SECTION II

THE MAGELLANIC CLOUDS

50. THE ROLE OF THE MAGELLANIC CLOUDS IN THE UNDERSTANDING OF GALAXIES

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In order to introduce this Symposium on the Magellanic Clouds I feel the most valuable thing I can do is to discuss our understanding of galaxies in general, then show how the Magellanic Clouds in particular fit into the sequence of galactic forms, and finally note a few of the critical problems of galaxies which we might solve by studying the Magellanic Clouds. There are six main points which I wish to mention.

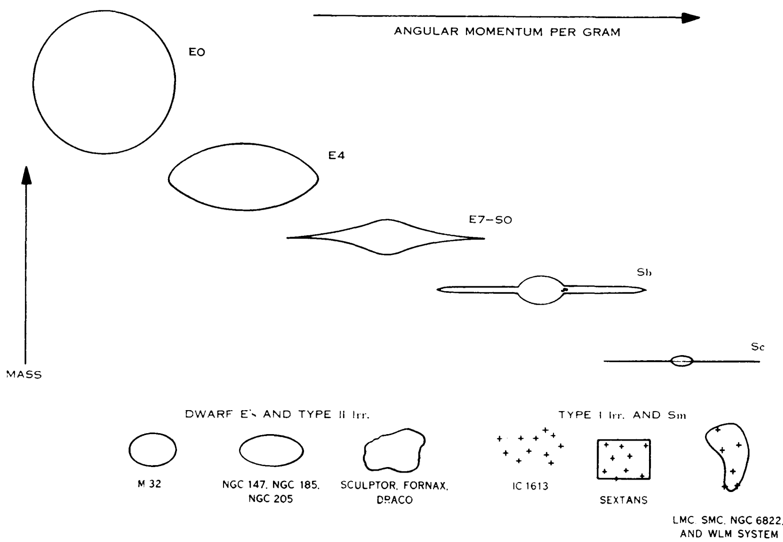

Fig. 1.—The relation between the average mass and the approximate mean rotational energies for galaxies of class E0 through Irregular.

I. Sequence of Galactic Forms

Figure 1 shows the relation between the presumably non-evolvable parameters of mass and rotational energy for the average galaxy type from E0 to Sc. The masses are from Page (1962) and the Burbidges. The mean rotational energy per unit mass is qualitatively judged from the cross sectional flattening of the stars at the time of their condensation. Another way of estimating this relative rotational

https://doi.org/10.1017/S0074180900052621 Published online by Cambridge University Press

energy is to note that the spherical component of a galaxy is usually considered to have relatively small angular momentum. As we proceed down the sequence of galactic forms the proportion of spherical component steadily diminishes and a larger and larger percentage of the high angular momentum disk population appears. Despite the difficulty of making quantitative statements there is clearly a general relation between mass and average rotational energy throughout the sequences of galaxy types. In addition, there is a very marked change in stellar content along

TABLE 1
INTEGRATED COLOURS AND AGES OF STAR CLUSTERS

Cluster	No. of Stars Integrated M_V	$\int(B-V)_0$	$\int(U-B)_0$	Age*	Remarks†
NGC 2264	−5·6	−0·18	−0·98	$2–5\times10^6$	With yellow giants
NGC 2264	−5·5	−0·24	−1·00	$2–5\times10^6$	Without yellow giants
IC 5146	−4·0	−0·21	−0·83	$2–5\times10^6$	
NGC 2362	−4·7	−0·21	−0·79	$2–5\times10^6$	
h Per (nuc)	−8·7	−0·18	−0·63	3×10^6	
Pleiades	−4·2	−0·10	−0·37	6×10^7	
NGC 129	−5·7	+0·61	+0·31	8×10^7	With both M giants
Coma	−1·9	+0·22	+0·07	3×10^8	
Hyades	−2·7	+0·40	+0·19	5×10^8	
Praesepe	−2·8	+0·37	+0·16	5×10^8	
NGC 2158	−5·7	+0·66	+0·18	8×10^8	
NGC 7789	−6·5	+0·62	+0·07	1×10^9	Full amount of blue stars
NGC 7789	−6·4	+0·71	+0·19	1×10^9	Half amount of blue stars
M67	−3·0	+0·71	+0·44‡	9×10^9	
NGC 188	−3·2	+0·78	+0·43	16×10^9	
ω Cen	−5·7	+0·60	+0·17	9×10^9	
M13	−6·5	+0·81	+0·37	9×10^9	
M3	−9·0	+0·67	+0·06	14×10^9	
M5	−6·5	+0·74	+0·22	12×10^9	

* Ages from deviation of evolved from unevolved main sequence and only approximate. Globular cluster ages from Arp (1962).

† See text for discussion of ages.

‡ Johnson (1959) gives a considerably different integrated $U-B$ colour for M67, namely, 0·25 mag.

this sequence and Table 1 demonstrates that the age of the characteristic stars in these populations is the parameter which changes the most. The integrated colour of each star cluster in Table 1 is obtained by adding the contribution of all the stars in the published colour-magnitude diagrams for these clusters. The ages are estimated from the turn-off points of evolving main sequences and approximate fits to the loci of Haselgrove-Hoyle evolutionary tracks. It is clear that these ages are not very accurate at present but Table 1 is published now with the idea that when later, more accurate ages become available they can be filled in opposite these integrated colours which apply to stars of that particular age. In the meantime Table 1 serves to demonstrate that as a large aggregate of stars grows older its integrated colour becomes increasingly red. In fact we can in principle look at the colour of a galaxy or part of a galaxy and say that the majority of stars are of a certain age, say 10^8, 10^9, or 10^{10} years old. We can in the present context look down the sequence of galactic forms in Figure 1 and say that the average age of the stars becomes steadily younger as we pass along the sequence towards higher rotation. (See also Table 2.)

The other parameter which characterizes a stellar population, the chemical content, is harder to trace along the sequence of galactic forms. In our own Galaxy the oldest stars are generally metal-poor and the younger ones "normal". What little additional evidence is available, however, indicates that at the same age stars formed in low density regions have a higher percentage of hydrogen whereas stars

TABLE 2

REDUCTION IN LIGHT OF A STAR CLUSTER DUE TO EVOLUTION OF THE STARS

Cluster*	$\Delta\int M_V$	Age (yr)
h Per (nuc)	reference	3×10^6
Pleiades	$+1\cdot08$	6×10^7
Coma	$+2\cdot43$	3×10^8
Hyades	$+2\cdot93$	5×10^8
Praesepe	$+2\cdot60$	5×10^8
M67	$+3\cdot33$	9×10^9
NGC 188	$+3\cdot94$	16×10^9

* These clusters have all been normalized to the same number of stars on the unevolved main sequence.

formed in high density regions are composed of an increased percentage of heavier elements. Spectra by Spinrad (1961) of E galaxies and the nuclei of Sb galaxies indicates that in these high density regions the stellar populations consist of old, relatively high metal content stars and many dwarfs. Independently the same thing can be shown from Table 1 where it is easy to reproduce the observed E and S0 galaxy $U-B$, $B-V$ colours by adding about 40% of K7 dwarfs to old but "normal" chemical composition galactic cluster NGC 188. There is no way of adding dwarfs to the low metal globular clusters to obtain the observed $U-B$, $B-V$ colours of E and S0 galaxies. The correlation of low density with low heavy element abundance is important in the Magellanic Clouds, because with their relatively large numbers of young stars in low density regions they may furnish us with our first known examples of young, low metal content stars (Arp 1961). In this connection it is clear that the average age of the stars decreases as we go down the mass-rotation sequence in Figure 1, but since, as we shall see, the density also decreases down this sequence it is difficult to predict how the average chemical composition will run.

In order to investigate how the density changes along the sequence, diameters of representative galactic forms were taken from Holmberg (1958). The average intrinsic diameters for the different types of galaxies which were derived when distance criteria were applied are listed in Table 3. An adjoining column lists the masses adopted from previously mentioned sources. The density in g/cm^3 is given in the last column where assumptions about the geometric figure of each particular galaxy are noted. The derived values of density are only rough but they serve to illustrate that there is a general decrease in density along the mass-rotation relation for galaxies. Of particular interest are the densities of the Magellanic Clouds which are lower than any of the other galaxy types. It should be noted that Feast, Thackeray,

TABLE 3

MASS DENSITIES

Object	Diameter* (to $B=26\cdot7$ mag/square sec)†	Distance (kpc)	Diameter (kpc)	Mass‡ ($10^{10}M_\odot$)	Log Density (g/cm^3)	Remarks
LMC	15°	60	16	1	−24·2	Assumed flattening ratio of 5 : 1
SMC (stars)	5°	60	5	0·07		
(gas)				0·04		
				0·11 (sum line)	−24·2	No flattening assumed
Av. dwarf galaxy			8	0·05	−24·3	Av. flattening of 5 : 1 assumed
Av. Sc			20	3	−23·8	Flattening 5 : 1
Av. Sb			30	15	−23·6	Flattening 5 : 1
Av. E			34	60	−23·4	Flattening 3 : 1

* Apparent diameters of Magellanic Clouds are taken from data quoted by de Vaucouleurs (1960).

† Holmberg 1958.

‡ Masses are rough estimates in the various classes from data by Page (1962) and Burbidge and Burbidge. The mass for the average dwarf galaxy was taken from unpublished results by the author on luminosities of dwarfs in van den Bergh's catalogue and an M/L ratio of $1\cdot3$ (Page 1962).

and Wesselink (1961) compute a density within 4·2 kpc of the centre of the LMC of $\log \rho = -23$. The Holmberg isophotal outer diameters used in Table 3, however, refer to a very faint ($B=26\cdot7$ mag/square sec) outer limit. If a diameter limit as bright as that used by Feast, Thackeray, and Wesselink was used in Table 3, all the densities would be higher by about a factor of 10, but they would all scale up in proportion and the relative densities in the different galaxy types would remain the same. It is the relative decrease of density with later galaxy type which is being emphasized here. Holmberg (1958) also computes about a factor 10 density decrease from E to Sc galaxies. He further points out that because the surface brightness is decreasing down this sequence and the M/L ratio is also decreasing, that the projected mass density must certainly be decreasing from E to S galaxies.

https://doi.org/10.1017/S0074180900052621 Published online by Cambridge University Press

II. Dwarf Galaxies

van den Bergh (1959) has catalogued 222 low surface brightness galaxies from the Palomar Sky Survey. Of these, 59 are designated as resolved to some extent. In a current investigation at Palomar, I have photographed 12 of this latter group and estimated apparent magnitudes of their brightest stars. Very roughly it can be computed within 6×10^6 pc from our own Galaxy that the average density of these kinds of dwarfs is about 9×10^{-20} dwarf galaxies/pc^3. The average absolute magnitude for this kind of dwarf galaxy is about $M_{pg} = -16$ mag. Assuming the mass-luminosity which is appropriate for spirals ($M/L = 1 \cdot 3$ (Page 1962)) gives an average mass of $M = 5 \times 10^8$ $m_\odot$. The average mass density in space contributed by these dwarf galaxies comes out to be roughly 3×10^{-33} g/cm^3. This is about 100 times less than the Oort limit of visible matter in the universe and indicates that there is not an unsuspected contribution to the mass of the universe from these numerous and little studied dwarfs. Moreover, their distribution in space has not yet been studied and it may well turn out that their numbers fall off outside the local group, therefore contributing even less to the total mass of the universe.

TABLE 4

NUMBER AND MASS DENSITY OF DIFFERENT TYPES OF GALAXIES

Type	E–S0	Sa–Sc	Sd–Im
Observed frequency	46·5	49·5	4
Space abundances by number	11%	23%	66%
By mass	93%	6·5%	0·5%

Nevertheless, dwarf galaxies are very numerous, as can be seen by correcting their observed frequency for the fact that they are fainter than other types of galaxies. The observed frequencies in Table 4 are from de Vaucouleurs (1959).

There are really two points which I would like to make in this part of the discussion. The first is that the Magellanic Clouds and in particular the SMC are fairly typical members of this group of dwarf galaxies which we have just been discussing. This is most strikingly shown in Table 3 where it is seen that the LMC is about twice as big and the SMC about 50% smaller than the average dwarf galaxy. In all the other properties such as mass and stellar content the two Magellanic Clouds resemble each other and together are a good example of the spread around the mean, of the properties of dwarf galaxies as a whole.

The second point which is important is that this group of magellanic-type dwarfs forms a continuation in every property along the sequence in Figure 1. The following quantities progress systematically along the sequence from E0 to Im:

(i) Mass decreases;

(ii) density decreases;

(iii) amount of young stars increases;

(iv) the geometric structure becomes continuously more irregular in the late types (Sc; Sd; Sm; Im);

(v) rotation increases.

In order to indicate why the relative amount of rotation probably increases right into the class of dwarf galaxies we should return to the mass-rotation relation shown in Figure 1.

III. Formation of Galaxies from Gas Clouds

If a gas cloud which is condensing to form a galaxy has very much rotation it will tend to form itself into a thin, circular disk as it contracts. If there is some ionized gas, however, and any kind of magnetic field this differential motion of the gas will twist the magnetic lines of force, increase the magnetic field, and eventually the field will become an agent of viscosity. In this case the rotating gas will partake to some extent of rigid body characteristics and will have a tendency to elongate, fission, or fragment. With this picture, the explanation of Figure 1 becomes very simple, namely, that as the gas clouds differentiated out of the original medium in the universe and started to form galaxies those clouds with slow rotation could form massive, slowly rotating systems. Those clouds with faster rotation could not form all their mass into a single system and they got rid of this excess angular momentum by shedding mass, fissioning, or fragmenting. The process is pictured in Figure 2 where an initially chaotic magnetic field has been assumed. If there is some flow along the magnetic lines of force stretched out in the bar then probably two cases result:

(*a*) Where the kinetic energy density becomes greater than the magnetic energy density close to the centre, the outflow material bends around quickly under the influence of differential rotation into the classical logarithmic spiral galaxies.

(*b*) Where the magnetic energy density remains strong compared to the kinetic energy density out to appreciable distances from the centre, the galaxy turns into one of the classical barred spiral types.

On the other hand, if flow does not proceed along the initial elongation but strong kinks develop, then either a small portion of the galaxy will fragment off or the whole galaxy will fission, depending on where the magnetic knot develops. This mechanism would be represented by the group of connected galaxies which will be mentioned later. One strong prediction of the above theory is that any ordered, large-scale magnetic fields should be along the bars and arms of spiral galaxies and along the filaments connecting galaxies.

In the previous section it was shown that a very small percentage of all the mass in galaxies (0·5%) is formed into a great number of dwarf galaxies (66% by number). In view of the preceding discussion it would be reasonable to identify the dwarf galaxies as the 0·5% of the original mass in the universe with the highest rotation energy. They would now represent the numerous fragments which have carried away the initially excess angular momentum. The continuous behaviour mentioned in the preceding section of all the other properties along the mass-rotation sequence gives empirical support to this conclusion.

IV. Galaxies with Companions and Multiple Galaxies

In order to obtain information on the relation which the Magellanic Clouds bear to our own Milky Way all the spirals brighter than $m_{pg}=11\cdot0$ in the Shapley-Ames (1930) Catalogue were examined. Of 31 galaxies, 20 had companions within four times their diameter. The companions tend to be more numerous around the brighter galaxies. Most important, however, the character of the companion galaxies became systematic later as the type of the parent galaxy became later. For example,

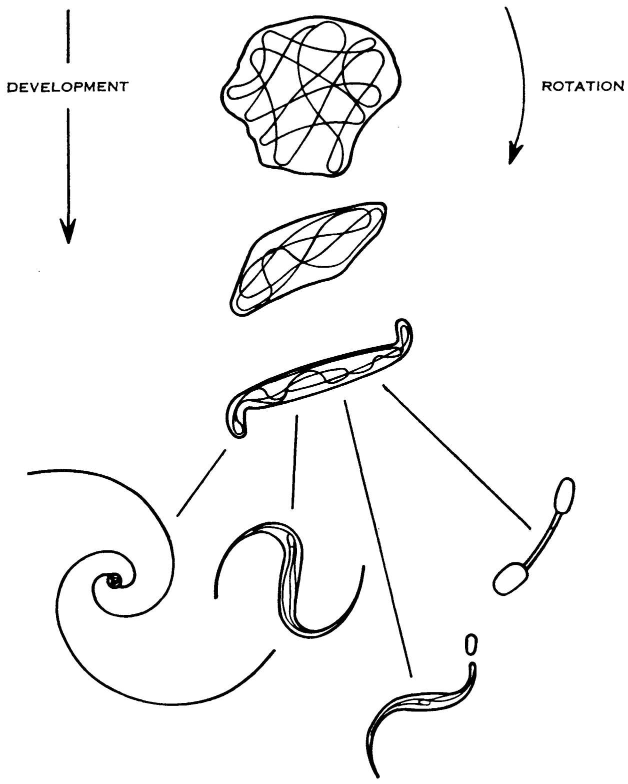

Fig. 2.—Suggested contraction of original gas cloud to form galaxy. Thin interior lines represent magnetic fields which partially control motion of the gas.

the companion galaxies at Sb onwards are 30% Im's (remainder dE's) but by Sc the companions are 100% Im's. The surface brightness and the population type of the companions imitate very closely those of the main galaxy. Some of these galaxies, of course, look like the Magellanic Cloud–Milky Way system viewed from outside.

If larger companion galaxies are considered we come into the class of double galaxies. Holmberg (1937, 1958) demonstrated that components of a close physical system have stellar contents of a similar type and mean luminosity densities that are approximately the same. He concluded the simplest explanation of this is to assume that most double systems were formed by disintegrations of a single galaxy. Ambartsumian (1962) stresses the possible formation of separating subsystems within a galaxy.

In the present connection we would like only to note that about 22% of all galaxies are multiple. If rotational fragmentation is responsible, then the dwarfs, which are the most numerous, and connected with the high rotation spirals, must fit at the extreme end of the mass-rotation sequence. Moreover, the Magellanic Clouds are prime examples of this extreme end of the sequence. Possibly the most significant question we can ask is what keeps the density low at this end of the sequence, and this question points to another important problem, namely, that of star formation.

V. Magnetic Tubes and Star Formation

Most calculations on star condensation in regions where it has occurred recently encounter great difficulty in finding densities high enough for gravitational collapse of a star to occur within a reasonable time. Neither do radiation pressure and collisional impacting seem adequate. One consequence of the picture of magnetic tubes along spiral arms and in connecting filaments between galaxies, however, is that if these tubes are stretched there will be a compressional force tending to reduce the diameter of the tube. Within the tube turbulence eddies undoubtedly wind up field lines until the ionized material is controlled, and in some cases probably strongly compressed by the magnetic fields if the lines are pulled oppositely. This is a possible way in which star formation could occur in a region which is not generally dense enough for gravitational star condensation. If such, what might be called magnetic cooling, is involved in the process of star formation it would be possible to study it only in the spiral arms of our own Galaxy or in the nearby Magellanic Clouds. It is interesting to note in this respect, that star formation appears to be taking place in spiral arms over a narrow region, perhaps less than 200 pc across. In the Magellanic Clouds, however, regions of star formation are much broader, exceeding 500 pc in extent.

VI. Critical Problems in the Magellanic Clouds

From the foregoing discussion then it seems to me that the following problems are of vital interest.

(*a*) *Magnetic Fields.*—Radio polarization in the gas masses associated with the Clouds and along the bridge connecting them should give an overall picture of the magnetic field in the system. Comparison with optical polarization should give the relation between optical polarization and magnetic field. Optical polarization can be pushed to very small regions particularly around regions of present star formation. This should yield information on the possible role of magnetic fields in star formation.

(*b*) *Energy Spectrum of Eddies.*—Both optical and radio velocities of subgroups and clouds within the system could be obtained and roughly analysed in order to study the differences between the way the energies are distributed over different-sized clouds, in the Clouds and in our own Galaxy. One outstanding puzzle is why

https://doi.org/10.1017/S0074180900052621 Published online by Cambridge University Press

young clusters which are very rich can be formed in the Magellanic Clouds (like NGC 330, NGC 458, and NGC 1866) whereas the young clusters in our own Galaxy are all sparse.

(*c*) *Exact Places of Star Formation.*—Allied with the previous two problems is the one of star formation taking place over a loose cluster or association in the Cloud but apparently occurring at slightly different times in slightly different places. It would be important to pinpoint areas of present star formation and try to discover differences between them and neighbouring areas where star formation has just ceased.

(*d*) *Connection with Galaxy.*—Recent work by Vorontsov-Velyaminov and others serves to re-emphasize de Vaucouleurs' suggestion that a search for a connection between the Magellanic Clouds and our own Galaxy be made. If the gas does not show it, perhaps looking for stars of 10^8 or 10^9 years of age in that general direction would give positive results.

(*e*) *Chemical Composition.*—Every spectroscopic and photometric effort (particularly studying ultraviolet excesses in stars) should be made to establish whether there are chemical composition differences with respect to our own region of the Galaxy. If chemical composition differences appear for stars younger than a certain age, that age should mark the onset of a different evolutionary history and might be connected with a time of separation from our own Galaxy.

(*f*) *Properties of Subsystems within Clouds.*—By studying colour-magnitude diagrams of various regions of the clouds and integrated $U-B$ and $B-V$ colours of those same regions much can be learned about the age composition of the stars in various regions within the Clouds. In combination with the velocity data a beginning could be made on the problem of how the locus of star formation has moved within the system as a function of time.

Finally, it is a great pleasure to open this part of the Symposium on the Magellanic Clouds. I look forward with intense interest to the results and discussion which will follow and which I feel sure will advance our understanding of the behaviour of all galaxies.

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