Landscape Cartography: A Coarse Survey of Gauge Group Rank and Stabilization of the Proton

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The landscape of string/M theory is surveyed over a large class of type IIB flux compactifications vacua. We derive a simple formula for the average size of the gauge group rank on the landscape under assumptions that we clearly state. We also compute the rank under the restriction of small cosmological constant, and find a slight increase. We discuss how this calculation could impact proton stability by computing the suppression factor for the number of vacua with additional gauge group rank that could be used to protect the proton. Finally, we present our views on the utility and limitations of landscape averages, especially in the context of this analysis.

Introduction: Recently, there has been renewed interest in studying mechanisms whereby flux contributions to the superpotential fix moduli [1,2,3,4]. There is now a substantial amount of evidence that such flux vacua are abundant, and there exist explicit constructions for type IIB compactifications on orientifolds where all geometric moduli can be fixed [5].

Although the construction of actual vacua is exceedingly difficult, it seems that aggregate knowledge of large classes of vacua is easier to come by. For example, efforts in this direction have led to interesting discussions on the likelihood of low-scale supersymmetry breaking [4]. However, the program should also allow study of issues for which current data is available, such as the size of the effective theory gauge group, the number of generations, the stability of the proton, etc. We primarily focus on this first issue of gauge group rank in this paper, and discuss how gauge group rank issues on the landscape may have relevance to the proton lifetime question.

It is first necessary to consider the type of questions that one can ask (and hopefully answer) using the string landscape. One type of question is a “what” question, such as, what is the string vacua(um) that describes us?, and how many vacua do we expect to be close to what we observe in nature? Another type of question is a “why” question, namely why we live in this vacuum and not any other. This second question often brings anthropic arguments into play. We will not rely on such arguments, but instead emphasize that aggregate analyses on the landscape may help us to sharpen both questions.

We will focus on a statistical study of the rank of the D3-brane gauge group on the portion of the landscape described by orientifolded Calabi-Yau 3-fold compactifications of Type IIB string theory. Our emphasis will be on quantitative results which are nevertheless applicable to as broad a class of flux vacua as possible.

In the paragraphs below we will calculate an ensemble average of the gauge group rank over flux vacua, as a function of the 3-fold parameters. We will compute the average rank again in the more restrictive domain of small cosmological constant. We will use these averages to generate estimates for the percentage of vacua that could plausibly stabilize the proton from extra gauge symmetries. We will then discuss at more length the interpretation of these results, and close with some ideas for future development.

Average Gauge Group Rank: We will consider flux vacua of an orientifolded Calabi-Yau 3-fold compactification of Type IIB string theory. Our aim will be to compute the “average” rank of the D3-brane gauge group for any choice $Y$ of Calabi-Yau 3-fold.

We let $X$ denote a Calabi-Yau 4-fold such that the orientifold limit of F-theory compactified on $X$ is Type IIB compactified on the orientifold of $Y$. The tadpole cancellation condition is

$$L_* = \chi (X) \frac{24}{N_{D3}} + \int F^{RR} \wedge H^{NS}$$

where $\chi$ is the Euler character and $N_{D3}$ is the net D3-brane charge. For any particular choice of $Y$ plus orientifold action (or equivalently, $X$), $L_*$ will be fixed. But clearly $N_{D3}$ will need to vary with the choice of fluxes for each vacuum. We will calculate an ensemble average of $N_{D3}$ over all flux vacua.

We quickly review the conventions and notation we use, which follow those of [13,14]. If $n$ is the number of complex structure moduli of $Y$ which are not projected out by the orientifold, then the number of independent fluxes which may be turned on is $2m = 2n + 2$. As argued in [15], the superpotential can be written as

$$W = \int \Omega G \wedge \Omega (z)$$

where $G_3 = F^{RR} - \tau H^{NS}$ and the $z$ are the complex structure moduli. The perturbative superpotential is thus determined by the fluxes, and it is indeed possible to invert this relationship and define a basis for the fluxes whose coefficients are determined by the superpotential.
The coefficients are written as

\[ W = X \]
\[ D_A W = Y_A \]
\[ D_0 D_I W = Z_I \]

where \( A = 1 \ldots n + 1, I = 1 \ldots n \).

The tadpole condition can now be rewritten as 

\[ L = \int F^{RR} \wedge H^{NS} = |X|^2 - |Y|^2 + |Z|^2 \]  

(4)

Note that although \( X, Y \) and \( Z \) are generically not quantized, \( L \) itself is an integer quantized in string units, \( X, Y \) and \( Z \) are determined by the choice of fluxes \( N \) in the integral basis and the complex structure moduli \( z \), so that for any choice of \( z \) they should be discrete, though not necessarily quantized.

The number of supersymmetric flux vacua (by which we mean that supersymmetry is not broken at tree-level by the fluxes, though it can be broken by non-perturbative dynamics) satisfying the tadpole condition is \[ N(L \leq L_*) = \frac{(2\pi L_*)^{2m}}{(2m)!} |\det \eta|^{-\frac{1}{2}} \int d^{2m} z \det g \rho(z) \]  

(5)

where \( \rho \) is the flux vacua density on the complex structure moduli space, \( g \) is the metric on moduli space, and \( \eta \) is the Jacobian for the change of variables from integer fluxes \( N \) to \( X, Y \) and \( Z \). We will not discuss these factors further (referring the reader instead to \[ 14 \]), since these factors will not be essential for us.

What we are interested in is the number of vacua for which \( N_{D3} = L_* - L \geq R_0 \). This is given by

\[ N(R_0) = \frac{(2\pi)^{2n+2}}{(2n+2)!} (L_* - R_0)^{2n+2} |\det \eta|^{-\frac{1}{2}} \times \int d^{2m} z \det g \rho(z) = c_Y (L_* - R_0)^{2n+2} \]  

(6)

where \( R_0 \) is the lower-bound on the gauge group rank, subject to some caveats that we explain shortly. We thus find the “rank density” of flux

\[ \rho(R) = \frac{\partial N(R)}{\partial R} = (2n + 2)c_Y (L_* - R)^{2n+1} \]  

(7)

An average rank of the D3-brane gauge group can then be computed

\[ \langle R_{D3} \rangle = \frac{1}{N(0)} \int_0^{L_*} dR \rho(R) R \]
\[ = \frac{1}{2n+3} c_Y L_*^{2n+3} \]
\[ = \frac{L_*}{2n+3} \]  

(8)

Note that all dependence on the geometric data of the Calabi-Yau is contained in the constant \( c_Y \), which factors out. Thus the average size of the gauge group depends only on the number of complex structure moduli and the Euler character of the 4-fold, but not on the detailed structure of the Calabi-Yau.

One subtlety here is a possible additional \( c^n \) degeneracy factor that would be expected\(^2 \) for a gauge theory arising from \( N \) branes \[ 17 \]. This degeneracy comes from the multiplicity of vacua describing different stabilizations of matter, and is thus in the category of “gauge dynamics” that ultimately determines the preserved gauge group rank in the low-energy limit. Our accounting of rank does not take into account the various subsequent symmetry breaking patterns giving rise to distributed preserved gauge groups with rank \( R \) less than \( R = N_{D3} \).

In the simplest case imaginable, where \( Y \) is K-the standard \( T^6/Z_2 \) orientifold with symmetric fluxes, one finds \( n = 1 \) and \( L_* = 16 \). This yields \( \langle R_{D3} \rangle = \frac{16}{7} \), which of course is close to the SM gauge group rank of 4. One should not take this specific result literally for phenomenology, and we mention it only as a curiosity. It may be suggestive of a more general result over a large class of manifolds, and certainly gives hope that searches for quasi-realistic string models on type IIB orientifold backgrounds with flux may generically have gauge group rank near that of the SM.

It is important to interpret the gauge group rank average carefully. It is not a prediction for what the rank of the D3-brane gauge group must be if the real world is represented by an orientifold of Type IIB on a Calabi-Yau 3-fold. It is computed in the ensemble where each flux vacuum is given equal weight, and it is not clear that such an ensemble is correct for the purposes of vacuum selection. We will discuss more thoroughly the uses of this type of average later in this paper.

One should also keep in mind that, strictly speaking, we have not computed the average rank of the D3-brane gauge group. It is more properly the average net D3-brane charge. We might add several \( D3/\overline{D3} \) pairs, which will change the rank without changing the net charge.

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\(^1\) See also \[ 14 \], where power law dependence on \( L_* \) is verified in a particular model. Note also that \( L_* \) must be somewhat larger than \( n \) in order for the integration to give a good approximation to a discrete sum over fluxes. This condition will be satisfied for a wide class of models, including ones which are phenomenologically interesting.

\(^2\) We thank M. Douglas for discussions on this point.
However, these states are at best meta-stable, and will decay to a state with flux, but no anti-branes \[13\]. In principle, we should consider such states that have a lifetime of cosmological scales, but for this coarse survey we can ignore them.

It is interesting to note that the rank of the D7-brane gauge group is given by \[19\]

\[ R_{D7} = h^{1,1}(X) - h^{1,1}(B) - 1 \]  

where \( B \) is the 3-fold base of the elliptically fibered Calabi-Yau 4-fold \( X \). Both the average D3-brane and D7-brane gauge group rank can be written as simple functions of the Betti numbers of the Calabi-Yau 4-fold and its base. Note, however, that the D7-brane gauge group rank is fixed for a given choice of Calabi-Yau, and is independent of the choice of flux. Also note its dependence on \( \text{K}"\( \text{ähler moduli, as opposed to complex structure moduli in the case of the D3-brane rank.} \]

**Impact of Small Cosmological Constant:** We would like to study the topography of the landscape in the limit of small cosmological constant. In particular, we would like to consider the average D3-brane gauge group rank in the small \( \lambda \) limit. Our computation is greatly aided by the underlying analysis of \[14\]. They showed that the number of supersymmetric vacua that satisfy the tadpole condition and \( \lambda = |W|^2 \leq \lambda_\star \) is given by \[3\]

\[ N_{\lambda_\star} = \frac{(2\pi L_\star)^{2n+2}}{(2n+2)!} |\det \eta|^{-1} \int_M d^{2n+2}g \int_0^{\lambda_\star} d\rho(\lambda, z) \]  

(10)

In the limit where \( \lambda_\star \ll L_\star \) (the small cosmological constant limit), this can be simplified to

\[ \lim_{\lambda_\star \ll L_\star} N_{\lambda_\star} \rightarrow 2\pi (2L_\star)^{2n+1} |\det \eta|^{-1} \int_M d^{2n+2}g I(\mathcal{F}) \]  

\[ = b_7 L_\star^{2n+1} \lambda_\star \]  

(11)

We then find that the number of flux vacua with \( N_{D3} > R_0 \) and \( \lambda \leq \lambda_\star \ll L_\star - R_0 \) is

\[ N_{\lambda_\star}(R_0) = b_7 (L_\star - R_0)^{2n+1} \lambda_\star \]  

(12)

As before, we can compute the rank density of flux vacua and use this to compute the average rank. We find

\[ \rho_{\lambda_\star}(R) = \frac{(2n+1)(L_\star - R)^{2n}\lambda_\star}{\lambda_\star} \]

\[ \langle R_{D3} \rangle_{\lambda_\star} = \frac{1}{N_{\lambda_\star}(0)} \int_0^{L_\star} dR \rho_{\lambda_\star}(R)R \]

\[ = \frac{L_\star}{2n+2} \]  

(13)

Note again that this ensemble average does not depend on the geometric data of the Calabi-Yau, but only on the Euler character of the 4-fold and on the number of complex structure moduli. For the \( T^n/Z_2 \) orientifold model \( \langle R_{D3} \rangle_{\lambda_\star} = 4 \), which again is curiously close to (same as) the SM rank.

**Stability of the Proton:** The proton lives longer than \( 10^{32} \) years. Explaining why this must be so in a more fundamental theory is a major research challenge. The survey on gauge group rank performed above has relevance to this issue.

The renormalizable operators of the SM effective theory forbid baryon number interactions due to an accidental symmetry resulting from the restricted particle content. In string models with low or intermediate scales (including string scale), which many type IIB flux vacua apparently have \[20, 21, 22\], accidental symmetries are not enough to protect the proton, as a bevy of induced higher-dimensional operators would generically destabilize the proton.

In supersymmetric effective theories, proton destabilizing operators are present even at the renormalizable level. It is likely that a symmetry would be at play in these circumstances, since assuming that every one of the many dangerous operators had a tiny coefficient by accident would be hard to fathom.

The most commonly assumed symmetry to stabilize the proton in supersymmetry is a \( Z_2 \) \( R \)-parity. One often takes \( R \)-parity for granted in low-scale model building and implicitly imposes it as a global symmetry on the theory. However, treating global symmetries as fundamental is disfavored in string/M theory.

Despite the allusion to \( R \)-symmetry, \( R \)-parity can be interpreted entirely as a \( Z_2 \) matter parity on the chiral superfields. The \( Z_2 \) in turn can be thought of as arising from a discrete subgroup of a gauged symmetry, \( G \supset U(1)_{B-L} \supset Z_2 \), that is broken by a condensing scalar carrying the appropriate charge \[23, 27\]. The resulting \( Z_2 \) symmetry is discrete-gauge anomaly free \[23\] on the MSSM particle content, as is expected since \( U(1)_{B-L} \) is also anomaly free. Other discrete symmetries in addition to the \( Z_2 \) \( R \)-parity could also stabilize the proton and come from higher gauge group symmetry breaking \[23\].

The above discussion suggests that the rank of the gauge group of nature may need to be at least one step

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\[3\] This distribution reflects only the contribution to the vacuum energy from the flux potential and from the Kahler potential derived from special geometry. One expects corrections, but under the assumption that these corrections are random, the final distribution should be somewhat similar. The distribution used here would then be a good toy model.
higher than that of the SM in order to stabilize the proton using gauge symmetries, and possibly many steps higher. For example, nature may have chosen $SO(10)$ unification with an embedded $R$-parity. Given the conventional assignments of the MSSM states, the lowest dimensional representation of $SO(10)$ that can condense to give $R$-parity is the $26 \oplus 24 \oplus 24 \oplus 24$. Such a high-index field is not easy to obtain in these stacked $D$-brane models, since we expect lower-index bifundamentals. (High-index $SO(10)$ fields are hard to obtain in other constructions as well [27].) In this case, the starting-point gauge group would need significantly higher rank. Brane separation could then Higgs this high-rank group down to $SO(126)$ of $SO(10)$ (and other needed states). All unwanted states would need to be lifted by normal Higgs mechanisms or projected out of the effective theory by judicious choices of the compactification.

The suggestion that gauge symmetries are at the origin of proton stabilization gains even more strength when we consider the generalized Green-Schwarz mechanism [29] of type IIB theories, which admits additional pseudo-anomalous $U(1)$’s that would otherwise look unacceptable from an effective field theory point of view. This enhanced set of $U(1)$ theories is at nature’s disposal to stabilize the proton [30], and the hypothesis that protons are stabilized by an additional gauge group looks quite promising.

The computation of gauge group rank now becomes relevant to proton decay in this context. We would therefore like to compute the percentage of susy flux vacua (for any given choice of CY compactification) that can allow for an extra $U(1)$ on the D3-branes. If $R_{sm}$ is the rank of the SM gauge group, then we can rephrase this by asking what fraction of vacua contain D3-branes such that $N_{D3} = R > R_{sm}$. This is the same as the number of flux vacua with $L < L_{s} - R_{sm}$.

As shown earlier, this number is given by $N = c_{y}(L_{s} - R_{sm})^{2n+2}$. From this we see that the fraction of all susy vacua that have $R$ larger than the SM group is given by

$$
\eta = \frac{(L_{s} - R_{sm})^{2n+2}}{L_{s}^{2n+2}} = \left(1 - \frac{R_{sm}}{L_{s}}\right)^{2n+2} \quad (14)
$$

We will assume that we are in the limit where the number of unprojected complex structure moduli is large, $n \gg 1$. Then $\langle R \rangle = \frac{L_{s}}{2n+3} \sim \frac{L_{s}}{2n+2}$, where $\langle R \rangle = \langle N_{D3} \rangle$ is the average rank of the gauge group (possibly, unification gauge group) for that choice of CY compactification. We then see that

$$
\eta \sim \left(1 - \frac{R_{sm}}{\langle R \rangle(2n+2)}\right)^{2n+2} \sim e^{-R_{sm}/\langle R \rangle} \quad (15)
$$

in the high $n$ limit. In practice, as long as $R_{sm}/\langle R \rangle \sim 1$ we only require that $2n + 2 \gg 1$ (e.g., even $n = 1$ would suffice) for the above exponential formula to be a good approximation.

This is the fraction of susy vacua with $D3$-brane gauge group rank greater than that of the SM. Note that it only depends on $\langle R \rangle$ in the limit of a large number of moduli. It does not depend on the details of the CY moduli space, on any singularities, or even on the Euler character of the relevant 4-fold.

Earlier we found that $\langle R \rangle = 16/5$ (or 4, when restricting to small $\lambda_{s}$) for the $T^{6}/Z_{2}$ orientifold example, which implies that the suppression price one pays for having a group with rank higher than the SM gauge group is not more than a factor of 5 in the approximation. This relatively low suppression factor is interesting$^{4}$. It could be indicative of a fruitful direction in string model-building: vacua that stabilize the proton with additional gauge symmetries may be more stringy/landscape natural than ones that utilize intrinsic discrete symmetries.

This very tentative supposition emerges partly from taking into consideration the analysis of [31]. Although $T^{6}/Z_{2}$ orientifold compactifications of type IIB theories may have large discrete symmetries, the fluxes typically break them all. Very large exponential suppression factors result. It was later suggested that this analysis is based on models that might not be realistic enough to draw definitive conclusions [11], and discrete symmetries might be more abundant than originally thought [32].

Nevertheless, the landscape terrain of [31] is very similar to the landscape terrain we are considering here. On this terrain, extra gauge symmetries that might have a chance to stabilize the proton are perhaps more copious than extra stringy discrete symmetries that might have a chance to stabilize the proton.

Utility of Landscape Averages: Perhaps as important as a survey of the landscape is the question of what to do with this information. Landscape averages of the form computed above do not necessarily provide predictions of the real world. Similarly, a failure of an average to match experimental data would not falsify the landscape, let alone string theory. How landscape data could be used depends on the question one asks.

For example, if one is attempting to build a specific string model that matches the real world, then landscape statistics are useful in determining “good” criteria. Suppose one decides to look for a model that has the experimentally determined properties $P_{1}, ..., P_{n}$ as a candidate

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$^{4}$ If the minimal rank $R_{M}$ of the unified theory needs to be significantly above $R_{sm}$, as might be required by $SO(10)$ with a $126$ representation, the compactification manifold would need a high-enough Euler number to reach the requisite $L_{s}$. Eq. (15) would still be valid except $R_{sm}$ would be replaced by $R_{M} - 1$. 

for the real world\textsuperscript{5}. If these properties are in fact rather generic on the landscape, they would not provide good search criteria for selecting a model to study. In particular, if given properties $P_1$, $\ldots$, $P_{n-1}$, one finds that property $P_n$ is rather generic, then $P_n$ provides little useful information and is not a good search criterion. Instead, one would hope that a sophisticated understanding of the landscape would identify search criteria that are both tractable for a model-builder and highly non-generic\textsuperscript{6}, as this would imply that those properties that had these properties is more likely to be “the right one.”

One might instead be interested in understanding what, if any, principles determine the selection of the vacuum. In this case, an understanding of the statistics of the landscape would allow one to identify which properties actually require such a Vacuum Selection Principle. For example, suppose it is found that, given experimentally determined properties $P_1$, $\ldots$, $P_{n-1}$, the property $P_n$ appears generically on the landscape. From this, one might conclude that the appearance of property $P_n$ in the real world does not require an independent explanation (although it may in fact have one): it is simply a very generic result on the space of vacua.

One the other hand, it is important to note that the landscape does not require all experimentally measured features to be generic. On the contrary, it seems clear that many properties will be non-generic given a set of prior properties. In those cases, one would need to find a principle that selects the non-generic properties. The anthropic principle could be viewed as a possible such principle, but one could certainly imagine that other principles would emerge.

Conclusions: In this work, we have made some rather simple calculations of ensemble averages of quantities to gain insight into the average rank of the D3-brane gauge group in flux compactifications. We found that the average rank can be computed quite generally, and has very little dependence on the detailed geometric data of the Calabi-Yau. We also found that employing extra gauge symmetry to protect the proton is an apparently reasonable supposition on the landscape, as every increment in gauge group rank does not generate a huge suppression factor on the landscape.

Given that we have computed averages of the D3-brane gauge group rank, one would like to know how this relates to phenomenology. One natural hope would be that the D3-brane gauge group corresponds to some unification group. Note, however, that there are several other mechanisms by which non-abelian gauge groups can appear. For example, these gauge groups can arise from D7-branes (which were discussed earlier) as well as from the enhancement of gauge symmetry due to D-branes wrapping shrinking cycles of the Calabi-Yau. Thus, it could also be that the visible sector unification group arises from some other mechanism, while the D3-branes generate a hidden sector gauge group. Either way, these orientifold constructions will contain some sector given by the gauge theory on these D3-branes. Independent of how we might want to interpret the D3-brane sector in phenomenology, it seems likely that there is a larger class of vacua which are dual to these models, and thus contain a gauge group (arising from various mechanisms) which is dual to the D3-brane group.

This limited success suggests more avenues of study. It would be interesting to examine ensemble averages of other quantities, such as $R$-symmetry breaking parameters and supersymmetry breaking parameters in regimes where supersymmetry is broken at tree level by fluxes. This data could be useful for examining the possible appearance of interesting effects like intermediate-scale supersymmetry breaking and proton stabilization by means other than the pure gauge group discussion we presented here.

It would also be useful to consider large classes of orientifolded Calabi-Yau 3-fold compactifications to determine if there are any trends that persist in a more encompassing averaging procedure. Another way to view this problem is to perform our survey along the lines discussed above, but with an additional averaging over a large class of Calabi-Yau 4-folds in F-theory compactifications\textsuperscript{33}, with well-enumerated moduli that survive the orientifold projections. In a sense, this would require including appropriately normalized integrals over the $L_*$ and the $n$ complex structure moduli of eq. 3.

The calculations here are at the very beginning of a potentially interesting road. With a much more detailed survey of the landscape, one might hope to be able to provide useful input to model-builders, as well as sharpen the questions that a vacuum selection principle, if it exists, would need to answer.

Note added: As we were preparing to submit this paper, Conlon and Quevedo posted an article\textsuperscript{34} which also discusses gauge group rank issues on the landscape.

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\textsuperscript{5} These properties are similar to what Dine, Gorbatov and Thomas\textsuperscript{11} refer to as priors, though we use them in a different context.

\textsuperscript{6} To emphasize, genericness on the landscape is neither “good” nor “bad” in our view. It is only useful or not useful depending on the question one is trying to answer.
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