944	SAm	220.1
UGC 9797	SBb	1309.0
UGC 9805	SAb	207.8

Since the gravitational redshift will be derived from kinematic data, it is highly preferable to analize only those galaxies having "regular" velocity fields, i.e. no too obvious kinematic disturbances and no neighbours so near that the HI clouds start to overlap. These considerations led to the rejection of UGC 5931, UGC 5935 and UGC 6944 after an inspection of these galaxies on the WHISP homepage. This also led to the rejection of UGC 9805, since its total mass turned out to be only 82.6 10^8 $M_\odot$. Finally, after the velocity fields were created and a tilted ring model was fitted as described below, UGC 5316 turned out to have some kinematic disturbance and was therefore rejected afterwards, leaving a sample of six galaxies.

3.3 Measurement

3.3.1 Procedure

The gravitational redshift was measured by comparing the systemic velocities at different distances from the center. The first idea was to take the average over all points of a velocity field in a certain ring around the center. The result should be the average of all the points at that specific distance from the center, since a redshifted point on one side of the ring is "compensated" by a blueshifted point on the other side. Since points containing too little signal to be a reliable data point are marked as blank and these points are not symmetrically distributed around the center, this idea turned out to be very sensitive to the presence of blanks. Therefore a decision was made to fit a tilted ring model to the data.
All measurements were done using the Groningen Image Processing System[2] (GIPSY). A detailed description of the most important packages from the view of this project, can be found in the Appendix. A detailed description of the way in which the measurements were done, is given below.

1. View the galaxy with `VIEW INSET=u<UGC number>cl f RECORD=y`. After entering the clipping levels (the values suggested by GIPSY will do in this case), GIPSY will open a new window (GIDS) and start loading the (RA,DEC)-planes of the data-cube in sequence. GIDS offers some useful tools to study the data such as zooming, making slices through the cube, etc. These options should be used to get a notion of the parameters needed later.

[2] *http://www.astro.rug.nl/~gipsy*

2. Read the header of `u<UGC number>mask60` using `HEADER`. This program will ask for the file of which the header should be shown. The filename should be entered without the extension. Use the information shown to find out which frequency range is covered by the mask file (the mask file covers only the frequency range which is relevant to the galaxy).

3. The mask file is made using the data cube smoothed at 60 arcsec, which has a high signal-to-noise ratio, but poor resolution. Because of the lower resolution, the galaxy covers far less pixels then on the high resolution maps. Therefore the mask file needs some rescaling before it can be used to filter the high resolution map. This is done by using `REPROJ`. First `REPROJ` will ask for the file to be rescaled. This is `u<UGC number>mask60`. After entering the box to be rescaled (rescale the entire subset), `REPROJ` will ask for a data set conform which the rescaling should be done. In this case rescaling should be done conform `u<UGC number>cl`. Since the dimensions should be equal, enter `u<UGC number>cl f <frequency range covered by mask file>`. After giving a filename for the output, `REPROJ` will ask for the scale of the box used for interpolation and how the interpolation should be done. `REPROJ` offers two options for interpolation, bilinear interpolation or using the value of the nearest pixel. A decision was made to use the bilinear interpolation, since this is probably the most realistic way to assign a value to a pixel lying on the border of two pixels of the old grid. This, however, doesn't matter when creating a mask file.

4. After rescaling the mask file to fit to the data, `CONDIT` was used to filter the data such that the points corresponding to data values in the mask file were transferred to the output set, while the points corresponding to the blanks in the mask file were blocked. This can be done the following way. First enter the data set (`u<UGC number>cl f <frequency range covered by mask set>`) taking as box the entire subset. Then enter the mask set and enter a box which *exactly* fits the data set.

5. The next step is to create an intensity weighted mean velocity map. This can be done using `MOMENTS` with `INSET` equal to the result of the previous step. After the standard questions `MOMENTS` will ask for the range of data values to be used. If a data point has another value than the range of values entered here, it will be regarded as blank. This range was set to `0 INF`, since if the value is negative, it may cause problems calculating the intensity weighted mean ($\sum I$ can become negative or zero, giving unwanted results), while it is 100% sure that that point contains mainly noise ("normal" intensities are positive). No window was used.

6. Since `ROTCUR` takes a point into account only when the center of that point lies within the specified ring, `REPROJ` was used again to project the velocity field made in the previous step on an even finer grid assigning values to the pixels on the new grid using bilinear interpolation on the pixels of the old grid. The result is a velocity field which looks exactly identical, but in which each data pixel covers, for example, 5 by 5 grid pixels, which forces `ROTCUR` to use at least part of a data pixel if its center lies outside the specified ring.

7. Before using `ROTCUR` check the units of the velocity field using `HEADER`. If the units are given in Westerbork units (`'W.U.'`), `ROTCUR` won't be able to convert them to km/s and will come to a halt. If this problem occurs, it can be solved using `FIXHED`.

8. Before `ROTCUR` is started one should have estimates of the position angle (the angle between the north direction on the sky and the major axis of the receding half of the galaxy taken in the anti-clockwise direction) the inclination, the position of the center, the systemic velocity, the expansion velocity and the rotational velocity. If there is more than one galaxy in the field, one might want to find a box which contains only the galaxy of one's interest. Most of these things can be estimated from the velocity field, which can be viewed using `VIEW`.

9. Start `ROTCUR`, enter the initial estimates and make a first fit. The center was given a fixed value using optical data. When the results show that another parameter, for example the inclination, turns out to be very constant over all rings, one may want improve the fit by repeating this step keeping the inclination fixed too.

During the reduction procedure, some velocity fields are created, which can also be used. Therefore one doesn't have to make a velocity field. A good reason to do it yourself is that the standard reduction procedures asks for a high-quality velocity map. If you don't have the best data possible this results in a velocity map containing about ten points, which is useless. If one wants more points, one has to use a velocity field of lower resolution. For this project a high resolution is quite important, so a high signal-to-noise ratio should be sacrificed for higher resolution.
Finally, GIPSY offers another way to make a velocity field, namely by fitting (skew-symmetric) Gaussians to the data. This is a powerful method if the data is very noisy, in which case the trick of neglecting the negative intensities results in large biases. It was chosen not to use this as the default procedure, since it is less physical.
Another way to get around the problem caused by the negative intensities is to use `MOMENTS` to create a total HI map and use this map to filter out all points with a very small or negative intensity. The resulting cube will only contain lines-of-sight with a clear signal, which can then be used to create a velocity field using `MOMENTS` without introducing biases by throwing away points with negative intensity. During the analysis of the data both options were used to obtain the best possible fit to the data.

3.3.2 Sample session

This section contains a sample session using UGC 9797 to illustrate the procedure described in the previous section. It should be possible to get similar results by typing the commands written in `typewriter font` on the GIPSY-prompt. This sample session was created using the software available on the Kapteyn Institute.

getting the data At the Kapteyn Institute one has to obtain WHISP data from tape.[3] This can be done by logging in on a machine with a tapestreamer and mounting the tapestreamer by typing `mt -f /dev/rmt/0mn status`. All tapes have the same file structure. The first six files are the fits-files containing the raw data from which the data cubes are created. To skip these files type `mt -f /dev/rmt/0mn fsf 6` meaning file search forward 6 files. The next two files are tar-files containing the data cube and the other files from the reduction process. To copy the files in the tar-files to the working directory type `tar -xvf /dev/rmt/0mn` twice. Finally, to unmount the tape type `mt`

[3]By the time this report is finished, the data will also be available on CD-ROM

`-f /dev/rmt/0mn rewoff` which means rewind, turn off and eject. After doing this, the working directory will contain all te necessary data files.

start GIPSY

view the data This can be done by typing

```
view inset=u9797cl f record=y
VIEW CLIP=
VIEW NEXT=
```

Note that nothing was entered after `VIEW CLIP=` and `VIEW NEXT=`. This means that the default values suggested by GIPSY were used in these cases. These are the full range of intensity values and "Y" (yes) respectively. In the rest of this section the notation `VIEW NEXT=[Y]` will be used to denote that the default value was used.

Note that GIDS uses another way to count the subsets than GIPSY. In GIDS the subsets have numbers from 1 to 63, while in GIPSY these numbers range from -31 to 31.

take a look at the header by typing

```
header
HEADER INSET=u9797mask60
```

In the header the range of values on every axis (RA, DEC and FREQ) can be found. In this case it turned out that the RA and DEC values ranged from -128 to 127 while FREQ values ranged from -13 to 15.

rescale the mask file using `REPROJ`:

```
REPROJ INSET=u9797mask60 f
REPROJ BOX=[entire subset]
REPROJ DEFSET=u9797cl f -13:15
REPROJ OUTBOX=[-512 -512 508 508]
REPROJ OUTSET=mask
REPROJ SPEEDMAT=[1 1]
REPROJ DATAMODE=[B]
```

The additional specification of the subsets entered after `REPROJ DEFSET=u9797cl f` is not strictly necessary and can be omitted. The result is the file `mask` which contains a mask at the same resolution as `u9797cl`.

filter the data using the mask file

```
condit
CONDIT INSET=u9797cl f -13:15
CONDIT BOX=[entire subset]
CONDIT MASKSET=mask f
CONDIT MASKBOX=[D 512,512]
CONDIT CPOS=0 0
CONDIT OUTSET=u9797masked
CONDIT RGMODE=[T]
CONDIT RANGE=[All values]
CONDIT BLMODE=[B]
CONDTI BLOCKVAL=[blank]
```

Note that the default for `MASKBOX` is `[D 512,512]`, which means that the box should have a length of 512 grid spacings along the RA-axis as well as along the DEC-axis. If this default is used, the next question will be to give the center (CPOS).

create a velocity map using MOMENTS

```
MOMENTS INSET=u9797masked f
MOMENTS BOX=[entire subset]
MOMENTS OPTION=[List options]
MOMENTS OPTION=1
MOMENTS OUTSET=velfield
MOMENTS RANGE=0 INF
MOMENTS WINDOW=[0, i.e.  no window]
```

When first prompted for OPTION the list of options was requested. GIPSY returns this list after which an option can be chosen. Option 1 gives the intensity weighted mean in the profile.

view the velocity map by typing

```
view
VIEW INSET=velfield p
VIEW CLIP=[3204.61,3642.41]
```

Since the third axis is now a parameter axis instead of a frequency axis, it is now called PARAM and therefore one should type a "p" instead of an "f".

rescale the velocity map using REPROJ again

```
REPROJ INSET=velfield p
REPROJ BOX=-80 -80 80 80
REPROJ DEFSET=[manual input]
REPROJ ROTATEONLY=[N]
REPROJ OUTPOS=[copy from input map]
REPROJ CDELT=1 1
REPROJ CHANGE=[Y]
REPROJ SKYSYS=[copy from input map]
REPROJ EPOCH=[old:  1950]
REPROJ PROSYS=[copy from input map]
REPROJ CROTA=[from input map]
REPROJ OUTBOX=[-400 -400 400 400]
REPROJ DIMINISH=[Y]
REPROJ OUTSET=velmap
REPROJ SPEEDMAT=[1 1]
REPROJ DATAMODE=[B]
```

The aim here is just to get a finer grid instead of rescaling conform another file. Therefore manual input is needed. Most things can just be copied from the input map. CDELT gives the new grid spacing in arcsec. In this case a grid spacing of 1 arcsec is chosen in both directions. Since the first number had a negative value in the original file, REPROJ asks whether this sign should be changed. By answering "Y" (yes) the velocity field is prevented from flipping.

Since the original grid spacing was about 5 arcsec in both directions, the new grid will have 5 times as many points in both directions. This is already calculated by GIPSY,

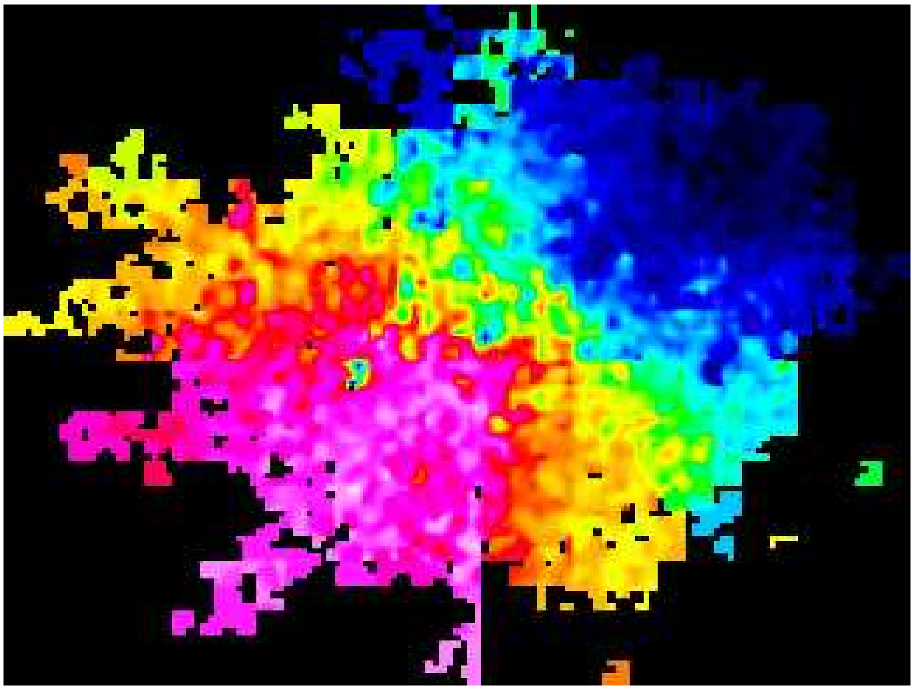

Figure 3.1: The resulting velocity field after zooming on the main galaxy. Note that there is more hydrogen detected on the redshifted side of the galaxy than on the blueshifted side.

so one can just use the default for OUTBOX.
After this step you should have obtained a velocity field that looks like the one in figure 3.1.

fit a tilted ring model using ROTCUR

```
ROTCUR INSET=velmap
ROTCUR BOX=[whole map]
ROTCUR RADII=1 2 3 5:200:5
ROTCUR WIDTHS=2 2 3 5
```

This defines three inner rings with a radius of 1, 2 and 3 arcsec and a width of 2, 2 and 3 arcsec respectively. The other rings, starting with a ring of radius 5 arcsec and ending with a ring of radius 200 arcsec and a spacing of 5 arcsec all have a width of 5 arcsec. The next fields provide initial estimates for the fitting procedure.

```
ROTCUR VSYS=3392
ROTCUR VROT=20 40 70 100 150 200
ROTCUR VROT=
ROTCUR VEXP=0
ROTCUR VEXP=
ROTCUR PA=135
ROTCUR PA=
ROTCUR INCL=48.6
ROTCUR INCL=
ROTCUR CENTRE=0 0
```

The initial estimate for the center is set to [0 0]. This is based on the fact that the telescoop has been aimed in such a way that the galaxy of interest is found right in the center. The exact location expressed in fractional pixels will probably not be exactly (0,0). Since the chosen grid is finer than usual, deviations should be expected.

`ROTCUR FREEANGLE=0`

This is the angle around the minor axis within which points are neglected. One may be willing to use this option if one has an almost edge-on galaxy, since the measurement becomes very sensitive along the minor axis in that case.

```
ROTCUR SIDE=[BOTH]
ROTCUR WEIGHT=UNIFORM
ROTCUR FIXED=[NONE]
```

The fit will be made by using data from both sides of the galaxy, a uniform weighting function and no parameters fixed.

`ROTCUR FILENAME=[rotcur.02]`

`ROTCUR` keeps track of the filenames already in use, so using the default is a save option. Furthermore the extensions form a sequence. The next time `ROTCUR` is used, it will propose `rotcur.03`. Using this therefore results in a kind of history of the fitting process. The contents of the file `rotcur.02` are listed in appendix A.

3.3.3 Finding the center

The crucial point in the procedure described in the previous sections is fixing the center at the right position. In principle it should be possible to obtain this position from the data, since the center is one of the parameters of `ROTCUR`. This however turned out to be quite troublesome, as can be seen from the data from the sample session shown in appendix A. The inner rings are fitted based on only a few points, while the number of parameters is quite large. This leads to large and even non-physical errors. The outer rings do have a usable accuracy, but don't agree with each other.

The next attempt involved the total HI map of the galaxy. Assuming that the HI distribution follows the overall mass distribution of the galaxy, an attempt was made to find the center by finding the centroid of the HI map. This gave even poorer results, because some galaxies clearly have an asymmetrical HI distribution. Therefore this method was also rejected.

Finally a decision was made to use the optical center, since the optical center can normally be determined with a high accuracy. The positions of the optical center could be obtained from the NASA Extragalactic Database[4] (NED) and from Cotton e.a. (1999). Although there are slight differences between the positions mentioned in these sources, the results obtained are quite similar, as is illustrated by the plots in figure 3.2. Therefore only the results obtained by using the positions given by Cotton e.a. will be shown in the next chapter.

3.3.4 Discussion

The key point in the measurement was that it should involve as little modeling as possible. Therefore the most ideal situation would be to calculate the average velocity of pointsymmetric rings of different radii. Unfortunately, the distribution of blanks is mostly not pointsymmetric, which makes fitting a better method since blanks are less disturbing. This method however has its own disadvantages which are pointed out below.

[4] *http://nedwww.ipac.caltech.edu/*

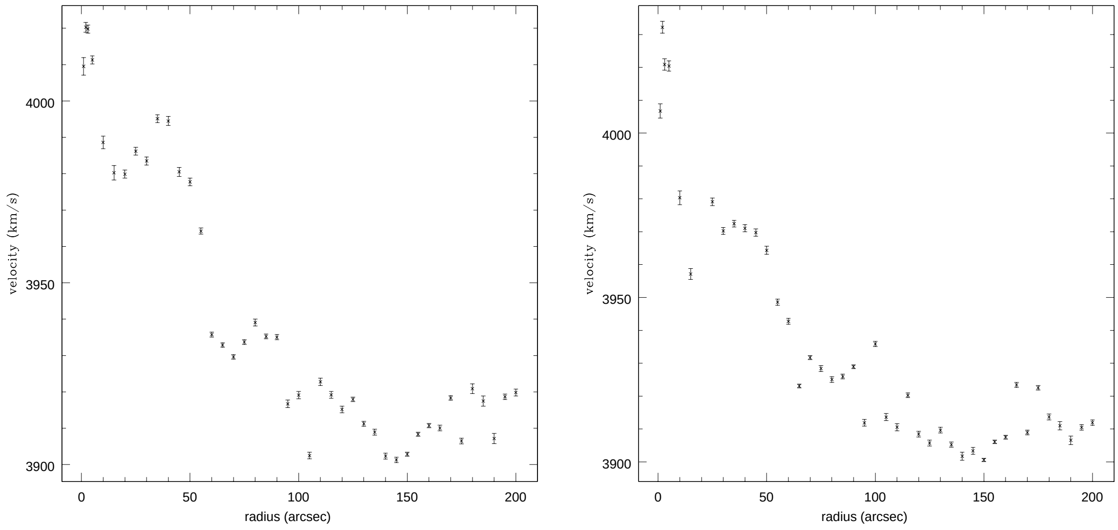

Figure 3.2: These plots show the systemic velocities of tilted rings at the given distance from the center of the galaxy for UGC 3334. The left plot is based on the position of the center given by NED, the right plot is based on the position given by Cotton e.a. (1999). Although some small differences may be noted when comparing the plots point by point, the results obtained may be regarded as being the same.

The mask file is created from the data file smoothed at 60 arcsec. This is basically the best way to create a mask file, since it has a high signal-to-noise ratio. The spatial resolution on the other hand is quite poor, which results in straight instead of curved boundaries between the galaxy and its background. Therefore there is probably more data thrown away then is strictly needed when applying the mask to the data cube. The data points which are potentially thrown away mostly lie on the edge of the galaxy. Although this effect may be important, especially along the frequency axis which contains only a few points, the effects on the final results will be quite small, because the fit is made over a lot of points. Therefore this is quite a small sacrifice for getting rid of over 99% of the noise in the data cube.

The process of cutting away the negative values in `MOMENTS` is more difficult problem, since this may lead to small biases, because only negative noise-values are cut away. On the other hand these are only a very small fraction of the points, since points lying within the galaxy have a certain intensity, which allows for a negative noise value at that point without that point being discarded as long as the overall value stays positive. Again, most of the points which are neglected will be points at the edges of the galaxy, but the edges can be edges along the frequency axis. Since the number of points along the frequency axis through the galaxy is very small at each (RA,DEC)-position, neglecting a point can change the intensity weighted mean considerably. But these are only changes in one specific point in the velocity field. As long as averaging is done over many points, these random variations will cancel out. The problem is that right in the center there are only very few points to take an average over. Therefore this effect can have bad effects in the center.

A possible way to avoid this problem is to filter the cube keeping only those lines of sight which have a certain amount of signal by using a total HI map as pointed out earlier.

A method which is less sensitive to these negative values is the fitting of (skew-symmetric) Gaussians. The disadvantage of this method is, that it assumes that the distribution of intensities in a galaxy along any line of sight has the form of a (skew-symmetric) Gaussian. It is therefore a function which can be fitted to any series of data points even if it is bare nonsense. Although there are good reasons to believe that it is reasonable to fit a (skew-symmetric) Gaussian, taking the intensity weighted mean relates closer to the physics.
An intrinsic property of much of the radio data in the WHISP-database is the poor spatial resolution. This may become problematic in this project, since its aim is to measure the systemic velocity on a line *close* to the center. This requires a high resolution in the center. This problem may be less severe as it seems since in most galaxies the intensity drops quickly when moving away from the center. If this drop-off occurs fast enough, the central pixels will be so strongly dominated by the light from the center that the intensity of the central pixels is mainly caused by the center of the galaxy and therefore resembles the properties of the center of the galaxy well, as was pointed out in section 2.3.
The discussion above naturally leads to questions about the errors in the measured values. GIPSY uses standard numerical techniques for making least squares fits and therefore returns the standard errors, which are one standard deviation. The real errors, however, will be larger than this, because there are also intrinsic errors in the velocity field caused by the measurement itself and the reduction procedure. Since it is hard to get an estimation of these errors, the best way to find them is probably to use different procedures to find the answer and look at the differences between the results.
These errors may cause less trouble in the final result. The aim of this project is to measure the redshift in the cores of galaxies. If, for example, 19 out of 24 galaxies do have a redshifted core, it can be stated statistically save that galaxies do have a redshifted core, despite the fact that one doesn't know whether the error in one's velocity measurements is 3 km/s or 5 km/s.

Chapter 4

Results

4.1 Results from radio data

The results obtained from the WHISP data are shown in figure 4.1. The plots show the systemic velocity as a function of the distance from the center according to the tilted ring fit.

4.2 Results from optical data

Nigel Douglas has been working on optical data. Assuming a symmetric rotation curve, his approach was to minimize the value of the symmetry parameter $Symm(r) = L(-r) + R(r)$ by varying the position of the center to r. $L(-r)$ and $R(r)$ are (a set of) the velocities at the same distance left and right from the center respectively when the center is shifted to r. At $r = 0$ the velocity should be equal to the systemic velocities derived from the outer parts. If the core is redshifted however, the velocity measured at $r = 0$ will be higher than this value.
Nigel Douglas has written a program which makes a fit to optical data of the outer parts of a galaxy using cubic splines or polynomials. This fit was used to interpolate between the data points which in turn was used to find the value of r which minized the value of the symmetry parameter.
The next step was to find optical archival data. Only UGC 1886 and UGC 5253 have optical and radio data in usable form. Unfortunately the quality of the optical data on UGC 1886 was not high, so UGC 5253 was the only galaxy usable for the optical as well as the radio approach. The optical data is shown in figure 4.2 as well as the best fit of an n=3 polynomial to the data found by Nigel Douglas. A redshifted core with $V_0 = 13.22$ km/s was found.

4.3 Conclusions

In this sample of galaxies only UGC 1810 shows a blueshifted center, while four show a redshifted center. The core of UGC 2855 seems neither redshifted nor blueshifted. Although the sample is quite small and the effect of gravitational redshift is so small that it is hard to rule out kinematic effects, this result is suggestive.
UGC 5253 is a very interesting case, since we were able to analyze radio as well as optical data. The optical data showed a redshifted core which was shifted by 13.22 km/s. The radio data also displays a redshifted core although the measured effect is about three times as large.

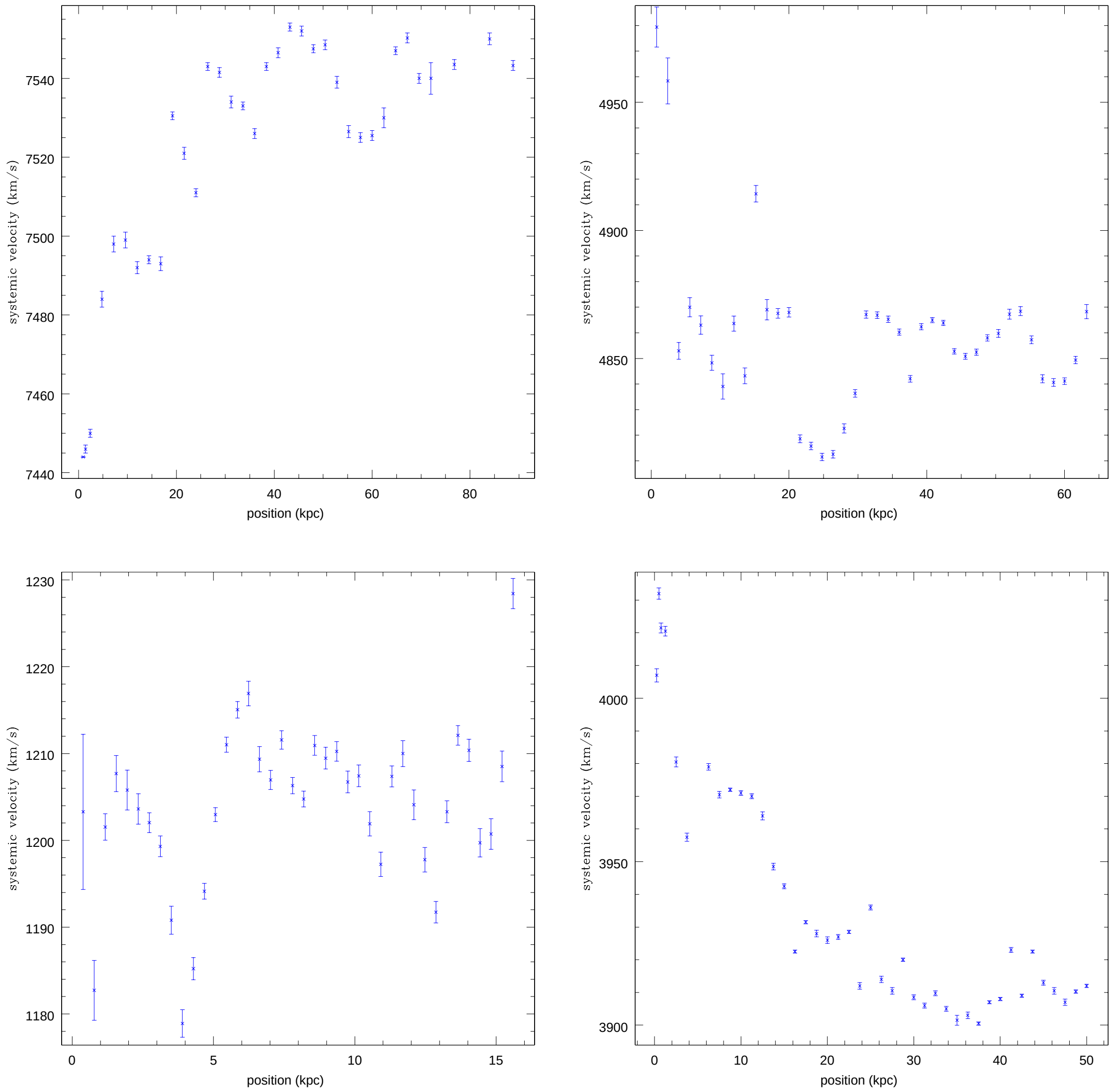

Figure 4.1: These plots show the systemic velocity at different radii according to a tilted ring fit for UGC 1810 (upper left), UGC 1886 (upper right), UGC 2855 (lower left) en UGC 3334 (lower right). *(continued on next page)*

Furthermore the peak drops off fast enough to make the effect of a gravitational redshift an explanation which can't be ruled out in advance.
There almost surely is a kinematic effect involved in the case of UGC 3334. Since the effect is very large (almost 150 km/s) and drops off only over many kiloparsecs, it is quite unlikely that this can be ascribed to a gravitational redshift only. The steep rise near the center may however be caused by gravitation, but it is clear that there should also be some kinematic effect involved here.
The errors in the plots are the 1σ-errors calculated in a standard least squares fitting procedure for a ring of that specific radius. The real errors however will be larger, since `ROTCUR` fits all the rings independent of the other rings, while in reality these rings are not independent,

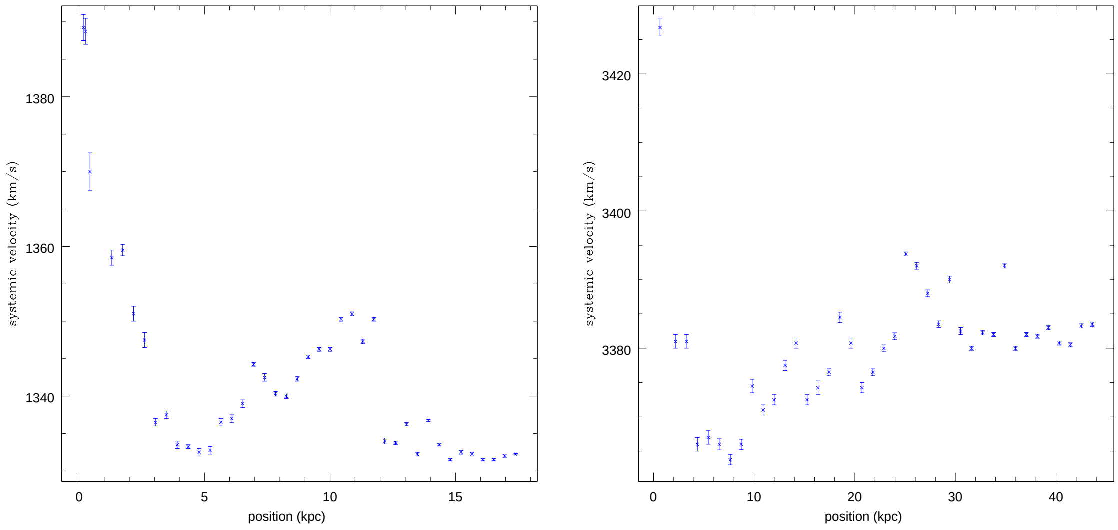

Figure 4.1: These plots show the systemic velocity at different radii according to a tilted ring fit for UGC 5253 (left) and UGC 9797 (right).

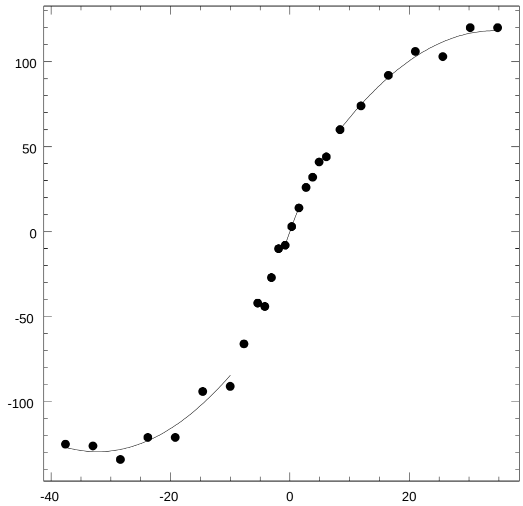

Figure 4.2: Interpolation function (n=3 polynomial with 7.3 points) superimposed on the velocity data for UGC 5253 (Héraudeau (1999)). The resulting best shift by $0.77''$ (curve is to be fitted by this amount to the left) corresponds to a redshifted core with $V_0 = 13.22$ km/s.

since they should all follow the same global kinematics. This puts an additional constraint on the fit which isn't applied here, because this would involve too much modeling. This should be kept in mind when assessing the errors.

Finally a note about the spatial resolution of the radio data. Binney and Merrifield (1998) give a criterion for the spatial resolution needed to make an accurate velocity profile of the galaxy; the scale length should be at least twice as large as the beamwidth. Given the beamwidth of

Westerbork of about $13''$, this means that only the data for UGC 2855 and UGC 5253 can meet this criterion.

Literature

Bahcall, N.A., Cen, R., Davé, R., Ostriker, J.P., Yu, Q., ApJ, **541**, pp 1-9, 2000
Binney, J., Tremaine, S., *Galactic Dynamics*, Princeton, Princeton U.P., 1988
Binney, J., Merrifield, M., *Galactic Astronomy*, Princeton, Princeton U.P., 1998
Cotton, W.D., Condon, J.J., Arbizzani, E., ApJS, **125**, 409, 1999
Dehnen, W., MNRAS, **265**, pp 250-256, 1993
Héraudeau, Ph., Simien, F., Maubon, G., Prugniel, Ph., A&AS, **136**, pp 509-514, 1999
Hernquist, L., ApJ, **356**, pp 359-364, 1990
Jaffe, W., MNRAS, **202**, pp 995-999, 1983
Shaya, E., Peebles, P.J.E., Phelps, S., Tully, R.B., IAU Colloquium 174, ASP Conference Series, Volume 209, p 445, 2000
Stiavelli, M., Setti, G., MNRAS, **262**, pp L51-54, 1993

Appendix A

Results from `ROTCUR`

The final output of `ROTCUR` as obtained after running through the sample session is shown on the next page. As can readily be seen from this output, some errors are quite large or even unphysical. Chapter 3 contains a more detailed discussion on these errors.

! radius (arcsec)	width (arcsec)	systemic velocity (km/s)	error (km/s)	rotation velocity (km/s)	error (km/s)	expansion velocity (km/s)	error (km/s)	pos. angle (deg.)	error (deg.)	incli- nation (deg.)	error (deg.)	x-pos. centre (grid)	error (grid)	y-pos. centre (grid)	error (grid)	npts	sigma velocity (km/s)
2.00	2.00	3399.15	0.00	0.00	0.00	-0.00	0.00	135.00	0.00	48.22	0.00	0.00	0.00	0.00	0.00	18	0.000
3.00	3.00	3423.71	4.14	40.94	4.72	-37.21	5.11	263.20	36.20	77.88	34.95	-2.31	0.36	-2.58	0.14	13	9.40
5.00	5.00	3411.28	3.63	142.27	6.21	-71.24	5.38	200.73	12.54	16.72	11.62	-0.72	0.47	-2.97	0.54	143	26.8
10.00	5.00	3389.71	1.91	87.14	2.71	0.42	6.03	180.21	4.06	63.32	3.56	-4.28	0.21	0.06	0.36	139	19.6
15.00	5.00	3372.38	1.46	257.83	999.99	340.62	999.99	85.54	999.99	8.21	259.67	-7.77	0.55	11.56	0.54	466	19.1
20.00	5.00	3364.20	1.51	200.53	999.99	292.42	515.24	72.38	222.14	13.10	46.74	0.28	0.62	6.67	0.61	612	21.9
25.00	5.00	3358.32	1.33	79.96	405.04	-30.39	148.29	166.06	84.97	55.63	26.89	2.49	0.67	1.03	0.60	440	21.2
30.00	5.00	3342.19	2.38	91.61	3.58	-11.97	3.52	162.56	1.37	82.57	1.37	13.44	0.27	-2.17	1.39	113	19.8
35.00	5.00	3357.53	1.29	51.05	8.74	-54.32	2.39	207.13	19.37	74.48	18.65	13.82	1.24	-5.38	1.22	290	28.3
40.00	5.00	3355.09	1.21	97.08	86.45	-62.39	15.07	175.97	34.40	44.82	20.35	6.00	0.82	3.91	0.96	902	22.6
45.00	5.00	3359.98	1.28	96.76	4.57	-43.01	6.12	170.47	3.40	62.65	2.64	9.14	0.63	-4.29	0.76	627	22.8
50.00	5.00	3384.70	1.37	100.65	1.31	-11.53	2.93	157.56	1.49	59.53	1.28	-9.26	0.66	-6.97	0.91	784	25.4
55.00	5.00	3385.36	1.40	129.84	1.36	-19.95	2.75	159.18	1.27	66.64	1.14	3.05	0.53	-14.85	1.01	687	22.3
60.00	5.00	3402.10	1.46	131.39	1.40	21.28	2.43	139.51	0.99	69.12	0.93	-5.40	0.83	-21.72	0.90	672	22.4
65.00	5.00	3399.96	1.52	133.73	1.48	17.45	2.50	141.51	0.94	70.92	0.89	-3.88	0.89	-19.11	1.01	664	23.4
70.00	5.00	3401.58	1.46	131.66	1.43	16.55	2.44	140.49	0.95	70.87	0.90	-6.34	0.96	-22.21	1.05	700	23.5
75.00	5.00	3369.30	1.06	159.69	3.61	-58.54	5.17	161.58	2.37	44.77	1.69	14.73	1.14	-19.91	0.81	1648	26.7
80.00	5.00	3392.83	1.26	163.42	1.32	19.10	2.91	130.65	1.19	51.27	1.01	-3.87	1.12	-25.77	0.90	1570	28.1
85.00	5.00	3399.64	0.92	168.86	1.36	34.77	2.23	121.07	1.04	51.29	0.88	-11.96	0.97	-20.18	0.57	1658	21.9
90.00	5.00	3400.62	0.85	169.65	1.46	27.79	2.28	121.69	1.06	56.41	0.91	-10.92	0.89	-19.06	0.53	1566	20.7
95.00	5.00	3405.49	0.91	171.85	1.11	22.42	2.19	122.80	0.87	59.94	0.76	-17.02	0.88	-22.42	0.62	1492	21.3
100.00	5.00	3408.36	0.85	170.15	1.46	19.19	2.81	126.80	1.08	57.00	0.88	-18.05	0.88	-29.50	0.70	1725	21.2
105.00	5.00	3404.23	0.85	169.39	1.16	17.72	2.50	125.43	0.92	59.28	0.77	-15.87	0.86	-27.96	0.71	1678	21.1
110.00	5.00	3404.45	0.82	165.46	1.08	16.73	2.34	127.06	0.89	60.86	0.76	-15.75	0.92	-26.90	0.69	1678	21.0
115.00	5.00	3409.48	0.76	179.86	1.27	9.12	2.43	132.47	0.97	60.32	0.81	-15.06	0.93	-26.30	0.63	1780	23.4
120.00	5.00	3406.54	0.76	181.07	1.43	3.94	2.70	134.38	1.02	61.48	0.83	-12.08	0.92	-21.11	0.65	1780	24.5
125.00	5.00	3403.27	0.82	174.62	1.03	13.62	2.34	129.93	0.85	55.73	0.70	-10.79	0.96	-18.10	0.92	2218	22.3
130.00	5.00	3382.61	0.84	177.89	0.83	-11.49	1.98	137.80	0.64	61.18	0.56	7.05	0.89	-2.17	0.81	1979	23.2
135.00	5.00	3391.72	0.76	181.72	0.76	1.32	1.83	134.62	0.62	61.06	0.54	-1.62	0.88	-13.48	0.81	2053	21.1
140.00	5.00	3392.11	0.72	182.94	0.70	4.57	1.66	134.94	0.54	62.37	0.48	1.39	0.84	-13.21	0.75	2035	19.6
145.00	5.00	3388.66	0.74	185.83	0.76	-2.33	1.84	136.84	0.60	60.62	0.51	5.15	0.87	-14.16	0.85	2205	20.6
150.00	5.00	3385.49	0.64	201.05	0.73	0.59	1.71	133.12	0.55	54.73	0.46	9.20	0.77	-7.2	0.80	2707	19.5
155.00	5.00	3387.52	0.59	196.83	0.65	-3.45	1.53	134.60	0.50	54.40	0.42	9.11	0.77	-14.67	0.76	2827	17.8
160.00	5.00	3391.90	0.56	200.48	2.05	0.60	3.18	134.76	0.93	48.54	0.67	-0.03	0.85	0.04	0.71	3319	22.0
165.00	5.00	3395.27	0.61	185.54	2.04	-4.96	3.30	136.81	0.97	51.61	0.71	-0.55	0.93	1.44	0.77	3222	27.1
170.00	5.00	3385.24	0.42	228.30	2.88	54.43	3.73	119.70	0.98	41.08	0.63	0.46	0.66	-4.69	0.64	3956	15.4
175.00	5.00	3384.54	0.39	214.71	3.36	75.83	3.65	112.49	1.03	41.92	0.65	-3.11	0.66	-6.38	0.61	4094	14.9
180.00	5.00	3383.29	0.46	239.37	5.67	53.08	4.26	118.91	1.57	38.04	0.99	1.73	0.90	-4.65	0.72	4417	18.8
185.00	5.00	3385.81	0.41	217.62	3.36	46.09	3.40	120.94	1.09	45.24	0.72	-2.78	0.77	-3.99	0.65	4097	16.2
190.00	5.00	3392.02	0.42	207.95	2.97	63.34	3.45	115.17	0.99	46.52	0.65	-9.24	0.73	-12.63	0.67	4099	16.9
195.00	5.00	3387.99	0.49	251.16	3.39	40.84	4.44	124.02	1.16	38.50	0.72	-6.94	0.92	-4.99	0.87	4727	19.6
200.00	5.00	3386.90	0.48	235.73	2.69	31.06	3.72	125.40	1.01	41.69	0.66	-4.52	0.91	-0.69	0.85	4551	18.8

Appendix B

Important GIPSY packages

The information in the following sections has been compiled from the GIPSY-homepage[1].

B.1 `REPROJ`

B.1.1 Purpose

Reproject a spatial map into another map with a different coordinate system.

B.1.2 Description

This program reprojects a spatial input set into another set with a different coordinate system. A coordinate system is specified by the following parameters:

projection center The projection center (PC) is the intersection point of the line of sight with the celestial sphere. The PC in physical coordinates is attached to grid coordinate (0,0). Together with the sky and projection systems, the grid spacing and the map rotation, it connects a physical coordinate system to a grid mesh.
A PC can be specified in the standard GIPSY way, i.e. in grid units, in galactic longitude and latitude in degrees, in ecliptic longitude and latitude in degrees and in supergalactic longitude and latitude in degrees. It is also possible to specify the grid center of the input map as the new projection center. This can be realized with 'AC' (axis center e.g. `OUTPOS=AC`). If the length of axis i is NAXISi and the reference pixel is CRPIXi, then the i-th coordinate is given by the expression NAXISi / 2 - CRPIXi.

grid spacing `REPROJ` converts only spatial maps. For each axis in a map it must be possible to convert a spacing in header units to seconds of arc. The sign of the grid spacing in longitude determines the direction of rotation. For equatorial maps with a negative grid spacing in longitude (RA), rotation will be counter-clockwise.

rotation angle For rotations of maps where sky and projection systems are fixed, use `ROTATEONLY=YES`. Then the angle over which you want to rotate will be asked in `ROTANGLE=`. Otherwise the program will prompt you to give the new systems and the "header" rotation angle 'CROTA'. In both cases a rotation over x degrees implies a

[1] *http://www.astro.rug.nl/˜gipsy*

change in 'CROTA' with ± x degrees. 'CROTA' is defined for the input PC and thus the rotation center is always this input center.
For a rotation around a different center, program REPROJ has to run twice. The first time to change the PC, the second time to rotate the map. However, for maps which do not cover a too large fraction of the sky, and/or are not too close to a pole of the projection system, the result of a rotation is nearly independent of your choice of the rotation center. A rotation can then safely be performed around the default rotation center which is the original PC.

sky system and epoch

projection system

New values for these parameters are either given by the user or read from the header of the set in `DEFSET=`.

B.1.2.1 blanks

If a pixel at certain position in the input set is a blank, then the corresponding pixel in the output set will be set to blank. If a pixel in the output set corresponds to a pixel outside the box or frame of the input set, this pixel is set to blank also.

B.1.2.2 Interpolation of data (not positions)

For each grid position (integer x, y) in the output set a grid position (floating x', y') in the input set is calculated. The position (x', y') has distance dx, dy to the nearest pixel m_1. If dx and dy were both 0.0 then the pixel value of m_1 is returned. However, in most cases the values for dx and dy will not be equal to 0.0. Then the 3 closest neighbours are involved in an interpolation. If the pixel value at (x', y') is a blank, then a blank is returned to the output set. Else an interpolation is used to calculate the pixel value. Given 4 values m_1, m_2, m_3 and m_4 at positions (0,0), (1,0), (1,1) and (0,1) and two fractions $0.0 \leq dx \leq 0.5$ and $0.0 \leq dy \leq 0.5$, then there are a number of interpolation schemes depending on the number of blank pixels. If all pixels are non blank, a bilinear interpolation is involved. If the start pixel m_1 is blank then a blank is returned. If one of the other pixels is blank, the interpolation is in the plane of the pixels that are not blank. For two non blank pixels there is a linear interpolation. The number of blanks in a map will therefore not increase or decrease. If you change the values for the grid spacing, then only intensities will be conserved (not the flux!).

B.1.2.3 Interpolation of positions (the 'speed matrix')

For a 1000x1000 pixels map, a rotation over 45 degrees takes 63.3 cpu sec on a certain machine if all pixels were transformed. But if a 'speedmatrix' of 1000x1000 is used then the process takes only 14.4 cpu sec.

B.1.2.4 Reprojecting a map without a coordinate system

It is not possible to shift or rotate an arbitrary map without a valid coordinate system. You can fit such a coordinate system if you know the physical position of some grids in your map by using `ASTROM`. A coordinate system of an existing set can be changed by program `FIXHED`.

B.1.2.5 Rotation

Suppose i and j are grids in a map. Then the physical values are calculated using: $x = (i - CRPIX_i) \times CDELT_i$ and $y = (j - CRPIX_j) \times CDELT_j$ where CRPIX is the reference pixel (if CRPIX=1 then the first pixel is grid 0) and CDELT is the grid spacing. If ρ is equal to 'CROTA' (angle associated with the latitude-like axis) and l and m are the direction cosines, then: $l = x\cos(\rho) - y\sin(\rho)$ and $m = y\cos(\rho) + x\sin(\rho)$, where l is the longitude and m the latitude direction. ρ is an angle from the +y axis to the +x axis, i.e. counter clockwise if the grid spacing in longitude is less than 0.

B.2 `CONDIT`

B.2.1 Purpose

Transfer values if test value within certain range.

B.2.2 Description

Copy values in `INSET=` to `OUTSET=` under certain conditions. These conditions apply to data in a mask set called `MASKSET=` First, you have to select whether you want to use the `RANGE=` keyword to transfer data (`RGMODE=T`) or to block data (`RGMODE=B`) while copying `INSET=` Then you enter the range with `RANGE=`. A value in `MASKSET=` that is greater than or equal to the first value and smaller than or equal to the second value in `RANGE=` causes a transfer or a block (depending on `RGMODE=`) of a value in `INSET=`. If `MASKSET=` contains blank values, then transfer or blocking is set by a separate keyword `BLMODE=` If (`BLMODE=T`), data in `INSET=` will be transferred if the value in `MASKSET=` is a blank else it will be blocked. At positions where blocking was applied, usually a blank is copied. However, you can replace this value.

B.3 `MOMENTS`

B.3.1 Purpose

Program to calculate moments and other properties of a profile

B.3.2 Description

To calculate moments in profiles you first need to specify the set and the subsets. The number of subsets must be greater than 1 and less than 2048 and the subsets are specified by giving the name of the axis in the direction in which you want your profiles. The program will create a new set in which the axis along which the profile is taken has disappeared and is replaced by a new axis (`PARAM`)m which contains the subsets for the different profiles specified by the user. In general, the program will work for profiles in any direction and instead of velocity you could think of any kind of physical coordinate. The program inserts automatically the correct units in the header of the output set.
Use can be made of a cutoff in the data values. This is achieved by specifying a range in amplitudes with the keyword `RANGE=`. At the `RANGE=` keyword, the values `-INF` and `INF` can be input also. These values represent the minimum and maximum values of the current system. So, all values outside the range are set to blank and calculations are done on all non

blank values in a profile, except when a window was selected i.e. at the `WINDOW=` prompt a value greater than 0 was given.
If there are a certain number of adjacent subsets with amplitudes within the given range, and this number of subsets is greater than or equal to `WINDOW`, these subsets are taken into account. If this number of subsets is less than `WINDOW`, they are not taken into account. If there are more peaks with width equal to or greater than `WINDOW`, you have to select an operation mode. The default (`WINMODE=0`) selects the peak with the greatest flux and its data contributes to the statistics. If however `WINMODE=1` all valid peaks contribute to the statistics. In this mode, it is, for example, possible to exclude one pixel wide noise peaks from the profile with: `MOMENTS WINDOW=2 WINMODE=1` The program updates minimum, maximum, number of blanks and the units of the output at subset level and writes a comment, (source of header information and date) at set level.
Option 7 (intensity weighted Mode, only with WINDOW=0) is implemented as an alternative method of determining the (weighted) physical coordinate at the maximum in the profile. It uses the calculation of the 'mode'. For non-symmetrical profiles, the method should result in better approximations than the intensity weighted mean. The intensity weighted mode is calculated using the relation: skewness = (mean-MODE)/(dispersion) where mean, dispersion and skewness are the first, second and third weighted moments. The skewness is not part of the output of moments, but it can be retrieved using the above formula.

B.4 ROTCUR

B.4.1 Purpose

ROTCUR derives the kinematical parameters from the observed velocity field by fitting tilted-rings to the velocity field.

B.4.2 Description

This program does a least-squares-fitting to the function:

$$v(x,y) = VSYS + VROT\cos(\theta)\sin(INCL) + VEXP\sin(\theta)\sin(INCL) \tag{B.1}$$

where

$$\cos(\theta) = \frac{-(x - XPOS)\sin(PA) + (y - YPOS)\cos(PA)}{r} \tag{B.2}$$

and

$$\sin\theta = \frac{-(x - XPOS)\cos(PA) - (y - YPOS)\sin(PA)}{r\cos(INCL)} \tag{B.3}$$

Here $v(x,y)$ denotes the radial velocity at rectangular sky coordinates x and y, VSYS the systemic velocity, VROT the rotational velocity, VEXP the expansion velocity, INCL the inclination angle and θ the azimuthal distance from the major axis in the plane of the galaxy. θ is a function of the inclination (INCL) and the position angle (PA) of the major axis. XPOS and YPOS denote the position of the rotation center. This program will fit for each ring the parameters VSYS, VROT, VEXP, INCL, PA, XPOS and YPOS. Note that the position angle (PA) of the major axis is defined as the angle, taken in anti-clockwise direction between the north direction on the sky and the major axis of the receding half of the galaxy.