A NEW HYPOTHESIS TO EXPLAIN ROTATION CURVES IN SPIRAL GALAXIES WITHOUT DARK MATTER HALOES BY MEANS OF THE ACCRETION OF THE INTERGALACTIC MEDIUM

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RESUMEN

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ABSTRACT

A new hypothesis to explain rotation curves in spiral galaxies by means of the accretion of the intergalactic flows on to the disc is proposed. Assuming that galactic discs are nearly aligned perpendicular to the motion of the galaxy through the intergalactic medium, and that the flow transmits part of its linear momentum to the disc because of friction, flat or nearly flat rotation curves are obtained. The alignment of the galaxies with measured rotation curves might be associated with the formation and evolution of the galaxy within a dense intergalactic medium, but it might also be a selection effect that avoids the measurement of rotation curves in the outer part of the discs in S-shaped warped cases, which are misaligned galaxies with respect the relative motion of the intergalactic medium in the context of the present hypothesis. There is no need for fine tuning to explain the flatness of the rotation curves in the present hypothesis. The mechanism also causes U-shaped distortions in the galactic disc whose amplitude is of the order of magnitude of the observed cases.

As an alternative to the standard dark matter haloes, the present hypothesis might be applicable to all, any or none of the spiral galaxies depending on the values of the different parameters. At present, it is just a proposed mechanism that works, and whose effects are compatible with the observations of many galaxies, maybe most of them. The universality of flatness, or nearly flatness, of rotation curves from a few kpc radius to several tens of kpc can be explained by the proposed mechanism if one accepts that the density of the flow surrounding a galaxy is inversely proportional to the size of the galaxy, remaining this to be proven in the context of galaxy formation scenarios. The different characteristics of the intergalactic flows in cluster galaxies might explain further expected features of asymmetries and correlations which have already been observed. Even if the proposed effect is not predominant for a galaxy, the present mechanism could be a second order effect which produces anomalies in the rotation curves explained by other mechanisms (dark matter haloes, MOND or magnetic fields).

Key Words: **DARK MATTER — GALAXIES: KINEMATIC AND DYNAMICS — INTERGALACTIC MEDIUM**

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1. INTRODUCTION

One of the most important controversies concerning the world of the galaxies is the observational evidence that shows rotation curves corresponding to galactic masses much larger than those corresponding to the luminous masses (see the magnificent recent reviews on rotation curves by Battaner & Florido 2000 and Sofue & Rubin 2001). This controversy has been declared solved, the solution being called "dark matter"; that is, the difference between the mass derived from rotation curves and the luminous mass is some kind of matter that does not emit light. This is striking. The fact the luminous mass is exclusively in the very center of the galaxy whereas most of the dark mass is far from the center is even more striking. The Tully-Fischer relation ($v_{\rm rot}^4 \propto$ luminosity) is also strange since this requires the dark matter fraction to rise as the luminous surface density declines; the same circular velocity is observed in all galaxies of a given luminosity, no matter how widely dispersed the luminous material. Nevertheless, the existence of dark matter must not be considered something exotic, since planets, brown dwarfs, etc., are examples of dark matter and there is abundant evidence of their existence, and there is much evidence that baryonic dark matter also exists (Silk 1996). Non-baryonic matter is far more exotic but, since our knowledges concerning the existence of exotic particles is limited, we cannot discount their existence yet.

I am not going to discuss the problem of dark matter in a cosmological context. Disney's (2000) observation, which I agree, that cosmological inferences should be tentatively made and skeptically received is something that has been little respected in recent years. Nowadays, fashionable cosmological models populate the Universe with CDM and include a cosmological constant; however, few years ago many other models populate the books about cosmology (HDM, MDM, TDM, CDM without cosmological constant, etc.). Current CDM models predict the existence of dark matter haloes for each galaxy whose density profiles fall approximately as r^{-2}, but the original ideas (White & Rees 1978) concerning hierarchical structures with CDM, which gave birth to the present models, was that the dark matter was distributed without internal substructure, more like a halo with galaxies than galaxies with a halo. This curious development of the CDM hierarchical scenarios is also worthy of note (see review in Battaner & Florido 2000, §4.2).

Apart from cosmological speculations, if we consider the problem only from a galactic astronomy point of view, we must see that the evidence in favour of very massive dark matter halos (ten times more massive than the luminous mass in galaxies) stems mainly from rotation curves. The galactic stability problem, which led first to the introduction of dark haloes, may be solved by other means (Toomre 1981); instabilities could lead to the formation of bars, and stability in unbarred galaxies could be explained in terms of hard centers rather than massive dark haloes. The question of galaxy pairs or satellites to determine the mass of a galaxy can also be solved by taking into account the intergalactic medium filling the space between the members of the pairs (as we shall see in this paper). The presence of massive haloes to explain warped discs can be substituted by alternative hypotheses such as the infall of intergalactic matter also (López-Corredoira et al. 2002).

Some authors have been led to question the very existence of dark matter since its evidence is weak on galactic scales (Nelson 1988; Battaner et al. 1992; Battaner & Florido 2000; McGaugh 2000; Sellwood & Kosowky 2001; Evans 2001; Tasitsiomi 2002). In particular, cusped haloes with a substantial proportion of the halo mass in the inner Galaxy, such as those predicted by CDM cosmology, go against many strands of evidence (Evans 2001, Tasitsiomi 2002, and references therein). The predicted angular momentum is much less than the observed one ("angular momentum catastrophe"; Evans 2001, Tasitsiomi 2002). Microlensing surveys (Lasserre et al. 2000) constrain the mass of the halo in the form of dim stars and brown dwarfs to be much less than that necessary for dark matter haloes. Some observations are inconsistent with the dominant dark matter component being collisionless (Moore 1994). Neither are black hole haloes a consistent scenario (Moore 1993). The nature of the dark matter has been investigated (Sadoulet 1999) and there are no suitable candidates. There are still many further aspects in which CDM hypothesis does not work in galactic and subgalactic scales (Evans 2001, Tasitsiomi 2002, and references therein). Some of these evidences could possibly be refuted, but perhaps the massive dark matter halo scenario has reached a crisis.

All these difficulties with the dark halo hypothesis might encourage a search of an alternative hypothesis to explain rotation curves. The hypothesis of a dark halo with ten times the luminous mass of the galaxy is not yet completely discounted, but it is under suspicion. Indeed, other options have already been proposed. Ad hoc modifications of Newtonian gravity (MOND; Milgrom 1983a,b,c; Rodrigo-Blanco & Pérez-Mercader 1998; Sanders & McGaugh 2002) can reproduce some aspects of the observed curves. This theory is not compatible with general relativity, and to date no agreement has been achieved between both theories (Sanders 1998). Certain postulates of the field equations in an expanding universe within the general relativity context (Carmeli 1998) could explain the Tully–Fisher relation, but not the rotation curves themselves, without dark matter.

Another serious proposal to be taken into account is the action of electromagnetic forces (Peratt 1983, 1984; Lerner 1991, ch. 1; Nelson 1988; Battaner et al. 1992; Battaner & Florido 1995, 2000). Peratt et al. (1980) and Peratt & Green (1983) developed numerical simulations of plasmas in which the trajectory of each electron or ion was followed step by step to explain the formation of galaxies. Currents flowing through filaments twist themselves into a spiral form. This is observed in the laboratory in small scale plasmas. The results of the simulations, when varying parameters such as the distance between the two filaments, reproduce the shape of different types of galaxies (Lerner 1991, ch. 6). Peratt's simulations explain the formation of the galaxies and solve at the same time the problem of flat rotation curves. The action of extragalactic magnetic fields in the disc once it is formed is also another way to search for solutions to the problem (review in Battaner & Florido 2000).

In this paper I offer a new alternative to the controversy of the rotation curves based on the interaction of the spiral galaxies with the surrounding intergalactic medium.

2. ACCRETION OF INTERGALACTIC MATTER BY GALAXIES

The scenario proposed in this paper is not totally new in the literature: it is the accretion of intergalactic matter by the galaxies. The infall of intergalactic matter was previously explored by other authors a long time ago (e.g. Kahn & Woltjer 1959).

Many observations imply that there must be an infall of material into galaxies (Binney 2000): Local Group members approach each other, the high velocity clouds around the Galaxy having on average a net negative velocity (Blitz et al. 1999; Braun & Burton 1999; López-Corredoira et al. 1999). In a more general context, the general secular infall of matter is not the only factor. The exchange of matter between two galaxies can supply accretable intergalactic matter: an intergalactic flow is produced between the two galaxies.

There are good reasons for believing that part of the infalling baryonic matter is accreted directly by the disc. The principal supporting arguments here are those based on the observed chemical evolution (Ostriker & Binney 1989; López-Corredoira et al. 1999). Significant accretion of metal-poor gas is necessary to justify the observations concerning star formation and metallicity distribution in the galactic disc, often termed the G-dwarf problem (Tinsley 1980), and the details of time-dependent evolution of individual metals (Casuso & Beckman 1997; 2000). Recent results implying that this accretion has been constant, or has even increased, during the disc lifetime, are found in Rocha-Pinto et al. (2000). The additional presence of a hypothetical halo should introduce friction with the accreted matter with low efficiency, since its mean baryonic density would be very low. Hence, either the accreted matter transmits the momentum to the disc or it is probably not transmitted at all.

López-Corredoira et al. (2002) propose two possible scenarios for this intergalactic medium and its motion:

- The galaxy is passing through a continuous intergalactic medium, i.e. the velocity of the flow is due to the relative motion of the galaxy with respect to the rest frame of the intergalactic medium. In this case, the flow may be well approximated by a beam of infinite extent. This may be a representative scenario for most galaxies.
- The galaxy has an interacting companion and some exchange of material is produced due to tidal effects. The stream of material goes from the companion to the main galaxy. This would better represent the galaxies that are not isolated and exchange mass with their neighbours.

3. ACCRETION OF INTERGALACTIC FLOWS ONTO THE DISCS OF SPIRAL GALAXIES

A mechanism to explain the excess velocities of rotation curves is an excess radial force whose origin is not gravitational but due to the transfer of linear momentum by the infalling flow. The transfer of angular momentum is another aspect to be studied, and this was already done by López-Corredoira et al. (2002), who argue this to be a possible reason to explain the existence of warps in the discs of spiral galaxies.

The intergalactic medium is presumably gas. We will consider that the pressure which is exerted over this gas is negligible while it is in the intergalactic medium. The pressure would collimate or decollimate the gas-particles trajectories, but only when there is an interaction with the galactic disc which crosses. Assuming the disc is very thin, which is a very reasonable assumption for a typical spiral galaxy, we will have that the gas behaves as a beam of particles in most part of its trajectory. This beam of particles comes from an infinite distance towards the galactic disc with velocity $\vec{v_0}$. Each particle of the beam follows a trajectory that is not a straight line, due to the gravitational attraction of the galaxy, until it reaches the galactic plane ($z = 0$). As it intersects the plane, it collides with the gas of the galaxy. We adopt the following hypotheses on the flow (see Fig. 1):

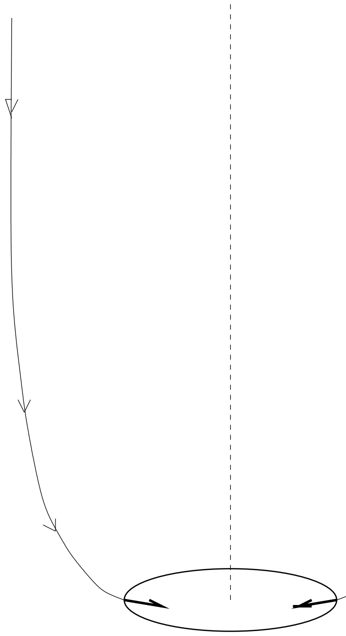

Fig. 1. Graphical representation of a galactic disc and infall of material from a polar direction. When the flow reaches the disc, it leaves behind linear momentum parallel to its velocity. The radial component of this linear momentum is the force which is posited to be a possible cause of the excess velocity in the rotation curves. See text for details.

1. The average velocity of the intergalactic medium at infinity is nearly perpendicular to the plane of the galaxy.
2. When the intergalactic flow reaches the disc it leaves a fraction of its linear momentum in the disc.
3. Most of the infalling matter, after losing that fraction of linear momentum, crosses the disc and it is not trapped by it.

Hypothesis 1 is actually a gratuitous assumption. There are no proofs that the flows infall through the polar directions of the galaxy, although there is no evidence against it. In other words, we are proposing that the disc of the galaxies are not randomly oriented but perpendicular to the direction of motion through the intergalactic medium. Each galaxy would be oriented in order to have the local flow perpendicular to the plane. Since the intergalactic flow is connected on large scales, we should observe in this case that the galaxies are not randomly r. This is actually observed (Godlowski 1993): the planes of the galaxies in the Local Supercluster tend to be oriented perpendicularly to the Local Supercluster plane. This alignment among galaxies is not always observed, but this does not imply anything. The important point is the alignment of the galactic axis with the invisible intergalactic flow velocity, which is much more difficult to test (see further discussion in §6.1). Which could be the reason for the galaxy to be oriented perpendicularly to the flow? Tentative explanations could be: a) The formation of the galaxy is produced coupled with the interaction with the surrounding intergalactic medium and, by means of some mechanism in the formation of the galaxy, the disc is born with an orientation perpendicular to the velocity of the inflow. b) During the evolution of the galaxy, the pressure exerted by the flow to the Galaxy asymptotically produces an alignment perpendicular to the inflow. c) There is not such an alignment for all galaxies but only for those whose rotation curve in the outer part of the disc was measured; galaxies with S-shaped warps are not used to measure the rotation curve, and these are precisely the misaligned ones with respect the relative motion of the intergalactic medium in the context of the present hypothesis (see López-Corredoira et al. 2002, or §6.2 in this paper). None of these tentative mechanism has been proven yet. There is much that we do not know about the formation and evolution of galaxies in the presence of an intergalactic medium, so nothing can be said at present with regard this question.

Hypothesis 2 is easier to justify. The friction of the infalling flow when it crosses the disc can reduce its velocity and transfer its lost momentum to the disc. Either, if the conditions of the interaction with the disc are supersonic, the shock waves could be responsible of the deceleration in part of the material which achieves the disc (Franco et al. 1988). If the density of the disc is too low (this must be true in the outer parts of the disc) then the flow will cross the disc, with a velocity still great enough to escape from the galaxy as posited in the Hypothesis 3. In the inner part of the disc, the infalling matter is trapped instead; but we are not concerned with the inner part of the disc and its interaction with the accreted matter but with the outer disc, where the excess velocity in the rotation curves is observed.

3.1. *Kinematics of a particle of the intergalactic flow before achieving the disc*

In this subsection and the next one, I will carry out some calculations about the trajectory of a gas particle which travels through the intergalactic medium attracted by the potential of a galaxy. We can interpret these particles to be atoms or clouds. This ballistic approach is valid, as said, while the gas does not feel the pressure in the intergalactic space.

In Fig. 2, we give a graphical representation of the galactic disc centred at O, and the trajectory of a particle which intersects the disc. A particle comes from infinity with velocity v_0 in the normalized direction $\vec{e_0}$ given by angles ϕ_0, θ_0 in spherical coordinates (in Fig. 2, $\theta_0 < 0$), where

$$\vec{v_0} = v_0(\cos\phi_0\cos\theta_0\vec{i} + \sin\phi_0\cos\theta_0\vec{j} + \sin\theta_0\vec{k}), \tag{1}$$

and follows a trajectory that crosses the galactic disc at some point Q whose distance from the centre is R and angle with respect to the x-axis is ϕ, i.e.

$$\overline{OQ} = \vec{R} = R\cos\phi\ \vec{i} + R\sin\phi\ \vec{j}. \tag{2}$$

The same trajectory is represented in Fig. 3 in the plane of the orbit $x'y'$. It is assumed that the trajectory is a hyperbola typical of a two-body gravitating system where the heavier body is the galaxy, whose mass is $M_{\rm gal}$, concentrated at the point O. Some minor effects due to the dispersion of the mass throughout the disc are expected but they are negligible if R is larger than several disc scale lengths. The orbit is a hyperbola because the energy of the system is positive, since the velocity at infinite distance, $|\vec{v_0}|$, is greater than zero. Therefore,

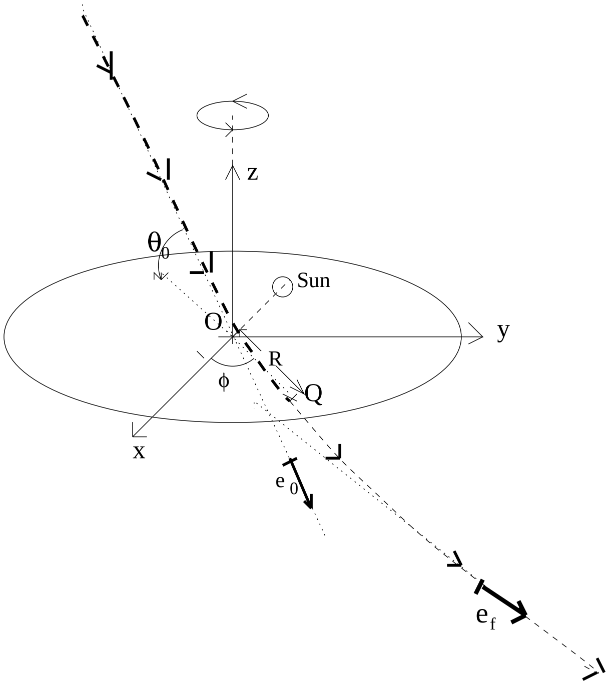

Fig. 2. Graphical representation of the disc of a spiral galaxy in the coordinate system (x, y, z) and the hyperbolical trajectory of an infalling particle.

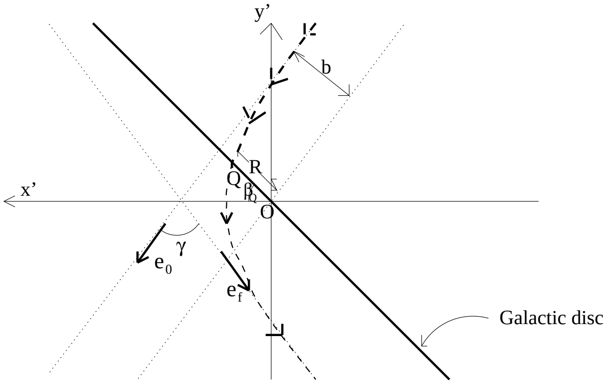

Fig. 3. Graphical representation of the hyperbolic trajectory of an infalling particle in the plane of the orbit.

the plane of the orbit will be determined by the independent vectors $\vec{r}$ and $\vec{v_0}$ and the equation of the orbit in the $x'y'$ system is (r and β are the polar coordinates in this system; see Fig. 3):

$$\frac{\epsilon}{A\ r} = 1 + \epsilon \cos\beta, \tag{3}$$

where ϵ is the eccentricity of the orbit,

$$\epsilon = \sqrt{1 + \left(\frac{b\ v_0^2}{G\ M_{\rm gal}}\right)^2}, \tag{4}$$

and

$$A = \sqrt{\left(\frac{G\ M_{\rm gal}}{v_0^2 b^2}\right)^2 + \frac{1}{b^2}} = \frac{v_0^2}{GM_{\rm gal}} \frac{\epsilon}{\epsilon^2 - 1}. \tag{5}$$

The impact parameter is b and the net asymptotic angular deviation, γ (see Fig. 3), is given by

$$\tan\frac{\gamma}{2} = \frac{1}{\sqrt{\epsilon^2 - 1}} = \frac{GM_{\rm gal}}{bv_0^2}. \tag{6}$$

The determination of the point of intersection of the orbit with the disc of the galaxy is a simple trigonometric problem. From the triangle shown in Fig. 3, we can derive:

$$\beta_Q = \frac{\pi}{2} + \frac{\gamma}{2} - \cos^{-1}(e_{0Q}) \tag{7}$$

and

$$e_{0Q} = \cos(\vec{v_0}, \vec{r_Q}) = \frac{\vec{v_0}\vec{r_Q}}{v_0 r_Q} = \cos(\theta_0)\cos(\phi_0 - \phi). \tag{8}$$

From these expressions, together with (3), (4), (5) and (6), the radial galactocentric distance, R, of the point of orbit intersection with the galactic plane is:

$$R = r_Q = \frac{b^2 v_0^2}{b\ v_0^2\sqrt{1 - e_{0Q}^2} + G\ M_{\rm gal}(1 - e_{0Q})}. \tag{9}$$

The velocity of a particle when it achieves the disc is $\vec{v}$, whose components are:

$$v_R = v\cos(\vec{R_Q}, \vec{v}), \tag{10}$$

$$v_\phi = v\sin(\vec{R_Q}, \vec{v})\cos\theta_0 \sin(\phi_0 - \phi), \tag{11}$$

$$v_z = v\sin(\vec{R_Q}, \vec{v})\sqrt{1 - \cos^2\theta_0 \sin^2(\phi_0 - \phi)}. \tag{12}$$

The different factors account for the projections of the velocity on the different components. It is not easy to visualize the origin of these factors; but they can be understood by reference to Figures 2 and 3.

From the conservation of the angular momentum and energy we obtain the following relations:

$$|\vec{J}|=v_0b=v\ R_Q\sin(\vec{R_Q},\vec{v}) \tag{13}$$

and

$$\frac{1}{2}v^2=\frac{1}{2}v_0^2+\frac{GM_{\rm gal}}{R_Q}. \tag{14}$$

Hence, the velocity is:

$$v_R=\sqrt{v_0^2+\frac{2GM_{\rm gal}}{R_Q}}\left(\pm\sqrt{1-\frac{b^2}{R_Q^2+\frac{2GM_{\rm gal}}{v_0^2}R_Q}}\right), \tag{15}$$

$$v_\phi=\frac{v_0b}{R_Q}\cos\theta_0\sin(\phi_0-\phi), \tag{16}$$

$$v_z=\frac{v_0b}{R_Q}\sqrt{1-\cos^2\theta_0\sin^2(\phi_0-\phi)}. \tag{17}$$

3.2. *Force*

The velocity of the flow material is reduced by the friction with the disc and/or the shock waves. Its lost momentum is added to the local region of the intersection with the disc (Q). The subsonic ram-pressure mechanism of interaction of clouds with the galactic interstellar medium might be the responsible of that friction. This mechanism would affect the rotation curve of the gas. However, a supersonic collision of clouds (Santillán et al. 1999; Franco et al. 1988; Tenorio-Tagle et al. 1986, 1987) with the disc is perhaps a more likely mechanism. Stars are not affected directly by this transfer of momentum but we are concerned here with the outer radii of the galaxies, which are constituted by gas.

The transmission of net angular momentum to each ring of the disc will also produce a visible warping effect, as explained by López-Corredoira et al. (2002).

The net force transmitted to the disc by a fall of a mass dm in a time dt is

$$\vec{F}=f_{lm}\frac{dm}{dt}\vec{v}. \tag{18}$$

$f_{\rm lm}(R)$ stands for the fraction of linear momentum that is transmitted to the disc and depends on R in an axisymmetric disc and other factors (we will analyze this in §4). This force must be integrated for all the disc to calculate the different components.

With the expression (18) evaluated with the galactocentric velocity $\vec{v}$ we calculate the force exerted over the disc without taking into account its rotation velocity. We will neglect the effects of the rotation. In the expected scenario, the infalling material is supposed to achieve the disc with supersonic velocity with respect to the disc (Santillán et al. 1999; Franco et al. 1988; Tenorio-Tagle et al. 1986, 1987). The disc clouds are cold and consequently they have a low sound velocity. Hence, the result of the interaction infalling cloud-disc is a double shock wave: one which comprises, piles up and heats the disc; and another which decelerates the infalling material. Therefore, only the material within the shell limited by the two waves feels the effect of the rotation, because the rest of the material does not feel any force. A long time collision (only possible for a thick disc) would let the rotation produce some distortions in the shell, but in an approximation of a thin disc this effect would be negligible. There is also an acceleration of the cloud after it crosses the midplane. All these accelerations and decelerations are produced in the direction of the gradient of density, so this affect the radial and vertical forces, but not the azimuthal; the effects of the rotation would only be visible in the distortion of the material which is in the shell between the two shock-waves, and this is negligible for a thin disc.

3.3. *Total radial force due to collision with a particle beam*

Expressions (15), (16), (17) and (18) give the force produced by a particle which falls to the disc with an impact parameter b and intersects the disc at $\vec{r_Q}$. If we want to know the total force produced by all the particles that come with any b and intersect the disc at a distance between R and $R+dR$ with any azimuth ϕ, we have to integrate over all the particles of the beam that fall within this ring. The whole beam is then represented by varying in the plane perpendicular to $\vec{v_0}$ the initial position (at infinity) of the falling particle, whose polar coordinates are b and ϕ_b. Thus, the total radial force exerted over the point in the disc with radius between R and $R+dR$ and azimuth between ϕ and $\phi+d\phi$ is

$$F_R(R,\phi)dRd\phi = \int_0^{2\pi} d\phi_b \int_{0;R<R_Q<R+dR;\phi<\phi_Q<\phi_Q+d\phi}^{\infty} db\ b\ f_{\rm lm}(R)\frac{dm}{dt}$$

$$\times\sqrt{v_0^2+\frac{2GM_{\rm gal}}{R_Q}}\left(\pm\sqrt{1-\frac{b^2}{R^2+\frac{2GM_{\rm gal}}{v_0^2}R}}\right), \tag{19}$$

where

$$dm = \rho_{\rm b}\ v_0 dt \tag{20}$$

and $\rho_{\rm b}$ is the density of baryonic matter in the particle beam at infinity, assumed to be independent of b and ϕ_b. Any non-baryonic matter in the inflow would not collide with the disc so it should not be taken into account within the total mass of the flow for the purpose of computing the force. In the notation, $\vec{F}$ stands for the force per unit galactocentric radial length. Note that ϕ_b is the polar angle in the plane perpendicular to $\vec{v_0}$ and is generally different from the polar angle ϕ in the galactic disc, but they are coincident for a polar flow ($\theta_0 \approx \pi/2$).

We change the variables of integration in the expression (19) to R and ϕ (the Jacobian of the transformation is $\frac{\partial b(R,\phi)}{\partial R}$) and obtain

$$F_R(R,\phi)dRd\phi = \rho_{\rm b} f_{\rm lm}(R) v_0\sqrt{v_0^2+\frac{2GM_{\rm gal}}{R}}$$

$$\times\left(\pm\sqrt{1-\frac{b^2}{R^2+\frac{2GM_{\rm gal}}{v_0^2}R}}\right)\frac{\partial b(R,\phi)}{\partial R}b(R,\phi), \tag{21}$$

where $b(R,\phi)$ is derived from (9):

$$b(R,\phi) = \frac{1}{2}R\sqrt{1-e_{0Q}^2(\phi)}+\sqrt{\frac{1}{4}R^2(1-e_{0Q}^2(\phi))+R\ G\ M_{\rm gal}v_0^{-2}(1-e_{0Q}(\phi))}. \tag{22}$$

Now, for a polar flow ($\theta_0 \approx \pi/2$),

$$F_R(R)dRd\phi \approx -\rho_{\rm b} f_{\rm lm}(R) v_0 \sqrt{v_0^2 + \frac{2GM_{\rm gal}}{R}} \sqrt{1 - \frac{b^2}{R^2 + \frac{2GM_{\rm gal}}{v_0^2}R} \frac{db(R)}{dR} b(R)} \tag{23}$$

and

$$b(R) \approx \frac{R}{2} + \sqrt{\frac{R^2}{4} + \frac{RGM_{\rm gal}}{v_0^2}}. \tag{24}$$

The corresponding acceleration for the local element of the disc is:

$$a_R(R) = \frac{F_R(R)dRd\phi}{dR(Rd\phi)\sigma(R)}$$

$$= -\frac{\rho_{\rm b} f_{\rm lm}(R) v_0 \sqrt{v_0^2 + \frac{2GM_{\rm gal}}{R}}}{R\sigma(R)} \sqrt{1 - \frac{b^2}{R^2 + \frac{2GM_{\rm gal}}{v_0^2}R} \frac{db(R)}{dR} b(R)}, \tag{25}$$

where $\sigma(R)$ is the surface density of the disc.

This radial acceleration would be almost independent of any azimuth, ϕ, for polar flows. For other values of θ_0 substantially different from $\pi/2$, the radial acceleration would not be constant, and there would be a contribution of an azimuthal component of the acceleration.

3.4. *Vertical force*

It is obvious from Fig. 1 that, together with a radial force, the polar flow will produce a vertical force. The other component in cylindrical coordinates, the azimuthal force, would be null for polar flows as noted above. Following calculations similar to those in the previous subsection, we derive the vertical acceleration as:

$$|a_z(R)| = \frac{|F_z(R)dRd\phi|}{dR(Rd\phi)\sigma(R)} = \frac{\rho_{\rm b} f_{\rm lm}(R) v_0^2}{R^2\sigma(R)} \frac{db(R)}{dR} b^2(R). \tag{26}$$

4. RATIO OF LOST LINEAR MOMENTUM IN THE INFALLING FLOW

The intergalactic medium crossing the galactic disc is losing part of the linear momentum because of the friction or supersonic shockwaves production between the incoming gas and the disc gas. The degree of non-interaction depends on the density of the disc. It will be $\exp\left[-K_f\sigma(R)/\sin(\vec{R},\vec{v})\right]$, i.e. it will be nearly unity for a very low density disc and exponentially decreasing as the density becomes higher, becoming zero for a very dense disc. K_f is a constant related to the interaction. The factor $1/\sin(...)$ stems from the geometry of the path crossing the disc; an inclined infall suffers further friction along its path than a vertical infall. If this probability of interaction is related with the probability of losing linear momentum, then the general expression for the ratio of lost linear momentum in the infalling flow may be represented by

$$f_{\rm lm}(R) = 1 - e^{-K_f\sigma(R)/\sin(\vec{R},\vec{v})}. \tag{27}$$

For low densities in the disc ($\sigma(R) \ll 1/K_f$) and using (13), we obtain:

$$f_{\rm lm}(R) \approx K_f \sigma(R) \frac{R}{b(R)} \sqrt{1+\frac{2GM_{\rm gal}}{v_0^2 R}} \tag{28}$$

The value of K_f remains unknown since we do know neither the nature of the infalling material nor its parameters, except the density (temperature, dust or hydrogen or whatever, in clouds or in free particles, etc.).

Ram-pressure, due to the friction of clouds against the interstellar medium, is perhaps the most plausible mechanism (Sofue & Wakamatsu 1993; Sofue 1994). Although, as remarked above, a supersonic case is more plausible than a subsonic one. Franco et al. (1988) give an expression for the dragging of the infalling high velocity clouds that is compatible with the above expression. According to them, the non-conservative acceleration (i.e. the friction apart from the gravitational attraction) is $\ddot{z} = -\beta(R)\left[\rho_{\rm disc}(R,z)/\rho_{\rm disc}(R,z=0)\right]\dot{z}^2$. This means that, for nearly constant $\dot{z}$, and $\rho_{\rm disc}(R,z) \propto \exp\left(-|z|/h_z\right)$, $\Delta\dot{z} = \int_{-\infty}^{\infty}\ddot{z}\,(dz/\dot{z}) = -2\beta(R)h_z\dot{z}$, and $f_{\rm lm}(R) = \left(-\Delta\dot{z}/\dot{z}\right)(R) = 2\beta(R)h_z$. In the solar neighbourhood, Franco et al. (1988) constrain the value of $\beta \approx 10^{-21}$ cm^{-1}. If we take $h_z = 100$ pc for the scale height of the gas disc, $\sigma(R_\odot) = 48$ M$_\odot$ pc^{-2} (Kuijken & Gilmore 1989): $K_f = \left[2\beta(R_\odot)h_z\right]/\left[\sigma(R_\odot)\right] \approx 6$ m^2/kg. The ram-pressure may also be very different from the one calculated by Franco et al. (1988). Indeed, we would need to know the exact parameters of the infalling clouds (mean density ρ_c and radius R_c) since $\beta \propto \frac{1}{R_c\rho_c}$, and for this we would need to know how clumpy is the intergalactic medium. Therefore, the value of K_f is uncertain and can vary some orders of magnitude.

5. ROTATION CURVES

The hypothesis of this section is that the inflow can produce the observed rotation curves without the need for a massive dark matter halo. The radial force is nearly independent of the azimuth for the polar inflow, so the orbits will be nearly circular and the velocity of rotation:

$$v_{\rm rot}(R) = \sqrt{|a_R(R)|R + \frac{GM_{\rm gal}(R)}{R}} \tag{29}$$

The following characteristics of the curves are independent of the choice of parameters:

1. Gravitational effects are dominant for smaller radii while the infall effect is dominant for larger radii. This is due to the much lower values of a_R when $f_{\rm lm}(R) \approx 1$, i.e. when the disc is too dense to be crossed by the flow. In this case, a_R depends inversely on $\sigma(R)$, so it is exponentially decreased as R decreases.

2. The rotational velocity decreases slowly (a nearly flat rotation curve) for very low disc densities, when $f_{\rm lm}(R)$ is given by (28). In this case, the velocity of rotation due to the infall is:

$$v_{\rm rot,infall} = \left[\rho_{\rm b} K_f v_0^2 R \left(1+\frac{2GM_{\rm gal}}{v_0^2 R}\right)\sqrt{1-\frac{b^2}{R^2+\frac{2GM_{\rm gal}}{v_0^2}R}\frac{db(R)}{dR}}\right]^{1/2}, \tag{30}$$

which is independent of $\sigma(R)$, and whose dependence on R is quite smooth. The limit of high R is

$$v_{\rm rot,infall} = (\rho_{\rm b} K_f G M_{\rm gal})^{1/2} \, , \tag{31}$$

representing an exactly flat rotation curve, i.e. independent of R; it is also nearly independent of v_0. This behaviour can be observed in Figure 5. Note that the velocity is proportional to a power of the mass of the galaxy, which should be proportional to some power of the luminosity.

With the above values, and assuming $\rho_{\rm b} \sim 10^{-24}$ kg/m^3 (the approximate value to have a S-warp with the observed amplitude of the Milky Way if $\theta_0 \approx 85°$, López-Corredoira et al. 2002) and $M_{\rm gal} = 2 \times 10^{11}$ M$_\odot$, we would need a frictional constant of $K_f \sim 10^3$ m^2/kg to obtain $v_{\rm rot,infall} = 190$ km/s. These values are reasonable; we can think about an intergalactic matter with these characteristics.

These characteristics are not the result of a fine tuning of parameters; the nearly flat rotation curve for the largest values of R is independent of the parameters. However, the amplitude is dependent on the parameters as mentioned previously.

For $M_{\rm gal}(R) = R v^2_{\rm rot,gravit}/G$, $v_{\rm rot,gravit} = 200$ km/s for $R < 15$ kpc and a constant $M_{\rm gal}(R) = 2 \times 10^{11}$ M$_\odot$ for $R > 15$ kpc, a typical total mass of a galaxy such as the Milky Way without including a hypothetical massive halo (Honma & Sofue 1996). Note, however, that this Galactic model includes a halo within 15 kpc. We assume indeed there is a halo as proposed by Homma & Sofue (1996), but this is not a very massive halo (ten times more massive than the disc) which extends up to 100 or 200 kpc, typical of dark matter hypotheses. $\sigma(R) = \sigma(R_\odot) \exp\left[(R - R_\odot)/h_R\right]$ (where $\sigma(R_\odot) = 48$ M$_\odot$pc^{-2} [Kuijken & Gilmore 1989]; $h_R = 3.5$ kpc [Bahcall & Soneira 1980]; $R_\odot = 7.9$ kpc [López-Corredoira et al. 2000]); $v_0 = 100$ km/s, $\rho_b = 10^{-24}$ kg/m^3; the acceleration a_R of eq. (25) and the fraction of transmitted linear momentum of eq. (27) with $K_f = 10^3$ m^2/kg, we obtain the rotational velocity of the Figure 4.

Different values of v_0 have already been tested (see Fig. 5) to check that the curve becomes nearly flat for high values of R nearly independently of v_0. The amplitude varies, especially for low velocities, but the shape of the curve is practically the same. This amplitude of the contribution to the rotation curve by the infall is approximately fixed by the expression (31).

The small valley in Fig. 4 for the total velocity indicates the region of transition between the zone where the gravity dominates and the zone where the infall dominates the rotation curve: between 15 and 25 kpc. This distance is not dependent on ρ_b or v_0, but on K_f. A higher K_f would move the knee of $v_{\rm rot,infall}$ to the right (greater distance) and we would get lower values of ρ_b according to (31); a lower K_f would move it to the left (shorter distance), making necessary higher values of ρ_b.

5.1. *What is the effect of the vertical acceleration?*

Clearly, the vertical acceleration will also affect the galactic disc. The creation of a U-shaped distortion (a rim) is to be expected, i.e. the external rings of the disc will be shifted

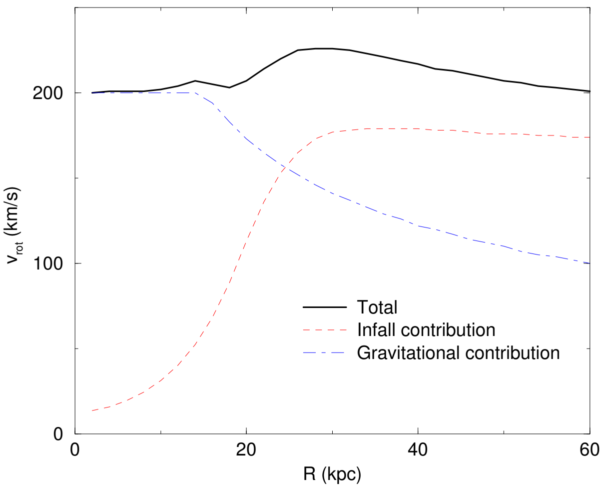

Fig. 4. Rotational velocity on the hypothesis of infall of intergalactic flow. Lower radii are dominated by the gravitation of the galaxy, while larger radii are dominated by infall effects.

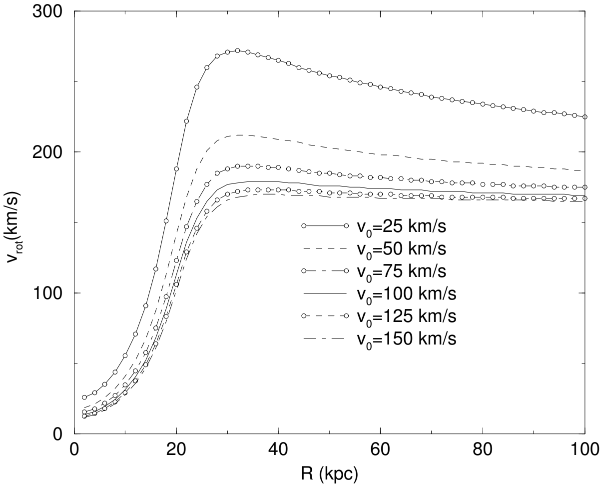

Fig. 5. Different contributions of the infall to the rotation curve for different initial infall velocities, v_0 (for a given set of parameters ρ_b, K_f; note that the amplitude also varies if we change ρ_b or K_f).

in the vertical axis to compensate for the vertical linear momentum transmitted by the flow according to eq. (26). The limit for high R is

$$|a_z| \approx \rho_b K_f v_0^2, \tag{32}$$

to be compensated for by the gravitation acceleration ($-GM_{\rm gal}z/R^3$ in a monopolar approximation), so

$$|z| \approx \left(\frac{v_{\rm rot,infall}v_0}{GM_{\rm gal}}\right)^2 R^3. \tag{33}$$

With $v_0 = 100$ km/s, $v_{\rm rot,infall} = 190$ km/s and $M_{\rm gal} = 2 \times 10^{11}$ $M_\odot$,

$$|z| \approx \left(\frac{R}{13\ {\rm kpc}}\right)^3. \tag{34}$$

For $R = 13$ kpc the distortion is 1 kpc, and for larger values of R grows proportionally to R^3. This value is somewhat higher. Perhaps, it should be somewhat lower, as obtained for lower v_0:

$$|z| \approx \left(\frac{R}{21\ {\rm kpc}}\right)^3 \text{ for } v_0 = 50 \text{ km/s}, \tag{35}$$

$$|z| \approx \left(\frac{R}{33\ {\rm kpc}}\right)^3 \text{ for } v_0 = 25 \text{ km/s}, \tag{36}$$

$$|z| \approx \left(\frac{R}{60\ {\rm kpc}}\right)^3 \text{ for } v_0 = 10 \text{ km/s}. \tag{37}$$

These distortions are reasonably small in the range where they can be detected. Nevertheless, they are not small enough to be undetectable, and if the present mechanism is responsible for the rotation curves, we should also observe U-shaped galaxies in some cases.

6. DISCUSSION ON THE PLAUSIBILITY OF THE PRESENT MECHANISM FOR EXPLAINING ROTATION CURVES

Is this mechanism for producing rotation curves with higher velocities than expected without invoking a massive dark matter halo plausible? Since this is a new idea, it is not the goal of this paper to explain perfectly all the details and caveats which can be associated with the mechanism. Nonetheless, one could say that the present mechanism works and works reasonably well if one accepts the hypotheses posited about the infalling flow.

The mechanism also produces U-shaped galaxies. Is this compatible with the observations? Reshetnikov & Combes's (1998) statistics of 540 galaxies indicate that around 35% were U-shaped. Many more could also be U-shaped but their orientations could conceal this feature, as well as many other in which the warp (S-shape) dominates. There might also be many galaxies with a very low amplitude of the U-shape deformation. The order of magnitude of the amplitude of the U-shape deformation is compatible with our estimates. This observational fact leaves room for the possibility that this mechanism is present in some degree in at least some galaxies.

Although we have considered negligible the effect of the galactic rotation in the transfer of azimuthal moment (see §3), it might be the case of some galaxies where its effect be not so negligible, perhaps because the disc is not so thin and the amount of material compressed between the two shock waves is high. In such cases, we would expect a loss of angular momentum for the disc, leading to a disc contraction (Sofue & Wakamatsu 1993). Sofue & Wakamatsu (1993) think that this would explain the radius variation along the evolution of these galaxies, probably leading to counter rotation of the gas with respect the stellar population. It is an interesting idea which is in agreement of what is observed in some systems (Bettoni et al. 1990).

The amplitude for baryonic density used in the example of Fig. 4 was taken as $\rho_b = 10^{-24}$ kg/m^3. This is equivalent to $n_{HI} = 6 \times 10^{-4} f_{HI}$ cm^{-3}, where f_{HI} is the fraction of HI in baryonic intergalactic matter. This value leads to a total accretion rate of the galactic disc out to $R_{\rm max} = 15$ kpc of ~ 10 M$_\odot$/yr for this density (López-Corredoira et al. 2002). This is the order of the accretion rate required to resolve the G-dwarf problem in our Galaxy, as well as explaining a number of phenomena of chemical evolution that require the long-term infall of low metallicity gas (López-Corredoira et al. 1999; Wakker et al. 1999). Blitz et al. (1999) gives a value of 7.5 M$_\odot$/yr. This value is also of the order of magnitude of the required density to explain warps in terms of this infall for an angle $\theta_0 = 85°$ (López-Corredoira et al. 2002). Note, however, that in the external disc the accreted mass crosses the disc, as posited in the hypothesis 3. So, only in the inner disc the accretion contribute to increment the mass of the disc, not in the external disc. Nevertheless, other values around this are also compatible with the present mechanism to explain flat rotation curves; it depends on K_f. In the example used in Fig. 4, the required density is $\rho_b \sim 10^{-21}$ kg/m^3/ (K_f [m^2/kg]) or even less for low velocities v_0.

The shape of the rotation curve in Fig. 4, an example of the application of the present hypothesis, shows two regimes and a small valley among them; the two regimes represent the gravitational and the infall predominance respectively. Looking at the review of rotation curves by Battaner & Florido (2000), one can easily deduce that there are many rotation curves that present this feature: NGC 2460 is a remarkable example with a valley that reduces the rotation curve by $\sim 25\%$ with respect to the maximum value in both regimes. This is explained in the standard theory as the regions being dominated by the disc and halo respectively, but the infall can substitute the halo for the second regime. In some other galaxies the transition is smooth, and this smoothness in the transition is difficult to explain. It needs a fine tuning of parameters, especially of the density, ρ_b. This question also affects the standard theory of dark matter and has been called the "conspiracy" problem (Bahcall & Casertano 1985); the transition region is in the optical edge of the galaxy. Perhaps, as said above, the solution has something to do with the formation and evolution of the galaxy surrounded by an intergalactic medium.

Another question to solve is the kind of matter that is affected by infall. Since the friction is between gases, it would be expected that the disc gas is affected rather than the stars. If this is true, we could expect that some galaxies have a stellar disc and a gas disc that do not corotate. This is also a fact. Although the stellar disc and the gas in the disc usually corotate, non-corotation is also very frequent, more than is generally assumed. Very often the rotation curve of the stars and gas differ greatly (Vega-Beltrán 1999). Important deviations are found in 14 out of 22 galaxies in Vega-Beltrán's sample, where gas and stellar rotation curves were measured independently. In IC 4889, for instance, gas exhibits a flat curve while the stars decline in a Keplerian-like fall-off.

6.1. *More considerations about the polar flow*

We have assumed that infall flows are polar ($|\theta_0| \approx 90^\circ$). One would expect some deviations from a strictly polar infall. If these deviations are small ($|\theta_0| >\approx 85^\circ$) the average deviations from a constant radial force are less than 10%; the mean azimuthal force would be null with average deviations less than 20% of the value of the mean radial force. This would give some deviations from perfectly axisymmetric rotation curves and also some lopsidedness in the distribution density. A study of rotation curves in Virgo (Rubin et al. 1999; Rubin & Haltiwanger 2001), i.e. in a cluster of galaxies where the infall effects are presumably greater, shows that more than 50% have disturbed rotation curves. They present asymmetric rotational velocities on both sides of the major axis, falling outer rotation curves, inner velocity peculiarities, including velocities hovering near zero at smaller radii, and dips in mid-disc rotational velocities. It is not only in the clusters were non-axisymmetric features in the disc are present. Of 1700 HI profiles, at least 50% show lopsidedness (Richter & Sancisi 1994; Haynes et al. 1998; Swaters et al. 1999).

As was already said, the correlation among the orientation of the galaxies, as observed for instance by Godlowski (1993) in the Local Supercluster and other superclusters too (Flin 1988), could find an explanation in this scenario: the galaxies are slightly aligned because they have their discs perpendicular to the intergalactic medium, which has a homogeneous motion, and the peculiar velocities of the galaxies among themselves is small. It was also found that cluster orientations are correlated in scales of less than 100 Mpc (Binggeli 1982, Faltenbacher et al. 2002). It was also observed (Flin 1988) that the double galaxies in the superclusters have not a random orientations but there is a significant excess of pairs with small angles between the rotation axis of both galaxies, and a defect of pairs with near perpendicular configurations. However, the fact we do not find alignment in many other cases is not evidence against the polar flow. The hypothesis could be correct in a scenario in which the intergalactic medium is in rest, and each galaxy move in a different direction, almost randomly (the velocities are related because each galaxy has gravitational effects on each other, but the distribution of velocity directions is almost random). In such a case, the orientation of each galaxy would be different, with the disc perpendicular to its direction of motion. Another second solution would be to have an intergalactic medium with local turbulences such that the flux velocity changes in scales relatively small, smaller than the typical distance among galaxies (see Fig. 6).

This hypothesis is an important point in the construction of the present theory, and it is not easy to test its plausibility. As said, it is perfectly possible that the discs of the galaxies are perpendicular to the flow due to the formation of the galaxies with the minor axis parallel to the flow or the alignment due to the continuous accretion of the intergalactic flows during the first stages of their life. We must also bear in mind that probably there is a strong selection

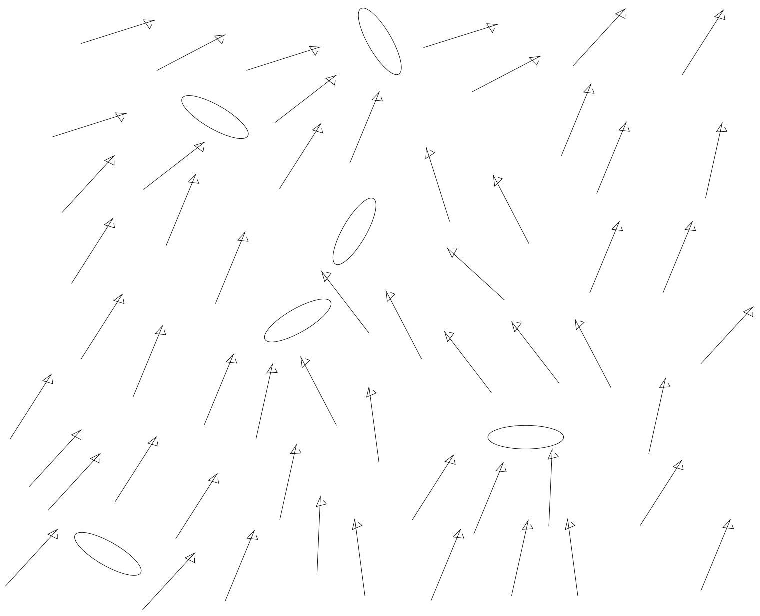

Fig. 6. Representation of a possible scenario of cluster of galaxies with flow velocities of the intergalactic medium nearly perpendicular to the galaxies (assumed in rest; in a more realistic representation, the galaxies would also have peculiar motions).

effect, in favour of alignment, because S-warped galaxies are avoided to measure rotation curves (López-Corredoira et al. 2002; §6.2 in this paper). However, these arguments are not proven yet and they are only temptative explanations.

6.2. *Relationship between warp formation and rotation curves*

The infall of intergalactic flows could also explain the warps ($m = 1$ distortions; S-shaped) in galactic discs for $|\theta_0| \neq 90^\circ$ (López-Corredoira et al. 2002) through the angular momentum transmission of the flow. López-Corredoira et al. (2002) show that for $\theta_0 \approx 85^\circ$ the amplitude of the U-shaped distortion is similar to the S-shaped distortion; Reshetnikov & Combes (1998) show that there are as many spiral galaxies dominated by a S-shape as dominated by an U-shape (around 35% each). Perhaps one could conclude that an infalling angle of $\approx 85^\circ$ is typical.

Therefore, the same mechanism could be responsible for warps formation and the flat rotation curves. According to this hypothesis (López-Corredoira et al. 2002 and the present paper), the degree of asymmetry in the warp is due to the mixture of S-warps and U-warps (always associated with flat rotation curves). It is more asymmetric for $|\theta_0|$ closer to 90°. Curiously, Castro-Rodríguez et al. (2002, Figs. 1i,2i) shows that the degree of warp asymmetry is anticorrelated with the amplitude of the warp. This stands to reason in the present hypothesis, since the higher it is the warp amplitude (higher $|\theta_0| - 90^\circ$) the lower it is the ratio U-warp/S-warp and, therefore, the lower it is the asymmetry. Also, Castro-Rodríguez et al. (2002, Figs. 1e,2e) shows a relation between the asymmetry and mass/luminosity ratio. If we interpret this mass/luminosity ratio in terms of the ratio (infall+gravitational)/gravitational contribution to the rotation curve [instead of ("dark mass"+"luminous mass")/"luminous mass"] we get that the angle θ_0 is related to the infall ratio, which stands to reason again. However, as explained in Castro-Rodríguez et al. (2002), the massive-halo hypothesis for the formation of warps does not work to explain their observations.

6.3. *Universality of the flat rotation curve?*

Are the flat rotation curves a question of fine tuning of parameters? It has been shown above that the shape of the curve is nearly independent of the parameters. The amplitude does depend directly on ρ_b, particularly $v_{\rm rot,infall} \propto \rho_b^{1/2}$. Apart from the amplitude, fine tuning seems unnecessary since the shape of the curve fits quite well for a wide ranges for the set of parameters.

How to explain the coincidence between $v_{\rm rot,infall} \sim v_{\rm rot,gravit}$? Although an explanation to this cannot be evaluated from the present analysis, it could be tentatively assumed that the formation and evolution of the galaxies has something to do with it. The solution to this question is beyond the scope of this paper. In any case, it should also be noted that this coincidence is not necessary for all galaxies and there are many in which there exist important discrepancies with regard to a flat rotation curve. Honma & Sofue (1997b) have found that a significant fraction of rotation curves possibly become Keplerian within 10 times the disk scale length. Our Galaxy might be a case (Honma & Sofue 1997a). Therefore, several galaxies may have a rather small contribution of the infall when ρ_b is smaller than usual. The amplitude could oscillate in a range of values producing several cases: flat rotation curves, Keplerian rotation curves and intermediate cases.

Apart from the exceptions, the observed "universal"[2] flatness of the rotation curves is then translated here into a fine tuning of the amplitudes $v_{\rm rot,infall} \approx v_{\rm rot,gravit}$. The first amplitude depends on the density of the flow. If we were to accept that this mechanism applies to all flat rotation curves, the following relation should be followed from (29), (31):

$$\rho_b \sim \frac{1}{K_f R_{\rm gal}}, \tag{38}$$

where $R_{\rm gal}$ is the size of the galaxy, the radius at which the halo finishes or gives negligible contribution to the mass. This is a rough relationship, since it depends also on other variables. The expression says us that the size of the galaxy is inversely proportional to the mean density of the surrounding gas. In other words, larger galaxies should be surrounded by less dense intergalactic flows. It is not new that the initial environment where a galaxy forms can determine the parameters of the galaxy (mass distribution and others) (Burstein et al. 1986) so, perhaps one could think that this is not a foolish remark.

Equation (38) says us that there is a relation of the size of the galaxy with the density of the environment and this relation is that they are inversely proportional. Were we able to demonstrate this from a theory of galaxy formation, we would have demonstrated the fine tuning of $v_{\rm rot,infall} \approx v_{\rm rot,gravit}$. This theory is not in our hands yet since the actual proposed scenarios of galaxy formation do not contemplate the possibility of a remaining intergalactic medium. However, the relation (38) stands to reason: the larger is the galaxy, the less dense is the surrounding gas since it was consumed in the formation of the galaxy.

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[2] This universality should perhaps change its name, because there are too many exceptions to the rule.

The calculations in the present paper were very simplistic. It was assumed that the flow with a constant density falls from the infinity. In a more realistic scenario, the flow geometry and its density distribution are coupled with the galaxy which surrounds.

Another important question to remark is that the proposed intergalactic matter which fills all the space, with a distribution of densities depending on the galaxy which is closer, is very dark to be detected. That is, the detection of the intergalactic matter of these characteristic was not detected yet. Some intergalactic matter was already detected, for instance HVCs or intracluster gas when it has a strong X-ray emission. However, those are probably not the total intergalactic gas, but a small part of it. Therefore, if we do not see signals of intergalactic gas around a galaxy, it does not mean that it does not exist, but that we have not detected it due to its faint emission. In the same manner, if we observe that the galaxies within a cluster are embedded in a medium which emits strongly in X-ray, it does not mean that the medium is richer than in isolated galaxies but that it is brighter in X-ray, just that. Hence, very large differences in emission of intergalactic matter around galaxies should not lead us to think that the densities are so different. The relationship (38) is not in contradiction with our knowledge about the intergalactic medium, since that knowledge is very scarce.

The clusters of galaxies may have different characteristics of intergalactic medium in general from the medium surrounding isolated galaxies, although these differences may not be as large as is usually believed. If so, there should be some different features for the rotation curves in the cluster of galaxies. Some effects are actually observed. As a matter of fact, there is a correlation between outer rotational velocity gradients and the distances of galaxies from the cluster center in cluster galaxies (Burstein et al. 1986; Rubin et al. 1988; Whitmore et al. 1988, 1989). Amazingly, the statistics show no correlation of the rotation curves with the intrinsic properties of the galaxy (Burstein & Rubin 1985), but instead a correlation with environment. This should lead us to suspect that rotation curves have more to do with the external environment (intergalactic medium and interaction with other galaxies) than with intrinsic galactic parameters.

6.4. *Summing up*

Summing up, we see that the proposed mechanism is plausible, and that its effects are actually observed in many galaxies. Perhaps the mechanism is actually present for few galaxies, or perhaps it is applicable to most of the galaxies, as opposed to the massive dark halo hypothesis or other hypotheses; or perhaps it is not an important effect for any galaxy because the density of the intergalactic medium is not high enough. The universality of the effects presented here to explain the flat-rotation curves is likely, if one accepts a priori a relationship of the type (38) which could perhaps be strictly proven in the context of galaxy formation. At present, we do not have many strong arguments in favour of the intergalactic flows with the given conditions. The origin of a polar infall is still an assumption, although one that is no more gratuitous than the assumptions in the standard theory to explain the nature of a hypothetical dark halo, or in the magnetic forces hypothesis or in the MOND theory. In any case, neither are there strong arguments against this mechanism for at least some galaxies. The mechanism works and this should be borne in mind and an attempt made to contrast future data with this hypothesis in order to seek further arguments for or against it. Even if the effect is not predominant for any galaxy, the present mechanism could be a second order effect which produce anomalies in the rotation curves explained by another mechanisms (dark matter haloes, MOND or magnetic fields).

7. CONCLUSIONS

The following conclusions are drawn from the present paper:

- The existence of massive dark matter haloes is mainly supported by the observations of non-Keplerian rotation curves. However, other theories can also explain the rotation curves: MOND, magnetic forces and polar infall of intergalactic matter on to the disc, as proposed in this paper.

- There is no need for fine tuning to explain the flatness of the rotation curve according to the present hypothesis, but it is necessary to explain the amplitude of the curve, as well as the "conspiracy" problem.

- The present mechanism also causes small U-shape distortions (a rim) in the galactic disc whose amplitude is proportional to the square of the velocity of the flow at large distances.

- We have not treated the possible deceleration of the disc due to a transmission of a negative azimuthal component of the linear momentum. Their effects in a scenario of supersonic interaction with thin disc were considered negligible. Were this contribution not negligible, we would have to add a disc contraction to the present effects.

- It remains to explain why the infall is polar. Tentative explanations are related to the formation and evolution of the galaxies, with the orientation of the disc perpendicular to the flow; or it might also be a selection effect that avoids the measurement of rotation curves in the outer part of the disc in S-shaped warped cases, which are misaligned galaxies with respect the relative motion of the intergalactic medium in the context of the present hypothesis. This question is not solved yet and needs further study.

- The present hypothesis might be applicable to all, some or none of the spiral galaxies. At present, a mechanism has been proposed that works and whose effects are compatible with observations of many galaxies, maybe for most of them, but whose validity is not proven yet. The universality of flatness, or nearly flatness, of rotation curves from a few kpc radius to several tens of kpc can be explained by the proposed mechanism if one accepts that the density of the flow surrounding a galaxy is inversely proportional to the size of the galaxy, remaining this to be proven in the context of galaxy formation scenarios. The different characteristics of the intergalactic flows in cluster galaxies (not necessarily much denser) might explain further expected features of asymmetries and correlations which have already been found.

- If the proposed mechanism turns out to be real, the massive dark halo of the standard theory would be without support from a galactic astronomy point of view. Nevertheless, it is also possible that this mechanism works in some galaxies and that a dark halo, magnetic forces, or MOND be present too. The different hypotheses are not exclusive; several of them may be valid at the same time.

- Even if the proposed effect is not predominant for any galaxy, the present mechanism could be a second order effect which produce anomalies in the rotation curves explained by other mechanisms (dark matter haloes, MOND or magnetic fields).

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