Star Formation Processes and Chemical Evolution:

More Invited Reviews and Contributed Papers

Structure and Evolution of Stellar Populations in Local Group Galaxies

J. Einasto and P. Tenjes

Tartu Observatory, EE-2444 Tõravere, Estonia

Abstract. We use detailed modeling of stellar populations of nearby galaxies to calculate population parameters. Our sample of galaxies includes most galaxies of the Local Group and several more distant giant galaxies. Available data are sufficient to decompose galaxies into the nucleus, the metal rich core, the bulge, the halo, the young and old disks, and the dark halo. We compare mass-to-luminosity ratios and colors of bulges, disks and halos with results of models of galactic chemical evolution. The luminosity-weighted mean of the mass-to-luminosity ratio of visible stellar population is $M/L_B = 4 \pm 1.4$ in solar units. This ratio is surprisingly constant for galaxies of very different absolute magnitude.

1. Introduction

Direct photometric, spectroscopic and dynamical observations yield integrated information on galaxies. To find physical parameters of individual galactic populations, detailed modeling of galaxies and their populations is needed. In most models only 3 luminous populations are considered, the bulge, the halo and the disk, and additionally the dark halo. A method to determine population parameters from observational data has been elaborated by Einasto (1974) and Einasto & Haud (1989). This method permits to decompose galaxies into more stellar populations. The first series of models was reported at the First European Astronomical Meeting (Einasto 1974). A new series of models with better data and improved modeling procedure is now in progress, so far models are published for our Galaxy (Haud & Einasto 1989), M87 (Tenjes, Einasto & Haud 1991), M31 (Tenjes, Haud & Einasto 1994), M81 (Tenjes, Haud & Einasto 1998). Modeling information is presently available for most members of the Local Group and several other galaxies. Data for more distant bright galaxies is useful to compare population parameters for galaxies of different morphological types.

Here we shall review the principal modeling data for all galaxies for which detailed models are available. We consider only three principal populations of galaxies, the bulge, halo and disk, data on other populations can be found in original publications. We compare population parameters with results of calculation of chemical evolution of galaxies.

2. Population Models

In our models we assume that galaxies are in hydrostatic equilibrium, i.e. that rotational velocities of young disk objects can be identified with circular velocities. We describe the spatial density distribution of populations by the modified exponential law:

$$\rho(a) = \rho(0)\exp(-[a/(ka_0)]^{1/N}).$$

Here $\rho(0)$ is the central density of the population, a is the major semi-axis of the equidensity ellipsoid, a_0 is the harmonic mean radius of the population, and k and N are dimensionless structural parameters. The parameter N determines the density law of the population; $N = 0.5$, $N = 1$ and $N = 4$ correspond to the conventional Gaussian, exponential, and de Vaucouleurs models (de Vaucouleurs applied this law for projected density, here we use it for the spatial density).

Table 1. Galaxy parameters

Name	M_B	Type	Disk		Bulge		Halo		Visible matter		Total
			M/L_B	$B-V$	M/L_B	$B-V$	M/L_B	$B-V$	M/L_B	$B-V$	M/L_B
M31	−20.8	Sb	7.1	0.71	3.0	0.98	2.0	0.79	4.8	0.80	200
M32	−15.7	cE2			2.4	0.90			2.4	0.90	
M81	−20.2	Sab	9.4	0.76	5.8	1.02	2.4	0.70	5.4	0.83	230
M87	−22.2	E0-1			8.0	1.01	2.5	0.74	4.9	0.87	1200:
M104	−22.3	Sa	5.0	1.00	2.9	1.01	2.7	0.77	3.2	0.87	47:
N 3115	−20.0	S0	6.7	0.93	4.9	1.00	2.3	0.75	4.6	0.87	180
N 2841	−20.4	Sb	9.3	0.95	7.7	0.95			8.9	0.95	220
N 4321	−20.7	Sbc	3.3	0.74	1.7	0.60			3.1	0.71	?
N 5457	−21.3	Scd	3.2	0.62	3.4	0.78			3.3	0.62	150
N 6503	−18.0	Scd	2.0	0.71	1.8	0.57			2.0	0.71	130:
N 7793	−18.7	Sdm	2.5	0.55	2.0	0.62			2.5	0.55	300:
For	−12.1	dSph					1.2	0.63	1.2	0.63	> 12
Scl	−10.1	dSph					2.0	0.67	2.0	0.67	> 8
Car	−8.0	dSph					1.3	0.70	1.3	0.70	> 40
Dra	−8.1	dSph					1.9	0.62	1.9	0.62	> 80
UMi	−8.3	dSph					1.5	0.63	1.5	0.63	> 60
Leo I	−10.3	dSph					1.4	0.80	1.4	0.80	> 7
Sex	−8.4	dSph					1.6	0.66	1.6	0.66	> 120
Leo II	−8.6	dSph					1.7	0.65	1.7	0.65	> 10

Population models are found by successive approximations. First, a zero approximation model is determined from fits of observed descriptive functions with standard functions (density law, rotational velocity law etc.). Using approximate values for population parameters, model descriptive functions are calculated and compared with observations. The difference between calculated and observed functions gives information to correct population parameters; and the next approximation is found. The program looks at which population parameters influence descriptive functions less; these parameters are temporarily excluded from the least squares fit. Our experience shows that the process converges rapidly and the population parameters found are rather stable, i.e. small deviations in observed functions do not lead to large deviations of population parameters.
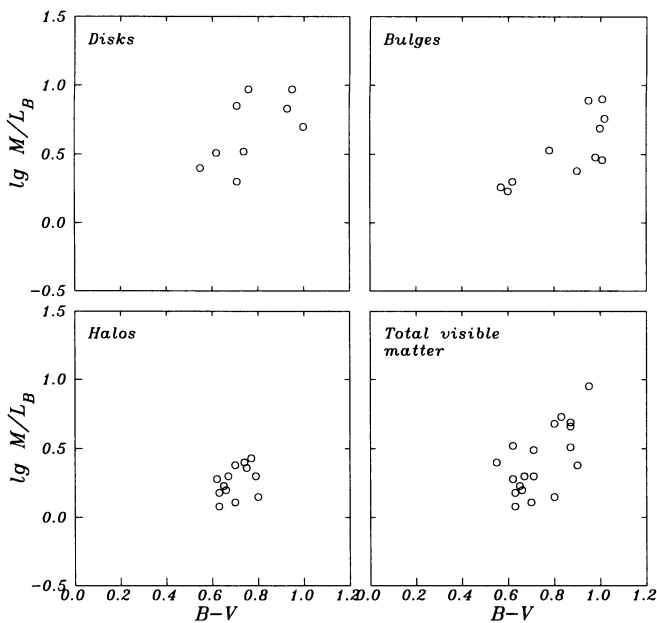
Figure 1.   Population parameters for galactic disks, bulges and halos, and for all visible matter.

3.   Parameters of Stellar Populations

Table 1 gives a summary of the main population parameters for our models. We give here only two parameters for each population, the mass-to-luminosity ratio, M/L_B, and the color index, $B - V$. Additionally we give the mass-to-luminosity ratio and the color for the whole galaxy (for visible populations). M/L_B is given also for the galaxy as a whole, including its dark halo. These parameters characterize the mean stellar content and the evolutionary status of the galaxy.

Population parameters are plotted in Fig. 1, separately for disks, bulges, and halos, and for the total visible matter. We see that the parameters of disks and bulges have a fairly large spread, whereas the spread of parameters for halos is much smaller. Evidently, halos are more homogeneous in their stellar content. There exists a weak relation between the mean color and the mass-to-luminosity ratio for disks, bulges and total visible matter: redder populations have higher mass-to-luminosity ratios.

The relation between color and M/L_B is easily explained by theoretical models, see Fig. 2. In young populations luminous blue main sequence stars dominate, in old populations the dominating stars are red giants which are less luminous and red. The agreement of evolution models with population models is very good quantitatively. This agreement shows that current models of chemical evolution are accurate enough, and that our population models describe actual properties of populations satisfactorily.
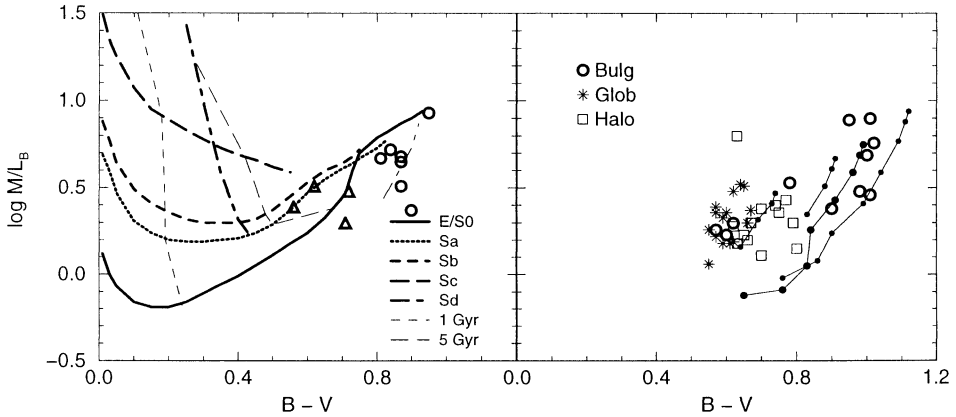
Figure 2.   Comparison of parameters of galactic populations with models of chemical evolution. The left panel shows integrated data on galaxies, the right panel, data on galactic populations. Galaxies are denoted as follows: open circles – E/S0, Sa, Sb galaxies; triangles – Sc and Sd galaxies. Chemical evolution models are given for galaxies of different morphological type (solid lines); dotted lines show isochrones. Evolution models are taken from Tantalo et al. (1998). In right panel open circles are for bulges, stars for globular clusters, squares for halos. Solid lines show evolution models for single populations of metallicities [Fe/H] = −2, −1, −0.3, 0, 0.4 (from left to right) and ages from 1.5 to 17 Gyr (from bottom up) (Worthey 1994, 1996). For metallicities [Fe/H] ≤ −0.3 only ages greater than 8 Gyr are available.

It is interesting to compare the mean M/L_B of galaxies with their absolute magnitudes. This is done in Fig. 3. Our models span a very large range in absolute magnitude – dwarf spheroidal galaxies are more than million times less luminous than giant spiral and elliptical galaxies. The figure shows, in a different perspective, that stellar halos have a rather small spread of their properties. For disks and bulges the spread is larger, but also rather limited: all populations have M/L_B between 1 and 10.

The mean mass-to-luminosity ratio for all visible matter, weighed with the luminosities of galaxies, is $M/L_B = 4.1 \pm 1.4$ for the luminosity function of Sandage et al. (1985).

4.   Discussion and Summary

The first set of population models was reported at the First European Astronomical Meeting in Athens 1972. At this time models for our Galaxy, M31, M32, M87, Fornax and Sculptor galaxy were available. This first application of the modeling method had several important consequences. It was clear that galaxies are surrounded by dark halos or coronas (Einasto 1974). Further it was found that all stellar populations have a mass-to-luminosity ratio between 1 and ≈ 10 (except very metal-rich nuclei and cores which have slightly higher M/L_B
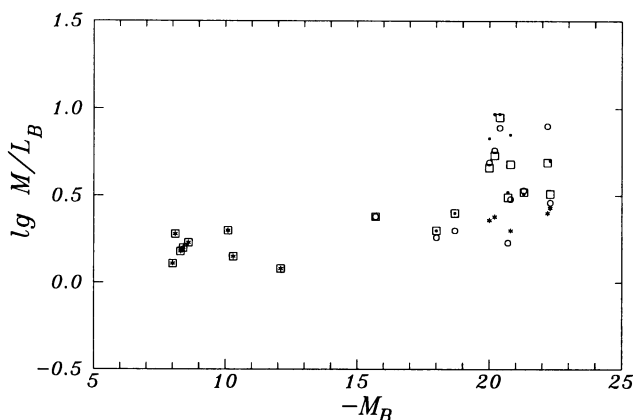
Figure 3. Mass-to-luminosity ratio of galactic populations in galaxies of different total absolute magnitude, M_B. Open circles denote bulges, asterisks – halos, dots – disks, open squares denote total visible matter in galaxies.

values). Remember that in the early 1970s, most astronomers believed that M/L_B for bulges of elliptical galaxies was very high (to explain large relative velocities of their companion galaxies). The oldest metal poor population, the stellar halo, has the lowest M/L_B of all populations. On the other hand, the extended dark population has extremely high M/L_B, and thus differs very much from all conventional stellar populations. A few years later a direct confirmation of a low M/L_B for bulges of elliptical galaxies followed when Faber et al. (1976) measured the rotational velocity of the thin gaseous disk of the Sombrero galaxy and derived for the bulge of this galaxy $M/L_B \approx 3$, in very good agreement with our population models for bulges of other galaxies.

Modern modeling data have confirmed these early results. The basic difference between old and new models lies in the fact that, according to new data, velocity dispersions near the centers of galaxies are lower than believed earlier, which leads to smaller values of M/L_B. Thus the spread of M/L_B of stellar populations is, according to new data, smaller than assumed in the 1970s. The contrast between ordinary populations and the dark population is even greater. We repeat here the main differences in parameters of stellar populations and the dark matter halo.

1. All stellar populations have $1 \le M/L_B \le 10$, the dark matter population has $M/L_B >> 1000$.

2. There exists a continuous transition of stellar populations from stellar halo to bulge, from bulge to old disk, from old to young disk; these intermediate populations are observed in our Galaxy. All stellar populations contain a continuous sequence of stars of different mass, some of these stars have masses corresponding to the mass of red giants for the age of the population. Red giants have high luminosity, thus all stellar populations are visible, in contrast to the dark population.

3. The density of stellar populations rapidly increases towards the plane or the center of the galaxy, the dark matter population has very low central concentration of mass.

These arguments show qualitatively that dark matter must have originated much earlier than ordinary stellar populations, and that there must be a large gap between the formation time of the dark halo and oldest visible stellar populations, since there exists no intermediate population between the dark and ordinary populations. These arguments were known already in the early 1970s and played a crucial role in the development of the concept of dark matter in the Universe.

In the present set of models, the parameters of stellar populations are fixed rather well (for the discussion of parameter errors see original papers). The central density of the dark halo is also fixed with good accuracy. The least accurate parameter is the radius of the dark halo and its total mass, since there are only a few mass indicators at large distances from the main galaxy. The Local Group offers a unique possibility to determine the mass and radius of the dark halos of the Galaxy and M31 with high accuracy. The level of the rotational velocity of both galaxies is known well, this determines the density in the inner regions of dark halos. The total mass of galaxies is given by the relative velocity of centers of galaxies, following arguments by Kahn & Woltjer (1959), Einasto & Lynden-Bell (1982) and Valtonen et al. (1993). This calculation shows that masses determined from the internal dynamics of galaxies and their relative velocity coincide, if we adopt outer radii of dark halos at about 200 – 300 kpc.

References

Einasto, J. 1974, in: *Stars and the Milky Way System*, Vol. 2, (ed.) L.N. Mavridis, Springer, Berlin-Heidelberg-New York, p. 291

Einasto, J., Haud, U. 1989, A&A, 223, 89

Einasto, J., Lynden-Bell, D. 1982, MNRAS, 199, 67

Faber, S.M., Balick, B., Gallagher, J.S., Knapp, G.R. 1977, ApJ, 214, 383

Haud, U., Einasto, J. 1989, A&A, 223, 95

Kahn, F.D., Woltjer, L. 1959, ApJ, 130, 705

Sandage, A., Bingelli, B., Tammann, G.A. 1985, AJ, 90, 1759

Tantalo, R., Chiosi, C., Bressan, A., Marigo, P., Portinari, L. 1998, A&A, in press, astro-ph/9710079

Tenjes, P., Einasto, J., Haud, U. 1991, A&A, 248, 395

Tenjes, P., Haud, U., Einasto, J. 1994, A&A, 286, 753

Tenjes, P., Haud, U., Einasto, J. 1998, A&A, 335, 449

Valtonen, M.J., Byrd, G.G., McCall, M.L., Innanen, K.A. 1993, AJ, 105, 886

Worthey, G. 1994, ApJS, 95, 107

Worthey, G. 1996, AAS, CD-ROM, 7

Discussion

Gurzadyan: What is your opinion on the recently discussed idea on the possibility of cold gas (i.e., of baryonic matter) to be the main component of the dark matter in spiral galaxies?

Einasto: There are two dark matter problems, the local one, i.e., DM concentrated to the thin disk, and the global one, i.e., DM in extended and thick halo. Dynamical determinations by Kuzmin, Eelsalu and Joeveer in Tartu have shown that there exist no discrepancy between the dynamical determinations of the local spatial density of matter in the solar vicinity and the total mass density of the known populations, including low-mass stars and cold gas. These populations have a negligible contribution to the rotational velocity and extended halo.

Irwin: Have you considered the possibility that brown dwarfs or cool white dwarfs make up the dark halo matter?

Einasto: Brown dwarfs and cool white dwarfs are possible considerations for Population III objects. They definitely contribute to dark halo mass. However, this population is hardly dominating for several reasons. First, in clusters hot X-ray gas is observed, it dominates over visible stellar populations. Second, there is still a large discrepancy between the total amount of baryonic matter from nucleosynthesis data, $\Omega_{bar} \sim 0.04$, and overall dynamical density, $\Omega_{matter} \sim 0.2 - 0.3$, thus most of DM must be non-baryonic.