BARYONIC CONTENT OF GALACTIC HALOS AND CONSTRAINTS ON MODELS FOR STRUCTURE FORMATION

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The recent detection of microlensing of stars of LMC by compact objects in the halo of our galaxy[1−2] suggests that our galaxy is surrounded by a non-luminous halo made of compact objects with mass of about $(0.03-0.5)M_\odot$. The rate of detection could be consistent[3−4] with the assumption that these halo objects are distributed with a softened isothermal profile with a core radius of $(2-8)$Kpc and asymptotic circular velocity of $220\mathrm{km\,s}^{-1}$. Taken in isolation, this observation is consistent with a universe having only baryonic dark matter (BDM, hereafter) contributing $\Omega_b = \Omega_{total} \simeq 0.06$. Such a model, however, will violently contradict several other large scale observations, notably the COBE-DMR results. The simplest way to reconcile the microlensing observations with such constraints is to assume that galaxies like ours are surrounded by both BDM and non-baryonic dark matter (NBDM, hereafter). A model with a single component for NBDM with, say, $\Omega_b \simeq 0.06, \Omega_{cdm} \simeq 0.94$, is also ruled out if we demand that: (i) at least thirty percent of the dark matter density within 100 kpc is baryonic and (ii) galactic structures should have collapsed by redshift of $z = 1$. If further microlensing observations suggest that half or more of the dark matter within 100 kpc is baryonic, then we are led to the powerful constraint that the maximum value of Ω_{dm}, contributed by NBDM clustered at galactic scales, is about $\Omega_{max} \simeq 0.29$. Hence if we demand that $\Omega_{tot} = 1$, then about 70 percent of dark matter must be distributed smoothly over galactic scales. Models with C+HDM cannot satisfy this constraint but Λ+CDM models are still viable. Even in such a hy-hybrid model it is not clear

*The ordering of the names of the authors was determined by tossing a coin, which is a somewhat simpler procedure than reading T.S.Eliot's poems whether one can consistently explain the abundance of quasars and absorption systems.

Several experiments are underway at present[5] to detect microlensing of stars in the Large Magellanic Cloud by compact objects (MACHOs) which could exist in the dark halo of our galaxy. If this dark halo is modelled as softened isothermal sphere made of MACHOs, with a core radius of $(2-8)$ kpc and a rotation velocity of 220km s^{-1}, then the expected optical depth to microlensing is[3-4] about 5×10^{-7}. Recently 3 such possible microlensing events have been reported[1-2] which could be consistent with this optical depth. The time scale of the flux variation of the background stars indicates a MACHO mass in the range $(0.03-0.5)M_\odot$. This observation, taken in isolation, is consistent with a universe having only baryonic dark matter with $\Omega_b \simeq 0.06$ - a value which will also satisfy the bounds from primordial nucleosynthesis if $h=0.5$. However, a model with $\Omega_{total} = \Omega_b = 0.06$ will produce too large[6] a microwave anisotropy to be consistent with COBE-DMR observations. (Adiabatic fluctuations will be worse than isocurvature perturbations in this regard but both will be ruled out). Such a model will also have difficulty in explaining several other large scale observations and the virial mass estimates of clusters.

One is, therefore, led to study models in which galctic halos contain both baryonic and non-baryonic dark matter. Let us consider the simplest of such models in which BDM and cold dark matter (CDM) halos around a galaxy are described by the density profiles

$$\rho_{bdm} = \frac{\rho_b}{1+(r/r_b)^2}; \quad \rho_{cdm} = \frac{\rho_c}{1+(r/r_c)^2} \tag{1}$$

We shall take a baryonic core radius of $r_b = 2$ kpc, but keep the other parameters unspecified at this stage. The square of the rotational velocity $u^2(r) = u_c^2(r) + u_b^2(r)$ at any radius is the sum of the contributions from CDM and BDM with, for example,

$$u_b^2(r) = v_b^2 \left[1 - \frac{tan^{-1}(r/r_b)}{(r/r_b)}\right] \tag{2}$$

where $v_b^2 = 4\pi G\rho_b r_b^2$ and with a similar expression for $u_c^2(r)$. We shall define a parameter λ by $v_b = 220\lambda$km s^{-1} so that λ^2 represents the baryonic contribution to density asymptotically. The mass of the BDM within 100 kpc can be easily found by integrating (1) and we get $M_{bdm}(100kpc) \simeq \lambda^2 \times 10^{12} M_\odot$. If we take the CDM halo attched to the galaxy to be μ times more massive, we find the CDM contribution to halo mass to be $M_{cdm} = \mu\lambda^2 \times 10^{12} M_\odot$. If such a halo has collapsed and virialised by a redshift z, then we can relate the z, M_{cdm} and v_c using the spherical top hat model. This relation[7] gives

$$v_c = 81.65 \text{km s}^{-1} (1+z)^{1/2} \lambda^{2/3} \mu^{1/3} \tag{3}$$

Asymtotically, we need to obtain a flat rotation velocity of 220km s^{-1} for our galaxy[8]. Using (3) and setting $v_b = 220\lambda$km s^{-1} in the relation $v^2 = v_c^2 + v_b^2 = (220\text{km s}^{-1})^2$ at large r, we get $\lambda^2 + 0.138\lambda^{4/3}\mu^{2/3}(1+z) = 1$ or, equivalently,

$$\mu = 19.5 \frac{(1-\lambda^2)^{3/2}}{\lambda^2(1+z)^{3/2}} \tag{4}$$

This condition relates $\mu = (M_{cdm}/M_{bdm})$ to the redshift of formation (z) and the contribution of BDM to rotation velocity (λ). The limit $\lambda = 1$ corresponds to a purely BDM model with $\mu = 0$. We are interested in a model with $\Omega_{tot} = 1, \Omega_B \simeq 0.06, \Omega_{cdm} \simeq 0.94$ for which $\mu = \Omega_{cdm}/\Omega_{bdm} = 0.94/0.06 = 15.67$. Even if we assume that as much as half the mass within 100 kpc is nonbaryonic (so that $\lambda^2 = 0.5$), we only get $\mu = 13.8$ for $z = 0$ and $\mu = 4.88$ for $z = 1$. One has to lower the value of λ^2 to about 0.273 to get $\mu = 15.67$ for $z = 1$. In other words, this model can be ruled out if more than about 27 percent of the dark matter within 100 kpc is in baryonic MACHOs.

The precise bound on the amount of NBDM that can exist within 100 kpc depends on the detailed statitics of the microlensing events and as the statistics improves, we will have tighter bounds on nonbaryonic contribution. (that is, the minimum allowed value for λ will increase). We have also tried to see whether it is possible to accommodate CDM and BDM by increasing r_c and decreasing ρ_c. We find that it is not possible to have flat rotation curve with the correct asymptotic value (since for large r_c, CDM contributes a $u_c(r) \propto r$) for any combination of parameters which satisfy the other constraints. It seems that the simplest model with both CDM and BDM coexisting in the halo is ruled out if: (a) at least half the dark matter within 100kpc is contributed by BDM and (b) galactic halos have collapsed at least by the redshift of $z = 1$.

If the second condition is relaxed, one can marginally satisfy the first condition with $\lambda^2 = 0.48$. Such a model still faces other difficulties. In such a scenario each galaxy is associated with $M_{bdm} \simeq 4.8 \times 10^{11} M_\odot$ and $M_{cdm} \simeq 7.2 \times 10^{12} M_\odot$ which is about an order of magnitude higher than the conventional masses associated with galxies. Correspondingly, the masses associated with clusters will be one order of magnitude higher. Clusters will therefore contribute an amount $\Omega_{clus} \simeq 0.09(M_{clus}/5 \times 10^{15} h^{-1} M_\odot)$ to the closure density. From the Press-Schecter analysis[9-10], one can relate the linear density contrast $\sigma(M)$ at M to the fractional contribution to the density, $\Omega(M)$, from masses higher than M at a redshift z. The relation is

$$\Omega(M) = erfc\left[\frac{\delta_c(1+z)}{\sqrt{2}\Delta(M)}\right] \tag{5}$$

where $\delta_c = 1.68$ and $erfc(x)$ is the complementary error function. To get $\Omega = 0.09$ at $z = 0$ at cluster scales we need $\Delta(M_{clus}) \simeq 1$. This condition is difficult to achieve in standard models without making the slope of galaxy-galaxy correlation function too high.

These difficulties are independent of the processes[11-12] which may have led to the formation of baryonic compact objects in our halo. Of course, astrophysical considerations regarding the formation of brown dwarfs etc. will impose other constraints on these models. However, the arguments given above appear to be more robust and free from astrophysical uncertainties.

If one insists that $\Omega_{tot} = 1$ and $\Omega_b = 0.06$, then it seems necessary to distribute the NBDM in two components, one clustered at galactic scales and another which has a smoother distribution. Assuming that at least half the matter within 100kpc is baryonic(i.e, $\lambda^2 = 0.5$) and that galactic structures have collapsed by $z = 1$, we find from (4) that $\mu = 4.88$. Since the maximum value for Ω_b permitted by nucleosynthesis is about 0.06, we conclude that the clustered non-baryonic mass in galactic scales can only be $\Omega_{max} = \mu\Omega_{bmax} \simeq 0.29$. Thus if we want a flat universe, nearly 70 percent of the dark matter must be unclustered. Two component dark matter models with C+HDM or Λ+CDM were extensively investigated recently[13−17] since they were in better agreement with large scale observations and COBE. Of these, H+CDM models have[16] $\Omega_{cdm} \simeq 0.7$ and are not compatible with our constraints. The Λ+CDM models can be made marginally consistent[17] with $\Omega_{cdm} \simeq (0.2 - 0.3)$ and could be viable. This model needs to be studied more carefully especialy as regards abundance of quasars and absorption systems.[18] Even this model will be ruled out if the improved analysis of lensing events shows that significant fraction of halo dark matter is baryonic.

We have assumed throughout the discussion that machos are made of baryons. If they are condensates of more exotic elementary particles or primordial blackholes, then it is possible that MACHOs can mimic some properties of CDM and the conclusions could be different. However, the mass scale of $0.1 M_{\odot}$ enters the hubble radius when $T \simeq 1.1 MeV$. Since no unusal physics seem to occur at this energy, it seems somewhat unlikely that exotic objects with this mass scale can be formed with sufficient abundance to provide closure density.

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