Exploring Properties of Dark and Visible Mass Distribution on Different Scales in the Universe

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In this short note we discuss recent observation of linear correlation on log-log scale between distribution of dark and visible mass in gravitationally bound systems. The coefficient of such correlation appears to be essentially the same for various systems of dramatically different scales such as spiral galaxies of different luminosities and galaxy clusters. We briefly touch possible interpretations of this observation and implications for the mass of dark matter particle.

Presence in the Universe of large amounts of dark (non-luminous) matter has been one of the central puzzles in cosmology since the beginning of last century. Starting from 1920th, it had been observed that Rotation Curves (RC) in spiral galaxies measured up to twice the extent of the galaxy stellar disk show yet no Keplerian fall-off. These observations provided first indications that spiral galaxies are submerged into vast, isothermal, almost spherical dark halos. More insight had been obtained in the recent years using phenomenon of gravitational lensing which spectacularly showed presence of huge amounts of nonluminous matter in the galaxy clusters. These days, thanks to extensive observations and computer simulations, we gained a better understanding of dark matter and its role in the Universe evolution. Given observed smoothness of dark mass distribution, large mass-to-light ratio and failure of earth-based experiments to get reliable dark-matter events, it is believed that dark matter is made of nonbaryonic heavy weakly interacting particles. A number of candidates in various extensions of the Standard Model had been put forward but any of them are yet to be confirmed in experiments. Recently an interesting property of dark and visible mass distribution in gravitationally bound systems has been pointed out, which may be ultimately related to microscopic properties of dark matter. Specifically, based on the study of rotation curves in a large sample of spiral galaxies by Persic, Salucci and Stel [1] and the analysis of mass distribution in galaxy cluster CL0024 by Tyson, Kochanski and Del'Antonio [2], we observed that the distribution of dark and visible mass in these systems is well consistent with linearly correlated on log-log scale with what appears to be a universal correlation coefficient $\kappa \approx 3.5 \pm 1.5$ [3].

In 1998, Tyson *et al* [2] carried out analysis of the Hubble Space Telescope images of strong gravitational lensing in galaxy cluster CL0024+1654. This cluster is one of the examples of strong gravitational lensing in which a number of images of a background galaxy with distinctive color is formed. Detailed distribution of

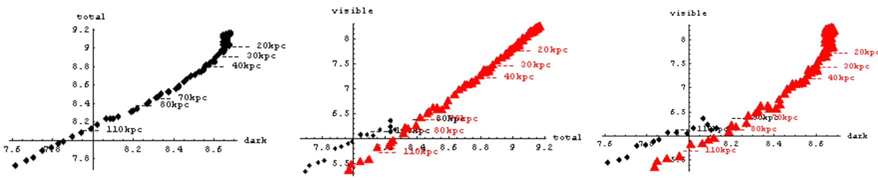

Fig. 1.

mass and azimuth-averaged distributions of total and visible mass in the cluster had been obtained. The primary conclusion of this study was the failure of Cold Dark Matter simulations in description of the observed flat-core mass profile. We have reexamined the mass profiles presented in [2] with the emphasis of search for relations between dark and visible components and observed that if any two mass profiles are plotted one vs another on log-log scale the data points form a straight line. Deviations from this linear correlation are only observed in small region in the center of the cluster. As is shown in Figs.(1a), e.g., very good linear correlation is present between log of total and log of dark mass distributions with correlation coefficient of about $\kappa_{td} \approx 1.15 - 1.9$ for a region of well over 100kpc. The same effect is observed for any two profiles in the data, as can be seen in Fig.(1b) and (1c). The correlation coefficients in these cases were found to be for visible-total mass $\kappa_{vt} \approx 1.4 - 2.25$ and for visible-dark mass $\kappa_{vd} \approx 2.10 - 4.40$. Such feature in the galaxy cluster CL0024 is rather interesting and may indicate approximate large scale thermal equilibrium in both visible and dark components in the cluster. In that case,

$$\ln \rho_v = \frac{\mu_v}{T_v}\Phi \sim \ln \rho_d = \frac{\mu_d}{T_d}\Phi. \tag{1}$$

Still, to make this result more significant we would like to see more examples of this behavior in other systems. While we do not know of comparable studies of galaxy clusters, we note that there is yet another observable heavily affected by the presence of dark matter, i.e. RC in spiral galaxies.

In Persic *et al* analysis [1] of a sample of over 1000 spiral galaxies had shown that RCs grouped by galaxy luminosity and normalized to dimensionless units via optical radius r_{opt} (i.e. extent of the stellar disk) and rotation velocity at the optical radius v_{opt} follow universal profiles called by the authors Universal Rotation Curves (URCs). In [1], URCs had been fit using simple mass model to within their rms. In this fit the stellar disk is described as a thin disk with the surface mass density $\rho_v(r) \sim exp(-3.2r/r_{opt})$. This can be motivated with the notion that visible mass distribution should follow the surface brightness in the stellar disk which decays exponentially as is well known from the stellar-disk photometry. The gravitational potential from exponentially thin disk is known and contribution from visible mass into RC v_v^2 in this model can be obtained analytically. In [1], this distribution was modeled for convenience with a good analytical fit within few percents. The contribution from the dark halo was parametrized in the form

$$v_d^2 \approx (1-\beta)(1+\alpha^2)\frac{x^2}{x^2+\alpha^2}. \tag{2}$$

Here α and β are the fit parameters describing extent and amount of the dark halo in the galaxy. RC is described in this way as $v_{URC}^2 = v_v^2 + v_d^2$.

Guided by the idea of log-log-linear correlation, we investigated the question if URCs can be reproduced and to what accuracy with the dark mass distribution

$$\rho_d \sim \exp(-ar/r_{opt}). \tag{3}$$

For all absolute luminosities that Persic *et al* applied their model (i.e. $-23 < M < -19$) we found that a perfect fit can be obtained to the URC with spherical dark halo distributed according to Eq.(3). The best fit coefficient a varies quite moderately with galaxy luminosity M and is in the range of $\kappa_{vd} \approx 2.5 - 4.11$.

The coincidence of this estimate with $\kappa_{vd} \approx 2.1 - 4.4$ in CL0024 is striking. Log-log-linear correlation, thus, may be seen as an indication of approximate large scale thermal equilibrium in visible and dark components: $\kappa \approx T_d/T_v \cdot \mu_v/\mu_d$. $\kappa_{vd} \approx const \approx 3$ can be understood as $T_v/T_d \approx 1$ so that $\kappa_{vd} \approx \mu_v/\mu_d$ and $\mu_d \approx 200 - 1000 MeV$. While these phenomenological conclusions are quite coherent, it is hard to understand how such thermal equilibrium can be reached given our current views about dark matter. One may note that spiral galaxy is not a virialized object, unlike galaxy cluster. Thus, significance and existence of such correlation can not be easily understood. Also, one would not expect κ_{vd} to be the same in different systems. More reasonable expectations would be either $\kappa \approx 1$ in galaxy clusters (primarily due to gravitational heating in which case $T_{v,d} \approx \mu_{v,d}\Delta\Phi$ and $\kappa \approx 1$) or $\kappa >> 1$ in spiral galaxies (cooling of visible component is strong while dark matter is noninteracting and nondissipative). In this respect, examining alternative interpretations of the log-log-linear correlation is important. Among such alternatives is some unknown underlying feature of structure formation, thermalization due to purely gravitational interaction, or even relations of dark matter to QCD condensates due to $\mu_d \approx \Lambda_{QCD}$. Finally, given a large number of uncertainties in any astrophysical study of this sort, e.g. visible-dark separation in RC or uncertainties in inferring visible matter amount, a larger number of observations of log-log-linear correlation is desirable. In this sense a large survey of gravitational lensing in galaxy clusters with emphasis on dark vs. visible matter distribution would be most beneficial.

References

1. M. Persic, P. Salucci and F. Stel, F.Stel: MNRAS, **281**, 27 (1996).
2. J. A. Tyson, G. P. Kochanski, I. P. Dell'Antonio, astro-ph/9801193 (1998).
3. Y. Mishchenko and C.-R. Ji, Phys. Rev. D**68**, 063503 (2003); astro-ph/0406563 (2004).