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Stable non-BPS states on a 3-brane probe

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ABSTRACT: As a novel application of string junctions, we construct stable non-BPS states on a 3-brane probe in the 7-brane background associated with $N = 2$ SU(2) Super-Yang-Mills theory. These states introduce a second curve of marginal stability, across which some of them decay. Moduli space is therefore divided into four regions, each containing a different stable particle spectrum.

KEYWORDS: F-Theory, Brane Dynamics in Gauge Theories.

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1. Introduction

Type IIB string junctions [1], and more generally string webs[1] [2], have proven to be quite useful in determining the BPS spectra of supersymmetric field theories, which can be realized as world-volume theories on certain branes [3–10]. The two fundamental properties of string junctions that allow us to learn about the spectrum of BPS states is that their total NSNS and RR charges vanish [1], and that the orientations of the strings are correlated with their (p, q) type such that the net force on the junction vanishes [11]. For planar webs, the second property guarantees that the configuration is (classically) supersymmetric [2].

Previously we constructed the BPS states of $N = 2$ SU(2) SYM using string webs [6]. The theory is realized as the world-volume field theory of a 3-brane probe in the background of two mutually non-local 7-branes [12, 13], and the BPS states correspond to supersymmetric string webs connecting the three branes. We found string webs corresponding to all the known BPS states, i.e. the W-bosons and $(2n, 1)$ dyons, and were able to explain the discontinuity in the BPS spectrum ("jumping" phenomenon) as a simple process of decay of a string web into a pair of strings. However, we found additional string webs which did not correspond to known BPS states. We argued that although these webs were classically supersymmetric, they should exhibit some sort of supersymmetry anomaly analogous to the "s-rule" [14]. The issue was subsequently resolved in [8, 9], where a suitable generalization of the s-rule was given, which eliminates all the extra states from the BPS spectrum. On the other hand this raises the question of what these additional string webs correspond to, given that they satisfy the aforementioned fundamental properties.

[1] By string junctions we mean a fundamental string ending on a D-string, or any of its $SL(2, \mathbb{Z})$ counterparts. String webs are composed of several string junctions.

In a parallel line of development, certain *non-perturbative* stable non-BPS states have been identified in string theory [15, 16, 17]. In all these examples the existence of the non-perturbative state was predicted by knowledge of a *perturbative* stable non-BPS state, together with some knowledge of the strong coupling behavior, e.g. duality. A notable class of examples is the Ωp-plane–Dp-brane system, in which the lowest mass charged state is not BPS.[2] The strong coupling behavior is different for each p, but in every case there should exist a stable non-BPS state. These have been found so far for $p = 4, 5, 6$, and 7. For $p = 7$ the state corresponds to a string web connecting three mutually non-local 7-branes, which describe the strong coupling behavior of the $\Omega 7$–D7 system. The web satisfies the two fundamental properties, but is nevertheless non-BPS, as it violates the "s-rule" [15].

The additional string webs found in [6] fit nicely into this category of states, and therefore seem to correspond to stable non-BPS states in $N = 2$ SU(2) SYM. Unlike the previous examples however, these non-BPS states are not predicted by the perturbative picture. In this paper we shall extend this result, and find even more stable non-BPS string webs connecting the 3-brane and the two 7-branes. Furthermore, we will find a second curve of marginal stability $\mathcal{C}'_M$ (in addition to the usual one $\mathcal{C}_M$), across which some of these webs decay. This suggests that the moduli space of $N = 2$ SU(2) SYM theory is actually divided into *four* regions, each of which has a different stable (but not necessarily BPS) particle spectrum. In the *semi-classical* regime, i.e. outside both curves of marginal stability, the spectrum includes states of arbitrary even electric charge, and *arbitrary magnetic charge* (modulo reducibility of the corresponding web).

The paper is organized as follows. In section 2 we review the conditions for a string web to be supersymmetric, and the construction of the BPS states in $N = 2$ SU(2) SYM. In section 3 we relax the above conditions to incorporate stable, but not necessarily supersymmetric, string webs, and solve for the stable particle spectrum. Section 4 contains our conclusions.

2. String junctions and the BPS spectrum

Let us first recall how the BPS spectrum is derived in the 3-brane probe picture. Consider a string web lying in the z-plane, and ending on N (p, q) 7-branes and M 3-branes, which are transverse to the plane. Denote the charges of the external strings by (p_i, q_i), where $i = 1, \ldots, N$ for those ending on 7-branes, and $i = N+1, \ldots, N+M$ for those ending on 3-branes.[3] The strings are taken to be oriented outward, and

[2] Another class of stable non-BPS states corresponds to non-planar webs [5].

[3] Note that p_i and q_i need not be mutually prime. However, if (p_i, q_i) have the same common divisor (≥ 2) for all i the configuration is reducible, and therefore at most marginally bound.

ordered counterclockwise. We define the *self-intersection* number of the web as [18]

$$\mathcal{I} \equiv \sum_{1\leq i<j\leq N+M} \begin{vmatrix} p_i & p_j \\ q_i & q_j \end{vmatrix} - \sum_{i=1}^{N} \Big(\mathrm{gcd}(p_i, q_i)\Big)^2 . \tag{2.1}$$

The first contribution is due to the string junctions, and the second to the strings ending on 7-branes. To preserve supersymmetry, the webs must satisfy the following:[4]

a. Strings lie on trajectories of minimal mass, i.e. (p, q)-geodesics.

b. The orientations of the strings are correlated with their (p, q) type, such that

$$\theta_{p,q}(z) = \begin{cases} \arg(p + q\tau(z)) + \theta_{1,0}(z) \\ \quad \text{or} \\ \arg(p + q\overline{\tau(z)}) + \theta_{1,0}(z) . \end{cases} \tag{2.2}$$

These reduce to the zero force condition when applied to the junction points.

c. The self-intersection number of the web satisfies the following inequality[5]

$$\mathcal{I} \geq -2 + \sum_{i=N+1}^{N+M} \mathrm{gcd}(p_i, q_i) . \tag{2.3}$$

In fact, this inequality must be satisfied for each irreducible sub-web, where strings not ending on 7-branes count as strings ending on 3-branes.

Conditions **a** and **b** guarantee that the string web preserves supersymmetry at the *classical* level. At the *quantum* level there may be supersymmetry anomalies, i.e. the true ground state of the configuration may break supersymmetry. The so-called "s-rule" [14] is an example of such an anomaly. For our setup the statement of the s-rule is that given a (p, q) 7-brane and an (r, s) string transverse to it, the number of (p, q) strings that can link the two while still preserving supersymmetry is bounded above by $|ps - qr|$ [7]. Condition **c** is a generalization of this rule.

The background corresponding to pure SU(2) SYM consists of two mutually non-local 7-branes. Using our previous conventions [6, 7], the 7-branes are located at $z = +1$ and $z = -1$, and their charges are $(0, 1)$ and $(2, \pm 1)$, respectively. Both branch cuts extend along the negative real axis. The sign for the second 7-brane is

[4]The complete list of necessary and sufficient conditions for supersymmetry in the string picture is not known. In the lift to M-theory string webs become membranes with boundaries, in which case a necessary and sufficient condition for supersymmetry is that the membranes wrap holomorphic curves.

[5]This follows from the M-theory picture, since holomorphic curves embedded in surfaces of vanishing first Chern class (like T^4 and $K3$) have a self-intersection number $\# = 2g - 2 + b$, where b is identified with the number of co-prime strings not ending on 7-branes.

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+ when viewed from above the cut and − when viewed from below the cut. The (p,q)-metric on the transverse plane is given by [13]

$$T_{p,q}ds = |pda + qda_D|\,, \tag{2.4}$$

where $a(z)$ and $a_D(z)$ are the integrals of the Seiberg-Witten differential over the two cycles of the auxiliary Riemann surface [19]. For the purpose of numerical analysis they are best expressed in terms of hypergeometric functions,

$$\begin{aligned} a(z) &= \left(\frac{z+1}{2}\right)^{1/2} F\left(-\frac{1}{2},\frac{1}{2},1;\frac{2}{z+1}\right) \\ a_D(z) &= i\left(\frac{z-1}{2}\right) F\left(\frac{1}{2},\frac{1}{2},2;\frac{1-z}{2}\right). \end{aligned} \tag{2.5}$$

Thus (p,q)-geodesics satisfy the equation

$$p\frac{da}{dt} + q\frac{da_D}{dt} = (p + q\tau(z))\frac{da}{dt} = c_{p,q}\,, \tag{2.6}$$

and their tangents are therefore oriented along

$$\theta_{p,q}(z) = \arg(p + q\overline{\tau(z)}) - \arg(da/dz) + \arg(c_{p,q})\,. \tag{2.7}$$

It is immediately clear that the second equation in (2.2) is compatible with (2.7), whereas the first one is not. This is because the 7-brane background picks out a unique complex structure on the transverse plane, in which only strings oriented according to $p + q\bar{\tau}$ can be supersymmetric [18]. It then follows that conditions **a** and **b** are satisfied if and only if

$$\arg c_{p,q} = \phi \qquad \text{for all } (p,q) \text{ strings}\,, \tag{2.8}$$

where ϕ is arbitrary.

Denote the positions of the $(0,1)$ 7-brane, $(2,\pm 1)$ 7-brane, and 3-brane by z_1, z_2, and z_3, respectively. Likewise, denote the charges of the strings ending on the branes by (p_i, q_i), where $i = 1,2,3$. We assume that the string webs are completely *degenerate*, i.e. that all internal strings have a vanishing length, so that there is effectively a single junction point at z_0.[6] The geodesic constants are therefore given by

$$c_{p_i,q_i} = p_i\Big(a(z_i) - a(z_0)\Big) + q_i\Big(a_D(z_i) - a_D(z_0)\Big)\,. \tag{2.9}$$

For the strings ending on 7-branes these simplify since $p_i a(z_i) + q_i a_D(z_i) = 0$ for $i = 1,2$.

[6]The webs could in principle possess hidden faces, but since these correspond to zero modes, the assumption of degeneration will not alter our result. As it turns out, none of the solutions have zero modes however.

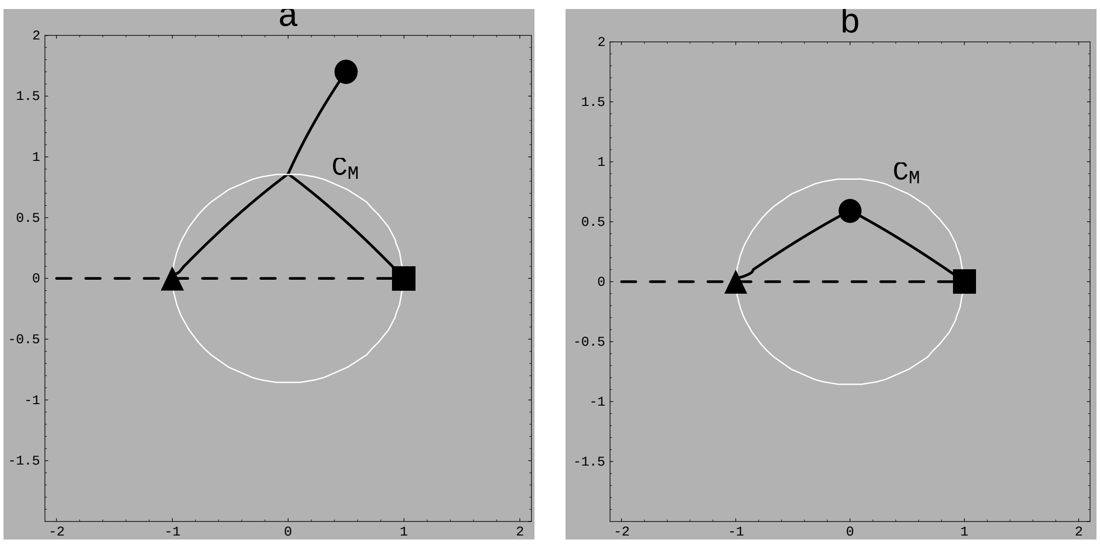

Figure 1: (a) 3-brane outside $\mathcal{C}_M$, BPS state exists. (b) 3-brane inside $\mathcal{C}_M$, BPS state decays into $(0,1)$'s and $(2,\pm 1)$'s.

Solutions to (2.8) were found for $(p_3, q_3) = (\pm 2, 0)$ and $(2n, \pm 1)$, corresponding respectively to the W-bosons and dyon hypermultiplets. Furthermore, these webs satisfy condition **c**, so the corresponding states are indeed BPS saturated. In all cases the solution restricts the junction to lie on the curve defined by

$$\mathrm{Im}\frac{a_D(z_0)}{a(z_0)} = 0\,, \qquad \mathrm{Re}\frac{a_D(z_0)}{a(z_0)} \in \begin{cases} [-2,0] \text{ if } z_0 \in H^+ \\ [0,+2] \text{ if } z_0 \in H^-\,, \end{cases} \tag{2.10}$$

and the 3-brane to lie on a curve defined by

$$\mathrm{Im}\frac{p_3 a(z_3) + q_3 a_D(z_3)}{p_3 a(z_0) + q_3 a_D(z_0)} = 0\,, \qquad \mathrm{Re}\frac{p_3 a(z_3) + q_3 a_D(z_3)}{p_3 a(z_0) + q_3 a_D(z_0)} > 1\,. \tag{2.11}$$

The first curve is well known as the curve of marginal stability $\mathcal{C}_M$, and the second is a curve of constant phase for the function $p_3 a(z) + q_3 a_D(z)$. The second condition in (2.11) implies that the 3-brane must lie outside $\mathcal{C}_M$. Thus the string junction picture confirms that, with the exception of the states $(0,1)$ and $(2,1)$, which correspond to single strings, the above BPS states exist only outside $\mathcal{C}_M$ (figure 1).

3. String junctions and stable non-BPS states

There are actually additional solutions to (2.8) [6]. However, as these carry magnetic charges of magnitude greater than 1, they can easily be shown to violate condition **c** [9]. They do not therefore correspond to BPS states. On the other hand, the fact that they satisfy conditions **a** and **b** suggests that they are stable string webs, and therefore that we identify them as stable non-BPS states in the field theory.

More generally, classical stability of a string web requires only that all the forces cancel. This means that for stable (but not necessarily supersymmetric) string webs condition **b** is replaced by:

b'. The orientations of the strings *at the junctions* satisfy

$$\theta_{p,q}(z_0) = \begin{cases} \arg(p + q\tau(z_0)) + \theta_{1,0}(z_0) \\ \quad \text{or} \\ \arg(p + q\overline{\tau(z_0)}) + \theta_{1,0}(z_0)\,, \end{cases} \tag{3.1}$$

which guarantees that the forces on the junctions due to the string tensions cancel. This generalizes condition **b**, which restricted the orientations at *all* points along the strings.

For string webs which satisfy **b'** but not **b** supersymmetry is completely broken, and therefore there are actually non-vanishing forces between the strings. This means that their trajectories deviate from (p,q)-geodesics, and condition **a** must be modified. The deviation is such that the string-string forces are balanced by elastic forces,

$$\frac{\Delta r}{l_s^2} \sim \frac{l_s^5}{r^6}\,, \tag{3.2}$$

and is therefore negligible in the limit where the distances (in the string metric) between the branes are much greater than l_s. We can therefore approximate the trajectories by (p,q)-geodesics in this limit. Since this is precisely the regime where the stringy picture makes sense, we conclude that conditions **a** and **b'** guarantee that the string web is classically stable. On the other hand, the field theory description holds when all distances are much *smaller* than l_s. Since the above string webs are not supersymmetric, their existence does not a-priori guarantee that the corresponding non-BPS states will be stable in the field theory. We shall return to this point later on.

Both orientations in (3.1) are now compatible with the geodesic condition. This means there are two kinds of junctions which can potentially be stable. Let us refer to them as τ-junctions and $\bar{\tau}$-junctions, according to whether we use $(p+q\tau)$ or $(p+q\bar{\tau})$ to determine the orientations at the junction point. These correspond to the two different ways of ordering the three strings around the junction (and therefore $\mathcal{I}_\tau = -\mathcal{I}_{\bar{\tau}}$).

For a given position of the 3-brane, a state with a given set of charges (p_3, q_3) (other than $(2,\pm1),(0,1)$) can either correspond to a τ-junction or to a $\bar{\tau}$-junction, but not both. We can understand this qualitatively as follows. As $\tau \to \bar{\tau}$ the ordering of the strings changes. If we keep the 3-brane fixed, the $(0,1)$ and $(2,1)$ strings are exchanged. So for one of the junctions they would have to cross in order to end on the appropriate 7-branes. This leads to a closed loop of string, which is unstable to shrink to a point, giving back the other junction (figure 2). This will be verified by solving the stability conditions **a** and $\mathbf{b}'$, and finding all the stable states corresponding to τ-junctions and $\bar{\tau}$-junctions.

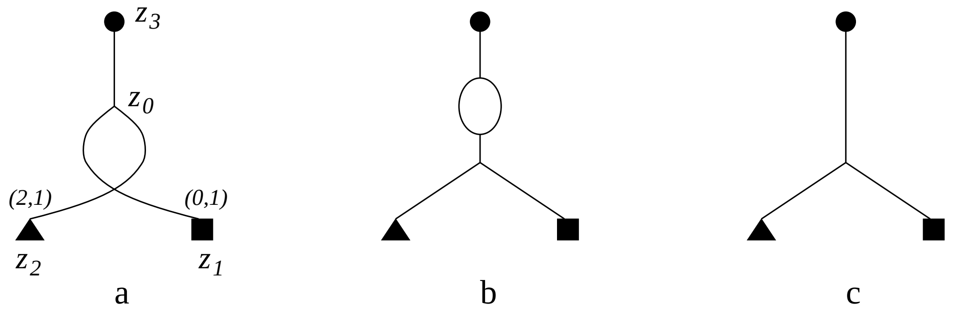

Figure 2: Starting with a τ (or $\bar\tau$) junction in which the strings cross (a), the crossing point splits into two junctions (b), and the loop of string contracts to a point giving a $\bar\tau$ (or τ) junction (c).

As in the previous section, combining conditions **a** and **b'** we find conditions on the arguments of c_{p_i,q_i},

$$\arg c_{p_i,q_i} = \begin{cases} \phi + \arg(p_i + q_i\tau(z_0))^2 & \tau-\text{junction} \\ \phi & \bar\tau-\text{junction}\,. \end{cases} \tag{3.3}$$

Since (p_1,q_1) and (p_2,q_2) must be integer multiples of $(0,1)$ and $(2,\pm1)$, respectively, we can set $(p_3,q_3) = (2n,m)$. Therefore $(p_1,q_1) = (-m\pm n)(0,1)$, and $(p_2,q_2) = -n(2,\pm1)$, where the sign depends on whether the string ending on the 7-brane at $z_1 = -1$ comes from the upper half-plane (upper sign) or the lower half-plane (lower sign). Given (2.9), the conditions in (3.3) then imply

$$\mathrm{Im} f(z_0) = 0\,, \qquad \mathrm{sgn}(f(z_0)) = \mathrm{sgn}\left(\frac{m\mp n}{n}\right), \tag{3.4}$$

and

$$\mathrm{Im}\, g(z_0,z_3) = 0\,, \qquad \mathrm{sgn}(g(z_0,z_3)) = \mathrm{sgn}(m\mp n)\,, \tag{3.5}$$

where

$$f(z) \equiv \frac{2a(z)+a_D(z)}{a_D(z)} \times \begin{cases} \tau(z)^2/(2+\tau(z))^2 & \tau-\text{junction} \\ 1 & \bar\tau-\text{junction}\,, \end{cases} \tag{3.6}$$

and

$$g(z,w) \equiv \frac{2n\Big(a(w)-a(z)\Big) + m\Big(a_D(w)-a_D(z)\Big)}{a_D(z)} \times \begin{cases} \tau(z)^2/(2+\tau(z))^2 & \tau-\text{junc.} \\ 1 & \bar\tau-\text{junc.} \end{cases} \tag{3.7}$$

Solutions to (3.4) and (3.5) will correspond to force-free string webs, and therefore to stable states. There are four cases to consider, depending on whether the junction is τ or $\bar\tau$, and whether the junction point z_0 is in the upper or lower half-plane.

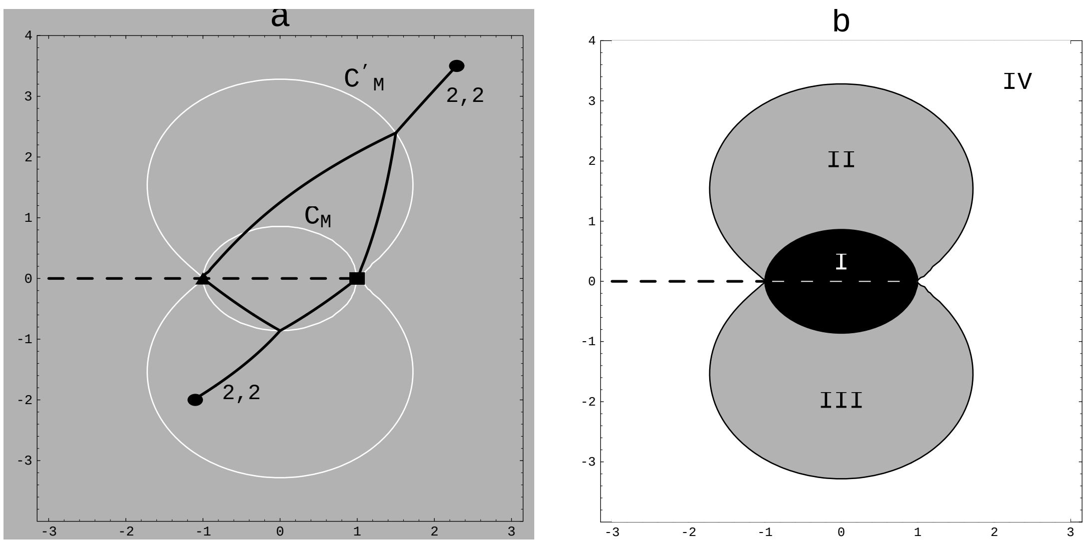

Figure 3: (a) Stable non-BPS string webs; The example shown has $(2n, m) = (2, 2)$, and is therefore given by a τ-junction in the upper half-plane, and by a $\bar{\tau}$-junction in the lower half-plane. (b) The two marginal stability curves divide moduli space into four regions.

$\bar{\tau}$-junctions. $\mathrm{Im} f = 0$ corresponds to the familiar curve of marginal stability $\mathcal{C}_M$. On the other hand, it follows from (2.10) that $\mathrm{Re} f < 0$ on the upper half-plane segment of $\mathcal{C}_M$, and $\mathrm{Re} f > 0$ on the lower half-plane segment. Solutions to (3.4) therefore exist only for $(n - m)/n > 0$ and $(n + m)/n > 0$ in the upper and lower half-planes, respectively.

τ-junctions. $\mathrm{Im} f = 0$ defines a *new* closed curve $\mathcal{C}'_M$ which is diffeomorphic to $\mathcal{C}_M$, and, like $\mathcal{C}_M$, intersects the two 7-branes (figure 3). However the behavior of $\mathrm{Re} f$ is precisely the opposite: $\mathrm{Re} f > 0$ on the upper half-plane segment of $\mathcal{C}'_M$, and $\mathrm{Re} f < 0$ on the lower half-plane segment (this has been verified numerically). Consequently solutions to (3.4) exist only for $(n - m)/n < 0$ and $(n + m)/n < 0$ in the upper and lower half-planes, respectively. Therefore, as promised, τ-junctions and $\bar{\tau}$-junctions are completely complementary.

Once the junction position z_0 has been fixed on either $\mathcal{C}_M$ or $\mathcal{C}'_M$, the condition $\mathrm{Im} g = 0$ determines a curve intersecting z_0 on which the 3-brane is to be placed. Since $g = 0$ when $z_3 = z_0$, i.e. when the 3-brane is precisely on $\mathcal{C}_M$ (or $\mathcal{C}'_M$), the sign of g determines whether the 3-brane is inside or outside $\mathcal{C}_M$ (or $\mathcal{C}'_M$). The condition on the sign of g in (3.5) in fact requires the 3-brane to always be *outside* $\mathcal{C}_M$ (or $\mathcal{C}'_M$) (this has also been verified numerically). Consequently stable $\bar{\tau}$-junctions can only occur when the 3-brane is outside $\mathcal{C}_M$, and stable τ-junctions can only occur when it is outside $\mathcal{C}'_M$ (figure 3a). When the 3-brane coincides with $\mathcal{C}_M$ ($\mathcal{C}'_M$) all $\bar{\tau}$ (τ) junctions become marginal, and when it moves inside they decay into open strings. Therefore $\mathcal{C}_M$ serves as a curve of marginal stability for states satisfying $(n - m)/n > 0$ in the upper half-plane, and for states satisfying $(n+m)/n > 0$ in the lower half-plane (both include the BPS states discussed in the previous section). Likewise, the new curve $\mathcal{C}'_M$ is a marginal stability curve for states satisfying $(n-m)/n < 0$ in the upper half-plane, and for states satisfying $(n+m)/n < 0$ in the lower half-plane.

The picture that emerges is that moduli space is divided into four regions (figure 3b). In region I only $(0,1)$ and $(2,\pm1)$ are stable. In region II only states satisfying $(n-m)/n > 0$ are stable, and in region III only those satisfying $(n+m)/n > 0$ are stable. In region IV, which includes the semiclassical regime, all values of n and m correspond to stable states. Recall however that if the string web is reducible it can at most be marginally bound, in which case we will not count it as one of the stable states. The condition for irreducibility is given by

$$\mathrm{gcd}\Big[\mathrm{gcd}(2n,m), n, -m \pm n\Big] = 1\,, \tag{3.8}$$

where the sign is again correlated with which half-plane ($H^{\pm}$) we are considering.

$\tau \to \bar{\tau}$ **transitions.** As the 3-brane moves around moduli space (without crossing marginal stability curves) the junction point slides along the curve of marginal stability, and eventually crosses one of the 7-branes, resulting in a string junction transition, by which strings get annihilated or created [7]. This does not change the charges of the string ending on the 3-brane $(2n,m)$, since at the same time the 7-brane at z_2 changes its identity from $(2,1)$ to $(2,-1)$ (or vice versa), which precisely compensates for the string creation/annihilation effect. In the BPS case the junction point always remains on $\mathcal{C}_M$. In the non-BPS case, on the other hand, it is possible for the junction point to "jump" from $\mathcal{C}_M$ to $\mathcal{C}'_M$, or vice versa. This is because the spectrum in region II is different from that in region III, so there are some states which correspond to τ-junctions in one half-plane and to $\bar{\tau}$-junctions in the other half-plane, like for example the state $(2,2)$ shown in figure 3a.

4. Conclusions

In this paper we have extended the application of string junctions to the construction of stable non-BPS states in $N=2$ SU(2) SYM. These correspond to string webs satisfying a reduced set of properties, whereby the webs are classically stable, but do not preserve supersymmetry. The non-BPS webs introduce a new curve of marginal stability into the moduli space, which in addition to the original one divides moduli space into four regions. In the region outside both curves we expect to see stable non-BPS dyons of arbitrary even electric charge and arbitrary magnetic charge. The stable particle spectrum would thus be invariant under $\Gamma(2)$. It would be worth while to find these states directly in the field theory.

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It should be stressed that all the results are classical, and therefore subject to quantum corrections. In particular, the webs we have constructed exist in the limit where all distances are much greater than l_s. Since the field theory limit corresponds to all distances being much smaller than l_s, it does not immediately follow that these webs correspond to stable non-BPS states in the field theory. One could however imagine starting with the string web picture, and gradually reducing the distances between the branes, while keeping the 3-branes always outside the curves of marginal stability. In this way the state should remain stable down to the field theory limit. The masses of the states and the precise form of the marginal stability curves (with regard to the non-BPS states) will of-course differ from their classical (string web) values.

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