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ON THE WAVY NATURE OF ROTATION CURVES IN GALAXIES

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Sumario

Los estudios realizados en los últimos años sobre las velocidades radiales en las galaxias espirales han aumentado considerablemente nuestro conocimiento de la ley de rotación en éstas. (Véase numerosos artículos de Burbidge y colaboradores, publicados en el Ap. J. principiando con el Vol. 130, 1959). El propósito de estos trabajos ha sido el de determinar la variación de la densidad en las galaxias y su masa total. Para lograr este propósito se han hecho algunas simplificaciones: se ha supuesto que las galaxias poseen simetría axial y que su campo de velocidades proviene de una rotación alrededor del eje de simetría, siendo despreciables las demás componentes del campo.

El procedimiento adoptado en la determinación de la densidad requiere la representación de la variación de la velocidad de rotación por un polinomio de hasta 7 términos. Pero aún con este número de términos la representación tiende a suavizar las curvas de rotación.

El presente trabajo tiene por objeto señalar las fluctuaciones o las "ondas" en la curva de velocidades de las galaxias espirales observadas por Burbidge y colaboradores y discutiendo su significado físico proponer una interpretación de su existencia.

Se estudia el caso particular de NGC 4258, una espiral de tipo Sb, en cuya curva de velocidad se advierten 4 máximos y mínimos (4 ondas). Se demuestra, calculando *convencionalmente* la variación de la densidad a partir de la curva ondulatoria de velocidad, que los máximos y mínimos en la curva de rotación no pueden ser causados por una variación de la densidad dentro de la galaxia, pues la brusca variación calculada en NGC 4258 no es compatible con la variación observada en su luminosidad. Esto implica que la suposición principal en la que se basa el cálculo de la densidad no es correcta, es decir, que las componentes en direcciones radial y perpendicular, (direcciones $\tilde{\omega}$ y z) del campo de velocidades en una galaxia son apreciables. Dicho de otro modo, la dispersión de velocidades no es despreciable en todos los puntos de una espiral.

Por lo anterior se propone, que el fenómeno de las "ondas" puede explicarse extendiendo a las nubes interestelares nuestro concepto actual sobre las poblaciones estelares. De acuerdo con este concepto, en las regiones en donde la velocidad de rotación disminuye, la contribución se debe principalmente a las nubes con características de población II. El conjunto de tales nubes —que individualmente describen órbitas excéntricas e inclinadas al plano galáctico— muestra una velocidad de rotación más lenta que el conjunto de las nubes pertenecientes a los brazos espirales. Estas últimas describen órbitas casi circulares dentro del plano galáctico y muestran poca dispersión de velocidades a mayor rapidez de una rotación de conjunto.

Por último se señala que la existencia de nubes de alta velocidad, necesaria para la interpretación propuesta arriba, encuentra apoyo observacional tanto por métodos ópticos como radioastronómicos.

Introduction

Studies of radial velocities of mostly emission lines in spiral galaxies using the long-slit technique have added greatly to our information regarding the variation, along the radius, of the velocity of rotation — the so called "rotation-law" (see for example numerous papers by Burbidge *et al,* in Ap. J. starting with Vol. 130, 1959). The main purpose of these studies is to estimate the total mass and the variation of density within the galaxy. In so doing the principal simplifying assumption, aside from that of axial symmetry, is that the field of velocities in a spiral is mainly one of axial rotation, all other motions being negligible. Accordingly, the gravitational acceleration due to the mass interior to a point should balance the centrifugal acceleration of the rotational motion at that point. Thus, the rotational velocity being an observable quantity, the mass interior to a point may in principle be determined.

Inspection of the velocity vs. distance diagrams reveals that they are not smooth but show fluctuations; the latter may be due to accidental and systematic errors, but may also be, at least in part, real features inherent in the dynamics of the galaxy.

The procedure adopted so far in the determination of mass has been to express the "rotation-law" by an analytic representation of the observations. Yet in a large number of cases, if not in all spirals studied so far, the obvious and quite regular small scale variation, we believe, cannot be overlooked as an accidental feature. The procedure just mentioned tends to smooth out the rotation curve ignoring thus the fluctuations.

It is the purpose of the present report to call attention to these variations —which we call "waves"— in the rotation curves, argue in favor of their physical reality and attempt an interpretation of them. As a concrete case NGC 4258 will be taken up.

It will be shown that within the frame of the conventional assumption (only circular motions and no velocity dispersion,* that is no appreciable $\tilde{\omega}$ or z components) the waves cannot be explained

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* This velocity dispersion is that of the gas clouds taken as a whole, although the dispersion of velocity of the particles or mass motions, within a cloud may also be considerable.

by fluctuations of the density. The assumption of only circular motion must therefore not be adequate in all parts of such a galaxy. The suggestion is made that, while in the neighborhood of the velocity maxima motions are indeed circular (Pop. I) and the velocity dispersion negligible, at regions of minimum rotational velocity the state of affairs is not so; at these regions one is observing essentially the average circular velocity of objects with kinematical behavior quite different from that of population I; in other words one is observing the low circular velocity of objects resembling the population II. Here the dispersion of velocity may no more be negligible and this circumstance joins hands with the centrifugal acceleration in counteracting the gravitational force due to the mass interior to the point.

The Reality of Wavy Features of Rotation Curves

1) In the nuclear region of many galaxies the circular velocity tends to increase linearly with the radius. This is particularly true of barred spirals where the linearity extends all along the bar. The velocity then descends to a minimum to rise again. In barred spirals the very minimum is seldom measured, due probably to the faintness of the region. Thus there often appears a gap in the velocity curve. But the rising branch following the gap starts from a much lower velocity than the peak of the linear portion, suggesting that a minimum has just preceded it. Such features are noted in all barred spirals studied so far (see for example NGC 613, 3504 and 5383). There is therefore no doubt that at the nuclear regions of barred spirals (and in some normal spirals) the existence of one dip in the rotation curve is well established.

2) In "normal" spirals the extent of the region of constant angular velocity appears to be very small and difficult to detect. However with the electronic camera Lallemand *et al* (1961) have been able to measure the radial velocities at the nucleus of M31. Their results show that to a distance of 7.3 pc from the center the rotational velocity increases linearly up to 80 km sec^{-1} dropping then abruptly to < 40, to rise again, but slowly. There can hardly be any doubt about the reality of this variation.

3) Aside from this maximum very close to the center, described in (2), there appear further maxima and minima in the rotation curves of "normal" spirals. These variations are related roughly to the crossings of the spiral arms.

4) There are indications that in our Galaxy similar fluctuations of velocity of rotation do exist. The rotation curve given by Kraft and Schmidt (1963), based on galactic Cepheids, is not incompatible with a wavy variation. Also the rotation curve given by Kerr (1964) using the 21-cm hydrogen data shows clearly a wave with a dip at 5.4 kpc from the galactic center and maxima at 4.4 and 6.5 kpc.

TABLE 1

Name	*Type*	$\tilde{\varpi}_0$	$\tilde{\varpi}_1$	N_{max}	*Reference*	*Notes*
NGC 2146	Sap	2330	280	none?	Ap. J. **130,** 739, 1959	1
5055	Sb	1050	500	4	**131,** 282, 1960	2
3556	Sc	8000	600	3	**131,** 549, 1960	3
2903	Sb	4070	150	3	**132,** 640, 1960	
7479	SBb	14960	9133	2	**132,** 654, 1960	
3504	SBb	4800	530	gap; 2	**132,** 661, 1960	
5005	Sb	6160	700	2	**133,** 814, 1961	
3623	Sa/Sb	4280	900	1	**134,** 232, 1961	
3646	Sc	20000	237	none?	**134,** 237, 1961	4
157	Sc	9000	?	2	**134,** 874, 1961	5
4736	Sb	12180?	150	?	**135,** 366, 1962	6
5248	Sc	4500	373	gap; 2?	**136,** 128, 1962	
253	Sc	6000	1500?	3	**136,** 339, 1962	
5383	SBb	9000	1350	gap; 2?	**136,** 704, 1962	
1084	Sc	5120	1100	1?	**137,** 376, 1962	
7469	Seyfert	3600	650	none?	**137,** 1022, 1963	7
4258	Sb	7153	480	4	**138,** 375, 1963	
139	Sc	5020	330	2	**139,** 80, 1963	3
6503	Sc	1925	?	2	**139,** 539, 1963	
3521	Sb	7050	825	2	**139,** 1058, 1963	
1792	Sc	5000	330	2?	**140,** 80, 1964	6
613	Sbc	9600	700	gap; 2	**140,** 85, 1964	
925	Sc/SBc	3740	?	?	**140,** 94, 1964	8

But in both cases (Cepheids and HI) the amplitude of variation does not exceed 20 km sec^{-1} whereas for NGC 4258 (Sb) amplitudes around 50 km sec^{-1} are noted. It is conceivable that the phenomenon causing the dips is more pronounced in earlier type spirals.

Table I gives some information, useful for our argument, regarding the galaxies studied by Burbidge and collaborators. For the sake of uniformity of data, we have limited the discussion to only those galaxies to which the long-slit technique is applied.

The table is arranged according to the succession in which the investigation on the galaxy was published. Columns 1 and 2 are self-explanatory. Column 3 gives, in parsecs, the radius of the region explored for radial velocity, while Column 4, the radius of the linear portion of the velocity curve. Column 5 gives the probable number of maxima shown by the velocity-curve and references and notes are listed in Column 6 and 7 respectively.

Notes to Table I

1.—Irregular fluctuations; no waves can be distinguished. The galaxy is classified as peculiar.

2.—Large dispersion of velocities; 4 maxima of small amplitude can be distinguished. DeVaucouleurs classifies it as a barred spiral.

3.—Waves of small amplitude.

4.—A rather peculiar galaxy.

5.—Large scatter of velocities.

6.—The position angle of the major axis is probably incorrect. This is one of the frequent cases where the apparent major axis does not give the line of the nodes itself because the contours of the arms are not projections of circles but are projections of spirals. Furthermore if the spiral is not logarithmic the apparent major axes will deviate gradually for the different turns. This remark will be discussed in a later publication.

7.—Large dispersion of velocities; a very distant object.

8.—Velocity-curve shows large dispersion. Probably the orientation of the galaxy is uncertain.

Twenty-three galaxies are listed in Table I. A linear portion of the velocity curve is noted in 17 of these galaxies. Excluding the peculiar galaxies and those of ambiguous determination of orientation, we are left with 17. Of these, at least 80% show waves in their rotation-curves with 2 or more maxima.

Evaluation of density from a Wavy Rotation Curve

The conventional attitude with respect to irregularities in rotation curves is to ascribe the variations to deviations from a smooth potential, namely to the local agglomeration of mass, presumably in the spiral arms. While a slight variation in the velocity of rotation may result in such cases, such variations would be far too small to match the large effect emphasized here. Although it appears that the "waves" in the circular velocity are related to spiral features, it is quite improbable that variations of mass from arm to interarm sections may be its cause. It is well known that spiral arms are more spectacular than massive; the potential in our Galaxy (and probably in other spirals as well) is, by and large, determined by the rather structureless disk component and the halo component. The observed increase of light from arm to interarm would not yield the increase of mass of the required order of magnitude.

For a quantitative evaluation of the hypothetical density variations necessary to give rise to the observed wiggles in the rotation curves, we have chosen, as an example, the spiral galaxy NGC 4258 for which the velocity-curve is known and which presents at least three maxima within 7153 pcs from the center.

For the sake of clarity in our arguments to follow, a brief sketch is given here of the method employed by Burbidge and collaborators (1959) to evaluate the density variation along the radius of a galaxy. They assume a model of a galaxy where the equidensity surfaces are similar spheroids. Next, by equating the centrifugal acceleration at a point to that of gravity due to mass interior to the point, the following expression is obtained for $V(\tilde{\varpi})$, the observed circular velocity at distance $\tilde{\varpi}$ from the center.

$$V^2(\tilde{\varpi}) = 4\pi G\,(1-k^2)^{1/2} \int_0^{\tilde{\varpi}} \frac{\varrho(a)\,a^2\,da}{(\tilde{\varpi}^2 - k^2 a^2)^{1/2}} \qquad (1)$$

Here ρ is the density, G, the gravitational constant, a, the semi-major axis and k, the eccentricity of the spheroids.

The quantity to be determined is $\rho(\varpi)$, the density at distance ϖ, and this is to be obtained as the solution of the integral equation (1) for which no analytic solution is known. Burbidge *et al* solve for ρ by substituting Taylor expansions for $V(\varpi)$ and $\rho(a)$ (with up to 7 terms in some cases), and determine the coefficients by solving the necessary simultaneous equations.

This method will not be followed here, since a polynomial with a practicably large number of terms will still tend to smooth out the waves in the rotation-curves. And it is precisely the deviations from a smooth curve which we propose to analyze.

The procedure developed by Brandt (1960) is therefore employed. Brandt shows that in the limiting case, where c/a —the ratio of minor to major axes of the spheroids— tends to zero, the integral equation can be solved to give the mass, $M(\varpi)$, interior to ϖ as follows:

$$M(\varpi) = \frac{2}{G\pi} \int_0^{\varpi} \frac{V^2(a)\,da}{(\varpi^2 - a^2)^{1/2}} \tag{2}$$

Formula (2) now enables one to compute the mass interior to ϖ and hence the surface density as a function of the radius vector given any rotation-curve without having to force the observations into an analytic expression. In this way the effect of fluctuations is not concealed but is exhibited fully.

Although the approximation of infinite flattening of the mass distribution of a galaxy and in particular of NGC 4258 is a poor one, we believe that the surface density thus obtained will safely give the right order of magnitude of the relative fluctuations. Thus the ratio of the surface density at maxima to what it is at minima in its immediate neighborhood should not be far from that which would be obtained if $c/a > o$.

Computed Hypothetical Density Fluctuations in NGC 4258

The rotation curve of NGC 4258 used for the computions is taken from Burbidge, Burbidge and Prendergast (1963). Due to the scarcity of observations on the SE side of the nucleus, observations of the NW side are used only. A curve is drawn through the points, following all the wavy fluctuations. Figure 2 gives the individual observations and the curve drawn through these. The adopted V for our computation is then read out from the curve.

The mass within 10″, 20″, . . . , 220″ of the center of NGC 4258 is obtained by integrating expression (2) with the V's thus obtained. Within 10″ no integration is attempted since the method of Brandt breaks down close to the center. The mean surface density, σ, is now calculated in each ring of 2″ thickness. The results are given in graphical form in Fig. 2. We note that the density at all minima is close to vanishing.

Let ϖ_{max} indicate the radius vector at a maximum (σ_{max}) of surface density. Let further σ'_{max} indicate the ordinate read on a smooth curve through the minima at ϖ_{max}. The ratio $\sigma_{max}/\sigma'_{max}$ may reasonably give a measure of the fluctuations of the density curve. The ratio $\sigma_{max}/\sigma'_{max}$ at maxima A, B, C and D are 36, 18, 9 and 18 respectively. These ratios are extremely large and are not supported by optical evidence as will be seen below.

Tracings of photographs of spirals indicate that the magnitude difference between maximum light intensity, namely at the spiral arms, and at the smooth intensity curve underneath, is around 0.5 magnitudes and in no case exceeds one whole magnitude. This implies that the ratio of mass density of arm to interarm is not larger than 2.5. If one allows for the fact that spiral arms are brighter in blue light, as compared to the interarm regions, the ratio of densities may be lower still. Although no tracings are done for NGC 4258 in particular, the fluctuations of intensity of light do not seem to deviate appreciably from the galaxies treated by Seyfert (1943) and de Vaucouleurs (1959, 1961, 1963). We therefore conclude that the fluctuations of the velocity of rotation of NGC 4258 and of similar galaxies cannot be explained by fluctuations of mass in a galaxy — where the mass is computed with the assumption of only circular motions.

Consequently, the assumption that at all points in the galaxy the gravitational acceleration is counteracted by the centrifugal acceleration of the purely circular motion cannot be justified. There

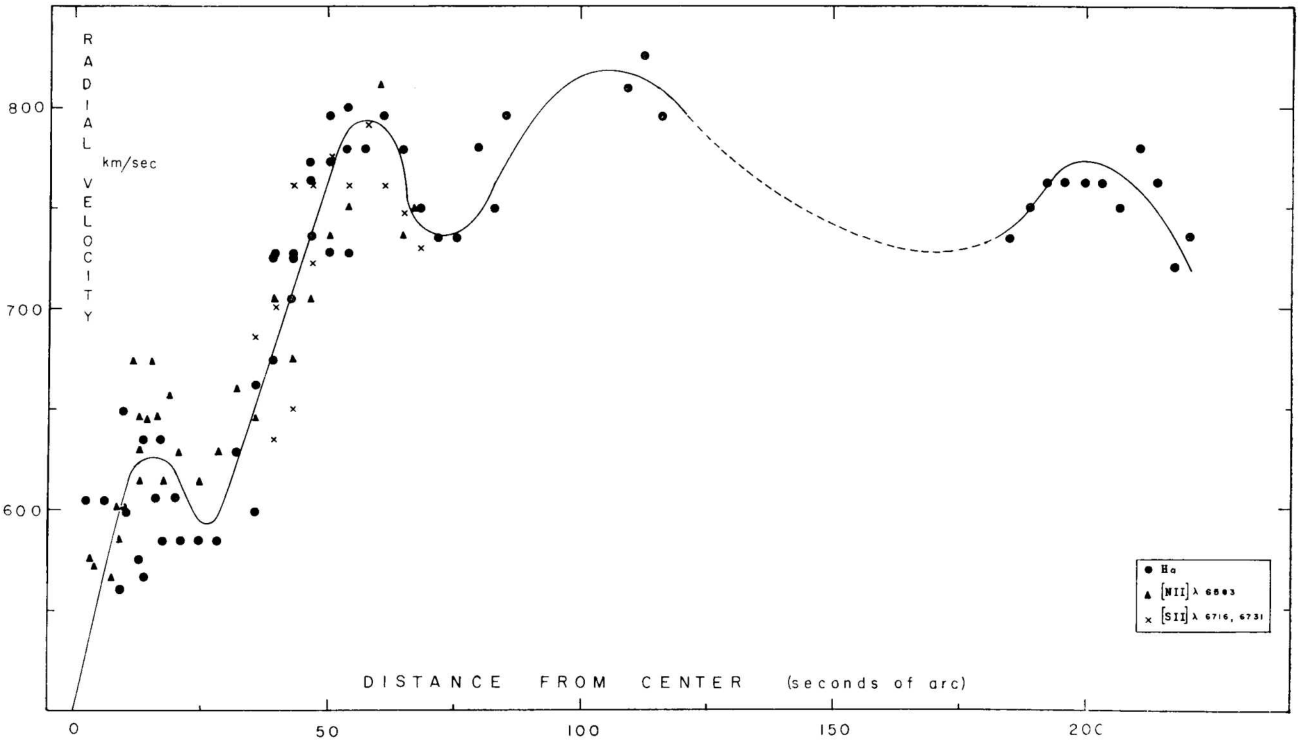

Figura 1.—*Velocities along major axis, uncorrected for rotation of our Galaxy or inclination of equatorial plane, as a function of distance from center of NGC 4258. Velocities of only the NW side of the nucleus are reproduced here. The data are taken from Burbidge, Burbirdge and Prendergast (1963).*

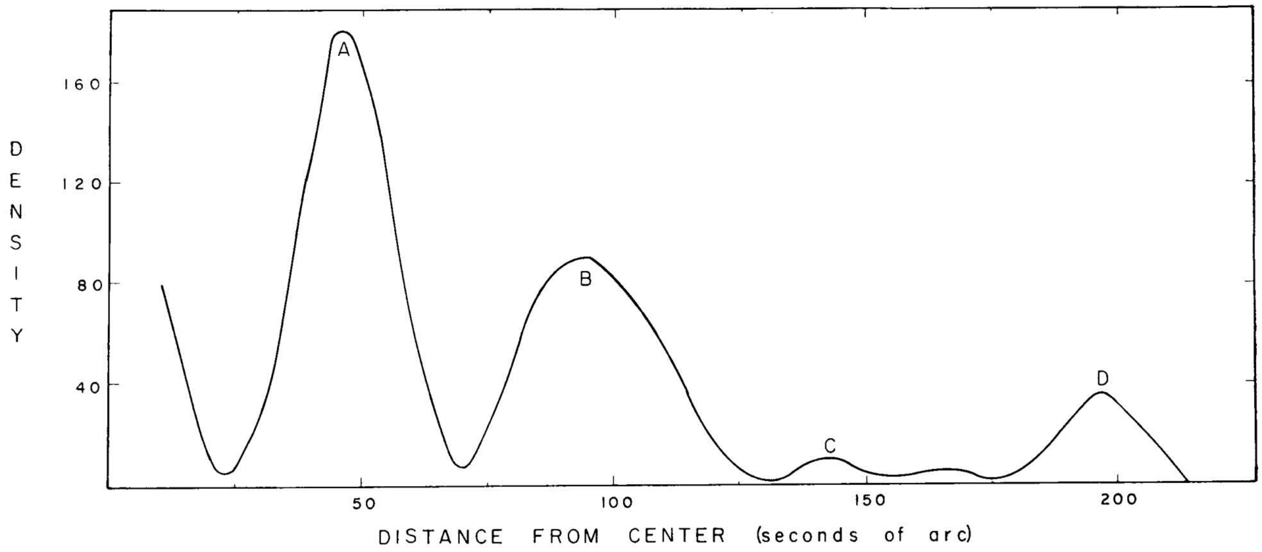

Figura 2.—*Relative density as a function of distance from center computed with velocity curve given in Fig. 1 and with equation (2).*

are obviously other forces involved in the equilibrium of a mass element in the galaxy. The orbits of the objects of which the net rotational components are observed must be appreciably eccentric. In other words it seems that the velocity dispersion of the group increases at the expense of the rotational velocity which tends to decrease. Eccentric orbits and slower speed of rotation of objects as a group is typical of precisely population II objects in our Galaxy. In this population the eccentric orbits are also inclined to the galactic plane.

We therefore arrive at the proposition that *where the velocity of rotation drops to a minimum we are mostly observing clouds with appreciably large components of velocity in the* ϖ *and z directions.* They may be clouds with characteristics resembling the population II, namely of low average circular velocity and high dispersion of velocities within the group. (If these clouds represent a transient phenomenon one may expect them to be falling into the galactic plane while describing trajectories in line with population II characteristics).

Evidence supporting our Proposition

Several independent lines of evidence gathered lately point to the existence of gas clouds at high galactic latitudes. We mention these here without any detailed discussion.

1) Radio data from the 21 cm band show that there are clouds at intermediate galactic latitudes and that they partake in the galactic rotation, as their velocities show a double sine wave (Blaauw 1962). Their mean distance from the sun, *r*, is estimated assuming the standard value for *A*, Oort's constant, adopted from the flat component in the Galaxy. But the quantity obtained from the observations is *rA*. A possible alternative is that for the intermediate latitude clouds, *A* is smaller than assumed, in which case the clouds would be more distant and their *z* distance higher. Thus a lower velocity of rotation for these clouds is not incompatible with the 21-cm data.

2) Münch and Zirin (1961), by studying the interstellar lines of stars at high galactic latitudes have shown that there exist gas clouds up to $z = 1$ kpc or even higher. Moreover they state that "high values for the velocity components of the interstellar clouds seem to occur more frequently in the *z* direction than in the galactic plane".

3) A survey of the 21 cm radiation, made by N. H. Dieter (1964), in the region from $b = 80°$ to the north galactic pole has shown that appreciable mass (about 0.4 of the total neutral hydrogen in the region explored) is in the form of clouds which show high negative velocities with respect to the local standard of rest.

4) The existence of gas clouds at high latitudes and the preponderance of their negative velocities is strengthened by the radio observations of the Leiden-Groningen group (Muller *et al* 1963) in the longitude interval 70° to 170°. An infall of gas clouds to the galactic plane is suggested by these observations. If there exist clouds with high negative velocities in the Galaxy one can reasonably expect some of them to have reached the galactic plane. Furthermore if such phenomena occur in our own Galaxy it is highly probable that they also occur in other spirals, although the rate of infall may differ from one spiral to another, presumably as a result of dynamical evolution and/or initial conditions in a galaxy.

It is not possible at this stage to ascertain whether the phenomenon of high velocity clouds is one of infall from all directions into the galactic plane or that it is the phenomenon of "asymmetry" of motions of high velocity clouds of which the stellar counterpart is well-known. Until the survey of high latitude hydrogen clouds is completed by its extension to the southern hemisphere, one cannot decide between the two possibilities.

5) Burke, Turner and Tuve (1964) have carried out a high resolution study of the outer parts of the Galaxy, between $l = 10°$ and 50°, using the 21-cm hydrogen band. Fig. 4 of their paper gives a relation between *Vr* the radial velocity, and sin *l*, for the interval of *l* studied. *Vr* is negative and it increases, in absolute value, linearly with the increase of galactic longitude from 10° to 50°. This curve is precisely what one would obtain if the cloud motions showed "asymmetry", that is, slower rotational velocities with respect to the local standard of rest.

One way or another, whether an infall of clouds or asymmetry, the net effect of high velocity clouds would be to lower the circular velocity observed in certain regions of a galaxy, presumably at the interarm regions of spirals.

We may therefore make the statement that the waves in the rotation curves of galaxies may be real effects caused by the existence, in these regions, of clouds with relatively low average circular velocity and high motions in directions ϖ and *z*.

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