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LETTERS

DES map shows a smoother distribution of matter than expected: a possible explanation

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Abstract The largest and most detailed map of the distribution of dark matter in the Universe has been recently created by the Dark Energy Survey (DES) team. The distribution was found to be slightly (by a few percent) smoother and less clumpy than predicted by general relativity. This result was considered as a hint of some new physical laws. In the present paper we offer a relatively simple model that could explain the above result *without resorting to any new physical laws*. The model deals with the dynamics of a system consisting of a large number of gravitating neutral particles, whose mass is equal to the mass of hydrogen atoms. The central point of the model is a partial inhibition of the gravitation for a relatively small subsystem of the entire system. It would be sufficient for this subsystem to constitute just about a few percent of the total ensemble of particles for explaining the few percent more smooth distribution of dark matter (observed by the DES team) compared to the prediction of general relativity. The most viable candidate for the dark matter particles in this model is the second flavor of hydrogen atoms (SFHA) that has only S-states and therefore does not couple to the electric dipole radiation or even to higher multipole radiation, so that the SFHA is practically dark. The SFHA has experimental confirmation from atomic experiments, it does not go beyond the Standard Model, it is based on standard quantum mechanics and it explains puzzling astrophysical observations of the redshifted line 21 cm from the early Universe. Thus, our model explaining the DES result of a little too smooth distribution of dark matter *without resorting to any new physical laws* seems to be self-consistent.

Key words: (cosmology:) dark matter — gravitation — atomic processes — astroparticle physics

1 INTRODUCTION

The largest and most detailed map of the distribution of dark matter in the Universe has been recently created by the Dark Energy Survey (DES) team (Chang et al. 2018; Jeffrey et al. 2021). The distribution was found to be slightly (by a few percent) smoother and less clumpy than predicted by general relativity (Jeffrey et al. 2021). This result was considered as a hint of some new physical laws. In the present paper we offer a relatively simple model that could explain the above result *without resorting to any new physical laws*. The model deals with the dynamics of a system consisting of a large number of gravitating neutral particles, whose mass is equal to the mass of hydrogen atoms. The central point of the model is a partial inhibition of gravitation for a relatively small part of the system.

2 THE MODEL

We consider a system of a large number of gravitating neutral particles of mass M equal to the mass of hydrogen atoms. (The nature of the particles will be specified later on.) At any instant of time, the system has a subsystem of relatively isolated pairs of particles, i.e., pairs where the separation within the pair is much smaller than their distance to other particles. The subsystem is open. This means that after some time, some pairs would not qualify any more as subsystem members (because they can no longer be considered as relatively isolated), while some other pairs could become relatively isolated and qualify as new members of the subsystem. Here the word "subsystem" means a subset of particles within the ensemble - the subset of pairs (not located in one particular volume) that are relatively isolated. The pairs lose energy by gravitational radiation and the separation within the pair decreases. This is similar to the classical description of a usual hydrogenic atom or ion: it emits electromagnetic radiation and the separation between the electron and the nucleus decreases. While classically the latter process would lead to the fall of the electron into the nucleus, in the quantum description there arises the average minimum separation $R_{\rm min}$ (the Bohr radius in the case of hydrogen atoms), at which the "fall" of the electron into the nucleus stops

$$R_{\rm min} = \hbar^2/(\mu\alpha). \quad (1)$$

In Equation (1), μ is the reduced mass of the pair and α is the coupling coefficient in the corresponding potential energy V

$$V = -\alpha/R. \quad (2)$$

Similarly, for the pairs of gravitating particles, there is the average minimum separation, at which the gravitational radiation stops and there is no further decrease in the separation within the pair. In this situation, one has

$$\mu = M/2,\ \alpha = GM^2, \quad (3)$$

(where G is the gravitational constant), so that

$$R_{\rm min} = 2\hbar^2/(GM^3). \quad (4)$$

On substituting the mass M equal to the mass of hydrogen atoms in Equation (4), we get $R_{\rm min} = 2.3$ Mpc. This is practically the same as the average observed separation between galaxies. So, at the separation within the pair of gravitating particles $R \sim R_{\rm min}$, their further approach to each other stops. This is equivalent to a partial inhibition of classical gravitation. In other words, if the minimum non-zero separation $R_{\rm min}$ did not exist, then the average separation within any such pair of two gravitating hydrogen atoms would become smaller and smaller without any lower limit (corresponding to the uninhibited "clumping" of dark matter). However, due to the existence of the minimum non-zero separation $R_{\rm min}$, the further "clumping" becomes inhibited for such pairs. In terms of the total ensemble of hydrogen atoms, the further "clumping" becomes inhibited only for a relatively small part of the ensemble: for the subsystem of such pairs. We note that because the subsystem of such pairs of hydrogen atoms is relatively small, this effect manifests only in some additional smoothness of the dark matter distribution, but it does not manifest in the rotation curves of galaxies. Now let us address the following question: how much time does it take for the pair of gravitating hydrogen atoms to reach the state of non-zero minimal separation. In Appendix A we show that the corresponding time T scales with the initial angular momentum L_0 of the pair as L_0^3. Consequently, for sufficiently small L_0, the time T can be much smaller than any benchmark. For instance, it can be not only much smaller than the age of the Universe, but also much smaller than the duration of any specific stage of the Universe evolution. Next, we estimate the percentage of such pairs of hydrogen atoms in the total ensemble of hydrogen atoms. According to quantum mechanics, for a given principal quantum number n, describing the gravitating pair of hydrogen atoms, the angular momentum L_0 can take the following n values: $0, \hbar, 2\hbar, ..., (n-1)\hbar$, where $\hbar$ is the Planck constant. Let us assume that only for $L_0 = 0$, the time T is smaller than the corresponding benchmark time, characterizing the Universe or its stage of evolution. In the subsystem of pairs, each pair can be initially in the state of some particular principal quantum number $n \leqslant n_{\rm max}$, where the value of $n_{\rm max} \gg 1$ will be estimated in the next paragraph. Then the total number K of possible values of the initial values L_0 of the angular momentum is the following

$$K = \sum_{n=1}^{n_{\rm max}} n = n_{\rm max}(n_{\rm max}+1)/2 \approx n_{\rm max}^2/2, \quad (5)$$

where in the utmost right side we used the inequality $n_{\rm max} \gg 1$. The number of pairs of $L_0 = 0$ is

$$k = \sum_{n=1}^{n_{\rm max}} 1 = n_{\rm max}. \quad (6)$$

Thus, the share of pairs, having enough time to reach the state of non-zero minimal separation (the ground state, corresponding to inhibition of the gravitational interaction), is

$$k/K \approx 2/n_{\rm max}. \quad (7)$$

The value of $n_{\rm max}$ can be estimated as follows. According to quantum mechanics, the average size R of a pair of hydrogen atoms in the state of the principal quantum number n is

$$R \sim n^2 R_{\rm min}, \quad (8)$$

where $R_{\rm min}$ is given by Equation (4). The maximum possible value of R should be smaller or of the order of magnitude of the radius of the Universe R_U. Consequently, we get

$$n_{\rm max} \lesssim (R_U/R_{\rm min})^{1/2}. \quad (9)$$

Since $R_{\rm min} \sim 2.3$ Mpc and $R_U \sim 1.4\times10^4$ Mpc, Equation (9) yields $n_{\rm max} \lesssim 80$. Then, according to Equation (7), the share of pairs, having enough time to reach the ground state (corresponding to the inhibition of the gravitational interaction) is

$$k/K \gtrsim 1/40 = 2.5\%\,. \quad (10)$$

This estimate of the percentage of the pairs, exhibiting the inhibition of gravitational interaction and thus the inhibition of unlimited "clumping", agrees with (and could explain) the few percent more smooth, less clumpy distribution of dark matter (observed by the DES team) compared to the prediction from general relativity.

Now let us address the question of whether dark matter particles can have the mass of hydrogen atoms. There is a definitive proof from atomic experiments that there are two kinds – or two flavors – of hydrogen atoms: the usual ones and the second flavor (Oks 2001). Only the existence

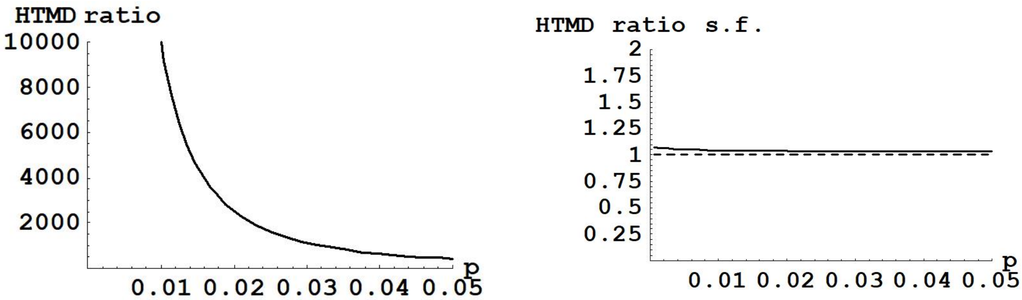

Fig. 1 Ratio of the theoretical and experimental results for the HTMD. Left panel: for the ground state of usual hydrogen atoms. Right panel: for the ground state of the SFHA signified by the *solid line*; the *dashed line* is the horizontal line at HTMD $= 1$ shown for visualizing how close the *solid line* is to unity. The linear momentum p is in units of mc, where m is the electron mass and c is the speed of light.

of this alternative kind of hydrogen atom eliminated a huge (many orders of magnitude) discrepancy between the experimental and theoretical results for the high energy tail of the linear momentum distribution (HTMD) in the ground state of hydrogen atoms (Oks 2001) – see Figure 1.

The second flavor of hydrogen atoms (SFHA) has only states of zero angular momentum (the S-states) both in the discrete and continuous spectra (Oks 2001; Oks 2020a; Oks 2020b). Therefore, due to the selection rules, the SFHA does not have states that can be coupled by electric dipole radiation, as noted in those papers. Moreover, the SFHA cannot be coupled by electric quadrupole or a higher multipole radiation either. (This fact is new: it was not mentioned in the above-referenced papers.) This is because the quadrupole, octupole and all higher multipole terms, containing linear combinations of various powers of the radius-vector operator **r** of the atomic electron, yield zeros in all orders of the perturbation theory – both diagonal and non-diagonal matrix elements of the operator **r** are zeros for the S-states. Therefore, the SFHA is practically "dark": it is dark in all ranges of the electromagnetic spectrum except for the 21 cm line, corresponding to the radiative transition between the hyperfine sublevels of the ground state. In addition to the definitive proof from atomic experiments, there seems to be also other evidence in favor of the existence of the SFHA – from astrophysics. Its existence can explain recent puzzling astrophysical observations concerning the redshifted 21 cm radio line from the early Universe (Bowman et al. 2018): the explanation presented in Oks (2020a) did not require resorting to hypothetical, never discovered subatomic particles – in contrast to the explanation from Barkana (2018)[1]. It should be emphasized that the SFHA did not result from changing physical laws. In fact, the description of the SFHA is based on standard quantum mechanics: namely, on the employment of the so-called "singular" solution of the Dirac equation (Oks 2001). The SFHA is the only candidate for dark matter that has the following four features simultaneously: 1) it has experimental confirmation, namely from the analysis of atomic experiments (Oks 2001); 2) it does not go beyond the Standard Model (and thus is favored by the principle of Occam's razor); 3) it is based on standard quantum mechanics – without any change to physical laws (and thus is favored by the principle of Occam's razor); 4) it explains the puzzling astrophysical observations by Bowman et al. (2018). Thus, the SFHA is a viable candidate for dark matter or at least a part of it. Therefore, the above model explaining the DES result of a little too smooth distribution of dark matter seems to be self-consistent.

3 CONCLUSIONS

We analyzed a system of a large number of gravitating neutral particles, whose mass is equal to the mass of hydrogen atoms, and focused at the subsystem of relatively isolated pairs of these particles. The pairs lose energy by gravitational radiation and the separation within the pair decreases. We demonstrated that this process would stop as the separation between the particles within the pair would decrease to the minimum value of the order of a few megaparsecs. This minimum value is practically the same as the average observed separation between galaxies. The termination of gravitational radiation and of the further decrease in the separation of the particles with the pairs is equivalent to a partial inhibition of classical gravitation. Our estimate of the percentage of the pairs, exhibiting the inhibition of gravitational interaction and thus the inhibition of unlimited "clumping", is $\gtrsim 2.5\%$. This agrees with the percentage observed by the DES team: the few percent more smooth, less clumpy distribution of dark matter compared to the prediction from general relativity. Dark matter particles having the mass of hydrogen atoms

[1] We note that McGaugh (2018) examined the results by Bowman et al. (2018) and by Barkana (2018), and came to the following important conclusion: the observations by Bowman et al. (2018) constitute an unambiguous proof that dark matter is baryonic, so that models introducing a non-baryonic nature of dark matter have to be rejected.

could be the SFHA that has only S-states and therefore does not couple to the electric dipole radiation or even to higher multipole radiation, so that the SFHA is practically dark[2]. The SFHA has experimental confirmation from atomic experiments, it does not go beyond the Standard Model, it is based on standard quantum mechanics and it explains the puzzling astrophysical observations by Bowman et al. (2018). Thus, our model explaining the DES result of a little too smooth distribution of dark matter *without resorting to any new physical laws* seems to be self-consistent. While the model is relatively simple – just to get the message across – we hope it would motivate further studies.

Appendix A: TIME REQUIRED TO REACH THE STATE OF NON-ZERO MINIMAL SEPARATION

For a pair of two hydrogen atoms revolving in elliptical orbits about their barycenter, the loss of energy E and of angular momentum L (both averaged over the period of motion) per unit time due to gravitational radiation is given by the following expressions (see, e.g., the textbook by Landau & Lifshitz (1975)):

$$d|E|/dt = \frac{64G^4M^5(1+73e^2/24+37e^4/96)}{[5c^5a^5(1-e^2)^{7/2}]}, \quad (A.1)$$

$$dL/dt = -\frac{2^{11/2}G^{7/2}M^{9/2}(1+7e^2/4)}{[5c^5a^{7/2}(1-e^2)^2]}. \quad (A.2)$$

In Equations (A.1) and (A.2), G is the gravitational constant, M is the hydrogen atom mass (to distinguish from which we denoted the angular momentum by L); a and e are the semi-major axis and the eccentricity of the elliptical orbit, respectively

$$a = GM^2/(2|E|),\ e = [1-4|E|L^2/(G^2M^5)]^{1/2}. \quad (A.3)$$

We are interested in elliptical orbits with a relatively large eccentricity, such as

$$(1-e^2) = 4|E|L^2/(G^2M^5) \ll 1. \quad (A.4)$$

In this situation, Equations (A.1) and (A.2) simplify as follows:

$$d|E|/dt \approx 170G^4M^5/[3c^5a^5(1-e^2)^{7/2}], \quad (A.5)$$

$$dL/dt \approx -2^{7/2}11G^{7/2}M^{9/2}/[5c^5a^{7/2}(1-e^2)^2]. \quad (A.6)$$

After dividing Equation (A.5) by Equation (A.6) and substituting a and e from Equation (A.3), we get

$$d|E|/dL \approx -425G^2M^5/(264L^3). \quad (A.7)$$

By integrating Equation (A.7), we obtain

$$|E| \approx |E_0| + (425/528)G^2M^5(1/L^2 - 1/L_0^2), \quad (A.8)$$

where E_0 and L_0 are the initial values of the energy and angular momentum, respectively. On substituting in Equation (A.6) the expressions for a and e from Equation (A.3), as well as the expression for $|E|$ from Equation (A.8), we find

$$dL/dt \approx -[88G^4M^{15/2}|E_0|^{3/2}/(5c^5L^7)] \times [L^2 + b(L_0^2 - L^2)]^{3/2}, \quad (A.9)$$

where

$$b = 425G^2M^5/(528L_0^2|E_0|).$$

After integrating Equation (A.9) in the limits from L_0 to 0 (with respect to L) and from 0 to T (with respect to t), we obtain

$$T \approx c^5L_0^5(1+4b^{1/2}+5b)/[88G^4M^{15/2}|E_0|^{3/2}]. \quad (A.10)$$

From Equation (A.4) it follows that $b \gg 1$, so that $(1 + 4b^{1/2} + 5b) \approx 5b$ and Equation (A.10) simplifies to the following final form

$$T \approx 2125c^5L_0^3/(46\,464G^2M^{5/2}|E_0|^{5/2}). \quad (A.11)$$

From Equation (A.11) it is seen that the time T, required for two gravitating hydrogen atoms to reach the state of non-zero minimal separation (the ground state), scales with the initial angular momentum L_0 as L_0^3. Therefore, for sufficiently small L_0, the time T can be much smaller than any benchmark: e.g., much smaller than the age of the Universe or even much smaller than the duration of any specific stage of the Universe's evolution.

[2] There is also a slight difference between the SFHA and usual hydrogen atoms in cross-sections of charge exchange with an incoming proton (Oks 2021).

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