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THE MASS-TO-LIGHT RATIO OF THE VISIBLE MATTER

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Abstract. The physical properties of galactic populations are studied on the basis of modelling the structure of nearby galaxies. From these models, the relation between the mass-to-light ratios for old spheroidal subsystems and their colour indices was constructed. It is concluded that both old and young stars are present in the bulges of late-type (Sc – Sdm) spiral galaxies. The effective age of these bulges is 1.5–4 Gyr. For the bulges of early-type spirals (S0 – Sb) and ellipticals, the differences in their M/L ratios must be ascribed to different initial chemical composition. A similar relation was constructed also for the disk models. For a given $B-V$, a larger scatter of mass-to-light ratios exists. Probably, this is the result of infall or capture events unrelated to the bulk of the galaxy formation process. Because our sample of galaxies includes representatives of all the main morphological types with a wide range of luminosities, we calculated the mean mass-to-light ratio in our local neighbourhood ($V_0 \leq 1000$ km/s). By using the luminosity function of the "standard" Virgo cluster of galaxies, the mean luminosity weighed mass-to-light ratio of the visible matter was found to be $M/L_B = 4.1 \pm 1.4$ $M_\odot/L_\odot$. When using the luminosity function of the field galaxies, the corresponding value is $M/L_B = 3.7 \pm 1.3$ $M_\odot/L_\odot$.

Key words: galaxies: structure, stellar content, evolution

1. Introduction

During the collapse of the protogalaxy and continuing star formation, the morphology of galaxies was established. The star formation products of different eras (the stellar populations) differ from each other physically, having different spatial distribution, chemical composition, as well as different kinematic properties that maintain the spatial distributions. While studying the structure of stellar populations in galaxies, it is possible to obtain quantitative information which helps us to understand the formation and evolution processes. The most effective tool for the analysis of the structure of stellar systems is the construction of models. An appropriate empirical model of a galaxy should represent distribution of various structural constituents (globular clusters, gas, etc.), kinematical data, changes in chemical composition, etc. It is clear that such models must have multiple components.

As an example, a useful diagnostics of galactic structure and evolution, at least for spheroidal systems, is provided by the structure of isophotes and the metallicity gradients that are often observed in elliptical galaxies and bulges of spirals (Kormendy and Djorgovski 1989). Models of galaxy formation involving dissipative or dissipationless collapse or mergers (Larson 1990) predict relations between colour distribution and stellar density. Also, scenarios of galaxy formation, in which mergers play an important role, predict core – halo colour differences as opposed to smooth continuous gradients. These changes are represented in our models as transitions from one subsystem to another.

In the present paper, on the basis of the models constructed earlier (Tenjes 1993, Tenjes et al. 1991, 1993), we analyse the most important parameter of galactic subsystems – the mass-to-luminosity ratio. The M/L ratio of a stellar ensemble depends on the balance between the amount of large- and low-mass stars. This, in turn, depends mainly on the age and initial metallicity of the ensemble. We investigate what we can conclude about these quantities. A sample of galaxies under the modelling (q.v. Table 1) was selected from the list of elite galaxies (Tenjes et al. 1982).

2. Overview of the model components – the galactic populations

Photometry of galaxies made in excellent seeing conditions reveals the presence of a compact and bright *nucleus* in the very centre of a galaxy. Kinematical data indicate that the nucleus is dynamically nearly independent from the remaining body of a galaxy.

Although the nuclei are the prominent structural features, in the context of the present paper they are of little importance.

The spheroidal part of galaxies is far from physical homogeneity, and several components must be distinguished there. *The bulge* is dominated by old stars with a normal metal content. Its flattening is modest with comparable amounts of rotational and pressure support. The inner part of the bulge is often more metal-rich (the colour index U–B may differ by 0.1 – 0.3 mag). For this reason we can separate a metal-rich *core* from the bulge. The third spheroidal component, *the halo,* is an old metal-poor population consisting of globular clusters and old field stars (like RR Lyrae variables). The total mass of the halo is larger, by two orders of magnitude, than the total mass of globular clusters.

In spiral galaxies there exist two disk-like components. *The disk* consists of stars of normal metal content but with quite different ages (the mean age is about 5–7 Gyr). From observations it follows that the disk has a nearly exponential density distribution. The youngest stars belong to the "spiral-arm population" which we call *the flat subsystem.* Typical representatives of this component are open clusters, OB-associations, O–B stars, etc. The flat subsystem includes also a nonstellar component (neutral and molecular hydrogen and dust). Its flatness is the largest. In our models we fix the axial ratio of the flat subsystems on the basis of our Galaxy. For disk-like components we allow a toroidal structure, i.e. the central density minimum.

Different kinds of observations (the rotational curves, the X-ray data, the gravitational lensing effects) show that a significant amount of dark matter may be associated with galaxies. Following Einasto et al. (1974), we call this component *the corona.* To probe the gravitational field of the corona, most distant test bodies must be used, for example, dwarf satellite galaxies, surrounding the parent galaxy.

3. Model construction

A detailed description of the modelling technique has been given in Tenjes et al. (1993), so here we shall review only the basic features.

We assume a galaxy to consist of several physically homogeneous components with masses M, mass-to-light ratios M/L and fixed colour indices. The density distribution of each component is approximated as an inhomogeneous ellipsoid or as a sum of these ellipsoids.

The density distribution of the visible components is approximated by the exponential law

$$\rho(a) = \rho(0)\exp(-[a/(a_c)]^{1/N}),$$

where a is the distance along the semi-major axis of the ellipsoid, a_c is some characteristic radius, N is the structural parameter and $\rho(0)$ is the central density. The density distribution of the corona is assumed to follow the modified isothermal law

$$\rho(a) = \begin{cases} \rho(0)([1+(\frac{a}{a_c})^2]^{-1} - [1+(\frac{a^0}{a_c})^2]^{-1}) & a \leq a^0 \\ 0 & a > a^0, \end{cases}$$

where a^0 is the outer cut-off radius. From the analysis of galactic groups by Vennik (1986) we find that the distribution of dwarf galaxies in a synthetic group is well described by the parameter $a^0/a_0 = 5.7$.

The surface brightness distribution for an inhomogeneous ellipsoid is

$$L(A) = 2\sum_i^n \frac{\epsilon_i}{E_i f_i} \int_A^\infty \frac{\rho_i(a)a da}{(a^2 - A^2)^{1/2}}.$$

In this equation n is the number of the components, A is the major semi-axis of equidensity ellipse of the projected light distribution, ϵ_i and E_i are the true and apparent isophotal axial ratios of the component i and f_i is the mass-to-light ratio of the component i.

The rotational velocities can be calculated from the equation

$$v_i^2(R) = 4\pi\epsilon_i G \int_0^R \frac{\rho_i(a)a^2 da}{(R^2 - e_i^2 a^2)^{1/2}},$$

$$V^2(R) = \sum_i^n v_i^2(R),$$

where G is the gravitational constant, R is the distance in the galactic plane and $e_i^2 = 1 - \epsilon_i^2$ is the eccentricity.

For spheroidal components the masses can be calculated from the tensor virial theorem

$$-M\mathbf{D} = \mathbf{W},$$

where $\mathbf{D}$ is the velocity dispersion tensor,

$$\mathbf{W} = \int \rho \vec{r} \otimes \vec{g} dV$$

is the potential energy tensor and $\vec{g}$ is the gravitational acceleration. For n-component systems the object of a "test" subsystem with index k moves under the gravitational potential of the whole galaxy and for this subsystem

$$-M_k \mathbf{D}_k = \int \rho_k \vec{r} \otimes \sum_{l=1}^{n} \vec{g}_l dV,$$

where $\vec{g}_l$ is the gravitational acceleration due to the subsystem with the index l. The mean line-of-sight velocity dispersion is in general

$$\langle \sigma^2 \rangle = \vec{e} \cdot \mathbf{D} \vec{e},$$

where $\vec{e} = (\cos\alpha, \cos\beta, \cos\gamma)$ is the line-of-sight unit vector. In components,

$$\langle \sigma^2 \rangle = d_{11} \cos^2\alpha + d_{22} \cos^2\beta + d_{33} \cos\gamma +$$

$$+2(d_{12} \cos\alpha \cos\beta + d_{13} \cos\alpha \cos\gamma + d_{23} \cos\beta \cos\gamma),$$

where d_{ij} are the elements of the tensor $\mathbf{D}$. In our case, we have

$$\langle \sigma^2 \rangle_k = \frac{G}{a_{0k}} \sum_{l=1}^{n} H_{kl} M_l.$$

The dimensionless coefficients H_{kl} depend on the mass distribution laws of the components k and l.

The above formulae are the main relations connecting model parameters with the observational data.

The best-approximation model parameters have been found on the basis of the least-squares method (Einasto and Haud 1989). In general, the set of initial data may consist of:

1) the surface photometry in three to seven colours,
2) the distribution of young objects,
3) the distribution of globular clusters,
4) the stellar velocity dispersions,
5) the rotation velocities of the gas,
6) the kinematics of globular clusters, planetary nebulae and satellite galaxies.

As an example in the case of modelling of the Andromeda galaxy, M31 (Tenjes et al. 1993), the number of observational data points was 390. The initial number of degrees of freedom was 57 (6 populations with nine parameters each (ϵ , a_0, M, κ, N, f_B, f_U, f_V, f_R) and the corona with three parameters (ϵ, a_0, M)). This number was reduced to 32, as some parameters can be fixed before the final approximation:

1) the model assumptions reduce five parameters;
2) the nucleus can be handled independently (eight parameters);
3) all halo parameters (with the exception of mass) result from the distribution of globular clusters (seven parameters);
4) the parameters ϵ, a_0, N, κ, M for a young subsystem can be determined separately (five parameters).

Further, the space of the remaining 32 parameters was split into several nearly separate regions which were handled independently. As a result, only seven parameters appear to be the most crucial: the radius and the structure parameters of the core, the bulge and the disk and the central depression of the disk. The space of these seven parameters was studied and the best-approximation solution was found.

A similar set of models was constructed for all galaxies of our sample, and the calculated model parameters are given in Tenjes (1993).

4. The mass-to-light ratios for spheroidal and disk subsystems

Sandage et al. (1970) suggested that the relative size of the spheroidal component in galaxies is determined by the relative amount of a low-angular-momentum matter in a protogalaxy, and that this matter fragments into stars during the rapid collapse phase, while the high-mean-angular-momentum matter subsequently settles to the disk in the gaseous form. Therefore, the spheroids and the disks should experience different star formation histories and these two components should be analysed separately.

The chemical evolution of a stellar system can be well represented by the dependence of the mass-to-light ratio of the stellar aggregate on its colour indices. In Fig. 1 we plot the calculated M/L_B versus $B-V$ for spheroidal subsystems – the core and the bulge. All the luminosities and colour indices are corrected for the absorption in our Galaxy according to Burstein and Heiles (1984).

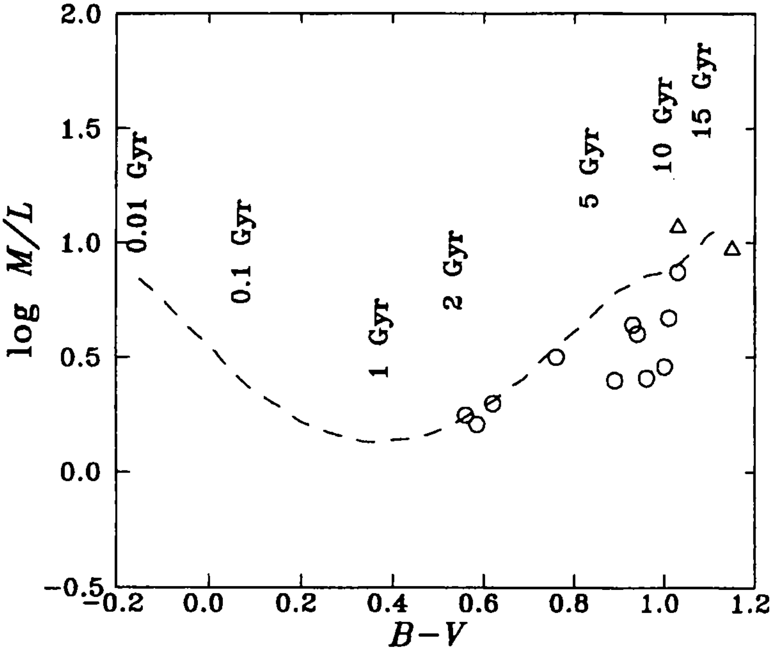

Fig. 1. The mass-to-light ratios in B-colour, M/L_B, for spheroidal galactic subsystems versus their colour index $B-V$. Triangles denote the core, open circles are for the bulge. The dashed curve with corresponding ages in the units of 10^9 yrs is from the chemical evolution model by Traat (1990).

It is seen that the spheroidal components lie in two quite separate regions. Points on the left-hand side (with colour indices 0.55–0.80) belong to late-type Sc – Sdm spiral galaxies, while those on the right-hand side belong to early-type spirals and elliptical galaxies.

The distinct structure of the bulges of early- and late-type spiral galaxies is supported by an analysis of their UV-colours. It was found by Frogel (1985) that the bulges of late-type spirals have energy distributions that are significantly bluer than those of early-type spirals and E galaxies. Their blue energy distribution arises from a population of young stars mixed with the old population. In fact, it may be misleading to speak of an "old" and "young" population in Sc–Sm galaxies, since star formation has probably never really stopped in many of them. This is further supported by the fact that in the central regions of late-type spirals, modelled by us, there is no or is only a little gas depression observed. This is obviously not the case for the early-type spirals (M31, M81, M104), where the disk-like components must have a toroidal structure (Einasto et al. 1980). From the comparison of our models with the chemical evolution models by Traat (1990) we find that their effective age is 1.5–4 Gyr.

The points corresponding to early-type bulges and ellipticals do not lie on the evolutionary curve. It is not possible to explain their position either by different star-formation rates or by gas accretion events. Probably the differences in their mass-to-light ratios must be ascribed to different initial chemical composition, from $Z = 0.02$ to $Z = 0.003$. However, we would like to emphasize that the conversion of the M/L versus $B-V$ relation into the initial value of Z depends also on other stellar evolution parameters (the rate of star formation, accretion processes, the form of IMF, etc.) and therefore is a complicated problem.

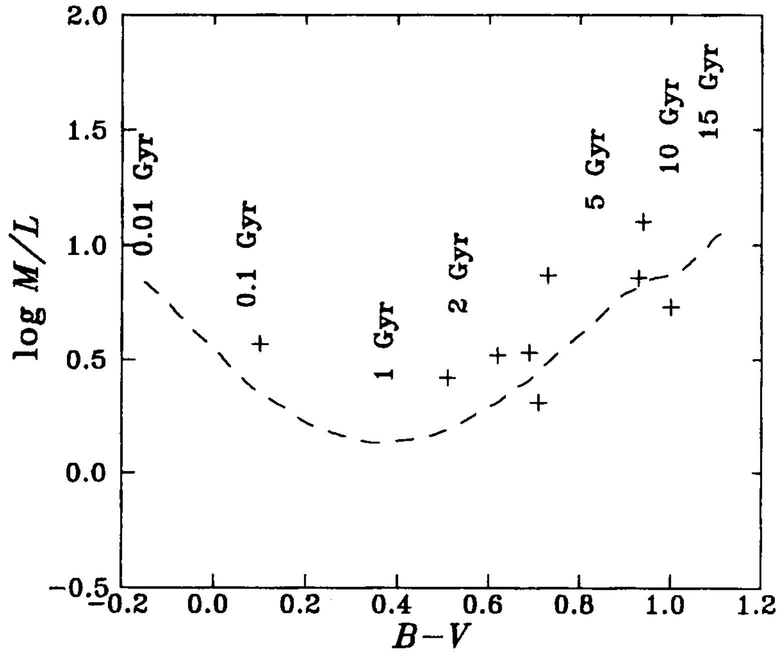

Fig. 2. Dependence of mass-to-light ratios M/L_B for disk models on their colour index $B-V$.

A similar relation was constructed also for disk models (Fig. 2). For a given $B-V$, a larger scatter of mass-to-light ratios exists. Probably this is the result of infall or capture events unrelated to the bulk of the galaxy-formation process.

5. The mean mass-to-light ratio of visible matter

One of the crucial problems in extragalactic astronomy is the decomposition of a galaxy into ordinary and dark matter populations and a study of their relationship. It is difficult to calculate directly the masses of visible and dark matter, because the dynamical information concerns the sum of the two kinds of matter and, as a rule, we do not know the mass distribution of the optically visible galactic populations. For this reason, some simplifying assumptions are often made, such as the "maximum disk" or "maximum bulge" hypothesis etc. However, in order to increase the accuracy of our final results, it is desirable to determine all the parameters of the galactic populations directly from observations. To do so, we have to use all the available data on populations, as it was described in Sect. 3.

In Table 1 calculated mass-to-light ratios of the visible matter are given for our sample of galaxies.

Table 1. The M/L ratios of the visible matter

Name	Type	Absolute magnitude	Distance (Mpc)	M/L_B ($M_\odot/L_\odot$)
Fornax	E0	–12.2	0.16	4.1
Sculptor	E3	–10.8	0.07	9.7
NGC 221	cE2	–15.7	0.7	2.1
NGC 3379	E1	–19.6	8.0	5.0
NGC 4486	E0-1	–22.2	20.	4.9
NGC 3115	S0	–20.0	10.	4.8
NGC 4594	SA(s)a	–22.3	20.	2.4
NGC 3031	SA(s)ab	–20.2	3.3	5.5
NGC 224	SA(s)b	–20.8	0.7	4.8
NGC 4321	SAB(s)bc	–20.7	20.	2.9
NGC 5457	SAB(s)cd	–21.3	7.2	3.3
NGC 6503	SA(s)cd	–18.0	6.1	2.0
NGC 7793	SA(s)dm	–18.7	3.1	2.4
NGC 2366	IB(s)m	–16.9	3.2	4.1

Knowing the luminosity function (LF) of galaxies, the mean mass-to-light ratio of the visible matter can be calculated. The galaxies in our sample cover the range in absolute luminosities from 10^7 to 10^{11} $L_\odot$. However, as it was emphasized by Binggeli et al. (1988), there is no universal LF for all galaxy types. Moreover, the mass-to-light ratios of the galaxies seem to depend rather on the morphological types than on their luminosities. (For elliptical galaxies Bacon et al. (1985) did not detect any clear correlation between the M/L ratio and the absolute luminosity of a galaxy.) Because the most complete data-set still is available for the "standard" Virgo cluster, we used the LFs by Sandage et al. (1985) to calculate the weights to the relative luminosity contribution of E, S0, Sa+Sb, Sc, Sd+Sm and dE morphological types. Our data from Table 1, together with the calculated weights, give the mean luminosity weighed mass-to-light ratio of the visible matter $M/L_B = 4.1 \pm 1.4$ $M_\odot/L_\odot$. While using the weights resulting from the LFs of a sample of field galaxies by Kraan-Korteweg & Tammann (1979) and Tammann et al. (1979), the mean luminosity weighted mass-to-light ratio is $M/L_B = 3.7 \pm 1.3$ $M_\odot/L_\odot$.

6. Discussion

The number of galaxies used is the minimum number that one needs for a statistical analysis. But at present it is difficult to increase the sample considerably, as we must limit ourselves only to well-observed galaxies.

In principle, the physical conditions in collapsing interstellar matter may vary largely from galaxy to galaxy. This must result in very different values for their M/L ratios. As it is seen from Table 1, the M/L ratio of visible matter varies surprisingly little from galaxy to galaxy, indicating rather similar overall properties of collapsing interstellar matter, as well as the star formation process.

We also find from our models that there is no universal rule whether to use the "maximum disk" model or not. It rather seems that every galaxy must be handled individually, and some kind of optimum disk must be chosen for every particular case.

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