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Spiral Structure and Nuclear Activity in Galaxies

P. C. VAN DER KRUIT

Hale Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California 91101

Spiral galaxies with strong density wave compression have a lower specific angular momentum than weak compression galaxies of the same mass. Such galaxies also have a larger degree of central mass concentration and generally better developed and possibly more active nuclei.

THE density wave theory of spiral structure is able to explain most observed overall properties of spiral galaxies. In particular, it offers a straightforward explanation for the observed ridges in the radio continuum brightness distribution of M51 (ref. 1) and some other spirals[2] as compression regions or "galactic shocks"[3]. But energy dissipation in these compression regions requires regeneration of the density waves about every 10^9 yr; a possible mechanism is gas expulsion from the nuclei from a model constructed[4] to explain the radio continuum brightness distribution of NGC4258. Oort[5] has recently discussed the "pros" and "cons" of such a model. Many difficulties remain and the description is still far from complete, so that it is felt that more research is required before it is accepted. It is, however, an interesting possibility which I accept as a working hypothesis for this article.

I have analysed observations of a large set of spiral galaxies made with the Westerbork Synthesis Radio Telescope (ref. 2 and unpublished work). The radio continuum observations provide a most sensitive measure of the compression strength in the compression regions, when the ratio between the flux densities in the spiral ridges and in the (extended) base disk is evaluated. This quantity is both direct and sensitive; direct because it derives directly from the observed flux densities at long and at short interferometer baselines (if corrected for the radio nucleus and background sources) and sensitive because of the strong dependence of the synchrotron volume emissivity on the magnetic field strength.

This property was found to relate to optical properties such as[6] luminosity class and average mass-luminosity ratio (in the sense that strong compression galaxies are luminosity class I or I–II and have a low M/L) and to the form of the rotation curve. I will discuss these in detail elsewhere. In short, the first derives from the fact that the compression triggers star formation, and the second relation occurs because the compression strength is chiefly determined by the relative speed between gas and pattern. The parameter used is $R_{\max}/R_o$, where $R_{\max}$ is the radius of the outermost H II region, which is assumed to correspond to corotation and R_o is the radius of the maximum in the rotation curve. The relative velocity is largest (and the compression strongest) in galaxies with low $R_{\max}/R_o$.

Here I attempt to extend these results to all spiral galaxies with well observed rotation curves and also discuss the questions of the relation of these properties with nuclear properties and what determines the different values for $R_{\max}/R_o$.

Compression Strength

From the Westerbork survey it was possible to derive a measure for the compression strength for only twelve galaxies. This is a rather small sample which is difficult to extend by further radio observations with the currently available radio telescopes. But the definite relations with the parameter $R_{\max}/R_o$ and with the van den Bergh luminosity class makes it in principle possible to extend it to all those galaxies with well observed rotation curves. Again, both these properties are convenient parameters to describe the compression strength because their determination does not require an assumption of the distance. The parameter $R_{\max}/R_o$ has been calculated for all those spiral galaxies for which optical rotation curves are published. Barred spirals and those galaxies for which the presence of non-circular motions hamper a reliable determination of $R_{\max}$ have been omitted. This defines a set of 26 spiral galaxies. R_o is defined as the radius of the outermost H II region and was evaluated from published photographs.

Figure 1 is a plot of $R_{\max}/R_o$ against the luminosity class. The relations indicated above are confirmed, because galaxies with low $R_{\max}/R_o$ (=strong compression) are relatively more luminous (=enhanced star formation). Galaxy NGC157 (marked in Fig. 1) is the only one which disobeys the relation. Its well defined spiral structure leads to the classification of class I, although the presence of many H II regions (patchy arms) is indicative of type III. The latter is consistent with the general trend of large bright H II regions to occur in weak compression galaxies. From a Hubble constant of 100 km s^{-1} Mpc^{-1}, it follows that $M_{pg} = -20.2$, which favours class I, but is not inconsistent with class II or III (ref. 6), especially in view of the presence of the many bright H II regions.

Two inferences can be drawn from Fig. 1. It confirms the enhancement of the density wave compression by increased

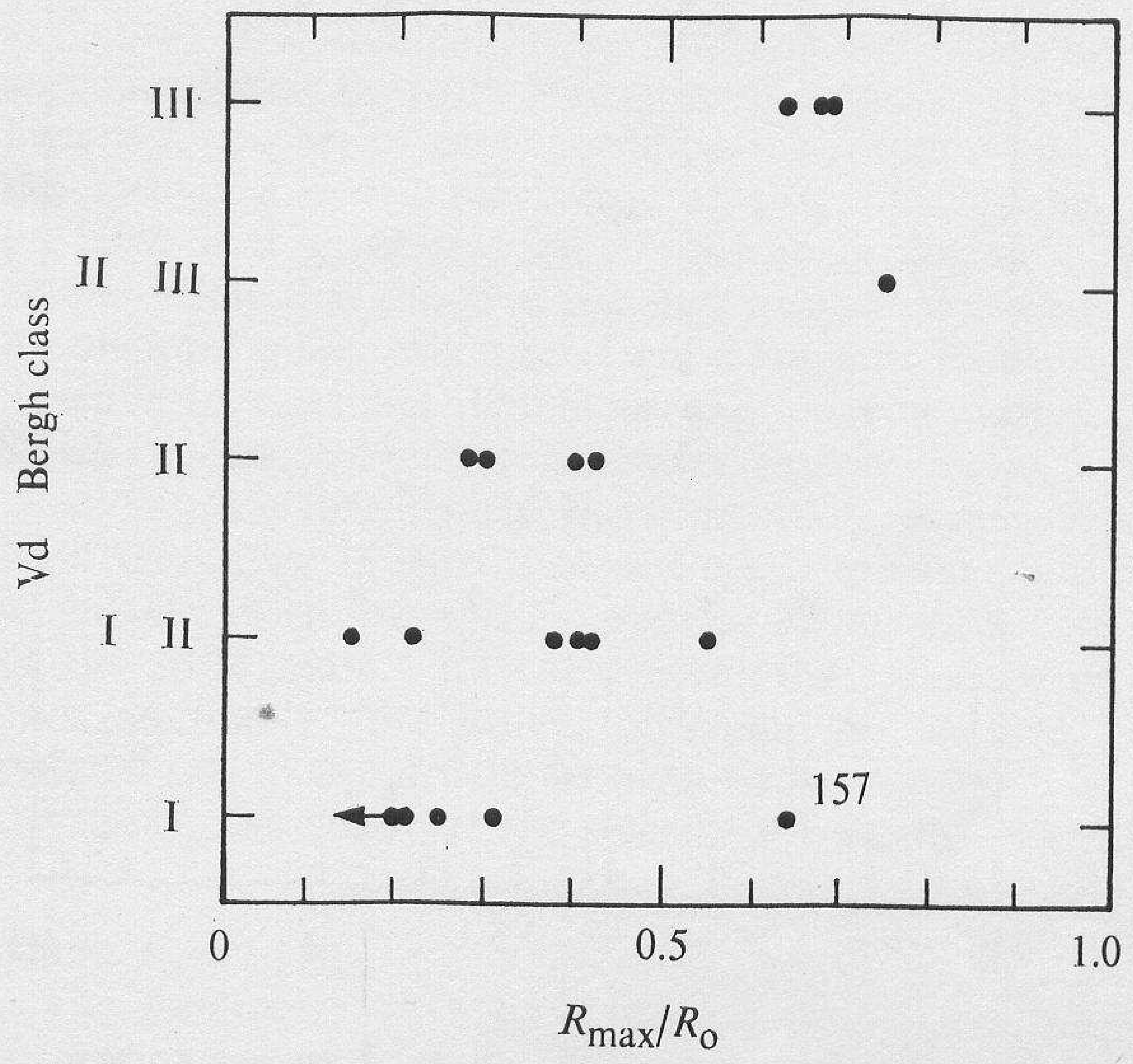

Fig. 1 Plot of the van den Bergh luminosity class against $R_{\max}/R_o$ for all spiral galaxies with optical rotation curves. NGC157 is indicated and discussed in the text.

differential rotation, which implies that $\Omega_p \approx \Omega(R_o)$. On the other hand, it poses the interesting question of what determines Ω_p (and thus R_o). I will return to this later.

Nuclear Activity and Spiral Structure

The next step is to compare the compression strength to observed properties of the nuclei that are indicative of nuclear activity and/or development of the nucleus. Such properties are the absolute optical[7–9] and radio[2] luminosity and the Byurakan class[7–9]. On average the optical and radio luminosities of the nuclei increase with decreasing R_{max}/R_o, although the scatter is considerable. But a comparison of the compression strength with the Byurakan type is especially important, since the latter is a good measure of how well developed the nucleus is (see the definition of the classification in ref. 10). The diagram is presented in Fig. 2. The two crosses indicate NGC157 and M33, which both have much weaker optical nuclei than other galaxies of type 5 (ref. 8); especially, the classification of M33 may be influenced by its proximity. The figure suggests that better developed nuclei occur in galaxies with low R_{max}/R_o, or with strong compression.

This is not completely unexpected, because R_{max}/R_o is a measure of the degree of central mass concentration, at least with respect to the extent of the optical spiral structure. I show later that it turns out to be an absolute measure of central concentration. I conclude from this that there is some tentative evidence that more developed ("late" Byurakan type) and more active (higher optical and radio luminosity) nuclei tend to occur in galaxies with strong density wave compression.

Specific Angular Momentum

There is a relation between the total mass M and the specific angular momentum L (defined as the total angular momentum divided by the total mass). On quite general grounds[11,12] it is found that

$$L \propto M^{2/3} \qquad (1)$$

In particular, Icke[12] obtained this from a basic "deformation balance", without detailed assumptions of the medium from which the proto galaxy contracts (such as primaeval turbulence). But this relation holds strictly only if the density distribution in the proto galaxy is uniform.

Freeman[13] has found empirically that the disks of spiral galaxies have an exponential surface brightness distribution $I(R) = I_o \exp(-\alpha r)$. On the proposition that the mass-luminosity ratio is constant (so that surface density $\mu(R) = \mu_o \exp(-\alpha r)$ he then showed that μ_o is approximately constant for most spiral galaxies, so that $L \propto M^{3/4}$, at least for the exponential disks. This was quoted to be in agreement with observations if rotation curves can be approximated by Brandt curves. I will use in the following

$$L \propto M^{(k-1)/k} \qquad (2)$$

where the above cases correspond to $k=3$ and $k=4$ respectively.

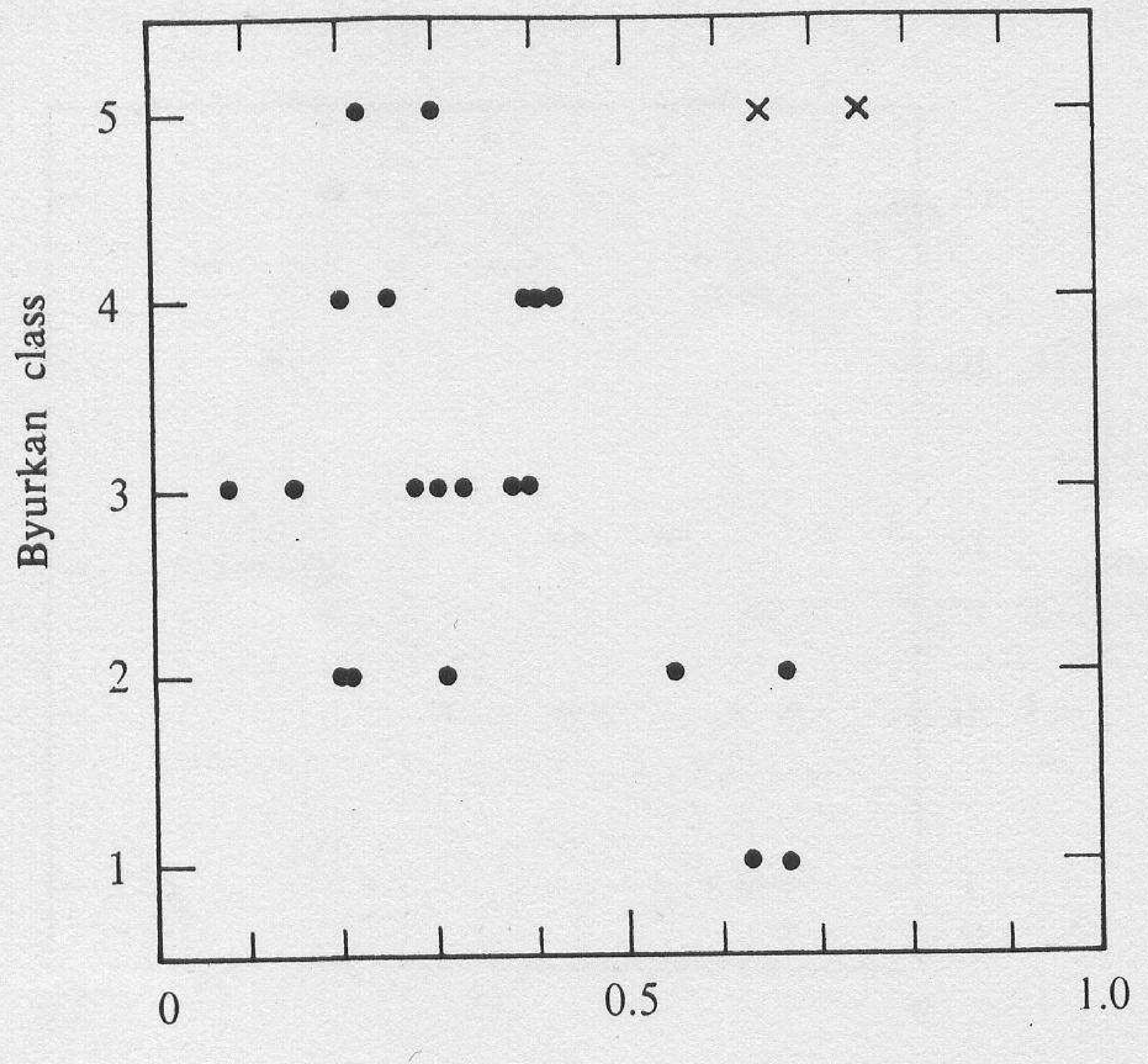

Fig. 2 The relation between Byurakan class of galactic nuclei and R_{max}/R_o. The crosses indicate NGC157 and M33 which have subluminous nuclei.

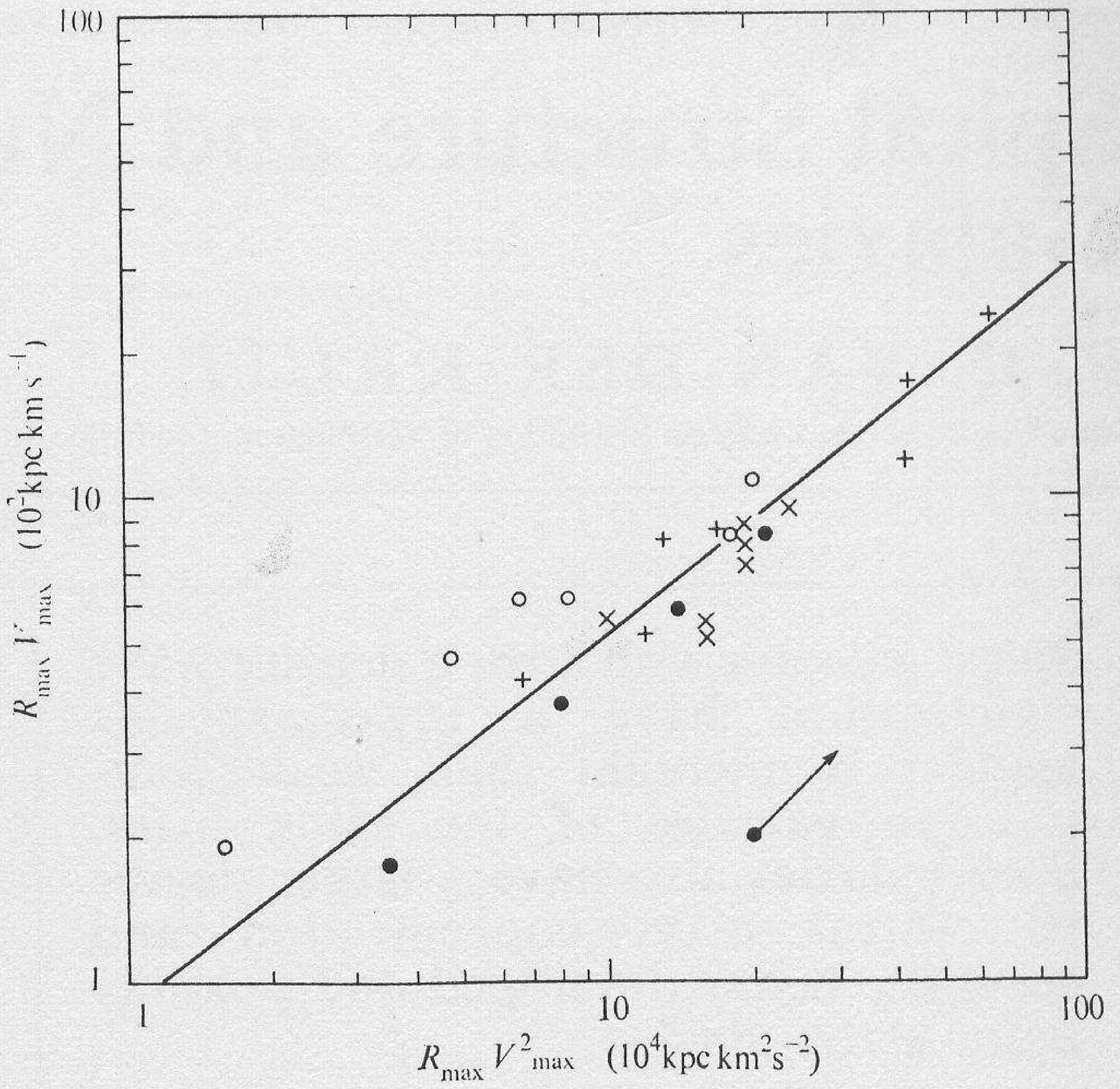

Fig. 3 The relation between indicative specific angular momentum ($R_{max} V_{max}$) and indicative total mass (R_{max} V_{max}^2) for spiral galaxies with optical rotation curves. ●, $0 \leq R_{max}/R_o < 0.2$; ×, $0.2 \leq R_{max}/R_o < 0.4$; +, $0.4 \leq R_{max}/R_o < 0.6$; ○, $0.6 \leq R_{max}/R_o \leq 1.0$. The arrow indicates the effect of distance uncertainties.

If rotation curves can be described by the same analytical function for all galaxies (as in ref. 13), it follows that

$$M \propto R_{max} V_{max}^2 \qquad (3)$$

where V_{max} is the maximum rotation velocity. For most analytical functions used for fits to observed rotation curves the proportionality constant for equation (3) changes only moderately. Evaluation of the specific angular momentum yields

$$L \propto R_{max} V_{max} \propto M/V_{max} \qquad (4)$$

Again the proportionality constant is slowly changing when different functions for the rotation curve are used.

The most extensive study of the relation between such dynamical properties for actually observed galaxies is by Takase and Kinoshita[14]. They fit different Brandt curves to the observed rotation curves and evaluate the total mass and angular momentum. They then find a well-defined relation between these two, which indicates $k=4$.

Figure 3 shows a plot of R_{max} V_{max} against R_{max} V_{max}^2 for the spiral galaxies discussed in the preceding sections. I will call these properties for the moment indicative specific angular momentum ($L_i = R_{max}$ V_{max}) and indicative mass ($M_i = R_{max}$ V_{max}^2). The line of best fit lies close to $L_i \propto M_i^{3/4}$ or $k=4$. The arrow indicates the effect on the points if the actual distance is 1.5 times larger than the distance used. Large distance modifications must be made to remove the scatter. The two galaxies with highest M_i and L_i are M31 and our Galaxy.

The values for R_{max}/R_o have been divided into four groups and indicated by different symbols in Fig. 3. The points move systematically from below the line of best fit to above when R_{max}/R_o increases. For $R_{max}/R_o < 0.2$ all four points are below the line; for the interval 0.2 to 0.4 there are five below, one on the line and one above, for 0.4 to 0.6 two below and five above, and for $R_{max}/R_o > 0.6$ one on the line and five above. Thus, the compression strength is not determined by the total mass or specific angular momentum, but by the deviation of the rotation curve from the mean. Figure 3 can be interpreted as implying that strong compression galaxies have too low (indicative) specific angular momentum for their (indicative) mass, which means that they are more centrally condensed than they should be according to their mass.

This can be made more quantitative. If the values for V_{max} and R_{max} are indicated on the graph they show—as expected—a general increase of V_{max} and R_{max} with increasing M_i or L_i, but also that points above the line have systematically too low V_{max} and too high R_{max}. The points on or close to the line define relations expected for $k=4$. For each galaxy one can then find what R_{max} and V_{max} should be according to their M_i and calculate the differences ΔR and ΔV when these are subtracted from the observed values. In Figs 4 and 5 they are plotted against the R_{max}/R_o values. I emphasize that these figures still contain uncertainties in the assumed distances. Our Galaxy has been indicated by the cross.

Strong compression galaxies have too high V_{max} and too low R_{max}. The concentration of mass in the centre is larger, when the angular rotation velocity Ω_c of the central part of the disk is larger. In general terms

$$\Omega \approx V_{max} R_{max}^{-1} \qquad (5)$$

so that high compression galaxies have a larger central mass concentration than low compression galaxies of the same indicative mass do. This refers to the central part of the disks but strictly not to the nucleus, although it is of course expected that centrally more condensed disks will have more massive nuclei.

Not unexpectedly, an evaluation of V_{max}/R_{max} for the galaxies shows a well defined increase of this property with decreasing R_{max}/R_o, so that it is fair to say that also on absolute terms strong compression galaxies tend to have more centrally condensed disks. But the reason for this is a lower L_i than expected from M_i and not a high or low specific angular momentum or total mass.

Takase and Kinoshita[14] have fitted different Brandt curves to the observed rotation curves. Comparing a plot of L (in their terms Q/M) against M with Fig. 3, I find that the scatter around the line of best fit is the same and the position of a galaxy with respect to the line of best fit is not changed. This indicates that the analysis in terms of M_i and L_i is not influenced by the fact that I used indicative parameters.

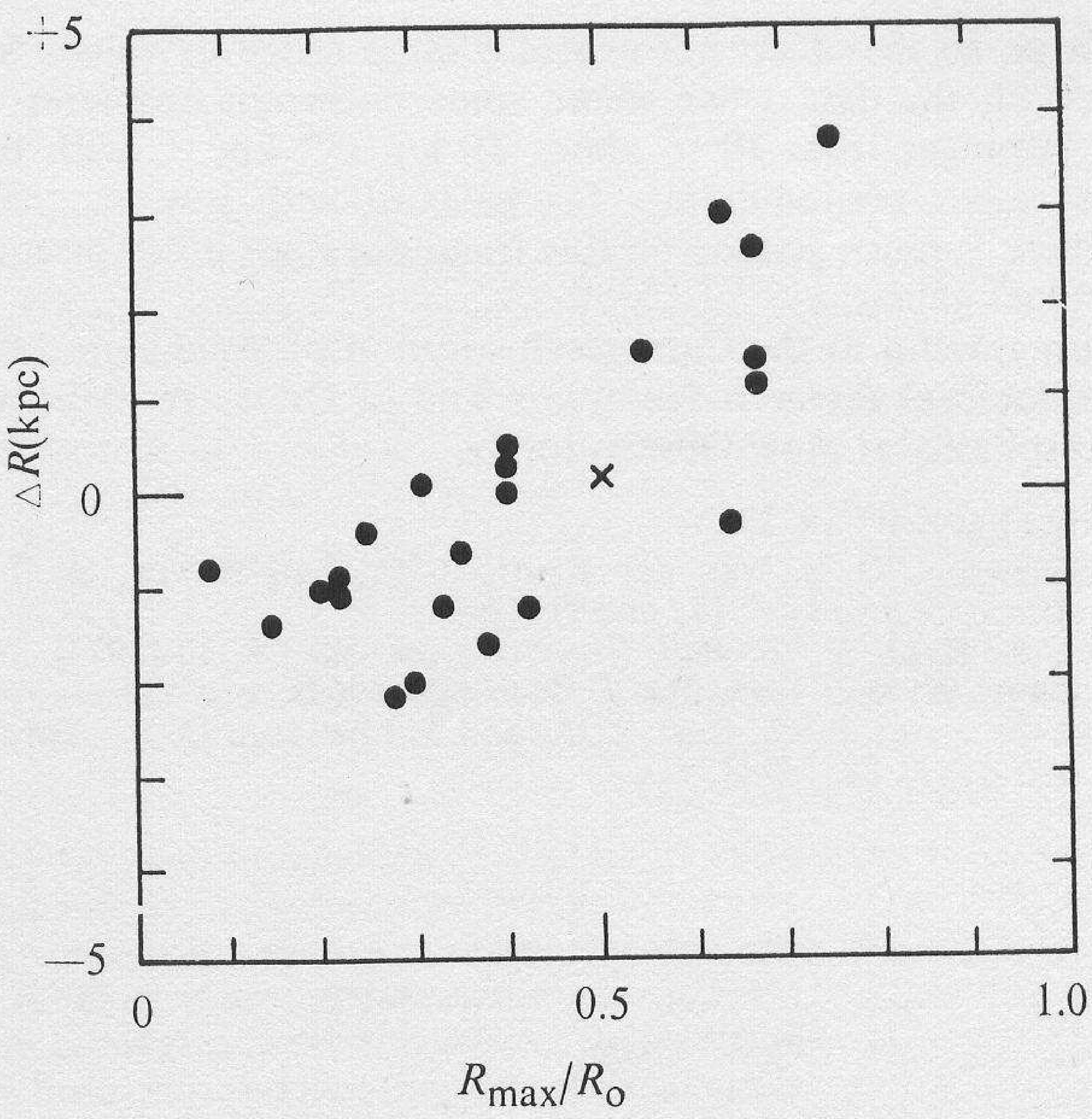

Fig. 5 The difference between observed R_{max} and R_{max} according to M_i as a function of R_{max}/R_o. The cross is our Galaxy.

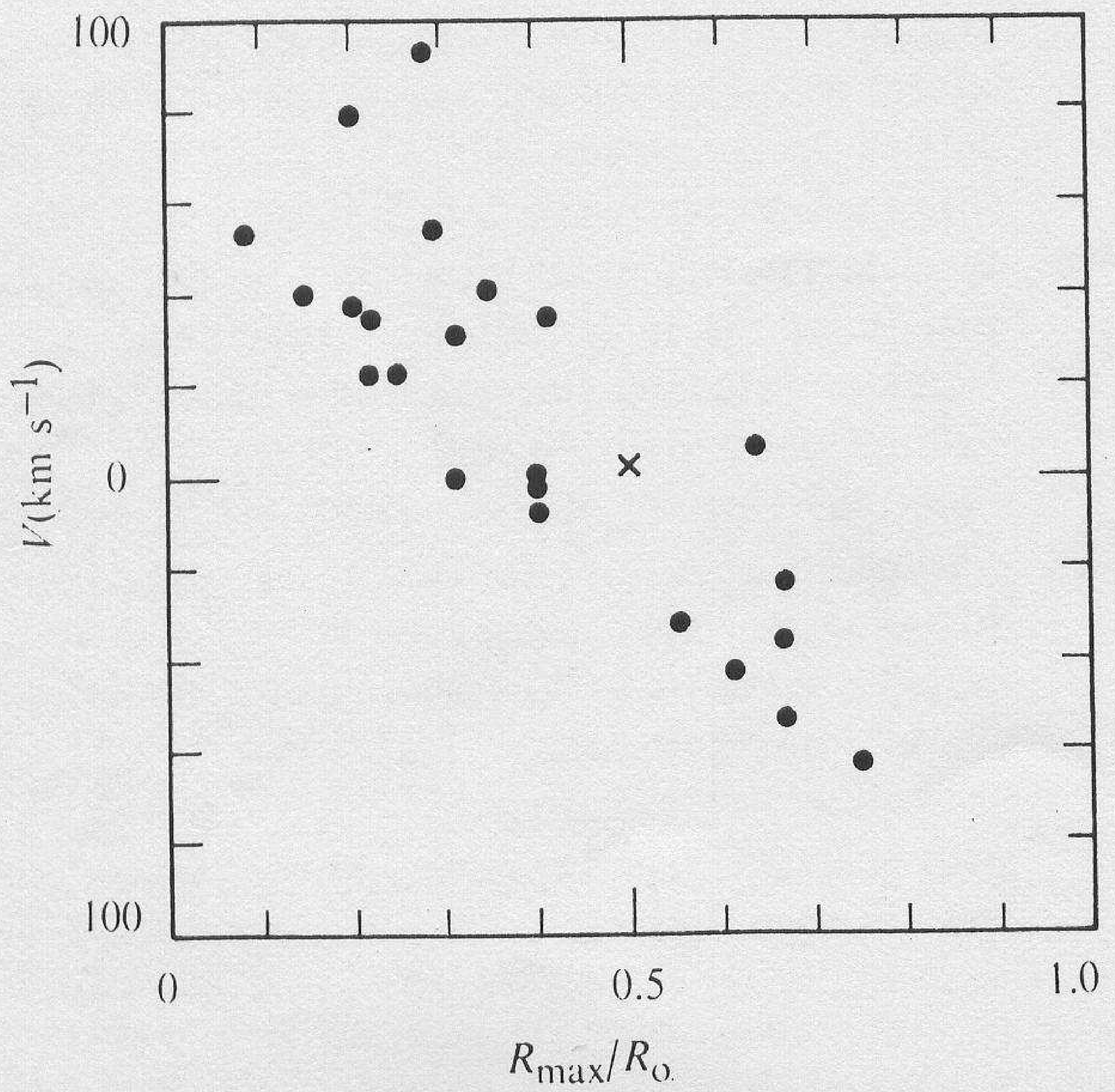

Fig. 4 The difference between observed V_{max} and V_{max} according to M_i as a function of R_{max}/R_o. The cross is our Galaxy.

Thus, strong compression galaxies have generally a high concentration of mass to the centre, the reason being that they have a lower specific angular momentum than low compression galaxies of the same mass. The ratio R_{max}/R_o is indeed an absolute measure for the degree of central mass concentration.

Implications for Galactic Structure

If a galaxy has a low specific angular momentum for its mass, it will have strong density wave compression, a larger degree of central mass concentration and a better developed and possibly more active nucleus. It has also been shown[15,16] that density waves transport angular momentum by dissipative effects in the compression regions. This transport is generally outward and will be enhanced when the compression strength and thus the dissipation is stronger. Lynden-Bell[17] has speculated that outward transport of angular momentum (or inward transport of gas) speeds up the rotation and increases the mass of a central black hole, so that it eventually becomes unstable and gives rise to a nuclear explosion. If future studies show that this and the suggestion that nuclear activity regenerates spiral structure[4] have a basis of reality, it will be possible to conclude that there exists a continuous cycle, in which nuclear activity regenerates density waves, while the latter in their turn add to the production of nuclear activity. Both directions in such a closed cycle operate more strongly in galaxies with low specific angular momentum with respect to the total mass. But at present the existence of such a cycle is highly speculative, although the various relations pointed out in this article do fit in such a scheme.

Finally, the speed of the density wave pattern is given by

$$\Omega_p \approx V_o/R_o = (V_o/V_{max})(R_{max}/R_o)\Omega_c$$

where $V_o = V(R_o)$.

The parameter V_o/V_{max} is difficult to evaluate because the determination of V_o generally involves an extrapolation of the observed part of the rotation curve. It is, however, likely to decrease with decreasing R_{max}/R_o. At the same time Ω_c

increases, so that I do not expect a large range of values for Ω_p. With the data I can make some uncertain estimates of Ω_p. It ranges from 10 to about 25 km s^{-1} kpc^{-1}, with the lower values predominantly for galaxies with low R_{max}/R_o. But there is much scatter, so this trend does not hold for each individual galaxy.

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