ABSTRACT: We propose a new equation of state for the Dark Energy component of the Universe. It is modeled on the equation of state $p = w(\rho - \rho_*)$ which can describe a liquid, for example water. We show that its energy density naturally decomposes into a component that behaves as a cosmological constant and one whose energy density scales as $a^{-3(1+w)}$, and fit the parameters specifying the equation of state to the new SNIa data, as well as WMAP and 2dF data. We consider both the case where the dark fluid is smooth (i.e. only the CDM component clusters gravitationally) as well as the case where the dark fluid also clusters. We find that for both cases, reasonable values of the parameters can be found that give our model the same $\chi^2$ as that of $\Lambda$CDM. Furthermore, in the case where our dark fluid clusters, allowing a blue tilt to the power spectrum allows us to fit all the requisite data with the dark fluid being the dominant component of the dark matter of the Universe. A remarkable feature of the model is that we can do all this with a microphysical $w > 0$. We also display a field theoretic model that yields this equation of state.

KEYWORDS: cos,ctg.
The nature of the dark energy component of the Universe [1, 2, 3] remains one of the deepest mysteries of cosmology. There is certainly no lack of candidates: a remnant cosmological constant, quintessence[4], k-essence[5], phantom energy[6]. Modifications of the Friedmann equation such as Cardassian expansion[9] as well as what might be derived from brane cosmology[10] have also been used to try to explain the acceleration of the Universe.

In this work, we offer a new candidate for the dark energy: Wet Dark Fluid (WDF). This model is in the spirit of the generalized Chaplygin gas (GCG) [11], where a physically motivated equation of state is offered with properties relevant for the dark energy problem. Here the motivation stems from an empirical equation of state proposed by Tait [7, 8] in 1888 to treat water and aqueous solutions. The equation of state for WDF is very simple,}

\[ p_{WDF} = w(\rho_{WDF} - \rho_*) \],

and is motivated by the fact that this is a good approximation for many fluids, including water, in which the internal attraction of the molecules makes negative pressures possible. One of the virtues of this model is that the square of the sound speed, \( c_s^2 \), which depends on \( \partial p/\partial \rho \), can be positive (as opposed to the case of phantom energy, say), while still giving rise to cosmic acceleration in the current epoch.

In real fluids negative pressures eventually lead to a breakdown of Eq. (1) due to cavitation [12], but for now we simply treat Eq. (1) as a phemenological equation[13]. We will show that this model can be made consistent with the most recent SNIa data[14], the WMAP results[15] as well as the constraints coming from measurements of the matter power spectrum[16]. The parameters \( w \) and \( \rho_* \) are taken to be positive and we restrict ourselves to \( 0 < w < 1 \). Note that if \( c_s \) denotes the adiabatic sound speed in WDF, then \( w = c_s^2 \).

To find how the WDF energy density scales with the scale factor \( a \), we use the energy conservation equation together with the equation of state in Eq. (1):

\[ \dot{\rho}_{WDF} + 3H(p_{WDF} + \rho_{WDF}) = 0 \]

\[ \Rightarrow \rho_{WDF} = \frac{w}{1 + w \rho_* + D(a_0/a)^{3(1+w)}} \],

where \( D \) is a constant of integration and \( a_0 \) is the scale factor today; we will set \( a_0 = 1 \) from now on.

WDF naturally includes two components: a piece that behaves as a cosmological constant as well as a piece that redshifts as a standard fluid with an equation of state \( p = w\rho \). We can show that \textit{if} we take \( D > 0 \), this fluid will never violate the strong energy condition \( p + \rho \geq 0 \):

\[ p_{WDF} + \rho_{WDF} = (1 + w)\rho_{WDF} - w\rho_* \]

\[ = D(1 + w)(\frac{a_0}{a})^{3(1+w)} \geq 0. \]

It is tempting to try to use the second component as the dark matter, thus unifying the two dark components. There is the potential problem that since the sound speed of the second component is non-zero, this would give rise to a pressure gradient term in the equation for linear fluctuations. At least in the case of the Chaplygin gas, this has been shown to slow down the growth of fluctuations to a level that would be inconsistent with measurements of the power spectrum[17] as well as with
the CMB fluctuations (although see [18, 19] for possible ways out of this predicament). We will start off by assuming that WDF does not cluster gravitationally and that the formation of structure is driven, as in the standard ΛCDM model, by the clustering of a cold dark matter component (this was done in ref.[20] for the GCG model). Later on in the paper, we will examine whether and to what extent fluctuations in the matter power spectrum (MPS) are suppressed if we allow fluctuations in the WDF fluid and whether adjusting the tilt of the power spectrum could reduce such a suppression.

The Friedmann and acceleration equations for the WDF/CDM system in a spatially flat FRW universe are:

\[ H^2 = H_0^2 \left[ \Omega_{CDM} a^{-3} + \Omega_{WDM} a^{-3(1+w)} + \Omega_{WDE} \right] \]

\[ \frac{\ddot{a}}{a} = -\frac{H_0^2}{2} \left[ \Omega_{CDM} a^{-3} - 2(\Omega_{WDE} + \Omega_{WDM}) + 3(1+w)\Omega_{WDM} a^{-3(1+w)} \right], \]

where WDE, WDM stand for wet dark energy/matter respectively and

\[ \Omega_{WDE} = \frac{8\pi G_N}{3H_0^2} \frac{w}{1+w}\rho_\star, \quad \Omega_{WDM} = \frac{8\pi G_N}{3H_0^2} D, \]

(5)

with \( \Omega_{WDE} + \Omega_{WDM} + \Omega_{CDM} = 1 \). We can also rewrite the equation of state in the more traditional form \( p_{\text{WDF}} = w_{\text{eff}}(z)\rho_{\text{WDF}} \) where

\[ w_{\text{eff}}(z) = \frac{w}{\Omega_{WDM}} \frac{\Omega_{WDM}(1+z)^{3(1+w)} - \Omega_{WDE}}{\Omega_{WDM}(1+z)^{3(1+w)} + \Omega_{WDE}}. \]

(6)

We see that \( w_{\text{eff}} \) interpolates between \( w \) at early times and \(-1\) at late times. Note that this is of a similar form to that used in [21], except that some of the parameters in their \( w_{\text{eff}} \) that they take to be positive are in fact negative in our version.

There are some obvious constraints our model must satisfy, namely that the WDM component of WDF should not dominate the energy density of the Universe at nucleosynthesis. Comparing the energy density of WDM to that of radiation, we find

\[ \frac{\rho_{\text{WDM}}}{\rho_{\text{rad}}} = \frac{\Omega_{WDM}}{\Omega_{\text{rad}}} (1+z)^{3w-1}. \]

(7)

Since the CDM and WDE components can be neglected at nucleosynthesis, we find that we can obtain a relation between \( w \) and \( \Omega_{WDM} \) by making use of [22]

\[ \rho_{\text{rad}} = \frac{\pi^2}{30} g_\star(T) T^4, \]

(8)

where \( g_\star(T \sim 1 \text{ MeV}) = g_\star^{\text{standard}} + \Delta g_\star \). The contribution of standard model particles in thermal equilibrium at \( T \sim 1 \text{ MeV} \) is \( g_\star^{\text{standard}} = 10.75 \). Standard BBN light element abundances lead to the bound \( g_\star(T \sim 1 \text{ MeV}) \leq 12.50 \), which in turn leads to:

\[ \Delta g_\star = \frac{\Omega_{WDM}}{\Omega_{\text{rad}}} (1+z_{\text{Nuc}})^{3w-1} g_\star^{\text{standard}} \leq 1.75 \Rightarrow \frac{\Omega_{WDM}}{\Omega_{\text{rad}}} \leq 0.16 (2.36 \times 10^{-10})^{3w-1}. \]

(9)

Using the value \( h = 0.7 \) for the Hubble parameter we find that getting the correct light element abundances imposes the following constraint: \( \ln \Omega_{WDM} \leq 11.0 - 66.5 \, w. \)
As mentioned above, we considered three distinct experiments: 1) CMB measurements from WMAP[15], 2) matter power spectrum from the 2dF survey[16] and 3) type Ia supernovae observations[14]. We used CMB-Fast[24] to compute the scalar power spectrum and the transfer functions for our equation of state. The transfer functions were then used to obtain the matter power spectrum.

To fit to the supernovae data we integrated
\[ d_L(z) = (1 + z) \int_0^z \frac{dz'}{H(z')} \]
umerically to obtain the red-shift/distance modulus relation for our model. We then simultaneously fit all three experiments by constructing the combined \( \chi^2 \). Although the full model has a number of parameters, including many nuisance parameters, in practice the CMB data places strong enough constraints on the domain of \( \Omega_{WDM} \) so that we can fix most of the parameters to their best fit value from \( \Lambda\)CDM, leaving us free to consider \( w \) and \( \Omega_{WDM} \). We calculated the combined \( \chi^2 \) on a grid of \( w, \Omega_{WDM} \) values to identify the confidence regions and found that the fit is primarily constrained by the CMB and the matter power spectrum, both of which generate similar confidence regions. The supernova data places only rather weak constraints on our model, as it only probes low \( z \) where the model looks identical to \( \Lambda\)CDM. Our best fit model has a combined \( \chi^2 \) statistically equivalent to the \( \chi^2 \) for \( \Lambda\)CDM.

Figure (1) indicates the confidence regions in the \( w, \Omega_{WDM} \) plane; figures (2), (3) and (4) depict, for the particular values of \( w \) and \( \Omega_{WDM} \) listed in table (1), the redshift-distance modulus relation and the CMB power spectrum and matter power spectrum respectively. Unless otherwise noted the models assume standard values for cosmological parameters: \( \Omega_{WDE} + \Omega_{WDM} = 0.73 \), \( \Omega_{CDM} = 0.226 \) and \( \Omega_b = 0.046 \). From these figures we see that there are parameter values for which smooth WDF provides as good a fit to all the available data as the concordance model based on \( \Lambda\)CDM. The trend from the \( \chi^2 \) contours is to drive \( \Omega_{WDM} \) to be relatively small, of order \( \Omega_{WDM} \sim 10^{-6} - 10^{-7} \), although larger values can be used by paying a relatively small price in the \( \chi^2 \) value. While the scaling behavior of WDM is such that it would dominate over radiation at some point, the smallness of \( \Omega_{WDM} \) means that this event lies sometime in the future history of the Universe.

What has become increasingly clear from various parameterizations of the equation of state is

| Description | Set 3* | \( \Omega_{CDM} = 0.004 \) | \( \Omega_{WDM} \) | \( w \) | \( \chi^2 \) |
|-------------|--------|-----------------|----------------|-----|-------|
| Set 3       | 2.850 \times 10^{-1} | 0.300000 | \( 0.200000 \) | 1.000 \times 10^{-3} | 2425.883 |
| Large \( \Omega_{WDM} \) good fit | 1.995 \times 10^{-4} | 0.031623 | \( 0.316228 \) | 5.012 \times 10^{-7} | 428.806 |
| Best fit point (approximate) | 427.291 | \( - \) | \( - \) | 427.263 |
| Concordance model | 428.806 | \( - \) | \( - \) | 427.291 |
| Sample point outside 2\( \sigma \) contour | 2425.883 | \( - \) | \( - \) | 2425.883 |
that it must be very close to ΛCDM at least up to $z \approx 1100$. This follows primarily from the precision CMB and matter power spectrum measurements. It is important that the equation of state be physically reasonable and approximate ΛCDM in the appropriate regime. However, we need to be able to distinguish it from ΛCDM and hopefully this will be possible by considering the growth of perturbations. This assumes additional significance when we consider that the model differs significantly from ΛCDM only behind the surface of last scattering, a region quite inaccessible to current experiments.
Let's now turn to the possibility that the WDF is also affected by the primordial density perturbations generated in the early universe, perhaps through an inflationary phase. If we consider the hydrodynamics of a fluid governed by some general equation of state characterized by $p = w(\rho)\rho$ and $v^2 = dp/d\rho$ then linear perturbation theory tells us that the evolution of perturbations is governed by \[29\]
\[
\ddot{\delta} + 8H\dot{\delta} + 15H^2 \delta = -\left(\frac{kv}{a}\right)^2 \delta.
\] (10)

where $\delta = \delta \rho/\rho$ and $k$ is the wavenumber of the mode. In the $\Lambda$CDM case the cosmological constant is homogeneous so that we need only consider the perturbations in the CDM component for which eq.(10) reduces to
\[
\ddot{\delta} + 2H\dot{\delta} - \frac{3}{2}H^2 \delta = 0.
\]

If we allow perturbations in the WDF, the scenario is quite different as the sound speed is a nonvanishing constant and $w(a)$ is no longer constant. At late times when $w \to -1$ we find
\[
\ddot{\delta} + 8H\dot{\delta} + 15H^2 \delta = -\left(\frac{kv}{a}\right)^2 \delta.
\] (11)

However, the fact that $w(a)$ does vary in time, will significantly modify the behavior of some of the modes. We recognize from the RHS of Eq. (11) a $k$ dependent suppression and that the coefficients of the homogeneous equations differ substantially from those of the $\Lambda$CDM case. We have used these equations in CMB-Fast to calculate the CMB angular correlations, and the matter power spectrum for various models. The results are quite interesting. If we normalize our calculated CMB power spectrum to the location and height of the first peak we find that even for $\Omega_{WDM} \geq \Omega_{CDM}$, our model agrees well with the WMAP results as seen in figure (5). The change in $\chi^2$ from the concordance model is just $\Delta \chi^2 = 5.3$ for $\Omega_{WDM} = \Omega_{CDM}$. Furthermore, with this normalization, our power spectrum also exhibits a low-$l$ suppression.

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**Figure 4:** The matter power spectrum in a WDF dominated universe.
As one might suspect, the matter power spectrum provides more restrictions on the model, as it probes higher values of $k$. As shown in Fig. (6) we observe an overall suppression in the MPS, as well as an enhancement of the baryon oscillations leading to $\Delta \chi^2 = 63.2$. The matter power spectrum constrains $\Omega_{\text{CDM}}$ to be greater than $\Omega_{\text{WDM}}$. However, this suppression can be compensated by increasing the tilt of the power spectrum without significantly affecting the fit to the WMAP data. This gives rise to a significant improvement of the fit, with $\Delta \chi^2 = 3.7$. 

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**Figure 5:** CMB temperature anisotropy with perturbed WDF and CDM

**Figure 6:** Matter power spectrum illustrating suppression. A tilted initial power spectrum can compensate for the suppression.
We have considered both smooth and perturbed WDF fluids. However, it would be very useful to have a field theoretic, microphysical model that could give rise to the WDF equation of state. We could use this to study the evolution of perturbations in a more detailed manner and it’s possible that entirely different properties may emerge when we consider candidate microphysical theories.

Consider the following scalar field lagrangian [25]:

\[ \mathcal{L} \equiv \mathcal{L}(X) \text{ where } X = g_{\mu \nu} \partial^\mu \phi \partial^\nu \phi. \]  

(12)

Such a Lagrangian can be made technically natural by the imposition of the shift symmetry \( \phi \rightarrow \phi + \text{const}. \) Computing the resulting stress-energy tensor we find

\[ T^\mu_\nu = -\mathcal{L} \delta^\mu_\nu + 2\partial^\mu \phi \partial_\nu \phi \frac{d\mathcal{L}}{dX}, \]  

(13)

from which we can obtain expressions for the energy density and pressure once we make assumptions of spatial homogeneity and isotropy. These assumptions imply that \( \partial_i \phi = 0 \) and \( X = \dot{\phi}^2 \), so we can write

\[ \rho = -\mathcal{L} + 2X \frac{d\mathcal{L}}{dX}, \]

\[ p = \mathcal{L}. \]  

(14)

Now, assume that the “vacuum” state this theory finds itself in has a non-zero value for \( X[26] \). Then we can arrive at a choice of \( \mathcal{L} \) that will give rise to the WDF equation of state by having \( \mathcal{L} \) satisfy the following differential equation:

\[ \frac{2w}{1+w} X \frac{d\mathcal{L}}{dX} - \mathcal{L} - \frac{w}{1+w} \rho_\star = 0. \]  

(15)

If we define \( \gamma = \frac{1+w}{w} \) and \( M \) an arbitrary constant with units of mass we can write the solution as:

\[ \mathcal{L}(X) = (M^2)^{2-\gamma} X^{\frac{\gamma}{2}} - \frac{\rho_\star}{\gamma}. \]  

(16)

The Euler-Lagrange equation following from this Lagrangian is

\[ \ddot{\phi} + 3w \frac{\dot{a}}{a} \dot{\phi} = 0 \]  

(17)

which implies \( \dot{\phi} \propto a^{-3w}. \)

While this lagrangian does serve our purpose, further work is required to investigate the nature of perturbations about the homogenous solution. We begin this work by constructing the equation for field fluctuations around this background. This entails the replacing of \( \phi \) with \( \phi + \varphi \) and the evaluation of the contributions to the stress energy and equation of motion, keeping only the first order terms in \( \varphi. \) We find

\[ \delta T^0_0 = -\gamma_1 \frac{\dot{\varphi}}{\phi} (\rho + p), \]  

(18)

\[ \delta T^0_i = -k_i \varphi \frac{\dot{\varphi}}{\phi} (\rho + p) \text{ and } \]  

(19)

\[ \delta T^0_0 = \frac{\dot{\varphi}}{\phi} (\rho + p) \delta^i_j. \]  

(20)
for the first order contributions to the stress energy, where the \((\rho + p)\) are the background homogeneous values. We need to choose a gauge to write the equation of motion and here we pick the conformal synchronous gauge\[27\] so that we find

\[
(\gamma - 1)\ddot{\phi} + (4 - \gamma)\frac{\dot{a}}{a}\dot{\phi} + k^2\phi + \frac{3}{2}\dot{\phi}h = 0,
\]

where \(h\) represents the scalar metric perturbations. To go further we have to encode these contributions in CMBFast and integrate them. We will pursue this procedure in a future work.

To conclude, we’ve started with an equation of state that is extremely simple and has a “microphysical” parameter \(w\) that is \textit{positive} and bounded so that the adiabatic sound speed in this fluid is less than 1. Furthermore, this equation of state describes the behavior of fluids as simple as water! From this we have extracted a cosmological model that agrees with all available data and is as statistically valid as the current favorite model, \(ΛCDM\). We would argue that this ushers in a new paradigm in understanding dark energy in the sense that we can move away from demanding that the microphysical \(w\) be negative and we can certainly offer an alternative to considering \(w < -1\)! Furthermore, we have come up with a proof of principle lagrangian that can describe this system. The next step is to see how the perturbations from this class of theories behaves, relative to \(ΛCDM\), models, say. This work is in progress.

Note: While we were writing this work up, [28] appeared which also deals with this equation of state. Their viewpoint is directed more towards the eventual fate of a Universe dominated by a WDF-like equation of state and does not have much overlap with the discussion in this paper.

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