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New M-theory Backgrounds with Frozen Moduli

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We propose examples, which involve orbifolds by elements of the U-duality group, with M-theory moduli fixed at the eleven-dimensional Planck scale. We begin by reviewing asymmetric orbifold constructions in perturbative string theory, which fix radial moduli at the string scale. Then we consider non-perturbative aspects of those backgrounds (brane probes and the orbifold action from the eleven-dimensional point of view). This leads us to consider mutually non-perturbative group actions. Using a combination of dualities, matrix theory, and ideas for the generalization of the perturbative orbifold prescription, we present evidence that the examples we construct are consistent M-theory backgrounds. In particular we argue that there should be consistent non-supersymmetric compactifications of M-theory.

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1. Introduction

One of the most interesting issues in M theory is the question of how the moduli become fixed. The natural length scale for the various radii is the eleven-dimensional Planck scale, l_P. Generic geometrical M-theory backgrounds preserving supersymmetry have either a moduli space of vacua, or develop a superpotential which vanishes at a supersymmetric solution which exists at infinity in some direction in moduli space [1].

In string theory, a set of non-geometrical backgrounds was introduced in [2] in which many moduli are projected out from the start. This rather economical method can eliminate radial moduli, though not the dilaton, in string theory.[1] The radii become fixed at the string scale, l_S. In this paper we study how these compactifications work non-perturbatively. We go on to argue that it is possible to generalize these constructions to orbifolds in M theory which freeze moduli at their natural scale, l_P. In the simplest example of this kind, the orbifold group breaks all the supersymmetry. Thus the perturbative problem that non-supersymmetric models are unstable (i.e. develop a dilaton tadpole) may be overcome.

The basic idea behind the asymmetric orbifold construction of [2] is as follows. String backgrounds, such as tori, have discrete symmetries, such as T-duality. At generic points in the moduli space, the symmetry is broken, but at special points it is restored. At these points, one can orbifold by this symmetry (perhaps combined with other symmetries of the system) as long as level-matching constraints are satisfied.

It is interesting to then consider non-perturbative aspects of the physics of these backgrounds. Because we know how T-duality acts on the various branes in the theory, we can determine how the orbifold group acts on the non-perturbative spectrum (at least the BPS spectrum).

The orbifold acts differently on left and right-movers on the string worldsheet. This, as well as the fact that the radii are fixed at the string scale, suggest that these backgrounds are not geometrical [2]. It is interesting to consider then what the moduli spaces of brane probes look like in these theories. We find that the branes do have non-trivial moduli spaces.

These backgrounds fix radial moduli in string theory. As for the problem of fixing the dilaton, string-string duality (or U-duality) suggests an answer: construct an orbifold by S-duality at the self-dual coupling. Modding out by U-duality symmetries was discussed in [4][5], where a number of interesting examples can be found.

[1] One can eliminate the dilaton in compactifications down to *two dimensions* [3], but in four dimensions the dilaton vertex operator remains invariant under perturbative string orbifolds that preserve the 4d Lorentz group.

Four-dimensional string-string duality maps T-duality to S-duality [6]. So the existence of a theory obtained by modding out by T-duality on one side implies that there is a sensible theory obtained by modding out by S-duality on the dual side (since there is only one theory involved, which happens to have two dual descriptions). Roughly speaking, modding out by both S and T dualities should fix all the moduli.

Another motivation for studying these somewhat exotic compactifications is matrix theory. For ordinary toroidal backgrounds, the matrix description one derives at finite discrete light cone momentum N does not decouple from gravity when the background has ≥ 6 compact dimensions [7][8]. It will be interesting to see what the situation is for non-geometrical backgrounds such as those discussed here.

This paper is organized as follows. In §2 we review asymmetric orbifolds and discuss branes and their moduli spaces on these backgrounds. This leads us to try to develop a more abstract formulation of orbifold theories than that which was developed for the perturbative string limits. In §3 we present an example in which we orbifold by two mutually non-perturbative symmetries, fixing the moduli and breaking supersymmetry. We use the matrix theory formulation of the orbifolds to argue for consistency. In §4 we give a preliminary discussion of the low-energy physics of these models, and in §5 we conclude by discussing several interesting open issues.

For other discussions of duality and supersymmetry breaking, see [9].

2. Branes and Asymmetric Orbifolds

Let us consider the following asymmetric orbifold in the perturbative type IIA string theory on T^4. Take a square torus with radii

$$R_1 = R_2 = R_3 = R_4 = l_S \tag{2.1}$$

and no B field. Then we can mod out by a symmetry generated by

$$g : (x_L^1, x_R^1; x_L^2, x_R^2; x_L^3, x_R^3; x_L^4, x_R^4) \rightarrow (-x_L^1, x_R^1; -x_L^2, x_R^2; -x_L^3, x_R^3; -x_L^4, x_R^4) \tag{2.2}$$

acting on the left and right moving bosons on the string world sheet. The action on the RNS fermions is determined by worldsheet supersymmetry. In this model as it stands, half of the left-moving supersymmetries in the untwisted sector are projected out, but the supersymmetry returns in the twisted sector. But if we combine this symmetry with an action $(-1)^{F_R}$, then one obtains no supersymmetry from the twisted sector.

¿From the expressions for the left and right moving momenta (zero modes of $x^i_L, x^i_R, i = 1, \ldots, 4$)

$$p^i_L = \frac{m^i}{R} - n^i \frac{R}{l_S^2} \tag{2.3}$$

$$p^i_R = \frac{m^i}{R} + n^i \frac{R}{l_S^2} \tag{2.4}$$

we see that the symmetry (2.2), at the self-dual radii (2.1), exchanges winding number n and momentum number m. The orbifold is then a modding out by T-duality, combined with additional action on fermionic degrees of freedom. One can compute the complete perturbative string spectrum following the methods in [2].

Let us consider the spectrum of branes in this background. For that we simply need to consider the action of T-duality on the branes. For D-branes, T-duality exchanges Dirichlet with Neumann boundary conditions for the open strings living on their worldvolumes [10]. So for example a D0-brane turns into a D4-brane wrapped on the T^4. The invariant states will then consist of k D0-branes and k D4-branes.

How does this all look in eleven dimensions? The D0-brane is a momentum mode p_{11} in the eleventh dimension, and the D4-brane is a longitudinal M-5-brane. So the orbifold exchanges momentum and winding in the eleventh dimension as well as in $x^1, \ldots, x^4$! The constraint on the moduli, (2.1), is

$$R_i = \frac{l_P^{\frac{3}{2}}}{R_{11}^{\frac{1}{2}}}. \tag{2.5}$$

So the M-5-brane wrapped on $x^1, \ldots, x^4, x^{11}$ indeed has the same energy, $1/R_{11}$, as the momentum mode p_{11}.

Let us now consider the moduli spaces of these branes. First consider the untwisted sector. The 0-0 strings map to 4-4 strings, while the 0-4 strings map to 4-0 strings. The positions of the D0-branes map to Wilson lines in the D4-brane field theory. So the combined D0/D4-brane bound state still has a moduli space whose Coulomb branch is k copies of the torus. In addition, there are Higgs branches in which the 0-4 and 4-0 strings get VEVs.

This is rather analogous to what happens for D-brane states on symmetric orbifolds. For example, consider D0-branes on the symmetric orbifold R^4/Z_2 [11]. There one introduces "mirror" D0-branes at the Z_2-reflected points on R^4. There is then a branch of the moduli space which is just R^2/Z_2. In addition, there is another branch which emanates from the orbifold fixed point. When the mirror pair of D0-branes sits there, they can separate in the transverse directions without spoiling the Z_2 symmetry. This branch is related to the twisted states which live at the orbifold fixed point. The "twisted states" of the orbifold correspond here to bound states of the D0-branes stuck at the orbifold fixed point. In our case, the "mirror" of the D0-brane is the D4-brane.

In the asymmetric case we are considering, there are also extra open string sectors, analogous to the Ramond and Neveu-Schwarz sectors one has in imposing the GSO projection. These sectors yield new open string moduli replacing those that were projected out from the untwisted sector. (This had to happen in the case of the orbifold by (2.2) without the additional $(-1)^{F_R}$ action, since this model is equivalent to the original unorbifolded theory. It also happens to be true for the theory with the extra $(-1)^{F_R}$ action as well.)

2.1. $3d \to 4d$?

One might stop at this point and consider the strong-coupling limit of the perturbative string asymmetric orbifold as a way to fix the moduli even in M-theory, by taking R_{11} to be the radius of the $4th$ dimension (i.e. by considering an asymmetric orbifold of IIA on T^7). This may be related to the proposal of [12] for supersymmetry breaking. In particular, by taking appropriate combinations of the action (2.2), shifts, and $(-1)^{F_R}$ on the T^7, one can construct examples with $3d$ $N = 1$ supersymmetry, whose strong coupling (four-dimensional) limit may have no supersymmetry. One example of such an orbifold group is generated by the following elements acting on the T^7:

a_1	a_2	a_3
(-1,1)	shift	(-1,1)
(-1,1)	shift	shift
(-1,1)	(-1,1)	(-1,1)
(-1,1)	(-1,1)	shift
shift	(-1,1)	(-1,1)
shift	(-1,1)	shift
shift	shift	(-1,1)
$(-1)^{F_R}$		

The shift here is symmetric between left and right-movers: it is a shift by half a momentum lattice vector (with no winding component). This orbifold level matches in all sectors, and preserves $3d$ $N = 1$ supersymmetry. There is no twisted supersymmetry or twisted scalars. The physics is very subtle here, because the orbifold has naively violated the Lorentz symmetry between the fourth dimension and the other three, and because the radii of the T^7 shrink to zero size (2.5) in the limit $R_{11} \to \infty$. There is some nonlocality in the physics, since as discussed above momentum in the eleventh (i.e. fourth) dimension is accompanied by a wrapped M-5-brane. We hope to pursue this further in future work.

2.2. Toward a non-perturbative definition of orbifolding

In ref. [13], a precise prescription for constructing orbifold models in perturbative string theory was developed. Call the orbifold group G. The rule is that one keeps all G-invariant single particle states of the original theory, and adds in twisted sector states obeying a similar condition. It is not clear how to formulate a non-perturbative definition of the orbifold. In particular, multi-particle states which are invariant under G are discarded if their single-particle components are not invariant. Within the framework of string perturbation theory, one can also give a precise set of rules for interactions.

The fact that it is difficult to give a non-perturbative definition of the orbifold does not mean that the orbifold does not make sense at strong coupling. In theories with sufficient supersymmetry, starting from the weak coupling construction, it follows that a moduli space exists. (For non-supersymmetric theories, as always in string/M theory, the situation is less clear.) Indeed, certain non-perturbative aspects of asymmetric orbifolds are accessible to study, as we now show. In the context of string-string dualities, orbifolding has been studied extensively following the suggestion in [6]; see [14] for a discussion of the rules there.

Let us consider the type IIA string theory orbifolded by G. In M theory, for each perturbative string state–or more accurately, for each $p_{11} = 0$ state–there must be a set of D0-brane bound states with the same quantum numbers; i.e. there must exist nonzero-p_{11} modes of each state. These should arise, as discussed in the previous section, from appropriate bound states of D0-branes.

So we are led to propose that the spectrum of an M-theory orbifold consists of all the G-invariant *bound states.* This agrees with the prescription in perturbative string theory of not keeping all invariant multi-particle states. It also gives a prescription for defining the more abstract orbifolds we are interested in here. In particular, we can consider the orbifold (2.1)- (2.5) at any value of R_{11}.

Perturbative string orbifolds must satisfy a set of consistency conditions imposed by modular invariance [15]. These level-matching constraints lead to simple conditions on the orbifold action. They are sometimes, but not always, equivalent to anomaly cancellation, which has so far been the only condition imposed on M theory orbifolds. Level-matching ensures that an orbifold model has a well-defined perturbative string description. It is possible that in general it is not a constraint, since one has the possibility of adding space-filling branes whose moduli can render a model consistent [14]. (One example is F-theory in $8d$, where seven branes are included at points in $T^2/Z_2 \sim \mathbf{P}^1$.)

One way to get a handle on level-matching conditions is to consider the spectrum of D-branes on an orbifold. As discussed after (2.5), in the case of the action (2.2), untwisted states seem to correspond to the D0-brane/D4-brane wavefunction supported on the interior of their Coulomb branch, while we expect the twisted states to correspond to states localized at the origin of the Higgs and Coulomb branches, in analogy to the twisted states of symmetric orbifolds [11].

If we tried to act with -1's on six left-movers, for example, instead of four, we would find that the perturbative string theory does not level-match. Correspondingly, the D0-brane/D6-brane system breaks supersymmetry, the branes repel, and there are no analogues of the "twisted states". So a natural guess is that requiring that each element of the orbifold group maps branes to other branes which preserve supersymmetry should ensure that the model is consistent.

In six dimensions, i.e. M theory on T^5, one can use matrix theory to define the orbifold models. There the consistency conditions are somewhat cleaner, since in that case U-duality becomes T-duality of the defining matrix theory (as we will review below) [16]. This will give us one set of models. We will then move on to consider four-dimensional examples where matrix theory is no longer helpful but we can at least ensure that the group elements map branes to other mutually supersymmetric branes.

3. Fixing the Dilaton: Mutually Non-perturbative Orbifold Groups

A perturbative string orbifold does not fix all the M-theory moduli (at best it relates them to R_{11} as in (2.5)). In this section we will generalize the asymmetric orbifold construction to construct orbifolds of M theory which fix radii at l_P. We will first study a six-dimensional example because there we can use the matrix formulation of [16][17] to get a handle on the consistency conditions. Then we will generalize the construction to four dimensions. In §4 we will discuss aspects of the low energy physics of the examples, including subtleties pertaining to the question of stability.

3.1. 6d Example

Let us begin as in §2 with M theory on T^5. In the matrix theory this is given by the (2,0) supersymmetric $6d$ string theory of [18][17] compactified on another five-torus $\widetilde{T}^5$. This torus has radii $\Sigma_1, \ldots, \Sigma_5$, which are related to the radii $L_1, \ldots, L_5$ of the spacetime T^5 as

$$\Sigma_i = \frac{l_P^3}{RL_i}, \quad i = 1, \ldots, 4 \tag{3.1}$$

$$\Sigma_5 = \frac{l_P^6}{RL_1L_2L_3L_4} \tag{3.2}$$

$$\widetilde{M}_S^2 = \frac{R^2 L_1 L_2 L_3 L_4 L_5}{l_P^9} \tag{3.3}$$

where R is the longitudinal radius and $\widetilde{M}_S$ is the string scale of the (2,0) string theory. This theory was obtained [17] by considering the limit of vanishing string coupling in the background of a symmetric fivebrane [18]. There is evidence [19] that although the theory decouples from gravity, it includes the full conformal field theory describing strings propagating on the throat of the solution [18] as well as along the five Poincare-invariant dimensions.

What we will need of this background is the fact that it has a T-duality symmetry $SO(5,5,Z)$ acting on the moduli of the $\widetilde{T}^5$. In general, because this string theory is strongly coupled, we cannot quantize the strings in the usual manner of perturbative string theory. However, in [19] it was observed that there is a regime in which this theory has weakly coupled strings. Here we will first discuss the orbifold action in this regime, where the strings are weakly coupled, and ensure there that the orbifold satisfies the level-matching conditions. In particular, let us consider the following orbifold group G, generated as follows by elements f and g, in the (2,0) string theory:

f	g	fg
(-1,1)	(1,1)	(-1,1)
(-1,1)	(1,-1)	(-1,-1)
(-1,1)	(1,-1)	(-1,-1)
(-1,1)	(1,-1)	(-1,-1)
(1,1)	(1,-1)	(1,-1)
$(-1)^{F_R}$	$(-1)^{F_L}$	$(-1)^{F_L+F_R}$

In the string theory, all group elements level-match. Because there is a weakly coupled regime, this is necessary for consistency of the model. Though this is of course not a proof–we do not know whether this is sufficient for consistency–we take it as strong evidence that the model is consistent.

The elements f and g together fix

$$\Sigma_1 = \Sigma_2 = \ldots = \Sigma_5 = \frac{1}{\widetilde{M}_S} \tag{3.4}$$

This translates in the spacetime theory into the condition

$$L_1 = L_2 = \ldots L_5 = l_P. \tag{3.5}$$

In spacetime the orbifold group G acts as follows. The element f acts as T-duality on L_1, L_2, L_3, L_4, along with $(-1)^F$, in the IIA theory with respect to which L_5 corresponds to the "eleventh" dimension. Similarly the element g acts as T-duality on L_2, L_3, L_4, L_5, along with $(-1)^F$, in the IIA theory with respect to which L_1 corresponds to the eleventh dimension.

This orbifold kills all the supersymmetries. We start with a 32-component supercharge ϵ in eleven dimensions. The element f leaves invariant half of the spinors satisfying $\epsilon = \Gamma_5 \epsilon$ (i.e. left-handed supersymmetries in the IIA theory with respect to which L_5 corresponds to the eleventh dimension). The element g leaves invariant half of the spinors satisfying $\epsilon = \Gamma_1 \epsilon$. From the point of view of the original IIA theory, Γ_1 changes the chirality of the spinor, so this condition is incompatible with the supersymmetries left invariant by g. We could preserve some supersymmetries, at the cost of introducing scalars with flat directions in their potential.

Without supersymmetry, there is an issue of whether the matrix theory has flat directions, at least at distances greater than l_P, which is required for spacetime to emerge. This is not yet clear to us, but the following points are relevant. As discussed above, the matrix theory for M theory on T^5 has as an analogue model the theory of N NS fivebranes on $\widetilde{T}^5$, in the limit $g_S \to 0$ (where g_S is the string coupling). The analogue model for our case is the theory of N NS fivebranes on $\widetilde{T}^5$ in the IIA theory modded out by the asymmetric orbifold given above, in the limit $g_S \to 0$. That theory has fivebranes at separate points (as long as the separation is greater than $1/\widetilde{M}_S = l_P^2/R$) with no force between them. This is because the way the force cancels in the supersymmetric theory is by cancellations between dilaton, graviton, and antisymmetric tensor exchange. All these fields are projected in by the orbifold, so the asymptotic flat directions remain. However, this is not sufficient to ensure that we have ordinary gravity.

Another feature of our model is the absence of tachyons, and the resulting improved supersymmetry properties at high mass levels [20][21]. This may be enough to produce asymptotic flat directions at the right scale in the potential [22], though we need better control over the fivebrane theory in order to analyze this.

3.2. 4d Example

We will now consider a $4d$ M-theory background obtained by orbifolding M-theory on T^7, with coordinates $(x_1, x_2, x_3, x_4, x_{5=11}, x_6, x_{7=\widetilde{11}})$. The orbifold group H is generated by two elements. The first, h_1, can be most easily described by considering M-theory on this T^7 as a IIA string theory with respect to which $x_{5=11}$ is the eleventh dimension. Then h_1 acts as T-duality on x_1, x_2, x_3, x_4, combined with $(-1)^F$. Similarly, we take h_2 to be T-duality on $x_3, x_4, x_{5=11}, x_6$ combined with $(-1)^F$ in a $\widetilde{IIA}$ theory in which $x_{7=\widetilde{11}}$ is the eleventh dimension. This action fixes all the radii of the T^7 to be l_P.

In this case we do not have a matrix realization to work with. We expect, however, that imposing the condition that each orbifold group element maps branes to mutually supersymmetric branes is likely to lead to consistent models. We checked this for the $4d$ model just proposed. This is automatic for the elements h_1 and h_2, so one just needs to check the products. For example, the M-5-brane wrapped on $x_1, x_2, x_3, x_4, x_{5=11}$ maps under $h_2 h_1$ to an M-2-brane wrapped on $x_{5=11}, x_{7=\widetilde{11}}$. These two objects preserve supersymmetry.

4. Low-energy physics of the models

What can we say about the spectrum of this theory? The first important question is whether there are scalars in the low-energy spectrum. We have certainly projected out the untwisted radii, since U-duality is only a symmetry at the self-dual radii. There can however in principle be scalars in the "twisted sectors" of our orbifolds. Note that while the phrase "twisted sector" refers to the perturbative construction, in fact these sectors are distinguished by discrete quantum numbers. Such quantum symmetries[23] are exact in perturbative orbifolds, and thus they might be expected to exist in this theory as well. If we preserve enough supersymmetry (e.g. by not including the $(-1)^{F_R}$ actions in our orbifolds), this happens because there are scalars in the supermultiplets. With enough supersymmetry, these scalars will have flat directions in their potential, and may be in general connected to geometrical models by going out along them, as in some of the examples in [24].

Without supersymmetry, as in the above examples including the $(-1)^{F_R}$ actions, we have less control over the orbifold. In order to determine whether there are scalars in the twisted sectors, we would need to know the quantum numbers of the bound states of the orbifold theory's Hamiltonian. We can choose the orbifold action so as to ensure that the fermionic zero modes which are free and decoupled generate non-trivial representations of the Lorentz group and no scalars. But in principle the rest of the degrees of freedom could interact in such a way as to cause the ground states to have different quantum numbers.

However, even if there are "twisted" scalars, it is likely that a potential is generated which lifts any flat directions they would otherwise have. In particular, the twisted scalars will be charged under the quantum symmetry, so the orbifold point will be an extremum of the potential. This is to be contrasted with earlier constructions of non-supersymmetric backgrounds in weakly-coupled string theory [25], which, though interesting, are generically unstable to running off to weak coupling.

Note also that we did not project out the graviton state. It corresponds to a diffeomorphism symmetry in the noncompact dimensions which remains unbroken by our orbifold action.

We should stress a subtlety here. As discussed in §2.2, modulo the matrix construction we do not have a complete, non-perturbative description of the orbifolding procedure. In perturbation theory, the orbifold procedure is not guaranteed to construct a stationary solution of string theory. In particular, there are examples where twisted moduli are at a maximum, instead of a minimum, of the potential, and untwisted massive fields have tadpoles. A well-known example of this phenomenon is provided by the compactification of the $O(32)$ heterotic string on a symmetric orbifold. In this construction, at order g^2, there is a Fayet-Iliopoulos D-term, and at order g^4 there is a dilaton tadpole. At still higher orders, one expects to generate tadpoles and curvature for all untwisted moduli and charged fields (e.g. masses can be generated at fourth order in the Fayet-Iliopoulos parameter). In all known cases, it is possible to shift some charged field so as to cancel the D-term and restore supersymmetry. But at the level of the orbifold procedure, it is not clear why this is true. In the models we have described, supersymmetry is completely broken, and there are no small dimensionless parameters. A priori, then, we might expect that, while there are no massless states, there might be tadpoles for massive fields and that the true ground state,[2] if any, might lie far away and have quite different properties than those suggested by the orbifold construction.

However, it will always be the case that the orbifold point will be an extremum of the potential. We find it likely that for some examples this extremum will be a minimum after taking into account any tadpoles of massive fields. In particular, we have presented a matrix formulation in §3.1 in terms of fivebranes in a non-supersymmetric string theory with $g \to 0$ and asymptotic supersymmetry. We find these features promising, but unfortunately the strong coupling at the core of the fivebrane precludes a more detailed analysis at present.

It is important to note that although we have fixed the moduli at l_P, this does not necessarily imply that the low-energy effective couplings are strong. In a theory with exact electric-magnetic duality, the gauge couplings are necessarily large at the self dual point. At such a point, one might worry that the self-dual value of the bare coupling is preserved in the effective theory due to degeneracy of electric and magnetic states. When

[2] It is perhaps worth recalling that in ordinary weak coupling string theory, tadpoles for massive particles are not important since they are cancelled by small shifts, and are automatically taken care of by properly "integrating out;" at strong coupling, the situation is inevitably more complicated.

one orbifolds by S-duality, as we essentially do here, this objection is evaded, since the orbifold does not leave all the independent electric and magnetic states.

Finally, and perhaps most crucially, there is still the question of whether there is a cosmological constant. In all known examples of perturbative string theories without supersymmetry, there is a non-zero cosmological constant at one loop. This might suggest that in theories without moduli, one should expect a cosmological constant scaled by M_p. However, there is an important difference between these cases: in weakly coupled theories, the 1-loop cosmological constant is proportional to a 1-loop dilaton tadpole [26]. The evolution of the system then tends to drive the cosmological constant to zero. In the present case, there is no such tadpole. There are very speculative arguments [27], based principally on the holographic principle [28], that such a cosmological term would not make sense. Models of the type we have discussed here should be a testing ground for these ideas.

If there is a non-zero cosmological constant, then there may well be a solution of M theory of this kind, but there is probably no sense in which one can speak of a "low energy theory" at all. For example, terms in the gravitational action involving high powers of the curvature, $\mathcal{R}$, will not be suppressed.

5. Conclusions and Open Questions

We have provided evidence that M theory has a set of backgrounds, essentially non-perturbative generalizations of asymmetric orbifolds, in which the moduli are projected out (fixed at l_P). We are limited computationally by strong couplings in the construction. However, there are many interesting questions this set of models raises. We would like a more detailed, direct understanding of what it means to mod out by S-duality, and how it works just within quantum field theory. Similarly it would be very nice to derive simple and general consistency conditions analogous to level-matching constraints in perturbative orbifolds. We would also like to pursue the low-energy physics of these models, in particular the $3d \to 4d$ model in §2.1.

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