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DYNAMICAL EVIDENCE ON MASSIVE CORONAS OF GALAXIES

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Abstract. Evidence is presented that galaxies are surrounded by massive coronas exceeding the masses of known stars by one order of magnitude. The virial mass discrepancy in clusters of galaxies is considerably reduced, the total density of matter in the galaxies being 20 % of the critical cosmological density.

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A long-standing unresolved problem in galactic astronomy is the mass discrepancy in clusters of galaxies. The virial mass of the cluster per galaxy and the mass-to-luminosity ratio are considerably larger than the corresponding quantities for individual galaxies. Explanation of this discrepancy by expansion and by recent origin of clusters is in contradiction to our present knowledge of the physical evolution and ages of galaxies[1]. Therefore one has to adopt an alternative hypothesis that the clusters of galaxies are stabilized by hidden matter.

The discovery of X-ray emission from clusters of galaxies can be explained in terms of hot intracluster gas. The mass of this gas, however, is insufficient to stabilize clusters[2].

Another possibility of removing the mass discrepancy is to suppose that the masses of individual galaxies have been underestimated. This hypothesis is supported by the fact of a very slow decrease in the rotational velocity of spiral galaxies, which indicates large amounts of matter in their outer regions[3]. On the other hand, the discovery of large halos of elliptical galaxies[4,5] shows that elliptical galaxies also contain previously unseen matter.

There exist several mass estimates of galaxies based on the new observational data mentioned above[6,7]. But a critical analysis shows that these estimates are very uncertain.

In the present paper we shall make an attempt to obtain more exact information on the mass distribution in the outer regions of galaxies.

Let us consider a test body moving in a circular orbit of radius R with a velocity V_c around the centre of the galaxy. If mass distribution is spherical, then

$$M(R) = RV_c^2/G$$

is the mass of the galaxy inside the sphere of radius R , G being the constant of gravity. The same formula can be used for a nonspherical mass distribution, neglecting an error of some ten per cent.

Spiral galaxies contain neutral hydrogen and HII regions moving in the plane of the galaxy in nearly circular orbits. Observations of these objects permit us to calculate the function $M(R)$ in some galaxies to rather large distances from the centre. We have made those calculations for 5 galaxies of different mass. The results for one galaxy (IC 342) are given in Fig. 1.

For all galaxies we have also found the mass distribution $M_s(R)$ of known stellar populations - the bulge, the halo and the disc. We assume that these populations are physically homogeneous, in particular that the mass-to-luminosity ratio of stars is constant for the whole population. The relevant parameters (luminosity L, effective radius R_0, mass-to-luminosity ratio f, axial ratio of equidensity ellipsoids ε) for all populations have been determined from combined photometric, spectrophotometric, kinematical and radio observations, using the method described in [7,8].

The resulting mass distribution of known stars $M_s(R)$ deviates considerably from the mass distribution $M(R)$, derived from the rotation curve. Rejecting the possibility of large systematic deviations from the circular velocity in the outer regions of galaxies, we come to the conclusion that galaxies contain a previously unrecognized massive population. It is convenient to call this population corona[7]. We have estimated the parameters of coronas for the five galaxies (Table 1, subscript c), adopting for simplicity an exponential density law

$$\varrho(R) = \varrho_c \exp(-R/R_0)$$

with spherical symmetry (a small axial ratio ε would result in a large part of kinetic energy in the form of rotation in contradiction to the recent results of Ostriker and Peebles[9]).

Table 1 — Parameters of Galactic Populations Individual Galaxies

Galaxy	L_s $10^{10} L_\odot$	M_s $10^{10} M_\odot$	M_c $10^{10} M_\odot$	R_{oc} kpc	$-\log \varrho_c$ g cm^{-3}
NGC 224	2.0	17	>35	>14	24.58
NGC 300	0.45	2.0	>2.9	>6	24.60
NGC 598	0.32	1.5	>2.8	>6	24.54
NGC 3031	1.8	12	>21	>11	24.52
IC 342	4.9	12	>34	>13	24.55

The available data permit us to derive the central density of the corona, ϱ_C, with great accuracy. The length of the observed rotation curve, however, is insufficient to determine the mass and extent of the corona.

To determine the total masses and dimensions of the galactic coronas, more distant test-bodies are needed. For this purpose isolated pairs of galaxies can be used, regarding secondary galaxies as test-bodies for determining the mass distribution of primary galaxies[10].

In the case of double galaxies we known the radial component of differential velocity, $v_r = \Delta V_r$. The projection factor, $p = V_C^2/v_r^2$, depending on the orientation of the velocity vector and on the shape of the orbit, remains unknown, but its expected value, $\langle p \rangle$, can be calculated. Therefore the mass distribution function can be found statistically only:

$$\langle M(R) \rangle = \langle p \rangle \langle R v_r^2 \rangle / G ,$$

where $\langle R v_r^2 \rangle$ is the corresponding mean value for a sample of pairs of galaxies.

From available sources [11-13] we have collected data on 105 pairs of galaxies with known types, radial velocities and estimates of magnitudes and dimensions. To prevent the sample from being contaminated by optical pairs, only pairs with signs of interaction or with a small differential motion $\Delta V_r / V_r < 0.23$ have been considered. The distances have been determined from the mean recession velocity $\bar{V}_r$, using the Hubble constant 50 km sec^{-1} Mpc^{-1}. For some nearby pairs other distance indicators have been used. The pairs have been divided according to the radius R into 5 equal groups. The resulting function $\langle M(R) \rangle$ is shown in Fig. 2.

We have also calculated the average mass distribution of known stellar populations $M_S(R)$ and have determined the distribution of mass in the corona $M_C(R)$ (Fig. 2). The resulting central density agrees well with our previous estimates from individual galaxies. The use of distant satellites as test-bodies enables us to derive masses and effective radii of coronas with a sufficient accuracy. There are enough pairs in our sample to estimate the masses of coronas separately for elliptical galaxies as primary ones and for bright and intermediate spirals. The estimated parameters are given in Table 2. In the case of elliptical primaries the total masses of coronas may be underestimated.

Table 2 Parameters of Galactic Populations
Pairs of Galaxies

Type of Primary Galaxy	$\langle L_s \rangle$ $10^{10} L_\odot$	$\langle M_s \rangle$ $10^{10} M_\odot$	$\langle M_c \rangle$ $10^{10} M_\odot$	$\langle R_{oc} \rangle$ kpc	Number of pairs
Spiral (intermediate)	3.8	38	350	25	33
Spiral (bright)	15	150	1600	47	32
Elliptical	12	250	$\geqslant 1500$	$\geqslant 46$	40

The main results of this study can be summarized as follows.

1. The combined kinematic and photometric data on single and double galaxies indicate the existence of a new population - corona - in all the galaxies and systems of galaxies studied.

2. The mass of galactic coronas exceeds the mass of populations of known stars by one order of magnitude, the effective dimensions - by a similar factor. The central density of coronas is surprisingly constant: log $\varrho_C = -24.5 \pm 0.1$ (g cm^{-3}).

3. The presence of massive coronas in galaxies considerably reduces (if not removes) the virial mass discrepancy in clusters of galaxies. The mass-to-luminosity ratio arises to $f \approx 100$ for spiral and $f \geqslant 120$ for elliptical galaxies. We recall that with H = 50km sec^{-1}Mpc^{-1} this ratio for the Coma cluster is 170[1].

4. According to new estimates the total mass density of matter in galaxies is 20 % of the critical cosmological density.

The possible physical nature of galactic coronas will be discussed in a separate paper.

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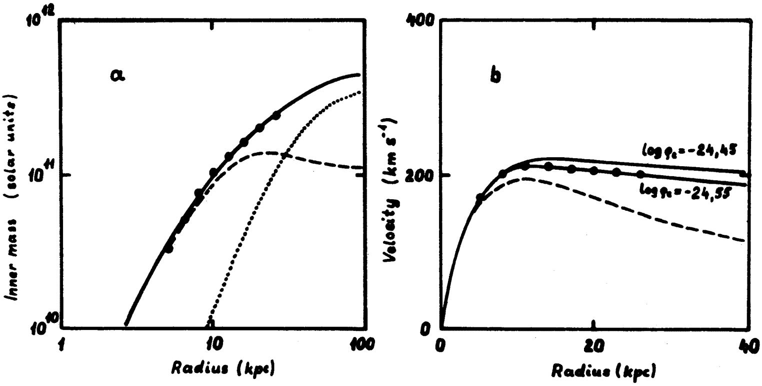

Fig. 1. The distributions of the inner mass $M(R)$ (a) and the circular velocity V_c (b) in the galaxy IC 342. Dots represent observed values, dashed lines - model functions for known stellar populations, dotted lines - the distributions for the corona and solid lines - the total distributions. In Fig. 1b two variants of the total velocity distribution are given to demonstrate its dependence on the central density of the corona.

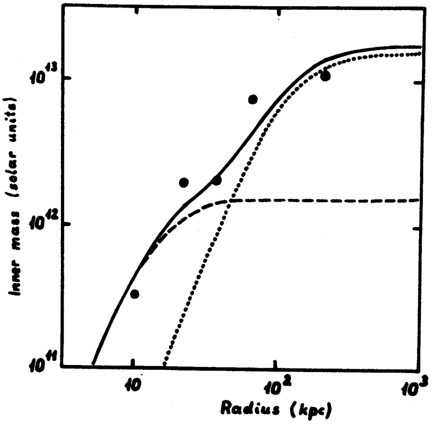

Fig. 2. The distribution of the mean inner mass $\langle M(R) \rangle$, obtained from 105 pairs of galaxies. The symbols as for Fig. 1.