# **Supernatural Inflation**

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(January 18, 1996)

# Abstract

Most models of inflation have small parameters, either to guarantee sufficient inflation or the correct magnitude of the density perturbations. In this paper we show that, in supersymmetric theories with weak scale supersymmetry breaking, one can construct viable inflationary models in which the requisite parameters appear naturally in the form of the ratio of mass scales that are already present in the theory. Successful inflationary models can be constructed from the flat-direction fields of a renormalizable supersymmetric potential, and such models can be realized even in the context of a simple GUT extension of the MSSM. We evade naive "naturalness" arguments by allowing for more than one field to be relevant to inflation, as in "hybrid inflation" models, and we argue that this is the most natural possibility if inflaton fields are to be associated with flat direction fields of a supersymmetric theory. Such models predict a very low Hubble constant during inflation, of order  $10^3$ - $10^4$  GeV, a scalar density perturbation index n which is very close to or greater than unity, and negligible tensor perturbations. In addition, these models lead to a large spike in the density perturbation spectrum at short wavelengths.

98.80.Cq, 04.70.-s, 12.60.Jv

#### I. INTRODUCTION

Inflationary models [1] in general require small parameters in the particle theory Lagrangian, to provide the flat potential needed for sufficient inflation and for the correct magnitude of density fluctuations. The need for unmotivated small parameters tends to weaken the credibility of a theory, so one hopes that the origin of these parameters can be understood. It is conceivable, of course, that the explanation lies beyond our present understanding, just as we presently have no accepted explanation of why the Yukawa coupling of the electron is  $2 \times 10^{-6}$ , or why the weak scale lies 17 orders of magnitude below the Planck scale. Nonetheless, it would be encouraging to find that the small parameters required by inflation could be obtained from small parameters that are already essential to the particle theory, so that no additional small parameters are introduced. Models in which the small parameters arise as ratios of known particle physics mass scales are particularly attractive [2].

From a field theoretical perspective, it is difficult to see how flat direction fields can be present in a nonsupersymmetric theory (with the exception of Goldstone bosons, considered in Ref. [3]) given the effect of radiative corrections. We will assume therefore that the world is supersymmetric, and ask whether an inflationary potential can arise naturally in the context of the mass scales which we expect might be present. Some natural candidates for these scales could be the Planck scale  $M_p \approx 10^{19}$  GeV, the GUT scale  $M_G \approx 10^{16}$  GeV, the intermediate scale  $M_I \approx 10^{11}$  GeV, and the supersymmetry breaking scale  $m_{3/2} \approx 1$  TeV.

In the context of supersymmetric models, an attractive scale for the vacuum energy density during inflation would be set by the intermediate scale,  $M_I$ . This scale is very likely to be present in a hidden sector model of supersymmetry breaking. It is also the right energy scale for the potential associated with moduli fields, which might be natural candidates for flat directions. The problem here, however, is that simple dimensional analysis arguments (to be reviewed in Sec. II) show that density perturbations would generically be either far too small [4,5] or far too large, depending on assumptions. For the case of inflation driven by a single moduli field, the dimensional arguments show that the requirements of sufficient inflation and correct density perturbations imply that 1) the variation of the inflaton (moduli) field during inflation is of order  $M_p$ , and 2) the energy density during inflation is of order  $M^4$  where  $M \approx 10^{16}$  GeV. An energy density of order  $M_I^4$  would produce density perturbations too small by about ten orders of magnitude. For the case of a chaotic inflationary scenario, the variation of the inflaton is again of order  $M_p$ , but in this case the density perturbations are much too large unless the quartic coupling  $\lambda$  is about  $10^{-12}$ .

In this paper, we show that the argument that inflation at an intermediate scale is untenable lacks sufficient generality, and can evaporate if one drops the assumption that inflation is driven by a single scalar field. We describe a class of two-field models, for which dimensional analysis estimates show that 1) the variation of the inflaton is of order  $M_I$  or less, and 2) the energy density during inflation is of order  $M_I^4$ . We then go on to illustrate these ideas with models motivated by supersymmetry with soft supersymmetry breaking. We will find that these models not only solve the naturalness problem of obtaining sufficiently many e-foldings of inflation, but also generate very nearly the correct size of density perturbations

based on the parameters of supersymmetry breaking. We therefore refer to our models as "supernatural" inflation.

This model contains a similar structure to the "hybrid" inflation models, proposed by Linde and studied by Copeland, Liddle, Lyth, Stewart, and Wands [6]. The fact that the standard dimensional naturalness arguments for the number of e-foldings and for  $\delta\rho/\rho$  do not apply, and that the Hubble scale during inflation will be low was also clearly recognized by these authors. Our point here is to emphasize that the most natural scales for successful implementation of two field inflation of the "waterfall" type are the scales associated with supersymmetry breaking and the Planck scale. Furthermore, our models more accurately reflect masses and couplings associated with flat direction fields, and we will motivate the parameters and potential we use by consideration of flat directions in the MSSM. Hybrid inflation in the context of SUSY leads one to the interesting conclusion that the Hubble scale during the inflation which established the density perturbations might have been of order  $10^3$ – $10^4$  GeV, rather than  $10^{13}$  GeV.

In the following section, we present the general arguments for why supersymmetry scales do not work in single field inflation models. We then review the general idea of "hybrid" or "waterfall" [6] models, and show why the single-field arguments do not apply to the two-field case. In Sec. III, we present supernatural inflation models, in which we assume the inflation sector consists of flat direction fields whose potential is generated through supersymmetry breaking and operators in the superpotential which do not permit the two fields to be simultaneously flat. We derive the constraints on parameters consistent with the requisite number of e-foldings and density perturbations. We conclude in the final section.

### II. ONE VS. TWO FIELD INFLATION

We begin this section by reviewing the "standard" arguments for why the inflaton in "natural" inflationary models varies on the scale  $M_p$  and why the scale for the energy density should be larger than the intermediate scale in inflationary models with a single field.

For the purposes of these dimensional arguments, we first assume the potential takes the form

$$\mathcal{V} = M^4 \mathcal{G}(\phi/f) , \qquad (1)$$

where  $\mathcal{G}$  is a bounded function of order unity. Here we have in mind for example a moduli field, with  $M \approx M_I$ . If we assume the slow roll equation of motion  $3H\dot{\phi} = -\mathcal{V}'$ , where H is the Hubble constant during inflation, the number of e-foldings is

$$N = \int H dt = \int d\phi \frac{H}{\dot{\phi}} = -\int d\phi \frac{\mathcal{V}}{M_p^2 \mathcal{V}'} \approx -\frac{\Delta \phi}{M_p} \frac{f}{M_p} \frac{\mathcal{G}}{\mathcal{G}'} . \tag{2}$$

There are essentially two possibilities. If  $\mathcal{G}$  is a bounded function, and  $\mathcal{G}'$  is not very tuned to have very flat sections, one is in the regime of what might be expected for a moduli type field. In this case, the requirement of about 60 e-foldings of inflation favors f of order  $M_p$  and a change in  $\phi$  during inflation at least of order  $M_p$ . Even when this is satisfied, some tuning of the potential is required.

The alternative possibility is that one is in a chaotic [7] inflationary scenario, in which case  $\mathcal{G}$  will be dominated by monomial behavior for sufficiently large field, and  $\mathcal{V}' \approx \mathcal{V}/\phi$ . In this case, f is not defined, but one would still conclude  $\Delta \phi \approx M_p$ .

Density fluctuations are also readily estimated under the assumed form of the potential. They are given by

$$\frac{\delta\rho}{\rho} \approx \frac{H^2}{\dot{\phi}} \approx \frac{H^3}{\mathcal{V}'} \approx \left(\frac{M}{M_p}\right)^2 \frac{f}{M_p} \frac{\mathcal{G}^{3/2}}{\mathcal{G}'} \ . \tag{3}$$

Assuming a potential of the moduli type, with  $\mathcal{G}$  and  $\mathcal{G}'$  of order unity and f of order  $M_p$ , we find that  $\delta \rho/\rho \approx (M/M_p)^2$  favoring  $M \approx 10^{-3} M_p$ . Detailed calculations might change M by an order of magnitude or so, but it is clear that  $M \approx 10^{11} \text{ GeV} \approx M_I$  is strongly disfavored.

In a chaotic scenario on the other hand, one would conclude that the density fluctuations are too large unless there is a small parameter. For example, a simple dimensional argument would lead to the conclusion that for  $V = \lambda \phi^4$ ,  $\lambda \approx 10^{-12}$ . Without further motivation for these small numbers, such a potential seems unlikely.

So one is led to the conclusion that it is difficult to naturally obtain sufficiently many e-foldings and the correct magnitude of density perturbations, without invoking either small numbers or a new mass scale.

It is apparent, however, that there is a loophole in the above argument. From Eq. (2) it is clear that the constraints on f and  $\Delta \phi$  during inflation arise because it is the same potential  $\mathcal{V}(\phi)$  that controls the inflation rate H and the speed of the inflation field  $\dot{\phi}$ . These constraints can be avoided, therefore, if the energy density during inflation is provided from some source other than the scalar field which rolls and controls the ending of inflation.

The simplest way to implement this idea would be with two fields. This idea is essentially that first proposed by Linde [6] as "hybrid" inflation or "waterfall" models. There are two fields  $\psi$  and  $\phi$ . The first field, which we call the inflaton, has a very flat potential. It starts at a large field value, and slowly rolls (via its classical field equations) to the origin.

The second field,  $\phi$ , has a potential whose minimum is far from the origin. In most previous incarnations of hybrid inflation, the scale of variation of this field is  $M_I$ , though in our models the scale will be  $M_p$ . When  $\psi$  has large field value, it gives a positive mass squared term in the  $\phi$  potential at the origin, so the classical field equations push  $\phi$  to the origin. When  $\psi$  gets sufficiently small (of order  $M_I$  or less in our models), the mass squared of  $\phi$  goes negative, and  $\phi$  makes the transition from the origin to  $M_p$ .

The key feature of this model is that the energy density during inflation is dominated by the potential energy of the  $\phi$  field at  $\phi = 0$ . There are no tunings in the  $\psi$  potential to get a small mass during inflation and a large mass afterwards, since its mass is always small, as is its potential energy. Because H depends on the value of  $\phi$  and is not determined by the field  $\psi$ , which acts as a switch to end inflation, the naive estimates do not apply.

The second key feature of this model is that the ending of inflation is controlled by when the  $\phi$  mass squared at the origin changes sign. One can obtain a large number of e-foldings with the variation of the inflaton field  $\psi$  much less than  $M_p$ . Let us see this explicitly.

We assume a potential which takes the form

$$\mathcal{V} = M^4 \mathcal{G}(|\phi|/f) + g(|\phi|, |\psi|) + m^2 |\psi|^2 , \qquad (4)$$

where M and f are to be determined, the function g is the term responsible for the  $\psi$  dependence of the  $\phi$  mass, and m is of order  $m_{3/2}$ .

We now have

$$N \approx \int d\psi \frac{H}{\dot{\psi}} \approx -\int \frac{H^2 d\psi}{m^2 \psi} \approx \frac{M^4}{m^2 M_p^2} \ln \left(\frac{\psi_{init}}{\psi_{final}}\right) . \tag{5}$$

Notice that the scale M in the numerator is independent of the mass and coupling of the  $\psi$  field (in the limit that the  $\psi$  contribution to the energy density is small) so that the previous arguments for one-field inflation no longer apply. Clearly for inflation to give several e-foldings requires only that  $\psi$  changes by an order of magnitude, and that  $M^4 \gtrsim m^2 M_p^2$ . No inflaton variation of order  $M_p$  is required, and so far, it seems  $M \approx M_I$  could be a good choice.

Let us now consider density fluctuations under the same assumed form for the potential. We find

$$\frac{\delta\rho}{\rho} \approx \frac{H^2}{\dot{\psi}} \approx \frac{H^3}{m^2\psi} \approx \frac{M^6}{M_n^3 m^2 \psi} \ . \tag{6}$$

The point is that the numerator  $H^3$  has its scale set by the  $\phi$  potential energy while the denominator is determined by the  $\psi$  field. We construct a model so that  $\psi$  at the end of inflation is of the order  $M_I$  or smaller. If we also take  $M \approx M_I$ , we find  $\delta \rho / \rho \approx M_I / M_p$  or bigger (rather than  $(M_I/M_p)^2$  as was the case in single field models). Although the coupling between the fields can have a coefficient which varies by many orders of magnitude, as does  $\psi$  in Eq. (6), the strong M dependence of Eq. (6) allows for agreement with the COBE constraint with only a relatively small M variation. This is very promising from the perspective of relating inflation models to real scales of particle physics. To answer the questions of how well these ideas really work, and how constrained the parameters of the models really are, requires a detailed investigation of particular examples of these ideas.

#### III. SUPERNATURAL INFLATION

We define Flat Direction Hybrid Inflation (FDHI) models as those motivated by the properties of moduli fields or flat directions of the standard model.

In the first model, we assume the existence of a superpotential which couples  $\psi$  and  $\phi$  but which is suppressed by a large mass scale M'. For standard model flat directions, such higher dimension operators are to be expected, with M' equal to  $M_p$ ,  $M_G$ , or some dynamical scale. In the case of moduli fields, it might be that this scale is of dynamical origin; one can readily determine how the answer changes with the form of the superpotential and the size of the mass scale. The example we take is

$$W = \frac{\phi^2 \psi^2}{2M'} \ . \tag{7}$$

We now need to specify the form of the supersymmetry breaking potential. We assume both  $\psi$  and  $\phi$  have mass of order the soft SUSY breaking scale of order 1 TeV (where we will need to test the consistency of this assumption). We assume that the potential for

the  $\psi$  field gives a positive mass squared at the origin, while the  $\phi$  field has negative mass squared at the origin. Furthermore, we assume that the cosmological constant is zero at the minimum of both  $\psi$  and  $\phi$ . The specific form of the potential we choose is

$$V = M^4 \cos^2\left(\phi/\sqrt{2}f\right) + \frac{m_{\psi}^2}{2}\psi^2 + \frac{\psi^4\phi^2 + \phi^4\psi^2}{8M'^2},$$
 (8)

where we have taken the scalar field to be real. When the parameters are motivated by supersymmetry breaking, we refer to our models by the name supernatural inflation. We will see that one very naturally obtains the correct magnitude of density perturbations, and sufficiently many e-foldings of inflation, using parameters and a potential which are well motivated in supersymmetric models.

The  $\psi$  mass is  $m_{\psi}$  and the magnitude of the (imaginary)  $\phi$  mass term (at the origin) is  $m_{\phi} \equiv M^2/f$ . During inflation,  $\phi$  is confined near the origin. The field  $\psi$  slowly rolls towards the origin and inflation ends about when  $\psi = \psi_c = \sqrt{2M'm_{\phi}}$ . It will turn out that either  $m_{\psi}/m_{\phi}$  or  $M'/M_p$  is small, so that during inflation the term  $m_{\psi}^2\psi^2$  is small relative to  $M^4$ . The Hubble parameter during inflation is therefore approximately  $H = \sqrt{8\pi/3}M^2/M_p$ .

We expect f is of order  $M_P$ , or equivalently,  $m_{\phi}^2$  is of order  $m_{3/2}^2$ . Although it looks like we took a very special form for the  $\phi$ -potential, the use of the cosine is not essential. As can be seen from a Taylor expansion, only at the very late stages of inflation are terms other than the constant and mass term relevant. We could equally well have specified a potential which is truncated at fifth order in the fields, or which has different higher order terms. Although both  $\psi$  and  $\phi$  might be moduli or standard model flat direction fields, we assume their potentials are of very different form; the particular case we assume is illustrative of how a model could work.

The constraint from density perturbations in the slow-roll regime is [8,9]  $V^{3/2}/[\tilde{M}_p^3(dV/d\psi)] = 6 \times 10^{-4}$ , where  $\tilde{M}_p \equiv M_p/\sqrt{8\pi}$ . This gives the constraint

$$\frac{M^5}{m_{\psi}^2 M_p^3} \sqrt{\frac{f}{M'}} e^{\mu_{\psi}^2 N/3} = 6.7 \times 10^{-6} \ . \tag{9}$$

Here we have defined  $\mu_{\psi} = m_{\psi}/H$  and have measured time in e-foldings away from the time N=0 when  $\psi=\psi_c$  (where inflation ends at positive N). It is clear that a lower M' makes the value of  $\psi$  at the end of inflation lower, which in turn *increases* the density perturbations. The exponential in Eq. (9) determines the scale dependence of the density perturbations, characterized by the scalar index.

The scalar index  $\alpha_s$  is readily determined from the scale dependence of the density perturbations to be  $-\mu_{\psi}^2/3$ . This can be seen directly from the formula for density perturbations above. Alternatively, it is extracted from the general formula [10]

$$n = 1 - 2\alpha_s = 1 - 3\left(\frac{V'}{V}\right)^2 + 2\frac{V''}{V} , \qquad (10)$$

where dimensionful factors should be compensated by  $\tilde{M}_p$ . Notice that the second term is negligible for all models for which the inflaton field value is much less than  $M_p$ . This is readily seen from the fourth expression in Eq. (2), which implies  $\tilde{M}_p V'/V \approx \Delta \phi/(NM_p)$ .

The third term is positive in our model, because the inflaton field rolls toward, rather than away, from the origin during the end of inflation.

We see for this model that n is always greater than 1, and is very close to 1 for small  $\mu_{\psi}$ , which is the case for large M'. This differs from the usual prediction for new inflation or chaotic inflation models. The current upper bound on n is uncertain as is summarized in Ref. [11]. These bounds, along with the validity of slow roll, prevent too large values of  $\mu_{\psi}$ . It turns out that in this model, the constraint for the correct magnitude of density fluctuations requires that when  $M' \approx M_p$ ,  $\mu_{\psi} \sim 1/100$ , when  $M' \approx M_G$ ,  $\mu_{\psi} \sim 1/10$ , and when  $M' \approx M_I$ ,  $\mu_{\psi} \sim 1$ . These constraints are given in more detail in Ref. [12].

Another distinctive feature of these models is that the ratio of the tensor to scalar contribution to the quadrupole  $\mathcal{R} = T/S \sim (V'/V)^2 \approx 0$ . Again this follows from the small value of the inflaton field  $\psi$  near the end of inflation.

As we have argued in the first section, models of inflation which have only a single field should have the inflaton field taking a value of order  $M_p$  near the end of inflation if 50 e-foldings are to be obtained without fine tuning. The combination of negligible  $\mathcal{R}$  and n never below 1 are distinctive features of these models which should help distinguish them from other possible inflationary models in the future.

Another distinctive feature of the perturbation spectrum from this model will be a spike at small wavelengths. This spike can be calculated from a detailed study of the evolution of the  $\psi$  and  $\phi$  fields, as is performed in Ref. [12]. Here we give the qualitative features of the evolution.

As we have emphasized, the  $\psi$  field acts as a trigger to end inflation. While the  $\phi$  field is confined to the origin, the evolution of the  $\psi$  field is straightforward; it moves in towards the origin according to the slow roll equation of motion.

While the  $\psi$  field is big, the  $\phi$  field has a large mass, so the field is strongly confined to the origin. As  $\psi$  rolls in towards the origin, the  $\phi$  mass is decreasing. Once the  $\phi$  mass is sufficiently small, it random walks away from the origin due to de Sitter fluctuations. As the mass squared of the  $\phi$  field becomes negative, the field value becomes sufficiently large that the classical potential dominates over the de Sitter fluctuations as a driving force. The  $\phi$  field then moves according to its classical equations of motion towards its true minimum.

Because of the coupling of the  $\psi$  and  $\phi$  fields, the mass of the  $\psi$  field increases as  $\phi$  increases. Eventually, the time dependent  $\psi$  mass is sufficiently large that the  $\psi$  field begins to oscillate about its true minimum as a coherent state, and subsequently decay. Once the  $\phi$  field oscillates about its true minimum, the exponential expansion of the universe ceases, and ultimately the  $\phi$  field decays, permitting the universe to reheat to a temperature somewhat above the weak scale.

The spike in the spectrum arises from fluctuations in the  $\phi$  field during the stage in its evolution where de Sitter fluctuations drive its motion. We have calculated this spike [12] and constrain our model so that inflation ends sufficiently rapidly that the spike is only relevant to perturbations on small (as yet unobservable) scales, less than 1 Mpc. This has given us a lower bound on  $\mu_{\phi}$ . We have also checked that the magnitude of the spike is consistent with known black hole constraints on these small scales.

An alternative model can be constructed based on a renormalizable potential. Although this seems strange since we are considering flat direction fields, it is often the case, even in the MSSM, that fields cannot be simultaneously flat. So we take the potential to contain the soft supersymmetry breaking terms as before but to contain a Yukawa coupling involving  $\psi$  and  $\phi$ . Specifically

$$V = M^4 \cos^2(\phi/\sqrt{2}f) + \frac{m_{\psi}^2 \psi^2}{2} + \lambda^2 \frac{\psi^2 \phi^2}{4} . \tag{11}$$

This model has the essential features of the FDHI model of the previous section. The difference is the value of  $\psi_c$  which in this model is  $\psi_c = \sqrt{2}m_{\phi}/\lambda$ . The density fluctuations give the constraint

$$\frac{\lambda H^3 e^{\mu_{\psi}^2 N/3}}{m_{\psi}^2 m_{\phi}} = 1.6 \times 10^{-4} \ . \tag{12}$$

If  $\lambda$  is of order unity, to satisfy Eq. (12) requires  $\mu_{\phi} > 10^3$ . However, if  $\lambda \approx 10^{-4} - 10^{-5}$ , the model works perfectly with  $\mu_{\psi}$  and  $\mu_{\phi}$  both of order unity. We see there is virtually no fine tuning, so long as a small  $\lambda$  exists. In Ref. [12] we discuss examples, and construct an explicit GUT extension of the MSSM in which the small Yukawa coupling required by the particle physics provides the small coupling needed for the correct amplitude of density fluctuations.

### IV. CONCLUSIONS

We have shown that with more than one field it is possible to construct models of inflation with no small parameters. Furthermore, the mass scales which seem to most naturally appear in these models are of order  $m_{3/2}$ , about 1 TeV, and  $M_I$ , about  $10^{11}$  GeV, leading to a natural association with supersymmetric models. These models give rise to the correctly normalized density perturbations, even though the Hubble constant is quite low, of order  $10^3 - 10^4$  GeV, because the value of the inflaton field at the end of inflation is much lower than the Planck scale. The key to producing more such models is a sensitive dependence of the  $\phi$  potential on the value of the  $\psi$  field, so that the motion of the  $\psi$  field can trigger the end of inflation while its value is small.

An important feature which distinguishes these models from previous examples of hybrid inflation is that both the  $\psi$  and  $\phi$  fields are assumed to have small mass. This is the more natural choice if both fields correspond to flat direction fields. Furthermore, because supersymmetry is broken during inflation, it is difficult to maintain the hierarchy between the two fields due to large radiative corrections. One would need further complications to maintain this hierarchy naturally. The small mass of  $\phi$  leads to the characteristic spike on small length scales.

Our model is also consistent with the gravitino bound and Affleck Dine baryogenesis [12]. It seems that multifield models are probably the most natural models which can implement inflation with weak scale Hubble constant, and that furthermore, these are probably the most natural inflation models in that they involve no new small parameters. The requisite small parameters arise naturally from the ratio of mass scales. These models have the further advantages that they can be explicitly realized and one can calculate the relevant parameters for any particular implementation. They might even occur in simple extensions of the MSSM.

Perhaps the most important property of a model is its testability, and our proposed models have several characteristics that are in principle observable. The scalar index n which characterizes the scale dependence of density perturbations is always greater than unity. It is very close to unity for the model of Eq. (8) with M' at the Planck or GUT scale, but for M' at the intermediate scale or for the model of Eq. (11), it could be as large as 1.2 for the parameters presented in our plots. In all cases tensor perturbations are negligible. An especially distinctive feature is a large spike in the density perturbation spectrum at present wavelengths of about 1 Mpc or less.

#### ACKNOWLEDGMENTS

We are very grateful to Andrew Liddle, David Lyth, and Ewan Stewart for discussions and the Aspen Center for Physics where these discussions took place. We also thank Sean Carroll, Csaba Csáki, Arthur Kosowsky, Andrei Linde, and Bharat Ratra for their comments. We thank Bernard Carr, Jim Lidsey, Avi Loeb, Paul Schechter, and Paul Steinhardt for discussions and correspondence about black holes. We also thank Krishna Rajagopal for his comments on the manuscript.

The work of L.R. was supported in part by the Department of Energy under cooperative agreement DE-FC02-94ER40818, NSF grant PHY89-04035, NSF Young Investigator Award, Alfred Sloan Foundation Fellowship, and DOE Outstanding Junior Investigator Award. The work of M.S. was supported in part by MIT UROP. The work of A.H.G. was supported in part by the Department of Energy under cooperative agreement DE-FC02-94ER40818.

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