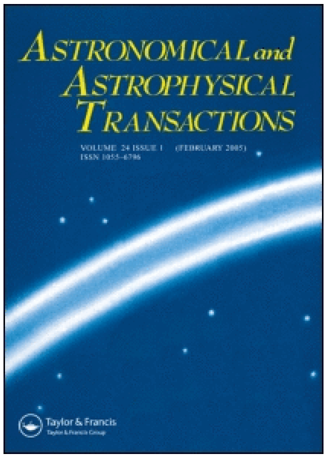

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Is the missing mass really missing?

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IS THE MISSING MASS REALLY MISSING?

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It is shown that giant vacuum bubbles, which may have been formed during the inflationary phase of the universe, result in a new "bubble force" which can keep galaxies, as well as clusters of galaxies, together without needing to invoke exotic forms of dark matter. The bubble force can be understood in the framework of the recently introduced concept of quantum gravity in which gravity results from a distortion of the vacuum pressure.

KEY WORDS Galaxies formation, inflationary phase of the universe, missing mass

The 65-year-old missing mass problem is undoubtedly one of the most baffling mysteries in modern astronomy. It reveals itself for instance through the discrepancy between the mass of a group of galaxies, estimated from the virial theorem, and that estimated from the luminosity of the individual members. Also from the discrepancy between the observed (Saslaw, 1970) flat rotation curves and the rotation curve expected from Kepler's third law, it was thought that some form of invisible dark matter had to surround the galaxies. Although many exotic forms of the missing dark matter have been proposed over recent years (Srednicki, 1990), no conclusive demonstration of its existence has been obtained. Adopting the recently introduced concept in which gravity results from a non-cancelled vacuum pressure on matter (Van Nieuwenhove, 1992) and making the assumption that galaxies (as well as clusters of galaxies) are located inside large spherical deviations of the vacuum energy density (bubbles), it is shown that these bubbles lead to an effective new force (a bubble force) which can then explain the kinematics of galaxies and clusters of galaxies without needing to invoke dark matter.

In Van Nieuwenhove (1992), it was argued that the gravitational force results from a non-cancelled vacuum pressure exerted on matter. Note that in this framework, the vacuum energy density ρ (however large) is non-gravitating since gravity in this model is only based on gradients of ρ. The gravitational force induced by a mass M can then be expressed as (Van Nieuwenhove, 1992)

$$F = V_M \left(\frac{dp}{dr}\right) \tag{1}$$

in which $p = -\rho$ and $V_M = Mc^2/\rho_V$ where ρ_V is the unperturbed vacuum energy density. Postulating now the existence of large, stable structures in the vacuum energy density in which the vacuum pressure is slightly reduced, equation (1) predicts the existence of a "bubble force" (BF) despite the fact that no visible or solid mass (particles) is present. Using this concept one is now in a position to understand the observed flat galaxy rotation curves (Saslaw, 1970). These rotation curves can generally be divided into a part in which the galaxy rotation increases linearly with the distance to the galactic centre (corresponding to the "bulge" region of the galaxy, considered to be a region of uniform mass density ρ_m), followed by an outer part of roughly constant velocity. Considering first the linear region, in which the radial separation r is small compared to the radius of the bubble, one can expect that the BF (on a test mass m) is proportional to the separation from the centre. In addition this force has to be proportional to the test mass m (because of (1)). This leads to a bubble force F_B given by:

$$F_B = \frac{4\pi G}{3} k\, m\, r \tag{2}$$

in which G is the gravitational constant and k is a proportionality constant with the dimension of a mass density and which has to be related exclusively to the properties of the bubble. From the force balance equation (applied to the test mass m) the rotation velocity v is then given by

$$v = \sqrt{\frac{4\pi G}{3}}\sqrt{\rho_m + k}\, r. \tag{3}$$

Thus the bubble force behaves *just like* the usual gravitational force caused by a homogeneous mass distribution with mass density k.

Considering next the region of the rotation curve outside the galactic bulge, we will describe, somewhat arbitrarily, the distorted vacuum (bubble) by the simple Gaussian form

$$\rho(r) = -\rho_V \left[1 - \left(1 - \frac{\rho_B}{\rho_V}\right) e^{-\left(\frac{r}{R_B}\right)^2}\right] \tag{4}$$

in which ρ_B is the vacuum energy density in the centre of the bubble and R_B the bubble "radius". Using equation (1), the inward force F_B then becomes

$$F_B = -m\,c^2 \left(1 - \frac{\rho_B}{\rho_V}\right)\left(\frac{2r}{R_B^2}\right) e^{-\left(\frac{r}{R_B}\right)^2} \tag{5}$$

The rotation curve is then determined by

$$v = \left[\frac{GM}{r} - c^2\left(1 - \frac{\rho_B}{\rho_V}\right)\left(\frac{2r^2}{R_B^2}\right) e^{-\left(\frac{r}{R_B}\right)^2}\right]^{1/2} \tag{6}$$

The second term between the brackets in (6) can now compensate the decreasing first term (for increasing r) over a certain range of r such that flat or even increasing

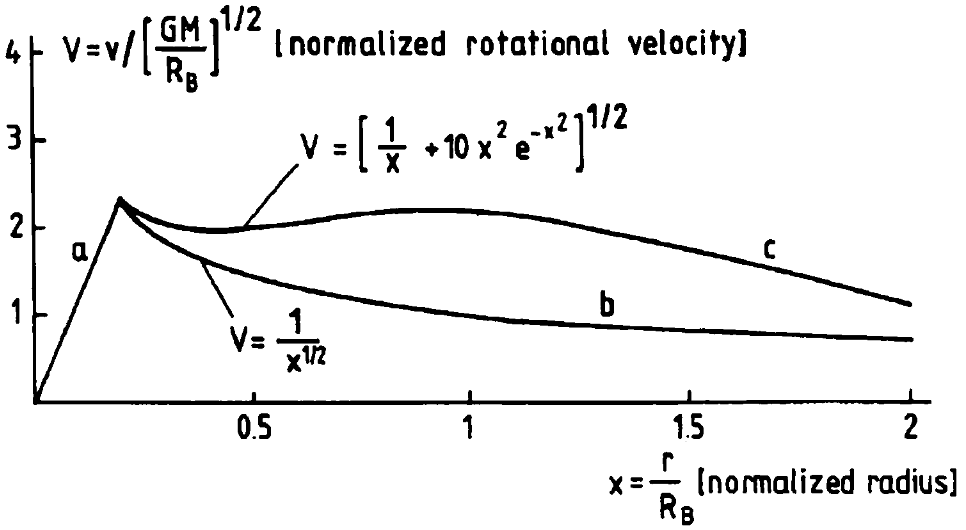

Figure 1 Schematic drawing of normalized galaxy rotation curves: (*a*) initial linear increase within the galaxy bulge; (*b*) Keplerian fall-off of galaxy rotation with increasing distance; (*c*) rotation curve corrected for the bubble force.

rotation velocities can be obtained in the outer regions of galaxies. To obtain this result for various galaxies seems to imply that there exists a close correlation between the properties of the bubbles and the mass contained within them. This fact, together with our previous assumption that galaxies are only located inside vacuum bubbles, seems to suggest a possible scenario for galaxy formation. To obtain an idea of the deviation of the vacuum energy density inside the bubble, we can use as a criterion that at some radius R within the bubble, the gravitational force ($F = G\,m\,M/r^2$) has to become comparable to the BF to cause an observable deviation from the expected rotation curve. Using equation (5) in which R is taken to be half the bubble radius R_B, one obtains

$$-\left(1 - \frac{\rho_B}{\rho_V}\right) = 5\frac{GM_G}{c^2 R_B}. \tag{7}$$

Using typical values $M_G \approx 4 \times 10^{41}$ kg and $R_B \approx 5 \times 10^{20}$ m (our galaxy), one obtains that $\rho_B/\rho_V = 1 + 3 \times 10^{-6}$ Thus the bubble represents only a very slight deviation from the background vacuum. Nevertheless, it can influence in a dramatic way the motion of stars within it. Combining equation (7) and (6) one obtains fairly flat rotation curves (see Figure 1) over the range $0.2 < r/R_B < 1.2$, over which the rotation velocity v is about $2(GM_G/R_B)^{1/2}$. Since the vacuum bubbles correspond to a slight, local increase of the vacuum energy density, they also represent a finite amount of mass, which could be substantially larger than the mass of the galaxy itself. This might then resolve also the missing mass problem in a cluster of galaxies.

The vacuum bubbles could have been formed during the inflationary phase of the universe (Linde, 1990) after which they could have grown to astronomical dimensions. From a more classical point of view these bubbles should correspond to non-linear stable solutions of the Einstein field equations in which the source of the curvature is the curvature itself. This self-supporting curvature then modifies the geodesics of the stars.

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