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X-RAY HALOES OF WIDE TRIPLETS OF GALAXIES AND STRUCTURE FORMATION ON THE SPATIAL SCALE OF $\sim$ 1 MPC

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We study dynamics of wide triplets of galaxies and argue that X-ray observations of these systems can provide new direct cosmological constraints by establishing whether ongoing clustering and hierarchical evolution are occurring on the mass scale of $\sim 10^{13}$ $M_\odot$ and space scale $\sim$ 1 Mpc or the systems on these scales are in the virial quasi-equilibrium.

1 Introduction

Current studies of groups of galaxies have bearing upon a number of deep questions in astronomy and cosmology. The formation, structure and dynamics of systems on different mass and spatial scales is one of the most fundamental of them. This issue is closely related to the problem of dark mass in various galaxy aggregates. Alongside with other groups of galaxies, triple systems provide an effective tool for estimation of the amount of dark matter and study of its distribution on intermediate scales between individual galaxies and rich galaxy clusters.

New important data for group and triplet studies can be provided by X-ray observations of these systems. The measurements of the temperature of X-ray gas and the size of the region where the gas is distributed make it possible to estimate the total mass of a group with an estimator which is essentially similar to the virial one, provided the group is in virial equilibrium and the gas component is in thermal and hydrostatic equilibrium in the potential well of the group mass. This way mass estimations for a dozen compact groups were obtained which proves to be $\sim 10^{13}$ $M_\odot$ (Mulchaey 1995, Zabludoff and Mulchaey 1998 and references therein). For compact galaxy groups, the sizes of the volume of X-ray gas are $\simeq 200 - 300$ kpc which is essentially larger that the sizes of the volume within which the galaxy move. The masses of several big groups are also estimated with X-ray data. With the mean harmonic separation in the range $400 - 600h^{-1}$ kpc and rms velocity dispersion in the range 300-450 km/s, both kinematic and X-ray estimates give for them masses in the range $(4-10) \times 10^{13}$ $M_\odot$ (Zabludoff and Mulchaey 1998).

It this work, we report computer simulations which indicate that wide triplets of galaxies are most probably far from virial equilibrium and rather in the state of ongoing collapse. This result can reliably be verified with special X-ray observations of these objects; the observations can provide new direct cosmological constraints by establishing whether ongoing clustering and hierarchical evolution are occurring on the mass scale of $\sim 10^{13}$ $M_\odot$ and space scale $\sim$ 1 Mpc or the systems on these scales are in the state of quasi-stationary virial equilibrium.

2 Basic optical data

A list of wide triple systems of galaxies was compiled by Trofimov and Chernin (1995) with the use of the data from the catalogues by Geller and Huchra (1983) (the Northern sky) and Maia *et al.* (1989) (the Southern sky). The list contains 108 systems; 38 of them can be considered isolated physical systems, according to a general criterion suggested by Anosova (1988).

The major statistical (median) characteristics of 38 physical systems are as follows: the projected rms velocity dispersion $V = 84$ km/s, projected mean harmonic separation $R = 556h^{-1}$ kpc, dimensionless crossing time $\tau = 0.95$, virial mass $M_{vir} = 1.5 \times 10^{12} h^{-1}$ $M_\odot$, if the later is calculated with the use of a 'standard' estimator (Binney and Tremaine 1987). The Hubble constant is normalized here to 75 km/s/Mpc.

We call the systems *wide* triplets, in contrast to *compact* triplets of galaxies with $R = 43$ kpc, studied in detail by Karachentseva *et al.* (1979) and Karachentsev *et al.* (1989). The compact and wide triplets differ from each other in a number of ways. Most obvious is the difference in size – more than an order of magnitude. The sizes of compact systems are so small that they are comparable to or likely less than the radii of extended dark matter halos around typical giant galaxies. On the contrary, in wide triplets, the separations between the member galaxies are considerably larger than the radii of the typical galaxy haloes; it means in particular that three-body treatment is adequate for these systems, at least in the first approximation - see Sec.3.

The dimensionless crossing time is a decade less than unity for the compact systems, while it about unity for the wide ones. The galaxies in compact triplets have made several crossings during their life-time, and this might be enough to reach virial equilibrium in the systems and their ensemble. In contrast to this, $\tau \sim 1$ for wide triplet ensemble, which means that the systems are dynamically young and far from virialized state. Most probably, wide triplets are in the state of ongoing collapse and clustering. An analysis of the dynamical and evolutionary state of wide triplets was first made by Dolgachev and Chernin (1997).

3 Computer simulations

Here we present new recent results of computer simulations of the systems based on an assumption that the member galaxies of the systems were at rest some 12 ± 2 Gyr ago. This is essentially the same physical conjecture as that of the model by Kahn and Voltjer (1959) for the Local Group. In the Kahn-Voltjer model, there was a moment in the past, 10-20 Gyr ago, when the centers of masses of two major galaxies of the Local Group were at rest after an earlier stage when the masses moved apart due to the whole Hubble expansion; since that moment, the galaxies move towards each other under the action of their mutual gravity. (The models with zero initial velocities are usually called free-fall models.) We also assume that the free-fall of galaxies in wide triplets can be treated as the motion of point masses (see above), and we take equal masses of the bodies in each system, for simplicity. A soften-potential code was used which is similar to one worked out by Aarseth (1971).

About 6 000 simulated dynamical states have been computed for various total masses M of the systems and their initial size L. Among them, 1 320 states with $M = 9 \times 10^{12}$ $M_\odot$ and $R_0 = 1.4 - 3$ Mpc have been found to reproduce the observational data most closely. They were used for statistical analysis, and, with a random number generator, 10 samples were produced with 50 states in each selected from this variety of states. It proves that the difference between the observed figures of V, R, τ and the dynamical characteristics given by the computer statistics does not exceed 10-20 %. This is a reasonable accuracy, given usual observational errors, especially in the velocity measurements for galaxies in the groups (see the catalogues by Geller and Huchra (1983) and Maia *et al.* 1989).

Not only median values of V, R and τ, but also the distributions of these quantities in the computer statistics demonstrate a rather high degree of similarity with the observed distributions (more details see in Chernin *et al.* 2000).

4 Results

Our analysis of the observational data, as well as our computer simulations, demonstrate clearly that wide triplets of galaxies present a special class of systems which are in the state of ongoing collapse and clustering. Many (if not all) bright galaxies of wide triplets must have smaller satellite galaxies, so that their collapse is actually collapse of subgroups. This way, wide triplets provide new direct cosmological constraints by establishing that hierarchical evolution is occurring on the space scale of ~ 1 Mpc.

The typical mass of a wide triplet estimated statistically on the basis of the simulations is $M \sim 10^{13}$ $M_\odot$. It is an order of magnitude larger than the virial mass estimated for these systems with the use of a 'standard' formula (Sec.2). This is a direct quantitative evidence that wide triplets are very far from virial equilibrium.

The mass of a typical wide triplet is about 3 times larger than the mass of the Local Group as estimated by the Kahn-Voltjer model. It indicates that three-body dynamics can 'hide' a larger mass than two-body dynamics behind similar visible sizes and velocities.

The mass of a typical wide triplet proves to be close to the total mass obtained for a dozen small compact groups with the use of X-ray data (Mulchaey 1995). It is essential that the compact groups are assumed to be in virial and thermal equilibrium (Mulchaey 1995), and so they are rather similar to compact triplets. Because of this one can expect that the total mass of a compact triplet (including their extended halo) is also $\sim 10^{13}$ $M_\odot$. If so, in both wide and compact triplets, the major contribution to the total mass is obviously due to dark matter. The corresponding mass-to-light ratio can be estimated as $(M/L) \approx (150 - 200)h \times (M_\odot/L_\odot)$. This figure indicates that dark matter mass is 15-30 times the mass of baryonic matter in the triplets of both types.

The comparison of wide triplets and compact triplets reveals that the group evolution on a given mass scale may proceed in various ways depending on the initial conditions. Compact systems like compact triplets evolved rapidly, and this might be possible only, if the initial (at the moment of the start of collapse) dark matter density was high enough. Slow evolution of wide systems was determined by relatively low initial density. It means that the cosmological density contrast might be essentially different on a given mass scale, depending, perhaps, on the location of the systems. Most probably, wide systems form in the outer areas of clusters and superclusters, while the compact ones form in their inner areas.

Though the free-fall models we have developed simulate the observed data on wide triple systems with reasonable accuracy, a question arises: Is this type of models the only possible? A drastic challenge to the free-fall models is presented by a sophisticated theory developed recently for the Local Group as an alternative to the Kahn-Voltjer model. Valtonen *et al.* (1993, 1995) and Byrd *et al.* (1994) argued that the pre-history of the Local Group might be full of violent events, including close passings, collisions and even merging of galaxies. It is also important that all this complex evolution does not need any considerable mass excess in the volume of the group. May an adaptation of this approach to wide triplets give rise to results that will be very different from what was discussed above? Were close passings, collisions and merging of galaxies possible in the early evolution of these systems? How frequently might they occur? Can any signs of these violent processes be found in observations? These questions remain open.

5 X-ray observations: a critical test

A critical observational test for the models developed above can be provided by special X-ray observations of wide triplets. The instruments (like ROSAT PSPC or XMM-NEWTON and CHANDRA) with a low energy coverage (0.1 - 3 keV), large field of view and high spatial resolution and sensitivity would be most suitable to study the low surface brightness diffuse gas in the triplets of galaxies.

In the free-fall models for wide triplets, member galaxies of these systems are treated as having individual dark matter haloes which have masses $(2-3) \times 10^{12} \mathrm{M}_{\odot}$ and sizes 100-300 kpc. Hot X-ray emitting gas is expected to be confined in these individual haloes, rather than in the volume of the triple system as a whole. The probable assumption is that the gas is trapped in the potential well of the haloes and is in the state of rough thermodynamic and hydrostatic equilibrium with isothermal temperature. Making this assumption, one may estimate the expected temperature of the X-ray gas with a relation (see, for instance, Mulchaey 1995)

$$T_{keV} \simeq 10^{-11} \alpha (M_i/M_{\odot}) R_{kpc}^{-1}, \tag{1}$$

where T_{keV} is the X-ray gas temperature in keV, M_i is the total mass of the galaxy which is mostly due to its dark matter halo, R_{kpc} is the halo radius in kpc; parameter $\alpha \simeq 1 - 0.3$ depends on the mass distribution in the halo and may be obtained form the observed X-ray surface brightness. For $M_i = 3 \times 10^{12} \mathrm{M}_{\odot}$ (see the section above) and $R_{kpc} = 100$, one has $T_{keV} \simeq 0.3 - 0.1$.

This temperature is near the temperature of the X-ray gas in the halos of giant isolated galaxies. The temperature of compact groups is somewhat higher, about 1 keV (Mulchaey 1995). A similar temperature is observed in big groups (Mulchaey and Zabludoff 1998); the X-ray gas temperature is about 10 keV in rich clusters.

According to our models, the X-ray emission of a typical wide triplet is expected to concentrate to each of the three member galaxies and not, say, to the center of mass of the system as a whole (in contrast, for instance, to a compact group NGC 2300 - see Mulchaey 1995). At a typical distance of 30-60 Mpc, the angular sizes of the halos of member galaxies are $\theta \simeq 20 - 10$ arcminutes.

The expected X-ray brightness of each of individual halos in a typical wide triplet is

$$B_x \simeq 10^{-10} - 10^{-12} \;\; erg s^{-1} cm^{-2}. \tag{2}$$

It may be seen that hot gas of individual halos of member galaxies in free-fall wide triplets needs more than 20-30 Gyr to be stripped and re-distributed in the whole volume of the system and then reach thermal and hydrostatic equilibrium in the process of virialization. In few systems, this process might already start, and so a portion of X-ray emission may be registered which may not be related to individual galaxies of the systems, but rather to the system as a whole. This emission, however, can hardly be in thermal equilibrium with isothermal distribution, and so no definite temperature can be prescribed to the stripped X-ray gas, in this case.

If, on the contrary, X-ray observations will show a significant thermally equilibrium component of the emission from a wide system as a whole, it would mean that dark matter forms a common halo of a wide triplet, rather than individual halos around its member galaxies. In this case, a typical wide triplet would be treated as a system with virialized and steady-state dark matter common halo of about 1 Mpc in size, in which three member galaxies move as almost test particles. The models of this type have also been analyzed (Dolgachev, Domozhilova and Chernin, in preparation); generally, they seem to be less attractive, but, stricktly speaking, they can hardly be completely rejected on the basis of the available kinematic data on the systems. Actually only special X-ray observations of wide triplets can provide the reliable solution of the problem.

The major goal of presenting this paper at the Meeting is to invite attention of the X-ray observers to wide triplets of galaxies. Indeed, X-ray observations of these systems are able to provide new direct cosmological constraints by establishing whether hierarchical evolution is occurring on the mass scale of $\sim 10^{13}$ $M_\odot$ and spatial scale of ~ 1 Mpc via ongoing collapse and clustering or the process of structure formation have already completed on this scale.

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