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Nature and Distribution of Dark matter: 2. Binaries, Groups and Clusters

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Abstract. We study the mass–radius relationship for aggregates of galaxies, viz. binaries, small groups and clusters. The data are subjected to a simple best-fit analysis similar to the one carried out earlier for individual field galaxies. The analysis shows that: (i) The data on binary galaxies are consistent with the assumption that binaries are just two galaxies, each with an individual isothermal ($M \propto R$) dark matter halo, moving under the mutual gravitational attraction, (ii) The data on the groups of galaxies are too scattered to obey a single power-law relation of the form $M = kR^n$ with any degree of reliability, (iii) The data on groups and clusters fit better with a law of the form $M = AR^3 + BR$. This form suggests the existence of two components in dark matter—one which is clustered around the galaxies ($M \propto R$) and another which is distributed smoothly ($M \propto R^3$). The smooth distributions becomes significant only at scales $\geqslant$ 1 Mpc and hence does not affect binaries significantly. We briefly discuss the theoretical implications of this analysis.

Key words: galaxies, dark matter—galaxies, binary—galaxies, clusters

1. Introduction and summary

In a previous paper (Padmanabhan & Vasanthi, 1985; hereafter referred to as Paper 1) we have discussed the constraints on the nature of distribution of dark matter (DM) based on the observations at galactic scales. We extend the analysis to larger structures in this paper.

The main conclusions of Paper 1 were the following: (i) There is evidence indicating individual dark matter haloes around galaxies and dwarf spheroidals with characteristic sizes of ~ 100 kpc and ~ 10 kpc respectively, (ii) Within a scale of about 100 kpc, there is no significant contribution from any smooth, constant density component of dark matter. (Dark matter which is attached to the galaxy as an isothermal halo will give rise to an $M \propto R^3$. AS shown in Paper 1, field galaxies showed a dominant $M \propto R$ behaviour). We concluded that 'hot' DM can at best be only marginally consistent with such a scenario. Thus we obtain some handle on the nature of the dark matter from kinematic considerations alone.

These conclusions lead us to ask: What kind of DM distribution is to be expected at larger scales?

If galaxies are the primary carriers of dark matter haloes then we expect the larger structures (binaries, groups and clusters) to obey the $M \propto R$ relation curve. On the other hand, if the universe contains a low-density, smooth, dark-matter distribution which is uniform at scales larger than 100 kpc, then we would expect an $M \propto R^3$ behaviour superimposed upon the $M \propto R$. In general, thus one may expect a behaviour of the form

$$M(R) = AR^3 + BR = \frac{4\pi}{3}\rho L^2 R\left[1 + \left(\frac{R}{L}\right)^2\right] \tag{1}$$

where we have defined $(4\pi\rho/3) = A$ and $L = (B/A)^{1/2}$. In the above phenomenological relation the BR term accounts for the mass attached to the individual galaxies in the system and AR^3 term is due to any smooth distribution of dark matter. Such a smooth distribution might be of primordial origin or can even arise from the merging of individual haloes. A previous study of the overall systematics of DM (Cowsik & Vasanthi 1986) does indicate the existence of a smooth component.

In principle we can now study the mass radius (*M–R*) data of multiple galaxy systems (MGS) and try to fit them to a relation of the form of (1). This will allow us to determine *A* and *B*. (The earliest attempt to deduce the nature of dark matter distribution by analysing the *M–R* relation seems to be due to Einasto, Krassik & Sarr, 1974 and Ostriker, Peebles & Yahil, 1974. There has been, however, considerable interest in the determination of (*M/L*) ratios. Detailed references can be found in the recent review by Trimble 1988.)

In practice, however, it is extremely difficult to obtain any firm conclusions in this matter. The *M–R* data for multiple galaxy systems suffer from many observational and theoretical uncertainties (This is in sharp contrast to the *M–R* data of galactic systems). Two main sources of trouble make both *M* and *R* determination difficult: (i) The masses of these systems are usually estimated by virial theorem which is accompanied by the following inaccuracies: (a) The instantaneous values for kinetic and potential energies are substituted for the time-average values, (b) Since only the projected position in the sky and radial components of velocities are measured, we lose information on one component of position and two velocity dimensions, (c) Limitations on observation-time forces one to select a subset of galaxies thereby introducing a bias, (d) Bias also arises from the fact that the brighter galaxies of a group (which are usually measured) also tend to be more massive than others. (ii) The radius *R* of a multiple galaxy system is intrinsically ill-defined. So is the criterion for cluster membership of a particular galaxy. (In addition to the above difficulties, there is also the question of whether virial theorem can really be used for low-density systems like clusters. Most astronomers seem to believe that it can be and we shall proceed with this assumption. It should be noted that we have no other—more reliable—method available for the estimation of total mass of an object like a cluster.)

Comparison with numerical simulations have shown that the above effects can easily lead to an uncertainty by a factor 2 in cluster parameters (see *e.g.* Heisler Tremaine & Bahcall 1985). This fact, coupled to normal random errors of measurement makes it very difficult to draw any firm conclusion.

Any conclusions we draw in this paper, therefore, will reflect the above uncertainties to considerable extent. Even then, we feel it is worthwhile to look at the available *M–R* data for multiple-galaxy-systems and see what conclusions can be arrived at. The basic results which we obtain in this paper may be summarized as follows:

(a) The $M \propto R$ law of field galaxies is obeyed reasonably well by binaries as well. Even the proportionality constant is almost the same for these two (1.86×10^{10} $M_{\odot}\mathrm{kpc}^{-1}$ for binaries compared to 1.4×10^{10} $M_{\odot}\mathrm{kpc}^{-1}$ for single spirals).

(b) At scales larger than about 1 Mpc (*i.e.* for most of the groups and clusters) the data are too scattered to fit meaningfully any single power law in *R*. Assuming a fit of the form in Equation (1) we estimate ρ and L to be $\sim 4.2 \times 10^{-28}$ gcm $^{-3}$ and ~ 3 Mpc respectively.

The details of the analysis are given below. The discussion of results as well as its relevance to a possible theoretical model is presented in section 3. Unless otherwise mentioned, we are using a value 50 kms $^{-1}$ Mpc $^{-1}$ for the Hubble constant.

2. Details of analysis

The first difficulty in performing a detailed analysis lies in the fact that various authors who have catalogued *M–R* values for multiple galactic systems follow different definitions for the basic variables. These inherent differences make it almost impossible to recaliberate all available data as a single set. In order to bypass this difficulty we will use data from single, large, comprehensive collection in each category. We hope that any sufficiently large sample will be representative of any other sample.(All the same, it would be interesting to subject different samples to the analysis presented in this paper and compare the results.Such a comparison is beyond the scope of the present paper; we hope to take up this issue in a future publication.)

The data for binaries and groups is taken from a detailed statistical analysis of groups of galaxies by Press and Davis (1982). The data for clusters is taken from the sample given by Dressier (1978).

Only those systems for which the crossing time is much less than the Hubble time are considered as interacting bound systems in the Press & Davis sample. The mass *M* is determined from virial theorem. The value of *R* is taken to be one-half the mean absolute projected separation of all pairs *i.e.*

$$R = \frac{1}{n(n-1)} \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} l_{ij} \tag{2}$$

Where l_{ij} is the projected separation of a pair indexed by *i* and *j*.

2.1 *Binaries*

The data on 45 binary galaxies with *R* varying from a few tenths of kpc up to a few Mpc and masses spanning three decades ranging from a few times 10^{12} $M_{\odot}$ to nearly 10^{15} $M_{\odot}$ are shown in Fig. 1. A best fit curve of the form

$$\mathrm{Log}\, M = m \log R + \log c \tag{3}$$

was attempted with this data. The best fit value turns out to be

$$m = 0.9, \quad \log c = 1.23. \tag{4}$$

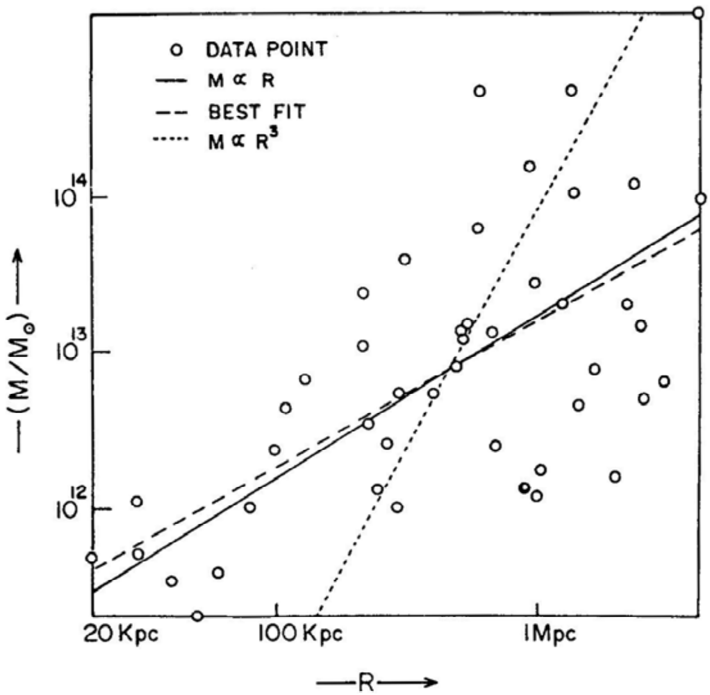

Figure 1. The M–R relation for binaries. Note that the best fit line is very close to the $M \propto R$ line.

The mean square deviation σ^2 for this best fit is 0.435. This suggests that the $M \propto R$ law which was true for individual galaxies (see Paper 1) continues to hold for binaries. (In Paper 1 we had obtained for the field galaxies the following results; The spiral galaxies of the type SAB showed a best fit index m of 1.2 with a σ^2 of 0.024 while that of SA galaxies had a best fit index of 0.82 with a σ^2 of 0.022. The mean square derivations for m = 1 were found to be 0.022 and 0.023 respectively. Our Milky Way showed best fit m = 0.9 with σ^2 of 0.0095. The theoretical $M \propto R$ (*i.e.* $m = 1$) gave a σ^2 of 0.01.) To test this hypothesis further, the mean square deviation, σ^2, was obtained for both $m = 1$ and $m = 3$. The σ^2 for $m = 1$ is 0.44 which is almost same as that for the best fit. On the other hand, for $m = 3$, σ^2 was 2.1, nearly 5 times larger. Clearly the data are much better represented by an isothermal DM halo ($\rho \propto r^{-2}$, $M \propto R$) rather than by a constant density profile ($\rho \sim$ constant, $M \propto R^3$).

The mass-radius relationship corresponding to the best-fit $M \propto R$ curve (shown as continuous line in Fig. 1) is

$$M(R) = 1.86 \times 10^{10}\, M_{\odot} \left(\frac{R}{1\,\mathrm{kpc}}\right) \text{(binaries)} \tag{5}$$

which may be compared with the M–R relation for the spirals derived in I [see (6) and (7) of I]:

$$M(R) = (3\text{–}9) \times 10^{10}\, M_{\odot} \left(\frac{R}{1\,\mathrm{kpc}}\right) \text{(spirals)}\,. \tag{6}$$

One may safely conclude that $M \propto R$ trend continues to be valid for binaries; in other words, most of the DM is still primarily attached to the galaxies.

As an additional check, the combined data of spirals and binaries were subjected to the best fit analysis. We then get

$$M(R) = 1.38 \times 10^{10} M_\odot \left(\frac{R}{1\,\text{kpc}}\right)^{1.13}. \tag{6a}$$

This is shown in Fig. 2. The exponent of R is, as expected, close to unity.

The data are, therefore, consistent with the assumption that the binaries are just two galaxies—each with an individual dark matter halo—moving under the mutual gravitational attraction.

2.2 *Groups and Clusters*

Groups of galaxies, (containing more than five members) do not follow any such simple pattern. The data in Fig. 3 show that the points in M–R plane are much more scattered.

No single power law ($M \propto R^n$) can represent the data well. The best fit value for n was about 1.9 with a σ^2 of 0.38. The σ^2 for $n = 1$ is 0.42 and that for $n = 3$ is 0.44. Since the σ^2 for these values are not significantly different, one cannot say that any single value of n is preferred significantly.

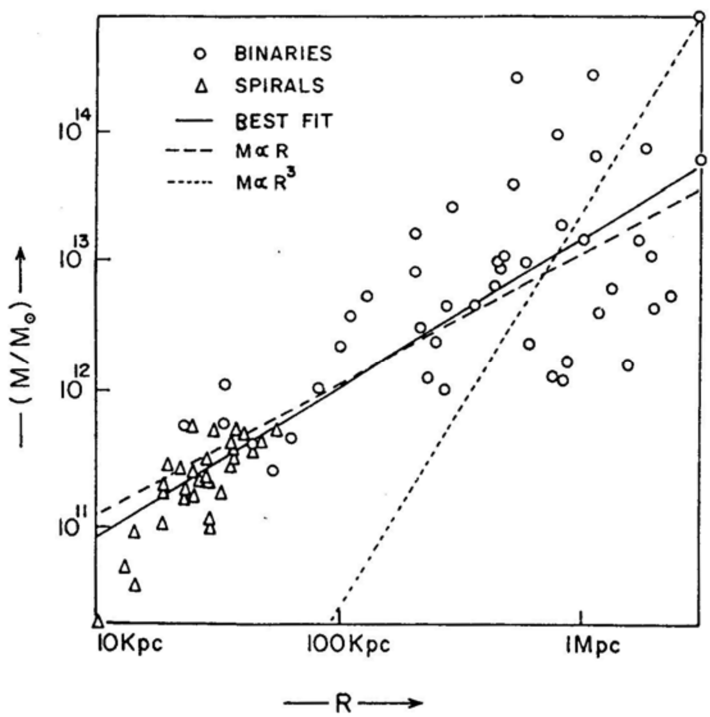

Figure 2. The M-R relation for spirals and binaries put together. The best fit is very close to the $M \propto R$ line.

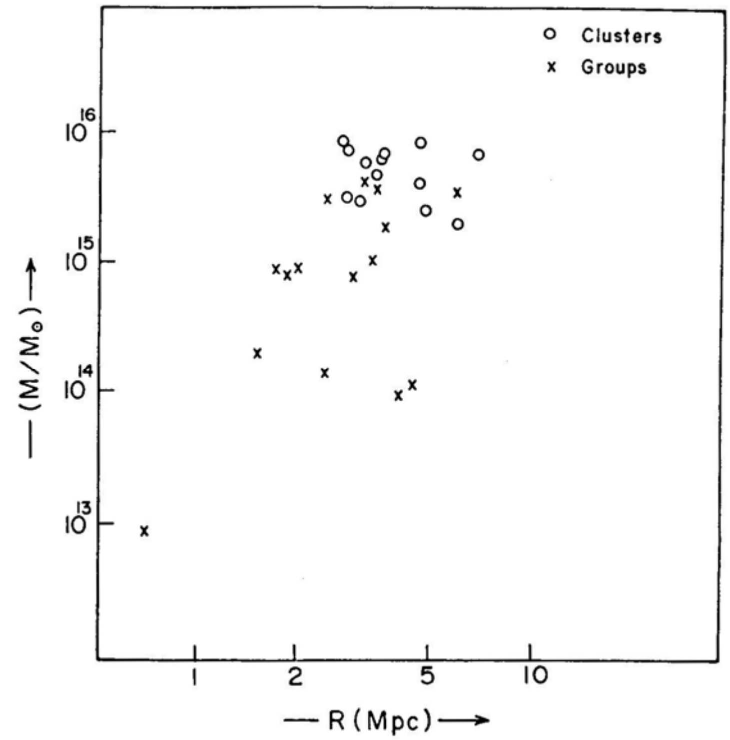

Figure 3. The *M–R* data for clusters. See text for discussion.

The same trend was observed for clusters as well. The σ^2 for best fit was found to be 0.04 which was not different from 0.07 for $m = 1$ and 0.03 for $m = 3$. For combined data (of groups and clusters), the trend was still the same with best fit σ^2 of 0.36 while $m = 1$ and $m = 3$ had σ^2 of 0.39 and 0.4 respectively.

One possible reason for this scatter could be the existence of a second smoother component to DM, which makes significant contribution at large scales. From Paper 1 as well as from Section 2.1 above we know that there exists one DM component attached to the galaxies and obeys $M \propto R$ law. The remaining contribution—if it is due to a smooth distribution—will follow a $M \propto R^3$ law. It is, therefore, reasonable to try to fit the data (of groups and clusters) with the relation of the form

$$M(R) = AR^3 + BR \equiv \frac{4\pi}{3}\rho L^2 R\left[1 + \left(\frac{R}{L}\right)^2\right]. \tag{7}$$

The best fit parameters turn out to be $A = 0.006$ and $B = 0.07$ with a σ^2 of 0.6. (Note that this σ^2 refers to M itself as a variable while the earlier σ^2 was for log M; therefore they should not be compared directly.) For comparison, best fit with $B = 0$ gives σ^2 of 11.5 while the fit with $A = 0$ gives a $\sigma^2 = 6.5$, clearly the σ^2 for Equation (7) is atleast an order of magnitude smaller than that for the cases $A = 0$ and $B = 0$ (corresponding to $M \propto R$ and $M \propto R^3$ behaviour respectively).

We also subjected the combined data of binaries, groups and clusters to the best fit analysis (since a smooth distribution cannot distinguish individual galaxies or galaxy pairs). The σ^2 was 0.4 for the best fit:

$$\frac{M}{(10^{15} M_\odot)} = 0.024\left(\frac{R}{1\,\mathrm{Mpc}}\right)^3 + 0.26\left(\frac{R}{1\,\mathrm{Mpc}}\right) \tag{8}$$

while the σ^2 was 4.42 with the R^3 term alone and 3.2 with the R term alone, showing that the combined data favours significantly a two-component form for the DM profile. (In realistic data with scatter, a two parameter fit will indeed give a somewhat lower σ^2 than a one-parameter fit; however, the difference by an order of magnitude suggests that the effect is not spurious.)

3. Results and discussion

The best-fit values of A and B indicate the following features: (i) The value of B obtained here is close to the one observed for individual galaxies and binaries. Thus our hypothesis that galaxies are the primary carriers of DM is once again verified, (ii) The best-fit values of A and B correspond to the values (from Equations 7 and 8)

$$\rho \simeq 4.2 \times 10^{-28}\,\mathrm{g\,cm^{-3}}, \quad L \simeq 3\,\mathrm{Mpc}\,. \tag{9}$$

Thus the smooth DM component has a density of about 4×10^{-28} g cm^{-3} and makes its presence felt at $R \gtrsim L \simeq$ 1 Mpc.

The data definitely show that binaries follow the $M \propto R$ laws. The rest of the above conclusions can only be taken as tentative. For structures larger than binaries the large scatter and uncertainties in the measurement plague the analysis and we cannot claim anything very definite.

The (suggestive) two-scale distribution of dark matter immediately raises the question regarding the nature of the dark matter candidate. The cold dark matter clusters efficiently at the small scales (see *e.g.* Blumenthal *et al.* 1984) while the hot matter condensates are of the Mpc sizes (see *e.g.* Doroshkevish *et al.* 1981). Thus, the simplest assumption would be that one cold DM (*e.g.* any of the "inos") and one hot DM (*e.g.* neutrino with mass ~ 10eV) candidate are present simultaneously. This assumption, apart from sounding somewhat artificial (requiring two completely independent kind of DM candidates) will lead to a wide latitude in the choice of parameters in a theory of DM distribution.

One way out of this arbitrariness is to invoke an unstable component to the DM. In such a model, an unstable heavy DM particle decays within the lifetime of the universe (in the recent past) but after the galactic scales have started going non-linear. The relics of the decay, when cooled by expansion can provide a smooth distribution at largescales. Various attempts to produce cosmological scenarios with unstable DM have been studied with unstable particle being 'hot' (see *e.g.* Gelmini, Schramm & Valle 1984; Turner, Steigman & Krauss 1984; Davis *et al.* 1981; Dicus, Kolb & Teblitz 1978; Fukugita & Yanagida 1984) as well as 'cold' (Turner, Steigman & Krauss 1984; Turner 1985; Suto, Kodama & Sato 1985; Olive, Sekel & Vishniac 1985).

A detailed model for the dark matter distribution with an unstable neutrino as dark matter candidate has been worked out by the authors (see Padmanabhan & Vasanthi, 1987). In this scenario, an unstable "warm" dark matter candidate—the heavy neutrino, ν_H—with mass of ~ 120eV decays into a "hot" particle (a light stable neutrino ν_L with mass ~ 6 eV) and a relativistic boson. Considerations of theoretical and observational constraints result in a model with following features: (1) Decay of ν_H disrupts the condensates made of primordial ν_L, thus lowering their mass (from the conventional 'hot' DM condensates of ~ $10^{15} M_\odot$) to about ~ $10^{12} M_\odot$. (2) The relativistic boson can contribute a fraction $\Omega_b = 0.25$ to the closure density. The model predicts two prominent scales in dark matter distribution: (a) A mass of ~ $4 \times 10^{12} M_\odot$ around the galaxies distributed over ~ 200kpc and (b) A smoother density of ~ 10^{-27} g cm^{-3} distributed over ~1 Mpc. We see that the features and figures described in this paper are consistent with the above theoretical model.

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