Chapter 14

THE MILKY WAY COMPARED TO EXTERNAL GALAXIES

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Abstract Kapteyn's work to map the Sidereal System was based on star counts. Now that we know that the Stellar System is comparable to many external spiral galaxies, this information can be used to further constrain models for the structure of our Galaxy. It is now possible to also use surface brightness distributions, both in the optical from the Pioneer spacecrafts and in the near-infrared with the COBE/DIRBE experiment. Star counts and surface photometry are discussed in a comparative sense. It turns out, that at least away from directions close to the Galactic center, surface brightness is dominated by the contribution from the disk, while faint star counts are dominated by the halo population. If low Galactic latitudes are ignored, surface brightness data can be used to constrain the parameters of the old stellar disk.

I repeat an earlier discussion in which older star counts are compared with current models for the distribution of stars in the Galactic disk. Herschel, in his famous *"Star Gauges"* of 1785, counted stars rather consistently to a visual magnitude of about 15. This is consistent with Herschel's own values for the *"gage or space penetrating powers"* of his telescopes and his *"extent of telescopic vision"*. Counts early this century by Kapteyn and van Rhijn seem to have significantly incorrect magnitude scales compared to the prediction of models, in the sense of being too bright by half a magnitude or more at photograpic magnitude 18.5. Yet, the counts are consistent across the sky and with limits on current parameters for the Galactic disk.

A discussion is given of the value of the exponential scalelength of the Galactic disk. A value of 4.5 to 5.0 kpc is still preferred in spite of smaller values from surveys in the near-infrared. Finally, I show that as far as structural parameters are concerned, NGC 891, 5033 and 5375 closely resemble the Milky Way Galaxy.

1. INTRODUCTION

Around 1990 the Kapteyn Astronomical Institute decided to start a preprint series[1] and we chose to display on the covers a picture of Kapteyn. Some of us were told privately and discretely by a few of our colleagues abroad (mostly in the US) that it was inappropriate to use this picture. After all, Kapteyn had been proven wrong in almost all respects; in spite of his (1909a,b,c) work on interstellar absorption he later chose to ignore the effect, while his model of the distribution of stars in space (Kapteyn and van Rhijn, 1920) and his description of the kinematics and dynamics in terms of circular motions in two Star Streams (Kapteyn, 1922) were also incorrect. A consensus among our staff eventually led to the replacement of that picture by a "more current" one; I regret having not more strongly opposed that then.

Along the same line, the tone of van Rhijn's (1951) *"J.C. Kapteyn Centennial"* is, at least to my taste, too apologetic. The judgement of the appropriateness of displaying Kapteyn on our preprints, and in fact the naming of our institute after him, is not primarily dependent upon whether he was in the end right or wrong. This volume testifies to the fact that Kapteyn's legacy is much greater than just his scientific conclusions, and the use of his name and picture is a tribute to that. I subscribe to the view, so eloquently described in Arthur Koestler's (1959) *"The Sleepwalkers"*, that the progress of science reminds one of a meandering river, sometimes flowing slowly and at other times rapidly, and also at times apparently backwards.

It is interesting to speculate how Kapteyn would have responded to the developments in astronomy in the 1920's had he lived, say, ten years longer. Surely, van Maanen (1922) made a most safe prediction, when he remarked, that *"if a longer life had been granted to him, undoubtedly we would have seen him elaborate his beloved subject"*. Kapteyn did see the results of Shapley on the distances of the Globular Clusters and lived when the famous *"Great Debate"* between Shapley and Curtis took place in 1920. It is known that Kapteyn seriously questioned Shapley's calibration of his cluster variables and hence his distance scale (Paul, 1981, 1986; Oort, 1981), and apparently staunchly defended his life's work. Would he by 1930 have discarded the "Kapteyn Universe" in the light of developments such as in particular the realisation that

[1]By this I mean the production of printed versions of papers in press, to be mailed to libraries and individuals around the world. The preprint series still exists, but the mailing of printed copies is replaced by electronically circulating a list every few months. Preprints are now accessible through anonymous ftp (file transfer), via our home page on the World Wide Web or through preprint servers as "Astro-ph".

Shapley's Globular Cluster distances were in gross terms correct, Hubble's distance determinations of M31 and M33 and the acceptance of the island universe concept, the theory of differential Galactic rotation of Oort and Lindblad, and Trumpler's determination of interstellar absorption? Obviously, we will never know, since he was never put to that test. He might have remained a conservative defender of his concept against all evidence, but he might also have embraced the new insight and enthousiastically gone foreward asking new questions.

It would seem obvious that such an immediate question would have been that of how our Galaxy compares to other galaxies. Hubble (1926, 1936) concluded that the Galaxy is of morphological type Sc, mainly based on the surface brightness of the disk as inferred by Seares (1920). This question is not yet definitely solved, as is that of the exponential scalelength of the stellar light distribution in the disk. I will address these matters in this contribution. Sections 2 and 4 are based on van der Kruit (1986). By comparing our Galaxy to others an important step must be made, not surprisingly also taken in Hubble's early work just referred to, namely from star counts to surface brightness.

2. STAR COUNTS AND SURFACE BRIGHTNESS.

Modern work on counts of stars to determine the structure of the Galaxy makes use of numerical models. A prime example of that is the one constructed by Bahcall and Soniera (1984). It builds up the Galaxy using components with a particular space distribution and assuming for each component a luminosity and color distribution of the stars it is made up of. In what follows we will almost entirely be concerned with the disk (for reasons that will become evident soon), so that "controversies" as to what color-magnitude diagrams to use for Population II and the presence of a "thick disk" play no role in our discussion. The disk population in the Bahcall–Soniera model is a double exponential disk, where the number of stars per unit volume can be written as

$$n(M_{\rm V},(B-V),R,z) \propto \exp\left(-\frac{R}{h}-\frac{z}{h_{\rm z}}\right).$$

Clearly, this is based on the observation that the surface brightness distributions in disks of external spiral galaxies show a radial exponential nature (Freeman, 1970) and in edge-on galaxies – at least away from the central dust layer – a distribution that approximates the exponential one with the added, surprising property that the vertical scaleheight $h_{\rm z}$ is independent of galactocentric radius (van der Kruit and Searle, 1980). The original Bahcall–Soniera model constrained the structural

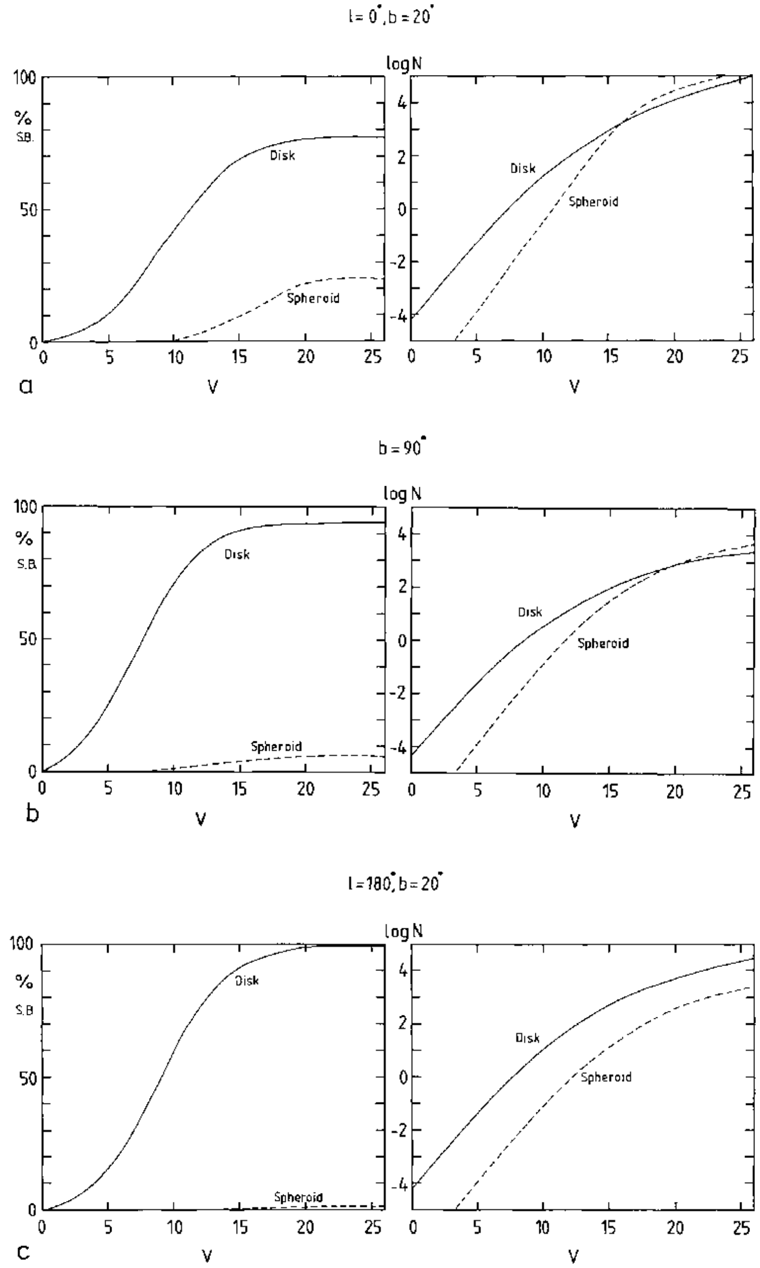

Figure 14.1 The cumulative distribution to the surface brightness (left) and counts (right) in stars per square degree from the disk and the halo in three directions.

parameters for the disk as follows:
• $h \approx 3.5$ kpc for all stellar constituents,
• $h_z \approx 90$ pc for young Population I,
• $h_z = 350 \pm 50$ pc for old dwarfs, and
• $h_z = 250 \pm 100$ pc for disk giants.
In addition, the model contained a recipe for treating absorption along the line of sight and contained an $R^{1/4}$–spheroid. In general terms it represented star counts at a number of optical wavelengths very well, except for the possible, intermediate thick disk component.

The currently accepted range of parameters is as follows:
• $h = 2.5$ - 6 kpc; I will discuss this in much more detail below,
• $h_z = 300$ - 375 pc from counts of main sequence stars near the turn-off and subgiants towards the Galactic poles (Gilmore and Reid, 1983) and I will assume the same value for old disk dwarfs and giants,
• the distance of the sun to the Galactic center $R_o = 7.5$ - 9 kpc.

With these parameters (and Balcall and Soniera's model for the bulge and halo; the spheroid), we can calculate the surface density of stars for any position on the sky – although to be treated with much care at low Galactic latitudes – and these can be summed to give surface brightnesses. This is illustrated for three selected positions in Fig. 1. We see then that except for the general direction of the anticenter, stars in the disk are at faint levels always outnumbered by those from the halo. However, in surface brightness the disk always dominates.

From the range of values for the two scale parameters, it follows that the disk's isodensity surfaces make an angle i with the Galactic plane

$$i = \tan^{-1}(h_z/h) = 3^\circ - 8^\circ.$$

The distribution of surface brightness accross the sky, containing no distance information, can of course only be used to constrain *ratio's* of size parameters. In particular, we can restrict h/h_z; but the value of i just given, shows that we need to be able to obtain reliable photometry at latitudes well below 10° in order to find useful constraints on h/R_o.

Although not important in an analysis of the optical surface brightness distributions I will sometimes refer to the photometric parameters of the Galactic bulge. For this I take the following values (see also de Vaucouleurs and Pence, 1978), based on an "$R^{1/4}$" surface brightness distribution:
• effective radius $R_e = 2.7$ kpc,
• central surface brightness $\mu_o \approx 15.1$ B-mag arcsec^{-2},
• from various literature sources the ratio of the rotation velocity of the Globular Cluster System and its velocity dispersion $V_m/\sigma = (60 \pm 30)$ $/(110 \pm 10)$; compared to other bulges this suggest an axis ratio of $b/a =$

0.5 ± 0.15,
• and from this follows the total luminosity $L_{\rm B} = 3 \times 10^9\ L_{\odot}$.

3. PIONEER 10 PHOTOMETRY

The planetary probe *Pioneer 10* was launched on March 3, 1972 and encountered Jupiter on December 3, 1973. During the intervening time the spacecraft was used to map the whole sky (as far as available due to the sun) at two optical wavelength bands, roughly corresponding to B and somewhat redder than V. These observations were performed when the spacecraft was at solar distances larger than 3 A.U. (i.e. beyond the asteroid belt), so that there was little or no contribution from zodiacal light. The reason for performing this experiment actually was to be able to correct zodiacal light measurements from or near the earth for background starlight. These data can, however, also be used for studies of the starlight distribution in the Galaxy; the following summary is from the study in van der Kruit (1986).

The Pioneer 10 all-sky maps, corrected for point sources (all stars brighter than $m_{\rm V} = 6.5$) and for diffuse Galactic light (only important at low latitudes), and smoothed to an 8° resolution are shown in Fig. 2. Note that such a map can in principle also be derived from star counts by adding up the stellar fluxes, if performed down to magnitudes of 20 or so (see Fig.1). In that sense these maps are comparable in scope to star count studies performed accross the sky, as in Kapteyn's *"Plan of Selected Areas"*.

The analysis can only be performed for those parts of the maps where interstellar absorption is small, although the effects of absorption continue to be treated explicitly in the modelling. Burstein and Heiles (1982) have derived a map of Galactic extinction (to beyond the extent the Galaxy) over most of the sky based on maps of neutral hydrogen (HI) and counts of galaxies. The area analysed was restricted to those positions where these maps indicate a color excess $E(B-V)$ less than 0.09 mag. This effectively excluded all area's at latitudes below 20°. As follows from the discussion in the preceeding section, this means that only studies of the disk can be made and as far as structural parameters are concerned only information on the ratio of the disk's scalelength and scaleheight $(h/h_{\rm z})$ can be derived.

The way in which the modelling was done, was using the Bahcall–Soniera model. That this is in the first place a model to produce star counts is important. This is so, because for a comparison to observations it is necessary to also delete the contribution from bright stars (that have been subtracted from the observed maps) in the model. Only then can

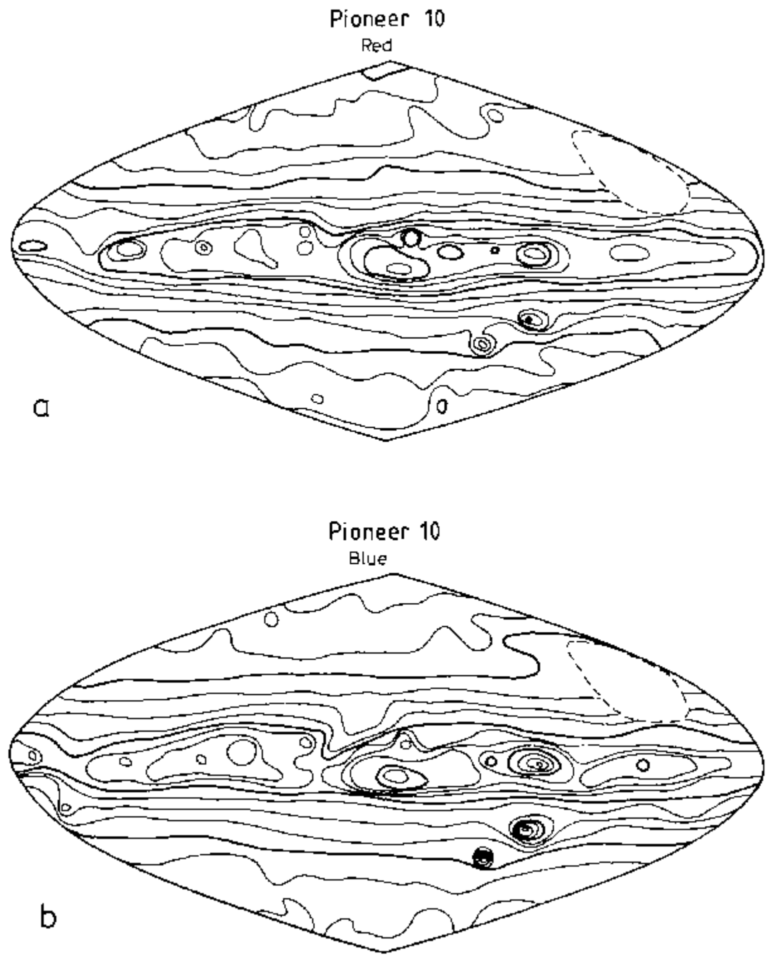

Figure 14.2 The surface brightness distribution over the whole sky of integrated starlight at red and blue optical wavelengths, as observed by Pioneer 10. The data have been corrected for diffuse light from dust and for bright stars ($m_V \leq 6.5$). Contour intervals are 0.25 mag arcsec^{-2} with the faintest at 24 V-mag arcsec^{-2} in part **a** and 24 B-mag arcsec^{-2} in **b**. The Galactic center is in the middle of the pictures and the Galactic North Pole at the top. In addition to the Milky Way, the Magellanic Clouds are clearly visible. The missing part is the general direction of the sun seen from Jupiter at the time of the Pioneer observations.

the contributions from stars at all remaining apparent magnitudes be added to provide surface brightnesses. The model than can be rerun for various choices of the structural parameters. A result is shown in Fig. 3, where along lines at three constant latitudes the data and the best

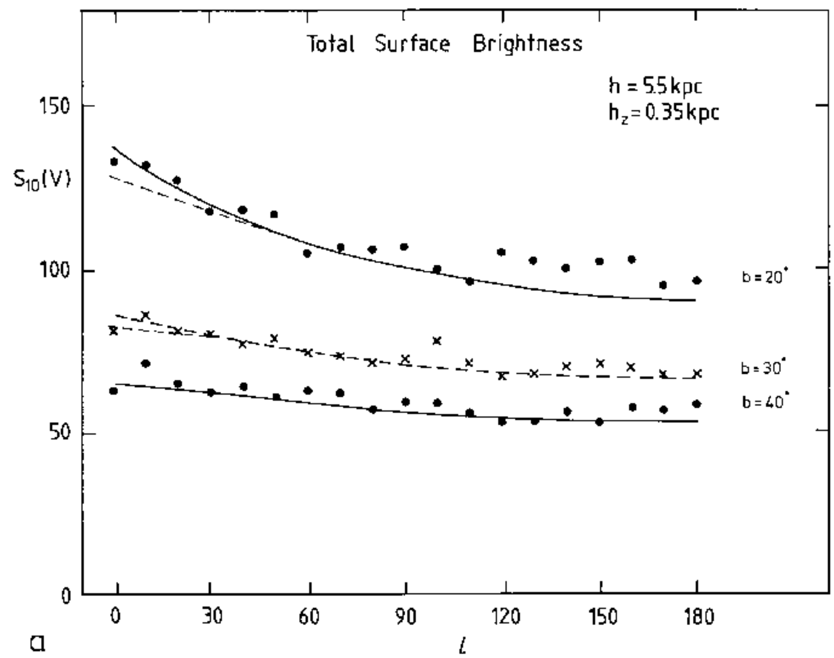

Figure 14.3 Comparison of the Pioneer 10 blue surface brightness and that resulting from simulated star counts at three Galactic latitudes b as a function of longitude l. In the model the scalelength and -height have been taken as indicated, but the data are only sensitive to their ratio. Both in the data and the model stars brighter than V-magnitude 6.5 have been "subtracted". The vertical scale is linear and the unit is explained in the text.

fitting model are compared. Although h and h_z are given in absolute units, the fits are only sensitive to the ratio of the two. The vertical scale is *linear*; the unit, in full $S_{10}(V)_{GV2}$, is the equivalent number per square degree of stars of spectral type GV2, that have apparent magnitude 10 in the V-band. $S_{10}(V)_{GV2} = 1$ corresponds to 28.49 B-mag arcsec^{-2} or 0.265 $L_\odot$ pc^{-2}.

The best fit of the models to the data give the following results:

- the ratio of the scalelength and -height is $h/h_z = 8.5 \pm 1.3$,
- from star counts in the Galactic poles (Gilmore and Reid, 1983) the scaleheight in the solar neighborhood has been determined as $h_z = 350 \pm 50$ pc,
- from this we then find $h = 5.5 \pm 1.0$ kpc. Below I will extensively discuss

the value of the Milky Way's scalelength and conclude on a value of 4.5 to 5 kpc,
• the surface brightness of the Galaxy's disk at the solar position is $\mu(R_\odot) = 22.1 \pm 0.3$ B-mag arcsec^{-2} and the color $(B-V) = 0.84 \pm 0.15$,
• the total luminosity of the disk is then $L_B = (1.8 \pm 1.3) \times 10^{10}\ L_\odot$, of which $\sim 1.0 \times 10^{10}\ L_\odot$ is in the form of old disk stars,
• since it is well-known that HII-regions and OB stars can be observed out to at least 20 kpc, the radius of the (stellar) disk is $R_{\max} = 20 - 25$ kpc,
• using also the values indicated above for the bulge of the Galaxy, we find that the old disk contains about 80% of the total luminosity of the Galaxy.

4. HERSCHEL AND KAPTEYN

The analysis of the Pioneer 10 data is in some ways reminiscent of Kapteyn's program. An important difference is that surface brightness is used rather than star counts. But in order to do the fitting, star counts had to be simulated first. Of course, the Bahcall–Soniera model that is used, has as input many sources of information such as color-magnitude distributions and information on the structure of other galaxies (although that is also surface photometry). Now that we have a reasonably trustworthy model for the distribution of stars in the Galaxy, we can use this to compare to older counts. This has already been published in van der Kruit (1986), but has probably escaped attention by historians of astronomy and it may seem to be useful to repeat it here.

First I take Herschel's (1785) famous crosscut of the *"Sidereal System"* based on his *"Star Gauges"* along a great circle on the sky. Herschel counted stars and assumed that he could fathom the Sidereal System to its edges and that the space density of stars is constant, so that the distance R to the edge of of the system (*"rays"*) should be related to the surface density n of stars by $R \propto n^{2/3}$. Herschel expressed his radii in the distance to Sirius and marked this in inches on his drawing of the Sidereal System. From this it follows that his system measured about 850 by 200 Sirius distances. I measured all *"rays"* with a ruler and with the formula given and Herschel's description of his calculations, these can then be transferred into the number of stars in his telescopic field of view. His 20-foot telescope (with aperture 18.7 inches) is reported to have a field of view of 15 arcmin. We can then calculate the surface density Herschel counted in stars deg^{-2}.

Next we have to determine where Herschel's great circle was located on the sky. His description is somewhat cumbersome: from geographic

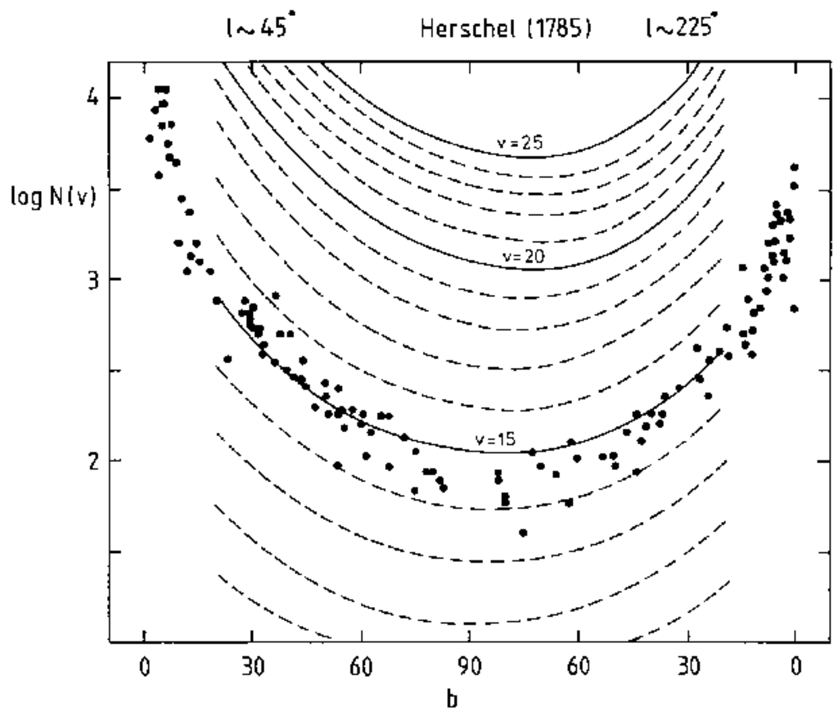

Figure 14.4 Comparison of the star counts by Herschel (1785) to those from current models for the Galaxy. $N(V)$ is the number of stars per square degree in the V-band. Herschel's great circle had Galactic longitudes of about 45° and 225°, and missed the Galactic poles by only about 5°. The dots are Herschel's counts as inferred from his famous crosscut of the Sidereal System (the positive and negative latitudes have been combined into one figure). The lines are counts in the V—band according to the star count model with the structural parameters as given in section 3.

latitude 55° it traces out the horizon when the star τ Ceti culminates. Elementary astronomy allows one to derive from this, that this great circle crosses the Galactic plane at longitudes about 45° and 225°, and that it misses the Galactic poles by about 5°. With this it is then possible to calculate the expected star counts using the Bahcall–Soniera model, but adapted to the structural parameters given in the previous section. The result is in Fig. 4. To compare to the Herschel counts I use V-magnitudes for the model predictions. Herschel's counts are the dots and the lines give the predicted surface density of stars down to the V-magnitudes given at the corresponding positions. Because of absorption the model calculations have not been carried to lower latitudes than 20°.

It follows that Herschel counted apparently down to magnitude about 15.

There is clearly some scatter in the figure; this is more likely due to fluctuations in stellar surface densities than uncertainties. Herschel himself reduced the effects of fluctuations by not admitting areas where *"stars happened either to be uncommonly crowded or deficient in number"*. The value of magnitude ~ 15 is somewhat fainter than the value of 14 that was derived in a much cruder way by Roach and Gordon (1973).

It is possible to check this further by analysing Herschel's (1871) own estimates. He quotes values for the *"gaging or space penentrating powers"* of his telescopes. This is the increase in distance out to which he could see stars compared to the unaided eye. The latter was calibrated by his *"equalization of starlight"* experiments as about 12 times the distance to Sirius. He also derived his pupil diameter as 0.2 inch and found experimentally that his mirrors had efficiencies of 67% (that means that 33% of the light was absorbed per reflection in his telescopes). Taking also the blocking of his primary mirror by the secondary into account, Herschel derived a gauging power of his 20-foot telescope as 75. This corresponded to a decrease in brightness of $75^2 = 5.6 \times 10^3$ or 9.4 magintudes. Thus he figured he could count stars with this telescope down to apparent magnitudes a little over 9 magnitudes fainter than with his naked eye, which also gets us to about magnitude 15.

Herschel described in own words his *"extent of telescopic vision"* as that *"stars beyond its* [that is his 20-foot telescope] *reach must have been farther from us than the 900th order of distances than stars of the size and lustre of Sirius, Arcturus, Capella, etc."*. A factor 900 in distance corresponds to a factor of 8×10^5 in brightness or 14.8 mag. Again this would give us a value of 15 or so for his limiting magnitude.

A similar thing can be done for Kapteyn's counts. For this purpose I will use the Selected Area counts in van Rhijn (1925). A similar comparison as above for Herschel is now made in Fig. 5. Here we see cumulative counts down to magnitude 18.5. Since these are photographic magnitudes, I have now done the calculations in the Bahcall–Soniera model for B-magnitudes. It is clear that at faint levels the Kapteyn-van Rhijn magnitude scales go wrong in the sense that in these counts they are quoted too bright. The effect is not small, it amounts to half to three-quarter of a magnitude at the limits.

We also see, that the shape of the counts and the model are closely the same. That means that there is an excellent level of consistency all across the sky. That is a remarkable achievement. The same holds for Herschel's counts. From what I have shown above we can see that

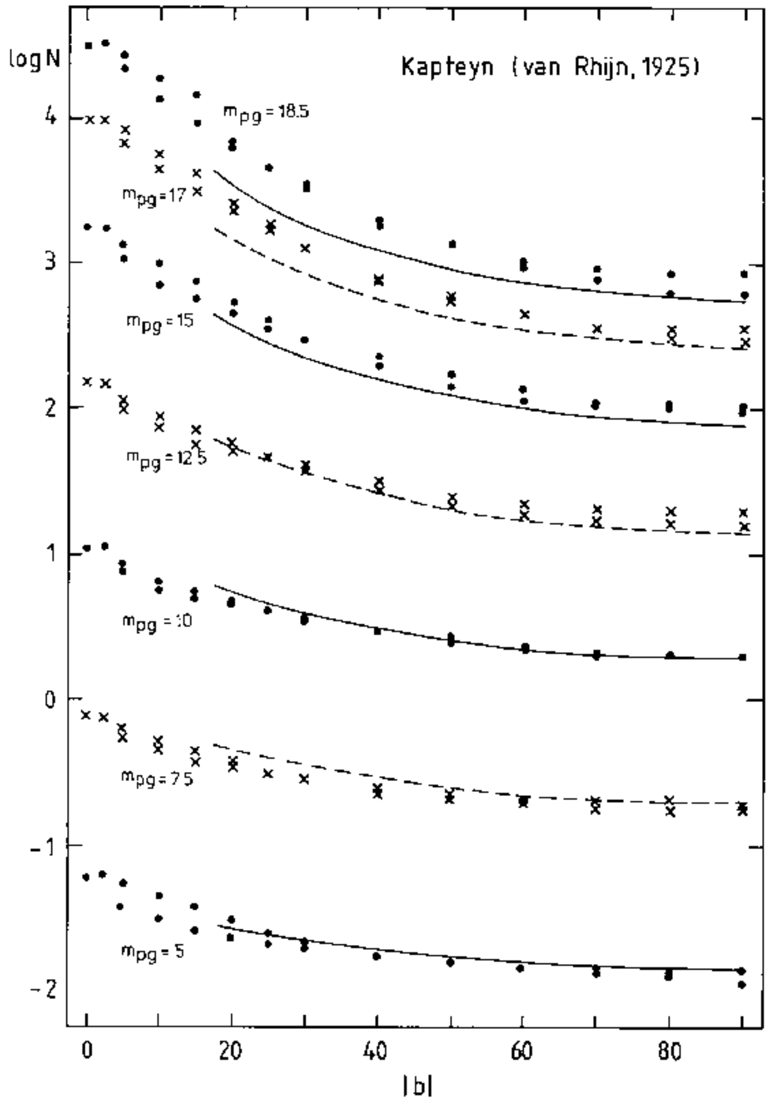

Figure 14.5 Comparison of the "Kapteyn" star counts in Selected Area's and the star count model with the structural parameters of section 3. The star counts are the ones from van Rhijn (1925). The two values at each position come from positive and negative latitudes. N is the number of stars per square degree.

Herschel and Kapteyn observed 95% or more of the surface brightness of the background starlight. It mostly refers to the disk of the Galaxy, as we now know in hindsight. The shape of Kapteyn's counts in Fig. 5

as a guide to *relative* variations resulting from the stellar distribution in space, actually contains rather strong constraints on what we now call the ratio h/h_z.

5. THE SCALELENGTH OF THE GALACTIC DISK

The canonical value for the scalelength of the disk of the Galaxy – and actually the one used in the standard Bahcall–Soniera model – is 3.5 kpc and comes from de Vaucouleurs (1979). He derived it using three arguments.

• Freeman (1970) showed that the disks of the most common, bright spiral galaxies have extrapolated, face-on central surface brightnesses of $\mu_o = 21.6 \pm 0.4$ B-mag arcsec^{-2}. Using the best star counts in the Galactic poles available then, de Vaucouleurs estimated the surface brightness of the disk in the solar neighborhood and he calculated the ratio of the scalelength and the distance to the Galactic center h/R_o. We can use modern values for this. From the Pioneer 10 photometry we find that the disk surface brightness near the sun is $\mu_{\mathrm{B},\odot} = 23.8 \pm 0.1$ B-mag arcsec^{-2}. With Freeman's central surface brightness this gives $h/R_\mathrm{o} = 0.49 \pm 0.10$. The most commonly accepted distance from us to the Galactic center is $R_\mathrm{o} = 8.5 \pm 1.0$ kpc, so that we find $h = 4.2 \pm 1.0$ kpc.

• De Vaucouleurs assumed that the scalelength of the gas layer (HI plus molecules) within the solar circle is similar to that of the stars. We now know that the gas has a central depression and a strong peak near 4 kpc from the center and this method now appears unusable.

• De Vaucouleurs assumed further that beyond the solar circle, the scalelength of the HI and the stars is the same. For this we now have much more information in external galaxies. E.g. the Palomar-Westerbork survey (Wevers *et al.*, 1986) shows that $h_{\mathrm{HI}} = (1.85 \pm 0.35)h_*$. However, this method is difficult to apply to the Galaxy, because kinematic uncertainties have a strong effect on the derived surface density distribution of HI beyond R_o.

So we may conclude that there is little support with the present knowledge for this older value of de Vaucouleurs. I will now review some other estimates for the scalelength.

• From Pioneer 10, see above, we found $h = 5.5 \pm 1.0$ kpc.

• In external edge-on galaxies the disk scalelength compared to the disk edge is $h/R_{\mathrm{max}} = 4.2 \pm 0.6$ (van der Kruit and Searle, 1982). Since for our Galaxy, on the basis of the distribution of HII-regions and OB stars, $R_{\mathrm{max}} = 20$–25 kpc, we get $h = 5.4 \pm 1.0$ kpc.

• Lewis and Freeman (1989) determined a radial gradient in the velocity dispersion of K-giants in the disk. This can be described by an exponential scalelength of 8.7 ± 0.6 kpc. Since disks have a constant thickness with radius (van der Kruit and Searle, 1981) this should be twice the scalelength of the density distribution, so that $h = 4.4 \pm 0.3$ kpc.

• Stars with a higher velocity dispersion will lag more behind Galactic rotation. The relevant equation from galactic dynamics for this so-called asymmetric drift is

$$\frac{\partial}{\partial R} \ln \langle V_{\rm R}^2 \rangle + \frac{\partial}{\partial R} \ln \rho = \frac{V_{\rm t}^2 - V_{\rm rot}^2}{R \langle V_{\rm R}^2 \rangle^{1/2}} - \frac{1}{R} \left(1 - \frac{B}{B-A} \right) .$$

Here $\langle V_{\rm R}^2 \rangle^{1/2}$ is the radial velocity dispersion, ρ the density, $V_{\rm t}$ the tangential velocity of the group of stars, $V_{\rm rot}$ the circular rotation speed (and thus the asymmetric drift is $V_{\rm rot} - V_{\rm t}$) and A and B the local Oort constants. The two terms on the left-hand side are in the exponential disk model with constant scaleheight equal to $-1/h$. From Plaut's (1965) old disk variables this would give $h = 4.3$–5.8 kpc.

Taking all of this together gives us a scalelength $h = 4.5$–5.0 kpc.

6. GALACTIC STRUCTURE FROM COBE

The *Cosmic Background Explorer* (COBE) mapped the sky in 1989-1990 at wavelengths ranging from the near-infrared to millimeter wavelengths. The *Diffuse Infrared Background Experiment* (DIRBE) made among others maps in approximately the J, K, L and M-bands (1.2, 2.2, 3.5 and 4.9μ) at resolution of order half a degree. An example of such a map is shown in Fig. 6. These data have been analyzed by Freudenreich (1996, 1998). Freudenreich found values for the scalelength of the Galactic disk of about 2.5 kpc and furthermore found it to be truncated at about 12 kpc. These values are both substantially lower than the ones derived above.

It might be thought that the use of the near-infrared has many advantages over optical wavelengths, mainly because interstellar absorption is less important. Actually, the COBE/DIRBE studies were preceded by less complete mappings, such as by Kent *et al.* (1991), who used data from Spacelab. That particular study was restricted to a little more than one quadrant of the Galactic plane (longitudes roughly from 340° to 120°) and latitudes below 10° (although observations went up to latitudes of 30°). Yet, they also found scalelengths of order 2.5 kpc. It should be remembered that the lesser absorption has the added difficulty, that more structure in the Galaxy becomes visible (a central bar for example), while at low latitudes one always has to worry about red supergiants. These young stars are unlikely to be indicative of the dis-

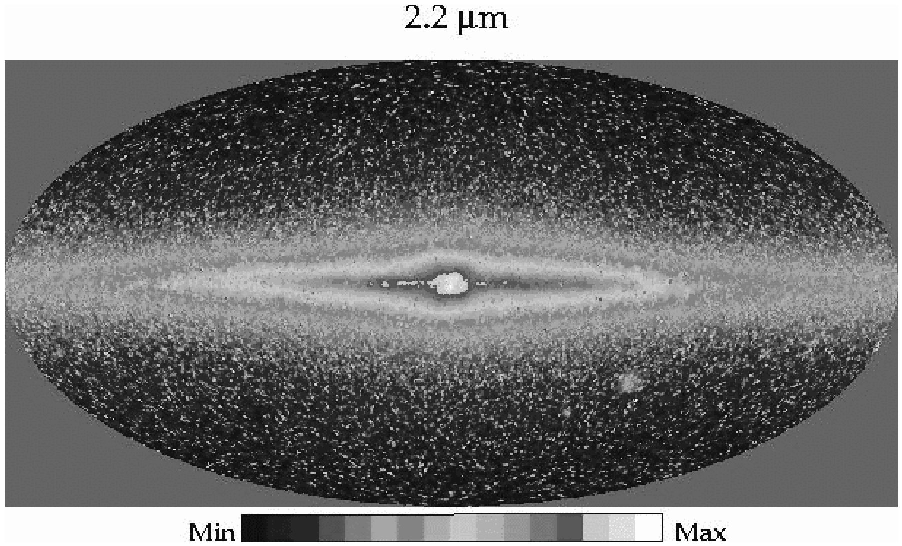

Figure 14.6 The COBE/DIRBE 2.2μ (K-band) map of the Milky Way.

tribution of total light in the disk (and certainly not the mass) but are significant contributors to near-infrared light. Furthermore, the highly concentrated, warm dust in Giant Molecular Clouds forced Freudenreich to exclude significant area's of the sky before being able to analyse the data.

There has also been analyses of (part of) the COBE/DIRBE data relevant to Galactic structure, preceeding Freudenreich's analysis of the full-sky data. For example, Arendt *et al.* (1994) looked at the so-called first and fourth quadrant of the Galactic plane (the 180° that has the Galactic center in the middle) and concluded that at 1.25 μ (J-band) there is up to 4 magnitudes of extinction. So even distributed interstellar absorption is a potential problem to be – to say the least – treated with care. Also, when they "unreddened" the maps, they found that the (near-infrared) color of the disk is similar as those of late-K and M-giants. This again emphasizes that red supergiants may be substantial contributors to the DIRBE-maps at low latitudes.

The fact that at low latitudes so much detail in the structure of the Galaxy can be seen, results in the necessity to make fits with many free parameters. Freundenreich's final fit includes for a fit in one wavelength band:

• two parameters for the solar position,
• four parameters for the disk (one is a fiducial luminosity density and three more of these are necessary to fit the other maps),
• three parameters to fit a possible central hole in the disk,
• five parameters to fit a possible warp in the disk,
• eleven parameters to fit a central bar (really an elongated bulge) in the central regions (again three extra parameters are necessary for the other bands),
• eight parameters to model the dust extinction and emission at low lattitudes (again three more are necessary for the other bands).

All in all, the model ended up needing in total 47 free parameters, of which a few are not yet mentioned. Fits are then performed by calculating a single figure of merit for various models over the whole sky.

The model has no explicit treatment of the young population in the disk. The components of the model, in particular the disk, have a volume emissivity that has everywhere the same color. The young population is treated through the dust component, for which the emission is assumed to be due to OB stars and these then have an assumed spatial distribution with a scalelength as the old disk and a thickness and warp as the dust itself. No allowance for the presence of red supergiants is made. All of this may be unrealistic.

A most dangerous aspect of the modelling is the treatment of the unresolved sources (the apparently bright stars). These have been removed from the observed maps and what is done in Freudenreich's models is simply assume that up to some distance from the sun (which then is different in each of the wavelength bands) the volume emissivity is zero. These distances then are taken along as free parameters in the fits. It is, however not clear at all, that this is a correct procedure. In my modelling of the Pioneer 10 data, this issue was treated correctly by first simulating the star counts and then deleting stars to the same apparent magnitude as was done in the observations. Of course, such a procedure can not be followed when the model only has luminosity densities.

My criticism of the Freudenreich analysis consists of the following points:
• improper treatment of the young population and no allowance for the presence of red supergiants; the latter are certainly making an important contribution at low latitudes.
• improper treatment of the point sources,
• fitting with a single figure of merit, rather than also attempting fits to restricted area's where a certain component dominates.

The latter point is important for the disk scalelength. Above some latitude (probably 15° or so) the surface brightness on the sky is dominated by the old stellar disk and the disk parameters could be determined using only those area's and fitting only to the relevant parameters. Similarly, only the central regions contain information on the bar and bulge (and a possible central hole in the disk). Only after first attempts to fit in this way restricted parts of the model and with these parameters as guidelines, should a full fit with all the 47 parameters be attempted.

Better still would be to make an adapted version of the Bahcall–Soniera model for these wavelength bands, so that the bright stars can be treated properly. Some work to extend the model to (near) infrared spectral bands has been undertaken already by Mamon and Soniera (1984) and Franceschini *et al.* (1991). These studies show that no insurmountable difficulties are to be expected in the J- and K-bands, but lack of good input data is a problem in bands at longer wavelengths.

The fact that detailed structure in the Galaxy contributes substantially to the surface brightness distribution at low latitudes, makes these area's unsuitable for the determination of the old disk scalelength. In summery: a new determination of that property should be attempted at higher latitudes using a near-infrared version of a star count model.

A first attempt of such an approach has been performed by Porcel *et al.* (1998), who surveyed a region between longitudes 30° and 70° at a latitude of about 5° as part of the *Two Micron Galactic Survey* and selected stars in the magnitude range 9 to 10. These are, according to these authors, predominantly K-giants. The resulting scalelength from this survey is 2.1 ± 0.3 kpc.

7. SCALELENGTHS IN OTHER GALAXIES

In the following I will try to find galaxies that are similar to our own. For such an exercise the size of the Galaxy will play an important role and therefore the disk scalelength is an important parameter. So, I will first look at a comparison of the Galaxy with external systems for which good surface photometry is available.

Two recent samples, that also are statistically complete, are the ones by de Jong (1995, 1996) and de Grijs (1997, 1998). Both observed samples of spiral galaxies at optical and near-infrared wavelengths, de Jong moderately inclined galaxies and de Grijs edge-on ones. Among their results are fits to the disk surface brightness distributions and determinations of the scalelengths.

From the literature de Grijs has collected the integrated HI profiles and I have done so for the sample of de Jong. From this the rotation

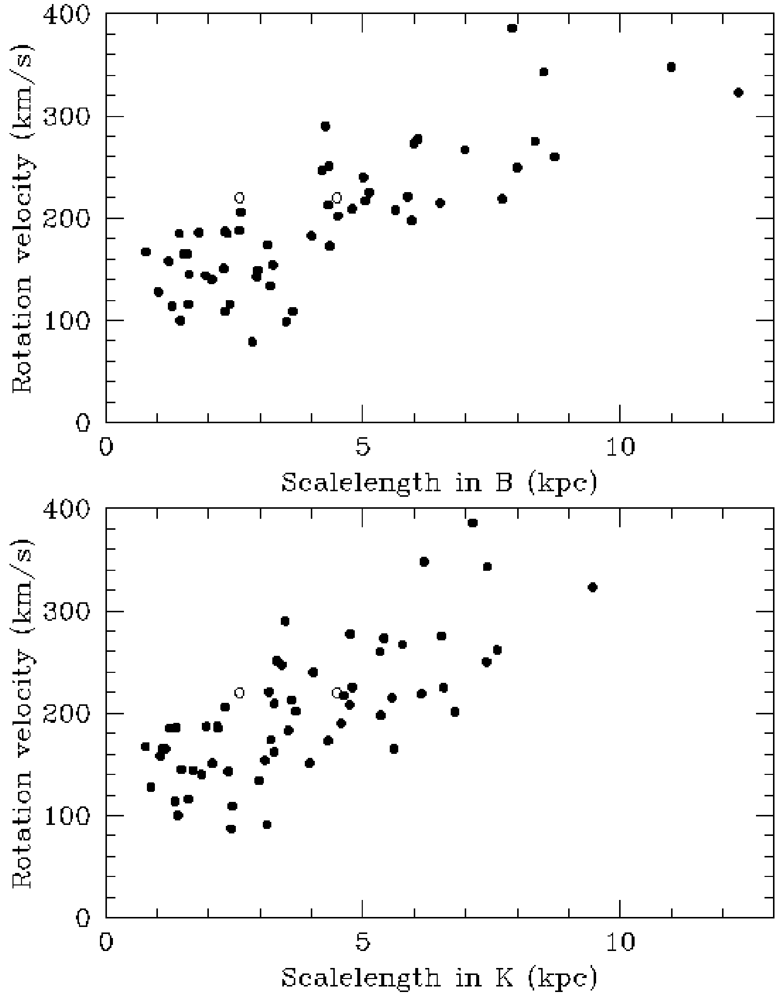

Figure 14.7 The disk scalelength in B and K versus rotation velocity for the samples of galaxies by de Jong (1995, 1996) and de Grijs (1997, 1998). The Galaxy (open dots) has been indicated for scalelengths of 2.5 and 4.5 kpc.

velocities can be estimated reliably, except for galaxies with low inclinations (close to face-on), so I have restricted the sample to systems with inclinations $i \geq 30°$. In Fig. 7 I plot the scalelength (in B and K) against the rotation velocity, deleting any galaxy with a Hubble type earlier than Sab. These results are also summarized in Table 1. For this a distance scale based on a Hubble constant of 75 km s^{-1} Mpc^{-1} has been used, which is close to the value emerging from the Hubble Space Telescope Key Project on the extragalactic distance scale (e.g. Madore

Table 14.1 Scalelength of the exponential disk as a function of rotation velocity.

$V_{\rm rot}$ (km s^{-1})	n	h_B (kpc)	n	h_K (kpc)
$<$ 150	15	2.32 ± 0.83	12	1.97 ± 0.70
150 - 200	15	2.57 ± 1.38	20	2.75 ± 1.48
200 - 250	10	5.09 ± 1.38	15	4.68 ± 1.52
$\leq$ 250	12	7.70 ± 2.52	12	6.04 ± 1.76

et al., 1999). There obviously is a general correlation in the sense that a larger rotation corresponds to a larger scalelength.

On general principles this is not unexpected. It is a direct consequence of the Tully-Fisher relation $L_{\rm tot} \propto V_{\rm rot}^{3-4}$. The total disk luminosity (which for later type systems is not much different from the total luminosity $L_{\rm tot}$) $L_{\rm disk} \propto \mu_o h^2$. For galaxies with central surface brightnesses μ_o following Freeman's law, it follows that $h \propto V_{\rm rot}^{1.5-2}$, roughly as observed.

Also plotted in Fig. 7 by open dots are scalelengths for the Galaxy of 2.5 and 4.5 kpc (at $V_{\rm rot}$ = 220 km s^{-1}). Both from Table 1 and from Fig. 7 it appears that a "normal" value for the scalelength in a galaxy with a rotation velocity of 220 km s^{-1} is 4.5 to 5.0 kpc, although it is also true that Fig. 7 shows that a value of 2.5 kpc (as inferred from the COBE data) cannot be ruled out on the basis of these data.

De Jong (and for a different complete sample van der Kruit, 1987a) has determined the bivariate distribution function of scalelengths and central surface brightness. Of all galaxies, less than about 1 percent has a scalelength larger than 5 kpc and only of order 10% larger than 2.5 kpc.

For comparison we may also look at the Virgo cluster, using the extensive (more than 100 systems) surface photometry of Watanabe (1983). The 6 largest Sb-galaxies have scalelengths of 52±5 arcsec and the 5 largest Sc-galaxies 50±5 arcsec. Using the distance to the Virgo Cluster of Graham *et al.* (1999), which is based on Cepheid distances from Hubble Space Telescope observations, of 16±2 Mpc, this corresponds to scalelengths of respectively 4.0±0.6 and 3.9±0.6 kpc. So, we see that our Galaxy with scalelength 4.5–5.0 kpc and the Andromeda Nebula M31 with 6.0±0.5 kpc belong to the larger spiral galaxies in the Universe. Actually, I have used this argument (van der Kruit, 1986) to argue that the Hubble constant cannot be larger than 65±10 km s^{-1} Mpc^{-1}.

8. GALAXIES SIMILAR TO OUR OWN

Finally, I will look for galaxies that closely resemble ours. Before going into this, we would need to answer the question of what Hubble type applies to the Milky Way Galaxy. For a detailed discussion I refer to van der Kruit (1987b), where also relevant references can be found. Important elements in that discussion were the following. The color of the Galactic disk from the Pioneer data is $(B-V) = 0.85 \pm 0.15$, which seems to point to a type Sb. The logarithm of the ratio of the HI-surface density to the total optical surface brightness at three scalelengths is -0.5±0.3. In the survey of Wevers (1984) only Sb galaxies attain such a low value. The bulge-to-disk luminosity ratio is not discriminating very much and Sb and Sc are both viable options. Very important is the distribution of carbonmonoxide; in the Galaxy the CO definitely shows a central depression or hole and this occurs in external systems only in Sb galaxies. The conclusion then is, that our Galaxy is most likely of type Sb. Comparison with the surface photometry of Watanabe (1983) in the Virgo Cluster indicates I-II as the most likely option for the luminosity class.

I now turn to the question of finding galaxies closely comparable to our own. Code and Houck (1955) were the first to make a photograph of the Galaxy (see upper-right panel in Fig. 8). This picture has the center of the Galaxy close to the zenith (which occurs during winter nights in the southern hemisphere) and has been taken with a camera, standing an a tripod, looking down at a mirror-coated sphere. This view of our Galaxy has often been compared to the edge-on spiral NGC 891, which has been reproduced in the upper-left panel of Fig. 8. For comparison, Fig. 8 shows a modern version of the wide-angle photograph from the southern hemisphere, but now with a fish-eye objective in the camera. This photograph (lower-right in Fig. 8) has the center of the Galaxy towards the top near the horizon. The picture in the lower-left panel is a carefully calibrated and rectified representation of the Galaxy's surface brightness distribution by Hoffmann *et al.* (1998), produced from a set of pictures such as the one by Code and Houck. This picture rougly encompasses the range in longitude from -60° through the Galactic center to 200° and latitudes between -40° and +40°. As has been often remarked by astronomers observing from the southern hemisphere, the appearance of the Milky Way spanning the winter skies from these latitudes with the center near the zenith, is reminiscent in many respects of NGC 891.

It would be of interest to find galaxies that are selected by their morphological characteristics similar to the Galaxy (after all we have no

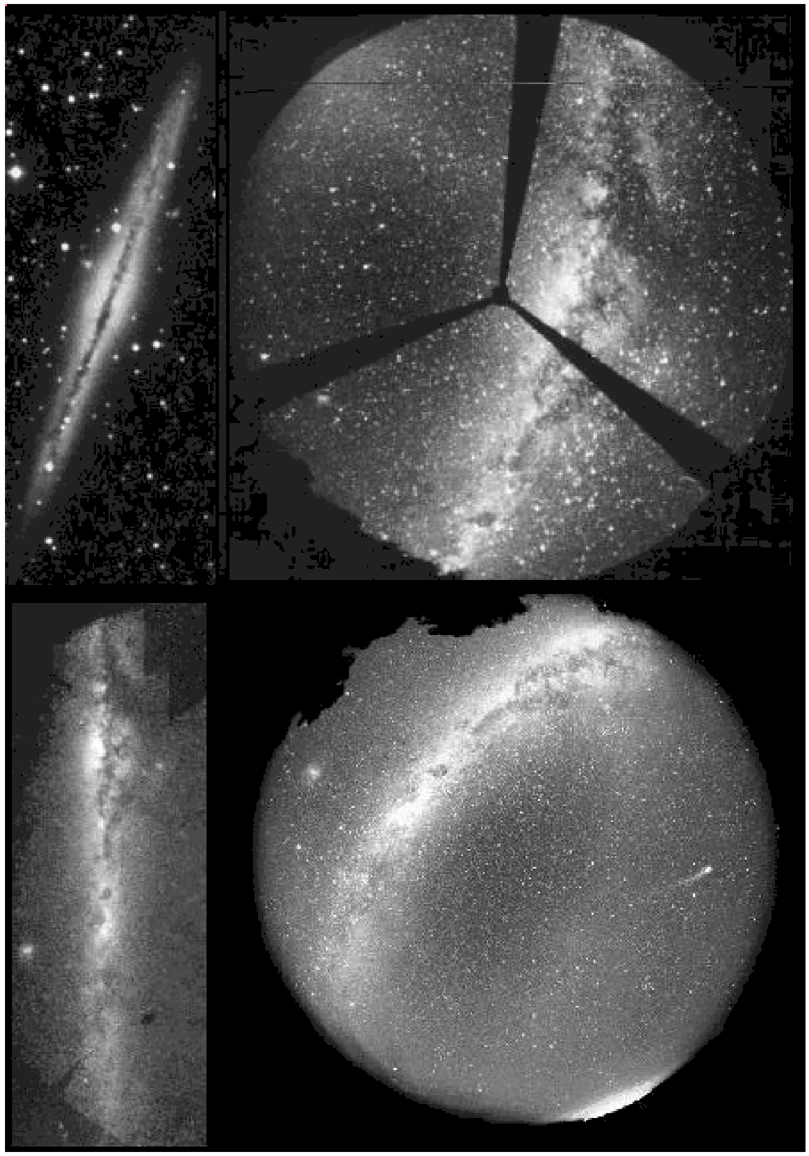

Figure 14.8 Comparison of the appearance of the Milky Way with NGC 891. At the upper-right is the well-known picture of the whole southern sky by Code and Houck (1955). The lower-right has a modern version taken with a fish-eye camera; this picture has been taken at random from the World Wide Web. On the upper-left is NGC 891; this picture is taken from the Digitized Sky Survey. On the lower-left is a calibrated and rectified surface photometry map due to Hoffmann *et al.* (1998).

Figure 14.9 Pictures of NGC5033 and NGC5375, taken from the Digitized Sky Survey.

idea what it would look like face-on), but using more quantifyable properties. I have done such an exercise in van der Kruit (1989), but the purpose here will be to use newer data to see if any new candidates can be identified.

The question is, which galaxies are similar to the Galaxy according to the following criteria:

- Disk scalelength $h = 4 - 6$ kpc;
- disk color $(B - V) = 0.6 - 0.8$;
- bulge luminosity to total luminosity $(L/L_{\rm tot}) = 0.10 - 0.20$;
- bulge effective radius $R_{\rm e} = 2 - 3$ kpc;
- rotation velocity $V_{\rm rot} = 210 - 230$ km/s;
- HI-mass $M_{\rm HI} = (4 - 10) \times 10^9 M_\odot$.

Again I will use for this exercise a Hubble constant of $H = 75$ km s^{-1} Mpc^{-1}. I previously found only two galaxies that conform to all

Table 14.2 Comparison of the Galaxy to NGC 891, NGC 5033 and NGC 5375. For the latter eveywhere the word "bulge" should be replaced by "bar".

		GALAXY	NGC 891	NGC 5033	NGC 5375
	Type	SbI-II	Sb	SbcI-II	SBb
⇒	Bulge R_e (kpc)	2.7	2.3	2.9	3.2×1.5
	Bulge c/a	~ 0.7	0.7	?	?
	$L_{\rm bulge}(L_\odot)$	2×10^9	1.5×10^9	4×10^9	2×10^9
	Disk $\mu_{0,\rm B}$	22.1	22.9	22.0	21.8
⇒	Disk h (kpc)	5	4.9	5	5
	$L_{\rm disk}(L_\odot)$	1.7×10^{10}	6.9×10^9	1.7×10^{10}	1.7×10^{10}
⇒	$(B-V)$	0.8	0.9	0.6	~ 0.7
	Disk $R_{\rm max}$ (kpc)	20 - 25	21	22	< 18
⇒	$L_{\rm bulge}/L_{\rm tot}$	0.12	0.07	0.19	0.12
⇒	$V_{\rm rot}$ (km s^{-1})	220	225	215	217
⇒	$M_{\rm HI}(M_\odot)$	8×10^9	4×10^9	4×10^9	4×10^9

the criteria, namely NGC 891 and NGC 5033. Their properties are collected in Table 2. The arrows on the lefthand side point to properties that were used to select the galaxies. I have examined in addition to this the galaxies in the surveys of de Jong (1995, 1997) and de Grijs (1997, 1998). No additional systems turned up.

The starting point that has been taken here, was stated as that only structural parameters are being used and no morphological criteria. This, however, is not entirely true. In the analysis of the photometric profiles of both our Galaxy and NGC 891, the assumption has been made that the bulge is essentially axisymmetric. In other words that these systems are not severely barred. It is now clear, that bulges with a box-shaped morphology in edge-on galaxies can actually correspond to an edge-on bar, as is also evident from the stellar kinematics (e.g. Merrifield and Kuijken, 1999). So, for the Galaxy and NGC 891 the assumption has been made that they are non-barred. Yet, a close inspection of their luminosity definitely shows some evidence for "boxy bulges". Therefore the conditions should be relaxed in the sense that those pertaining to the bulge (namely its luminosity and [effective] radius) could also be those for a bar in less inclined systems. In that case, NGC 5375 (from de Jong's sample) would also qualify. It is therefore included in Table 2. Pictures of these galaxies – taken from the Digitized Sky Survey – are shown in Fig. 9.

Acknowledgments

I am grateful to Ron Allen and the Space Telescope Science Institute for hospitality in the period when I was writing the text of this contribution. Copyrights for the Digitized Sky Survey belong to many organisations (to be found through the homepage of STScI at http://archive.stsci.edu/dss/copyright.html). Fig. 6 has been taken from the COBE Web-page (http://www.gsfc.nasa.gov/astro/cobe/cobe_home.html).

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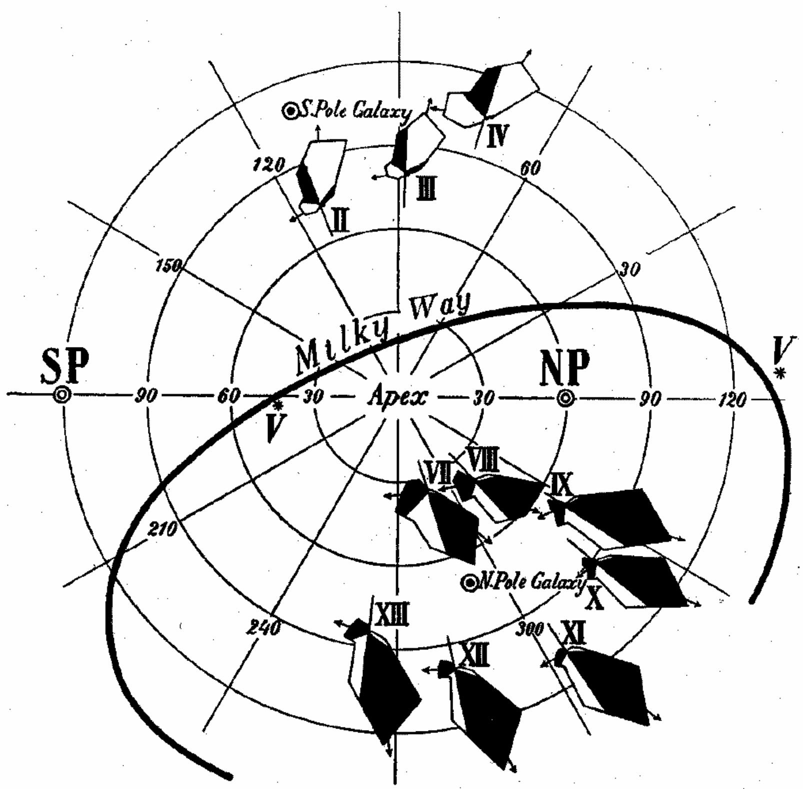
SULLIVAN: What value of H_o did you use when calculating parameters for the Milky Way look-alikes? If you varried the assumed H_o, you might find other best-fit curves.
VAN DER KRUIT: I used 75 km s^{-1} Mpc^{-1}, which in view of the results of the Hubble Space Telescope Key-project (e.g. Madore *et al.*, 1999) seems close to the value most researches are converging on. If H_o were different, we would end up with different look-alikes. But the Hubble constant now seems constrained to a relatively small range of values and I am therefore reasonably confident that the results are good examples.



Kapteyn's illustration of his two Star Streams (1904). At only a selection of the regions for which he had data (10 of the available 28), he plots the distribution of proper motions on the sky. If there were no preferential streamings each distribution would be round, but Kapteyn found these distributions to be asymmetrical and to point to an apex in the middle of the figure. The systematic behaviour across the sky is evidence for two Star Streams. It was soon shown by K. Schwarzschild that the pattern could in an alternative, but much more physical manner be explained as an anisotropy in the distribution of the stellar velocities.