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The formation of matter structures in the Universe*

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We discuss the formation of matter structures in the Universe, and show that spherical Higgs bosonic membranes were possibly produced homogeneously in the early Universe and expanded rapidly. After a period of evolution, the composition of the membranes began to change, the massive particles replaced the imaginary Higgs bosons through the Higgs mechanism, while the energy came from the Universe expansion. After that, the membranes reduced their speed and broke into pieces, which became the seeds of matter structures. It is proven that microscopic principles may affect the formation of large-scale structures, and the formation of structures such as cosmic foam is also possible.

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One of the fundamental challenges of cosmology is to explain the variety of large-scale structures observed in current redshift surveys.[1] Among these structures the walls of galaxies and voids are most prominent.[2−4] The analysis of peculiar velocity fields shows that these voids can really be devoid of matter.[5] In-depth surveys give an indication that strongly underdense regions, separated by walls of matter, can extend to very large distances.[6]

In Ref.[7], a unified theory describing k-dimensional topological defects was presented, and their topological quantization and motion equations in the general case were formulated. The evolution equations of these topological defects are

$$g^{AB}\frac{\partial g_{\nu\lambda}}{\partial x^{\mu}}\frac{\partial x^{\nu}}{\partial u^{A}}\frac{\partial x^{\lambda}}{\partial u^{B}} - 2\frac{1}{\sqrt{g_u}}\frac{\partial}{\partial u^{A}}\left(\sqrt{g_u}g^{AB}g_{\mu\nu}\frac{\partial x^{\nu}}{\partial u^{B}}\right)=0, \quad A,B=1,\cdots,k. \tag{1}$$

The vacuum structure in many spontaneously broken gauge theories is very rich. Topologically stable configurations of gauge and Higgs fields exist as domain walls, cosmic strings, and monopoles. In addition, p-branes, which have been found to play important roles in M-theory, have also been proven in recent years to be topological defects in gauge theory.

In recent years, Hill, Schramm and Fry[8] introduced the so-called "light" domain walls. They considered a late-time (post-decoupling) phase transition and found that light domain walls could be produced and that this is not necessarily in contradiction with the observed large-scale structure of the Universe. A few years later, Maggiore,[9] Larsen and Lousto[10] and Christensen *et al.*[11] have pointed out that the dimensions of the domain walls are much greater than their thickness. The term relativistic membranes is thus appropriate to the domain walls.

The simplest action describing a relativistic bosonic membrane is[9]

$$S=\frac{-T}{2}\int \mathrm{d}^3\xi\sqrt{-h}[h^{ij}g_{\mu\nu}\partial_i x^{\mu}\partial_j x^{\nu}-1], \tag{2}$$

where T is the membrane tension, h=deth_{ij}, and h_{ij} is the metric induced by $g_{\mu\nu}$ on the surface of the membrane. Then

$$h_{ij}=g_{\mu\nu}\partial_i x^{\mu}\partial_j x^{\nu}. \tag{3}$$

We use Planck units, $\hbar=c=G=1$, and the signature is Minkowskian.

Variation of the action (2) with respect to x^{μ} gives equations of motion

$$\partial_i(\sqrt{-h}\ h^{ij}g_{\mu\nu}\partial_j x^{\nu}) - \frac{1}{2}\sqrt{-h}\ h^{ij}g_{\rho\sigma,\mu}\partial_i x^{\rho}\partial_j x^{\sigma}=0. \tag{4}$$

Equation (4) is the special case of Eq.(1) which has a four-dimensional Riemann manifold.

We introduce the "polar fields", defined by

$$x^{\mu}=(x^0, r\sin\theta\cos\phi, r\sin\theta\sin\phi, r\cos\theta), \tag{5}$$

then make the spherical ansatz, $r(\tau,\theta,\phi)=r(\tau)$.

The metric of our model comes from a quadratic gravity suggested by quantum and superstring theories appropriate to the early Universe.[1] It is

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$$\mathrm{d}s^2 = \mathrm{e}^{2\omega}\left[-\mathrm{d}t^2 + R^2(t)\left(\frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\theta^2 + r^2\sin^2\theta\mathrm{d}\phi^2\right)\right].6$$

Now, the induced metric is computed from Eqs.(3) and (6) with the gauge $x_0(\tau,\theta,\phi)=\tau$, so we have

$$h_{ij} = \begin{pmatrix} \left[-1+\dfrac{R^2\dot{r}^2}{1-kr^2}\right]\mathrm{e}^{2\omega} & & \\ & \mathrm{e}^{2\omega}R^2r^2 & \\ & & \mathrm{e}^{2\omega}R^2r^2\sin^2\theta \end{pmatrix}. \tag{7}$$

Using the ansatz (5), the equation of motion (4) with μ=0, 1, 2 and 3 reduce to the two equations

$$\begin{aligned}&(4\dot{R}r\dot{r}+3Rr\dot{r}\dot{\omega}+2R\dot{r}^2+Rr\ddot{r})(1-kr^2)^2\\&+(-3R^3r\dot{r}^3\dot{\omega}-3R^2\dot{R}r\dot{r}^3+2kRr^2\dot{r}^2\\&-2R^3\dot{r}^4)(1-kr^2)-kR^3r^2\dot{r}^4=0,\end{aligned} \tag{8}$$

$$\begin{aligned}&(-3r\omega'-2)(1-kr^2)^2+(6R^2r\dot{r}^2\omega'-3R^2r\dot{r}^2\dot{\omega}\\&-2R\dot{R}r\dot{r}^2-2R^2\dot{r}^3-2R\dot{R}r\dot{r}-R^2r\ddot{r}+4R^2\dot{r}^2)\\&\times(1-kr^2)+R^3\dot{R}r\dot{r}^3-kR^2r^2\dot{r}^2-3R^4r\dot{r}^4\omega'\\&+3R^4r\dot{r}^4\dot{\omega}+2R^3\dot{R}r\dot{r}^4+2R^4\dot{r}^5-2R^4\dot{r}^4=0,\end{aligned} \tag{9}$$

where an overdot denotes $\partial/\partial\tau$, and a prime denotes $\partial/\partial r$.

With the solution r=const removed, Eqs.(8) and (9) are solved by a special solution

$$k=0,\ \ R=1,\ \ \dot{r}=1,\ \ \omega=\omega(t), \tag{10}$$

where $\omega(t)$ is an arbitrary function of conformal time t. Then the metric (6) becomes

$$\mathrm{d}s^2 = \mathrm{e}^{2\omega}[-\mathrm{d}t^2+(\mathrm{d}r^2+r^2\mathrm{d}\theta^2+r^2\sin^2\theta\mathrm{d}\phi^2)]. \tag{11}$$

The membranes expand with the speed of light in the spacetime, and the spatial curvature is zero.

Since $\omega(t)$ is an arbitrary function of t, we assume $\mathrm{e}^{2\omega}=R^2(t)$, then Eq.(11) becomes

$$\begin{aligned}\mathrm{d}s^2 =&R^2(t)[-\mathrm{d}t^2+(\mathrm{d}r^2+r^2\mathrm{d}\theta^2+r^2\sin^2\theta\mathrm{d}\phi^2)]\\=&-\mathrm{d}t_1^2+R^2(t)(\mathrm{d}r^2+r^2\mathrm{d}\theta^2+r^2\sin^2\theta\mathrm{d}\phi^2),\end{aligned} \tag{12}$$

where $\mathrm{d}t_1=R(t)\mathrm{d}t$, with t_1 being the cosmic time.

So, the speed of membranes in the expanding Universe is

$$v=\frac{\mathrm{d}r_1}{\mathrm{d}t_1}=\frac{R(t)\mathrm{d}r}{R(t)\mathrm{d}t}=\frac{\mathrm{d}r}{\mathrm{d}t}=\dot{r}=1, \tag{13}$$

which is also the speed of light. So there are many bosonic membranes in the early Universe, which in fact are Higgs bosonic membranes.

We can obtain solutions similar to that described above as follows. The Robertson–Walker metric of the Universe is[12]

$$\mathrm{d}s^2 = -\mathrm{d}t^2+R^2(t)\left[\frac{\mathrm{d}r^2}{1-kr^2}+r^2\mathrm{d}\theta^2+r^2\sin^2\theta\mathrm{d}\phi^2\right]. \tag{14}$$

It is often convenient to express the metric in terms of "conformal time" η, defined by $\mathrm{d}\eta=\mathrm{d}t/R(t)$, thus

$$\mathrm{d}s^2 = R^2(\eta)\left[-\mathrm{d}\eta^2+\frac{\mathrm{d}r^2}{1-kr^2}+r^2\mathrm{d}\theta^2+r^2\sin^2\theta\mathrm{d}\phi^2\right].$$

By redefining variables, it can be written as

$$\mathrm{d}s^2 = R^2(t)\left[-\mathrm{d}t^2+\frac{\mathrm{d}r^2}{1-kr^2}+r^2\mathrm{d}\theta^2+r^2\sin^2\theta\mathrm{d}\phi^2\right]. \tag{15}$$

Now, the induced metric is computed from Eqs.(3) and (15) with the gauge $x_0(\tau,\theta,\phi)=\tau$, so we have

$$h_{ij} = \begin{bmatrix} [-1+\dot{r}^2/(1-kr^2)]R^2 & & \\ & R^2r^2 & \\ & & R^2r^2\sin^2\theta \end{bmatrix}. \tag{16}$$

Using the ansatz (5), the equations of motion (4) with μ=0,1,2 and 3 reduce to the two equations

$$\begin{aligned}&[(Rr\ddot{r}+3\dot{R}r\dot{r})(1-kr^2)+2R\dot{r}^2\\&-3\dot{R}r\dot{r}^3](1-kr^2)-R\dot{r}^4(2-kr^2)=0,\end{aligned} \tag{17}$$

$$\begin{aligned}&[-2R(kr^2-1)+3\dot{R}r\dot{r}+Rr\ddot{r}](kr^2-1)\\&+R\dot{r}^2(2-3kr^2)+3\dot{R}r\dot{r}^3=0,\end{aligned} \tag{18}$$

where an overdot denotes $\partial/\partial\tau$.

With the solution $r=k^{-1/2}$ removed, Eqs.(17) and (18) are solved by

$$\begin{cases}\dot{r}^2=1, & (k=0)\\ \dot{r}^2=1-r^2, & (k=+1),\\ \dot{r}^2=1+r^2, & (k=-1).\end{cases} \tag{19}$$

The membranes are under the condition of light-like motion since $\frac{\dot{r}^2}{(1-kr^2)} = 1$.

The discovery of the Higgs mechanism is a key to understanding matter-structure formation from the Higgs bosonic membranes produced in the early Universe.[13,14]

The simplest Pais–Uhlenbeck equation is[15]

$$(g_{\mu\nu}\partial^\mu\partial^\nu + m^2)\varphi(x) = y\rho(x), \tag{20}$$

where y is the coupling constant, and $\rho(x)$ is the source of the scalar field $\varphi(x)$. Let us now consider the simplest Higgs field $\phi(x)$, its Lagrangian being

$$L = \frac{1}{2}\{(\partial^\mu\phi)(\partial_\mu\phi) - \mu^2\phi^2\} - \frac{\lambda}{4!}\phi^4. \tag{21}$$

The field equations are

$$(g_{\mu\nu}\partial^\mu\partial^\nu + \mu^2)\phi + \frac{\lambda}{3!}\phi^3 = 0. \tag{22}$$

Comparing Eqs.(20) with Eq.(22), we see that $-\frac{\lambda}{3!}$ is the coupling constant, and ϕ^3 is the source of the Higgs field ϕ. Hence the crux of the Higgs field is its nonlinearity and its self-interaction. Since $\lambda > 0$ and $\mu^2 < 0$, it shows that the field has a mass term corresponding to an imaginary mass, so the Higgs field can move with the speed of light or a speed exceeding light velocity.

The Higgs field has several forms with different properties. The Higgs mechanism shows that it is possible to change gauge fields from massless ones to massive ones, and at the same time to change the Higgs field from imaginary mass to physical mass.

The membranes formed from Higgs bosonic field were produced in the early Universe, and it seems to be waves stimulated by phase transitions and the Universe expansion. They expand rapidly, and after a period of evolution the composition of the membranes began to change. The massive particles, real Higgs particles and gauge vector particles, replace the imaginary Higgs particles. This is easy to understand: since the Universe is expanding, producing large volumes with negative gravitational energy, which can subsequently create a large amount of matter, it produces large positive energy. The Higgs mechanism plays an important role in the process.

We have shown that spherical Higgs bosonic membranes can be automatically formed in the early Universe. They expand rapidly during a period of evolution, and the particles on the membranes acquire real masses, after which the membranes reduce their expanding speed and break into pieces. The pieces spread and keep an essentially spherical distribution; again their sizes become larger and larger along with the expanding Universe. By means of their gravity they make themselves the seeds of supergroups of galaxies.

Since the pieces of the spherical membranes are the seeds of galaxies, the structures in the Universe usually group as observed today. They are in tiers, the tiered structures gather in sheets, such as "walls of galaxies", the sheets again roll up into vacant-bubbled spheres, the diameters of which can be 3×10^8 light years, and the hollow spheres assemble into the cosmic foam filling the whole Universe. The structures described above have been observed in astronomical surveys.

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