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On Some Properties of the Halo of Disk-Shaped Galaxies

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Abstract. This paper presents the results of a statistical analysis of a sample of 101 spiral galaxies with known halo and disk physical parameters. A correlation analysis between the halo and disk parameters was conducted, and a number of empirical relationships were found, along with corresponding graphs and histograms. In particular, an empirical relationship was obtained between the dispersion of particle velocities in the halo and its mass, as well as the total stellar mass. Furthermore, a relationship was found between the total stellar mass and the mass of the dark matter halo. We classify galactic halos into three classes based on the ratio of the halo mass to the total stellar mass.

INTRODUCTION

The halo of disk galaxies is spherical and extends beyond the visible part of the galaxy. It consists primarily of tenuous hot gas, stars, and dark matter, which makes up the bulk of the galaxy's mass. It should be noted that the dark matter (DM) halo extends throughout the galaxy, extending far beyond its visible components. The mass of the DM halo significantly exceeds the mass of other galactic components. Its existence is proposed to explain the gravitational potential that determines the dynamics of bodies within galaxies. The nature of the DM halo is an important area of research in modern cosmology, particularly its connection to the formation and evolution of galaxies [1-3].

García-Díaz et al. studied the properties and data from the 3.6μm S4G Spitzer Survey of disk galaxies [4,5]. They estimated the halo mass to total stellar mass ratio (M_h/M_*) inside the optical disk and compared it with the total stellar mass (M*). It turned out that, on average, the amount of DM in the optical disk is ~4% of its total halo mass. The metallicity distribution of giant stars as a function of the altitude above the galactic plane (z) in the range $5<z\leq15$ kpc can be described by a three-humped Gaussian model with peaks at [Fe/H]~-0.6 ± 0.1, -1.2 ± 0.3 and -2.0 ± 0.2, which corresponds to a ratio of 19%, 74% and 7%, respectively. [α/Fe] is needed to associate these three peaks with the components of the thick disk, inner halo, and outer halo of the Galaxy [6,7]. The metallicity distribution of these giant stars, consistent with the three-component Gaussian model, shows an increasing proportion of inner halo components and a decreasing proportion of thick disk components with increasing distance from the galactic plane. In particular, edge-on galaxies were modeled [8,9]. They obtained estimates of the parameters of stellar disks, dark halos, and bulges. The lower limit of the dark-to-light mass ratio of galaxies is of the order of unity within their stellar disks. They found that dark halos predominate by mass in galaxies with very thin stellar disks. Spiral galaxies are known to be highly diverse and differ from each other not only in their appearance but also in their internal physical characteristics. A number of spiral galaxy catalogs exist that collect key parameters, such as radial and tangential velocities, stellar magnitudes, redshifts, stellar masses, etc. [10-20]. It should be noted that, to date, no catalog has been compiled that would contain parameters related solely to their disks and halos. Based on this, we have compiled a consolidated catalog of 101 disk galaxies, which contains the physical parameters of their halos and disks [21, (appendix)]. The selection was carried out in such a way as to cover as many physical parameters of both the galactic halo and disk as possible. Observational data were obtained from various sources. For example, data such as the total stellar mass of the galaxy, the optical radius of the halo and

galaxy, the dispersion of particle velocities in the halo, and the ratio of the halo mass to the total mass of the galaxies were obtained from [4, 5]. Data related to the dark-mass halos were obtained from a study studying the surface density of the dark-mass halos [22]. Data regarding the disks of spiral galaxies were found in studies that used photometry of disk galaxies to determine the disk mass distribution model [23]. In addition, a variety of sources was studied in search of physical parameters of the halo. For example, measurements of X-ray emission from the galactic halo for 110 XMM-Newton survey lines are presented. The temperature is uniform at around $0.63\text{-}2.22\times10^{6}$ K, and the intrinsic surface brightness varies from $\sim0.5\text{-}7\times10^{-12}$ erg/cm2 s deg^{-2}. Also, all CGM-MASS galaxies have diffuse X-ray emission from hot gas detected above the background, extending out to ~(30-100) kpc from the galactic center. The ratio of radiative cooling to free-fall times of hot gas far exceeds the critical value of ~10 throughout the halos of all CGM-MASS galaxies, indicating inefficient gas cooling and precipitation in the CGM. Thus, the hot CGM in massive spiral galaxies is most likely in a hydrostatic state, where feedback material mixes with the CGM rather than escaping from the halo or falling back onto the disk. Measured temperatures, luminosities, and spatial distributions of the gas can be used to constrain models of the dominant halo heating sources [24, 25]. A strong correlation was also found between Hα and UV radiation; the scale height in Hα is ~0.74. This may indicate a multiphase nature of diffuse ionized gas and dust in galactic halos. Scale heights in non-planar Hα ejections correlate well with the surface density of star formation rates in galaxies [26]. An estimate of the halo mass, possible correlations associated with it, and the statistical error in the estimate are presented in [27–33].

RESULTS OF QUANTITATIVE ANALYSIS

The catalog we compiled contains the following data [20]: 1. Galaxy name (galaxy designation). 2. Galaxy coordinates. 3. Galaxy morphological type according to the Vaucouleurs classification. 4. Distance to the galaxy. 5. Total stellar mass of the galaxy M_*. 6. Halo optical radius Rh. 7. Halo particle velocity dispersion Vh. 8. Halo mass to total stellar mass ratio Mh/M_*. 9. Effective disk radius Rd. 10. Disk surface brightness SBd. 11. Disk angular velocity Vd. 12. Dark matter halo surface density μDM. 13. Dark matter halo Newtonian acceleration log gDM. 14. Dark matter halo mass within the optical radius log MDM. Analysis of this catalog shows that distances to galaxies range from 3 to 65 Mpc. The total stellar mass of galaxies varies in the range of $(2.41\times10^{7} \div 1.68\times10^{11})$ Mcs. The halo radius extends from 1.023 kpc to 49.132 kpc. The HI velocity dispersion in the halo varies from 43.565 to 635.412 km/s. However, the halo mass to total stellar mass ratio varies in an even wider range: from 0.129 to 67.232. The disk radii can be from 0.6 to 10.71 kpc. In addition, the disk plane rotation velocities vary from 34.5 km/s to 293.6 km/s. The halo surface density of dark matter occupies the range from log μ ~1.46 to log μ ~3.0 Mcs/pc^{2}. The average Newtonian acceleration of a DM halo is log g ~ -8.3 cm/s2. The average DM halo mass is also log Mh ~ 10.33 M_{Sol}. The catalog contains barless spiral galaxies (62%), transitional spiral galaxies (24%), and spiral galaxies with very pronounced bars (14%). It should be noted that low-mass halos are most common in this catalog. The histogram (Fig. 1) shows that 49 galaxies have a halo mass to total stellar mass ratio of Mh\M* = 0-3, while the remaining galaxies have $Mh\backslash M_*$ = 4-10. Several galaxies also have very high halo masses, $Mh\backslash M_*$ ~ 100.

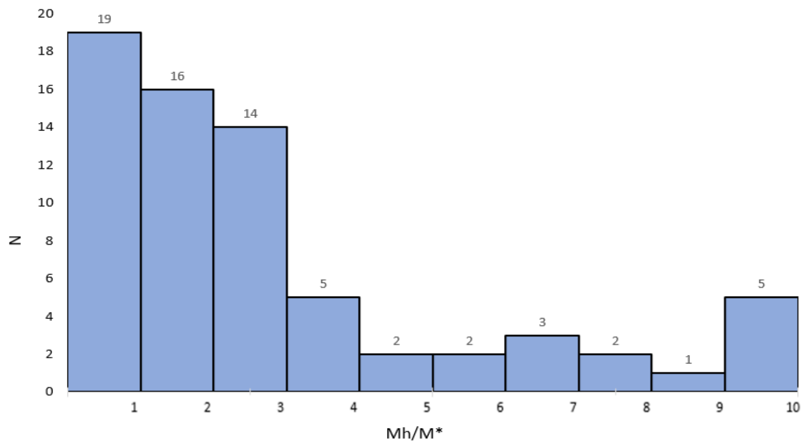

FIGURE 1. Quantitative estimate of the halo mass to total stellar mass ratio.

HALO CLASSIFICATION BY MASS

Based on the above results, we decided to classify halos by their mass. The histogram in Fig. 1 shows that moderately massive, semi-massive, massive, and supermassive (see Table 1).

TABLE 1. Halo Classification

CLASS NAMES	NUMBER OF GALAXIES	Mh/M_*	AVERAGE HALO OUTER RADIUS (kpc)	MOST CHARACTERISTIC GALAXY TYPE
I Low-mass	19	≤1	30	SO, SAB
II-Moderately massive	16	1÷2	50	SAB
III-Semi-massive	14	2÷3	45	SA
IV-Massive	9	3÷6	15	SA, SB
V-Supermassive	11	6 <	10	SB

In our catalog, 28% of disk galaxies have low-mass halos, 23% moderately massive, 20% semi-massive, 13% massive, and 16% supermassive. The first class includes halos with masses less than or approximately equal to the total stellar mass in the galaxy ($Mh/M_*\leq1$). These galaxies also include lenticular galaxies and barless galaxies with varying degrees of spiral arm-twisting. The next class (moderately massive) has halos for which $Mh/M_*=1\div2$ and an average outer halo radius of approximately 50 kpc. In the third class (Table 2), the halo mass is correspondingly greater than the total mass of the stars by a factor of 2 or more. These galaxies most often include galaxies with pronounced bars. The table also shows that semi-massive halos are found in the SB, Sa, Sb, Sc, and Sm morphological types (Table 2.1). Furthermore, the average outer radius of semi-massive halos varies around 45 kpc. In the following classes (massive and supermassive), the halo radius varies from 15 kpc to 10 kpc, indicating that denser rather than more voluminous halos are found among massive galaxies. Massive halos are also more common in galaxies without bars and twisted spiral arms.

STATISTICAL ANALYSIS RESULTS

We have conducted a statistical analysis of the observed disk and halo parameters of spiral galaxies. Correlation coefficients are presented as empirical relationships between various disk and halo parameters (Table 2).

TABLE 2. Correlation coefficients between various disk and halo parameters

corr. coeff	Rh	Rd	Vh	Mh	lgMdm
M*	**0,82**	**0,67**	**0,85**	**0,79**	**0,70**
Mh	**0,74**		**0,82**		
Vh	**0,79**				**0,72**
M_GC	**0,66**				

An empirical relationship was found between the total stellar mass and the disk radius, with a correlation coefficient of cc = 0.72. This relationship is linear (Fig. 2), and the corresponding formula is (1)

$$M^* = 0.411(\pm0.005)\cdot R_d + 2.36(\pm0.008) \tag{1}$$

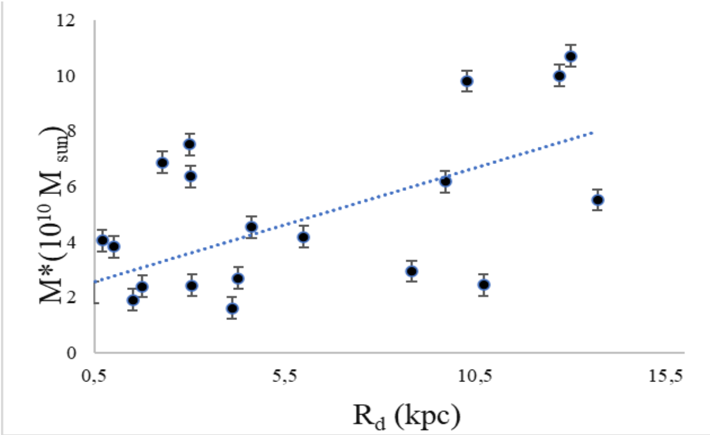

FIGURE 2. Relationship between disk radius and total stellar mass

A relationship was also found between the total stellar mass and the halo radius, with a correlation coefficient of cc = 0.82. This relationship (2) also has a linear form (Fig. 3), where the halo radius increases with increasing total stellar mass (apparently due to an influx of gas and clouds into the halo):

$$M^* = 0.304(\pm 0.021) \cdot R_h - 0.623(\pm 0.085) \quad (2)$$

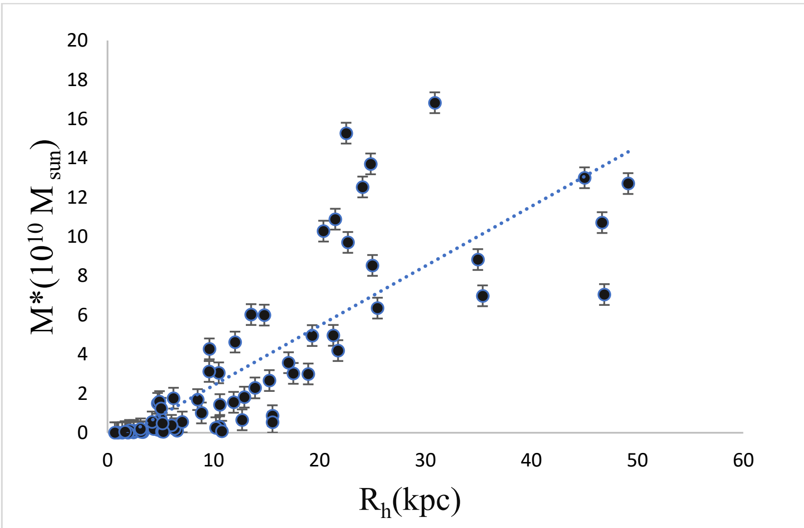

FIGURE 3. Relationship between halo radius and total stellar mass

A linear relationship (3) was also obtained between the halo mass and the velocity dispersion of particles in the halo (Fig. 4). As the halo mass increases, the velocity dispersion of halo particles also increases, and the correlation is quite good, cc=0.81:

$$V_h = 12.592(\pm 0.002) \cdot M_d + 115.31(\pm 0.004) \quad (3)$$

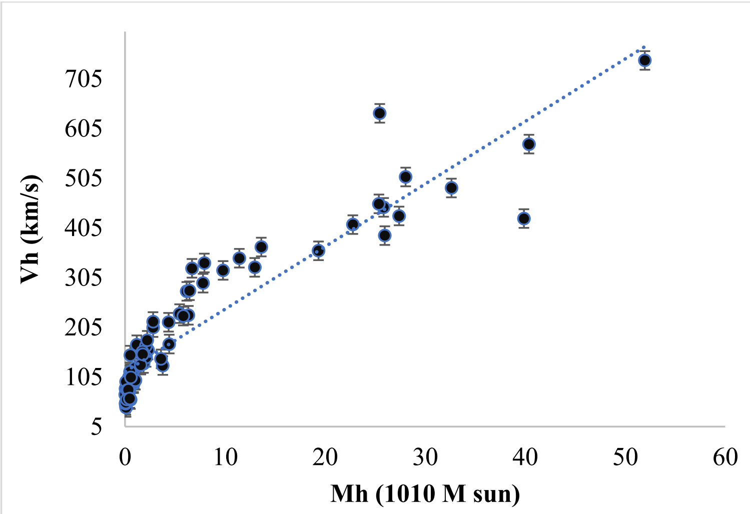

FIGURE 4. The Relationship between the Halo Mass and the Velocity Dispersion in It

Similarly, to the above, as the mass of stars in galaxies increases, the velocity dispersion of particles in the halo increases (Fig. 5). The correlation coefficient is quite high, cc = 0.85 and the corresponding statistical relationship is (4):

$$V_h = 30.152(\pm 0.008) \cdot M^* + 105.641(\pm 0.002) \quad (4)$$

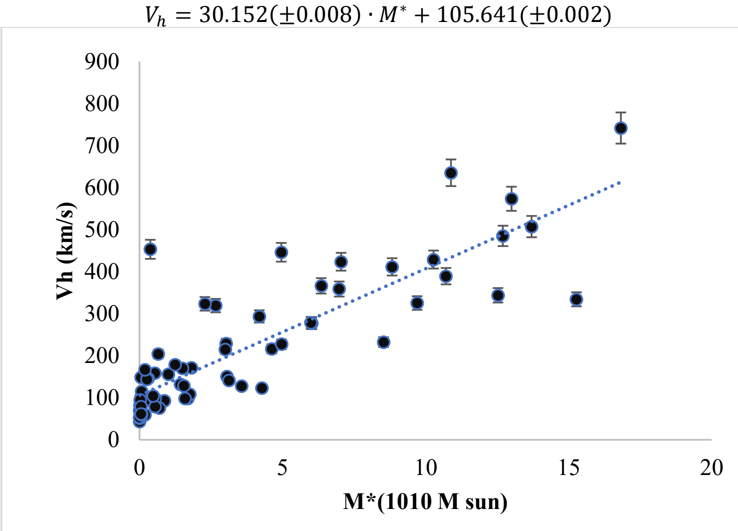

FIGURE 5. Relationship between the Total Mass of Stars in a Galaxy and the Velocity Dispersions of Halo Components

Next, we found a relationship (5) between the halo mass and the mass of stars in galaxies (Fig. 6), but the correlation coefficient is cc = 0.79:

$$M_h = 2.076(\pm 0.005) \cdot M^* + 0.323(\pm 0.003) \quad (5)$$

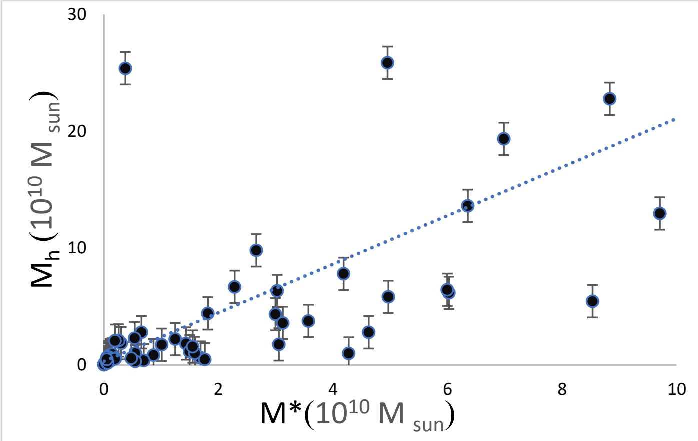

FIGURE 6. Relationship between the Mass of Shared Stars in a Galaxy and the Halo Mass

The following relationship was obtained between the mass of shared stars and the halo mass of the dark matter. The graph shows that increasing the mass of shared stars affects the halo mass of the dark matter (Fig. 7). The correlation coefficient is cc = 0.7 and the empirical formula is (6)

$$\log M_{dm} = 0.0113(\pm 0.0012) \cdot M^{*} + 9.891(\pm 0.0098) \quad (6)$$

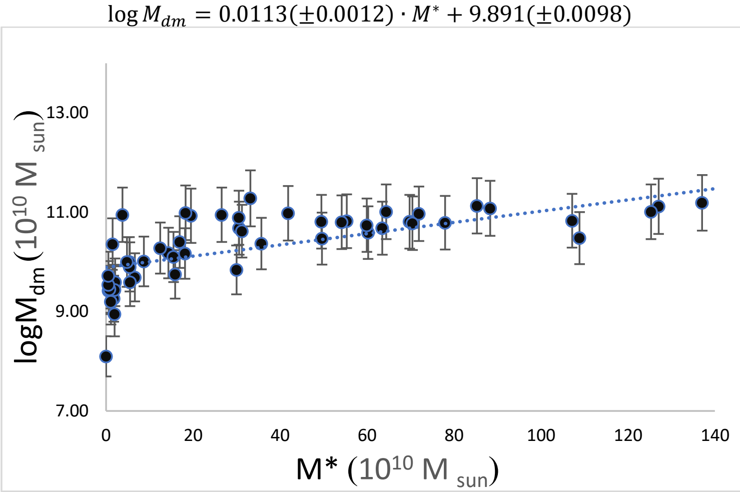

FIGURE 7. Relationship between the Total Mass of Stars in a Galaxy and the Halo Mass of the Dark Matter

We also obtained a relationship between the halo radius and the particle velocity dispersion within it. It was previously found [32] that the outer halo of the Galaxy rotates counterclockwise (relative to the disk component) at a velocity of approximately 80 km/s, with velocity dispersions in a spherical coordinate system originating at the center of the Galaxy being (178, 149, 127) km/s. The inner halo barely rotates and has velocity dispersions slightly smaller: (160, 102, and 83) km/s. From the graph we constructed in Fig. 8, we can also conclude that the velocity is lower near the center of the Galaxy than in its vicinity. In this case, the correlation coefficient was cc = 0.78 and the corresponding relationship took the form (7):

$$V_h = 10.377(\pm 0.004) \cdot R_h + 70.588(\pm 0.005) \quad (7)$$

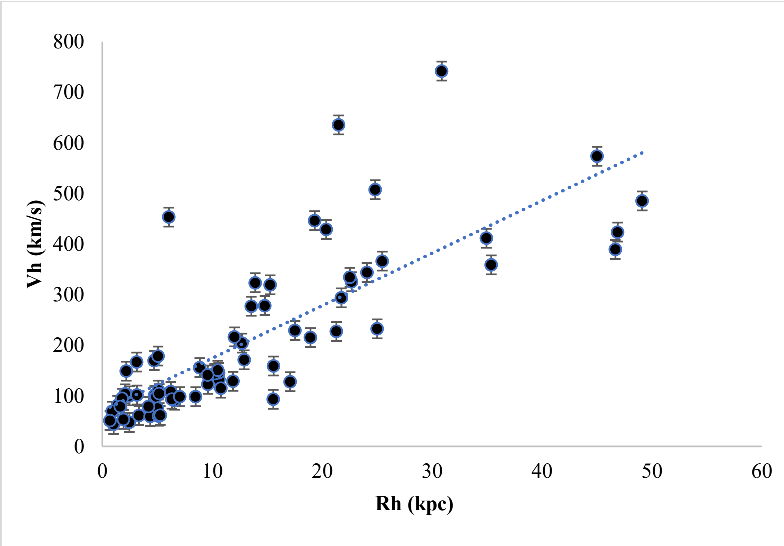

FIGURE 8. Relationship between the Halo Radius and the Velocity Dispersion of Halo Components

Next, we found the relationship (8) between the DM halo mass and the velocity dispersion of particles in the halo with a correlation coefficient of cc = 0.77. Here, the relationship is exponential (Fig. 9):

$$V_h = 0.049(\pm 0.002) \cdot e^{0.801 \cdot M_{dm}} \quad (8)$$

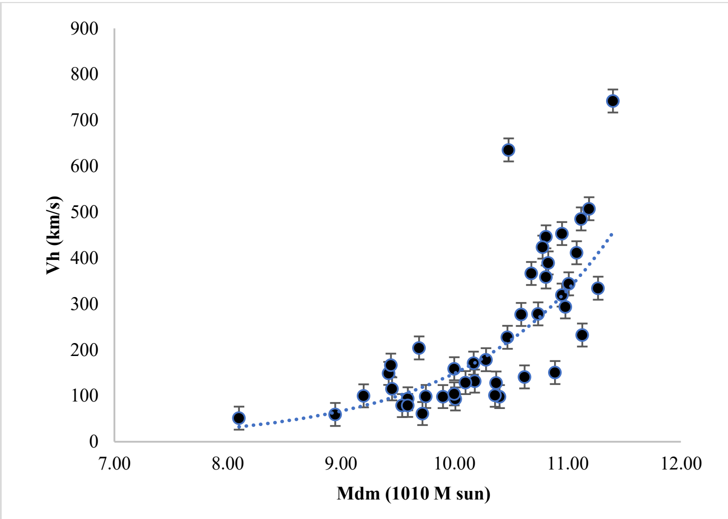

FIGURE 9. Relationship between the DM halo mass and the velocity dispersion of components in the halo

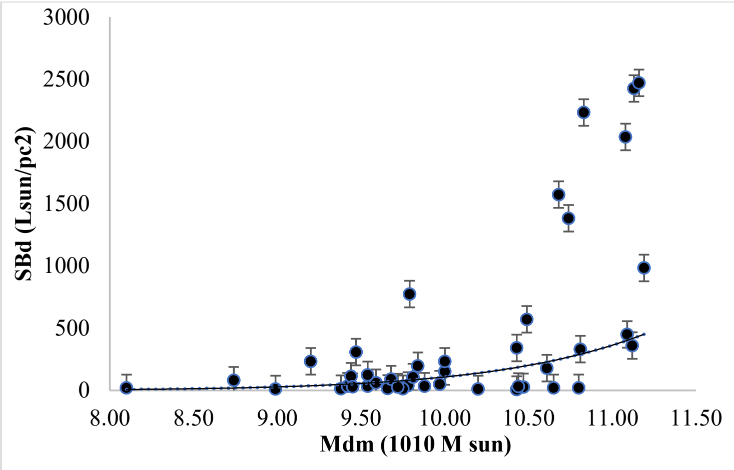

FIGURE 10. Relationship between the halo mass DM and the disk surface density

We also found a logarithmic relationship between the DM halo mass and the disk surface density. From the graph in Fig. 10, it can be seen that the DM halo mass has little effect on the increase in disk surface brightness, with a correlation coefficient of cc = 0.58. In general, this relationship has the form (9):

$$SBd = 2,10923(\pm 0,32541)\ M_{dm}{}^{12,7093671(\pm 0,7548)} \quad (9)$$

A relationship was also obtained between the logarithm of the globular cluster mass and the halo radius, with a correlation coefficient of cc = 0.66 (Fig. 11). The corresponding empirical relationship is obtained in the form (10)

$$M\_GC = 6.5012 \cdot e^{0.0106R_h} \quad (10)$$

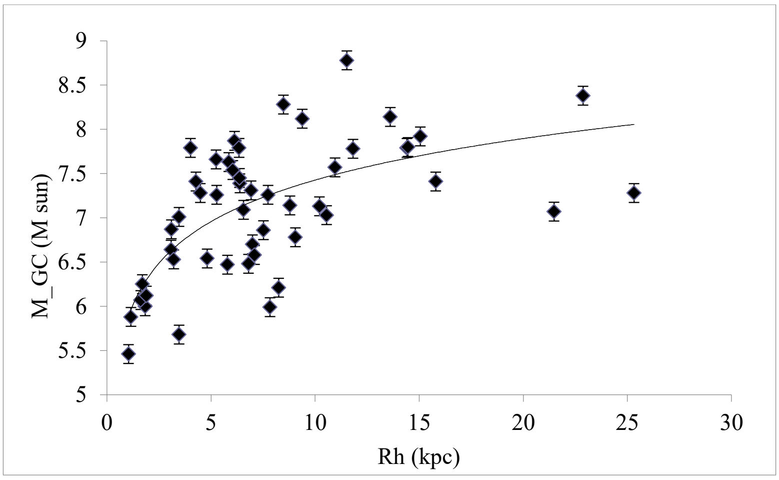

FIGURE 11. Relationship between the halo radius and the mass of globular clusters

CONCLUSION

We briefly summarize our main results:

1. To study the observational halo data, we compiled a consolidated galaxy catalog containing the known halo and disk parameters of spiral galaxies. We also conducted a quantitative and statistical analysis of these parameters.

2. Thus, we proposed dividing halos into three classes based on their mass: A, B, and C, corresponding to low mass, massive, and supermassive halos (in class A, $M_h/M_* \leq 1$, in B, $1 < M_h/M_* < 10$, and in C, $M_h/M_* \geq 10$).
3. Correlation coefficients were calculated in empirical relationships between various disk and halo parameters.
4. Linear empirical relationships were found between the total stellar mass, on the one hand, and the disk and halo radius, on the other.
5. Relationships were obtained between the dispersion of particle velocities in the halo, the halo mass, and the total mass of stars in the galaxy.
6. A relationship was constructed between the total mass of stars and the mass of the DM halo. According to the authors,
7. A relationship has been constructed between the total mass of stars and the mass of the DM halo. According to the authors of [33], the mass of the DM halo in galaxies is statistically related to their stellar composition, and therefore to the nature of the evolution of the stellar population: for the most evolved galaxies, which have few young stars, the contribution of dark mass is, on average, smaller.
8. A relationship has been obtained between the velocity dispersion of halo components relative to the radius and mass of the DM halo.
9. A relationship has been found between the mass of the DM halo and the surface density of the disk. The main observable property correlating with the mass fraction of the dark halo is the surface density of the disk, not the mass.
10. A logarithmic relationship has also been obtained between the mass of globular clusters and the halo radius.

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