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Negative Gravitational Mass: A Perfect Solution for Primordial Inflation and Dark Energy in the Early Universe

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Abstract

This paper proposes a physical solution to primordial inflation. It occurs by a scalar field with a slow-rolling period. It starts at the phase transition giving rise to the gravitational interaction at time $t_i \sim 10^{-44}\ \mathrm{s}$, Planck time, and ends at time $t_f \sim 10^{-42}\ \mathrm{s}$ (or more exactly about 70 e-folds later). This scalar field is carried by a primordial particle of inert mass $m_p \sim 10^{-8}\ \mathrm{kg}$, and size $r_p \sim 10^{-35}\ \mathrm{m}$. This mass and this time are compliant with the energy density expected at this date, namely 10^{19} GeV, obtained from the potential of this scalar field. This solution assumes the existence of particles with negative gravitational mass and positive inert mass, a hypothesis compatible with General Relativity. The incredible adequacy of this solution with what is expected and required by the theory of inflation appears as a strong indication of the validity of both this hypothesis of negative gravitational mass and that of primordial inflation.

Subject Areas

Cosmology, Particle Physics, Theoretical Physics

Keywords

Cosmology, Cosmic Inflation, Dark Energy, Negative Mass

1. Introduction

Theoretical studies on the beginnings of the Universe lead to postulate the existence of a period of primordial inflation in the very first moments of the Universe ([1] [2]). And more recently, the observation indicates an acceleration of the expansion of our Universe ([3] [4]). In both cases, this requires the presence of a repulsive force, the source of which is currently unknown. This is known as dark energy and is one of the most important puzzles in physics today. This article aims to provide theoretical elements that explain this primordial inflation in accordance with General Relativity (GR) and with the theory of inflation using a scalar field with slow-rolling. The solution studied in this article is the hypothesis of the existence of particles with negative gravitational mass and positive inert mass (HP1), currently being tested in experiments such as AEgIS or Alpha at CERN. As a reminder, this hypothesis (HP1) has many major interests ([5] [6] [7]) which are not addressed in this article:

- It is compliant with the GR,
- It is a theoretical necessity resulting from general relativity equations in the same way that the existence of antimatter is a theoretical necessity resulting from the Dirac equation,
- It justifies the principle of mass equivalence,
- It explains the absence of antimatter in our Universe,
- It can explain the recent acceleration of the expansion of our Universe,
- It can explain the dipolar anisotropy of the CMB.

In this study, we see that this hypothesis (HP1) necessitates an inflationary period defined by a scalar field with a slow rolling.

What you need to know about this hypothesis (HP1) for this article is that it necessarily implies a repulsive gravitational force between masses of different signs and an attractive gravitational force between masses of the same sign [8]. We will note in this regard the beauty of this hypothesis since it makes the gravitational interaction symmetrical or rather complementary to the electromagnetic interaction (EM). Together (EM and GR), they complete the possible interactions. They are complementary both in the nature of the relations (attractive for a charge of the same sign for one and for charges of opposite signs for the other) and in their application (dominant on a large scale for one, dominant on a small scale for the other).

We begin by presenting this solution first qualitatively by recounting the course of events and explaining the physical conditions that accompany these events. Then we put this story into equations. We will verify that this solution corresponds exactly to what is expected for cosmological inflation generated by a scalar field with slow-rolling by determining this scalar field, its potential and their relations, leading to the description of a primordial particle.

2. Preamble and Cosmological Prehistory

2.1. Phase Transitions and Symmetry Breaking

As for the appearance of electromagnetic, weak and strong interactions [9], in our solution, the gravitational interaction is revealed by the appearance of pairs of particles of opposite charges (*i.e.*, of gravitational masses), emerging from a primordial fluid according to the principle of symmetry breaking. Before the appearance of the interaction, the gravitational mass is naturally zero; after the phase transition, we have pairs of particles within which the gravitational masses are identical in magnitude but of opposite signs. Thus, each pair of particles has zero gravitational mass as before the symmetry breaking. As expected in cosmology [10], the first interaction that emerges from this primordial fluid is the gravitational interaction. As a result, in each pair of particles of opposite gravitational masses, the dominating interaction turns out to be a gravitationally repulsive force.

2.2. Equilibrium of Environmental Pressure and Repulsive Force => Phase Transition

We are, therefore, at a time when all forces are still unified with an unknown primordial fluid but subject to gigantic pressure, energy density and temperature. The basic scenario of cosmology is to start from a primordial fluid that cools and whose energy decreases (**Figure 4**). In our solution, this will result in particular in the reduction of environmental pressure. As long as the pressure is greater than the repulsive force of the pairs of opposing gravitational masses, when they emerge, no pairs persist and they recombine to disappear immediately. They appear transiently, a bit like virtual particles. But when the pressure becomes of the same order of magnitude as this repulsive force, the pairs that emerge persist over time. The pressure can no longer recombine them. A first threshold is reached which triggers the phase transition revealing the gravitational force. The primordial fluid then condenses into a primordial cloud of pairs of opposing gravitational masses. This pressure, which will be called environmental pressure, is not the internal pressure of the primordial fluid. The internal pressure which will be at the origin of the accelerated expansion will be due to the force of repulsion as we will see and will therefore have a negative sign unlike the pressure of the environment.

2.3. Equilibrium of Forces => Particles in Contact

The phase transition of the gravitational interaction takes place because the pairs of particles succeed in no longer merging. The environmental pressure has lowered enough for the repulsive force within the pairs to compensate for this pressure. The pair of particles that emerges at equilibrium does not explode under the force of repulsion. The 2 particles remain side by side; they do not disperse. At the phase transition, the balance of forces therefore results in pairs of particles at the limit of recombination, of overlapping, that is to say, by particles in contact with each other within pairs.

2.4. Universe without Expansion before Inflation => Slow Evolution of Environmental Pressure

As we have just said, cosmological evolution is carried out by considering a decrease in energy, in the temperature by which the phase transitions follow one another. When we consider the expanding universe, we can expect that this expansion is one of the dominant factors explaining this decrease. But at the 1st phase of transition (which in our solution will give rise to inflation), there is not yet this important component of expansion. As a result, we can expect a much smoother evolution of environmental conditions. The evolution of the environmental pressure on the cloud will therefore most certainly take place very smoothly.

2.5. Slow Evolution of Environmental Pressure => Extension of the Primordial Cloud

This smooth evolution of the environmental pressure has the consequence of maintaining the state of equilibrium of this phase transition. This leaves time for the neighborhood (which undergoes the same physical conditions) to also make its transition. We thus have the appearance of a large number of pairs of particles which will accumulate to form a large condensation cloud. This 1st phase will serve as an energy accumulator (slow-rolling), which will in a 2nd phase become cataclysmic and generate an incredibly powerful and extraordinarily short-lived accelerated expansion.

2.6. Agitation and Unstable Structure => Mixing and Dynamic Diffusion => Homogeneity beyond the Pair and No Aggregates

Two facts make this cloud extremely homogeneous. Given the energy level, there is a great thermal agitation (but strongly constrained by enormous environmental pressure) which prevents any aggregation of particles with masses of the same sign from being maintained. The agglomerates are quickly dislocated. This agitation does not produce shocks (the particles are in contact) but rolling particles on top of each other. This very dynamic mixture causes great homogeneity in temperature and in the distribution of positive masses and negative masses.

There is also the fact that the pairs of particles in a 3D space, although very compact, cannot organize themselves in a stable way to obtain a regular arrangement of opposite mass (unlike for example an alternating arrangement in 1D). As such, a static arrangement is not possible; a dynamic arrangement is set up. This fact causes an incessant rearrangement of the 3D structure of the cloud which causes a maximization of the alternation of the masses, a constant search for the greatest balance, the best homogenization. In this case, too, this leads to the incessant rolling of particles on top of each other without aggregations of masses of the same sign. This rolling dynamic ensures pair-level homogeneity across the entire cloud.

These 2 effects which result in rolling of particles on each other, at the same time generate an extreme homogenization of the cloud. The particles diffuse intensely and constantly share their energy with their neighbors generating a cloud with extremely homogeneous initial conditions, very compact (arrangement according to Kepler's conjecture about sphere packing) and without aggregate (or at least always transiently and statistically either of positive gravitational masses, or negative with the same probability which consequently neutralizes each other on average).

2.7. Agitation and Unstable Structure => Masking Gravitation beyond the Pair => Cloud Physics, Dominated by Physics within the Pairs

We can also refine this last point. Agitation and structural instability constantly erase attractive rearrangements. This extremely dynamic balance is a true mechanism of extremely fine adjustment. Statistically, we have on average an optimization of the alternation of particles of positive and negative gravitational masses. According to Kepler's conjecture, a particle will have a maximum of 12 direct neighbors. For a short period of time, it will have more neighbors with positive gravitational masses, but in another period of time it will have more neighbors with negative gravitational masses. All combinations will be equiprobable with respect to the sign of the gravitational mass. The optimization of the alternation and the systematic dislocation of the aggregates then lead on average a particle to have the same number of neighbors of opposite masses, namely 6 positive and 6 negative masses. A consequence of such mixing efficiency is that beyond the first neighbors (particles directly in contact) we can neglect the more distant particles which are masked because their gravitational charge appears globally as zero. Thus, by focusing on what is happening within a pair of particles, we will have a very good approximation of the fields involved in this cloud.

2.8. Kinetic Energy $\ll$ Potential Energy

The fact that the density is maximum, *i.e.*, particles in contact, implies that the particles (a bit like in the heart of a star) roll over each other without being able to escape or with great difficulty, very chaotically. They therefore have a relatively low kinetic energy, especially in comparison to the repulsive gravitational force which is contained by the pressure of the environment and which translates (as we will see later) into enormous potential energy.

2.9. Slow Evolution of This Potential

As we said before, the pressure of the environment evolves slowly. It controls the evolution of the cloud by containing the force of repulsion. Its slow evolution leads to a slow evolution of the potential, in addition to letting the cloud grows. Note that this is one of the expected effects in the study of inflation. But here, it is not the flatness of the potential that explains the inflation, but rather the physical conditions that explain the flatness of the potential.

2.10. Decrease in Environmental Pressure => Increase in Aggregate Size

As long as the accelerated expansion has not occurred, the environmental pressure will quietly decrease. The space between the particles will just as slowly begin to increase. One might think that the large number of pairs associated with an increase in the distance between particles for each of these pairs would cause a tremendous swelling of the cloud. But that would be without counting on attractive gravitation. Indeed, with the decrease in environmental pressure, the repulsion force will certainly allow the spaces between the particles of opposite masses to increase, but this benefits the gravitational interaction which can then gradually aggregate masses of the same signs. The decrease in pressure releases the effects of both gravitational repulsion and gravitational attraction. In other words, the cloud maintains its density of particles but the pairs which at the start consisted of a particle of negative mass and a particle of positive mass are transformed little by little into pairs composed of an aggregate of particles of negative masses and an aggregate of the same size of particles of positive masses (see Figure 1). The extremely homogeneous conditions and the slow evolution of the environmental pressure allow a homogeneous evolution of the primordial cloud, even in this initial phase of growth of the pairs of aggregates.

2.11. Smooth Growth in the Size of the Aggregates => Exponential Growth of the Force of Repulsion => Accelerated Expansion and End of the Inflation Phase

This change of scale of the aggregates (going from 1 particle to N particles) on the whole of the primordial cloud very quickly causes a domination of the repulsive force. It will be seen that simply tripling the distance between particles of opposite masses (allowing aggregates of 13 particles as in Figure 1(b)) suffices to increase the repulsion force twenty-fold. The balance will then suddenly breaks and trigger the accelerated expansion. A simple further tripling of the distance between aggregates then generates a repulsive force 350 times greater. It's a real explosion. There will therefore be no intermediate period where the distance changes enough to invalidate the density constancy hypothesis before the expansion takes place. This is a strong point of this solution in total agreement with what the theory predicts. Let us also add that this formidable explosion has the consequence of providing the gigantic impulse explaining not only the accelerated expansion of the 1st moments of the universe but also quite simply the expansion of the universe. And like any explosion, no sooner has it started than it ends, ending this primordial inflationary phase.

So, the constancy of the density and the potential during this phase is verified for 2 reasons. First, the initial growth of the aggregates always occurs with the particles rolling on top of each other, so as long as the aggregates are close each other, the density remains the same. Second, the aggregates will only move away from each other when the accelerated expansion kicks in. But this "explosive" sequence does not last long because as soon as it occurs, it puts an end to this phase of inflation.

Note: The very agitated initial dynamics of the primordial cloud means that the gravitational attraction cannot play its role of agglomerating until spaces begin to be created. The effects of attraction are neutralized in this slow-rolling phase by the incessant rolling of the particles on top of each other. This is how the repulsion within each pair dominates at this point. But on the other hand, surprisingly, the gravitational attraction will become essential to trigger the explosion of this cloud by making it unstable by making the aggregates of masses of the same sign grow. The Universe thus begins with a beautiful figure of speech, an oxymoron, because it is the attraction that amplifies repulsion.

2.12. Summary of the Inflation Phase (Slow-Rolling Then Accelerated Expansion)

The phase transition giving rise to the 1st interaction (the gravitational interaction) is triggered when the pressure of the environment slightly decreases and is in equilibrium with the gravitational repulsion. The maximum density is achieved in the sense that the particles are in contact with each other (if they were closer they would annihilate). The great thermal agitation means that the particles constantly roll over each other and that no agglomerate of particles of gravitational masses of the same sign can be created or at least persists. This also makes it possible, on average to neutralize the effects beyond the first neighbors (masking effect). The release of environmental pressure is occurring slowly because expansion due to inflation has not yet occurred. This procedure allows time for the transition to take place in different places and for the different "condensation bubbles" to grow and join together in order to create a large-scale cloud. This agitation (which mixes) and this slow evolution of the pressure of the environment contribute to the establishment of extremely homogeneous initial conditions over the entire primordial cloud. This relaxation allows the repulsive gravitation to move away the masses of opposite signs, but at the same time, the attractive gravitation begins to aggregate the masses of the same sign (by filling the voids generated by the repulsion). These 2 complementary phenomena thus

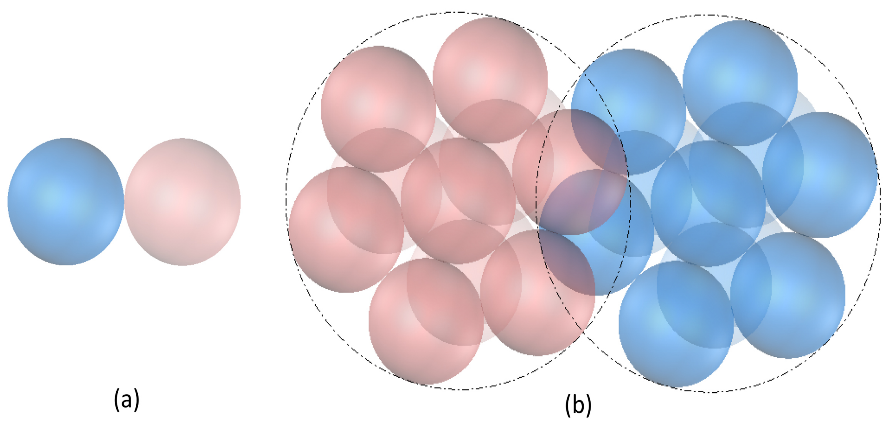

Figure 1. The end of inflation is caused when the primordial cloud is no longer structured around pairs of aggregates of 1 particle (a) but around pairs of aggregates of a few particles (b). The repulsion then quickly becomes dominant and the balance with the environment is broken. An accelerated expansion begins, putting an end to this phase of inflation. One color indifferently indicates a mass of a certain sign and the other color the opposite mass.

maintain the density of the cloud. But this cloud is gradually seeing its fragmentation change in scale. While initially, it was fragmented into pairs of single particles (1 positive gravitational mass and 1 negative gravitational mass), it slowly and continuously evolves into pairs of particle aggregates (N positive masses and N negative masses). The extremely dynamic equilibrium of this cloud makes it possible to have an evolution with aggregates of non-integer numbers of particles, reflecting the more or less long maintenance of these aggregates. As soon as the size of the aggregates is a few units larger, very quickly then the force of repulsion by this evolution begins to dominate. It suffices to simply triple the distance between masses of opposite signs and therefore letting enough space for only one neighboring particle of the same mass to twenty-fold the repulsion force (**Figure 1(b)**). This will trigger the accelerated expansion but also will very quickly put an end to this acceleration and will then end the inflation phase. But the expansion will now begin.

Note: The total gravitational mass of the cloud is zero (as many particles with positive gravitational masses as particles with negative gravitational masses). In this solution, the absence of negative gravitational mass in our current Universe is intimately linked to the absence of antimatter in our Universe (it is the antimatter that should carry a negative gravitational mass) and is explained quite naturally thanks to repulsive gravitation [5].

3. Equation of Our Inflation Model

We are now going to put this solution into equations. Let's start by defining the parameters useful for our modelling.

3.1. Primordial Particle of Radius R_p and Gravitational Mass ± M_p; Parameters $r_a(t)$ and $m_a(t)$

It is assumed that the phase transition causing the gravitational interaction to emerge is achieved by the creation of a single type of particle, which will be called the primordial particle, with gravitational mass $\pm|M_p|$, inert mass $M_{ip}=|M_p|$ and radius R_p. The parameters which will characterize the Newtonian force of repulsion within the pairs are on the one hand, $m_a(t)$, the gravitational mass, and consequently the number of particles, forming each aggregate of masses of the same sign and on the other hand $r_a(t)$, the distance between these neighboring aggregates of opposite signs. In this primordial cloud where the particles are on top of each other, $r_a(t)$ will be approximately the contact distance between the surface of the aggregate on which the forces act and the center of gravity of the neighboring aggregate generating the gravitational field (**Figure 2**). In this context, $r_a(t)$ will roughly correspond to the radius of the aggregates. It is important to understand that this distance is not subject to the same evolution as the scale factor which will be noted $R(t)$. The scale factor somehow follows two particles "at rest" (attached to the "fabric of space") and characterizes the "conveyor belt" effect that space makes them undergo. The

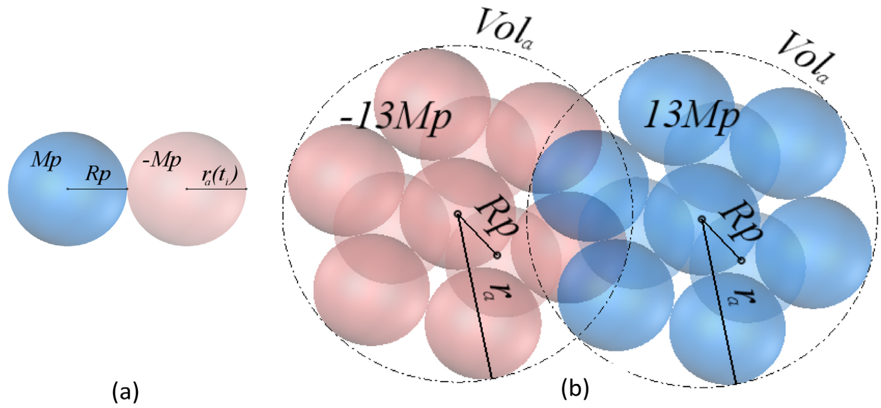

Figure 2. Pairs of aggregates of particles of opposite gravitational masses. One color indifferently indicates a mass of a certain sign and the other color the opposite mass. The pair of (a) (aggregate with 1 particle) represents the basic structuring element of the primordial cloud at its birth, that of b) the basic structuring element of the primordial cloud towards its end.

distance $r_a(t)$ is the distance between two neighboring aggregates of opposite signs (more exactly between the center of the aggregate and the surface of the neighboring aggregate of opposite mass). And in our solution, these aggregates are constantly changing. We therefore do not follow 2 particles in particular but aggregates which are certainly direct neighbors but which are never the same. In this phase (at constant particle density), the evolution as a function of time of $r_a(t)$ in fact translates the evolution of the size of the aggregates and not that of the "fabric of space" which is, on the other hand, the role of the scale factor.

We will note t_i the instant of the beginning of the inflation phase, t_f the instant of the end of the inflation phase and $\Delta t_{\min} = t_f - t_i$ the duration of the inflation phase. We will thus have $r_a(t_i) = R_p$ and also $m_a(t_i) = M_p$. Note also the volume of an aggregate $Vol_a(t) = \frac{4}{3}\pi r_a^3(t)$ and the volume of the primordial particle $Vol_p = \frac{4}{3}\pi R_p^3$. We will therefore have $Vol_a(t_i) = Vol_p$.

3.2. Order of Magnitude of the Initial Energy Density, Homogeneity and Constancy

Since the particles are in contact with each other, an order of magnitude of the inert mass density of the environment can be obtained. We can expect an arrangement as dense as possible, verifying Kepler's conjecture about sphere packing in 3D. We remind that R_p is the radius of the primordial particle and $|M_p|$ the inert mass of this particle (where $M_p = \pm|M_p|$ represents its gravitational mass), Vol_p the volume of the primordial particle, ρ_p the gravitational mass density of the primordial particle, ρ_{ip} the inert mass density of the primordial particle:

$$\rho_{ip} = |\rho_p| = \frac{|M_p|}{Vol_p} = \left(\frac{3}{4}\right)\frac{|M_p|}{\pi R_p^3} \tag{1}$$

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In our solution, the particles are in contact with each other. We can therefore apply Kepler's conjecture about sphere packing (which gives a density $d = \frac{\pi}{3\sqrt{2}}$).

Let ρ_i be the inert mass density of space, of the environment:

$$\frac{\rho_i}{\rho_{ip}} = d = \frac{\pi}{3\sqrt{2}}(\text{Kepler's Conjecture}) \Rightarrow \rho_i = \left(\frac{1}{4\sqrt{2}}\right)\frac{|M_p|}{R_p^3} \quad (2)$$

This relation of the inert mass density ρ_i will remain valid as long as the particles are very close to each other. This will be achieved, as we will see later, as long as inflation has not occurred (concreted by an exponential separation of the particles). This phase will therefore be characterized by an energy density that is both homogeneous in space (at the maximum of what it can be according to Kepler's conjecture about sphere packing) but also constant over time (thanks to a slow evolution of the pressure that maintains the transition around the balance of forces). Even when the accelerated expansion begins, it is the nature of the aggregates, in this case, their size, that will cause the cloud to explode while the density will remain the same.

3.3. Order of Magnitude of the Initial Repulsion Force within a Pair

Within a pair (Figure 3), the two gravitational masses of opposite sign undergo, at their point of contact, the gravitational force $\boldsymbol{F}_{1\to 2}$ exerted by particle 1 on particle 2, with $\boldsymbol{u}_{1\to 2}$ the unit vector from particle 1 to particle 2 (and inversely for the other particle):

$$\boldsymbol{F}_{1\to 2} \sim \frac{G|M_{p1}||M_{p2}|}{R_p^2}\boldsymbol{u}_{1\to 2} \Rightarrow \|F\| \sim \frac{G|M_{p1}||M_{p2}|}{R_p^2} = G\frac{M_p^2}{R_p^2} \quad (3)$$

The sign of $\boldsymbol{F}_{1\to 2}$ is positive because it is a repulsive force (therefore centrifugal) since one of the 2 gravitational masses is negative. The particles are in contact with each other, this potential is maintained in space from pair to pair. We therefore have an extremely homogeneous potential, in a first approximation, throughout the cloud.

3.4. Order of Magnitude of the Initial Pressure

Since pairs of particles of opposite masses are assumed to become persistent,

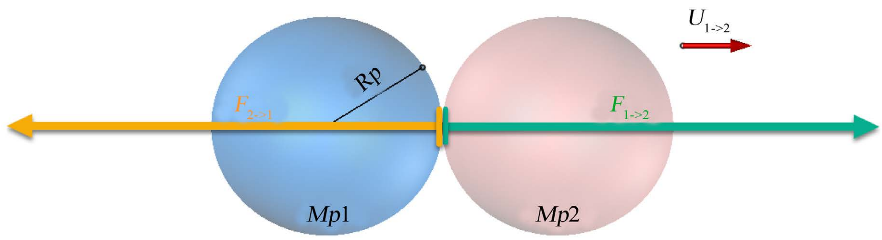

Figure 3. Repulsive gravitational forces within a pair of 1-particle aggregates of opposite gravitational masses.

when the pressure has decreased enough that it no longer recombines the pairs, this means that the pressure at this step becomes of the same order of magnitude as the repulsive gravitation. Since the particles are in contact with each other, the repulsive gravitational force of one particle applied to the other must then correspond to the pressure force in this state of equilibrium, homogeneous throughout the cloud. Approximately, we can find an order of magnitude of this pressure due to the gravitational repulsion which balances the environment pressure within a pair in contact with the 2 particles of radius R_p with S_p the surface of the particle undergoing the contact forces of its neighbors:

$$p = \frac{\|F\|}{S_p} \sim -\frac{GM_p^2}{R_p^2}\frac{1}{4\pi R_p^2} \sim -\frac{1}{4\pi}G\frac{M_p^2}{R_p^4} \tag{4}$$

The pressure is negative because in our case the gravitation between particles of opposite signs is centrifugal. We will find this expression in a more precise way a little later which will be slightly larger as we can expect because we have not considered here the different neighboring particles which alternate in time and space between positive and negative masses.

3.5. Low Kinetic Energy and High Potential Energy

We have just seen that the balance between the pressure of the environment and the repulsive gravitation on the pairs allows the establishment of an extensive and high-density cloud. The particles are all in contact with each other. But this cloud has a very special balance and stability, because the opposing forces that hold it together are gigantic. We can schematically represent this cloud as an assembly alternately of positive and negative particles in contact with each other that the repulsion tries somehow to keep away and whose spaces that are created are immediately filled thanks to the pressure. We can therefore expect that this cloud is not immobile, but that the particles roll over each other in an anarchic way, in a constant search for the best balance. But these strong constrained movements nevertheless reflect a low kinetic energy because the particles do not escape. Thus, at each point of this cloud, we have a low kinetic and homogeneous energy because the same physical conditions apply throughout the cloud.

On the other hand, in comparison, we have enormous potential energy at each point of this cloud. Indeed, since the dynamics of this cloud is essentially dominated by the repulsion force within each pair, the gravitational potential $\Phi^{(0)}\left(r_a(t)\right)$ exerted by an aggregate of mass $m_a(t)$ at its radius is:

$$\Phi^{(0)}(r_a) \sim -G\frac{m_a}{r_a} \tag{5}$$

This is the potential that applies to the point of contact of all the 1st neighbors. Thus, in the 1st approximation (indicated by the exponent "(0)" on Φ), this gravitational potential is homogeneous over the entire cloud of particles because these contacts are found throughout the cloud and on the scale of particle size. The incredible agitation within the cloud occurs with particles rolling over each other without moving apart (at least initially) because we are on the threshold of the phase transition where the particles no longer recombine but keep their distance. Under these conditions and at this step, the potential is maintained and can also be considered as constant. During most of this phase, we will have $r_a(t_i) \sim R_p$ and $m_a(t_i) \sim \pm|M_p|$. And as we will calculate later, we will have an order of magnitude $R_p \sim 10^{-35}\ \text{m}$, $|M_p| \sim 10^{-8}\ \text{kg}$ which gives approximately for the potential energy $m_a\Phi^{(0)} \sim -10^9\ \text{kg}\cdot\text{m}^2\cdot\text{s}^{-2}$. Kinetic energy of the same order would require velocities of the order of magnitude of the speed of light for the primordial particles at the core of this primordial cloud, which is clearly not the case. We therefore have potential energy that dominates.

3.6. Evolution of This Primordial Cloud in 1st Approximation, Scalar Field $\phi^{(0)}(t)$ and Potential $V(\phi)$

In general, the theories of inflation for a scalar field $\phi(\boldsymbol{x},t)$ decompose this field into a homogeneous component depending only on time $\phi^{(0)}(t)$ and into a component characterizing the inhomogeneities $\delta\phi(\boldsymbol{x},t)$. $\phi^{(0)}(t)$ then corresponds to the 1st order approximation of the field while $\delta\phi(\boldsymbol{x},t)$ is a 2nd order, weaker. In our solution, we also find these terms. Our cloud is indeed very homogeneous with relatively stable physical conditions as long as the particles remain in contact with each other. But since the size of the aggregates will gradually evolve, we will still have a time dependence on this main term. But we can notice that the average volume Vol_a around the aggregates interpenetrate as we have represented in **Figure 2** because the particles in contact with each other only form a sphere in the first approximation. As a result, depending on the place of contact, there will be slight variations in force. Moreover, the sizes of an aggregate in the 3 space dimensions are not identical. We rather have a flattened sphere (for example, shorter in the 3rd dimension perpendicular to the plane represented in **Figure 2**). These geometric characteristics contribute to this dynamic balance of this cloud. There is no stable and regular arrangement at all times. But we can add that on average these inhomogeneities are "erased", because they are variations around an average value. These variations $\delta\phi(\boldsymbol{x},t)$ are thus of a lower order than the mean term that we will deal with $\phi^{(0)}(t)$. In our solution, this therefore justifies the traditional approximation on the scalar field, namely:

$$\phi(\boldsymbol{x},t) = \phi^{(0)}(t) + \delta\phi(\boldsymbol{x},t) \tag{6}$$

The time dependence for our solution intervenes in the evolution of the distance $r_a(t)$ between particles of opposite masses (roughly the radius of an aggregate pair when aggregates are close to each other). In our study, we will focus on the first order term $\phi^{(0)}(t)$. Inhomogeneities modeled by $\delta\phi(\boldsymbol{x},t)$ will not be processed.

The previously calculated gravitational potential (5) represents the potential acting on an aggregate. Each aggregate densely covering space, this same gravitational potential is continuously distributed in space. We can thus take the expression of the gravitational potential and express it in the form of potential density $\varphi^{(0)}(r_a)$ using the volume of the aggregate $Vol_a \sim \frac{4}{3}\pi r_a^3$. We can write:

$$\varphi^{(0)}(r_a) = \frac{\Phi^{(0)}(r_a)}{Vol_a} \sim -\left(\frac{3}{4\pi}\right) G \frac{m_a}{r_a^4} \quad (7)$$

Thus, an immediately neighboring particle (in contact with its surface) of gravitational mass m_{a1}, will be subjected to a potential energy density $U^{(0)}(r_a)$:

$$U^{(0)}(r_a) \sim m_{a1}\varphi^{(0)}(r_a) \sim -m_{a1}\left(\frac{3}{4\pi}\right) G \frac{m_a}{r_a^4} = \left(\frac{3}{4\pi}\right) G \frac{|m_a|^2}{r_a^4} \quad (8)$$

The last equality is explained because it is the potential energy of a mass of a certain sign in the potential of a mass of another sign. The masses m_a and m_{a1} are therefore systematically of opposite sign, thus removing the negative sign from the expression (as a reminder $r_a(t)$ is a distance between masses of opposite signs of nearest neighbor). And the potential energy density in mass equivalent $V^{(0)}(r_a)$ is written as:

$$V^{(0)}(r_a) = \frac{1}{c^2} U^{(0)}(r_a) \sim \left(\frac{3}{4\pi}\right) \frac{G}{c^2} \frac{|m_a|^2}{r_a^4} \quad (9)$$

To take advantage of the theoretical studies already carried out on inflation, we will use the traditional notations of this field. According to the Euler-Lagrange equations, the scalar field ϕ verifies the following:

$$\square^2 \phi + \frac{1}{c^2} \frac{\mathrm{d}V(\phi)}{\mathrm{d}\phi} = 0 \quad (10)$$

A possible potential of the scalar field $V(\phi)$ is (with the inert mass of the aggregate m_{ia}):

$$V(\phi) = \frac{1}{2} \frac{m_{ia}^2 c^4}{\hbar^2} \phi^2 \quad (11)$$

Which makes it possible to obtain the Klein-Gordon equation (with $m_{ia} = |m_a|$):

$$\square^2 \phi + \frac{|m_a|^2 c^2}{\hbar^2} \phi = 0 \quad (12)$$

We can write our potential in this form:

$$\begin{aligned} V^{(0)}(r_a) &\sim \left(\frac{3}{4\pi}\right) \frac{G}{c^2} \frac{|m_a|^2}{r_a^4} = \frac{1}{2} \frac{|m_a|^2 c^4}{\hbar^2} \left(2 \frac{\hbar^2}{|m_a|^2 c^4} \left(\frac{3}{4\pi}\right) \frac{G}{c^2} \frac{|m_a|^2}{r_a^4} \right) \\ &= \frac{1}{2} \frac{|m_a|^2 c^4}{\hbar^2} \left(2\hbar^2 \left(\frac{3}{4\pi}\right) \frac{G}{c^6} \frac{1}{r_a^4} \right) \end{aligned} \quad (13)$$

Which gives the scalar field ϕ (with α a constant defined by the initial parameters of the primordial cloud):

$$\phi = \left[2\hbar^2\left(\frac{3}{4\pi}\right)\frac{G}{c^6}\frac{1}{r_a{}^4}\right]^{1/2} = \frac{\alpha}{r_a{}^2} \text{ with } \alpha = \frac{\hbar}{c^3}\left[G\left(\frac{3}{2\pi}\right)\right]^{1/2}$$
$$\text{and } V(\phi) = \frac{1}{2}\frac{|m_a|^2 c^4}{\hbar^2}\phi^2 \qquad (14)$$

In our solution, the unknown parameters are no longer the potential $V(\phi)$ and the field $\phi^{(0)}$ but the mass of the aggregate $m_a(t)$ and the size of this aggregate $r_a(t)$ during the time.

Note about the characteristic terms that will appear in the exponentials (further in the article): According to the story described in the 1st chapter, most of the time, the inflation phase takes place without aggregation, with a homogeneous and relatively constant density. The end of inflation is then achieved very quickly when aggregates begin to form. For the same reasons that we limited ourselves to the study at the 1st order $\phi^{(0)}(t)$, we can make the hypothesis that $|m_a|(t) \sim \text{Constant}$ at the 1st order as well as $r_a(t) \sim \text{Constant}$ to 1st order during this phase. Consequently, when these terms appear in the characteristic times as an exponential parameter, only the constant term will be kept at that time. We can add that inflation theories expect $V(\phi)$ to be relatively constant during this phase. However, with the conditions implied by our solution on $|m_a|(t)$ and $r_a(t)$, this is consistent with our expression of $V(\phi)$.

3.7. Inflation

To have an inflation, we need: $\dot{\phi}^2 < V(\phi)$. Let's calculate the derivatives of the scalar field:

$$\dot{\phi}(t) = \frac{\mathrm{d}\phi(t)}{\mathrm{d}t} = \alpha\frac{\mathrm{d}\left[\frac{1}{r_a(t)^2}\right]}{\mathrm{d}t} = -2\alpha\frac{\dot{r}_a(t)}{r_a^3(t)} \qquad (15)$$

$$\ddot{\phi}(t) = -2\alpha\frac{\mathrm{d}\left[\frac{\dot{r}_a(t)}{r_a^3(t)}\right]}{\mathrm{d}t} = 2\alpha\left(3\frac{\dot{r}_a^2(t)}{r_a^4(t)} - \frac{\ddot{r}_a(t)}{r_a^3(t)}\right) \qquad (16)$$

The relation $\dot{\phi}^2 < V(\phi)$ gives the condition (using (13) and (14)):

$$4\alpha^2\frac{\dot{r}_a^2(t)}{r_a^6(t)} < \left(\frac{3}{4\pi}\right)\frac{G}{c^2}\frac{|m_a|^2}{r_a^4} \Rightarrow \frac{\dot{r}_a^2(t)}{r_a^2(t)} < \left(\frac{3}{4\pi}\right)\frac{G}{c^2}\frac{|m_a|^2}{4\alpha^2} = \left(\frac{1}{8}\right)\frac{c^4}{\hbar^2}|m_a|^2$$
$$\Rightarrow \left|\frac{\dot{r}_a(t)}{r_a(t)}\right| < \left(\frac{1}{2\sqrt{2}}\right)|m_a|\frac{c^2}{\hbar} \qquad (17)$$

Let us introduce a dimensionless parameter $\vartheta < 1$ and a characteristic time τ_{i_r} of the change in distance $r_a(t)$ between aggregates of opposite masses. And as previously indicated, we have $|m_a|(t) \sim \text{Constant}$ at the 1st order, the term in the exponential can therefore be considered as constant, in this case $|m_a|^{(0)}(t) = |M_p|$. Thus, during inflation, *i.e.*, between t_i the beginning of inflation and t_f the end of inflation, the distance $r_a(t)$ between aggregates of opposite masses must satisfy:

$$r_a(t) = r_a(t_i)\,\mathrm{e}^{t/\tau_{i\_r}} \text{ with } \tau_{i\_r} = \frac{2\sqrt{2}\hbar}{\vartheta |M_p| c^2} \text{ for } t_i < t < t_f \text{ and } \vartheta < 1 \tag{18}$$

Since $r_a(t_i) = R_p$ we can write:

$$r_a(t) = R_p \mathrm{e}^{\frac{\vartheta |M_p| c^2}{2\sqrt{2}\hbar} t} \text{ for } t_i < t < t_f \text{ with } \vartheta < 1 \tag{19}$$

3.8. Slow Rolling

To have a slow-rolling phase, we need: $\ddot{\phi} \ll \frac{\mathrm{d}V(\phi)}{\mathrm{d}\phi}$. Let's calculate the derivative of the potential:

$$\begin{aligned} &\frac{\mathrm{d}V(\phi)}{\mathrm{d}\phi} = |m_a|^2 \frac{c^4}{\hbar^2}\phi = |m_a|^2 \frac{c^4}{\hbar^2}\frac{\alpha}{r_a(t)^2} \\ &\Rightarrow 2\alpha\left(3\frac{\dot{r}_a^2(t)}{r_a^4(t)} - \frac{\ddot{r}_a(t)}{r_a^3(t)}\right) \ll |m_a|^2 \frac{c^4}{\hbar^2}\frac{\alpha}{r_a(t)^2} \\ &\Rightarrow \left(3\frac{\dot{r}_a^2(t)}{r_a^2(t)} - \frac{\ddot{r}_a(t)}{r_a(t)}\right) \ll \frac{1}{2}|M_p|^2 \frac{c^4}{\hbar^2} \end{aligned} \tag{20}$$

For the last relation, we use, as before, the fact that $|m_a|(t) \sim \text{Constant}$ at the 1st order, the term in the exponential can then be considered as constant, in this case $|m_a|^{(0)}(t) = |M_p|$.

According to relation (19), we already have the following constraint:

$$r_a(t) = R_p \mathrm{e}^{\frac{\vartheta |M_p| c^2}{2\sqrt{2}\hbar} t} \text{ with } \vartheta < 1 \tag{21}$$

So:

$$\dot{r}_a(t) = \frac{\vartheta |M_p| c^2}{2\sqrt{2}\hbar} r_a(t) \tag{22}$$

$$\ddot{r}_a(t) = \frac{\vartheta^2 |M_p|^2 c^4}{8\hbar^2} r_a(t) \tag{23}$$

$$\left(3\frac{\dot{r}_a^2(t)}{r_a^2(t)} - \frac{\ddot{r}_a(t)}{r_a(t)}\right) = \frac{\vartheta^2 |M_p|^2 c^4}{4\hbar^2} \tag{24}$$

To have (20), the parameter ϑ must verify: $\vartheta \ll \sqrt{2}$

In conclusion, in our solution to have an inflation ($\dot{\phi}^2 < V(\phi)$) and a slow rolling ($\ddot{\phi} \ll \frac{\mathrm{d}V(\phi)}{\mathrm{d}\phi}$), the distance $r_a(t)$ is therefore constrained as follows:

$$r_a(t) = R_p \mathrm{e}^{t/\tau_{i\_r}} = R_p \mathrm{e}^{\frac{\vartheta |M_p| c^2}{2\sqrt{2}\hbar} t} \text{ with } \tau_{i\_r} = \frac{2\sqrt{2}\hbar}{\vartheta |M_p| c^2} \text{ for } t_i < t < t_f \text{ and } \vartheta \ll 1 \tag{25}$$

At this step, the introduction of this parameter ϑ and especially the obtaining of the relation $\vartheta \ll 1$ are only a translation of the conditions necessary to obtain inflation with slow rolling in our solution. But for the moment, nothing assures us that our solution imposes this relationship. In fact, the end of inflation in our solution will physically impose a value for the minimum distance between neighboring aggregates of opposite masses $r_a(t)$. This will result geometrically in obtaining the value of this parameter ϑ. We will obtain an order of magnitude $\vartheta \sim 10^{-1}$, thus verifying both the establishment of an inflation ($\vartheta < 1$) and of a slow-rolling ($\vartheta \ll 1$).

3.9. Pressure

Theoretical studies on inflation predict for the pressure that we have:

$$\frac{p}{c^2} = \frac{1}{2}\dot{\phi}^2 - V(\phi) - \frac{1}{2}\left(\frac{1}{c}\nabla\phi\right)^2 \tag{26}$$

In our case, we have a constant and homogeneous field ($\nabla\phi < V(\phi)$), as explained at the beginning of this article. And we will see later that the previous condition ($\dot{\phi}^2 < V(\phi)$) is indeed verified because our solution implies that $\vartheta \sim 10^{-1} \ll \sqrt{2}$. We can therefore write:

$$p \sim -c^2 V(\phi) \sim -\left(\frac{3}{4\pi}\right) G \frac{|m_a|^2}{r_a^4} \tag{27}$$

One can notice that one finds the order of magnitude of the initial pressure ($r_a(t_i) = R_p$ and $m_a(t_i) = M_p$) calculated previously (4).

3.10. Inert Mass Density

Theoretical studies on inflation predict for the inert mass density of space that we have:

$$\rho_i = \frac{1}{2}\dot{\phi}^2 + V(\phi) + \frac{1}{2}\left(\frac{1}{c}\nabla\phi\right)^2 \tag{28}$$

In our case, we have a constant and homogeneous field, so we can write:

$$\rho_i \sim V(\phi) \sim \left(\frac{3}{4\pi}\right) \frac{G}{c^2} \frac{|m_a|^2}{r_a^4} \tag{29}$$

At this step, we can already verify a relation necessary to obtain inflation, namely $p < -\frac{1}{3}\rho_i c^2$. Knowing ρ_i and p, we have:

$$-\left(\frac{3}{4\pi}\right) G \frac{|m_a|^2}{r_a^4} < -\frac{1}{3}\left(\frac{3}{4\pi}\right) G \frac{|m_a|^2}{r_a^4} \Rightarrow 1 > \frac{1}{3} \tag{30}$$

The relation $p < -\frac{1}{3}\rho_i c^2$ necessary to obtain inflation is thus well verified.

3.11. Energy

We previously calculated the energy density in two ways (relations (2) and (29)). Thus, our solution (with only 1 type of primordial particle and with its particles in contact with each other) leads to an important constraining relation on the characteristics of our primordial particle ($r_a(t_i) = R_p$ and $m_a(t_i) = M_p$):

$$(29) \Leftrightarrow \rho_i(t_i) \sim \left(\frac{3}{4\pi}\right)\frac{G}{c^2}\frac{|M_p|^2}{R_p^4} \text{ and } (2) \Leftrightarrow \rho_i(t_i) = \left(\frac{1}{4\sqrt{2}}\right)\frac{|M_p|}{R_p^3}$$

$$\Rightarrow \frac{|M_p|}{R_p} = \left(\frac{\pi}{3\sqrt{2}}\right)\frac{c^2}{G} = d\frac{c^2}{G} \quad (31)$$

This relationship is important because it means that in our solution, only one of the two initial parameters M_p and R_p is finally unknown. Moreover, since at the beginning of the inflation phase, the particles have low kinetic energy and are in contact with each other, we can write with a good approximation:

$$m_{ia}(t_i) = |m_a(t_i)| = |M_p| = \frac{E}{c^2} \Rightarrow R_p = \left(\frac{1}{d}\right)\frac{G}{c^2}|M_p| = \left(\frac{3\sqrt{2}}{\pi}\right)\frac{G}{c^4}E \quad (32)$$

In the following, we will use this relation to analyze our solution as a function of energy.

3.12. Scale Factor Parameter

The Friedman-Lemaître equations give us for $R(t)$ the scale factor:

$$\frac{1}{R(t)}\frac{\mathrm{d}^2R(t)}{\mathrm{d}t^2} = -\frac{4\pi G}{3}\left(\rho_i + \frac{3p}{c^2}\right) \quad (33)$$

Since in oursolution:

$$\rho_i \sim -\frac{p}{c^2} \sim \left(\frac{3}{4\pi}\right)\frac{G}{c^2}\frac{|m_a|^2}{r_a^4} \quad (34)$$

We have:

$$\frac{1}{R(t)}\frac{\mathrm{d}^2R(t)}{\mathrm{d}t^2} = -\frac{8\pi G}{3}\frac{p}{c^2} = -2\frac{G^2}{c^2}\frac{|m_a|^2}{r_a^4} \quad (35)$$

We can therefore write $R(t) = R(t_i)\mathrm{e}^{t/\tau_{i\_R}}$ with $R(t_i)$ the scale factor at the start of inflation and τ_{i_R} the characteristic time of the change in the scale factor (using (31)):

$$\tau_{i\_R} = \left(\frac{1}{2}\frac{c^2r_a^4}{G^2|m_a|^2}\right)^{1/2} \sim \left(\frac{c^2}{2G^2}\right)^{1/2}\frac{R_p^2}{|M_p|} \sim \left(\frac{c^2}{2G^2}\right)^{1/2}R_p\left(\frac{1}{d}\right)\frac{G}{c^2} \sim \left(\frac{3}{\pi}\right)\frac{R_p}{c} \quad (36)$$

As already explained previously, for the last relations, $|m_a|(t) \sim \text{Constant}$ at 1st order and $r_a(t) \sim \text{Constant}$ at 1st order, the term in the exponential can be considered as constant, in this case $|m_a|^{(0)}(t) = |M_p|$ and $r_a^{(0)}(t) \sim R_p$. Be careful not to confuse R_p the radius of the primordial particle with $R(t)$ the scale factor.

In our solution, the scale factor therefore follows the following relationship:

$$R(t) = R(t_i)\mathrm{e}^{t/\tau_{i\_R}} = R(t_i)\mathrm{e}^{\left(\frac{\pi}{3}\right)\frac{c}{R_p}t} \text{ with } \tau_{i\_R} = \left(\frac{3}{\pi}\right)\frac{R_p}{c} \text{ for } t_i < t < t_f \quad (37)$$

3.13. Finalization of Our Solution, Determination of t_i, $\Delta t_{\min}$ and E

We have established the set of relations that characterize the primordial inflation for our solution. We now have to concretely define at what time t_i this phase of inflation can be triggered, over what duration it can occur and at what energy. To do this, we are going to calculate the distance from the horizon at the end of inflation based on the one hand on previous period (inflation phase) and on the other hand on following period (radiation phase) of which we know the evolution of the scale factor. We resume here the reasoning and the values mentioned in [11].

Let's start by looking at how we can express the distance from the horizon at the end of inflation as a function of the characteristics of primordial inflation. Let $d_{h,i}$ be the distance from the horizon at the initial time t_i of inflation considering that the era before inflation is dominated by radiation, General Relativity gives us:

$$d_{h,i} = 2ct_i \tag{38}$$

By noting the final instant of inflation $t_f = t_i + \Delta t_{\min}$, and with an initial time $t_i \sim \tau_{i\_R}$, the distance from the horizon at the end of inflation $d_{h,f}$ which evolves according to the same law as the scale factor is then:

$$d_{h,f} \sim d_{h,i} \mathrm{e}^{\Delta t_{\min}/\tau_{i\_R}} \sim 2ct_i \mathrm{e}^{\Delta t_{\min}/\tau_{i\_R}} \tag{39}$$

This provides us with our 1st assessment of the horizon at the end of inflation.

Let us now look at how we can express this same distance from the horizon at the end of inflation from the period following the primordial inflation. It is expressed as a function of the distance from the current horizon $d_{h,0} \sim 4.5\times10^{26}\ \mathrm{m}$:

$$d_{h,f} = d_{h,0} R_{rad}\left(t_f\right) \tag{40}$$

The theory gives us for the scale factor during the era of radiation (period following inflation):

$$R_{rad}\left(t\right) = \left(\frac{16\pi G g_* a}{3c^2}\right)^{1/4} T_0 t^{1/2} \tag{41}$$

With g_* the number of effective degrees of freedom of all particles (estimated in the early Universe at $g_* \sim 160$ and currently at $g_* \sim 3$), the radiation constant $a \sim 7\times10^{-16}\ \mathrm{J\cdot m^{-3}\cdot K^{-4}}$ and current temperature $T_0 \sim 3\ \mathrm{K}$. This relationship gives us:

$$d_{h,f} = d_{h,0} R_{rad}\left(t_f\right) = d_{h,0}\left(\frac{16\pi G g_* a}{3c^2}\right)^{1/4} T_0 \left(t_i + \Delta t_{\min}\right)^{1/2} \tag{42}$$

This provides us with our 2nd assessment of the horizon at the end of inflation. These 2 expressions of $d_{h,f}$, (42) and (39), provide us with a constraint that our parameters must satisfy:

$$d_{h,0}\left(\frac{16\pi G g_* a}{3c^2}\right)^{1/4} T_0 \left(t_i + \Delta t_{\min}\right)^{1/2} = 2ct_i \mathrm{e}^{\Delta t_{\min}/\tau_i} \tag{43}$$

At the initial time $t_i \sim \tau_{i\_R}$, and for

$$t_f = t_i + \Delta t_{\min} \sim \tau_{i\_R} + \Delta t_{\min} = \tau_{i\_R}\left(1 + \frac{\Delta t_{\min}}{\tau_{i\_R}}\right)$$

$$\left(\frac{16\pi G g_* a}{3c^2}\right)^{1/4} \frac{d_{h,0} T_0}{2c} \frac{1}{\tau_{i\_R}^{1/2}} \left(1 + \frac{\Delta t_{\min}}{\tau_{i\_R}}\right)^{1/2} = \mathrm{e}^{\Delta t_{\min}/\tau_{i\_R}} \quad (44)$$

We can rewrite τ_{i_R}, relation (37), as a function of energy using relation (32):

$$\tau_{i\_R} = \left(\frac{3}{\pi}\right)\frac{R_p}{c} = \left(\frac{9\sqrt{2}}{\pi^2}\right)\frac{G}{c^5} E = \varepsilon E \quad \text{with } \varepsilon = \left(\frac{9\sqrt{2}}{\pi^2}\right)\frac{G}{c^5} \sim 3\times 10^{-53} \quad (45)$$

Which gives us the relationship:

$$\frac{\beta}{\varepsilon^{1/2}} \frac{1}{E^{1/2}} \left(1 + \frac{\Delta t_{\min}}{\varepsilon E}\right)^{1/2} = \mathrm{e}^{\frac{\Delta t_{\min}}{\varepsilon E}} \quad \text{with } \beta = \left(\frac{16\pi G g_* a}{3c^2}\right)^{1/4} \frac{d_{h,0} T_0}{2c} \quad (46)$$

By setting $E = 10^8 E_r$ and $\Delta t_{\min} = 10^{-44} DT$, we have:

$$\frac{\beta}{10^{-22}\gamma^{1/2}} \frac{1}{E_r^{1/2}} \left(1 + \frac{DT}{\gamma E_r}\right)^{1/2} = \mathrm{e}^{\frac{DT}{\gamma E_r}} \quad \text{with } \gamma = 10^{52}\varepsilon \quad (47)$$

Let's calculate γ and β:

$$\gamma = 10^{52}\left(\frac{9\sqrt{2}}{\pi^2}\right)\frac{G}{c^5} \sim 0.3 \sim \frac{1}{3}$$
$$\text{and } \beta = \left(\frac{16\pi G g_* a}{3c^2}\right)^{1/4} \frac{d_{h,0} T_0}{2c} \sim g_*^{1/4}\, 20.25\times 10^{6.75} \quad (48)$$

Knowing that the parameter g_* intervenes with a power of 1/4 and that it is therefore not necessary for it to be defined very precisely, we will take the value $g_* \sim 5$ to obtain:

$$\beta(g_* = 5) \sim 30\times 10^{6.75} \sim 10^{8.2} \quad (49)$$

We therefore have to solve the following equation with E_r and DT as unknowns:

$$\frac{1}{E_r^{1/2}}\left(1 + 3\frac{DT}{E_r}\right)^{1/2} = 10^{-30.4}\,\mathrm{e}^{3\frac{DT}{E_r}} = \mathrm{e}^{3\frac{DT}{E_r} - 70} \quad (50)$$

A parameter often used is the number of "e-folds" $N_{\text{e\_folds}}$ which is in our solution:

$$N_{\text{e\_folds}} = \frac{\Delta t_{\min}}{\tau_{i\_R}} = 3\frac{DT}{E_r} \quad (51)$$

Let us calculate several solutions as a function of energy, which allows us to determine DT then the start of inflation t_i and its duration $\Delta t_{\min}$. We find numerically the following approximate solutions:

It is then necessary to verify that one of the possible solutions is consistent with our current knowledge in terms of the value of the energy and of the instant t_i.

In **Table 1**, the line in bold is the only adequate solution with respect to current knowledge of the 1st moments of the Universe. Note that it is doubly consistent, which makes this solution really pertinent. Indeed, first, it is in very good agreement with the expected values of energy and dates, because for higher or lower energies, the dates disagree with the energies expected by the theory. And secondly, the numerical solution corresponds to the expected values of energy for the possible appearance of gravitation (**Figure 4**). Our theoretical solution corresponds to the emergence of gravitation. But it is important to remember that at no time do we impose energy or a date for this theoretical solution. This is also why we can apply our solution to different energy values. It is therefore remarkable that the only numerical solution in agreement with our knowledge is that of the appearance of gravitation and which is the one implied by our theoretical solution. This consistency is a very strong point of our solution. So much that one could say that this solution not only confirms the existence of primordial inflation of the universe but perhaps even more the hypothesis of the existence of negative gravitational masses.

We can calculate the radius and the mass of the primordial particle:

Table 1. Numerical solution of the Equation (50).

E_r	DT	$N_{\text{e\_folds}}$	$E\left[\text{kg}\cdot\text{m}^2\cdot\text{s}^{-2}\right]$	$t_i\left[\text{s}\right]$	$\Delta t_{\min}\left[\text{s}\right]$	$t_f\left[\text{s}\right]$
1000	22,889	69	10^{11}	3×10^{-42}	2.3×10^{-40}	2.3×10^{-40}
100	2328	70	10^{10}	3×10^{-43}	2.3×10^{-41}	2.4×10^{-41}
10	**236.6**	**71**	$\mathbf{10^{9}}$	$\mathbf{3\times10^{-44}}$	$\mathbf{2.4\times10^{-42}}$	$\mathbf{2.4\times10^{-42}}$
1	24.05	72	10^{8}	3×10^{-45}	2.4×10^{-43}	2.4×10^{-43}
0.1	2.444	73	10^{7}	3×10^{-46}	2.4×10^{-44}	2.5×10^{-44}

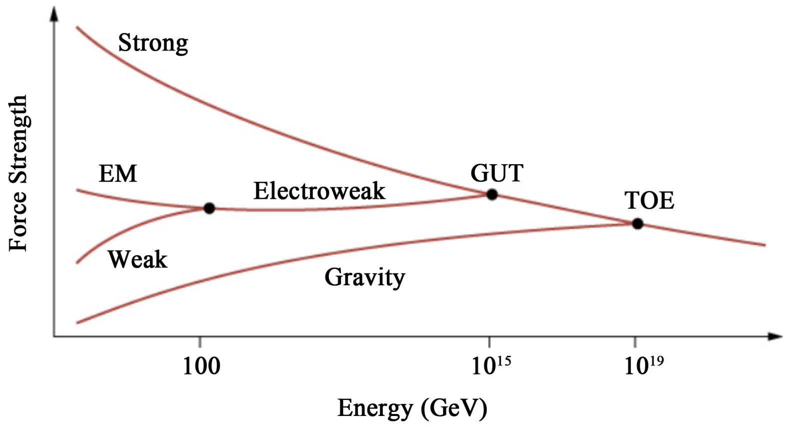

Figure 4. Appearance of interactions as a function of energy. TOE (theory of everything) is the theory that would unify the 4 interactions. GUT (Grand Unification Theory) is the theory that would unify all interactions except gravitation. The gravitational interaction would appear for $E\sim10^{9}\ \text{kg}\cdot\text{m}^2\cdot\text{s}^{-2}\sim10^{19}\ \text{GeV}$ (Source: jobilize https://www.jobilize.com/physics3/test/unification-theories-the-standard-model-by-openstax).

$$R_p = \left(\frac{3\sqrt{2}}{\pi}\right)\frac{G}{c^4}E = 10^{-35}\ \text{m} \tag{52}$$

$$\left|M_p\right| = \frac{E}{c^2} = \frac{10^9}{10^{17}} = 10^{-8}\ \text{kg} \tag{53}$$

Our solution finally gives the primordial particle a radius of the order of Planck's length and a mass of the order of Planck's mass, for a start of inflation of the order of Planck's time and energy of the order of Planck's energy.

3.14. End of Primordial Inflation

As the environmental pressure and the thermal agitation weaken, the agglomerates of the same sign gradually increase in size (the agitation no longer breaks them). Let us see how the repulsion force evolves within the pairs of aggregates when the number of particles per aggregate increases. For this, let's take two instants t_f^{--} and t_f^{-} which precede t_f with $t_f^{--} \lesssim t_f^{-} \lesssim t_f$. The simple fact of passing from an aggregate of one particle, $m_a(t_i) = \pm\left|M_p\right|$ and $r_a(t_i) = R_p$, to an aggregate of 13 particles, $m_a\left(\sim t_f^{--}\right) = \pm\left|13M_p\right|$ and $r_a\left(\sim t_f^{--}\right) = 3R_p$ (**Figure 2**), multiplies the repulsion force by 20:

$$\|F\| \sim \frac{G\left|13M_{p1}\right|\left|13M_{p2}\right|}{9R_p^2} \sim 20\frac{GM_p^2}{R_p^2} \tag{54}$$

This passage from 1 particle to 13 particles corresponds to leaving only a spacing of the size of one single particle along one dimension. And with a new spacing of the size of these aggregates, namely from $r_a\left(\sim t_f^{--}\right) = 3R_p$ to $r_a\left(\sim t_f^{-}\right) = 9r_a$ (spacing of the size of one single aggregate) with a set of 13 aggregates of 13 particles per aggregate, *i.e.*, 13 × 13 = 169 particles, the repulsion is 350 times stronger:

$$\|F\| \sim \frac{G\left|169M_{p1}\right|\left|169M_{p2}\right|}{81R_p^2} \sim 350\frac{GM_p^2}{R_p^2} \tag{55}$$

While the cloud initially was in equilibrium with the pressure of the environment and the repulsion force between pair of particles, it finds itself quite suddenly in imbalance with a repulsion force which grows exponentially ($\|F\| \sim \left(\frac{169}{9}\right)^J \|F_{initial}\|$ after J steps of "integer spaces"). And as we can also expect, this inflation by its explosive side, has everything not to last. Indeed, with such an expansion, the particles and their aggregates will very quickly no longer be in contact with each other. The repulsion force will then decrease because r_a will grow faster than the aggregations. For example, it is not even certain that we have the previous case of 350 times the initial repulsion because when we reach $9r_a$ the aggregates may not have had time to rearrange with 13 neighboring aggregates. So, accelerated expansion will very quickly give way to expansion that will gradually slow down.

3.15. Return on the Distance Parameter within a Pair of Neighboring Aggregates of Opposite Masses $r_a(t)$ during the Inflation Phase

To fully validate our solution, we still have to show that the condition of relation (25) is verified, *i.e.*, $\vartheta \ll 1$. During this slow-rolling phase, the density remains relatively constant, which constrains $r_a(t)$ to evolve very little. But by simply tripling or nine-fold the distance, it triggers the accelerated expansion. This is the beginning of the end of inflation. In other words, our solution implies that we have:

$$r_a(t_i) \sim R_p < r_a(t) < r_a(t_f) \sim 9R_p \tag{56}$$

But we have just calculated that we have: $t_i \sim 3\times10^{-44}\ \text{s}$ and $t_f \sim 3\times10^{-42}\ \text{s}$. We then have with $\hbar \sim 10^{-34}$ and $|M_p| \sim 10^{-8}$:

$$\begin{gathered}\tau_{i\_r} \sim \frac{2\sqrt{2}\hbar}{\vartheta|M_p|c^2} \sim 3\frac{10^{-43}}{\vartheta} \\ \Rightarrow r_a(t_i) \sim R_p e^{t_i/\tau_{i\_r}} \sim R_p e^{\vartheta 10^{-1}} \text{ and } r_a(t_f) \sim R_p e^{t_e/\tau_{i\_r}} \sim R_p e^{\vartheta 10^{1}}\end{gathered} \tag{57}$$

Our solution implies that $e^{\vartheta 10^1} \sim 9$ and therefore that $\vartheta \sim 2\times10^{-1} \ll 1$. Condition (25) is verified.

Note: Conversely, one can calculate a maximum value for $r_a(t_f) \sim NR_p$, by taking $\vartheta \sim 1$ (for larger values of ϑ, $r_a(t_i)$ would become too large). We would then have $e^{10^1} \sim N \sim 20000$. Our solution implies that the accelerated expansion must occur for $r_a(t_f) \ll 20000R_p$. But with such aggregates, the force of repulsion would be disproportionate compared to the initial force of repulsion and therefore to the pressure of the environment (which decreases). In other words, inflation is necessarily triggered well before this size, confirming that, whatever the exact value of ϑ, we necessarily have $\vartheta \ll 1$.

4. Discussion

4.1. After Inflation, Reheating Phase and Radiation Period Then Long Phase of Segregation of Gravitational Masses

One can imagine what happens after this phase of inflation. The accelerating expansion will have been so powerful that the attraction will no longer be able to grow the aggregates fast enough to keep the opposing mass aggregates in contact with each other. Distances will therefore grow faster than aggregates. The repulsion force will then decrease. Spaces will be created between these aggregates, causing no longer rolling but shocks. We can then expect a reheating phase, as expected by theory [12]. And this reheating by shocks must be accompanied by a change in the nature of this cloud. A period of radiation must indeed take place parallel to these innumerable shocks, also as expected by the theory [13]. These spaces will also allow a very large-scale grouping of masses of the same signs, a phase of mass segregation which should lead to the formation of immense zones of masses of the same signs; one of these zones will be our Universe exclusively of positive gravitational masses. A Universe whose first neighbors would then be universes exclusively of negative gravitational masses ([6] [8]). Thus, this primordial cloud with particles of alternating masses will have evolved until it forms a network of universes of alternating masses. We will have gone from the scale of pairs of aggregates of one particle to the scale of pairs of universe aggregates of 10^{80} particles (estimated number of particles in our Universe). The recent accelerated expansion could also be explained by the influence of this neighborhood of universes of negative gravitational masses but according to another particularity of the gravitational interaction defined by General Relativity at the origin of the Lense-Thirring effect [8].

4.2. About Quantum Mechanics

One last fact that is interesting to raise, our explanation does not involve Quantum Mechanics (QM), but still allows us to find a solution with coherent values. This can be explained by the fact that we only looked at the 1st order term, which turns out to be relatively stable on average due to the extremely dynamic equilibrium generated by this incessant mixing, which is nevertheless highly nonlinear. But one can wonder if this is not the sign that there could be an interpretation (still to be defined) more realistic than the one we currently know of QM. This could confirm that QM addresses highly nonlinear phenomena that it interprets with linear tools (and therefore not adapted to nonlinear), explaining its sometimes-destabilizing interpretation. For example, the absence of a classic trajectory in this highly dynamic cloud can be interpreted as the fact that at each instant the trajectory is non-derivable, because it is subject to innumerable changes of direction. At each moment, it is not just a single modification of direction but a multitude of changes that each particle undergoes. This multiplicity at the same time could provide an interpretation on the one hand of the fact that in QM it is necessary to carry out sums on all the possible trajectories, but on the other hand to the absence of a single trajectory in favor of a band, of a presence's interval not reducible to a line. When QM is applied, physical data would no longer be reducible to a point (keystone of linear interpretation) but reducible to more sophisticated "extended" elements [14].

5. Conclusion

We have studied the hypothesis of the existence of negative gravitational masses (with always a positive inert mass). Each of these masses appears accompanied by a positive gravitational mass, at the moment when the phase transition occurs which causes the gravitational interaction to emerge at the instant $t_i \sim 3\times10^{-44}\ \text{s}$. Each pair of particles of positive and negative masses gives rise to a repulsive gravitational force in equilibrium with the pressure of the environment. As the environment evolves slowly (before the accelerated expansion), this phase transition allows a vast cloud of pairs of particles to be put in place. Its density is maximum, that is to say, that its particles compactly fill the space (according to conjecture of Kepler about sphere packing). There are no shocks but an infernal rolling of particles on each other which makes it possible to obtain physical conditions of extreme homogeneity on the scale of the pairs of particles on the whole of this primordial cloud. The potential energy is very much greater than the kinetic energy. Thanks to a slow decrease in the pressure of the environment, the force of repulsion create spaces that the gravitational attraction will fill by aggregating masses of the same signs. These aggregates appear homogeneously throughout the cloud and in a symmetrical and balanced manner between positive and negative gravitational masses. As soon as aggregates of about ten particles with masses of the same sign appear, the repulsion force begins to grow exponentially, triggering an accelerated expansion. This expansion, which cannot keep the aggregates in contact with each other, causes the end of the inflation phase (at $t_f \sim 2.4\times10^{-42}$ s and $N_{\text{e\_folds}} = 71$) to give way to a reheating phase with countless shocks leading to a period of radiation. At the same time, a phase of segregation of gravitational masses will produce the gathering on a very large scale of vast areas alternately of positive masses (such as our Universe) and negative masses (anti-universes), thus explaining the absence of both antimatter and negative gravitational mass in our Universe. One can add that in this theoretical frame, antimatter is necessarily of negative gravitational mass. This network of universes and anti-universes would also make it possible to explain the recent acceleration of the expansion of our Universe by the Lense-Thirring effect of the neighboring anti-universes (effect of the 2nd component of the gravitational interaction of linearized General Relativity similar to the magnetic field in Electromagnetism). In other words, in this theoretical framework, dark energy is always due to negative gravitational masses but appears in two different aspects. The dark energy which generates the primordial inflation comes from the 1st component of the gravitational interaction which is exerted at a short distance (within the primordial pairs of particle-antiparticle). The dark energy which generates the recent acceleration of the expansion comes from the 2nd component of the gravitational interaction which is exerted at great distance between universe and neighboring anti-universe. Finally, let us note that the astonishing adequacy of this solution with what is expected and required by the theory of inflation appears as a strong indication of the validity of these two hypotheses of primordial inflation and negative gravitational mass.

Data Availability

There are no new data associated with this article.

Conflicts of Interest

The author declares no conflicts of interest.

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