PART II

COMPOSITION, STRUCTURE AND KINEMATICS

Musician Betty Schwarz and dynamicist Stefano Casertano discuss musical composition during Wednesday outing. LZ

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SECTION II.1

GALACTIC CONSTANTS, ROTATION AND MASS DISTRIBUTION

Tuesday 31 May, 0900 - 1020

Chairman: R. Wielen

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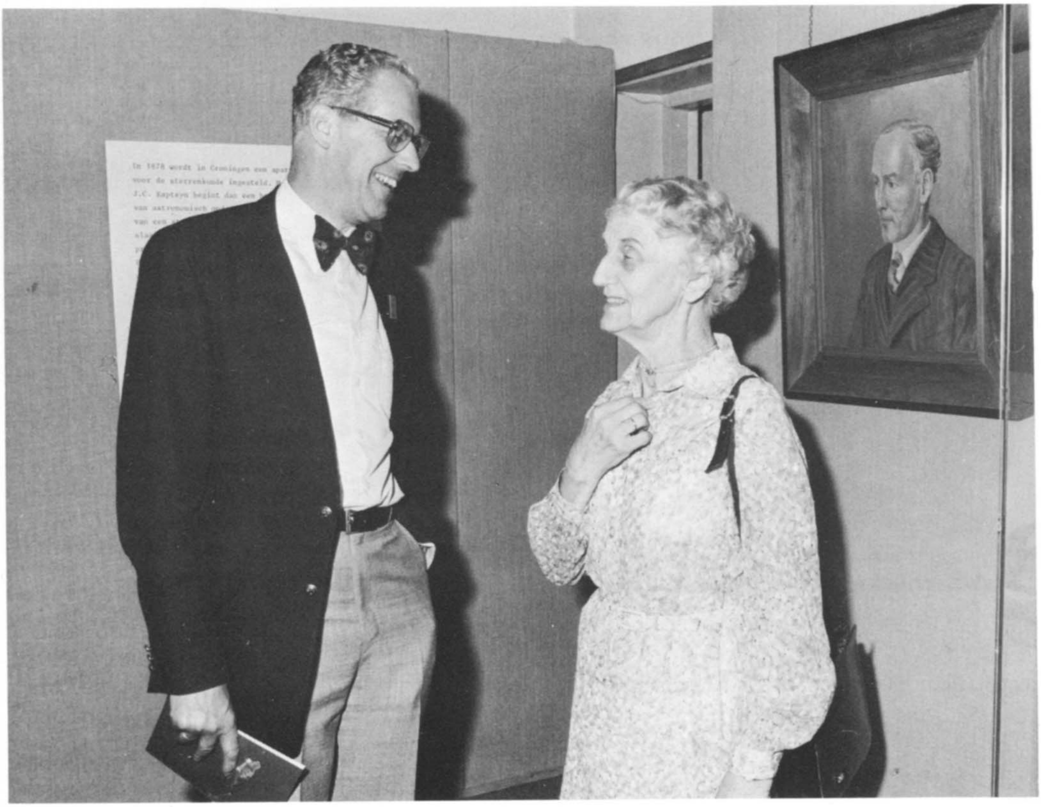

Three generations. At the Kapteyn-Van Rhijn exhibition, Maarten Schmidt has a conversation with Mrs. Reina van Rhijn, widow of Pieter J. van Rhijn, professor of astronomy at Groningen in 1921-1956.
At right: a portrait of Jan H. Oort, painted in 1938 by Dirk Nijland.

Schmidt was a student of Van Rhijn at Groningen and of Oort at Leiden, where he obtained his doctorate in 1956. Oort was a student of Kapteyn and obtained his doctorate from Van Rhijn in 1926. CFD

MODELS OF THE MASS DISTRIBUTION OF THE GALAXY

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1. INTRODUCTION

Mass models of the Galaxy play an important role in studies of the structure of the Galaxy. The various populations or components combine to yield a gravitational field that produces the observed rotation curve. For the spheroid and disk this requirement can be used to set limits on some of their properties. The properties of the dark corona are entirely defined this way.

Early models of the mass distribution were primarily based on the rotation curve interior to the Sun (see Schmidt 1965). Since that time, observations of late-type galaxies have shown that their rotation curves are flat or rising beyond a few kiloparsecs from the center (Krumm and Salpeter 1979; Rubin et al. 1980, 1982). This suggests that the overall density of matter decreases approximately as R^{-2}.

Due to our location and dust absorption in the galactic plane, we cannot reliably derive the distribution of stars in the disk of our Galaxy. Here, too, external galaxies have supplied important evidence: the disk component of their luminosity distribution exhibits an exponential profile (Freeman 1970).

We review briefly in the next section published mass models that have approximate exponential disks and flat rotation curves. Then, we report on some test models to investigate what range of model parameters is permissible for a given rotation curve. Finally, we comment on some of the properties of the dark corona which is postulated to explain the flat rotation curve.

2. MASS MODELS

Recent mass models of the Galaxy have been published by Clutton-Brock et al. (1977), Sinha (1978), Einasto (1979), Miyamoto et al. (1980), Caldwell and Ostriker (1981), Rohlfs and Kreitschmann (1981),

H. van Woerden et al. (eds.), The Milky Way Galaxy, 75–84.

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and Bahcall et al. (1983). A useful comparison between some of these models is given by Caldwell and Ostriker (1981, see Table 4).

In general, the models include three components: a) Spheroid--corresponding to the halo population (population II) such as subdwarfs and globular clusters. Densities usually follow a Hubble or de Vaucouleurs law. Shape approximately spherical. b) Disk--usually a flat disk with an exponential density law. The disk has sometimes a central hole. c) Dark Corona--a usually spherical component added to yield an approximately flat rotation curve.

The most interesting properties of the model components are the core radius and local density of the dark corona, for which there is no independent evidence, and the local density of the spheroid for which only an approximate lower limit is known, as discussed below. The total range of these properties in the above mentioned models is:

Spheroid:	local density	$= (2\text{-}35) \times 10^{-4} M_\odot/pc^3$
Dark Corona:	local density	$= 0.001\text{-}0.011\ M_\odot/pc^3$
	core radius	$= 2\text{-}15$ kpc.

It is difficult to trace in detail the origin of the very large ranges shown. One would suspect that a substantial part of the variation may be caused by different density laws and parameters of the components, different adopted rotation curves, etc. In order to investigate this aspect, we explore in the next section models made up of components with a given density law and based on a given rotation curve.

3. EXPLORATION OF TEST MODELS

On the basis of the evidence from external galaxies, we assume that the rotation curve of the outer parts of the Galaxy is essentially flat. Following a review by Knapp (1980) of available rotation curves,

we fit at	0.5	2.5	8.5	∞ kpc
to circular velocities of	240	195	220	220 km/sec.

We use $R_o = 8.5$ kpc and impose an asymptotic velocity of 220 km/sec at large distances.

For bulge and spheroid we use the following density law

$$\rho \sim R^{-1.5}(b^n+R^n)^{-1}$$

with n = 1.5 or 2. This approximately represents the $R^{-1.8}$ density law observed for IR/OH sources in the central bulge (Isaacman and Oort 1981) and at larger distances fits the R^{-3} or $R^{-3.5}$ density law observed for RR Lyrae stars and globular clusters (see Oort and Plaut 1975; Harris 1976).

The disk is represented by an inhomogeneous spheroid in which surfaces of constant density are oblate spheroids of constant excentricity. The density is given by a four-term polynomial such that the

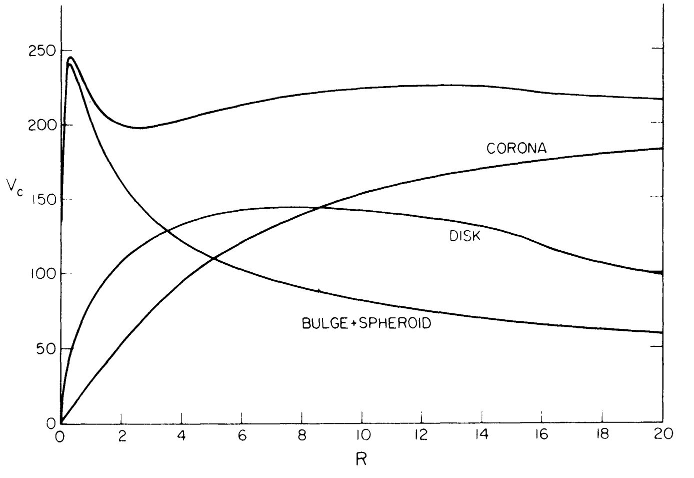

Figure 1. Rotation curve for a three-component mass model of the Galaxy. The contribution of each of the three components is shown separately.

surface density is approximately exp(-R/H). The polynomial is cut off at zero density, at R = 4.5 H, in approximate agreement with that observed by van der Kruit and Searle (1982) in edge-on galaxies. For the dark corona we assume a spherical shape and density law

$$\rho \sim (a^2+R^2)^{-1}$$

which yield an asymptotically flat rotation curve at large distance.

We show in Figure 1 the rotation curve corresponding to a model given by:

bulge + spheroid	b = 0.3 kpc	$\rho_o = 0.0002\ M_\odot/pc^3$
disk	H = 3.5 kpc	$\sigma_o = 50\ M_\odot/pc^2$
dark corona	a = 4.6 kpc	$\rho_o = 0.010\ M_\odot/pc^3$

where we used for the spheroid density law n = 2. The quantities ρ_o, σ_o are the local values (at R_o = 8.5 kpc) of volume and surface densities.

The rotation curve for R = 0 - 2 kpc is primarily determined by the bulge+spheroid component. For n = 2, corresponding to a $R^{-3.5}$ law in the spheroid, the local density in the model is 2 x $10^{-4}\ M_\odot/pc^3$. If we take n = 1.5, or a R^{-3} density law in the spheroid, then the local model density is 6 x $10^{-4}\ M_\odot/pc^3$. These densities may be compared to that based on the luminosity function of high-velocity stars which yields 1.7 x $10^{-4}\ M_\odot/pc^3$ (Schmidt 1975), and that derived from star counts, namely (0.4-0.6) x $10^{-4}\ M_\odot/pc^3$ (Bahcall et al. 1983).

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The star count derivation involves a considerable extrapolation of the mass function, since it is based on relatively bright stars (M_V = 4-8) which carry a small fraction of the total mass. The density determined from the high-velocity stars is based on the assumption that the median tangential velocity of spheroid stars is 250 km/sec. This value of the median tangential velocity may be somewhat high (Richstone and Graham 1981). If, instead, we adopt a median tangential velocity of 200 km/sec, then the corresponding mass density increases to 2.7×10^{-4} $M_\odot/pc^3$ (Schmidt 1975).

It appears that the local model density in the spheroid of 2×10^{-4} $M_\odot/pc^3$ for n = 2 is consistent with the observational evidence. For n = 1.5, the local model density is 6×10^{-4} $M_\odot/pc^3$ and a substantial part of the mass would have to be in stars below the hydrogen-burning mass limit, or in other dark objects.

Caldwell and Ostriker (1981) used a Hubble law in which the density falls approximately as R^{-3}, and derived a local model density of 11×10^{-4} $M_\odot/pc^3$. The difference with our R^{-3} model is probably caused by a combination of higher central velocity peak, a larger adopted value of R_O, a central hole in the disk component, and a somewhat different density law. I conclude that for a given density law, the local density in different models may differ by a factor of two, and that for a $R^{-3.5}$ spheroid density law, the local density of the spheroid is in approximate agreement with that derived from high-velocity stars.

In the range 2-8 kpc, the disk is the main contributor to the rotation curve. In the model shown in Figure 1 we used H = 3.5 kpc following de Vaucouleurs and Pence (1978) and a local surface density of 50 $M_\odot/pc^2$. Based on current estimates of the density of stars and gas, I would estimate at the present time a mass surface density of 39 $M_\odot/pc^2$. In order to compare this observed density to that based on the K_Z determination by Oort (1960), I use (for this purpose only) for a spherical component of the Galaxy a pseudo surface density that equals 1000 pc times the local volume mass density. The surface density corresponding to Oort's K_Z determination is 80 $M_\odot/pc^2$. The dark corona has a pseudo surface density of about 10 $M_\odot/pc^2$, and the spheroid contributes a negligible surface density, so we would expect for the disk about 70 $M_\odot/pc^2$. The difference with our estimated observed surface density of 39 $M_\odot/pc^2$ illustrates the local hidden-mass problem.

The model of Figure 1 employed a disk of 50 $M_\odot/pc^2$ and H = 3.5 kpc. The adopted points of the rotational velocity curve can still be fitted within about 5 km/sec for a surface density as large as 65 $M_\odot/pc^2$, if the core radius of the dark corona is increased to a = 6.5 kpc. Similarly, the exponential scale length H can be increased to 6 kpc, in which case a = 2.8 kpc. An H value as low as 3 kpc is only possible if the local disk surface density drops to 40 $M_\odot/pc^2$, in which case a = 4.4 kpc.

The dark corona is gravitationally the dominant component outside the solar radius. The local density and core radius are essentially set

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dynamically, through the models, as illustrated above. In the various models with different disk parameters discussed above, we find local densities in the range (0.008-0.011) $M_\odot/pc^3$ and a = 2.8-6.5 kpc.

We can summarize the results of this exercise in modelling as follows. Even with a given rotation curve and given density laws for the three components, there are a variety of acceptable solutions. The scale lengths of disk and dark corona have an allowable range of about a factor of 2, the local disk density a factor of 1.5, and the local spheroid density a factor of 3. The even larger range of properties shown by published models of the Galaxy (discussed in the beginning of this paper) is no doubt a consequence of the additional effect of different model components, different rotation curves, etc. We conclude that the complexities of mass modelling are such that properties derived from such models should be viewed with caution.

4. THE DARK CORONA

Since the dark corona is not seen but only felt through its gravitational effect, its properties are less well defined than those of disk and spheroid. We briefly discuss three questions and one comment:

1) Is a dark corona needed?
2) What is the evidence for an R^{-2} density law?
3) Is the dark corona spherical?
4) A comment about the balance between dark corona, disk and spheroid.

4.1. Is a dark corona needed?

Tests with the models discussed in the preceding section show that an essentially flat rotation curve out to 30 kpc can be obtained with disk parameters H = 8 kpc and σ_o = 200 $M_\odot/pc^2$. From local conditions in the solar neighborhood, we know that this surface density is far too large. With a realistic mass model, such as those discussed in the preceding section, the rotation velocity near the sun corresponding to disk and spheroid is no larger than 170 km/sec. Clearly, we need another mass component to boost the rotation velocity locally to its actual value, which probably lies between 200 and 250 km/sec.

4.2. What is the evidence for an R^{-2} law?

The notion of an R^{-2} density law is based on the flatness of the observed rotation curves. However, as Figure 1 shows, spheroid and disk account for a substantial fraction of the rotation curve inside the Sun. Outside, we balance the decreasing contributions of spheroid and disk with an increasing contribution of the dark component--but this gives little support for the need of an asymptotic R^{-2} law.

The situation might be different in those external galaxies where the flat rotation curves are observed out to large distances, where the

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effect of spheroid and disk might be thought to be small. This is, however, not the case as illustrated by Bahcall et al. (1982) who show that a dark corona with a local logarithmic density gradient of about -2.7 can yield an essentially flat rotation curve in the distance range 40 to 60 kpc. We conclude that on the basis of the observations there is little direct evidence for a R^{-2} or $(a^2+R^2)^{-1}$ density law.

4.3. Is the dark corona spherical?

We have assumed that the dark corona is spherical, in which case the local model density is 0.010 $M_\odot/pc^3$. If the corona is spheroidal in shape, then the density is larger by a factor equal to the inverse axial ratio. For an axial ratio of around 1/4, the local mass density of the dark corona would be of the same order as that of the hidden mass in the solar neighborhood needed to interpret K_z. This opens the possibility that the galactic dark mass and the local hidden mass could be the same material, unless there exist theoretical arguments why the corona should be spherical.

4.4. The balance between dark corona, disk, and spheroid.

Figure 1 shows that the spheroid dominates within the first few kiloparsecs. Beyond that, the disk is the main contributor to the rotational velocity interior to the Sun, and the dark corona dominates at larger distances. Each of these three mass components contributes about the same rotational velocity over their respective ranges of dominance. As a consequence, the rotation curve is essentially flat over a large galactocentric distance range.

Assuming that this situation holds for most external galaxies, the fact that they have essentially flat rotation curves suggests that there is a balance between spheroid, disk, and dark corona. If such a balance did not exist, there should be cases where the rotation velocity changes considerably with galactocentric distance, but few if any such cases are seen in the rotation curves obtained by Rubin et al. (1980, 1982). Further study of this apparent conspiracy between the different mass components of galaxies is warranted.

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DISCUSSION

D. Lynden-Bell: What evidence have you that the spheroid is round?

Schmidt: You mean: that it is a sphere? I believe the work on RR Lyrae stars by Oort and Plaut indicated that the distribution was very round, in fact almost prolate (which, however, was not proposed). Work at Lick by Wirtanen and Kinman in other directions seemed to indicate axial ratios of perhaps 0.7. I think in the present discussion it would not make much difference - it is a rather relaxed model, and if one flattens the spheroid a bit, the density would just go up in proportion.

J.H. Oort: But we know the globular-cluster distribution also.

Schmidt: And what would you say about that? Round?

Oort: Yes, except perhaps for the innermost part.

Lynden-Bell: What about the light of external galaxies?

Schmidt: There the axial ratio is typically around 0.7.

J.P. Ostriker: I have two comments of possible interest.
1) I would guess that in your model the total quasi-spherical mass interior to the Sun is of order 1/3 - 1/2 of the total, as in other published models. It is useful that this ratio is so invariant, since it insures (barely) the gross stability of the Galaxy.
2) I would propose that you could reduce the corona significantly, if you used only the constraints on the rotation curve interior to the Sun and were willing to take up the slack with the other components, leaving the M/L ratio of the spheroid free.

Ostriker and Schmidt during the boat trip. Foreground: Denoyelle; background T.S. van Albada and (partly hidden) Illingworth, Fujimoto and Norman. LZ

Schmidt: I doubt it, Jerry. Even with an R^{-3} law, the central velocities in the spheroid would come out much too high compared to observation.

Ostriker: I leave it for you as an exercise while you play with these parameters. I bet you can get rid of the corona and make a model which....

Schmidt: You do it, Jerry.

Oort: What is the evidence for a minimum in the rotation curve at 2 kpc?

Schmidt: The review by Knapp (1980) indicates such a minimum; I have not myself looked critically at the evidence. If one does not stick to this minimum, then surface densities and scale lengths beyond the ranges indicated by me are possible.

Oort: Why do you think there is no good evidence in the Galaxy for a flat rotation curve outside the solar circle? My impression was that the evidence is fairly convincing.

Schmidt: My point is that present knowledge of the rotation curve out-

Mrs. Oort, Oort, Schmidt, De Zeeuw and Lacey at the conference dinner. LZ

side the Sun, and of the interior components of the Galaxy, is not precise enough to base an R^{-2} law for the dark corona on it.

B.F. Burke: Evidence for dark coronae may best be found in external systems. J.M. Mahoney, J.M. van der Hulst and I are engaged in a study of simple interacting pairs of galaxies, using both the morphological data and HI radial-velocity fields. The presently observed tidal distortions are, in principle, a fossil record of the past orbital history, and if the interaction has been close enough, a large massive halo should modify the tidal interaction sufficiently to leave a dynamical record. Simple systems, in which only one encounter has occurred, would be preferred. The well-known "antennae", NGC 4038/39, are such a system, with simple, well-ordered structures, and we have completed VLA observations of this object. Model studies, now in progress, should evaluate the promise of the method. Perhaps those who study the tidal interactions of the Magellanic Clouds with the Milky Way can find evidence for our own corona if their work becomes sufficiently quantitative.

W.B. Burton: The problem of the minimum in the rotation curve at 2 kpc or somewhat less centres on the nature of the rotation curve at smaller galactocentric distances. There seem to me to be good reasons to think that the rotation curve does not change as abruptly as in the earlier interpretations of the observations. In the earlier observations absorption effects gave the appearance that there was no HI at negative velocities in the first quadrant, and that led to a steeply rising curve with very high rotation speeds. Molecular data which are not influenced by absorption effects indicate a much slower variation of velocity across the galactic centre, hence a less steep rotation curve in the interior part of the Galaxy. It remains difficult to derive an accurate rotation curve in the inner parts, partly because of lack of knowledge about the exact form of the potential. Present evidence should not be interpreted as requiring a steeply rising rotation curve.

Schmidt: As I said before, this will mean that the models are even less restrictive in (so that one will be able to use reasonable values for) scale length, disk mass and density.

Lynden-Bell: So you do not believe in that 250 km/s peak at R = 0.5 kpc?

Burton: Indeed, that peak is entirely open to question.

Schmidt: I do not necessarily disagree with you.