Cosmic Strings and Galaxy Formation

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Accretion onto closed loops of vacuum string results in the formation of compact objects of subgalactic mass which are comparable in number to the frequency of active galactic nuclei and quasars. Such structure develops in baryon- and neutrino-dominated, as well as in axion-dominated, cosmological models. Planar wakes also develop behind relativistically moving open strings and generate fluctuations of order unity in the galaxy density on scales comparable to those of galaxy superclusters.

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Two different mechanisms for producing density fluctuations in the early universe have been suggested. One of them is based on the inflationary-universe scenario and predicts a scale-invariant spectrum of adiabatic fluctuations.[1] The fluctuations are produced by quantum fluctuations of the Higgs field and have the form of random-phase waves. Most of the recent analytic and numerical work has concentrated on this case, with various assumptions about the dark matter of the universe, but it appears that all versions have serious difficulties of one kind or another.

The principal problem arises in trying to reconcile the inflationary prediction that the density parameter Ω be unity with the ages and peculiar velocities of galaxies and the galaxy correlation function, and is most severe if the universe is dominated by massive neutrinos.[2] A baryon-dominated universe is incompatible with inflation, since nucleosynthesis requires[3] $\Omega_b \sim 0.1$.

Even for a noninflationary baryon-dominated scenario, the scale-invariant fluctuation spectrum predicts excessive temperature fluctuations in the 3-K background radiation on small angular scales.[4] Unfortunately, the most attractive feature of the neutrino- or baryon-dominated models, namely, the large initial coherence length of the fluctuation spectrum, is not present in a cold-particle (axion) dominated universe.

An alternative for the origin of density fluctuations is based on superheavy strings which could be formed at a phase transition in the early universe.[5–7] In this scenario, galaxies and clusters condense around oscillating loops of string, while the loops gradually lose their energy by gravitational radiation and eventually disappear. The spectrum of fluctuations produced by strings has been calculated by Vilenkin and Shafi[8] for baryon-, neutrino-, and axion-dominated universes. The spectra on scales $M < 10^{15} M_\odot$ differ from the scale-invariant adiabatic fluctuations in a baryon- or neutrino-dominated universe. Small-scale fluctuations are not damped out, thereby allowing the possibility of early formation of some galaxies or quasars.

An important feature of the string scenario is that the fluctuations are not in the form of waves with random phases. Closed loops have sizes much smaller than those of the galaxies and clusters condensing around them, and produce large density perturbations in their immediate vicinity. This can result in accretion of matter onto the loops and formation of massive compact objects. On larger scales, rare supergiant loops could produce localized regions of density contrast much greater than one might expect from Gaussian fluctuations (such regions may have actually been observed[9]). Another interesting effect is the formation of thin planar wakes with large density contrast behind relativistically moving long strings. In the present paper we shall analyze these effects and discuss their cosmological consequences.

The cosmological evolution of strings has been discussed in Refs. 5 and 7 and by Kibble and Turok.[10] Loops of size $\sim R$ are formed at $t \sim R$ with typical distance between the loops also $\sim R$. The loops decay by gravitational radiation with a lifetime $\tau \sim R/G\mu$, where μ is the mass per unit length of string. Reasonable perturbation spectra are obtained for[9] $G\mu \sim 4\times 10^{-6}(\Omega h)^{-1}$. At any time t the sizes of the loops are in the range $G\mu t < R < t$ (all smaller loops have already decayed). The loops are typically formed with relativistic initial velocities, $v_i \sim 1$. However, we expect the velocity distribution to be rather broad, and so loops with $v_i << 1$ will also be present. In the course of expansion the velocities are red shifted, like $v \propto (1+z)$. The distances between the loops grow like $d \propto (1+z)^{-1}$, and it is easily checked that the distance traveled by the loops does not exceed their typical separation $(vt < d)$. Hence, the motion of the loops does not affect clustering on comoving scales $\sim d$.

On the other hand, velocities of the loops are crucially important for the accretion process. Loops do not capture any mass until their velocity becomes smaller than the escape velocity, $v < v_{\rm esc} \sim (GM/R)^{1/2} \sim (G\mu)^{1/2}$. To simplify the discussion, we shall concentrate on the loops present at the time of equal matter and radiation densities, $t_{\rm eq} \sim 4\times 10^{10}(\Omega h^2)^{-2}$ s:

$$G\mu t_{\rm eq} < R < t_{\rm eq}. \qquad (1)$$

This range includes the most interesting loops responsible for galaxy and cluster formation. Velocities of such loops at $t > t_{\rm eq}$ are given by

$$v \sim v_i (R/t_{\rm eq})^{1/2} (t_{\rm eq}/t)^{2/3}. \qquad (2)$$

One can readily see that v is always less than $v_{\rm esc}$ by the time that the loop decays. The condition $v < v_{\rm esc}$ is first satisfied at epoch

$$t_1 \sim v_i^{3/2} R^{3/4} t_{\rm eq}^{1/4} (G\mu)^{-3/4} \lesssim R/G\mu. \qquad (3)$$

In fact the loops are slowed down both by the expansion and by the gravitational drag due to small-angle gravitational scattering of particles. In a baryon- or axion-dominated universe, the motion of the loops is supersonic, and we can disregard thermal velocities of the particles. Then the drag acceleration is given by[11]

$$\dot{v} = -(v/t_*)\ln\theta_{\rm min}^{-1}, \qquad (4)$$

where

$$t_* = v^3/4\pi G^2 M\rho \sim v^3 t^2/GM, \qquad (5)$$

and we have used $\rho = 1/6\pi G t^2$ for the mean density of the universe. $\theta_{\rm min}$ in Eq. (4) is the minimum scattering angle; $\theta_{\rm min} \sim 2GM/v^2 r_{\rm max}$, where $r_{\rm max}$ is the maximum relevant impact parameter. In our case $r_{\rm max} = \int v\, dt \sim 3vt$.

It is clear from Eqs. (3) and (4) that the gravitational drag is important if $t_* < R/G\mu$, which gives

$$v_i \lesssim (R/T_{\rm eq})^{1/6}. \qquad (6)$$

Since the drag force rapidly increases as the loops are slowed down $(\dot{v} \propto v^{-2})$, we expect that loops satisfying condition (6) will be decelerated to subsonic velocities. (When v becomes smaller than the thermal velocity of particles, the drag force is greatly reduced.)

For loops with $R > t_{\rm eq}$, the velocity is $v \sim v_i (R/t)^{2/3}$ and the slow-down time due to the gravitational drag is $t_* \sim v_i^3 R/G\mu$. Note that in this case t_* never exceeds the lifetime of the loop. However, loops with $R > G\mu t_0$, where t_0 is the present cosmic time, have not decayed yet. Such supergiant loops could be slowed down by the gravitational drag only if $v_i > (G\mu t_0/R)^{1/3}$.

Hitherto, we have assumed that the loop motion is highly supersonic, as would be appropriate in an axion- or baryon-dominated universe. In the case of a neutrino-dominated universe this assumption is no longer valid for $R < t_{\rm nr}$, where $t_{\rm nr}$ is the epoch $(\sim t_{\rm eq})$ when the neutrinos first become nonrelativistic. For loops with $v << v_\nu$, the drag force due to neutrino scattering is small.[11] Baryon scattering is not affected by the presence of neutrinos for impact parameters $r < r_{\rm max} \sim (G\mu R/t)^{1/3} t$. ($r_{\rm max}$ is the radius of a sphere enclosing a mass of neutrinos comparable to that of the loop.) The drag due to baryons is reduced by a factor Ω_b/Ω, and is important for $v_i < (\Omega_b/\Omega)^{1/3)}(R/t_{\rm eq})^{1/6}$.

Once a loop is slowed down to $v < (G\mu)^{1/2}$ (either by expansion or by gravitational drag), it starts capturing particles with impact parameters $r < r_a = GM/v^2$. Neutrinos and axions are collisionless particles and are not captured by the loops. Accretion of baryons begins after decoupling $(t_{\rm dec})$, and the accretion rate is[12] $\dot{M} \sim (\Omega_b/\Omega)M/t_*$, where t_* is given by Eq. (5). For loops satisfying condition (6), the captured mass is $\delta M \sim (\Omega_b/\Omega)M$; for loops not satisfying (6),

$$\delta M \sim v_i^{-3}(\Omega_b/\Omega)(R/t_{\rm eq})^{1/2} M < (\Omega_b/\Omega)M.$$

Since Eq. (6) gives a rather mild restriction on v_i, we expect that a substantial fraction of the loops will capture a mass $\delta M \sim (\Omega_b/\Omega)M$. The captured mass is initially in the form of hot gas occupying a volume of radius $R \sim M/2\pi\mu$. The nonlinear evolution of this mass will be to condense as dissipation occurs, either into a massive compact object or, if fragmentation is important, into a dense stellar system. Such dense nuclei are plausible candidates for evolving into the nuclei of active galaxies and quasars.

For loops formed before $t_{\rm eq}$ $(R < t_{\rm eq})$, we obtain the number density and cosmological mass fraction of such candidate "black hole" remnants:

$$n_{\rm bh} \sim t_{\rm eq}^{1/2} t_0^{-2} R^{-3/2};$$

$$\Omega_{\rm bh} \sim G\mu(\Omega_b/\Omega)(t_{\rm eq}/R)^{1/2}.$$

For numerical estimates below, we shall take $\Omega \sim h \sim 1$, $\Omega_b \sim 0.1$, and $G\mu \sim 10^{-5}$. Then the radius of a nucleus of mass $M_{\rm bh}$ is $R \sim (M_{\rm bh}/10^8 M_\odot)$ pc and the corresponding density is $\rho \sim (10^{12} M_\odot / M_{\rm bh})^2 M_\odot/\mathrm{pc}^3$. "Black holes" formed by the loops present at $t_{\rm eq}$ have masses in the range $10^6 M_\odot \lesssim M_{\rm bh} \lesssim 10^{10} M_\odot$ (the lower limit comes from the requirement that the corresponding loops must decay at $t \gtrsim t_{\rm dec}$). For $M_{\rm bh} \lesssim 10^9 M_\odot$, $\rho \gtrsim 10^6 M_\odot/\mathrm{pc}^3$; at such densities, stellar relaxation is rapid and collisions become important, plausibly resulting in the formation of a massive black hole. The predicted number of nuclei is comparable to that of luminous galaxies ($\sim 10^{-3}$ Mpc^{-3}) for $M_{\rm bh} \sim (10^7 - 10^8) M_\odot$, and the more massive nuclei are comparable in number to quasars, whose number density is[13] 10^{-5} Mpc^{-3} at $z = 3$.

We now turn to the discussion of wakes formed by the motion of open strings (that is, strings of length greater than the horizon). The typical curvature radius of such strings at time t is $\sim t$ and the typical velocity is $v \sim 1$. The wake formed behind a straight string has the shape of a wedge[14] with an opening angle $8\pi G\mu$ (on the assumption that $4\pi G\mu v$ is greater than the thermal velocity). The density contrast in the wake is $\delta\rho/\rho \sim 1$, its length is $\sim t$, and its mass is comparable to that of the string: $M_w \sim 8\pi G\mu t^3 \delta\rho \sim \mu t$. Particles enter the wake with a transverse velocity $v_t \sim 4\pi G\mu$. The gravitational acceleration in the field of the wake is $g \sim 2\pi G M_w / t^2$, and collisionless particles (like axions) do not escape much further than the width of the wake: $v_t^2/2g \sim 4\pi G\mu t$. Baryons will lose their transverse velocity in a shock and will stay confined within the width of the wake.

Once formed, the wakes will grow by the usual gravitational instability mechanism. One expects the large-scale structure produced by the wakes to be similar to that in the pancake scenario. An important difference is that in the string scenario, galaxies form first and then fall in the gravitational field of the wakes.[15] Open-string-wake masses can be as large as those of galaxy superclusters (mass $\sim 10^{16} M_\odot$ with $\sim 10^3$ per present horizon volume).

In summary, it appears that strings open new possibilities either in baryon-, axion- or neutrino-dominated scenarios. In the first two, relatively small closed loops may give rise to compact objects which can provide the energy source for quasars and active galactic nuclei, while supergiant loops can produce non-Gaussian density fluctuations on large scales. (It has recently been suggested that splitting of loops can also explain the observed cluster-cluster correlations.[16]) Early formation of quasars can reionize the universe, smoothing out small-scale temperature fluctuations, and thus remove one of the difficulties of the baryon-dominated scenario. In the neutrino-dominated case, numerical simulations show that galaxies are formed very late ($z < 0.5$), which seems to be in conflict with the existence of quasars with $z > 1$. However, in the string scenario with neutrinos, quasars are formed well before galaxies, and this difficulty does not arise. In the baryon- and axion-dominated cases, planar wakes behind long, rapidly moving strings can help to explain the observed large-scale structure. (Note that the baryon-dominated scenario with strings leads to a hierarchical clustering picture[9] with galaxies being formed at $z \sim 40$.)

Finally, it may be worth pointing out that strings predict even smaller fluctuations in the microwave background radiation than would arise in an axion-dominated inflationary model.[17] This is because there is substantial power in the residual fluctuation spectrum[8] on scales below the comoving horizon scale $L_{\rm eq}$ at matter-radiation equality. Now one normalizes the predicted fluctuations in the observed galaxy distribution on a scale where the variance is unity ($L_g \sim 20 h^{-1}$ Mpc), whereas $L_{\rm eq} \sim 30(\Omega h^2)^{-1}$ Mpc. Consequently, the predicted radiation anisotropy on large angular scales will be reduced by a factor $\sim L_g/L_{\rm eq}$ relative to the $\Omega = 1$ axion model. This factor can be important in an axion-dominated universe if $\Omega \lesssim 0.2$, and suffices to remove the inconsistency[4] with observational limits in the $\Omega = 0.1$ baryon-dominated model.

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[14]An order-of-magnitude estimation shows that the drag force is not sufficient to slow long strings down to nonrelativistic speeds, even when the strings are substantially perturbed.

[15]We have also considered wakes formed behind rapidly moving closed loops. Our conclusion is that such wakes do not lead to any dramatic effects. In particular, they do not produce linear seeds of gravitational instability which can evolve into a filamentary structure (the gravitational potential is too weak to keep the particles confined within the wake).

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