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AN ALTERNATIVE VIEW OF FLAT ROTATION CURVES. II. THE OBSERVATIONS

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RESUMEN

Se investigan las curvas de rotación de 20 galaxias espirales usando el modelo propuesto por Soares (1992) que tiene como característica principal la de atribuir una alta razón M/L (= 30; H_o = 50 km s^{-1} Mpc^{-1}) para la materia visible. La rotación observada de todas las galaxias puede ser ajustada sin hacer la suposición de un halo obscuro.

Sin embargo, se sugiere que el hecho de que casi todas las medidas disponibles de velocidades de rotación son deducidas a partir de líneas emitidas por el gas de las galaxias (neutro o ionizado) las hace inadecuadas como indicadoras del potencial gravitacional. Para considerar esto, el modelo introduce un potencial efectivo apropiado para describir la hidrodinámica dentro del disco gaseoso. La morfología general de las curvas [i.e., la presencia de una meseta en $V(r) \times r$] se interpreta, en este tratamiento, como una consecuencia de las características hidrodinámicas de los discos galácticos.

La relación de Tully-Fisher se expresa en términos de los parámetros del modelo y se usa como una restricción adicional en el proceso de ajuste del modelo a la rotación observada de las galaxias.

ABSTRACT

The rotation curves of 20 spiral galaxies are examined in the light of a toy model (Soares 1992) which has as the main feature the assignment of a high M/L ratio (= 30; H_o = 50 km s^{-1} Mpc^{-1}) to the visible matter. The observed rotation of all galaxies can be accommodated without the assumption of a dark halo.

Moreover, the suggestion is made that the fact that almost all available rotational velocity measurements are derived from emission lines emitted by gas in galaxies (either neutral or ionized) makes them inappropriate as tracers of the galaxy gravitational potential. To account for that, the model introduces an effective potential meant to describe the hydrodynamics inside a gaseous disk. The general morphology of the curves [i.e., the presence of a plateau in $V(r) \times r$] is interpreted in this framework as a consequence of the hydrodynamical characteristics of disks in galaxies.

The Tully-Fisher relation is expressed in terms of model parameters and used as an additional constraint in the process of fitting the model to the observed rotation of the galaxies.

Key Words: **GALAXIES – SPIRAL — GALAXIES – KINEMATICS AND DYNAMICS**

1. INTRODUCTION

The mass discrepancy in spiral galaxies is still ı unsolved problem in astrophysics. Topical or :view papers have been copiously written in the st decade (e.g., Faber & Gallagher 1979; Rubin al. 1982; Whitmore et al. 1984; van Albada et al.)85; van Albada & Sancisi 1986; Trimble 1987; ınders 1990; Broeils 1992; Ashman 1992; Persic Salucci 1993) demonstrating renewed interest on .e subject.

The orthodox explanation of flat rotation curves of spiral galaxies is that they are the result of combined effects of luminous matter, with M/L typical of the solar neighborhood, and dark matter with much higher M/L. Luminous matter accounts for the rotation inside the luminous body and a dark extended halo is needed to fully account for the values above Keplerian observed in the outer regions of spirals. Popular alternative views include modifications of Newtonian dynamics (or gravity,

e.g., Milgrom 1983, 1988, 1991), and modifications of the classical view of spiral galaxies (e.g., Valentijn 1990; González-Serrano & Valentijn 1991; Battaner et al. 1992). This paper follows another (Soares 1992, hereafter Paper I) where we put forward an alternative idea for the mass discrepancy query.

In Paper I we suggested that real M/L for the luminous body of spiral galaxies should be those obtained from binary galaxy studies (e.g., Schweizer 1987; Soares 1989), which are as large as ten or fifteen times the local solar M/L. These values, in spite of disagreeing with classical stellar population calculations (e.g., Larson & Tinsley 1978), are by no means ruled out by standard stellar population synthesis of spiral galaxies; it is almost common sense nowadays that a population synthesis calculation of spiral galaxies can yield virtually *any* value of M/L, given the uncertainty on stellar metallicities and ages.

Furthermore, we pointed out that the observations of the rotation of spiral galaxies are inferred almost always from Doppler shifts of emission lines generated either by ionized or by neutral gas in galaxies, and gas motion cannot be used as a reliable tracer of the gravitational potential. Rather, gas motion is ruled by an *effective* potential wherein hydrodynamical effects are incorporated.

The last two paragraphs state the two basic work hypotheses of the alternative model (hereafter AMOD) described in Paper I.

In § 2 a short summary of the toy model of Paper I is made. The rotation curves of 20 spiral galaxies, observed by Rubin et al. (1982) are investigated in the framework of the AMOD potential (see eq. [1], below). In order to reduce the number of free parameters, we assume a fixed M/L for all of the galaxies in our sample. The adopted value is $M/L = 30$ (for $H_o = 50$ km s^{-1} Mpc^{-1}, here and throughout this paper). This figure is consistent with binary galaxy studies and is further justified by the application of the toy model to the well-known spiral galaxy NGC 3198 (e.g., van Albada et al. 1985; Begeman 1987, 1989); this is done in § 3. In § 4, an expression for the Tully-Fisher relation (Tully & Fisher 1977), in terms of model parameters, is derived, the fitting process is described and applied to the sample. The resulting Tully-Fisher diagram is plotted as well. A brief discussion of the results and our final conclusions are presented in § 5.

2. AMOD

The overall kinematics of gas in spiral galaxy disks is derived from the toy potential

$$U(r) = \frac{GM}{r}\left(1 + \beta e^{-r/r_o}\right) , \qquad (1)$$

where β and r_o are intrinsic scale parameters in ga axies.

A Seeliger-Neumann type potential (North 196! Assis 1992) was added to the Newtonian grav tational potential in order to describe the h drodynamics inside a spiral gaseous disk; the p rameters β and r_o determine the range of applic bility of the new potential component in each galax In Paper I, this additional component is associate with a kind of *buoyancy* potential. It is shown the also that equation (1) can be derived from a sin ple phenomenological description of the dynami of gas bubbles inside smooth gaseous disks.

The circular velocity of test particles is easi derived from the AMOD potential:

$$v_{circ}(r) = \left\{\frac{GM}{r}\left[1 + \beta\left(1 + \frac{r}{r_o}\right)e^{-r/r_o}\right]\right\}^{1/2} . \quad (!$$

The Keplerian rotation curve derived from the ligl profile of a spiral galaxy plus the usual values M/L is below observed gas rotation in the out regions. The conventional dark matter approac is to adopt an extended halo in such a way th the model velocities are pushed up to the observe levels. AMOD, on the other hand, assumes higher M/L, resulting in that the Keplerian cur will be located above the observed rotation curv With properly chosen β and r_o it was show in Paper I that equation (2) pulls down suc an overestimated rotation profile to the observe levels. This is illustrated in Figure 1, where w plot the rotation curve of a conventional $M/L =$ spiral galaxy. The Keplerian circular velociti are below the observations and are reconciled wi them with the aid of a dark halo. Also show

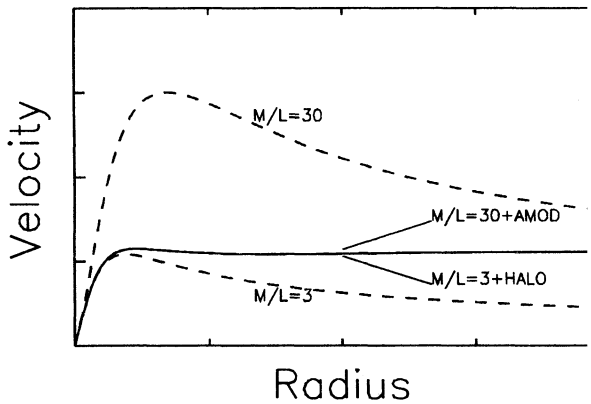


Fig. 1. A typical flat rotation curve can be explained by a suming galaxy luminous matter with solar neighborhoo M/L plus a dark halo. Alternatively, it can also be e plained with luminous matter having a high M/L a test particle circular velocities given by AMOD.

the Keplerian rotation curve of a $M/L = 30$ iral galaxy that does not fit the observations as ell. In this latter case the AMOD potential is plied and the observations are now well fitted. ıe exponential decay component present in the MOD potential represents an additional repulsive rce of hydrodynamical origin, which acts on the s test particles that are tracing the galaxy rotation.

3. AMOD FIT TO NGC 3198

As we have pointed out in Paper I, AMOD has e same mathematical formulation as the model ggested by Sanders (1984, 1986) to account for ass discrepancies in spiral galaxies, i.e., both are scribed by the same potential given by equation) with the sole difference that, in Sanders' model, e gravitational constant G is replaced by a new G_∞ ee below). This model, named FLAG (*finite length-ıle anti-gravity*), was later abandoned by Sanders 990), among others, mainly on the grounds of inability to explain one of the most important bserved features of spiral galaxies, namely the ılly-Fisher relation.

In FLAG, due to the new potential component he very same Seeliger-Neumann potential shown bove) the "effective" gravitational constant is now $_\infty = G/(1+\beta)$, where β, in the context of FLAG, is ıe coupling constant of the additional component gravity[1]. G is the usual Newtonian gravitational nstant. Sanders has used the galaxy NGC 3198 find out what are the values of FLAG's *universal* nstants, r_0 and β. He found, for a luminous isk with $M/L = 2.4$, $r_0 = 36$ kpc and $\beta = 0.92$ (for $H_0 = 50$ km s^{-1} Mpc^{-1}). These val-es can be used to calculate the AMOD M/L of GC 3198, i.e., $2.4/(1+\beta) = 30$. They are also used fit the observed rotation curve of NGC 3198 with quation (2). Again, as in Paper I, we represent M y a Plummer sphere (an $n = 5$ polytrope). Its mulative mass distribution is given by

$$M(r) = \frac{M_0 r^3}{(r^2+\epsilon^2)^{3/2}} , \qquad (3)$$

here M_0 is the total galaxy mass and ϵ is the lummer sphere core radius. In order to account or the fact that spirals have constant central sur-ıce brightness of $\approx 140\ L_\odot$ pc^{-2} (Freeman 1970; chweizer 1976), the core radius is scaled to the total alaxy mass as (e.g., Sanders 1988):

$$\epsilon = 1.6\ M_0^{1/2} . \qquad (4)$$

M_0 is given in units of $10^{11}\ M_\odot$ and ϵ in kpc. The total luminosity (B band) of NGC 3198 is $2.0 \times 10^{10}\ L_{B\odot}$ (Begeman 1987), which implies $M_0 = 6.0 \times 10^{11}\ M_\odot$ and $\epsilon = 3.9$ kpc. Equation (4) is also used below (in § 4) to model all the sample galaxies.

Figure 2 shows the fit to the observed rotation curve of NGC 3198 obtained with the above-mentioned parameters. The only difference between the AMOD fit and FLAG's one is the use by Sanders of an exponential disk to model the galaxy. It can be seen that with the spherical symmetric Plummer model the fit does not change too much. The general behavior of the rotation curve is reproduced in spite of losing fine features.

From the above investigation on NGC 3198, and from results of binary galaxy studies (e.g., Schweizer 1987; Soares 1989), we shall adopt the value of $M/L = 30$ to proceed with the AMOD analysis. Of course, the M/L of a given galaxy is an intrinsic parameter and might vary from galaxy to galaxy. The point here is that fixing M/L, we gain in reducing the free parameter space while not being too far from what ought to be individual values of M/L for each galaxy. It is worthwhile noting that, in the context of AMOD, such a high M/L is assigned to the *visible* body of the galaxy instead of being justified by the artificial assumption of the existence of an extended dark halo surrounding the visible galaxy.

The sample of 20 Sb galaxies of Rubin et al. (1982) will be considered in the next section taking into account the AMOD potential and the Tully-Fisher relation.

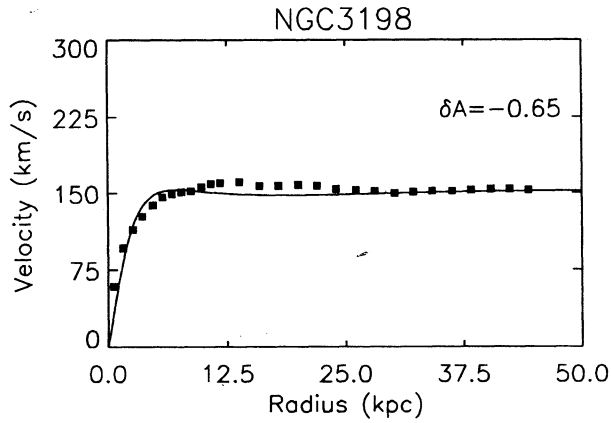


Fig. 2. The filled squares are the observed H I circular velocities for NGC 3198 (Begeman 1987). The solid line is the AMOD fit to the observations with $\beta = -0.92$, $r_0 = 36$ kpc, and $M/L = 30$. The galaxy mass distribution is modeled with a Plummer model.

[1] It is important to stress that in AMOD such a mponent is not an additional component of gravity, ther, it is a part of the "effective" potential in galaxies, d is responsible for describing the hydrodynamical be-avior of gas test particles inside a gaseous disk.

4. AMOD AND THE TULLY-FISHER RELATION

The main question in this section is whether AMOD is consistent or not with the Tully-Fisher relation. To investigate that, a set of observed rotational profiles is modeled with AMOD having the Tully-Fisher relation as an additional fitting constraint.

To begin with, one needs a convenient expression for the Tully-Fisher relation, i.e., a relationship which involves the relevant AMOD parameters. Let us consider the following form of the Tully-Fisher relation (Aaronson, Huchra, & Mould 1979):

$$L = k_{TF} V_p^4 \ , \qquad (5)$$

which, in spite of being oversimplified, is very useful to the sort of investigation underway.

For the evaluation of k_{TF} we have considered the spiral galaxies observed in the 21-cm line of neutral hydrogen by Begeman (1987). We took, for Begeman's eight galaxies, the luminosity in the B band (L) and the plateau velocity of the rotation curve (V_p). From a plot of $L \times V_p^4$, and in a system of units where luminosity is given in $10^{11}\ L_\odot$, time in 10^8 s, velocity in units of 97.8 km s^{-1} and $G = 4.50$, we derive $k_{TF} = 2.87 \times 10^{-2}$. A range of 30% error is allowed in equation (5) (see below) to account for the scattering in the diagram $L \times V_p^4$ which was used for the determination of k_{TF}.

The AMOD parameters are introduced in equation (5) through the expression for the circular velocity given by equation (2). Let $V_p = v_{circ}(r = 2 \times R_{25})$, where R_{25} is the de Vaucouleurs' radius of the galaxy (i.e., the radius of the galaxy to the 25th B magnitude per square arcsecond isophote). This is an arbitrary value for the model plateau velocity but the particular choice of V_p (at some $r \geq R_{25}$) does not change the analysis, as we have verified. The galaxy mass is converted into integrated blue luminosity via the M/L ratio. We can then re-write equation (5) as

$$A = \frac{1}{G k_{TF} V_p^2} \ , \qquad (6)$$

where A is the AMOD *index*, and is given by:

$$A = \frac{M/L}{2R_{25}} \left[1 + \beta \left(1 + \frac{2R_{25}}{r_o} \right) e^{-2R_{25}/r_o} \right] \ . \qquad (7)$$

The Tully-Fisher relation is now expressed through a relationship between the so-called AMOD index A and V_p (eq. [6]). $A(V_p)$ is the AMOD function one would expect if the Tully-Fisher relation can be expressed as equation (5). Equation (7) can be used then to derive an *observed* AMOD index (A_{fit}), taking into account intrinsic parameters of the galaxies (β, r_o, R_{25} and M/L). The AMOD parameter β and r_o, are obtained from the fits to the rotation curves.

A fit of the AMOD circular velocity to Rubin et al. (1982) observations of the rotation of 20 Sb spiral galaxies was done. The fitting procedure took into account the goodness of fitting to the Tully-Fisher relation (eq. [6]) too. A quantitative measure of the fitting of A_{fit} (defined through eq. [7]) to equation (6) can be given by δA, defined by

$$\delta A = \frac{A(V_p) - A_{fit}}{0.30 A(V_p)} \ . \qquad (8)$$

This quantity gives the amount of deviation of the fitted AMOD index from the predicted $A(V_p)$ curve in terms of a 30% error bar. The AMOD solutions $V_{AMOD}(r)$, for the rotation curves measured by Rubin et al., $V_{obs}(r)$, are those that simultaneously minimize $|\delta A|$ and $\Delta V = |V_{obs}(r) - V_{AMOD}(r)|$.

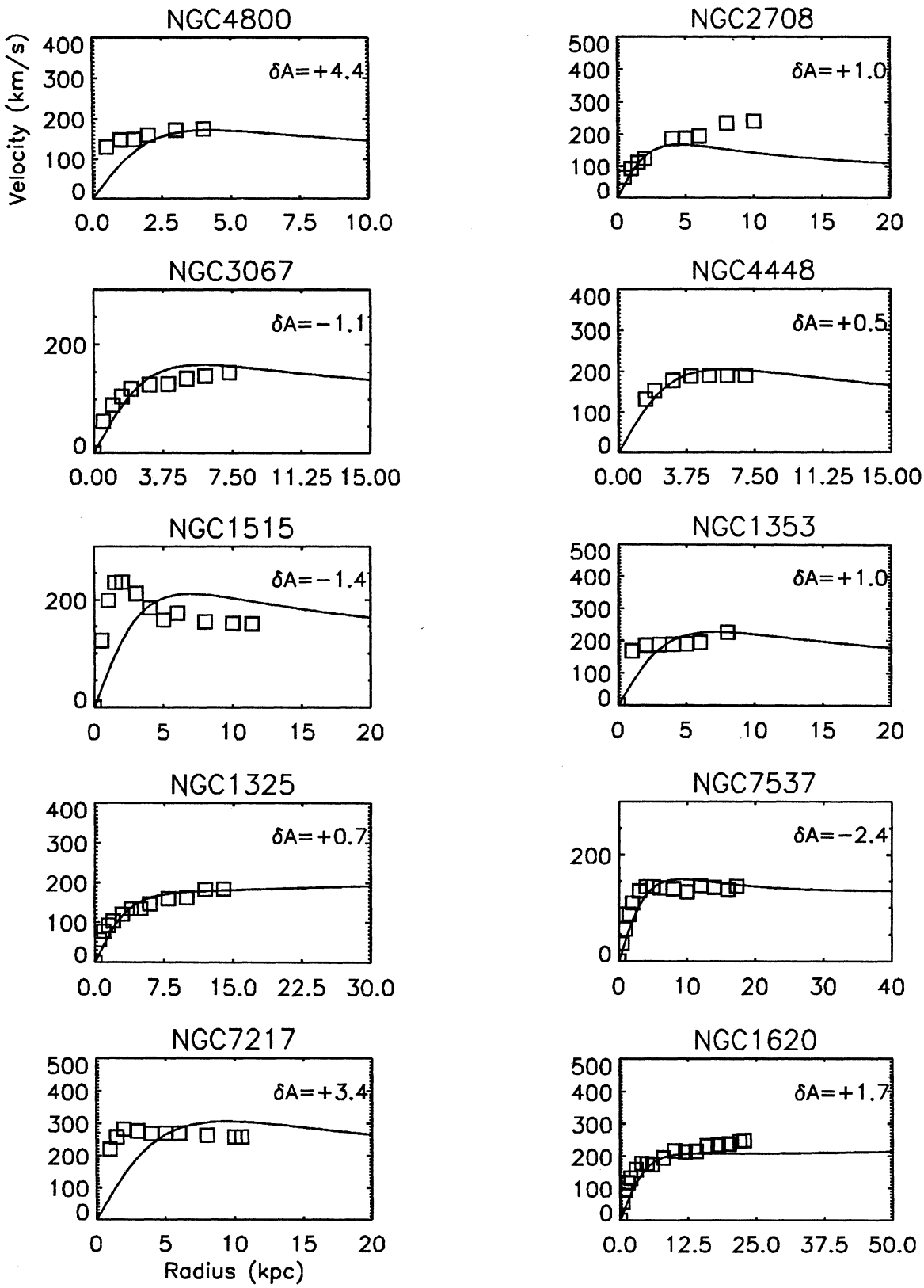
Figure 3 and Figure 4 show the result of the fitting process. The observed rotation curves by Rubin et al. are shown together with the AMOD fit in Figure 3. The Tully-Fisher relation is shown in Figure 4. Table 1 presents the relevant parameters of all studied galaxies. Column 1: galaxy name (NGC or UGC); column 2: plateau velocity, as given by Rubin et al. and by Begeman in the case of NGC 3198; column 3: de Vaucouleurs' radius, in kpc; column 4: characteristic AMOD radius, in kpc; column 5: AMOD coefficient β; column 6: AMOD index, defined by equation (7); column 8: relative error in A, defined by equation (8).

Both trends, in the rotational profiles and in the Tully-Fisher relation, are reasonably well reproduced, as can be seen in Figures 3 and 4. must be pointed out that the fact that the fitting procedure consists in minimizing $|\delta A|$ and ΔV does not necessarily imply that the distributions of points in the $A \times V_p$ diagram should follow the general trend given by equation (6); the points could be distributed in any possible way in that plane but amongst all of them, they do follow the behavior predicted from the observed Tully-Fisher relation.

5. DISCUSSION AND CONCLUSION

Presently, it is a very difficult task to deny the existence of extended dark material halos surrounding spiral galaxies, yet accepting them remains an uncomfortable position for many astronomers. The main reason for that is of course the fact that there is no *direct* observational evidence of such objects. They must be very dark, indeed.

Here, we have investigated the possibility of avoiding the dark halo hypothesis by means of a toy model which, in turn, suffers from a serious setback



ig. 3. The squares represent the observations by Rubin et al. (1982), and the line is the AMOD fit to the rotation curve. he relative error in the AMOD index (δA) is given in each frame.

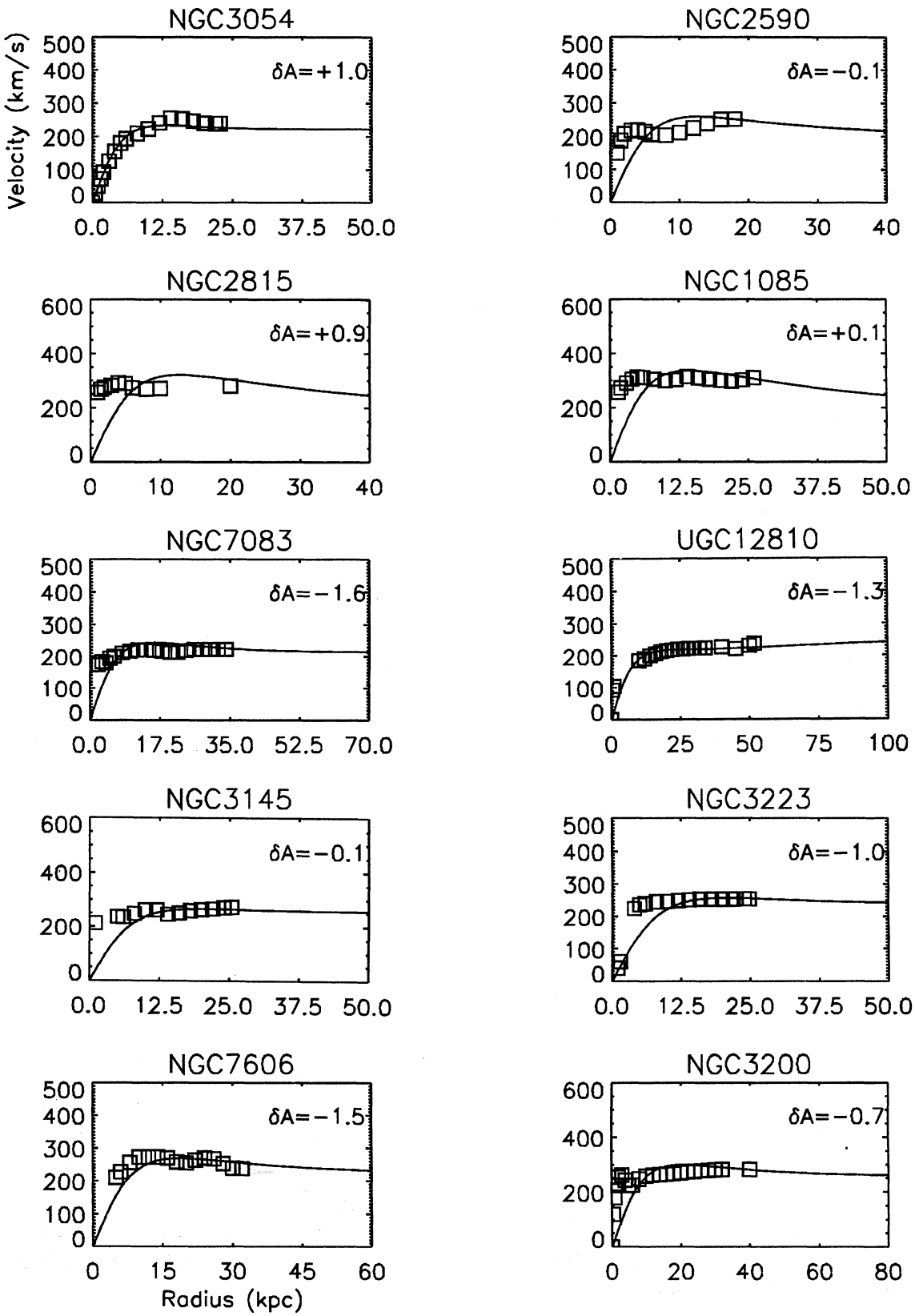
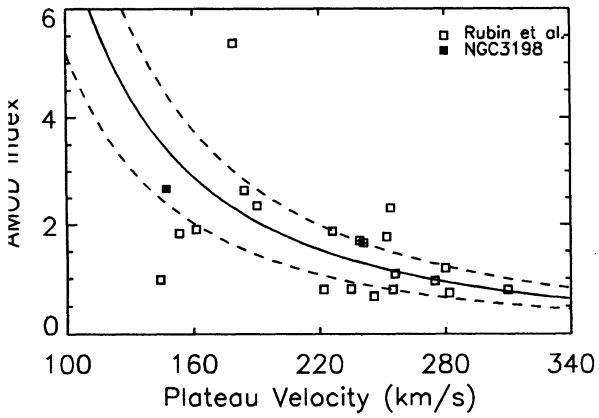


Fig. 3. (Continued).



ig. 4. The solid line is given by equation (6), i.e., the ully-Fisher relation in terms of the AMOD parameters A versus V_p). The dashed lines show the 30% error ar strip. The points were obtained from the fits to the otation curves shown in Figure 3, and follow the general end given by the predicted curve.

TABLE 1

PARAMETERS AND AMOD INDICES FOR SAMPLE GALAXIES

ame (1)	V_p (2)	R_{25} (3)	r_o (4)	$-\beta$ (5)	A (6)	δA (7)
3200	282.	46.0	140.0	0.90	0.74	−0.68
7606	246.	39.8	150.0	0.91	0.68	−1.48
3223	255.	34.8	120.0	0.92	0.80	−0.98
3145	275.	33.8	100.0	0.92	0.96	−0.07
12810	235.	51.4	110.0	0.95	0.81	−1.31
7083	222.	39.0	120.0	0.92	0.80	−1.56
1085	310.	34.8	260.0	0.84	0.80	+0.12
2815	280.	26.5	180.0	0.82	1.2	+0.85
2590	256.	39.6	100.0	0.88	1.1	−0.14
3054	239.	25.7	60.0	0.90	1.7	+1.03
1620	252.	29.8	55.0	0.92	1.8	+1.72
7217	254.	15.1	160.0	0.78	2.3	+3.37
7537	144.	18.3	90.0	0.94	0.98	−2.42
1325	184.	18.8	36.0	0.93	2.6	+0.69
1353	226.	14.0	140.0	0.84	1.9	+0.97
1515	153.	13.6	100.0	0.86	1.8	−1.40
4448	190.	11.0	120.0	0.84	2.4	+0.49
3067	161.	9.6	80.0	0.90	1.9	−1.11
2708	241.	14.7	120.0	0.86	1.7	+0.99
4800	179.	4.9	48.0	0.84	5.4	+4.41
3198	149.	17.1	36.0	0.92	2.7	−0.65

lotes: N3198 observed in H I by Begeman (1987), and ıe other galaxies in optical emission lines by Rubin et al. 1982). H_o = 50 km s^{-1} Mpc^{-1}, and M/L = 30 for all alaxies. The plateau velocity, V_p, is given in km s^{-1}; R_{25} nd r_o in kpc.

the whole idea is based upon a drastic assumption in view of current standards, namely, it requires a spiral galaxy with an exceedingly high M/L (about 10–15 times as large as accepted values). On the other hand, and justifying such a speculation, there is no firm *direct* observational evidence supporting current M/L values of spiral galaxies.

A common feature of almost all model rotation curves, shown in Figure 3, is the badness of fitting in the small radius range. The AMOD potential is not able to give a detailed description of the rotational properties of spiral galaxies in the inner regions. The reason for that might be the oversimplified modeling of the hydrodynamical behavior of the gas component. Nevertheless, it gives a reasonable account of the global rotation of the gaseous medium as can be seen in the fitting of all of the sample rotation curves. It must be realized also that the Plummer sphere cannot represent details of the luminosity (mass) profiles of real galaxies, which has certainly contributed for some of the features shown in Figure 3.

The main point we want to make here is that disk rotation curves (either from gas emission lines or absorption from young stars) are not reliable to trace out the gravitational potential of a spiral galaxy as a whole. The toy model, discussed here and in Paper I, suggests that gas rotation may be indicating internal properties of the gaseous disk component rather than giving global information about the galaxy mass distribution.

AMOD can be tested observationally through a comparison between stellar and gas rotation curves in the inner regions of spiral galaxies. There, the effects caused by the gaseous character of the material are stronger than in the outer regions. That could be done from absorption line measurements, in the case of stellar rotation curves, and from emission line measurements from H II regions. Of course, the gravitational potential is the same for both gas and stars but the question is whether the *effective* galactic potential for gas is the same as for the stellar component. The physical processes acting on the gas component are certainly different from those on the stellar component. Special care must be taken when choosing the lines for the absorption measurements: one should look preferentially to old disk stars. Young OB stars preserve the kinematical characteristics of the gas medium where they were formed and are likely to give the same results for the rotation velocities as compared to the gas measurements.

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REFERENCES

Aaronson, M., Huchra, J., & Mould, J. 1979, ApJ, 229, 1
Ashman, K.M. 1992, PASP, 104, 1109
Assis, A.K.T. 1992, Apeiron, 13, 3
Battaner, E., Garrido, J.L., Membrado, M., & Florido, E. 1992, Nature, 360, 624
Begeman, K.G. 1987, Ph.D. Thesis, University of Groningen
_____. 1989, A&A, 223, 47
Broeils, A.H. 1992, Ph.D. Thesis, University of Groningen
Faber, S.M., & Gallagher, J.S. 1979, ARA&A, 17, 135
Freeman, K.C. 1970, ApJ, 160, 811
González-Serrano, J.I., & Valentijn, E.A. 1991, A&A, 242, 334
Larson, R.B., & Tinsley, B.M. 1978, ApJ, 219, 46
Milgrom, M. 1983, ApJ, 270, 365
_____. 1988, ApJ, 333, 689
_____. 1991, ApJ, 367, 490
North, J.D. 1965, The Measure of the Universe, a History of Modern Cosmology, (Oxford: Clarendon Press)
Persic, M., & Salucci, P. 1993, MNRAS, 261, L21
Rubin, V.C., Ford, W.K., Thonnard, N., & Burstein, D. 1982, ApJ, 261, 439
Sanders, R.H. 1984, A&A, 136, L21
_____. 1986, A&A, 154, 135
_____. 1988, MNRAS, 235, 105
_____. 1990, A&AR, 2, 1
Schweizer, F. 1976, ApJS, 31, 313
Schweizer, L.S. 1987, ApJS, 64, 427
Soares, D.S.L. 1989, Ph.D. Thesis, University of Groninge
_____. 1992, RevMexAA, 24, 3, (Paper I)
Trimble, V. 1987, ARA&A, 25, 425
Tully, R.B., & Fisher, J.R. 1977, A&A, 54, 661
Valentijn, E.A. 1990, Nature, 346, 153
van Albada, T.S., Bahcall, J.N., Begeman, K., & Sancisi, R. 1985, ApJ, 295, 305
van Albada, T.S., & Sancisi, R. 1986, Phil. Trans. R, Soc. London, A 320, 447
Whitmore, B.C., Rubin, V.C., & Ford, W.K. 1984, ApJ, 287, 66

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