Mem. S.A.It. Vol. 80, 921

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Constraining dark matter-dark energy interaction with gas mass fraction in galaxy clusters

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Abstract. The recent observational evidence for the current cosmic acceleration have stimulated renewed interest in alternative cosmologies, such as scenarios with interaction in the dark sector (dark matter and dark energy). In general, such models contain an unknown negative-pressure dark component coupled with the pressureless dark matter and/or with the baryons that results in an evolution for the Universe rather different from the one predicted by the standard ΛCDM model. In this work we test the observational viability of such scenarios by using the most recent galaxy cluster gas mass fraction versus redshift data (42 X-ray luminous, dynamically relaxed galaxy clusters spanning the redshift range $0.063 < z < 1.063$) (Allen et al. 2008) to place bounds on the parameter ϵ that characterizes the dark matter/dark energy coupling. The resulting are consistent with, and typically as constraining as, those derived from other cosmological data. Although a time-independent cosmological constant (ΛCDM model) is a good fit to these galaxy cluster data, an interacting dark energy component cannot yet be ruled out.

Key words. Cosmology – Cosmological Parameters – Coupled Quintessence – Distance Scale – Galaxy Clusters.

1. Introduction

Although fundamental to our understanding of the Universe, several important questions involving the nature of the dark matter and dark energy components and their roles in the dynamics of the Universe remain unanswered. Among these questions, the possibility of interaction in the dark sector, which gave origin to the so-called models of coupled quintessence, has been largely explored in the literature. These scenarios are based on the premise that, unless some special and unknown symmetry in Nature prevents or suppresses a non-minimal coupling between these components (which has not been found), such interaction is in principle possible and, although no observational piece of evidence has so far been unambiguously presented, a weak coupling still below detection cannot be completely excluded (see Amendola 2000;Zimdahl et al. 2001; Barrow and Clifton 2006; Wu et al. 2008; Costa and Alcaniz 2009).

From the observational viewpoint, these models are capable of explaining the current

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cosmic acceleration, as well as other recent observational results. From the theoretical point of view, however, critiques to these scenarios do exist and are mainly related to the fact that in order to establish a model and study their observational and theoretical predictions, one needs first to specify a phenomenological coupling between the cosmic components.

In this work, instead of adopting the traditional approach, we follow the qualitative arguments used in (Wang and Meng 2005; Alcaniz and Lima 2005) and deduce the interacting law from a simple argument about the effect of the dark energy decay on the dark matter (CDM) expansion rate. The resulting expression is a very general law that has many of the previous phenomenological approaches as a particular case.

2. The model

By assuming that the radiation and baryonic fluids are separately conserved, the energy conservation law for the two interacting components ($u_\alpha T^{\alpha\beta}_{;\beta} = 0$, where $T^{\alpha\beta} = T^{\alpha\beta}_{DM} + T^{\alpha\beta}_{DE}$) reads (Jesus et al. 2008)

$$\dot{\rho}_{DM} + 3\frac{\dot{a}}{a}(\rho_{DM}) = -\dot{\rho}_{DE} - 3\frac{\dot{a}}{a}(\rho_{DE} + p_{DE}) \quad (1)$$

In order to complete the description of our interacting quintessence scenario we need to specify the interaction law. In principle, if the quintessence component is decaying into CDM particles, the CDM component will dilute more slowly compared to its standard (conserved) evolution. Therefore, if the deviation from the standard evolution is characterized by a constant ϵ we may write

$$\rho_{DM} = \rho_{DM,0}a^{-3+\epsilon} , \quad (2)$$

where ϵ is the interaction parameter and we have set the present-day value of the cosmological scale factor $a_0 = 1$.

In what follows we also consider that the dark energy component is described by an equation of state where the constant ω is a negative quantity. Now, by integrating Eq. (1) it is straightforward to show that the energy density of the dark energy component is given by

$$\rho_{DE} = \tilde{\rho}_{DE,0}a^{-3(1+\omega)} + \frac{\epsilon\rho_{DM,0}}{3|\omega| - \epsilon}a^{-3+\epsilon} , \quad (3)$$

where the integration constant is the present-day fraction of the dark energy density. Clearly, in the absence of a coupling with the CDM component, i.e., $\epsilon = 0$, the conventional non-interacting quintessence scenario is fully recovered. For $\omega = -1$ and $\epsilon = 0$, we may indentify (the current value of the vacuum), and the above expression reduces to the vacuum decaying scenario. Neglecting the radiation contribution, the Friedmann equation for this interacting dark matter-dark energy cosmology can be written as

$$\mathcal{H}^2 = \Omega_b a^{-3} + \frac{3|\omega|\Omega_{DM}}{3|\omega| - \epsilon}a^{-3+\epsilon} + \tilde{\Omega}_{DE}a^{-3(1+\omega)} , \quad (4)$$

where $\mathcal{H} = H(z)/H_0$ and Ω_b and $\Omega_D M$ are, respectively, the baryons and CDM present-day density parameters.

The parameter Ω_{DE} is defined, in terms of the density parameter of the dark energy component as

$$\tilde{\Omega}_{DE} = \Omega_{DE} - \frac{\epsilon\Omega_{DM}}{3|\omega| - \epsilon} , \quad (5)$$

and, therefore,

$$\tilde{\Omega}_{DE} = 1 - \Omega_b - \frac{3\Omega_{DM}}{3|\omega| - \epsilon} . \quad (6)$$

The above expression clearly shows that the conventional (non-interacting) quintessence scenario is considerably modified due to the dark energy decay into CDM particles. It is also worth noticing the importance of the baryonic contribution to this sort of scenario. Going back to high redshift we see that the presence of an explicit term redshifting as $(1+z)^3$ is well justified since the decaying dark energy component slows down the variation of of CDM density. Although being sub-dominant at the present stage of cosmic evolution, the baryonic content will be dominant (in comparision to CDM) at very high redshifts. Actually, it becomes sub-dominant just before nucleosynthesis ($z \sim 10^{10}$ for $\epsilon \sim 0.1$), so that the CDM component drives the evolution after the radiation phase.

3. Constraints from X-Ray gas mass fraction

In our analysis we consider the Chandra data analyzed in (Allen et al. 2008). The data consist of 42 clusters distributed over a wide range of redshift ($0.063 < z < 1.063$). The clusters studied are all regular, relatively relaxed systems for which independent confirmation of the matter density parameter results is available from gravitational lensing studies. The default cosmology used is the ΛCDM scenario with $H_0 = 70\,km\,s^{-1}Mpc^{-1}$. By assuming that the baryonic mass fraction in galaxy clusters provides a fair sample of the distribution of baryons at large scale (White et al. 1993), as well $f_{gas} \propto d_a^{3/2}$ (Sasaki 1996), the model function is defined by (Allen et al. 2008)

$$f_{gas}^{mod}(z) = \mathcal{G}\frac{\Omega_b}{\Omega_b + \Omega_{DM}a^{\epsilon}}\left[\frac{d_A^{\Lambda CDM}(z)}{d_A^{mod}(z)}\right]^{\frac{3}{2}}, \quad (7)$$

where $\mathcal{G} = \frac{K A \gamma b(z)}{1+s(z)}$, the parameters K, A, γ, $b(z)$ and $s(z)$ account for computational simulations for corrections under the assumption that f_{gas} should be approximately constant with redshift. On the other hand, the distance ratio $[d_A^{\Lambda CDM}(z)/d_A^{mod}(z)]^{3/2}$ accounts for deviations in the geometry of the universe from the ΛCDM model, where explicitly we have

$$d_A^{\Lambda CDM} = \frac{1}{1+z}\int_0^z \frac{dz}{H_0\sqrt{0.3a^{-3}+0.7}} \quad (8)$$

and

$$d_A^{mod} = \frac{1}{1+z}\int_0^z \frac{dz}{H_0\mathcal{H}} \quad (9)$$

where $\mathcal{H}$ is given by Eq. (4).

In order to determine the cosmological parameters ϵ and Ω_{DM} we use a χ^2 minimization. For this purpose we set $A = 1.0$ (Samushia et al. 2008), as well $\Omega_b = 0.044$ (Spergel et al. 1993) and marginalize over the other parameters. The expression for χ^2 is:

$$\chi^2 = \sum_{i=1}^{42}\frac{\left[f_{gas}^{obs}(z_i;\mathbf{p}) - f_{gas}^{mod}(z_i;\mathbf{p})\right]^2}{\sigma^2_{f_{gas}^{obs}}}, \quad (10)$$

where $\sigma_{f_{gas},i}$ are the symmetric root-mean-square errors for the ΛCDM data. The 68.3%, 95.4% and 99.73% confidence levels are defined by the conventional two-parameters χ^2 levels 2.30, 6.17 and 11.8, respectively.

Figs. 1,2 and 3 we show contours of constant likelihood (68% and 95%) in the $\epsilon - \Omega_{DM}$ plane for fixed values of $w = -0.8$ (coupled quintessence), $w = -1$ (vacuum decay) and $w = -1.2$ (coupling with phantom), respectively. At 68.3% c.l. we find $\Omega_{ME} = 0.207^{+0.010}_{-0.016}$ and $\epsilon = -0.215^{+0.167}_{-0.166}$, with $\chi^2_{min}/\nu = 1.241$ (when $\omega = -0.8$); $\Omega_{ME} = 0.206^{+0.009}_{-0.011}$ and $\epsilon = -0.040^{+0.231}_{-0.180}$, with $\chi^2_{min}/\nu = 1.211$ (when $\omega = -1.0$) and $\Omega_{ME} = 0.204^{+0.011}_{-0.024}$ and $\epsilon = 0.120^{+0.177}_{-0.069}$, with $\chi^2_{min}/\nu = 1.255$ (when $\omega = -1.2$). Note that for values of $w \geq -1.0$, the observational analysis favours a transfer of energy from dark matter to dark energy ($\epsilon < 0$).

4. A low-z test for DM-DE interaction

From Eq. (8), we see that at low-z the dependence with the cosmological model can be easily eliminated. Thus, we can rewrite the f_{gas} function as

$$f_{gas}^{mod}(z) = \frac{K A \gamma b(z)}{1+s(z)}\frac{\Omega_b}{\Omega_b + \Omega_{DM}a^{\epsilon}}. \quad (11)$$

Note that, although model-independent, the above equation can be used to distinguish between coupled and uncoupled scenarios since the the a^{ϵ} term cannot be removed. By restricting our sample to 11 clusters at $z \leq 0.23$, we perform our χ^2 analysis and find $\epsilon = -0.065$. A more detailed analysis of this low-z test involving a new set of f_{gas} data will appear in a forthcoming communication (Gonçalves et al. 2009).

5. Conclusions

We have used gas mass fraction data to test the viability of a general class of coupled quintessence models. In particular, we have proposed a new low-z test which in principle may be able to distinguish classes of coupled and uncoupled dark matter/energy models. We believe that with new and more precise data

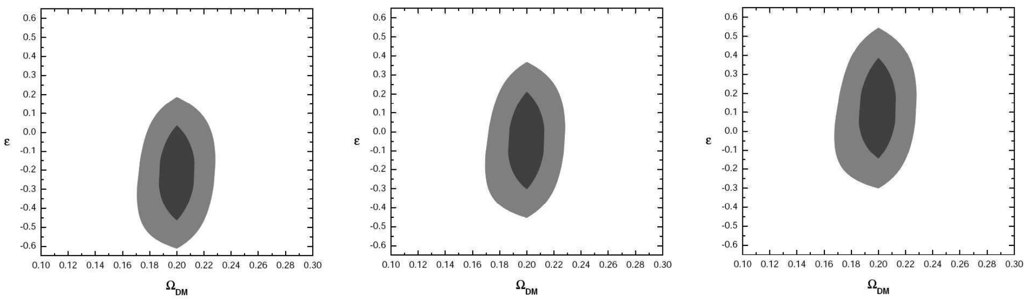

Fig. 1. Confidence regions in the $\epsilon - \Omega_{DM}$ plane. The Best-fit model for these data occurs for: (**Left**) $\Omega_{DM} = 0.207$ and $\epsilon = -0.215$, with $\chi^2_{min}/\nu = 1.241$, by fixing the value $\omega = -0.8$ (**Middle**) $\Omega_{DM} = 0.206$ and $\epsilon = -0.040$, with $\chi^2_{min}/\nu = 1.211$, by fixing the value $\omega = -1.0$ and (**Right**) $\Omega_{DM} = 0.204$ and $\epsilon = 0.120$, with $\chi^2_{min}/\nu = 1.255$, by fixing the value $\omega = -1.2$.

sets we will be able to use this test to place tighter and stronger bounds on the interacting parameter ϵ.

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