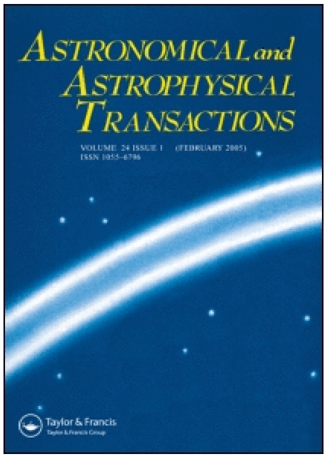


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# DARK MATTER IN FREE-FALL TRIPLETS OF GALAXIES

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We discuss the problem of dark matter in systems of galaxies, focusing on triple systems, for which the situation with dark matter is still less obvious than for the giant haloes of individual galaxies or rich clusters of galaxies. Using our numerical models for free-fall triplets of galaxies, we made a statistical estimation of the dark matter content in these systems. In a typical system, the mass of dark matter proves to be $(1.5\text{–}3) \times 10^{12}h^{-1}M_{\odot}$, which is 5–7 times greater than the mass of the total luminous matter of the galaxies in the triplet.

KEY WORDS Dark matter, groups of galaxies

## 1 INTRODUCTION

How much dark matter is there in galaxies, their groups and clusters? This is one of the cricical questions of astronomy and cosmology. Another question seems to be even more fundamental: what is the physical nature of dark matter?

We will not touch here the second of these questions at all; we can only say that currently discussed possibilities involve objects from weakly interacting elementary particles to massive compact bodies, so the range of the masses of the candidate objects spreads over 60 decades(!) This is an exact quantitative measure of our ignorance about it. Let us address the first question and focus mainly on groups of galaxies and especially triple systems of galaxies; we would like to present new empirical data and theoretical considerations concerning free-fall triple systems.

## 2 INDIVIDUAL HALOES AND RICH CLUSTERS

Optical and X-ray mass determinations suggest that dark matter may reside in very large haloes around giant galaxies, typically extending to 100–200 kpc. This is inferred from the high rotation speed of gas and stars in the outer parts of spiral galaxies, the high velocity dispersion in elliptical galaxies, extended X-ray haloes of hot gas, and motions of faint satellites at large distances around galaxies.

Since the first observations by Zwicky much evidence has also been accumulated for the existence of a large amount of dark matter in rich clusters of galaxies with sizes 1–3 Mpc. This is indicated by the high velocity dispersion of member galaxies and the high temperature of the intergalactic gas in clusters.

The relative contribution of the dark matter component specified in terms of mass-to-light ratio ($M/L$) is characterized by $M/L = (30\text{–}100) \times (M_\odot/L_\odot)$ for galactic haloes and $M/L = (100\text{–}500) \times (M_\odot/L_\odot)$ for rich clusters. These figures mean that the mass of dark matter is 3–10 times the mass of the luminous matter in galaxies and 10–50 times the luminous matter in rich clusters. A recent discussion of these figures can be found, for instance, in Bahcall *et al.* (1995).

The mass-to-light ratio increases, on average, with the space scales of the systems. Such a trend was first mentioned many year ago by Karachentsev (1966) on the basis of data available at that time on binary galaxies, groups, clusters and superclusters.

## 3 GROUPS

The mass estimation for groups of galaxies presents a thorny problem because only dynamical methods can yet be applied for these systems. These methods are not quite direct and reliable in this case due to two major causes: observations give only line-of-sight velocities of the member galaxies and their visible separations; and there is no fundamental theory which could enable one evaluate the total masses of the groups using these data.

Usually one uses mass estimators for groups, that have the form of the "virial" relation:

$$M = \alpha(V^2 R/G), \tag{1}$$

where $M$ is the total mass of the system, $V$, $R$ are the characteristic velocity (which may be the rms velocity relative to the centre of mass of the system) and size (which may be the mean harmonic separation), $G$ is the gravitational constant, and $\alpha$ is a dimensionless factor.

This equation may be justified by noting that it is, in a sence, more general than any theorem of mechanics, because it follows from simpe dimensional analysis: it gives a unique combination of $V$ and $R$, together with the gravitational constant $G$, which has the dimension of mass.

It is usually assumed that relations of this type can probably work at least statistically for ensembles (catalogues) of groups. But is the parameter $\alpha$ constant and universal, at least statistically?

Commonly assuming a positive answer to this question and taking

$$\alpha = 9\pi/2 \tag{2}$$

(for instance, from the well-known book by Binney and Tremaine), one can calculates median mass-to-light ratios for the CfA group catalogue,

$$M/L = (100\text{–}300)h \times (M_\odot/L_\odot), \tag{3}$$

and for the Hickson compact group catalogue,

$$M/L = (20\text{–}70) \times (M_\odot/L_\odot), \tag{4}$$

where $h = H/(100\ \mathrm{km/s/Mpc})$ (see Karachensev *et al.*, 1989, and again Bahcall *et al.*, 1995 for discussion and references).

Both figures together give the interval $M/L = (20\text{–}300)h(M_\odot/L_\odot)$ for groups which seems not too surprising, because it covers practically the interval from one extreme scale – individual galaxies – to the other extreme one – rich clusters (see Section 1).

However, reliability of these estimations seems to be questionable because of at least two reasons. First, the wide CfA groups are not in virial equilibrium: their ages are typically less than the crossing times for the galaxies in the systems; thus the usual approach to the mass estimation (like Binney–Tremaine) does not work in this situation. Second, physical separations in the Hickson compact groups (which are in virial equilibrium) are comparable with the sizes of the member galaxies, or even less than the sizes of their dark matter haloes; so these groups cannot be considered as point-mass systems. And it again means that the standard way of mass estimation is not valid here.

## 4 FREE-FALL TRIPLETS

Both problems can be solved for a special type of group – wide tiplets of galaxies. The catalogue of this system has recently been compiled by Trofimov and Chernin (1995). The problem with the sizes of the systems, which is essential for the compact groups and triplets, does not exist for the wide triplets: the median value of the mean harmonic (projected) separation for the physical wide triplets is $R = 740h^{-1}$ kpc. This means that the physical separation in wide triplets is about 10 times more, typically, than in compact triplets and well exceeds the sizes of individual galaxies, even with their dark matter haloes. For this reason, the three-body approximation should work well for them, and the computer physics for wide systems can be developed in a most direct way.

The wide triplets are not virialized systems. The galaxies in them fall towards each other making their first crossing within the systems. The median value of their velocities (relative to the centre of mass) is $V = 84$ km/s. In a sense, the dynamics of the wide triplets is similar to the dynamics of the Local Group, in which two main bodies – the Milky Way and the Andromeda Galaxy – move towards each other in their first approach. Their separation and the relative velocity are the same, on the order of magnitude, as the figures $R$ and $V$, correspondingly, for the wide triplets. As is well known, the estimation of the mass of the Local Group based on the two-body model depends on the assumed age of the system. One can expect that the estimation of the typical mass for the wide triplets should also depend on an additional assumption about their age.

We have developed computer statistical mechanics for the wide triplets, and on this basis discovered the kinetics of virialization in ensembles of these systems. It was found that the general trend of the evolution is towards the quasi-stationary state.

We also demonstrated that there may be a definite relation between the typical mass of the systems in an ensemble and their observed characteristics at any particular moment of time. The relation has again the form of the virial relation, but the factor $\alpha$ is now a function of time.

If the systems start their evolution from rest (like the Local Group), the velocities are near zero initially, and the factor $\alpha$ tends to infinity. This is because the ratio of potential energy to kinetic energy, $U/T$, tends to infinity at this state (the potential energy is determined as positive here with the calibration in which the energy is zero, if the distances between the bodies are infinite).

Our results (Dolgachev and Chernin, 1997) show how the ratio $U/T$ changes with time when the bodies in the system start their free fall (Figure 1). In accordance with this, we find that after an initial rapid drop from infinity, $\alpha(t)$ decreases less rapidly and reaches a minimal value which is about $9\pi/4$; then it increases asymptotically with oscillations to the value $\alpha = \alpha_0 \approx$ 14–16 found earlier for virialized ensembles of triple systems (Chernin and Mikkola, 1991).

If the age of the systems is in the interval 10–20 Gyr (which is less than the mean crossing time), a simple linear approximate expression for $U/T$ and $\alpha(t)$ may be taken from our computer statistical mechanics:

$$U/T \approx 4(3 - t_{10}); \quad \alpha(t) \approx 9\pi(3 - t_{10}), \tag{5}$$

where the typical age of the ensemble of systems $t$ is measured in 10 Gyr: $t_{10} = t(10\ \text{Gyr})$. With this result we can find a typical value of the mass of a wide triplet:

$$M \approx (3\text{–}1.5) \times 10^{12} h^{-1} \times M_{\odot}, \tag{6}$$

if the age of the systems lies within the interval 10–20 Gyr.

One may estimate also the mass-to-light ratio:

$$(M/L) \approx (200\text{–}100)h \times (M_{\odot}/L_{\odot}). \tag{7}$$

Both magnitudes $M$ and $(M/L)$ prove to be essentially greater than the values that can be obtained with the use of the "standard" $\alpha = 9\pi/4$.

The total characteristic mass of the free-fall triplets is fairly close to the mass estimated for the compact triplets (which are in stady-state statistically in their ensemble) (Chernin and Mikkola, 1991). This means that the dark matter content is more or less the same in the wide range of the space scales of the systems of galaxies, from 50 to 700 kpc. In this range of scales, one cannot see a linear increase of the

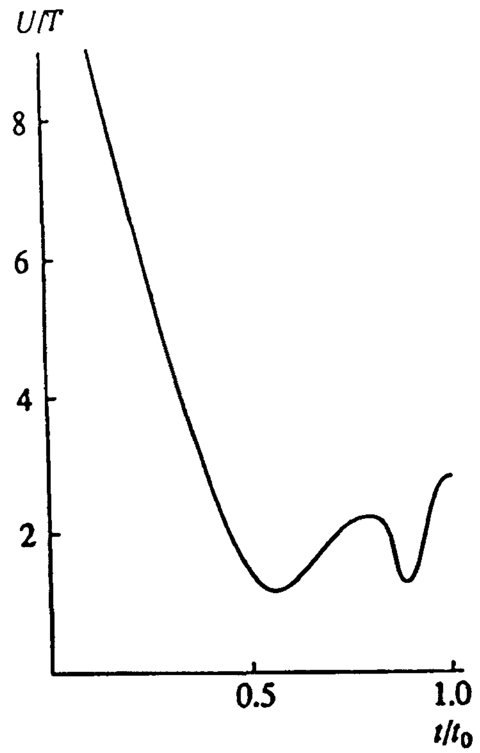


**Figure 1** Typical behaviour of the energy ratio, $U/T$, as a function of time. Here $t_0$ is the "initial crossing time": $t_0 = 2R_0/V_0$, $V_0 = (3Gm/R_0)^{1/2}$, and $R_0$ is the initial value of the mean harmonic separation.

dark matter mass with the size of the systems, while such a relation is roughly correct for a larger-scale range – from an individual galactic halo to the richest clusters and superclusters of galaxies (Karachensev, 1996).

## 5 CONCLUSION

Our determination of the masses of the wide triplets demonstrates that these systems contain considerable amounts of dark matter which is 5–7 times greater in mass than the luminous matter of their member galaxies. The dark matter is most probably gathered in the extended haloes of the galaxies, and it seems reasonable to believe that this estimation gives the total mass of the haloes – contrary to the estimates for individual galaxies with more or less arbitrary cut-off of the halo radii.

Based on our experience with the statistical dynamics of few-body systems, we may expect that the typical time behaviour of the parameter $\alpha(t)$ found for the wide triplets can be used for ensembles of wide groups of galaxies as well. In this case the typical mass of the CfA groups proves to be about the mass of the wide triplets found above.

As for compact few-body systems, adequate computer physics involves more complex models that include such processes as dynamical friction, tidal interaction, merging, etc. (Zheng *et al.*, 1993; Wiren *et al.*, 1996). These models give for the compact triplets (Karachentsev *et al.*, 1989) the resulting mass-to-light ratio of 50 solar units as a robust estimate. A similar figure can be obtained in this way also for the Hickson compact groups.

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