Astrophysical Letters, 1968, Vol. 3, pp. 153–159

MASSES AND ANGULAR MOMENTA OF GALAXIES

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The line widths of 48 galaxies measured at $\lambda = 21$ cm with the Nançay radiotelescope are used, together with other spectroscopic data, to obtain estimates of masses and angular momenta. The dependence upon galactic type of the mass-to-light ratios and of the mass-to-hydrogen content ratios are given and the masses are shown to be determined by two parameters: type and absolute luminosity. A relation between mass and angular momentum is found and, from it, it is possible to derive the density that the pregalactic gas clouds had when they reached their maximum extension.

INTRODUCTION

An initial program of observations at $\lambda = 21$ cm of small galaxies with the first-generation receiver of the Nançay radiotelescope has been completed, in collaboration with Bottinelli, Gouguenheim and J. Heidmann. Forty eight galaxies have been measured, and details of the observations will be found elsewhere (Bottinelli *et al.* 1968; Gouguenheim, to be published).

This paper presents statistical results on masses and angular momenta of galaxies obtained from the widths of the measured line profiles, supplemented by optical and 21 cm spectroscopic data from other sources. No elliptical galaxy is included in this study.

FIRST APPROXIMATION TO THE MASSES

Most of the angular diameters of the galaxies observed here are in the range 10–15 arc min. They are not large enough, compared to the radiotelescope beam (4 × 25 arc min), to yield rotation curves allowing valuable determinations of total masses M_T. However, a first indication of M_T is given by an indicative mass M_i which, as it will be shown, gives M_T to within a factor of 2, while its own range of variation is 1 to 10^3. M_i is defined (Bottinelli *et al.* 1968) by:

$$M_i = 3\ 10^{-5}\ a\ W^2, \qquad (1)$$

where M_i is in 10^9 solar masses, a is the optical diameter in kpc, and W is the total width of the global line profile corrected for inclination and band width effects in km/sec. The diameters are given by Holmberg (1958) or reduced to his system.

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The distances D used in this paper are those given by Bottinelli *et al.* (1958) or have been derived by similar procedures. Most of the inclinations are given by Danver (1942), or are deduced from Morgan's classes (1959) statistically reduced to Danver's inclinations. In Table I, D and M_i are listed, while W_{obs} is the total width of the global line profile corrected for band width but not for inclination. The estimated uncertainty on W_{obs} is 30 per cent.

In order to increase the statistical material, M_i has also been calculated for other galaxies from all published spectroscopic data, either of 21 cm or of optical origin. For a rotating system, W is simply twice the maximum rotational velocity. Altogether, values of M_i were obtained for 91 galaxies. They show a variation by a factor of 10^3, as a function of galaxy type.

INDICATIVE MASS, LUMINOSITY, AND HYDROGEN CONTENT RATIOS

M_i can be looked upon as a physical parameter defined by the maximum range of internal velocities, and by the optical extent of a galaxy. Its relation to the intrinsic absorption-free luminosity L_*, and to the hydrogen content M_H was investigated as a function of type τ. L_* is given by Holmberg (1964) or is derived in a similar manner. M_H is taken from published papers or from private data from Gouguenheim. τ is the stage along G. and A. de Vaucouleurs' classification (1964), with the notations shown on top of Figure 4. Galaxies of type I0 are considered separately.

Figure 1 is a three ratio-diagram showing the distribution of M_H/M_i, M_i/L_*, and M_H/L_* for 61 galaxies according to type. A pronounced shift

TABLE I Data for small galaxies observed at Nançay

(1) Name	(2) D	(3) W_{obs}	(4) M_i	(5) M_T	(6) A_i
N0428	13	200	30	50	220
N0628	9.1	130	47		330
N0925	7.6	260	75		440
N1023	11	340	130	250	630
N1055	7.9	290	70	20	390
N1097	15[a]	440	1000	700	2300
N1365	18[a]	380	380	500	1500
N1507	9.7[a]	200	24	15	200
N1532	14[a]	440	190	150	730
N1744	13	240	120	100	620
N2188	6.4[a]	120	3.7	2	50
N2366	2.9	140	5.0	15	58
N2541	6.0	240	27	30	180
N2835	7.6	180	41	25	260
N2903	8.0	400	220		780
N3079	11	440	190	300	730
N3115	5.8	280	54		320
N3198	8.7	300	85	30	460
N3319	9.5	200	31	25	250
N3344	10	190	220	150	700
N3521	7.6	550	320	300	900
N3556	7.3	320	74		390
N3621	5.7[a]	310	70	40	370
N3627	7.9	390	200	100	700
N4144	11	180	27	30	250
N4449	4.4	200	15		130
N4490	8.3	230	64		340
N4559	8.3	310	89	30	450
N4656	4.8	220	29		220
N5194	6.3	220	110		480
N5204	5.8	180	21	15	150
N5474	5.5	140	62	60	250
N5523	22	840	960	1500	1900
N5585	5.5	240	37	50	210
N5668	18	120	96	60	460
N5774	14	460	240	500	570
N5907	6.0	520	210	80	680
N5921	23	200	*a*	*a*	*a*
N6015	16	300	82	50	440
N6946	4.2[a]	140	38	15	230
N7217	18	200	140	150	680
N7331	9.6	540	380		1100
N7361	16[a]	240	*a*	*a*	*a*
N7640	8.7	270	73		450
N7793	2.5	220	*a*	*a*	*a*
I0010	1.3	94	0.56		9.4
A0814	2.3	95	1.9		35
A1009	1.2	120	1.3		19

Col. 1: N for NGC, I for IC, A for anonymous (according to G. and A. de Vaucouleurs, 1964).
Col. 2: Adopted distance, in Mpc; *a* denotes distance determined from redshift.
Col 3: Observed total width of global line profile corrected for band width, in km/sec.
Col. 4: Indicative mass, in 10^9 solar masses; *a* denotes galaxy too much face on.
Col. 5: Total mass, in 10^9 solar masses, when not already measured from detailed spectroscopy; *a* denotes galaxy too much face on.
Col. 6: Indicative specific angular momentum, in kpc. km/sec; *a* denotes galaxy too much face on.

is observed as one follows the sequence Sb... Mag. Irr. The proportions of hydrogen relative to indicative mass, or to luminosity, increase by about one order of magnitude, while the indicative mass to light ratio decreases from 9 to 4. This diagram provides a means to estimate the distance D of a galaxy from 21 cm observations of M_H and M_i, as M_H/L_* is independent of D, while M_H/M_i is proportional to D. When D is changed, the representative point of a galaxy moves on a vertical line in the diagram, and the nearest position to the center, corresponding to its type, gives D to within a mean factor of 2 or 3. The following discussion will show that the accuracy could be improved.

THE TWO-PARAMETER DEPENDENCE OF THE PROPERTIES OF GALAXIES

Figure 2 gives the distribution in the (τ,L_*) plane of the M_i values for 91 galaxies. It appears that the plane can be divided in well separated regions by lines of constant M_i values. These lines can be given quite simple forms to within one type interval, or a factor of 2 in L_*, or a factor of 2 in M_i for nearly all the points. They show how M_i is determined by τ and L_*. Figure 3 shows that M_H is also a function of τ and L_*, and a similar result was obtained by J. Heidmann (1967, 1969) for the optical diameters. Together with Chester and Roberts' (1964) type distribution in a magnitude–color index diagram, and Holmberg's (1964) type distribution in a density–color index diagram, these results demonstrate the fact that the main physical properties of galaxies are determined, at least in a first approximation, by two parameters only.

The introduction of a second parameter in Figures 2 and 3 for the analysis of the data should refine the information given by the three ratio-diagram of Figure 1. For any couple of values (τ,L_*), Figure 2 and 3 give a couple (M_i, M_H), and then a particular point $(M_i/L_*, M_H/L_*)$ in Figure 1. Then, if τ is kept fixed, this point should follow an arc of curve C_τ when L_* varies. Instead of being apparently dispersed at random, the points in Figure 1 belonging to a given type τ should follow such a curve C_τ. For the present, the data are not sufficient to delineate these C_τ curves, but it is hoped that the expanded program, which has been started with the second-generation receiver at Nançay, will provide the necessary information.

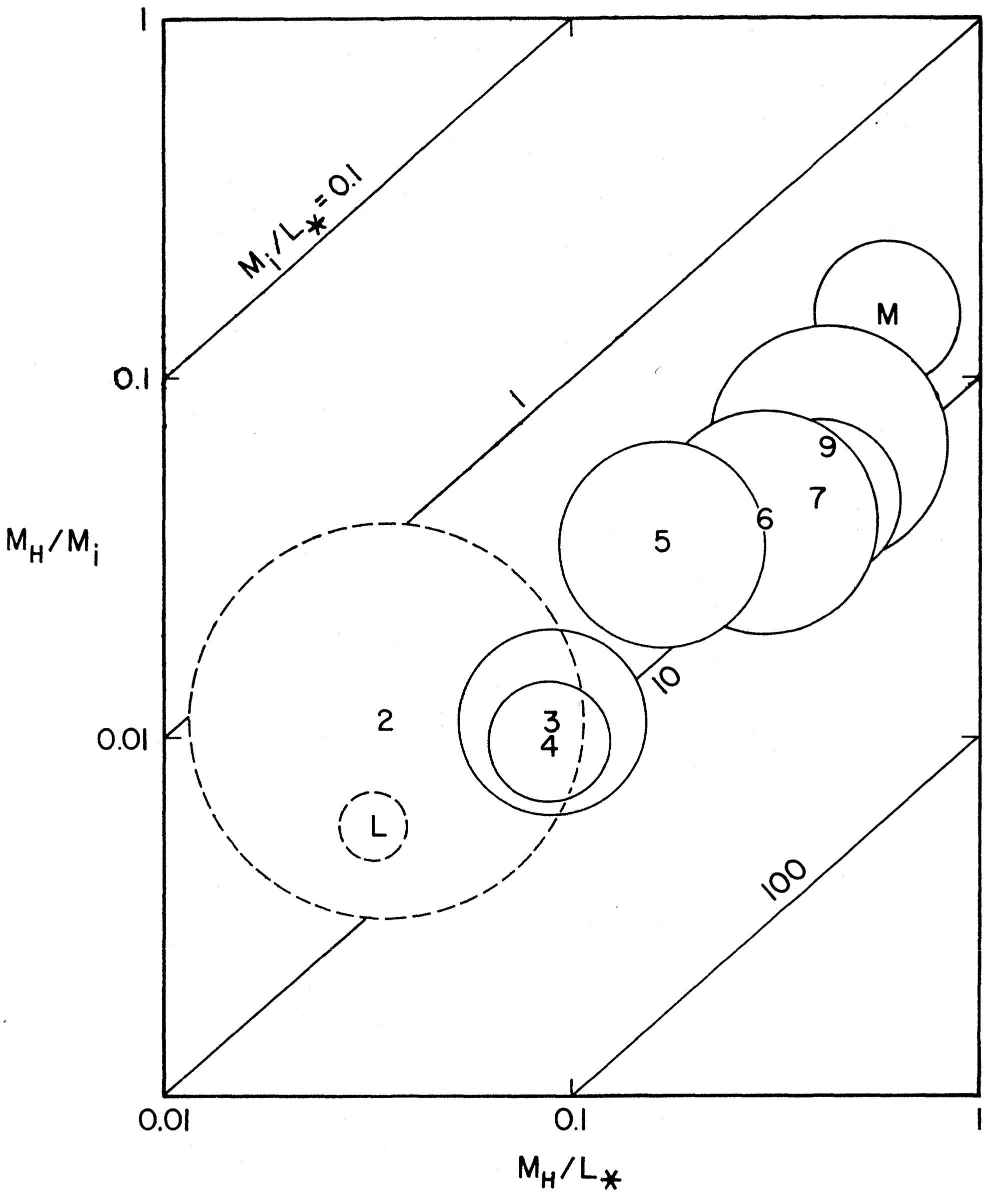

FIG. 1. Three-ratio diagram showing, according to type, the distribution of the ratios M_H/M_i, M_i/L_* and M_H/L_* for the hydrogen contents M_H, the indicative masses M_i and the absorption-free intrinsic luminosities L_*, in solar units. The center of each circle, marked by the type symbol, is located at the center of gravity of the representative points of the corresponding type. Its radius is such as to include half of these representative points. The circles for types L and 2 are indicated by broken lines because they are based on only two galaxies each, and are very uncertain.

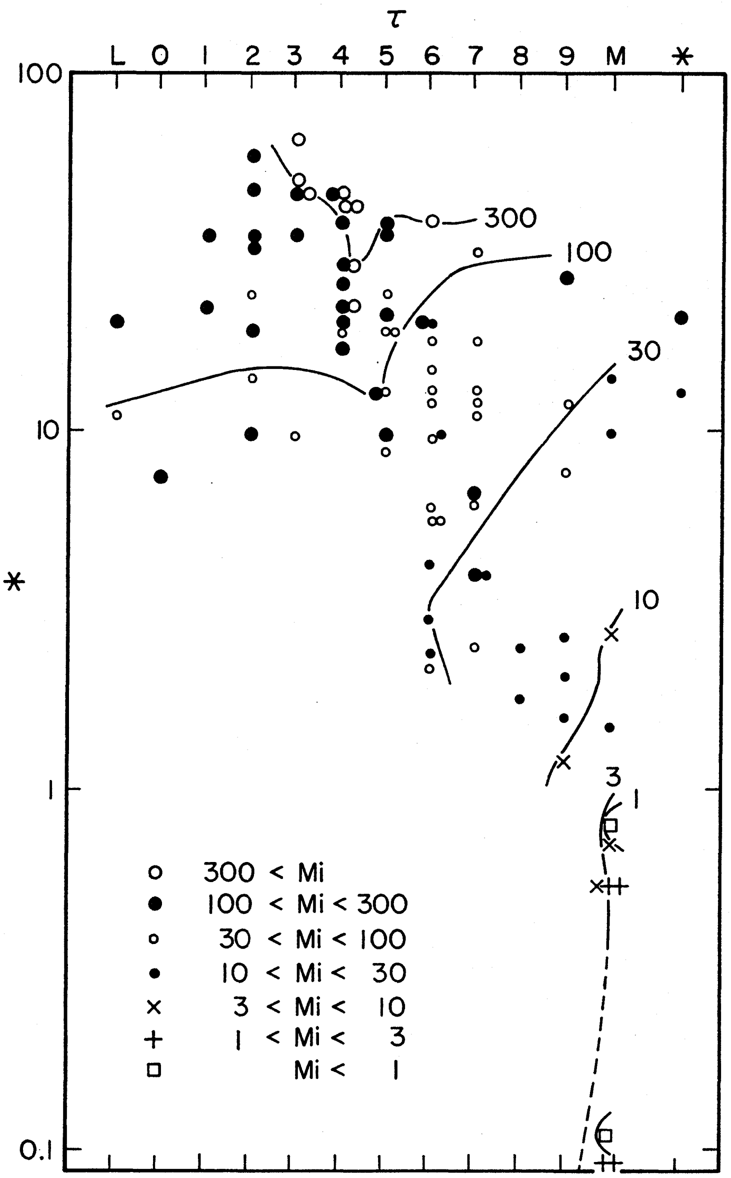

FIG. 2. Indicative mass values M_i as a function of type τ and luminosity L_*, in 10^9 solar units. Smoothed-out lines of constant M_i values, 300, 100, . . . 1, are drawn. Symbols correspond to these intervals.

TOTAL MASSES

One may attempt to convert indicative masses M_i to total masses M_T. For that purpose, the ratio $\mu = M_T/M_i$ was investigated, using the optical or 21 cm spectroscopic data in the literature which give rotation curves observed at least up to the turn-over radius. These μ ratios are plotted in Figure 4 as a function of galaxy type. They range from about 0.25 to 2. A plot of μ in the (τ, L_*) plane indicates that for a fixed τ, μ increases when L_* increases. Column 5 of Table I lists the M_T's derived from the M_i's by using this plot. However, because of the uncertainties of the total masses currently available, this plot is not expected to give μ, then M_T derived from M_i, to better than a factor of 1.5 to 2.

ANGULAR MOMENTA

Adopting again a phenomenological approach, an indicative specific (i.e. per unit mass) angular momentum is defined by:

$$A_i = 0.05aW \tag{2}$$

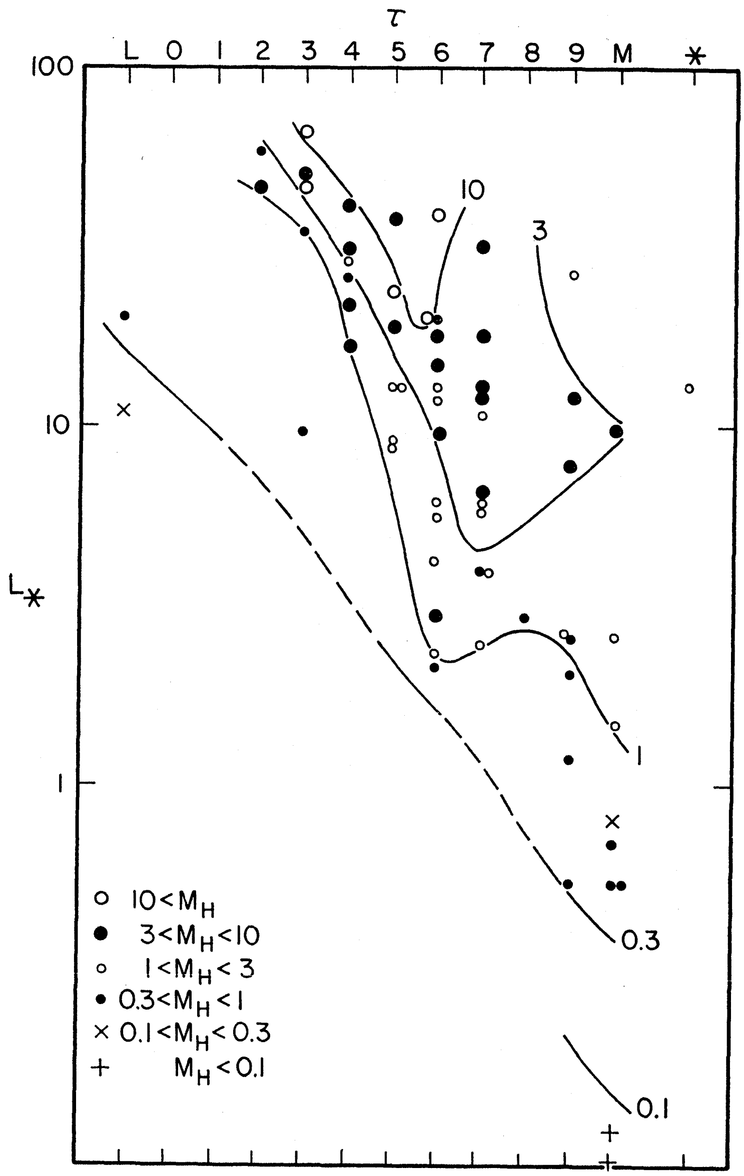

FIG. 3. Hydrogen content values M_H as a function of type τ and luminosity L_* in 10^9 solar units. Smoothed out lines of constant M_H values, 10, 3, . . . 0.1, are drawn. Symbols correspond to these intervals.

where A_i is in kpc km sec^{-1}, with the previous definitions for a and W. For a uniform disk in solid rotation, with diameter $a/5$, A_i would be its real specific angular momentum A. With this choice for the numerical constant in equation (2), it is expected that A/A_i, like M_T/M_i, will not differ greatly from unity. This point is being investigated by calculating the real momenta from photometric data. Preliminary results for the three late-type galaxies, NGC 300, NGC 598 and the Large Magellanic Cloud, give $A/A_i \sim 2$.

Figure 5 is a plot of M_i as a function of A_i for 91 galaxies. It shows a relation quite close to:

$$M_i \propto A_i^{3/2}. \quad (3)$$

Relations (1), (2), and (3) then give:

$$W/a \equiv \omega_g = (6.5 \times 10^7 \text{ years})^{-1}. \quad (4)$$

FORMATION OF GALAXIES

Relation (3) gives information about galaxy formation: density and epoch of maximum extension of the primeval clouds which gave rise to galaxies. Assume that the galaxies were formed

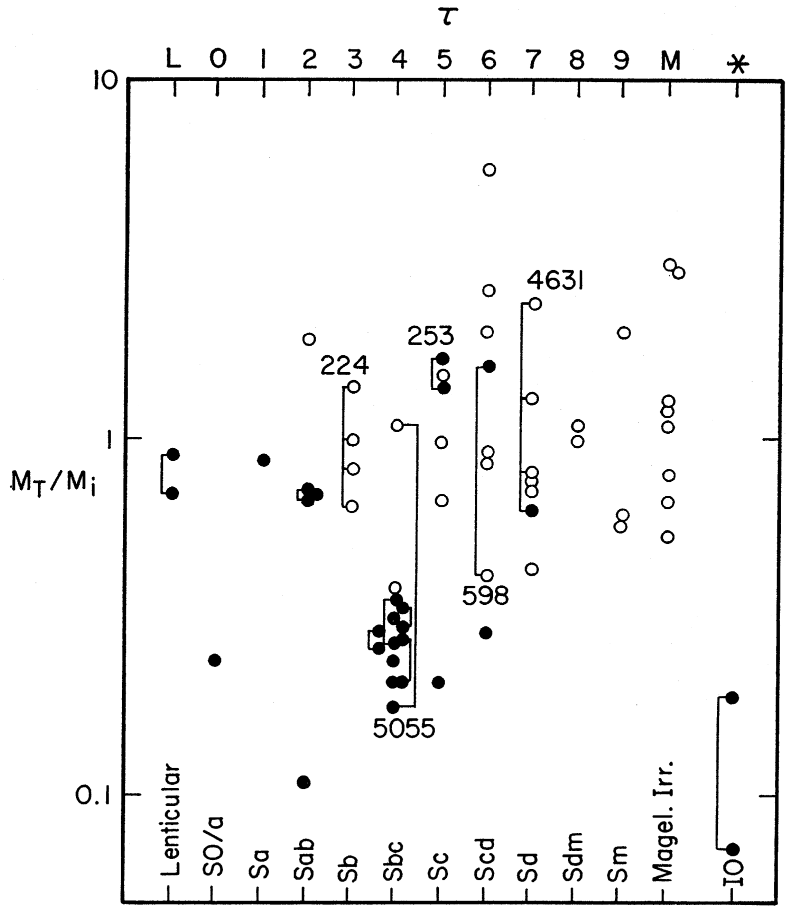

FIG. 4. Ratio of total mass M_T to indicative mass M_i, both derived from detailed rotation curves, as a function of galaxy type. ○ denotes 21 cm data; ● denotes optical data. Circles linked together pertain to the same galaxy, the different ordinates arising from different published values for M_T. Some NGC numbers are indicated.

from gaseous clouds, with conservation of total mass and total angular momentum. Taking for the clouds a very simple model made up of a sphere, with uniform density ρ, and in solid rotation with angular velocity ω, the mass and momentum of the cloud are related by:

$$\frac{M_T}{A^{3/2}} = \frac{4\pi}{3}\left(\frac{5}{2}\right)^{1/2} \frac{\rho}{\omega^{3/2}}, \tag{5}$$

whatever the radius of the sphere may be. Furthermore $M_T/A^{3/2}$ is constant during contraction with conservation of angular momentum. Relation (3) then leads to a universal (i.e. independent of time, cloud radius, and mass) constant K:

$$\rho/\omega^{3/2} = K = 0.22 \text{ cgs units.} \tag{6}$$

One can apply this relation to the particular cosmic time t_m at which, according to Partridge and Peebles' scheme (1967), a primeval cloud had its maximum extension. The density ρ_m and angular velocity ω_m of the cloud at t_m are then linked by equation (6). On the other hand, ω_m is probably close to the angular velocity of the galactic halo ω_h, if one considers this halo as the remnants of the maximum extension of the cloud. Furthermore, various estimates, for example from Mestel's calculations (1963), lead to $\omega_h \sim 0.2\, \omega_g$. Then relations (4) and (6) give:

$$\rho_m = 2 \times 10^{-25} \text{ g/cm}^3. \tag{7}$$

Putting this value for the cloud density at maximum extension in Partridge and Peebles' equation (3), we find the epoch of maximum cloud extension to be

$$t_m = 1.5 \times 10^8 \text{ years,} \tag{8}$$

which is the same as the value these authors obtained for our Galaxy.

The author thanks Drs. J. Heidmann, E. Schatz-

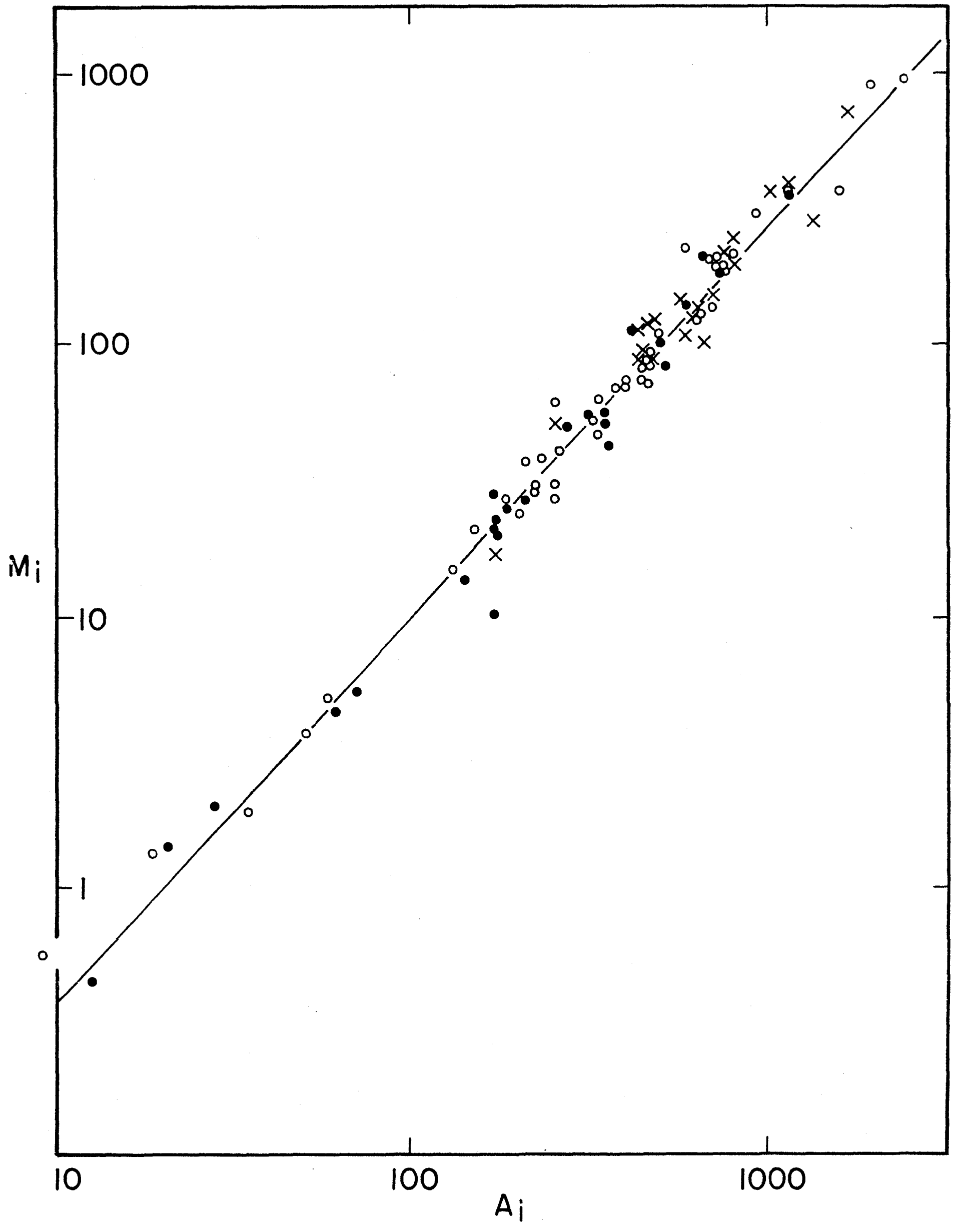

FIG. 5. Relation between indicative mass M_i, in 10^9 solar masses, and indicative specific angular momentum A_i, in kpc km sec^{-1}. ○ denotes data from Nançay 21 cm observations; ● denotes data from other 21 cm observations; X denotes data from optical observations. The line corresponds to $M_i \propto A_i^{3/2}$.

man and G. de Vaucouleurs for advice and illuminating discussions. This work forms part of a thesis filed at Paris C.N.R.S. under number AO-2716, to be presented in June 1969 to Drs. E. Schatzman, J. Delhaye and B. d'Espagnat at Paris University.

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Received 17 March 1969

NOTE ADDED IN PROOF

Distance determinations using M_H/M_T and τ (refer Figure 1) were made by N. H. Dieter (*Astron. J.* **67,** 313) and by M. S. Roberts (*Astron J.* **67,** 431)