MASS DISTRIBUTION AND DARK HALOS

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One of the most controversial astronomical paradoxes seems to be the mass paradox : the mass of large astronomical systems depends on the mass determination method. This paradox can be explained by supposing the existence of huge invisible coronas of unknown origin around galaxies. In the present paper we discuss basic empirical evidence of hidden matter in galaxies and examine the total mass distribution.

1. MASSIVE CORONAS AROUND GALAXIES

Photometric observations show that the density of ordinary galactic populations decreases exponentially with increasing distance from the galactic centre (de Vaucouleurs 1953). Due to this fact the mass inside a sphere of a given radius R approaches a certain limit M_{gal} with increasing R and therefore it is expected that the circular velocity should decrease, according to the Keplerian law. The observed rotation curves (Bosma 1978) as well as the dynamics of companion galaxies (Einasto et al. 1974a) show, however, that on the periphery rotation velocity is not decreasing, but is practically constant. This means that the internal mass must linearly grow with radius, indicating the presence of a previously unknown population, a massive corona or halo (Einasto 1972) that dominates in the outer regions of galaxies.

In 1980 Fabricant et al. mapped the X-ray surface brightness of M87. Takahara and Takahara (1980) showed that this X-ray source seems to have two components, and the central component, of which the temperature tallies with the velocity dispersion of M87 companions, can be explained by thermal emission of the gas which is in hydrostatic equilibrium in the gravitational potential of M87. This explanation demands the presence of a very massive halo around M87. Such a picture may also be applied to sources like A1060 and the Centaurus cluster (Mitchell, Mushotzky 1980).

Observations (Bosma 1978) suggest that all giant spirals have flat rotation curves and, consequently, are surrounded by massive coronas. On the other hand, dwarf irregular galaxies do not show this property. Sta-

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tistics of double galaxies of different absolute magnitude also indicate that low magnitude ($L < 0.1\ L_{Galaxy}$) galaxies have considerably smaller relative velocities than the brighter ones at the same relative linear distances (Einasto, Kaasik 1982). All this suggests that only giant galaxies have massive coronas.

The presence of coronas is probably connected with the existence of a system of companion galaxies. As noted by Lynden-Bell (1976), all companions of our Galaxy are located in a thin belt of which the inclination to the galactic plane is 70°. Recently (1981) he argued that companions of the Andromeda galaxy also form a flattened disk, highly tilted to the parent galaxy. However, the fact that galactic companions form a flat system does not mean that coronas themselves are also flat. On the contrary, there exists strong theoretical evidence favouring a more or less spherical form of coronas (Peebles 1980). Recent X-ray coronas are fairly spherical. These observations also show that the thermal component of X-radiation in M87 extends to about 320 kpc from the centre of the galaxy. Direct studies of the dynamics of the outer regions of galaxies (Bosma 1978, Ostriker et al. 1974) confirm that coronas extend to at least 100 ÷ 200 kpc.

If the radial mass distribution of the corona is similar to the radial distribution of their visible elements then the density distribution of the corona can be represented by a modified isothermal model (Einasto et al. 1974b)

$$\rho(a) = \begin{cases} \rho_0 \{ |1+(a/ka_0)^2|^{-N} - (1+x^2)^{-N} \}^{1/N}, & a \leq a^\circ \\ 0 & , a \geq a^\circ \end{cases} \qquad (1)$$

In this formula $\rho_0 = hM/4\pi\varepsilon a_0^3$ is the central density of the population, a_0 its harmonic mean radius, ε is the axial ratio of the equidensity ellipsoids, M is the mass of the population, N and x are structural parameters, h and k are dimensionless normalizing parameters depending on N and x, and $a^\circ = xka_0$ is the outer limiting radius of the corona. From the distribution of the cumulative number of companions of our Galaxy we can estimate a_0 = 75 kpc, N = 0.5 and log x = 1.4 (Einasto et al. 1976).

A unique possibility to estimate the mass of the corona is given in the Local Group of galaxies, which has two concentration centers, our Galaxy and the Andromeda galaxy. Total mass of the double system can be derived from available kinematical and geometric data. The result is $3 \div 6 \cdot 10^{12}\ M_\odot$ (Einasto, Lynden-Bell 1982). Gott III and Thuan (1978) have found the value $5.6 \cdot 10^{12}\ M_\odot$. Hartwick and Sargent (1978) measured radial velocities for stars in outlying satellites of the Galaxy. They found that the mass inside the 60 kpc radius is $3.4 \div 7.6 \cdot 10^{12}\ M_\odot$. Combining these mass estimates with earlier results on the mass distribution in the Corona, we can conclude that the total mass of the corona of your Galaxy lies in the range $1.2 \div 3.1 \cdot 10^{12}\ M_\odot$. For the mass inside the 200 kpc radius Webbink (see Faber and Gallagher 1979) derived the value $1.4 \cdot 10^{12} \cdot M_\odot$, which corresponds to a mass of the corona $1.7 \cdot 10^{12} M_\odot$. In the Andromeda galaxy the observed rotation curve goes out to the distances of about 40 kpc (Haud 1981). In these regions most of the inner mass is already due to the corona and therefore we can estimate the parameters of the corona directly from the rotation curve. The results are a_0 = 90 kpc, N = 0.5, log x = 1.5 and the mass of the corona is $3.3 \cdot 10^{12}$ $M_\odot$. As we can see, the sum of the masses of the coronas of the Galaxy and M31 agrees with the total mass of the Local Group.

2. GALACTIC MODELS

After examination of the overall mass distribution in galaxies we can obtain more detailed information about these systems only by modeling their properties. The most convenient way of determining a model is to use a certain analytic expression for the density of the galactic populations. Our experience has shown that the best representation can be obtained using an exponential function (Einasto 1972)

$$\rho(a) = \rho_0 \exp\left|-(a/ka_0)^{1/N}\right|, \qquad (2)$$

where all parameters have the same meaning as in (1). The spatial density of a disk with a central hole can be expressed as the sum of two spheroidal mass distributions, for which $N_- = N_+$, $a_{0-} = a_{0+}/\kappa$, $\varepsilon_- = \kappa\varepsilon_+$ and $M_- = -M_+/\kappa^2$, where $\kappa > 1$ is a parameter determining the amount of the hole in the center of the disk.

Models of M32, M81, M104 and our own Galaxy have been constructed at our institute. A model of the Andromeda galaxy M81 was also finished recently. To find the parameters of this model rotation curve, velocity dispersions of central populations, integral brightness profiles in four colors and distribution of young stars, HII regions and objects of the halo were all taken into account. The results are given in Table 1. As we can see from Figures 1 and 2, the observations have been approximated quite successfully - accuracy is 3.1 % on the average. Most inaccurate are the values of velocity dispersions of the bulge and halo - the deviations are 29 % and 26 %, respectively. These deviations are calculated on the basis of the most recent observations of the dispersions, but recently we found a correlation between the observed velocity dispersion and the resolution of the corresponding observations (Fig. 3). This means that the value for the nucleus - 177 km/s - used in modelling,may be overestimated 1.5 times in comparison to its actual value. If the same happened to the dispersions of the bulge and halo, then the model would represent actual values with the accuracy of 3 %. At the same time,accepting the corrected value for the velocity dispersion of the nucleus would mean that its mass is overestimated 2.25 times in the present model.

There are also rather large mean deviations of the model from the observed rotation curve and from the distribution of surface density in young population - 6.8 % and 13.6 %, respectively, but in this case we have to deal with the effect of spiral structure (Haud 1981). Correcting the observations on account of this perturbation, we find that the model represents the smoothed rotation curve and density profile with the accuracy of 4.4 % and 5.1. %, respectively. The mean deviation of the model falls then to 1.9 %, and considering corrections of dispersions to 1.7 %.

Table 1. M31 model parameters

Population	ε_+	κ	a_{0+} (kpc)	M_+ (10^{10} $M_\odot$)	N	M/L_B	M/L_V	M/L_{379}	M/L_{624}
Nucleus	0.655		0.0021	0.0130	1.394	45.452	45.146		
Core	0.910		0.1347	0.1930	0.323	22.829	12.851		
Bulge	0.724		0.6427	0.3890	1.610	2.011	1.374	3.297	1.294
Halo	0.443		1.3860	0.6064	6.408	1.257	1.199	1.821	3.522
Disk	0.080	1.570	4.9788	28.3042	2.424	18.178	16.178	27.799	15.752
Flat	0.020	1.209	8.8748	2.4516	0.233	1.913	1.318	1.497	2.312
Corona	1		90	330	0.5				

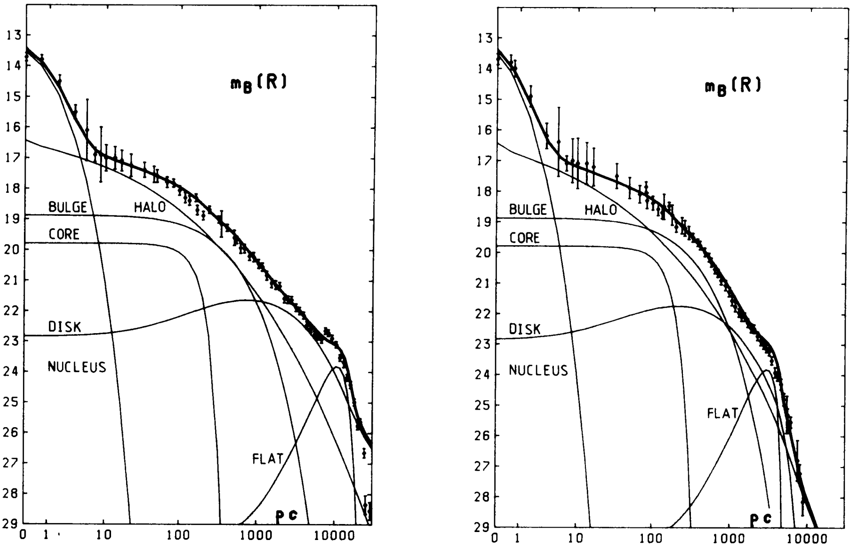

Fig. 1. Photometric profiles on the major (left) and minor semiaxis.

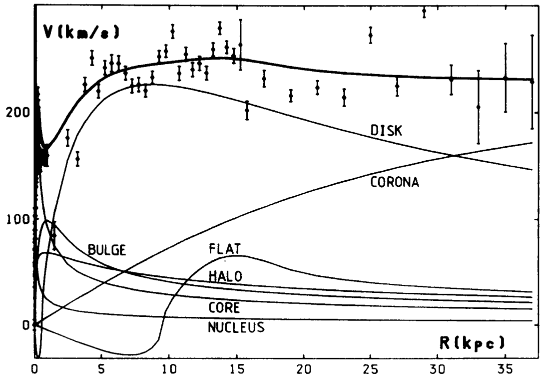

Fig. 2. Observed (crosses) and model rotation curve of M31.

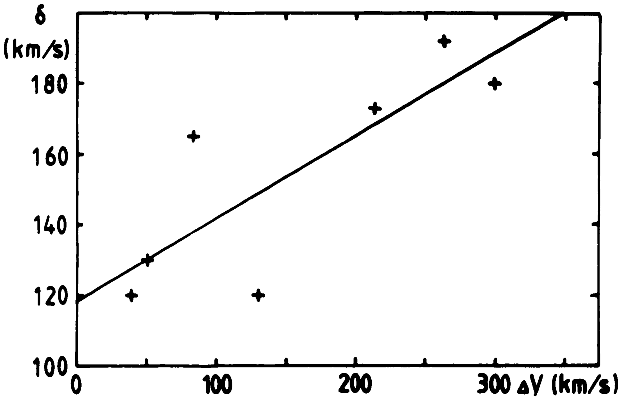

Fig. 3. Dependence of the velocity dispersion estimates of the nucleus of M31 on the resolution of the observations.

3. MASS-TO-LUMINOSITY RATIOS

Physical properties of galactic populations can be well expressed in mass-to-luminosity ratios, M/L. Very bright hot stars of young populations have small values of M/L. Old populations have higher M/L. M/L also depends on the composition of stars. Metal-rich cores of galaxies have higher M/L than metal-poor halo stars on the galactic outskirts. Thus, going outwards, the mean local value of M/L should decrease. The comparison of photometric and dynamic data indicates that this is indeed the case. However, at the very periphery of the galaxies M/L starts to increase rapidly and at the last measured point has the value M/L = 300 (Fig. 4). From these data a lower limit $(M/L)_{cor} > 10^3$ follows. Other methods give an even higher lower limit - $10^4 \div 10^5$ (Jaaniste and Saar 1976). At the same time Faber and Gallagher (1979) noted that M/L for spirals within the Holmberg radius R_{HO} is $\simeq 4 \div 6$, not much greater than the local M/L for the solar neighborhood. Our calculations show that the value of M/L within R_{HO} is closely correlated with the mean M/L of the optical populations and is only about 1.13 times higher. This indicates that unseen matter does not strongly dominate the mass within R_{HO} and that the physical properties of the coronal matter are completely different from the properties of conventional stellar populations.

Table 2. M/L in galaxies and systems of galaxies

Object	M/L	
Galaxies	(5 ÷ 10) h	Faber, Gallagher 1979
Local Group	160	Peebles 1980
Groups	(80 ÷ 300) h	Faber, Gallagher 1979
Clusters	(300 ÷ 650) h	Faber, Gallagher 1979
Virgo supercluster	800 h	Davies et al. 1980
Universe (Ω = 1)	2000 h	Einasto et al. 1980

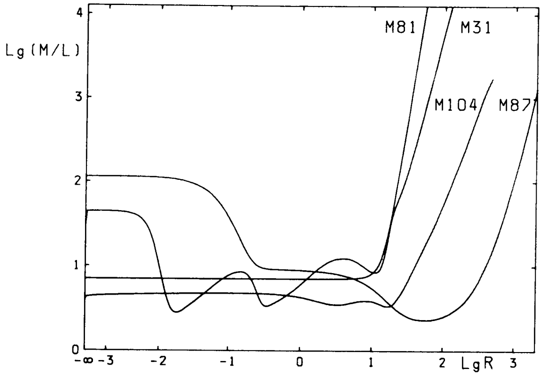

Fig. 4. Mean local M/L as a function of the galactocentric distance.

The comparison of the M/L of ordinary populations with the overall M/L (Table 2) shows that they comprise only 1 % of the whole known mass. Estimates (Bahcall and Sarazin 1977) show that the amount of intergalactic gas is approximately equal to the amount of the matter in galaxies. Taking this into consideration we conclude that about 2 % of the whole matter is in the ordinary form and 98 % is in a hidden form. This ratio is independent of the Hubble constant and we hope that it is correct within a factor of 2. We might also mention that the ordinary matter forms about 1 % of the critical density of the Universe (last entry in Table 2).

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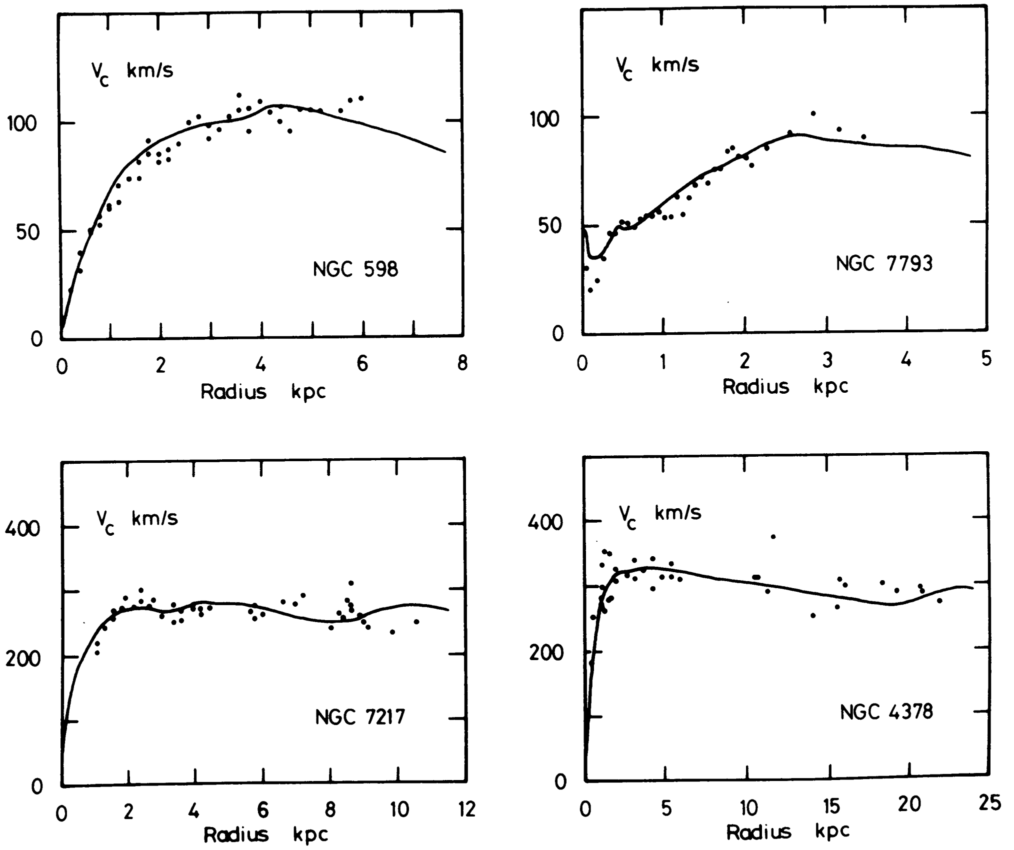
DISCUSSION

KALNAJS : The customary approach of deducing mass distribution from rotation curves involves an implicit or explicit extrapolation of the velocity data, and the often reported rise of M/L usually begins where the observed information runs out. I would like to show you a slide depicting four rotation curves computed from photometric data which has been converted into mass distributions by assuming that M/L is constant within a galaxy. The photometry extends to faint enough limits to completely determine the rotation curves. For NGC 4378 it was necessary to decompose the light into a bulge and a disk. For the others the decomposition gave essentially the same curves as would have been obtained from pure disks.
The rotation curves agree well with the observed velocity points, and thus demonstrate that the flat rotation curves of NGC 7217 and NGC 4378 need not lead one to conclude that there is dark matter in the outer parts of these galaxies.



Rotation curves computed from photometry assuming a constant M/L within each galaxy. The dots are the measured velocities. The values of M/L used are 5.0, 2.9, 4.2 and 6.5.

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somebody : HA, HA, HA.
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(The audience becomes restive and the massive halo enthusiasts slowly regain their composure).

HAUD : This is very interesting, but note the limited extent of the rotation curves of these four galaxies. Three of them extend to radii less than 12 kpc and the fourth one reaches 25 kpc. Usually the M/L starts to increase rapidly only outside roughly 30 kpc, and only giant galaxies have coronas.

RUBIN (to Kalnajs) : It is true that the analysis of the rotation curves presents the mass interior to any R, but not the distribution of the mass. Thus, while the mass could be in a disk, there are other reasons, stability especially, that suggest a halo. The velocities you show for NGC 4378 and 7217 come from our data, and both rotation curves are fairly exceptional in that the velocities fall slightly with increasing R. I suspect you would have more difficulty in fitting with constant M/L a flat or slightly rising rotation curve which extends to very large radii. In any case, it seems to me, you must be saying that the surface brightness of these galaxies falls slower than exponentially with increasing R.

GOTTESMAN : As a contrast to Dr Haud's presentation, I would like to offer the barred spiral NGC 3992. The HI in this system has been well-observed at the VLA. This data allows a mass to be determined within a radial distance of 15 - 20 kpc. There are also three satellites whose atomic hydrogen emission has been detected. Following the method of Bahcall and Tremaine one can use the satellites to calculate a mass within $\sim$ 60 kpc of NGC 3992. Within the errors, the two masses calculated are the same ($\sim 2\ 10^{11}\ M_\odot$).
One can also invert the argument. If NGC 3992 had an isothermal halo, the expected velocities of the satellites would be 3-4 times greater than observed values. Jim Hunter and I have therefore concluded that there is little or no room for a massive halo 10 times greater than the disk mass. The problem then remains to explain the observed flat rotation curve.

HAUD : I think that a mass calculated from three satellites only may have large statistical errors.