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UNSTABLE DARK MATTER AND GALAXY FORMATION*

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INTRODUCTION

Inflation has become a very attractive cosmological model because it can naturally resolve major cosmological puzzles that the standard Big Bang Cosmology leaves unanswered, such as the flatness, isotropy and homogeneity of the Universe and the origin of density perturbations; inflation naturally produces the scale-invariant, Harrison-Zeldovich spectrum of density perturbations as well. Because of the tremendous expansion that the Universe undergoes at very early times in the inflationary scenario, it is predicted to be extremely flat at present; if the cosmological constant vanishes, this implies that the mean energy density of the Universe ρ , in units of the critical density ρ_c , is $\Omega \equiv \rho/\rho_c = 1$ to a very high accuracy. Observations, on the hand, indicate that the clustered matter (including dark matter) on scales of up to a few megaparsecs amounts only to $\Omega_d = 0.1 - 0.3$ [1,2]. Several solutions to this puzzle have been proposed, such as a relic cosmological constant Λ [3] such that $\Omega + \Lambda/8\pi G\rho_c = 1$, or "biased" galaxy formation [4], in which it is postulated that galaxies are rare events, resulting only from large fluctuations of the density field —thus they would not be good tracers of mass in the Universe.

Here we consider another solution [5-7], which postulates that the non-radiative decay of a heavy elementary particle species, after it has driven the formation of galaxies and clusters, provides a smooth, undetected background of relativistic particles that at present contribute Ω_r to the total energy density of the Universe. In the original model [5,6] ("type I" models) the non-relativistic matter contributes $\Omega_m = \Omega_d$ to the total energy density and $\Omega_r = 1 - \Omega_m \sim 0.8$. Another possibility is that the Universe becomes dominated by a primordial, stable non-relativistic dark matter (DM) species after decay of the unstable species [8]; in these models ("type II") the decay of a heavy species unbinds large quantities of a primordial, stable light species causing it to stream away from clusters and larger structures, thus providing a smooth background of non-relativistic DM. Here $\Omega_d \sim 0.2$ reflects only the component of the DM that remains clustered on small scales, while the true Ω_m is ~ 0.8 .

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The redshift corresponding to the epoch of decay, z_d , is constrained by several astrophysical considerations. The isotropy of the microwave background requires that the decay happen sufficiently late, $1 + z_d \lesssim 5$ [9-11], because fluctuations can only grow until the epoch of decay in type I models. Also, $1 + z_d \lesssim 5$, for the cores of rich clusters to remain in virial equilibrium [12]; if the decay occurs on a time scale shorter than the dynamical time, a cluster would become unbound after loosing $\sim 50\%$ of its mass. A similar upper bound is implied if normal galaxies are assumed to be the source of gravitational lensing [13]. On the other hand, the decay must happen sufficiently early for our infall velocity towards the Virgo cluster not to be too large. A linear theory analysis implies $1 + z_d \gtrsim 20$ for type I models [12], but this bound is exponentially sensitive to uncertainties in the observational parameters and is affected by the non-sphericity [14] and non-linearity [15] of the infall, so a value as low as $1 + z_d \sim 5$ is not excluded. The large streaming velocities that seem to exist on large scales and the reported large amplitude of the rich-cluster correlation function would rule out type I models (see the article by BOND in this volume) as well as any cold- or hot-DM model of formation of structure in the universe. These observations, however, remain controversial (see the article by GUNN in this volume).

We discuss here the constraints imposed on cosmologies with unstable DM by the observed rotation curves of spiral galaxies [16] if galaxies are assumed to have formed via dissipative collapse inside a gravitationally induced protogalaxy consisting of a homogeneous mixture of dissipationless DM and a small fraction of baryonic material [17]. We discuss first a simple analytic model based on adiabatic invariants; one finds that the calculated rotation curves are sharply peaked if the fraction of stable DM is very small. Numerical models are discussed next: they relax many of the assumptions made in the analytic model, but they are still limited by numerical effects in the very inner parts of the galaxies; it is found that the analytic model works fairly well. The analytic model is then used to compute rotation curves, which are compared with the observational rotation curves of spirals; agreement is found only if at least 50% of the DM is stable. Finally, we

discuss the implications of this constraint for both type I and type II models and summarize the conclusions.

ANALYTIC MODEL

Consider a spherically symmetric protogalaxy of radius R that consists initially of a mass fraction F_i of baryons and $1 - F_i$ of DM particles that are well mixed initially (i.e. their density ratio is F_i throughout the protogalaxy). This is a rough approximation to the final shape of an expanding protogalaxy which will cut itself out of the general expansion with some characteristic size, although there is no reason to expect it to be exactly spherical. Two processes change the amount of mass inside a given radius: baryonic infall due to dissipation and mass loss due to DM decay. The astrophysical constraints discussed above imply that the DM must decay on a time scale $\tau \gtrsim 10^9$ years, and since the mass fraction in baryons at the present must be small [1], a DM particle's orbit about the protogalaxy is expected to change adiabatically during dissipation and decay. This allows one to calculate the effect of these processes on a galaxy halo with a simple analytic model [16].

For particles moving in circular orbits about a spherically symmetric mass distribution, $rM(r)$ is an adiabatic invariant provided that $M(r)$, the mass inside the orbital radius r , changes slowly with time (see the article by BLUMENTHAL in this volume, and references therein). For purely radial orbits, $r_{\max}M(r_{\max})$ is an adiabatic invariant as well, provided that $M(r)$ varies in a self-similar fashion. Since there is more phase space available for nearly circular orbits than for nearly radial orbits, we shall make the simplifying assumption that the orbits of DM particles are circular.

As the baryons cool, they fall into the center to a final mass distribution $M_b(r)$ which, in the case of a spiral galaxy, is constrained by the initial angular momentum (it will be assumed that no baryons fall inside R from beyond R). After the DM decay is complete, the baryonic mass fraction is $F \equiv M_b/M_f$, where M_f is the final total mass and M_b is the total mass in baryons. Since F must be small [1], $F_i \ll 1$, and the mass interior to a DM

particle's orbit will not show a large fractional change during one orbital period even if dissipation occurs rapidly, provided the particle is far enough from the galaxy center. This assures that the orbits of all but the innermost halo particles change adiabatically under baryonic infall. There is always some inner region of the halo that changes adiabatically under DM decay as well, since the mass inside the orbit of a halo particle with orbital time $t_{orb} \ll \tau$ changes slowly. For τ much longer than the system's dynamical time, t_{dyn} , the orbits of all (except, perhaps, the outermost) halo particles change adiabatically. Thus, after dissipation and decay are complete, a halo particle initially at radius r_i is at radius r , such that $rM(r) = \text{const.}$:

$$r [M_b(r) + M_{DM}(r)] = r_i M_i(r_i). \quad (1)$$

If shells of DM do not cross each other, $M_{DM}(r) = f(1 - F_i)M_i(r_i)$, where f is the mass fraction of stable DM. Thus (1) can be used to find the DM mass distribution $M_{DM}(r)$ once the initial distribution of total mass $M_i(r_i)$ and the final baryon mass distribution $M_b(r)$ are given. The initial mass distribution $M_i(r_i)$ must be an equilibrium configuration and will be taken to be that of an isothermal sphere with core radius $a \equiv 3v^2/4\pi G\rho_o$, where v is the one-dimensional velocity dispersion and ρ_o is the central density. The final radial mass distribution of the baryons is assumed to be $M_b(r) = M_b (1 - (1 + r/b)\exp(-r/b))$, which describes the mass distribution of a thin disk whose surface density falls off exponentially with scale length b . (When using (1) the baryonic mass is actually treated as if it were distributed spherically rather than in a disk. See second ref. of [17].)

Figure 1 shows rotation curves resulting from dissipation and decay within an initial isothermal sphere whose core radius is 42% of R . The two solid lines are the rotation curves for two values of f , and typical values of F and the collapse factor b/R . The ratio b/R is constrained by the initial angular momentum. Theoretical analysis and N-body simulations of the tidal torque theory of angular momentum estimate the mean value of the spin parameter $\lambda \equiv J|E_i|^{1/2}/GM_i^{5/2}$ to be 0.07 [18]; here J , E_i and M_i are respectively

the total angular momentum, energy and mass of a system (for reference, a rotationally supported sphere has $\lambda \sim 0.25$, and a uniform density disk $\lambda \sim 0.5$). Unlike F , which is assumed to be a spatial constant (as expected if most of the DM is non-baryonic), λ varies among protogalaxies with a dispersion about the mean of ~ 0.03 . This implies that $0.02 \lesssim b/R \lesssim 0.1$ with a mean value of 0.05 [19]. The effect of this dispersion on rotation curves is shown by the two dotted lines, which are rotation curves for $f = 0.25$ with collapse factors that correspond to b/R at its upper (3) and lower (5) limit. There are several observational and theoretical constraints on F that place it in the range $0.05 \lesssim F \lesssim 0.2$ [1]. Decreasing F produces less peaked rotation curves, as shown by the thick dotted line in Fig. 1, which is the rotation curve for $f = 0.75$ with $F = 0.05$ and $b/R = 0.1$.

The main result of Fig. 1 is that velocities decrease at large distances for small f . This can be understood as follows: after the baryons have cooled to an exponential disk (dissipation and decay do not commute since λ is invariant under decay in the adiabatic approximation), the DM decay hardly changes $v(r)$ at small radii because the baryons dominate there. At large radii, where the DM dominates, $v(r)$ decreases substantially as a result of the mass loss. Thus, a lower bound on f is anticipated from the constraint that observed rotation curves do not fall with distance even well outside the optical radius.

NUMERICAL MODEL

The analytic model just described assumes circular or purely radial orbits, spherical symmetry, an equilibrium starting configuration, no shell crossing, and does not include expansion. These assumptions can be relaxed and more general cases can be studied using N-body simulations. We carried out extensive numerical work to test the analytic model, using a dissipative N-body code based on the code developed by S. J. Aarseth [20]. Some of this work is discussed in more detail in Ref. 16; here we briefly outline its features and the conclusions one can draw from it.

The simulations follow a large number of particles that interact via a Newtonian

potential, softened on small scales in order to suppress spurious two-body relaxation effects due to the relatively small number of bodies in the simulation. Integration time steps were chosen so that the fractional change in the total energy is less than 1% over a whole simulation, and the integration continued for several dynamical times after the system reached approximate equilibrium ($t_{dyn} \equiv GM_i^{5/3}/|2E_i|^{3/2}$). The system was chosen to have total mass $M_i = 10^{12} M_\odot$, and to consist of $N_{1-f} + N_f$ dissipationless particles (the DM) and 500 dissipational particles (the baryons). We chose the number of stable (N_f) and unstable (N_{1-f}) DM particles large enough to have adequate statistics. For example for $f = 0.4$ we took $N_f = 500$ and $N_{1-f} = 750$. In all simulations, the baryonic particles were initially mixed uniformly with the DM particles.

In simulations with dissipation, the baryonic particles were assumed to have a collisional cross section σ , which was kept constant throughout a simulation. A collision occurred if two particles came within a distance $(\sigma/\pi)^{1/2}$ of each other, in which case they were merged to form a single particle located at their center of mass, moving with its velocity and mass. Their relative energy was thus dissipated (σ controls the rate of baryonic infall; for larger σ the baryons fall in faster). We chose σ such that the total energy loss rate due to inelastic collisions equals the physical cooling rate (assuming fully ionized H + He). For more discussion see [17].

The decay of the unstable DM was mimicked by randomly selecting N_{1-f} dissipationless particles and assigning them a time $t_{decay} = -\tau \log \theta$, where θ is a random number in the interval $(0,1]$ chosen for each particle. At time t_{decay} the particle was eliminated from the simulation.

As an example, in Fig. 2 the results of a “Hubble start” model are presented. The model starts with an expanding, homogeneous sphere with pure Hubble flow, except for a small amount of rigid-body rotation with $\lambda = 0.07$, and the final fraction of baryons is $F = 0.1$. At $t = 0$ the Hubble constant is chosen so that the protogalaxy expands by a factor of ~ 2.5 before collapse. The lower solid line is the resulting “velocity” profile,

$(M(r)/r)^{1/2}$ vs. r , after a fraction $1 - f = 0.4$ of the DM has decayed with a lifetime $\tau = 5t_{dyn}$, which corresponds to $1 + z_d \sim 4$, and no dissipation has taken place. The upper solid line is the resulting profile when the baryons are allowed to dissipate. The dotted line is the result of the analytic model for the same values of F and f , and a collapse factor $b/R = 0.05$ corresponding to the chosen values of λ and F ; the initial state needed was taken to be the profile resulting from an N-body simulation without dissipation nor decay. The agreement between the two models is fairly good and we regard it as confirming the validity of the analytic model.

DISCUSSION

The remarkably flat or rising velocity profiles of spiral galaxies [21,22] are a strong constraint on the models being studied. Figure 1 shows that for typical values of F and λ the final velocity profile is rather sensitive to the value of f and not every value of f yields acceptable rotation curves. The numerical simulations showed that the analytic model works well and, therefore, we can use it to study the theoretical rotation curves and compare them to observations.

The parameters of the analytic model are the final baryon fraction F , the collapse factor b/R , the core radius a/R of the initial isothermal sphere and the fraction of stable DM f . As Fig. 1 shows, if for a given value of f one obtains a falling velocity profile for F and R/b taken at their lowest values and $a/R \sim 0.4$, then only falling rotation curves can be produced for higher values of F and R/b . However, Fig. 3 shows that this is so for any value of the core radius for $f \lesssim 0.3$. The figure shows a measure of the flatness of the rotation curve, $\Delta v/v \equiv [v(3.5b)]/v(4.5b)$, plotted as a function of the core radius of the initial configuration for the lowest values of F and R/b (higher values would only lower the curves).

The rotation curves of spiral galaxies are observed to be remarkably flat or rising inside the optical radius, with only a small fraction $\sim 20\%$ of the Burstein-Rubin [21]

sample observed to have falling velocity profiles. For $f \lesssim 0.3$, however, Fig. 3 shows that the theoretical rotation curves decrease ($\Delta v/v < 0$) inside the optical radius $R_H \equiv 4.5b$ for all values of a/R , even for F and R/b at their lowest values. Furthermore, velocity profiles are observed to be flat or rising outside the optical radius as well [22] and this provides further constraints on f . Because we assume f to be a spatial constant, one can use the data of individual galaxies to constrain it. For example, no value of the initial core radius can yield a flat rotation curve out to $r = 11b$ (like that of NGC 3198 [23]) unless $f \gtrsim 0.4$ nor can a profile rising out to $r \sim 8b$ (like that of NGC 3109 [24]) be obtained if $f \lesssim 0.5$. These bounds are, again, for F and R/b taken at their minimum values.

CONCLUSIONS

The rotational profiles of spiral galaxies require that the fraction of stable DM $f \gtrsim 0.5$. One can relate f to the relative contribution by relativistic particles to the energy density:

$$\Omega_r/\Omega_{nr} \leq f^{-1}(1-f)(1-F)(1+z_d)^{-1} \quad (2)$$

(the equality is satisfied in the instantaneous decay approximation [3]). Since $F \ll 1$, for $f \geq 0.5$ one gets $\Omega_r/\Omega_{nr} \leq (1+z_d)^{-1}$. Thus, the Universe could not be dominated by weakly interacting relativistic particles. In the type I model, the relativistic contribution to the energy density required for $\Omega = 1$ amounts to $\Omega_r/\Omega_{nr} \sim 4$. Therefore, even for a decay epoch as recent as $1+z_d \sim 5$ Eq. 2 requires $f \sim 0.05$, a factor of 10 smaller than the bound obtained here. Thus, with the assumptions we have made, the type I model is ruled out. Only if a substantial fraction of the baryonic gas contracts and dissipates after the decay might one lower the upper bound on f , although it is not clear that such a scenario can lead to flat rotation curves. Type II models [8], however, do not require that the Universe be radiation dominated at present; in these models $\Omega_r/\Omega_{nr} \sim 0.25$, which is only marginally consistent with the upper bound of Eq. 2 even for a decay epoch as recent as $1+z_d \sim 4$. However, an upper bound on f must come from the requirement that on large scales Ω be unity with Ω_{cd} being only ~ 0.2 . We are trying to quantify this

constraint by studying in detail the formation of clusters and large scale structure within the framework of the unstable DM picture in type II models [25].

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REFERENCES

1. G. Blumenthal, S. Faber, J. Primack and M. Rees: *Nature* **311**, 517 (1984) and references therein
2. P. J. E. Peebles: *Nature*, **321**, 27 (1986)
3. P. J. E. Peebles: *Astrophys. J.* **284**, 439 (1984)
4. J. Bardeen, in E. W. Kolb *et. al.* eds.: *Inner Space/ Outer Space*, p. 212, U. of Chicago Press, 1986. N. Kaiser: *ibid.*, p. 258
5. M. S. Turner, G. Steigman and L. Krauss: *Phys. Rev. Lett.* **52**, 2090 (1984)
6. G. Gelmini, D. Schramm and J. Valle: *Phys. Lett.* **146B**, 311 (1984)
7. M. S. Turner: *Phys. Rev. D* **31**, 1212 (1985)
8. K. Olive, D. Seckel and E. Vishniac, *Astrophys. J.* **292**, 1 (1985)
9. J. Silk and N. Vittorio: *Phys. Rev. Lett.* **54**, 2269 (1985)
10. M. S. Turner: *Phys. Rev. Lett.* **55**, 549 (1985)
11. E. W. Kolb, K. Olive and N. Vittorio: preprint, Fermilab-PUB-86/40-A, 1986
12. G. Efstathiou: *M. N. R. A. S.* **213**, 29 (1985)
13. A. Dekel and T. Piran: Weizmann preprint WIS-86/30-June Ph
14. M. Davis and J. V. Villumsen: Berkeley preprint, 1985
15. Y. Hoffman: U. of Pennsylvania preprint UPR-0291-T (Jan. 1986)
16. R. Flores, G. Blumenthal, A. Dekel and J. Primack: UCSC preprint (April, 1986). (submitted to *Nature*)
17. G. Blumenthal, S. Faber, R. A. Flores and J. Primack: *Astrophys. J.* **301**, 27 (1986); UCSC preprint, in preparation
18. G. Efstathiou and B. J. T. Jones: *M. N. R. A. S.* **186**, 133 (1979)
19. S. M. Fall and G. Efstathiou, *M. N. R. A. S.* **193**, 189 (1980)
20. S. J. Aarseth, in J. U. Brackbill and B. I. Cohen eds.: *Multiple Times Scales*, p. 377, Academic Press, 1985
21. D. Burstein and V. C. Rubin: *Astrophys. J.* **297**, 423 (1985) and references therein
22. A. Bosma: *Astron. J.* **86**, 1791 (1981); *ibid.* **86**, 1825 (1981)
23. T. S. van Albada, J. N. Bahcall, K. Begman and R. Sansci: *Astrophys. J.* **295**, 305 (1985)
24. C. Carignan: *Astrophys. J.* **299**, 59 (1985)
25. G. Blumenthal, A. Dekel, R. Flores and J. Primack, in progress.

FIGURE CAPTIONS

Fig. 1: Rotation curves calculated with the analytic model: $v(r)$ is the rotational velocity, in the plane of the disk, needed by a particle to remain in circular orbit at distance r/b from the center and $v_H \equiv v(r = R_H \equiv 4.5b)$.

Fig. 2: "Rotation" curves for the numerical model. The y- axis is $(M(r)/r)^{1/2}$, where $M(r)$ is, at fixed r , averaged over several dynamical times after the system reached approximate equilibrium. The bars are one standard deviation fluctuation levels. The x-axis is the distance from the center in units of the radius that contains 80% of the final total mass (edge effects probably affect the results of the numerical models outside this radius). The dotted line is the result of the analytic model for $(M(r)/r)^{1/2}$.

Fig. 3: $\Delta v/v$ as a function of of the core radius of the initial isothermal sphere for $F = 0.05$ and $b/R = 0.1$ (e.g. $\Delta v/v \sim -0.1$ for a self-gravitating exponential disk).

Figure 1

Figure 2

Figure 3