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Holeum in the Century of Gravitation

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ABSTRACT

An exactly solvable effective model of quantum gravity is reviewed here. It is based on the conjecture that Primordial Black Holes may have formed stable gravitational atoms called Holeums in the early universe. A remarkable prediction of this model is that the Cosmic Rays and the very short duration Gamma Ray Bursts (GRBs) are merely two different components of the Hawking Radiation emitted by two Primordial Black Holes liberated when their parent Holeum suffers an ionizing collision. The model gives a unified treatment of ten cosmological phenomena in terms of Holeums: (1) Dark Matter (2) Cosmic Rays (3) Ultra High Energy Cosmic Rays (4) The GZK feature in the Ultra High Energy Cosmic Rays (5) Very short duration GRBs (6) Reality of Hawking Radiation (7) Gravitational Waves (8) Invisibility of Galactic Halos (9) Invisibility of Domain Walls(10) The ultimate fate of the PBHs. Strong indirect observational evidence for Holeums comes from Cosmic Rays and GRBs. The results of the Ice

Cube collaboration support the predictions of the Holeum model. LIGO may be able to detect the gravitational waves emitted by the Holeums. A direct detection test of Holeums is suggested.

Key words: Cosmic rays, dark matter, diffuse galactic gamma ray background, gamma ray bursts, gravitational waves, Hawking radiation, Holeum, Ice Cube, LIGO.

1. INTRODUCTION

In recent years major financial and manpower resources are being committed to the experimental study of the gravitational interaction and related phenomena (Maggiore, 2000; Maggiore, 2007). That is the reason why, in recent international conferences, the physicists have described the present century as the century of gravitation. In these conferences the experimentalists have called upon the theorists to make new predictions that can be tested in their experiments. The Holeum model was proposed to address this issue (Chavda and Chavda, 2002). Black hole binaries were also considered by Abdurashitov, Yants and Parfenov (2000) and Chavda (2000). Over the past decade the Holeum model has attempted to provide a unified account of Dark Matter (DM), Gravitational Waves , Cosmic Rays (Chavda and Chavda, 2004), Ultra High Energy Cosmic Rays (Chavda and Chavda, 2008; Chavda and Chavda, 2009)), Gamma Ray Bursts (Al Dallal, 2006)**,** Galactic Diffuse Gamma Ray Back Ground (Al Dallal, 2010), etc. The model has important implications for three major experiments going on right now: Laser Interferometer Gravity-wave Observatory (LIGO), the Ice Cube neutrino Observatory at the South Pole and Large Hadron Collider (LHC). LIGO may be able to detect the low frequency quantized gravitational radiation emitted by the atomic transitions of Holeums. The Ice Cube collaboration (2012) has already ruled out the Fire Ball model of Gamma Ray Bursts (GRB).The LHC is expected to produce micro black holes soon. If this is confirmed, it may pave the way for the laboratory production of the Holeums. These could be the first man-made atoms of DM. The Holeum model is reviewed in detail. Properties, observational evidence and tests for Holeums are described. Conclusions appear at the end.

2.0 MOTIVATION

2.1 The Holeum Conjecture: To address the issue of the experimentalists' calls for new predictions, we have made the conjecture that the Primordial Black Holes (PBHs) produced in the early universe may have formed stable gravitationally bound atoms that we call Holeums. The motivation for this conjecture is as follows: On the one hand it is known that a vast quantity of PBHs was produced in the early universe (Chavda and Chavda, 2008; Chavda and Chavda, 2009)) and on the other the WMAP experiment (Gold et al, 2011; Komatsu et al, 2011) has revealed that the amount of DM in the universe today is nearly six times that of the visible matter. But the nature of this DM is unknown at present. If the PBHs formed stable Holeums the latter would be present today as DM and it would account for a substantial part of the large amount of the DM revealed by the WMAP. Thus, the Holeum conjecture gives us a new form of DM and a well-known source for it. However, the crucial question is whether extremely short lived PBHs would form bound states. Let us examine the evidence for it. Although the life times of the PBHs are extremely short, it turns out that the PBHs having masses greater than about ten percent of the Planck mass have life times hundreds of times greater than the life time of the universe itself at the Planck epoch. Moreover, the PBHs absorbed matter and radiation from the primordial brew of which they were a part. This further enhanced their life - times. In the early universe the number density of the primordial brew was enormous. The gravitational force was immensely stronger than what it is today. The rate of gravitational interactions among the PBHs exceeded that of the expansion of the universe. That is, before they could decay, the PBHs had a large number of interactions among themselves and that, too, with an immensely stronger gravitational force. All this indicates a possibility that the PBHs may have formed bound states. This conclusion receives further support from the observation that the unstable neutrons form absolutely stable nuclei such as those of Carbon, Nitrogen, Iron etc. Therefore we may hope that nature may have produced other stable bound states like the Holeums from unstable PBHs. Holeums may have been produced in the early universe before the inflation or later during the reheating of the universe. In view of the expected production of micro black holes in the LHC soon, we may even envisage the production of their bound states in the terrestrial laboratories in not too distant a future.

2.2 Physics Potential of Holeum : Black holes are invisible. So are the Holeums. Thus, a Holeum is an atom of DM. It is a gravitational analogue of the Hydrogen atom. Its atomic transitions radiate gravitational waves that may be detected by LIGO and similar detectors. Since a Holeum has only the gravitational interaction, the weakest of the four fundamental interactions, Holeums would segregate to the periphery of any mixture of particles of ordinary matter and Holeums. Thus, they would accumulate in the Galactic Halos (GH) and the Domain Walls (DW) separating neighbouring universes. Since the Holeums are invisible, so would be the GHs and the DWs. Pressure ionization of Holeums in GHs would lead to liberation of two black holes which would decay giving off the Hawking Radiation (HR). This would be detected on the earth as the Cosmic Rays (CR). Thus, even a cursory assessment presents a number of tasks to an experimentalist: direct detection of the Holeum as a particle of DM, gravity waves, CRs from galactic halos, etc.

3.0 SEARCH FOR THE THEORY

Thus, the Holeum conjecture is well-motivated and it has a considerable physics potential. Therefore it is worthwhile to study the formation and the properties of Holeums. The problem of formation of a Holeum is a quantum mechanical one very similar to that of the formation of a Hydrogen atom. But whereas the theory of the electromagnetic interaction, responsible for binding of the Hydrogen atom, is well established, such is not the case with the theory of the gravitational interaction.

3.1 General Relativity: Therefore we begin our search for the appropriate theory for the formation of Holeum with General Relativity (GR) as every one of its predictions has come true. But the GR is a purely classical theory. When quantized, it leads to paradoxes and inconsistencies. The bound state problem is not solvable in GR except for the case of two maximally charged dilaton black holes (Sakamoto and Shiraishi, 2002). Here we are considering two uncharged spinless black holes. In the Quantum Gravity Regime (QGR) the presently known quantum field theory is expected to break down. The space-time is expected to be foamy there. The six quarks and the six leptons that we regard as fundamental particles are expected to make way for more fundamental entities called strings. In QGR the universe may reveal the presence of extra dimensions. Thus, the GR is ruled out for the task at hand.

3.2 String Theory: During the past several decades theoretical physicists have tried to develop consistent quantized string theories keeping in mind the special considerations mentioned above. They have developed Super Gravity Theory, Super String Theory, Theory of Everything, etc. (Randall, 2005). But none of these mathematical structures has been able to make any predictions that can be verified experimentally. Thus, the string theories, too, are ruled out for the task at hand. Thus, on the one hand we have an impasse in theoretical physics and on the other an imminent flood of new experimental data demanding theoretical explanation. Instead of sitting on the fence we would like to develop an effective model of Quantum Gravity. This will enable us not only to explore the hitherto forbidden QGR but also to provide answers to the problems that would be posed by the new experimental data with a known degree of accuracy.

3.3 Standard Paradigm of Quantum Gravity (SPQG): To this end we take a brief look at the way theoretical physicists tackled similar problems in the past. In the last one and a quarter century there have been numerous "droughts" in theoretical physics such as the Atomic Drought, the Electro-Weak Drought, the Quantum Gravity Drought, etc. (1) During the Atomic Drought Bohr successfully applied the then newly discovered idea of quantization of energy to the problem of the spectrum of the Hydrogen atom. How this semi classical break- through triggered a series of developments culminating in the second quantized Quantum Electrodynamics is too well-known to need repetition. (2) Electroweak Drought: To remove infinities from the Fermi theory of weak interactions Glashow postulated the fourth quark which he called the Charm quark. He found that this led to further infinities in each order of perturbation but in such a way that the new infinities exactly cancelled the old ones. He explicitly verified the cancellation for many orders of perturbation. But he could not prove it for all orders. So he conjectured that the cancellation is true for all orders. Based on this conjecture neutral currents were predicted and experimentally discovered (Haidt, 1994; Hasert, 1973a; Hasert, 1973b; Hasert, 1974). The psi particle, containing the Charm quark, too, was discovered experimentally (Aubert et al, 1974; Augustine et al, 1974). These break- throughs eventually led to the development of a consistent renormalized Electroweak theory due to the efforts of many physicists (Quigg, 2002). (3) Quantum Gravity Drought: Hawking made a foray into the QGR using the existing Quantum Field theory regardless of its inadequacy for the task at hand. He came away with several important results (Wald, 2000) : (a) A black hole has a temperature inversely proportional to its mass.(b) Black holes decay giving off a thermal radiation, now called the Hawking Radiation. (c) He derived a formula for the life time of a black hole. An analysis of these cases shows a pattern, a paradigm: whenever faced with a new phenomenon, one tries to understand it, in the first instance, in terms of the best available theory, however incomplete and rudimentary it may appear. It leads to break- throughs and commendable results. This is because the extant theories pack the cumulative empirical and theoretical inputs. We call this the method of Standard Paradigm (SP). These three examples bear a testimony to the efficacy of the SP. We follow the same method to arrive at a mathematical model for the task at hand. We call it the Standard Paradigm of Quantum Gravity (SPQG). It consists of two ingredients: the Schrodinger equation and the Newtonian Gravity (NG). With the help of these we can solve the problem of the bound state of two black holes. But first, we must justify these choices.

3.3.1 Justification of Newtonian Gravity: The formation of Holeum takes place in the strong field regime where the GR rules. But both GR and the NG lead to paradoxes and inconsistencies when quantized. Thus, there is no guarantee that a quantized GR will give better results than a quantized NG. This is the main reason for the choice of NG. Further, we offer the opinions of the following four well-known cosmologists in favour of NG (Kourganov, 1980): (1) "It reveals all the essential features of relativistic cosmology without the mathematical complexity." (Bondi, 1952). (2) "It reveals the implicit simplicity of the cosmological equations…….. and offers insight into their physical nature." (Harrison, 1965). (3) "It is not only of pedagogical value but also of great heuristic value since (some problems) are too difficult to be taken into account within the framework of GR." (Zeldovich, 1965). (4) "(NG) prepares the way towards understanding relativistic cosmology. Not only is the Newtonian theory mathematically simpler, it also leads to many results that are essentially the same as in Relativity." (Sciama, 1971).

In summary, we choose the NG due to (a) a lack of a manifestly superior quantized alternative, (b) simplicity, (c) transparency and (d) the exact solvability of the problem at hand. (e) The NG is the exact asymptotic form of the GR.

3.3.2 Justification of Schrodinger Equation: The Schrodinger equation is a trustworthy tool of a theoretical physicist. It was discovered during the atomic era. It was the main tool to explore the properties of the atoms through their spectra. It was the main tool during the nuclear era, too. In particle physics the quarkonium systems were successfully investigated using the Schrodinger equation with three types of confining potentials (Papp, 1986). The discovery of the Asymptotic Freedom (Gross and Wilczek, 1973) namely that the inter-quark potential goes to zero as the inter-quark distance tends to zero, legitimized the use of the Schrodinger equation for the heavy quarkonia.

In Holeums the masses of the constituent black holes would be greater than about 10^{10} GeV/c^2 which makes a Holeum a non-relativistic system. This would justify the use of the Newtonian potential and the Schrodinger equation. But the formation of a Holeum occurs in the strong field regime where the GR rules. But as noted above the GR gives us no clue to the nature of the potential within and near the bound state.

3.3.3 Bound State Wisdom (BSW): A regularity obeyed by the bound states in three layers of matter comes to our rescue here (Chavda and Chavda 2002). We call it the Bound State Wisdom. It may be stated as follows." The use of the correct asymptotic form of the binding potential everywhere, both within and without the bound state, gives at least an order of magnitude correct values of the bound state parameters." Let us examine the evidence for this very interesting regularity.

3.3.3.1 Evidence from Particle Physics: The quarkonia systems were treated with three potentials that gave quantitatively successful description of the energy levels of both the Charmonium and the Bottomonium systems with the same set of parameters (Papp, 1986). These potentials are: (1) a Coulomb plus a linear potential, (2) a logarithmic potential and (3) a small positive power potential. All three potentials go to infinity at large distances. This signifies the confinement of quarks. But within and near the bound state they are wildly different. The first one is highly singular at the origin. The second one is only mildly singular at the origin but the third one is not at all singular there. And yet all of them gave quantitatively acceptable values of the energy levels of the two quarkonium systems. This is the most succinct display of the BSW.

3.3.3.2 Evidence from the Deuteron in nuclear physics: Some text book treatments of the Deuteron problem take an infinitely repulsive hard core potential within a finite, attractive square-well one. Other treatments simply ignore the hard core potential. The first one is highly singular while the other is not. And yet both treatments give acceptable values of the parameters of the Deuteron.

3.3.3.3 Evidence from the Hydrogen Atom: Bench Marking the BSW: Having looked at the nuclear and particle layers we now extend the BSW to the third, atomic, layer. We check the efficacy of it by applying it to the accurately known case of a Hydrogen atom. We drastically modify or truncate the r^{-1} Coulomb potential of the Hydrogen atom within and near the bound state and then check the effect it produces on the values of the bound state parameters. Since the same r^{-1} Newtonian potential governs the Holeum, this example is of direct relevance to us. Consider the modified Coulomb potential (Chavda and Chavda, 2002).

$$V(r) = - e^2/r_0 \qquad 0 \leq r \leq r_0 \qquad (1)$$

$$= - e^2/r \qquad r_0 \leq r \leq \infty \qquad (2)$$

Here e is the magnitude of the charge on an electron. We have discarded the highly singular r^{-1} potential within and near the bound state. Instead, we have assumed the potential to be finite and constant there. We pretend that we are ignorant of the exact form of the potential within the bound state. r_0 is the radius of the region of our ignorance. The radial Schrodinger equation for the s-states is given by

$$d^2u/dr^2 + (2\mu/\hbar^2)(E - V(r))u(r) = 0 \qquad (3)$$

Here u(r) is the s-wave radial wave function with u(0) = 0. μ is the reduced mass of the electron. ħ is the Planck's constant divided by 2 π. E is the total energy of the system. For the region I, $0 \le r \le r_0$, this reduces to

$$d^2u/dr^2 + (2\mu/\hbar^2)(e^2/r_0 - |E|)\, u(r) = 0 \qquad (4)$$

We define a set of dimensionless parameters and the independent variable as follows:

$$a = \hbar^2 / (\mu e^2) \qquad (5)$$

$$x = r / r_0 \qquad (6)$$

$$p = r_0 / a \qquad (7)$$

$$\varepsilon = |E|/V_a \qquad (8)$$

$$V_a = e^2/a \qquad (9)$$

$$\lambda_1^2 = 2p(1 - p\,\varepsilon) \qquad (10)$$

In terms of this notation we rewrite equation (4) as

$$u''(x) + \lambda_1^2 u(x) = 0 \qquad (11)$$

The solution to this equation, subject to the condition u(0) = 0, is given by

$$u(x) = A \sin(\lambda_1 x) \qquad (12)$$

For the region II, $r_0 \le r \le \infty$ or $1 \le x \le \infty$, we denote the radial wave function by v(r) . It satisfies the radial Schrodinger equation

$$d^2v/dr^2 + (2\mu/\hbar^2)(e^2/r - |E|)\, v(r) = 0 \qquad (13)$$

In terms of the dimensionless variable x it reduces to

$$v''(x) = 2p(p\,\varepsilon - 1/x)\, v(x) \qquad (14)$$

The asymptotic solution to this equation as $x \to \infty$ is given by

$$v(x) \to \exp(-\lambda_2 x) \qquad (15)$$

$$\lambda_2^2 = 2\,\varepsilon\,p^2 \quad (16)$$

Now we consider the variational treatment for only the 1s state and take its wave function to be

$$v(x) = (a + bx)\exp(-\lambda_2 x) \quad (17)$$

The continuity of the logarithmic derivative at x = 1 gives us

$$\lambda_1 \cot \lambda_1 = -\lambda_2 + b/(a+b) \quad (18)$$

Equating the two values of v''(1) from equations (14) and (17) we get

$$[-2b\lambda_2 + (a+b)\lambda_2^2]\exp(-\lambda_2) = 2p(p\varepsilon - 1)(a+b)\exp(-\lambda_2) \quad (19)$$

From equations (18) and (19) we get

$$\lambda_2^2 - \lambda_1^2 + 2\lambda_2\lambda_1 \cot\lambda_1 = 0. \quad (20)$$

This equation depends upon two parameters p and ε. p is related to the size r_0 of the region of our ignorance and ε is related to the energy Eigen value of the ground state. Several results are presented in the Table 1.Here r_{max} is the most probable radius and E_g is the ground state energy. From the Table 1, we see that the most probable radius r_{max} varies between a/5 and 3.23 a where a is the first Bohr radius of the real Hydrogen atom. The ground state energy varies between 60 % and 80 % of the true value. As a "first glance" solution this would have been considered a valuable contribution to the pre-Bohr atomic physics.

Thus, the BSW rules over three layers of matter and therefore we assume that it will also apply equally well to the fourth layer of matter containing the Holeums. This means that we can use the 1 / r Newtonian potential everywhere both within and without the bound state and we can expect at least an order of magnitude accuracy for the bound state parameters. This last example of the Hydrogen atom shows that we can expect equally good results for the Holeums also. This is because we have used a scale-invariant analysis and because both Hydrogen atom and the Holeums are governed by the same 1/r potential.

4.0 HOLEUM THEORY:

For the sake of simplicity we consider two identical PBHs of equal mass m. The gravitational potential between them is given by (Chavda and Chavda, 2002)

$$V(r) = -m^2 G / r = -\alpha_g \hbar c / r \quad (21)$$

where r is the separation between the two PBHs and c and G are the speed of light in vacuum and Newton's universal gravitational coupling constant respectively. α_g, the gravitational analogue of the fine structure constant, is given by

$$\alpha_g = m^2 G / \hbar c = (m/m_P)^2 \quad (22)$$

where

$$m_P = (\hbar c/G)^{1/2} \quad (23)$$

is the Planck mass. The Schrodinger equation is exactly solvable for the 1/r potential. The energy eigen values, formally identical with those of the Hydrogen atom, are given by (Chavda and Chavda, 2002)

$$E_n = - \mu c^2 \alpha_g^2 /(2 n^2) \quad (24)$$

Here n is the principal quantum number n=1, 2, 3 ,………. ∞. μ is the reduced mass of the two PBHs. In the following, for the sake of simplicity, we will consider only the l = 0, the s-states . The eigen function for the ns state is given by

$$\psi_{ns} = A_n L^1{}_{n-1}(t) e^{-t/2} \quad (25)$$

where

$$t = 2 \chi r . \quad (26)$$

$$\chi = \alpha_g^2 /(nR) \quad (27)$$

$$R = 2mG/c^2 \quad (28)$$

where R is the Schwarzschild radius of the black holes. $L^m{}_n(x)$ is the Associated Laguerre Polynomial and

$$A_n = 4 \chi^3/(n^2 n!^2) \quad (29)$$

The maxima of the probability density

$$g(r) = r^2 | \psi_{ns} |^2 \quad (30)$$

give us the radii of the stable orbits. For the 1s state the radius of the stable orbit is given by

$$r_1 = R / \alpha_g^2 \quad (31)$$

For the 2s state there are two orbits with radii given by

$$r_{2\pm} = (3 \pm \sqrt{5}) R / \alpha_g^2 \quad (32)$$

In general, for an ns state there are n radii characterized by $r_{n'n}$ where n' = 1, 2, 3,…n (33)

For n >> 1, the maxima of the probability density are given by

$$g_{max} = n' \alpha_g^2 / (2n^3R) \quad (34)$$

Because of the large factor n^3 in the denominator g_{max} is appreciable only for n'= n. In the following we take n'= n >>1. Then the radii of the stable orbits are given by

$$r_n = \pi^2 n^2 R / (8 \alpha_g^2) \quad (35)$$

The mass of the bound state is given by

$$M_n = 2m + E_n = 2m(1 - \alpha_g^2 / 8n^2) \quad (36)$$

From Eqs.(35) and (36) we find

$$M_n / r_n = (16 \alpha_g^2 / \pi^2 n^2) (1 - \alpha_g^2 / 8n^2) (c^2/2G) \quad . \quad (37)$$

This may be written as

$$R_n = (16 \alpha_g^2 / \pi^2 n^2) (1 - \alpha_g^2 / 8n^2) \; r_n \quad (38)$$

where

$$R_n = 2 M_n G / c^2 \quad (39)$$

is the Schwarzschild radius of the bound state. From this it is clear that if

$$\alpha_g^2 < \pi^2 / 16 \quad (40)$$

then

$$R_n < r_n \quad (41)$$

5.0 PROPERTIES OF A HOLEUM:

5.1 Stability: Eq.(41) shows that the bound state radius is greater than its Schwarzschild radius. This means that the bound state is not a black hole despite containing two black holes in it! Therefore it will not emit the Hawking Radiation. It is a stable bound state of two unstable black holes! Thus, a Holeum is as stable as a Hydrogen atom whose gravitational analogue it is. From Eqs.(40) and (22) we see that the condition of stability of a Holeum is

$$m < m_c = (\sqrt{\pi} / 2) m_P \quad (42)$$

where the Planck mass, m_P, is given by Eq.(23). Eq.(41) is the mathematical proof of the stability of a Holeum. As long as Eq.(42), derived from Eq.(40), is satisfied by the mass of the constituent black holes of a Holeum the latter is guaranteed to be stable. In a semi classical argument we may argue, after Bohr, that when the circumference of the orbit is an integral multiple of the de Broglie wave length of the constituent black holes, a standing wave pattern is formed by the matter waves associated with the constituents. This makes a Holeum stable.

5.2 Holeum occupies space: From Eqs.(35) and (40) we see that

$$r_n > 2R \qquad \text{for all } n \tag{43}$$

This means that a Holeum cannot be compressed to a linear size less than 2R. Consequently **Holeum occupies space** just like the atoms of ordinary matter**.** For the latter, the Pauli Exclusion Principle is the cause. It stems from the spin ½ of the electrons in the atoms. We derived Eq.(35) from the maxima of the probability density. Therefore this property of Holeum is also a quantum mechanical property having no classical analogue. In summary, if the mass of the constituent black holes is less than m_c, given by Eq.(42), then the Holeum is stable and it occupies space.

5.3 Gravitational Waves: If a Holeum in an excited state n’ makes a transition to a lower state n, it will emit gravitational radiation of frequency given by

$$\nu = \nu_g \left(1/n^2 - 1/n'^2 \right) \tag{44}$$

where ν_g is the gravitational Rydberg constant given by

$$\nu_g = \nu_0 \, (m / m_P)^5 \tag{45}$$

where

$$\nu_0 = m_P c^2/4h = 7.4163\text{x}10^{41} \text{ Hz} . \tag{46}$$

Note that the spin of the graviton emitted in the transition is J=2. Consequently we must have n’ – n = 2. For a fixed value of m this is an exact gravitational analogue of the line spectrum emitted by a hydrogen atom. But as m varies such that $m < m_c$ each line gets replaced by a band and the line spectrum changes into an analogous band spectrum. It must be noted that the current efforts for the detection of the gravitational radiation are directed at the classical gravitational radiation predicted by the General Theory of Relativity. This will be a continuous spectrum. In contrast to this, we are considering here a quantized gravitational radiation emitted by the atomic transitions of a Holeum atom. This will be a band spectrum as just noted. Current efforts for the detection of the gravitational radiation are directed at the low frequencies up to about 1.5 kHz. It can be shown from the foregoing equations that Holeums of nuclear and atomic sizes would emit gravitational waves in this low frequency domain accessible to LIGO and similar other detectors. The masses of the corresponding constituent black holes are approximately in the range 10^{11} GeV/c^2 to 10^{12} GeV/c^2.

5.4 Dark Matter (DM): Black holes are invisible and so are the Holeums. Therefore a Holeum is an atom of DM. It is a gravitational analogue of a Hydrogen atom. Both are bound by the same r^{-1} potential. Of course, the binding energies and the frequencies emitted by them are enormously different. A vast quantity of PBHs was produced in the early universe. About a half of the astrophysical black holes are known to have formed black hole binaries. If we take this as a guide for the PBHs produced in the early universe also then it is clear that the Holeums must make up an important component of the total quantity of DM in the universe today (Olive, 2003; Rees, 2004).

5.5 Segregation Property: The gravitational force is the weakest of the four fundamental forces of nature. Holeums have only the gravitational force to interact with one another as well as with particles of ordinary matter. The latter, on the other hand have three other, stronger, forces also with which to interact with one another. Therefore the particles of ordinary matter have a much greater affinity for one another than for the holeums. Therefore the former would nudge the Holeums towards the periphery of any mixture of ordinary particles and the Holeums. But the Holeums will still cling to the group due to their gravitational attraction. Thus, the Holeums have a segregation property vis-à-vis the particles of ordinary matter. Consequently the Holeums would form halos around the planets, stars, nebulae and the galaxies. They would also accumulate in the Domain Walls (DW) separating neighbouring universes.

5.6 Invisibility of Domain Walls: One implication of the standard model of particle physics is that the universe may have a number of ground states separated by DWs. No such DWs have been detected. This is one of the open questions of the standard model. Because of the segregation property of the Holeums it would be natural for the Holeums to accumulate in the DWs separating the neighbouring universes. This would explain the invisibility of the DWs, if they exist. Of course, the DWs may also contain dark matter particles of other kinds such as the gravitino, the neutralino, the axion, etc. (Olive, 2003; Rees, 2004).

5.7 Invisibility of the Galactic Halos (GH): Apart from the segregation property mentioned above there is another important reason why the Holeums must accumulate in the Galactic Halos. This is the centrifugal force of rotating galaxies. The most important Holeums may have masses in the range 10^{10} GeV/c^2 to 10^{19} GeV/c^2 whereas the nuclei of ordinary matter have masses up to about 300 GeV/c^2. Thus, the centrifugal force on the Holeums would be many orders of magnitude greater than that on the particles of ordinary matter. This, too, would fling the Holeums into the GHs. This would explain the invisibility of the GHs. Again, we emphasize that the latter may also contain dark matter particles of other kinds mentioned above.

5.8 Holeums as the progenitors of the Cosmic Rays (CR): If the kinetic energy 3kT of the colliding Holeums in the GHs is greater than the binding energy of the Holeums, the latter can be ionized. Here k is the Boltzmann constant and T is the absolute temperature of the Holeums. In Table 2 we present several values of the masses of the constituent PBHs, the corresponding binding energies and the ionization temperatures T_i. Temperatures of the order of 10^6 K obtain at the centers of the stars. If similar temperatures obtain in the GHs also, then a look at the Table 2 shows that the Holeums of constituent masses up to 10^{14} GeV/c^2 can be ionized in the stars and the GHs. But the Holeums of constituent masses 10^{15} GeV/c^2 and above cannot be ionized because the required ionizing temperatures of the order of 4.35×10^{10} K and higher are feasible only in the early universe but not in the astrophysical context except perhaps during supernova explosions. This means that the Cosmic Rays cannot have energies above 10^{23} eV.

When a Holeum is ionized two black holes are liberated. They will emit two closely spaced streams of Hawking Radiation. This will be observed as the Cosmic Rays on the earth. Thus, the **theory predicts that Holeums are a natural source of Cosmic Rays** (Chavda and Chavda, 2004). And this group of Cosmic Rays consists entirely of the Hawking Radiation which is the only known source of antimatter in the universe. Cosmic rays are also produced by the super nova remnants (NASA, 2007; Science Daily2007) and Active Galactic Nuclei containing massive black holes.

5.8.1 Anti-matter in Cosmic Rays: Apart from the man-made accelerators on earth, there is no other known source of anti-matter in the universe, except the Hawking Radiation. The latter is a thermal radiation. It does not obey the CP symmetry. The emission of particles and anti-particles in it is completely random and uncorrelated. It does not emit particles and anti-particles in equal numbers. Thus, the presence of anti-matter in the Cosmic Rays lends strong support to the presence of Holeums in the universe. It is the unique signature of the Hawking Radiation emitted by ionized Holeums.

5.8.2 Halo origin of the Cosmic Rays: Because of the segregation property of the Holeums and the rotation of the galaxies Holeums accumulate in the GHs. Holeums would also be trapped in the gravitational potential wells of planets and the stars. But their numbers would be extremely small compared to their numbers in the GHs. Thus, we predict that an overwhelming quantity of Cosmic Rays will come from the GHs and a very insignificant one from the disks of the galaxies. As long ago as 1983 Giler (Giler, 1983) observed: “The observed anisotropy can be accounted for only if the diffusion in the disk is much smaller than that in the Halo.” This is a very strong support for the presence of Holeums in the halo of our galaxy.

5.9 Holeum origin of Ultra High Energy Cosmic rays (UHECR): In our model all Cosmic rays, including the Ultra-High Energy ones, originate in the ionization of Holeums (Chavda and Chavda, 2008). The pressure ionization of Holeums of constituent masses in the range 10^{13} GeV/c^2 to 10^{14} GeV/c^2 mentioned above will liberate two black holes. The latter will emit two streams of Hawking Radiation consisting of particles, anti-particles, photons, etc. Some of the emitted particles may carry kinetic energies of the order of 1% of the total energy liberated. These are the Ultra High Energy Cosmic Rays (UHECR) observed on the earth. The highest energy of the Cosmic Rays observed on earth is in the vicinity of 10^{20} eV (Chavda and Chavda, 2008). Each burst of the Hawking Radiation will have total energy up to 2.0×10^{23} eV. Remembering that a part of the liberated energy will be in the form of the rest energies of the emitted particles the figure 10^{20} eV for the highest energy of the Cosmic Rays observed on the earth is readily comprehensible in this model.

5.9.1 The GZK cut-off in UHECRs: The universe is filled with Cosmic Microwave Back-Ground Radiation (CMBR) which is uniformly distributed throughout the universe. This is a sea of photons having a temperature of 2.75 K. These photons are bundles of electromagnetic energy. They would interact with the protons and neutrons which are a part of the Cosmic Rays coming to the earth. At low energies these interactions would be elastic collisions. But at very high energies these collisions would be highly inelastic. Such high energy collisions would produce π-mesons of mass about 140 MeV/c^2. A cosmic ray nucleon will lose this much energy in each collision. It is estimated that the Cosmic Ray nucleons with kinetic energy above 4×10^{10} GeV would suffer severe energy losses due to this process (Greisen, 1966; Zatsepin and Kuzmin, 1966). The mean-free-path of the CMBR photons is a few Mpcs. Therefore the typical range of the Cosmic Ray nucleons would decrease rapidly above this energy leading to a “GZK cut-off” in the energy spectrum of the Cosmic Ray nucleons if the sources of the nucleons are cosmologically distant, that is, at distances much greater than 100 Mpcs. Recent observations have detected not a cut-off but only a mild dip or a feature. Our Holeum model readily explains this. The

Cosmic Ray nucleons coming from the halos of nearby galaxies will suffer little energy losses because they will undergo a much smaller number of inelastic collisions than those coming from cosmological distances. This will result in only a small dip rather than a cut-off.

5.10 Holeums as the Progenitors of Gamma Ray Bursts (GRB): GRBs were discovered in the late sixties by the Vela satellites (Klebesadel, Strong and Olson, 1973). Since then a great deal more data has been obtained (Cline, 1973; Mazets, Golenetskii and Illnskii, 1974). The analysis of these data has revolutionized GRB observations and our basic ideas on their nature (Fishman and Meegan, 1995).There are Long Duration GRBs which last more than two seconds. They originate at cosmological distances. Then there are short duration GRBs having duration of less than two seconds. These have both cosmological and the galactic origins. The short duration GRBs have one very short duration component of less than 100 ms. Some GRBs are characterized by an erratic, spiky component whereas the others have either a single smooth component or a few smooth components.

Al Dallal (2006) has explained some of the short duration GRBs in terms of the Holeum model as follows: In an ionizing collision two black holes are liberated. They will disintegrate via the Hawking Radiation; each black hole emitting a stream of particles and high energy photons (gamma rays).These are the primary gamma rays. Further secondary Gamma Rays will be emitted as follows: Since the Hawking Radiation produces both particles and antiparticles (not necessarily in equal numbers), particle-antiparticle annihilations can occur by the interactions of the two adjacent streams of the Hawking Radiation containing particles and antiparticles. This will produce secondary Gamma Rays. But these will be delayed and they will be completely random and erratic because of the thermal nature of the Hawking Radiation. Thus, the ionization of Holeums in the galactic halos is expected to produce very short duration GRBs and also the erratic and the spiky ones.

5.11 The Verdict of the Ice Cube: Over a period of two years the Ice Cube collaboration (2012) observed 307 GRBs. But none of these arrived in coincidence with a neutrino. This rules out the Fire Ball (FB) model. In a FB all particles like protons, pions, muons, neutrinos etc. travel at relativistic speeds. This means that a neutrino will arrive at the point of observation during the GRB or soon thereafter. But, as mentioned above, the Ice Cube verdict is against this. So the FB model is ruled out.

Chavda and Chavda (2012a) have shown that the Holeum model predicts exactly the observed behaviour. As mentioned above, in an ionizing collision primary and secondary gamma rays are emitted. The primary ones are followed by substantially delayed neutrinos but the secondary ones have no neutrinos at all. This is in agreement with the observations.

5.12 Reality of Hawking Radiation (HR): Some cosmologists, including some eminent ones, do not believe that Hawking Radiation is real. But in our model not only it is real, it is the Cosmic Rays plus the GRBs. The well-established presence of antiprotons and other antiparticles in the Cosmic Rays is a unique signature of the Hawking Radiation as seen above. The Ice Cube results also strongly favour the reality of HR which is the source of the GRBs and the neutrinos.

6.0 EXISTING INDIRECT OBSERVATIONAL EVIDENCE FOR HOLEUM :

Strong indirect observational support for Holeum comes from Cosmic Rays and GRBs.

6.1 As we have seen above the presence of antimatter in the Cosmic Rays is a unique signature of the Hawking Radiation. It lends strong support to the existence of Holeums.

6.2 The observed fact that the Cosmic Rays come mainly from the Halo of our galaxy and not from its disk lends strong support to the presence of the Holeums in the Halo of our galaxy.

6.3 The observed GZK feature in the UHECRs also lends strong support to the presence of Holeums in the Halos of galaxies.

6.4 The very short duration GRBs and especially the erratic and the spiky ones strongly support their Holeum origin (Al Dallal, 2006).

6.5 The Ice Cube results strongly support the Holeum origin of the GRBs.

7.0 DETECTION OF HOLEUMS :

7.1 The Gravitational waves. As seen above, Holeums of atomic and nuclear sizes having constituent masses in the approximate range 10^{11} GeV/c^2 to 10^{12} GeV/c^2 would emit gravitational waves in the low frequency kHz domain accessible to LIGO which has become operational now. The target sources are: Holeums forming a part of the Holeum wind passing through the earth and those trapped in the gravitational potential wells of the earth and the sun. The gravitational waves emitted by these Holeums may be detected by LIGO if their intensity is sufficiently high and if the constituent black holes of the Holeums involved have masses in the range mentioned above. LIGO will detect bands of gravitational waves. The band structure is isomorphic to the line spectrum of the hydrogen atom. Of course, LIGO is built to detect the gravitational waves predicted by the general theory of relativity. These waves are classical ones. Holeums, on the other hand, emit quantized gravitational waves. But both types can be detected in the kHz range.

7.2 Extensive Air Showers: Our solar system is passing through the Holeum wind blowing through the Halo of our galaxy. Consider a Holeum of constituent mass 10^{13} GeV/c^2 that is a part of this wind. From the Table 2 we see that it has a binding energy of $1.124\text{x}10^{-3}$ eV. The corresponding ionization temperature is only 4.35 K which readily obtains in the atmosphere of the earth. However, a Holeum has only the gravitational interaction which is the weakest of the four fundamental interactions of nature. Therefore the probability of its interaction with a particle of the atmosphere of the earth is extremely small. However, if one such Holeum suffers such a rare collision while passing through the atmosphere of the earth then the Holeum may get ionized. This will give off two closely spaced bursts of Hawking Radiation that will lead to an Extensive Air Shower in the atmosphere. This may be detected by the Auger project that has been set up to observe such showers. The shower must have two characteristics: (1) a total energy of upto $2\text{x}10^{22}$ eV. (2) It must contain antimatter.

7.3 Diffuse Gamma Ray excess in the vicinity of Supernova Explosions. Al Dallal (2010) has shown that the shock wave produced by a supernova explosion will lead to the dissociation or coalescence of the Holeums and the subsequent evaporation of the PBHs will lead to an excess of diffuse Gamma Ray emission in the vicinity of supernova remnants. This may be tested if the data on the Gamma Ray emission in the vicinity of the 1987 supernova explosion are available. An excess of the emission of neutrinos is known to have been recorded in this case.

7.4 Direct Detection of Holeums: A Holeum has only the gravitational interaction which is the weakest of the four fundamental interactions. This makes its direct detection far more difficult than that of another dark matter particle named WIMP (Weakly Interacting Massive Particle) that has a far stronger interaction. However the immense size of the Ice Cube Neutrino Observatory opens up a possibility of the direct detection. Chavda and Chavda (2012b) have shown that a Holeum having two constituent black holes of mass 10^{13} GeV each is a good candidate for direct detection in the Ice Cube observatory. Such a Holeum has a binding energy of 10^{-3} eV. It may score a direct hit with one of the protons in an ice molecule. The Holeums are a part of the Cold Dark Matter (CDM) in the halo of our galaxy. Our solar system and the earth are passing through a Holeum wind. If such a Holeum strikes a proton then the former will break up giving off two closely –spaced streams of HR. The latter is a thermal radiation consisting of particles, anti-particles, gamma rays, neutrinos etc. The charged particles of the HR will create a large number of streaks of Cherenkov radiation. This will be a unique event in the depths of the Ice Cube reminiscent of the phenomena in the upper atmosphere. And for a very good reason for in our theory cosmic rays which create such phenomena in the upper atmosphere are but a component of the HR. A confirmation of this event in the Ice Cube will prove the existence of not only the Holeum but also that of the reality of the HR which results from the quiver of the very firmament of the space-time, namely, the vacuum. But it may take many years to have such an event in the Ice cube Observatory.

8.0 DISCUSSIONS AND CONCLUSIONS: This almost exactly solvable effective model of Quantum Gravity gives a unified treatment of ten apparently unrelated cosmological phenomena: (1) Dark Matter (2) Cosmic Rays (3) Ultra High Energy Cosmic Rays (4) GZK feature of UHECRs (5) Gravitational Waves (6) GRBs (7) Reality of Hawking Radiation (8) Invisibility of Galactic Halos (9).Invisibility of Domain Walls. (10) It answers the question of the ultimate fate of the PBHs. It opens up the hither to forbidden Quantum Gravity Regime giving an order-of-magnitude accuracy for the bound state parameters. However, we note that there may be other forms of DM such as the WIMPS, etc. Therefore the invisibility of the GHs and the DWs may also be due to these other forms of DM. Similarly the CRs are also generated by the Supernova remnants and Active Galactic Nuclei. On the other hand there is no other model or theory that encompasses this wide range of phenomena. The quantized gravitational radiation with a band spectrum isomorphic to the line spectrum of a Hydrogen atom is an exclusive prediction of this model. There is a strong indirect observational support for Holeums from CRs and GRBs. The results of the Ice Cube collaboration have provided a crucial indirect observational support to this wide ranging model. We have proposed a direct detection test of the existence of the Holeums to be carried out at the Ice Cube neutrino observatory.

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Table 1. Results of a variational calculation of the energy E_g and the most probable radius r_{max} of the ground state of a Hydrogen atom with a modified Coulomb potential, Eqs.(1) and (2).

ε	p	λ_1	λ_2	E_g (eV)	r_0 (Å)	r_{max} (Å)
0.3000	1.0722	1.2061	0.8305	- 8.16	0.55	1.65
0.3079	1.0000	1.1765	0.7848	- 8.38	0.51	1.60
0.4000	0.3872	0.8090	0.3464	- 10.88	0.20	0.09

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Table 2. Masses of the constituent black holes of ionizable Holeums.

m GeV/c^2	Binding Energy eV	T_i K
10^{13}	1.124 x10^{-3}	4.35
10^{14}	112.4	4.35x10^{5}
10^{15}	11.24x10^{6}	4.35x10^{10}