Fermi National Accelerator Laboratory

FERMILAB-Pub-88/170-A
November 1988

IS THE GREAT ATTRACTOR REALLY A GREAT WALL?

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ABSTRACT

We discuss some of the cosmological consequences of a late-time ($z \lesssim 10^3$) phase transition which produces light domain walls. The observed peculiar velocity field of the Universe and the observed isotropy of the microwave background radiation severely constrain the wall surface density ($\equiv \sigma$) in such a scenario: $G\sigma \lesssim 10^{-4} H_0$ (H_0 is the present value of the Hubble parameter). The most interesting consequence of such a phase transition is the possibility that the local, coherent streaming motion of $\sim 600\,\mathrm{km\,sec^{-1}}$ reported by the Seven Samurai could be explained by the repulsive effect of a relic domain wall within our Hubble volume (the Great Wall) provided that $G\sigma/H_0 \simeq 10^{-4}$.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

At present the 'conventional scenarios' of structure formation are hot or cold dark matter with inflation-produced curvature perturbations, and hot or cold dark matter with cosmic string induced isocurvature perturbations. Of these four scenarios, one appears to be very promising—cold dark matter with curvature perturbations (White, et al 1988) and another—hot dark matter with cosmic strings (Brandenberger, et al 1987; Bertschinger, et al 1988) appears promising, but has yet to be examined in great detail. One piece of observational data which all four conventional scenarios have difficulty explaining (Bertschinger 1988a,b; Kaiser and Lahav 1988; van Dalen and Schramm 1988; Shellard, et al 1987) is the large ($\sim 600\,\mathrm{km\,sec}^{-1}$), coherent ($\sim 40h^{-1}$ Mpc) streaming motion of our local neighborhood reported by the Seven Samurai (Dressler, et al 1987; Burstein, et al 1987; hereafter Seven Samurai) and others (Aaronson, et al 1986, 1988; Collins, et al 1986). The simplest explanation of this motion seems to be provided by the Great Attractor model (Lynden-Bell, et al 1988), in which the coherent motion arises due to a concentrated mass of $\sim 10^{16} M_{\odot}$ at about a distance of $\sim 40h^{-1}$ Mpc, in the direction of Hydra-Centaurus. In the two most promising structure formation scenarios it is difficult to understand how such a large concentration of matter develops by the present epoch—although it is not impossible for such to occur (Bertschinger 1988a,b; Kaiser and Lahav 1988; Hoffman and Zurek 1988). The peculiar velocity field with this streaming motion subtracted out is not unlike that that one would expect in either the cold dark matter with inflation scenario or the hot dark matter and cosmic string scenario: RMS peculiar velocities of a few 100 km sec^{-1} on scales of $\sim 40h^{-1}$ Mpc (see, e.g., Gunn 1988). Thus, if the coherent velocity of ~ 600 km sec^{-1} could be explained by some other phenomenon, the observations of the Seven Samurai would not be troublesome for these two otherwise promising scenarios.

The main point of this *Letter* is to point out that an unconventional scenario, a late-time ($z \lesssim 10^3$) cosmological phase transition (Hill, et al 1988), might be able to account for such a coherent velocity. The idea is simple: If such a phase transition occurred and produced light domain walls, then the repulsive acceleration field of a relic wall within our present Hubble volume would lead to such a coherent velocity if the wall surface density σ were, $G\sigma/H_0 \simeq 10^{-4}$. As we will discuss, walls of such surface density are marginally consistent another cosmological observation, the observed large-scale isotropy of the microwave background radiation, $\delta T/T \lesssim 3 \times 10^{-5}$ (see, e.g., Partridge 1988). We will begin by outlining the cosmological consequences of such a phase transition, and then return to discuss the local coherent peculiar velocity field arising from a Great Wall and the associated microwave anisotropy.

The basic idea of a late-time cosmological phase transition is that at a temperature

$T_F \lesssim 1/3$ eV, a Z_2 (reflection symmetry, i.e., two degenerate vacuum states $\phi_- = -\phi_+$) is spontaneously broken due to ambient thermal effects, leading to the production of light domain walls (Hill, et al 1988). A domain wall is the topological soliton which interpolates between the two degenerate vacuum states, and which has an internal energy density ($\sim T_F^4$) owing to the vacuum energy density within the wall (see, e.g., Vilenkin 1985).

[It is very unlikely that such a phase transition involves thermal effects due to the photons, as such a phase transition could be produced in many contemporary astrophysical environments where $T \gtrsim T_F \sim 3000$ K or less. The simplest realization of such a transition involves the thermal effects of the neutrino backgrounds (Hill, et al 1988), in which case such a phase transition could only occur in the contemporary Universe if one could harness a thermal bath of neutrinos with temperature $\gtrsim T_F$ for a sufficiently long time. The most likely contemporary site for a neutrino oven is a type II supernova where $T_\nu \sim 4-80$ MeV; however, there, such a neutrino oven only exists for seconds, very probably too short a time for a phase transition back to the unbroken symmetry state to take place.]

For our purposes the most important parameter for describing the effects of the domain walls that are produced is the surface density σ, and we will parameterize σ as follows:

$$G\sigma \equiv \beta H_0 \equiv \beta_{-4} 10^{-4} H_0 \simeq 7 \times h 10^{11} \beta_{-4}\, GM_\odot/\mathrm{Mpc}^2$$

Such a parameterization is convenient as most of the important effects of the domain walls today involve only the product $G\sigma$. We have chosen to write $\beta = \beta_{-4}10^{-4}$ because consideration of the effects of such walls on the microwave background and the peculiar velocity field of the Universe today restrict β to be less than about 10^{-4}. If we make the reasonable assumption that the internal wall density $\rho_{\mathrm{wall}} \simeq \sigma/\delta$ is about equal to T_F^4, where δ is the characteristic thickness of a domain wall, then the other important wall parameter δ can be expressed in terms of $G\sigma$ and the red shift at which the phase transition takes place, $(1+z_F) \simeq T_F/2.75\mathrm{K}$, by

$$\delta \simeq 10^{-3} \beta_{-4} [(1+z_F)/100]^{-4}\,\mathrm{Mpc}$$

An important scale to keep in mind is the Hubble distance at the time of the phase transition: $H^{-1} = H_0^{-1}(1+z_F)^{-3/2} \simeq 2\,[(1+z_F)/100]^{-3/2}$ Mpc.

If the two vacuum states at $T \lesssim T_F$ are exactly degenerate, then we expect the domain wall system produced by the phase transition (Vilenkin 1985; Hodges 1988) to consist of a portion of an infinite wall per Hubble volume, and a spectrum of 'vacuum bags' (closed surfaces separating the two degenerate ground states) of characteristic sizes λ ranging from $\lambda \simeq \delta \simeq 10^{-3}\,\beta_{-4}[(1+z_F)/100]^{-4}$ Mpc to $\lambda \simeq H^{-1} \simeq 2\,[(1+z_F)/100]^{-3/2}$ Mpc.

Once produced, vacuum bags will begin to oscillate due to domain wall surface tension, with a characteristic period equal to λ. Likewise, the portion of the infinite wall in a given Hubble volume is expected to have ripples on it (with the same range of characteristic lengths), and it too should begin to oscillate. The fate of the domain walls produced depends upon a crucial, to our knowledge, unknown parameter, the intercommutation probability. If this probability is reasonable, then when a piece of wall encounters another piece of wall, or when a bag self-intersects, it will cut itself up (in the same way cosmic string does; see, Vilenkin 1985; Shellard 1987; Matzner 1988; Moriarty, et al 1988), and the cutting process will rapidly chop bags into successively smaller pieces until they can finally decay into elementary particles (time scale $\sim 2\lambda$). Unlike cosmic string, where there are non-self-intersecting loop trajectories, an oscillating vacuum bag cannot avoid self intersection. On the other hand, if this intercommutation probability is very low, then the only damping mechanism for an oscillating bag is the radiation of gravitational waves. In this case the time-varying quadrupole moment of an oscillating bag will dissipate its initial mass-energy ($\simeq 4\pi\sigma\lambda^2$) into gravitational waves in a time of order $\tau_{GW} \simeq (4\pi G\sigma)^{-1} \simeq 10^3\beta_{-4}^{-1}H_0^{-1}$, a time which is independent of the size of the bag (or the wavelength of a ripple on an infinite piece of wall).

Because of our ignorance about the intercommutation probability we come to a branch point in our discussion. If the probability is reasonable, as seems most plausible, then the vacuum bags will self destruct in a time $\sim 2\lambda$, before they have a chance to significantly perturb the matter distribution in the Universe. [Of course they will produce linear velocity perturbations in the Hubble flow, but these perturbations will not have sufficient growth time to develop non-linear effects on interestingly large scales by the present epoch.] On the other hand, if the intercommutation probability is very low, then vacuum bags will survive until they evaporate via gravitational radiation, in a time much longer than the present age of the Universe. In the case that the intercommutation probability is high, the story is over *except* for the important effects of the infinite wall, which we will return to shortly. [There is of course the possibility that a vacuum bag that cuts itself to pieces leaves behind a black hole which can then perturb the matter distribution. We will not consider that possibility here.]

Suppose that the intercommutation probability is low, so that vacuum bags survive for a long time. Until the average density of a vacuum bag ($\sim \sigma\lambda^2/\lambda^3$) is comparable to that of the cosmic density its gravitational effect will only be a linear perturbation, and one can easily show that the bags which cause the largest amount of matter to develop into a non-linear, bound structure at a particular time are those whose average density is

comparable to the ambient of the Universe. The ratio of the average density of a vacuum bag compared to the ambient density of the Universe at red shift $z \lesssim z_F$ is

$$\frac{\rho_{bag}}{\rho_U} \simeq 2(1+z)^{-3}\beta_{-4}\lambda_{\rm Mpc}^{-1}$$

Therefore the red shift z_{NL} at which a bag of characteristic size λ becomes a non-linear perturbation is given by

$$(1+z_{NL}) \simeq (2\lambda_{\rm Mpc}/\beta_{-4})^{-1/3}$$

When a vacuum bag becomes a non-linear perturbation it will, in a Hubble time, accrete a mass comparable to its own mass. [For our discussions we will assume that $\Omega_0 = 1$ (of course!) and that the bulk of the matter in the Universe is cold dark matter, although neither is a key assumption.] The mass of a vacuum bag of size λ is given by

$$M_{bag} \simeq 10^{13} M_\odot \beta_{-4}\lambda_{\rm Mpc}^2$$

From the expression above for $(1+z_{NL})$ we see that the only vacuum bags that lead to non-linear structures by a red shift of order a few have characteristic sizes $\lambda_{\rm Mpc} \lesssim 0.1\beta_{-4}$, corresponding to structure masses less than $\sim 10^{11}\beta_{-4}^3 M_\odot$, i.e., smaller than galaxies. While a range of vacuum bag masses are formed in the phase transition, $M_{bag} \simeq 10^7\beta_{-4}^3 M_\odot[(1+z_F)/100]^{-8} - 3\times 10^{13}\beta_{-4}M_\odot[(1+z_F)/100]^{-3}$, the constraint to their surface density provided by present observations, $G\sigma/H_0 \lesssim 10^{-4}$, severely limits the potential impact of the late-time phase transition scenario on structure formation. In fact we believe the most important effect probably has little to do with structure formation, but rather has to do with the contemporary effects which severely constrain the surface density σ. This is what we will now discuss.

According to the present understanding of the evolution of cosmologically-produced domain wall systems (Vilenkin 1985; Hodges 1988), at epochs after the phase transition there should be about one piece of an infinite domain wall per Hubble volume, which has ripples on it of a size not too different from the Hubble scale itself. For the purposes of the present discussion we will ignore the effects of any vacuum bags which may still be around, as we believe such effects are likely to be subdominant.

Consider a wall of surface density σ which stretches across the present Hubble volume, and is roughly planar on scales $d \gtrsim 100$ Mpc. On scales $\lesssim d$ the domain wall will act as an infinite plane of constant density, and will produce a constant, repulsive acceleration field (owing to the negative pressure within the wall, i.e., surface tension; see, Vilenkin 1985)

$$a = 2\pi G\sigma$$

In addition, a local radiation density underdensity of comparable magnitude will result when the wall formed ($z \sim z_F$), and will contribute an acceleration of roughly the same magnitude. Taking $\beta \simeq 10^{-4}$, we find that in a Hubble time a coherent velocity field of ~ 600 km sec^{-1} results from this acceleration field. Note that if β were significantly larger than 10^{-4} the peculiar velocity field produced would be at variance with present observations. Note too that at early times domain walls which are present will give rise to an acceleration field and peculiar velocities; however, the velocities produced in a Hubble time scale as $(1+z)^{-3/2}$. Thus the peculiar velocities produced at earlier times were much smaller; even the growing mode velocity perturbations induced will not grow to be comparable to those velocities produced recently. and will grow to be less than the velocities produced recently. [If the wall system should be more complicated, e.g., many walls within the present Hubble volume, our results may change quantitatively but not qualitatively. The wall system and compensating radiation underdensity should still produce a net acceleration field of magnitude, $a \sim few\ \pi G\sigma$.]

The portion of the infinite wall within our Hubble volume contibutions an energy density

$$\Omega_{\rm wall} \simeq 8G\sigma H_0^{-1} \simeq 10^{-3}\beta_{-4}$$

which is very small for $\beta_{-4} \lesssim 1$. Of course this contribution will grow with time as $H^{-1} \propto t$, and could eventually become significant (long after this paper has been forgotten). Likewise, any gravitational radiation produced by the wall by the present epoch is small, $\Omega_{\rm GW} \simeq 10^{-6}\beta_{-4}^2$.

The large domain wall within our present Hubble volume will also give rise to temperature fluctuations in the cosmic microwave background because of its effect on the gravitational potential, through the Sachs-Wolfe effect (see, e.g., the analogous discussion for cosmic strings by Stebbins 1988). To estimate the size of this effect consider a portion of wall which is undergoing oscillations with characteristic wavelength λ and amplitude of the same magnitude. In the region around the oscillating piece of wall, the Newtonian potential, $GM/R \sim G\sigma\lambda$, is changing by order unity on a light crossing ($\Delta t \sim \lambda$). As a result of the time-varying gravitational potential a temperature fluctuation of

$$\frac{\delta T}{T} \simeq G\sigma\lambda \simeq \beta\frac{\lambda}{H_0^{-1}}$$

will result. Simply put, the gravitational redshift suffered by a microwave photon as it approaches such an oscillating portion of wall differs from that suffered as it moves away by order unity. For $\beta \simeq 10^{-4}$, a temperature fluctuation of $\delta T/T \simeq 10^{-4}\lambda/H_0^{-1}$ is produced. [And if a line of sight to the surface of last scattering crosses N such pieces

of oscillating wall, the effect will be larger, by roughly $\sqrt{N}$.] If $\lambda \lesssim H_0^{-1}/10$ or so, the resulting temperature fluctuation will be less than about 3×10^{-5} or so, and therefore not inconsistent with the observed level of isotropy (Partridge 1988). Because of the inherent magnitude of the effect, $\delta T/T \sim G\sigma \sim \beta_{-4} 10^{-4}$, it is difficult to imagine that a value of β significantly greater than 10^{-4} could be consistent with the observed level of anisotropy. We should also emphasize the importance of the wall system having small-scale structure; if it does not, microwave anisotropies of order $\delta T/T \sim G\sigma H_0^{-1} \sim \beta_{-4} \times 10^{-4}$ will most certainly develop (Veeraraghavan and Stebbins 1988).

To summarize, we find that the severe constraint to the surface density of domain walls produced in a late-time, cosmological phase transition provided by the isotropy of the microwave background and the peculiar velocity field of the Universe likely precludes such a transition from playing a key role in structure formation. [We mention in passing if the two vacuum states, ϕ_+ and ϕ_-, are not exactly degenerate, so that the domain wall structures are not persistent, the constraints based upon present observations may not be applicable because the domain walls may have disappeared by the present (see, e.g., Gelmini, et al 1988), and thereby escape the stringent microwave constraint.] However, we find it very intriguing that a relic domain wall from such a transition (dubbed here the Great Wall) could possibly explain the coherent motion of ~ 600 km sec^{-1} observed in our local vicinity, and thereby resolve the problem that this observation had posed for the most promising structure formation scenarios. If the Great Wall scenario is correct, then one would expect the microwave fluctuations associated with the Great Wall to be at a level close to the present upper limits to the large-scale isotropy. In closing we should mention that the Great Wall (if it exists) would be found in a direction opposite to the direction of the Great Attractor; and one might ask if it would have observable effects beyond those discussed here. Since in the simplest models the wall only couples to neutrinos (or other weakly interacting particles) it seems very unlikely that it would make its presence known by other than its gravitational effects.

It is a pleasure to thank C. Hill, H.M. Hodges, and D.N. Schramm for useful and provocative conservations. This work was supported in part by the NSF (at UCSB), the DoE (at Chicago and Fermilab), and by the NASA (at Fermilab). AS would like to thank the NSERC and the Canadian Institute for Advanced Research for their support.

REFERENCES

Aaronson, M., et al 1986, *Ap. J.*, **302**, 536.

Aaronson, M., et al 1988, *Ap. J.*, submitted.

Bertschinger, E. 1988a, *Ap. J.*, **324**, 5.

Bertschinger, E. 1988b, in *The Post-Recombination Universe*, eds. N. Kaiser and A.N. Lasenby (Kluwer), p. 249.

Bertschinger, E., Mellot, A., and Scherrer, R.J. 1988, *Phys. Rev. Lett.*, submitted.

Brandenberger, R., et al 1987, *Phys. Rev. Lett.*, **59**, 2371.

Burstein, D., et al 1987, *Ap. J. Suppl.*, **64**, 601.

Collins, C.A., Joseph, R.D., and Robertson, N.A. 1986, *Nature*, **320**, 506.

van Dalen, A. and Schramm, D.N. 1988, *Ap. J.*, **326**, 70.

Dressler, A., et al 1987, *Ap. J. (Letters)*, **313**, L37.

Gelmini, G., Gleiser, M., and Kolb, E.W. 1988, Fermilab FNAL-PUB-88/151A.

Gunn, J. 1988, 'Deviations from Pure Hubble Flow: A Review,' Princeton Univ. preprint.

Hill, C., Fry, J., and Schramm, D.N. 1988, *Comments on Nucl. & Part. Sci.*, in press.

Hodges, H.M. 1988, *Phys. Rev. D*, submitted; Fermilab preprint.

Hoffman, Y. and Zurek, W. 1988, *Nature*, **333**, 46.

Kaiser, N. and Lahav, O. 1988, in *Large-scale Motions in the Universe: Proceedings of Vatican Study Week 27* (Pontifical Academy of Science).

Lynden-Bell, D., et al 1988, *Ap. J.*, **326**, 19.

Matzner, R. 1988, *Computers in Phys.*, **2**, 51.

Moriarty, K.J.M., Myers, E., and Rebbi, C. 1988, in *Proc. of the Yale Workshop on Cosmic Strings*, eds. F. Accetta and L.L. Krauss (Singapore: WSPC).

Partridge, R.B. 1988, *Rep. Prog. Phys.*, **51**, 647.

Shellard, E.P.S. 1987, *Nucl. Phys.*, **B283**, 624.

Shellard, E.P.S., Brandenberger, R., Kaiser, N., and Turok, N. 1987, *Nature*, **326**, 672.

Stebbins, A. 1988, *Ap. J.*, **327**, 584.

Veeraraghavan, S. and Stebbins, A. 1988, in preparation.

Vilenkin, A. 1985, *Phys. Repts.*, **121**, 263.

White, S.D.M., Davis, M., Efstathiou, G., and Frenk, C. 1988, *Nature*, **330**, 451.