The Role of Baryons in Unified Dark Matter Models

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We discuss the importance of including baryons in analyses of unified dark matter scenarios, focusing on toy models involving a generalized Chaplygin gas. We determine observational constraints on this unified dark matter scenario coming from large scale structure, type Ia Supernovae and CMB data showing how this component can bring about a different behaviour from classical ΛCDM and thus motivate further studies of this type of models. We also speculate on interesting new features which are likely to be important on non-linear scales in this context.

I. INTRODUCTION

Unified dark matter (UDM) models—also referred to as ‘quartessence’—where dark matter and dark energy are seen as different manifestations of a single substance have recently enjoyed considerable attention, the main reason for it being, to try and find viable alternatives to the highly fine-tuned potentials so characteristic of quintessence models. The price one has to pay seems to be the introduction of fluids obeying exotic equations of state. One such example is the class of models based on the Chaplygin gas, first suggested for this purpose in 1,2 and trivially generalized in 3.

There has been some controversy about the viability of these scenarios. Following an earlier, simpler analysis 4, we were able to obtain constraints on this type of model from a combined dataset of 92 high-z type Ia supernovae (including forecasts for the proposed SNAP experiment) as well as the matter power spectrum 5. This has been subsequently repeated by a number of authors 6,7, both of which confirm our earlier results, while 8 have done a Bayesian analysis of a sub-sample of the supernovae data set. The main message of these studies is the fact that constraints critically depend on whether one treats the Chaplygin gas as true quartessence (replacing both dark matter and dark energy) or if one allows it to coexist with a ‘normal’ dark matter component (which could be called the ‘Chaplygin quintessence’ scenario). As one might have expected ab initio, the case for the Chaplygin gas is stronger in the former scenario.

However, the above analyses essentially restrict themselves to the background cosmology. Going beyond this and studying perturbation theory in this context seemingly dealt the first blow to the UDM possibility. The authors of 9 have studied the implications of a single generalized Chaplygin component to the mass power spectrum and by comparing it to 2dF observations were able to constrain parameters controlling it to such values as to render it virtually indistinguishable from a usual ΛCDM scenario. The production of violent oscillations causing the exponential blowup of the power spectrum, totally inconsistent with observations was the reported fatal flaw. This was further claimed to be of a general nature within UDM scenarios, which if true could be construed as evidence for independent origins of dark matter and dark energy.

The main goal of this Letter is to show that such flaw is in fact due to 9 overlooking a most important ingredient describing the average Universe: baryons. (This concern has also been voiced, but not exploited, by 8). Our main objection can be brought down to the following point: The main property (cosmologically speaking) of a Chaplygin gas is that of mimicking cold dark matter (CDM) at early times as it progressively evolves into a cosmological constant. This results in perturbations in the Chaplygin gas component being heavily damped at late times. However, if to it we add an independent component with a low sound speed velocity (as baryons have), the normal growth of inhomogeneities can still go on when the Chaplygin gas starts behaving differently from CDM. By just considering the Chaplygin fluid the authors of 9 have artificially constrained the possible power spectra that UDM scenarios can cover. Although baryons are not that important for other studies such as constraining these scenarios from supernova luminosity distances, they are of critical importance in the context of large scale structure studies.

We should also mention two recent papers which accurately study perturbation growth in these models.
(including the cosmic microwave background). Although of a broader scope than ours (they consider a baryon+CDM+Chaplygin universe), we do not quite agree on the latter’s interpretation of UDM. While we agree with their conclusion that this ‘Chaplygin quintessence’ scenario is all but ruled out (or at least disfavored by the current data relative to ΛCDM) it seems to miss the point that these scenarios came into existence as an attempt to unify dark energy and dark matter, and that in this ‘quartessence’ context its behavior can be different from ΛCDM. Yet this quartessence scenario is all but ignored in their discussion. Therefore, we re-derived the analysis of [3] (in order to accommodate for baryons) and part of the analysis of [11] to explore more fully the viability of the ‘quartessence’ scenario.

II. GROWTH OF PERTURBATIONS

To study the role of baryons in a UDM model based on the Chaplygin gas we obviously need relativistic equations governing the evolution of perturbations in a two fluid system. For a general case of n gravitationally interacting fluids, the linear evolution of perturbations in the comoving synchronous gauge is given by [12]:

\[ h'' + (2 + \xi)h' + 3 \sum_i (1 + 3\omega_i^2)\Omega_i \delta_i = 0 \] (1)
\[ \delta_i' + (1 + \omega_i)(\theta_i/aH + h'/2) + 3(\nu_i^2 - \omega_i)\delta_i = 0 \] (2)
\[ \theta_i' + (1 - 3\nu_i^2)\theta_i + \frac{\nu_i^2}{aH(1 + \omega_i)}\nabla^2 \delta_i = 0 \] (3)

where \( t' \equiv d/dx, x = \ln a \) (note that [12] uses conformal time instead), \( h \) is the trace of the perturbation to the Friedmann-Robertson-Walker (FRW) metric, \( H \) is the Hubble parameter, \( \xi = H'/H \), \( \delta_i \) is the density contrast of the \( i \)-th fluid obeying \( \rho_i = \omega_i \rho_b \) with an adiabatic sound speed \( \nu_i \) and a \( \theta_i \) element velocity divergence. Note that (2) and (3) apply for all \( i = 1, \ldots, n \).

The first noticeable point is that for baryons (which we are treating as an ordinary CDM fluid with \( \omega_b = v_b^2 = 0 \)) Eq. (4) immediately renders \( \theta_b = \theta_{b0}/a \). Therefore, if \( \theta_{b0} = 0 \) then \( \theta_b = 0 \) at all times. Putting this into Eq. (2) we find that \( h' = -2\delta_b' \). Taking this into consideration, the Fourier modes of a two fluid model of baryons and a Chaplygin fluid with equation of state \( p = -\rho^\alpha \) (here \( C \) is a positive constant and \( \alpha \geq 0 \) turn out to be:

\[ \delta_{b0}'' + (2 + \xi)\delta_{b0}' - 3/2[\theta_b\delta_b + (1 - 3\omega_{cg})\Omega_{cg}\delta_{cg}] = 0 \] (4)
\[ \delta_{cg}' + (1 + \omega_{cg})(\theta_{cg}/aH - \delta_{cg}') - 3\omega_{cg}(1 + \alpha)\delta_{cg} = 0 \] (5)
\[ \theta_{cg}' + (1 + 3\omega_{cg})\theta_{cg} + \frac{\omega_{cg}k^2}{aH(1 + \omega_{cg})}\delta_{cg} = 0 \] (6)

where we have used the fact that \( v_{cg}^2 = -\omega_{cg} \) and \( \nabla \equiv -k^2 \). We thus have three equations for three unknowns: \( \delta_b, \delta_{cg}, \theta_{cg} \). Given \( \omega_{cg} \) and \( H \) (and \( \xi, \Omega_b, \Omega_{cg} \)) as functions of \( x \) we can easily transform this set into four first order differential equations and integrate it using a standard Runge-Kutta method. Since in the linear regime and deep into the matter era \( \delta_{b, cg} \propto a \) implying \( \delta'_{b, cg} \propto a \), normalized initial conditions \( [\delta_{b0}, \delta', \delta_{cg}, \theta_{cg}]_0 = [1, 1, 1, 0] \) were used. As in [3] we evolve our system for a plane Universe from \( z = 100 \) until today and obtain corresponding transfer function \( T_k \). But unlike in the case of [3], our transfer function now comes from the baryonic component and not from the Chaplygin component, thus avoiding in the baryonic component the violent oscillations in the Chaplygin gas that were so sensitive to \( \alpha \).

Note that a (CDM processed) scale invariant Harrison-Zel’dovich spectrum emerging from equality is accurately given by [13]

\[ |\delta_k|^2 = Ak \left( \frac{\ln(1 + \epsilon_0\zeta)}{\epsilon_0\zeta} \right)^2 \left( \sum_{i=0}^{4} (\epsilon_i\zeta)^i \right)^{-1/2} \] (7)

\( \zeta = k/\Gamma h \), where \( \Gamma = \Omega_{m0}h \) is the shape parameter (\( \Omega_m \) being the CDM energy fraction today), \( A \), a normalization constant, \( |k| = \text{Mpc}^{-1} \) and \( \epsilon = [2.34, 3.89, 16.1, 5.46, 6.71] \). As previously discussed in [3] the presence of a Chaplygin fluid (still firmly behaving as CDM at this epoch) only affects the shape parameter of the power spectrum according to \( \Gamma = \Omega_{m0}h \) where

\[ \Omega_{m0}^* = \Omega_{m0} + \Omega_{cg0}(1 - \mathcal{A})^{1/1+\alpha} \] (8)

\( \alpha \) and \( \mathcal{A} \) being the parameters controlling the (generalized) Chaplygin gas. Unfortunately, this simple result relies on the assumption of the absence of baryons. In order to take them explicitly into account, Sugiyama’s shape correction [14] must be used instead

\[ \Gamma^* = \Omega_{m0}^* h \exp \left( -\Omega_{b0}(1 + \sqrt{2}h/\Omega_{m0}^*) \right) \] (9)

where \( \Omega_{b0} \) stands for the baryon energy content today. (Note that in the absence of baryons \( \Gamma^* = \Gamma \) as it should). Thus, we have taken [3] as our initial power spectrum with a \( \Gamma^* \) shape parameter, further processing it through \( T_k \) so as to compare it to 2dF results.

III. THE ANALYSIS

By performing a likelihood analysis of our model of baryons and a Chaplygin fluid using the 2dF mass power spectrum we were able to constrain the \( (\alpha, \mathcal{A}) \) parameter space assuming only reasonable priors coming from WMAP [15], namely \( \Omega_m^0 = 0.044 \) and \( h = 0.71 \). Note that at the time of recombination, the Chaplygin gas would still firmly behave as CDM. Therefore, standard small scale CMB results are to be expected when one identifies \( \Omega_m \) with \( \Omega_{m0}^* \). The results could conceivably differ on very large scales, though here they would be competing against cosmic variance.
FIG. 1: 68%, 95% and 99% likelihood contours in the \((\alpha, A)\) parameter space for a model of baryons plus a (generalized) Chaplygin gas, coming from the 2dF mass power spectrum. Note the minute \(\Lambda\)CDM region near \(\alpha \sim 0\) (see text). The zone inside the solid lines corresponds to \(\Gamma^* = 0.2 \pm 0.03\).

FIG. 2: 68%, 95% and 99% likelihood contours for a model of baryons plus a (generalized) Chaplygin gas, coming from the 92 high-z type Ia supernovae. The zone inside the solid lines corresponds to \(\Gamma^* = 0.2 \pm 0.03\).

FIG. 3: 68%, 95% and 99% likelihood contours resulting from a joint analysis of large-scale structure (2dF) and type Ia supernovae for a model of baryons plus a (generalized) Chaplygin gas. The zone inside the solid lines corresponds to \(\Gamma^* = 0.2 \pm 0.03\).

As in [1] any 2dF data over \(k > 0.3\) hMpc\(^{-1}\) was discarded so as to stay firmly grounded in the linear regime where our analysis holds. Specifically, we have evaluated a \(500 \times 100 \times 100\) data grid for \(A, \overline{A}\) and \(\alpha\) with \(0 < \alpha < 1\) and \(0 < \overline{A} < 1\), where corresponding probabilities were found and posteriorly summed over \(\overline{A}\). Resulting confidence levels are shown in Fig. 1, where two disjoint regions can be found: one prominent, the other small (around \(\alpha \sim 0\) and \(\overline{A} \sim 0.75\)). We have also displayed the region of parameter space corresponding to a value of the shape parameter of \(\Gamma^* = 0.2 \pm 0.03\), as per [10].

The significance of this smaller area is as follows. One of the most noted proprieties of the Chaplygin gas class of models is that of reproducing to all orders a classical \(\Lambda\)CDM scenario when \(\alpha = 0\) (with \(1 - \overline{A}\) being the equivalent CDM fraction \(\Omega_m^0\)), which we know to be in good agreement with observations, though still lacking a sound fundamental physical motivation. In our case of baryons plus a Chaplygin fluid, we are basically in the same \(\Lambda\)CDM scenario, just with a slightly higher matter content because of them. Therefore, this small area around \(\alpha \sim 0\) is just the \(\Lambda\)CDM component of the model manifesting itself. On the other hand, we have an entirely disjoint region at very high confidence level. So, in fact, we have provided explicit evidence of a (generalized) Chaplygin gas not having to behave as \(\Lambda\)CDM in order to reproduce 2dF large-scale structure data.

Now, let us re-visit high-z type Ia supernovae. As previously emphasized, these are only sensitive to the model background evolution and not to the clustering details. So little information is to be gained for \(\alpha\) from a likelihood analysis of our model of baryons plus a Chaplygin fluid for the supernova data on their own. In fact, this analysis restricts mainly the value of \(\overline{A}\) since it more directly relates to the energy fueling the background expansion—a point already made in [5]. Fig. 2 shows the result of a likelihood analysis using a combined dataset of 92 high-z supernova observations [17, 18, 19] (see [5, 20] for more details).

However, notice that the degeneracy contours (large-scale structure and supernovae) of the two observables, are not parallel. This is of course to be expected since they are rather different in nature and effectively arise from very different redshifts. Therefore a joint analysis of Supernovae constraints with those of large-scale structure can moderately improve the constraints on \(\alpha\), as shown in Fig. 3.
IV. CONCLUSION

We have shown that baryons play a crucial role in the context of unified dark matter models involving a (generalized) Chaplygin gas, their presence enabling them to reproduce the 2dF mass power spectrum without having to behave as classical $\Lambda$CDM scenarios. The reason is that baryons can carry over gravitational clustering when the Chaplygin fluid starts behaving differently from CDM. This is of great importance since it allows the (generalized) Chaplygin gas to be a conceivable quintessence candidate.

On the other hand, it is easy to see why the Chaplygin quintessence scenario will be observationally uninteresting, quite apart from theoretical considerations: since in the standard scenario there is currently no preference of the data for quintessence over a plain cosmological constant, it is clear that if we add a Chaplygin fluid to baryons and CDM then the available data will prefer it to behave as a cosmological constant as well—which is the result of [11].

Hence the present results, combined with those of [11], strengthen our previous conclusions [5]. If by an independent method we determine the total matter density of the universe to be $\Omega_m \sim 0.3$ then in the context of this model we would in fact require a cosmological constant so as to account for the current observational results. Conversely, the quintessence case, where baryons are the only matter component present, is such that its differences with respect to the standard case are maximal, and indeed in this case the $\Lambda$-limit is already strongly disfavored by observational data.

We finally wish to emphasize that this study, as well as the rest of the published work so far, has been restricted to the linear regime. Interesting new features of this scenario may also appear on non-linear scales. An example would be the possibility of avoiding the cuspy dark matter halo profiles expected in the context of CDM models. We also anticipate that galaxy and cluster evolution could be modified in the context of UDM models based on the Chaplygin gas. This again results from the strong dependence of the properties of the Chaplygin gas on the background density.

Moreover, in the non-linear regime the density is much higher than the background density, and therefore one can not simply infer the behavior of the Chaplygin fluid through the usual sound speed (which uses the background density and pressure). So in a collapsed region the Chaplygin gas could still behave as CDM even though its background behavior may already be different. On the other hand, since in this case the pertinent scales are very small, even a tiny sound speed may be sufficient to halt collapse. Clearly these issues must be addressed before one can reach a final verdict on this scenario. We shall return to them in subsequent work.

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