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Missing Mass or Dark Matter?

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Direct determination of the mass of astronomical objects rests entirely on Newton's law of gravitation. It begins with binary stars and ends with clusters and superclusters of galaxies, with the application of the virial theorem. Indirect determination of the mass is based on mass-luminosity relation, determined from the former mass measurements, associated with measures of the luminosity. In the case of our galaxy, the mass-luminosity relation obtained from the study of binary stars leads to an estimate of the mass of visible objects. The velocity of rotation associated with a modeling of the gravitational potential leads to another estimate of the galactic mass.

The velocity of rotation, or *rotation curve*, of many galaxies has been measured either with the 21-cm line or with $H\alpha$ lines from gaseous nebulae excited by bright stars. They all show a flattening of the rotation curve with no indices of radial velocity. Thus, the outer parts of spiral galaxies show essentially a circular velocity which does not obey the classical Keplerian relation $V \sim r^{-1/2}$. What is the origin of this departure from the Keplerian law? There are three possibilities: (1) there is a certain amount of invisible matter which provide the extra gravitational mass which balances the extra centrifugal force; (2) the distribution of matter in space produces a gravitational potential which explains the velocity of rotation; and (3) there is an extra force which carries the interstellar matter and provides its high angular momentum—or there is a new physics of gravitation.

Possibility 2 has been considered by Lafon (1976). The trouble is that, at sufficiently large distances from the central part of galaxies the gravitational potential always converges towards a $1/r$ law and does not explain the constant velocity of rotation observed up to distances of 50 kpc. Possibility 3 has been considered by Nelson (1988), but, as shown by Livio and

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Schatzman (1988), if the weakly ionized plasma is carried by a magnetic field, this generates a strong centrifugal force which in turn produces a large radial velocity (up to 500 km sec^{-1}). There is no indication in the observations of any appreciable radial outflow. In the model of Nelson, the lines of force of the magnetic field being open, nothing can prevent the gas from escaping. As shown by Livio and Schatzman (1988), a strong chaotic and entangled field could possibly keep the gas, but this has to be reconciled with the observed shapes of the magnetic fields in galaxies and with the necessity of a consistent dynamo mechanism to maintain the field.

Possibility 1 is the most generally accepted one, with two possibilities: (1.1) The invisible mass is made of baryonic matter. This is the point of view of Bahcall and Casertano (1985); and (1.2) the invisible mass consists of the so-called *dark matter*, made up of any of the weakly interacting particles. I shall not consider here the attempts at changing the theory of gravitation.

The ratio of the density of matter in the universe to the critical density, $\Omega = 8\pi G\rho/H^2$, where H is the Hubble constant, when it is derived from the visible matter, is of the order of 0.1; derived from the primordial nucleogenesis, it is of the same order of magnitude. Ω is equal to 1 for a flat, expanding universe. It was therefore a great temptation to assume that the universe is flat and is filled for 90% of dark matter. Two reasons were in favor of this assumption: (1) this fits with the estimate of the gravitational mass obtained when applying the virial theorem to clusters of galaxies, and (2) the value of Ω is a function of time and was very close to one at the early times of the universe: at the Planck time, $t = 10^{-43}$ sec, $\Omega = 1 - 10^{-60}$. The origin of this extremely small difference from one led also to the idea that Ω has always been exactly equal to 1. However, there is no proof that clusters of galaxies are in a stationary state, which is the condition for applying the virial theorem. Mass determination from the hypothesis of hydrostatic equilibrium of the intergalactic gas gives a mass/luminosity ratio which is definitely smaller, about one-fifth of the mass given by the virial theorem (Cowic *et al.*, 1987). The discovery of the large bubble structures (Gregoy and Thomson, 1978; Tully and Fisher, 1978; Einasto *et al.*, 1980; Kirshner *et al.*, 1981; Davis *et al.*, 1982; de Lapparent *et al.*, 1986) suggests strongly that clusters of galaxies are in fact singular intersections of three bubble walls, and not spherically symmetric structures in statistical equilibrium. One should remember that a galaxy takes 20 billion years to cross a cluster; the propagation of sound waves takes about the same time: it is difficult to believe that clusters of galaxies are in a stationary state of equilibrium. Furthermore, it has been shown (Whitmore *et al.*, 1987) that spiral galaxies in clusters do not show the flat rotation curve of isolated spirals.

From the astronomical point of view, it is not possible yet to consider that the nature and the exact amount of dark matter have been established. This does not mean that all problems concerning the mass-luminosity ratio as established by Poveda (1961), with a remarkable growth of M/L as a function of mass, have been solved. Speculations on the possible existence of new particles are extremely important, but we first have to be sure that presently well-established physics cannot explain the astronomical data.

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