

# Lagrangian unknottedness in Stein surfaces

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**Abstract** *We show that the space of Lagrangian spheres inside the cotangent bundle of the 2-sphere is contractible. We then discuss the phenomenon of Lagrangian unknottedness in other Stein surfaces. There exist homotopic Lagrangian spheres which are not Hamiltonian isotopic, but we show that in a typical case all such spheres are still equivalent under a symplectomorphism.*

## 1 Introduction

Studying the space of Lagrangian submanifolds is a fundamental problem in symplectic topology. Lagrangian spheres appear naturally in the Leftschetz pencil picture of symplectic manifolds.

In this paper we demonstrate the uniqueness up to Hamiltonian isotopy of the Lagrangian spheres in some 4-dimensional Stein symplectic manifolds. The most important example is the cotangent bundle of the 2-sphere,  $T^*S^2$ , with its standard symplectic structure. In this case we will go on to study the space of all Lagrangian spheres in  $T^*S^2$ , showing that it is contractible.

Finally, we study an example of a Stein manifold in which a particular homotopy class (even isotopy class) contains Lagrangian spheres which are not Hamiltonian isotopic. We show that the spheres in this class are still unknotted in a weaker sense, namely they are all equivalent under a global (non Hamiltonian) symplectomorphism built by composing a Hamiltonian diffeomorphism

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with a product of symplectic Dehn twists.

We recall that if a convex symplectic manifold has a boundary of contact-type, then we can perform surgery operations on the manifold by adding handles to the boundary. In the 4-dimensional case these handles can be of index 1 or 2. Our first examples are symplectic manifolds formed by adding 1-handles to a unit cotangent bundle  $T^1S^2$ . Questions regarding Lagrangian isotopy classes are independent of which metric we use to define a unit tangent bundle or of any choices involved in adding 1-handles.

**Theorem 1** *Let  $M$  be  $T^*S^2$  or the result of adding any number of 1-handles to  $T^1S^2$  and  $L \subset M$  be a Lagrangian sphere. Then there exists a Hamiltonian diffeomorphism of  $M$  mapping  $L$  onto the zero-section.*

We will establish this theorem by utilizing an existence result for almost-complex structures on  $S^2 \times S^2$  with convenient properties, taken from [16], and a fact about diffeomorphisms of the 2-sphere.

In fact more is true. We let  $\mathcal{L}$  denote the space of Lagrangian spheres in  $T^*S^2$  endowed with the topology of smooth convergence.

**Theorem 2** *The topological space  $\mathcal{L}$  is contractible.*

It is a consequence of a general theorem of J. Coffey [3], combined with the result of [16], that the space of parameterized Lagrangian spheres in  $S^2 \times S^2$  is homotopic to  $SO(3) \times SO(3)$ . A theorem of Y. Eliashberg and L. Polterovich, see [10], says that the space of Lagrangian planes in a standard  $\mathbb{R}^4$ , equal to a fixed plane outside of a compact set, is also contractible. The proof here involves parameterized versions of the arguments in Theorem 1. In both cases we need a result about diffeomorphisms of the 2-sphere.

**Theorem 3** *The subset of fixed-point free maps contained in the diffeomorphism group of  $S^2$  is contractible.*

In section 2 we prove our result on the diffeomorphisms of  $S^2$ . In section 3, by using the conclusions of [16], we reduce our theorem in the case of  $M = T^*S^2$

to the statements in section 2. In section 4 we will deal with the addition of handles. This involves slightly generalizing the results from [16] so we will review them again there.

We now consider the addition of 2-handles. Let  $W$  be the Stein manifold formed by adding to  $T^1S^2$  a single 2-handle along the Legendrian curve in a single fiber of the boundary. As a Stein manifold it carries a symplectic structure which has a conformally expanding vector field whose flow exists for all time. The symplectic structure is the Kähler form associated to a plurisubharmonic exhaustion function and all such forms are equivalent up to symplectomorphism (see [9]). Alternatively  $W$  can be realized as the plumbing of two copies of  $T^1S^2$ . The resulting symplectic manifold  $W$  has two Lagrangian spheres  $L_1$  and  $L_2$  coming from the zero-sections in the  $T^1S^2$  (or the original zero-section and the stable manifold of the index 2 critical point in the added handle). Again we will establish a uniqueness result for Lagrangian spheres in  $W$ .

**Theorem 4** *Let  $L$  be a Lagrangian sphere in  $W$ , the plumbing of two copies of  $T^*S^2$ , which is homotopic to one of the zero-sections  $L_1$ . Then there exists a symplectomorphism  $\phi$  of  $W$  such that  $\phi(L) = L_1$ .*

The proof combines Theorem 1 with some previous work of the author and is described in section 5.

Thus any Lagrangian spheres which are homotopic to  $L_1$  but are knotted in the Hamiltonian sense must arise from global symplectomorphisms applied to  $L_1$ . Such symplectomorphisms do indeed exist. Recall that associated to any Lagrangian sphere  $L$  is a compactly supported symplectomorphism  $\tau_L$  called a generalized Dehn Twist. It is well-defined up to Hamiltonian symplectomorphism. The square  $\tau_L^2$  is smoothly but not necessarily symplectically isotopic to the identity. Thus  $\tau_{L_2}^{2r}(L_1)$  is a Lagrangian sphere in  $W$  which is smoothly isotopic to  $L_1$  for any integer  $r$ . However, as demonstrated by P. Seidel in [25], a Floer homology computation shows that none of the  $\tau_{L_2}^{2r}(L_1)$  are Hamiltonian isotopic. A natural question is whether these are the only examples of such Lagrangian knots, and we will show that this is indeed the case.

**Theorem 5** *Let  $L$  be a Lagrangian sphere in  $W$ . Then there exists a composition of Dehn twists  $\tau$  such that  $\tau(L)$  is Hamiltonian isotopic to  $L_1$  or  $L_2$ .*

This will be proven in section 6.

In a Stein manifold a Lagrangian isotopy can be composed with a conformally contracting vector field (the negative gradient of the plurisubharmonic exhaustion) so as to lie in an arbitrarily small neighborhood of the union of the stable manifolds of the critical points. Also, a theorem of Weinstein, [29], says that a Lagrangian sphere (or two Lagrangian spheres intersecting transversally in a single point) have tubular neighborhoods unique up to symplectomorphism. Thus Theorem 1 about Lagrangian spheres in  $T^*S^2$  implies the following.

**Theorem 6** *Let  $L_1$  be a Lagrangian sphere in a symplectic 4-manifold  $M$ . Then any other Lagrangian sphere  $L \subset M$  which is sufficiently  $C^0$  close to  $L_1$  is Hamiltonian isotopic to  $L_1$ .*

Theorem 5 similarly gives the following.

**Theorem 7** *Let  $L_1$  and  $L_2$  be two Lagrangian spheres in a symplectic 4-manifold  $M$ , intersecting transversally in a single point. Then for any other Lagrangian sphere  $L \subset M$  which is sufficiently  $C^0$  close to  $L_1 \cup L_2$  there exists a composition  $\tau$  of the Dehn twists  $\tau_{L_1}$  and  $\tau_{L_2}$  about  $L_1$  and  $L_2$  such that  $\tau(L)$  is Hamiltonian isotopic to  $L_1$  or  $L_2$ .*

Similar methods can generalize the unknottedness result of Theorem 5 to a larger class of Stein manifolds, but it is unclear whether or not it is true in general that homotopic Lagrangian spheres are equivalent under a global symplectomorphism composed of a Hamiltonian flow and Dehn twists.

As yet we are unable to prove any similar results for Lagrangian surfaces of genus at least 2, but A. Ivrii has established some similar results for Lagrangian tori. Here we make some remarks about the case of  $\mathbb{R}P^2$ . The results of [16] show that any Lagrangian sphere  $L$  in  $S^2 \times S^2$  homotopic to the antidiagonal  $\overline{\Delta}$  is in fact Lagrangian isotopic to  $\overline{\Delta}$ . In this paper we will show that if  $L$  is

disjoint from the diagonal  $\Delta$  then the Lagrangian isotopy can be chosen to lie in  $S^2 \times S^2 \setminus \Delta$ . Now, the involution  $\sigma$  of  $S^2 \times S^2$  interchanging the two factors has fixed-point set equal to  $\Delta$  and restricts to the antipodal map on  $\bar{\Delta}$ . If  $L$  is invariant under  $\sigma$  then the isotopy can also be chosen to be  $\sigma$ -equivariant. Now, quotienting out by  $\sigma$ , we observe that  $S^2 \times S^2 \setminus \Delta$  is a double-cover of a unit cotangent bundle of  $\mathbb{R}P^2$  and Lagrangian projective planes in  $T^*\mathbb{R}P^2$  homotopic to the zero-section therefore correspond to  $\sigma$ -invariant Lagrangian spheres in  $S^2 \times S^2 \setminus \Delta$  homotopic to  $\bar{\Delta}$ . Hence we have the following corollary.

**Corollary 8** *A Lagrangian  $\mathbb{R}P^2$  homotopic to the zero-section in  $T^*\mathbb{R}P^2$  must be Hamiltonian isotopic to the zero-section.*

A natural compactification of the (unit) cotangent bundle of  $\mathbb{R}P^2$  is  $\mathbb{C}P^2$ . Again the Lagrangian is unique.

**Theorem 9** *Let  $L$  be a Lagrangian  $\mathbb{R}P^2$  in  $\mathbb{C}P^2$ . Then there exists a Hamiltonian isotopy taking  $L$  onto the standard embedding.*

Perhaps our methods can be extended to cover this case, but the theorem can be established by other methods. For example, the surgery technique described by M. Symington in [27] replaces a Lagrangian  $\mathbb{R}P^2$  by a symplectic sphere, transforming  $\mathbb{C}P^2$  into an  $S^2 \times S^2$ . But the symplectic spheres in  $S^2 \times S^2$  have been classified up to Hamiltonian isotopy by B. Siebert and G. Tian in [26].

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## 2 Diffeomorphisms of the two-sphere

In this section we let  $f$  denote a diffeomorphism of the 2-sphere  $S^2$  and for a point  $x \in S^2$  we denote its antipodal point by  $-x$ .

We say that a diffeomorphism  $f$  has the property  $(*)$  if  $f(x) \neq -x$  for all  $x \in S^2$ .

The aim of the section is to prove the following theorem.

**Theorem 10** *Suppose that a smooth family of diffeomorphisms  $f_p$  depending upon a parameter  $p \in S^k$ ,  $k \geq 0$ , have the property (\*) and  $f_1 = \text{id}$  for a point  $1 \in S^k$ . Then there exists a family of isotopies  $f_{p,t}$ ,  $0 \leq t \leq 1$ , with  $f_{p,0} = f_p$  and  $f_{p,1} = \text{id}$  for all  $p$ ,  $f_{1,t} = \text{id}$  for all  $t$  and such that  $f_{p,t}$  has property (\*) for all  $p, t$ .*

**Proof of theorem**

Let  $E$  denote an equator on  $S^2$ . The complement of  $E$  consists of two open disks  $H_1$  and  $H_2$  with  $-H_1 = H_2$ .

We observe that any diffeomorphism  $g$  with property (\*) and which preserves  $E$  is indeed isotopic to the identity through diffeomorphisms  $G_t$  also satisfying (\*). To construct such an isotopy, we first isotope  $g$  to the identity in a neighbourhood of  $E$ . Now the resulting map restricts to a compactly supported diffeomorphism of  $H_1$  and  $H_2$ . But compactly supported diffeomorphisms of the disk are isotopic to the identity (see for instance [28], page 205). Combining these isotopies we get the required isotopy of  $g$ . It satisfies (\*) since  $-H_1 = H_2$ . This construction also applies in the case of parameterized maps  $f_p$ .

Hence it suffices to find a suitable family of isotopies from  $f_p$  to diffeomorphisms preserving an equator  $E$ .

We construct our isotopies by applying the following lemma.

**Lemma 11** *Let  $\Phi_p : (-1, 1) \times S^1 \rightarrow S^2$  be a family of smooth embeddings and  $L_{p,s} = \Phi_p(\frac{2}{\pi} \arctan(s) \times S^1)$ ,  $-\infty < s < \infty$  be a foliation of  $\Phi_p((-1, 1) \times S^1)$  by circles. Suppose that there exist  $K, N$  such that  $f_p(L_{p,s+N})$  is transverse to  $-L_{p,s}$  for all  $s > -K$ . Then there exists a family of isotopies  $f_{p,t}$  satisfying (\*) such that  $f_{p,0} = f_p$  and  $f_{p,t}(z) \in f_p(L_{p,s+tN})$  for all  $z \in L_{p,s}$ ,  $0 \leq t \leq 1$ ,  $s > -K$ . Further  $f_{p,t}(z) = f_p(z)$  for all  $z$  outside of the image of  $\Phi_p$ .*

**Remark 12** *Suppose that  $f_p(L_s) \subset B_\delta(z)$ , a ball of radius  $\delta$  centered at a point  $z \in S^2$ , for all large  $s$ , and that  $L_s$  is disjoint from  $B_\delta(-z)$  for all  $s$ . Then the hypotheses of Lemma 11 are satisfied for any  $K$  provided that  $N$  is chosen comparatively large. In particular, this can be guaranteed if the maps*

$\Phi_p$  extend to diffeomorphisms of  $S^2 = [-1, 1] \times S^1 / (\pm 1, \theta) \sim (\pm 1, \theta')$  such that  $\Phi_p(-1, \theta) = -f_p \Phi_p(1, \theta)$ .

**Proof**

As the condition (\*) on our isotopy is an open one, we may assume any necessary genericity properties for the diffeomorphisms  $f_p$  with respect to the foliation  $L_{p,s}$ . Specifically for any  $p, s, r$  we will assume that  $f_p(L_{p,r}) \cap -L_{p,s}$  consists of an isolated set of points and any tangencies are of finite order. For economy of notation we will omit the subscript  $p$  from the maps and circles described below, but will be careful throughout to ensure that all constructions apply to the parameterized situation.

Suppose that  $N > 0$ . For  $r \in \mathbb{R}$ , let  $a_r$  be a diffeomorphism of  $S^2$  such that  $a_r(L_s) = L_{s+r}$  and  $a_r$  extends as the identity outside of the image of  $\Phi$ . Then we will define  $f_t$  on the image of  $\Phi$  by

$$f_t(z) = h_t f a_{Nt}(z)$$

where  $h_t$  is a diffeomorphism of the image of  $f\Phi$  which preserves the foliation  $\{f(L_s)\}$  and extends by the identity to a diffeomorphism of  $S^2$ . We set  $h_{t,s} = h_t|_{f(L_{s+Nt})}$ .

Then we need to find smoothly varying  $h_{t,s}$  such that  $h_{t,s}(f(a_{tN}(z))) \neq -z$  for all  $z \in L_s$ ,  $s$  and  $0 \leq t \leq 1$ .

For  $s$  very large and  $z \in L_s$  we notice that  $a_{tN}(z)$  is very close to  $z$  (and hence away from  $-z$ ) and so we may choose  $h_{t,s} = \text{id}$ . It is required to show that we can extend these diffeomorphisms for all parameters  $s$ .

Again since property (\*) is an open condition, we observe that once we have defined the  $h_{t,s_0}$  for some  $s_0$  we can smoothly extend the functions to define  $h_{t,s}$  for  $s$  slightly less than  $s_0$ .

The following proposition will be useful.

**Proposition 13** *Suppose that there exist  $h_{t,s}$  for all  $0 \leq t \leq 1$ , all  $s \geq s'$  and for all parameters  $p$  such that the corresponding maps  $f_t$  restricted to  $\bigcup_{s \geq s'} L_s$*

have the property (\*). Then the isotopies  $f_t$  can be extended to isotopies of  $S^2$  still satisfying (\*) and mapping the circles  $\{L_s\}$  into the circles  $\{f(L_s)\}$ .

We remark that the maps  $f_t$  are not required to map  $L_s$  into  $f(L_{s+tN})$ . One application of the lemma is that it allows us to conclude the proof of Lemma 11 once the  $h_{t,s}$  have been defined for  $s > -K$ .

**Proof of Proposition 13** For  $x \in L_{s'}$ , let  $X(f_t(x)) = \frac{d}{dt}(f_t(x))$  define a vector field on  $\bigcup_{s'+N \geq s \geq s'} f(L_s)$ . Then  $X$  can be extended to all of  $S^2$  by setting  $X = 0$  outside of  $\bigcup_{s \geq s' - \epsilon} f(L_s)$  and defining  $X$  over  $\bigcup_{s' \geq s \geq s' - \epsilon} f(L_s)$  such that the corresponding flow  $\phi_t$  takes the circles  $f(L_s)$  into other such circles. The lemma will be established by setting  $f_t = \phi_t \circ f$  once we check that such an isotopy satisfies the condition (\*).

Again let  $x \in L_{s'}$ . Then  $f_t(x) \neq -x$  for all  $0 \leq t \leq 1$  and so in fact there exists a  $\delta$  such that  $f_t(x) \notin B_\delta(-x)$ , a  $\delta$ -ball about  $-x$ , for all  $0 \leq t \leq 1$ . (By compactness, the same  $\delta$  can be chosen for all  $x \in L_{s'}$  and for all parameters  $p$ .) Now  $-B_\delta(-x)$  is a ball about  $x$  and we may assume that if  $\epsilon$  is chosen sufficiently small then for all  $t > 0$  we have  $f^{-1}\phi_t^{-1}(f(x)) = f_t^{-1}(f(x)) \in -B_\delta(-x)$ . Thus the points which flow through  $f(x)$  also avoid their antipodal points and the extension of  $f_t$  has property (\*) as required. This completes the proof of Proposition 13.

For any  $s$  (and parameter  $p$ ), as  $t$  increases from 0 to 1 there is a varying collection of points  $I_{t,s} = f(L_{s+tN}) \cap -L_s$ . The diffeomorphisms  $h_{t,s}$  can be extended arbitrarily once they define the inverse image of these intersections.

For a fixed value of  $s$  and parameter  $p$  the  $I_{t,s}$  will consist of a set of points varying with  $t$ . Generically, for each  $t$ ,  $I_{t,s}$  is a finite set of points in  $f(L_{s+tN})$ . If we identify all  $f(L_{s+tN})$  then as  $t$  varies the only qualitative changes in  $I_{t,s}$  are pairs of points appearing or vanishing.

Now, fixing a typical  $s'$  and parameter  $p$  the families of points  $I_{t,s}$ ,  $0 \leq t \leq 1$ , will vary continuously with  $s$  for  $s$  close to  $s'$  in a manner which we will now make precise. (Since the condition (\*) is an open one it suffices to work in the continuous category.) This can be guaranteed if for instance  $f(L_{s'+tN})$

intersects  $-L_{s'}$  with order at most 2 for all  $t$  and transversally if  $t = 0$  or  $t = 1$ . Continuous variation with  $s$  means that for  $s$  close to  $s'$  we have smooth families of diffeomorphisms

$$\begin{aligned}\phi_s &: [0, 1] \rightarrow [0, 1] \\ g_{t,s} &: f(L_{s+t}N) \rightarrow f(L_{s'+\phi_s(t)}N) \\ b_{t,s} &: L_s \rightarrow L_{s'}\end{aligned}$$

such that  $\phi_{s'} = \text{id}$ ,  $g_{t,s'} = \text{id}$ ,  $b_{t,s'} = \text{id}$  and  $g_{0,s}(f(z)) = f(b_{0,s}(z))$ . They can be chosen such that  $g_{t,s}(I_{t,s}) = I_{\phi_s(t),s'}$  and if  $-z \in I_{t,s}$ , then  $g_{t,s}(-z) = -b_{t,s}(z)$ . The existence of such diffeomorphisms implies that if we have defined suitable  $h_{t,s'}$  then for an  $s$  close to  $s'$  we may define the  $h_{t,s}$  by

$$h_{t,s}(f(a_{tN}(z))) = g_{t,s}^{-1} h_{\phi_s(t),s'}(f(a_{\phi_s(t)N} b_{t,s}(z))).$$

We observe that this extension is canonical modulo a collection of diffeomorphisms of intervals, thus it can be carried out continuously in families.

In summary, if the  $h_{t,s}$  are defined for all  $t$  and for all  $s \geq s'$  then they can also be defined for such  $s < s'$  and parameters  $p$  for which the  $I_{t,s}$  vary continuously between  $s$  and  $s'$ .

For each fixed parameter  $p$  there are a finite collection of parameters  $s_i$  at which the pattern of intersections  $I_{t,s_i}$  will change from nearby values. Assuming  $f$  to be generic, the change will occur (fixing the parameter  $p$  and the  $s_i$ ) only near a single point in  $S^2$  for a single  $t$  parameter, when  $f(L_{s_i+t}N)$  is tangent to  $-L_{s_i}$ . It remains to show that the  $h_{t,s}$  can still be defined near such critical parameters. We can then extend their definition to all  $s$ .

Suppose that  $s''$  is such a critical parameter. By hypothesis we may assume that  $f(L_{s''+N})$  is transverse to  $-L_{s''}$ , and  $f(L_{s''})$  being tangent to  $-L_{s''}$  presents no problems since we can set  $h_{t,s''} = \text{id}$  for  $t$  close to 0.

So we consider the situation when  $f(L_{s''})$  and  $f(L_{s''+N})$  are transverse to  $-L_{s''}$ . Then since  $s''$  is critical there exists a  $\sigma$  with  $0 < \sigma < 1$  and  $f(L_{s''+\sigma N})$  tangent to high order with  $-L_{s''}$ , say at a point  $z$ . By this we mean that we

can choose local coordinates  $(x, y)$  in  $S^2$  about  $z$  such that  $-L_{s''} = \{y = 0\}$  and  $f(L_{s''+\sigma N}) = \{y = x^n\}$  for some integer  $n > 1$ , the order of the tangency.

Nevertheless  $I_{\sigma, s''}$  still consists of an isolated set of points. We suppose that  $h_{t, s'}$  can be defined for some  $s' > s''$  and  $s''$  the the largest critical parameter less than  $s'$ .

If the tangency is of even order then we notice that in fact the  $I_{t, s}$  do in fact vary continuously with  $s$  for  $s$  close to  $s''$ . Therefore we will assume that the order is odd.

We choose a small neighborhood  $U$  of  $z$  such that  $L_s \cap -U$  consists of a small interval for  $s'' \leq s \leq s'$  and which contains all of the points in  $I_{t, s}$  for  $t$  close to  $\sigma$  and  $s$  close to  $s''$  which converge to  $z$  as  $t \rightarrow \sigma$  and  $s \rightarrow s''$ . We note that for all such  $t$  the set  $U \cap I_{t, s}$  is nonempty by the assumption of odd order.

We will arrange that  $f_t(L_{s'} \cap -U)$  is disjoint from  $U$  for all  $t$ . To do this, we can suppose that  $f(L_{s'} \cap -U)$  is disjoint from  $U$  and as  $t$  increases the intervals  $f_t(L_{s'} \cap -U)$  may intersect but can never cross  $U \cap f(L_{s'+Nt})$ . (For, if the  $f_t(L_{s'} \cap -U)$  did move across  $U \cap f(L_{s'+Nt})$  then by the intermediate value theorem we would find a point  $x \in L_{s'}$  with  $f_t(x) = -x$  for some  $t$ , contrary to the assumption that  $f_t$  is defined to satisfy  $(*)$  when  $s = s'$ .) Thus by deforming the  $h_{t, s'}$  we can arrange that  $f_t(L_{s'} \cap -U)$  stays disjoint from  $U \cap -L_{s'}$ . It is important that the deformations of  $h_{t, s'}$  can have compact support near  $f_t(L_{s'} \cap -U)$  and are canonical modulo compactly supported diffeomorphisms, in particular, if the intervals do intersect then there is only one direction in which they can be deformed apart. Thus this construction can be carried out continuously in the parameter  $p$ . After this a further small adjustment can keep  $f_t(L_{s'} \cap -U)$  away from  $U$ .

For an  $\epsilon > 0$  and  $s' - s''$  sufficiently small the diffeomorphisms  $\phi_s, g_{t, s}$  and  $b_{t, s}$  can be defined as before for  $s'' \leq s \leq s'$  and satisfy the required properties for  $|t - \sigma| > \epsilon$ . For all  $t$  we can choose the maps such that  $g_{t, s}(I_{t, s} \setminus U) = I_{\phi_s(t), s'} \setminus U$  while  $g_{t, s}$  preserves  $U$  and  $b_{t, s}$  preserves  $-U$ . Then the maps  $h_{t, s}$  can be defined as before.

This completes the proof of Lemma 11.

We apply Lemma 11 in various situations to complete the proof of Theorem 10.

Let  $n$  denote the north pole in  $S^2$ , and define  $z_p = f_p(n)$ . Let  $\gamma_p$  be the great circle intersecting  $n$ ,  $z_p$  and  $-z_p$ . Then we can define the equators  $E_p$  to be the great circles perpendicular to  $\gamma_p$  and intersecting the midpoints of  $\gamma_p$  between  $n$  and  $-z_p$ . We note that  $n \neq -z_p$  and that  $-z_p$  and  $-n$  (the south pole) lie on the opposite side of  $E_p$  than  $n$  and  $z_p$ .

We can choose embeddings  $\Phi_p : (-1, 1) \times S^1 \rightarrow S^2$  with  $s \times S^1 \rightarrow n$  as  $s \rightarrow 1$  and  $s \times S^1 \rightarrow -z_p$  as  $s \rightarrow -1$ . Then by Lemma 11 and Remark 12 we can find smooth families of isotopies from  $f_p$  to a new family of maps, still denoted by  $f_p$  with  $f_p(n) = z_p$  and  $f_p(E_p) = C_p$ , a small circle around  $z_p$ .

Repeating this argument, we can choose another family  $\Phi_p$  of embeddings such that now  $s \times S^1 \rightarrow f_p^{-1}(-n)$  as  $s \rightarrow 1$  and  $s \times S^1 \rightarrow n$  as  $s \rightarrow -1$ . Then  $f_p \Phi_p((-1, 1) \times S^1)$  is a cylinder converging at its positive end to  $-n$  and at its negative end to  $z_p$ . As  $E_p$  separates these two points we can also choose  $\Phi_p$  such that  $f_p \Phi_p(\{0\} \times S^1) = E_p$  and  $f_p \Phi_p(\{-K\} \times S^1) = C_p$  for a  $K$  close to  $-1$ . Thus applying Lemma 11 again there will be a moment  $t_p$  when the corresponding diffeomorphisms  $f_{p,t_p}$  map  $E_p$  to itself. Reparameterizing the isotopies we may assume that all equators are preserved and thus the proof of Theorem 10 is complete.

### 3 Lagrangian spheres in $T^*S^2$

Let  $L$  be a Lagrangian sphere in  $T^*S^2$ . This has self-intersection number  $-2$  and so must be homotopic to the zero-section. By scaling in the fibers we may assume that  $L \subset T^1S^2$ . We will identify  $T^1S^2$  with the complement of the diagonal  $\Delta$  in  $S^2 \times S^2$  with its standard split symplectic form  $\omega = \omega_0 \oplus \omega_0$ . Under this identification, the zero-section in  $T^1S^2$  becomes the antidiagonal  $\overline{\Delta}$ . Thus Theorem 1 in this case is equivalent to the following.

**Theorem 14** *Given a Lagrangian sphere  $L \subset S^2 \times S^2 \setminus \Delta$  homotopic to  $\overline{\Delta}$ ,*

there exists a Hamiltonian isotopy of  $S^2 \times S^2$  which fixes  $\Delta$  and maps  $L$  onto  $\bar{\Delta}$ .

Given an almost-complex structure  $J$  on  $S^2 \times S^2$  tamed by  $\omega$ , Gromov showed in [11] that there exist unique foliations  $\mathcal{F}_0$  and  $\mathcal{F}_1$  by  $J$ -holomorphic curves in the classes  $[S^2 \times \text{pt}]$  and  $[\text{pt} \times S^2]$ . With respect to the standard almost-complex structure  $J_0 = i \oplus i$ , these foliations are exactly  $S^2 \times \text{pt}$  and  $\text{pt} \times S^2$ . The key lemma which we need from [16] is the following.

**Lemma 15** *There exists a tame almost-complex structure  $J$  on  $S^2 \times S^2$  such that each curve in the corresponding foliations  $\mathcal{F}_0$  and  $\mathcal{F}_1$  intersects  $L$  transversally in a single point. The almost-complex structure  $J$  can be taken to agree with  $J_0$  near  $\Delta$ .*

The second statement was not included in [16] but is clearly true from the proof.

There exists a family of tame almost-complex structures  $J_t$ ,  $0 \leq t \leq 1$  on  $S^2 \times S^2$  with  $J_1 = J$  and, for all  $t$ ,  $J_t = J_0 = i \oplus i$  near  $\Delta$ . In particular,  $\Delta$  is a  $J_t$ -holomorphic curve for all  $t$ . By the positivity of intersections for  $J_t$ -holomorphic curves, each holomorphic curve in the foliations  $\mathcal{F}_0$  and  $\mathcal{F}_1$  intersects  $\Delta$  transversally in a single point.

We define a diffeomorphism  $f : \Delta \rightarrow \Delta$  by  $f(x) = y$ , where  $y \in \Delta$  is the unique point such that the  $J$ -holomorphic curve in  $\mathcal{F}_1$  through  $y$  intersects the  $J$ -holomorphic curve in  $\mathcal{F}_0$  through  $x$  on  $L$ . Then  $f(x) \neq x$  for all  $x \in \Delta$ .

As in the previous section, for a point  $x \in \Delta$  we denote its image under the antipodal map by  $-x$ . Then the  $J_0$ -holomorphic curve in  $\mathcal{F}_0$  through  $x$  intersects the  $J_0$ -holomorphic curve in  $\mathcal{F}_1$  through  $-x$  on  $\bar{\Delta}$  for all  $x \in \Delta$ .

We can apply the theorem of section 2 without the parameter  $p$  (or in the case  $k = 0$ ) to get the following.

**Lemma 16** *There exists an isotopy  $g_t : \Delta \rightarrow \Delta$ ,  $0 \leq t \leq 1$ , with  $g_0 = \text{id}$ ,  $g_1 = -f^{-1}$  and  $g_t(x) \neq -x$  for all  $t$  and  $x \in \Delta$ .*

We now define maps  $\phi_t : S^2 \times S^2 \rightarrow S^2 \times S^2$  by requiring that  $\phi_t$  maps the  $J_t$ -holomorphic curves in  $\mathcal{F}_0$  and  $\mathcal{F}_1$  to the corresponding  $J_0$ -holomorphic foliations, the  $J_t$ -holomorphic curve in  $\mathcal{F}_0$  through  $x \in \Delta$  maps to the  $J_0$ -holomorphic curve in  $\mathcal{F}_0$  through  $x$  and the  $J_t$ -holomorphic curve in  $\mathcal{F}_1$  through  $x$  maps to the  $J_0$ -holomorphic curve in  $\mathcal{F}_1$  through  $g_t(x)$ .

Then  $\phi_0 = \text{id}$ ,  $\phi_1(L) = \overline{\Delta}$  and  $\phi_t(\Delta)$  is disjoint from  $\overline{\Delta}$  for all  $t$ . Let  $L_t = \phi_t^{-1}(\overline{\Delta})$ , so  $L_t$  gives a smooth isotopy from  $L$  to  $\overline{\Delta}$  in  $S^2 \times S^2 \setminus \Delta$ .

Also,  $\phi_{t*}(J_t)$  is tamed by the split form  $\omega$ , and we see from this that  $\phi_t(\Delta)$  is a symplectic submanifold for all  $t$ .

For fixed  $t$ , set  $\omega_s = s\phi_t^*(\omega) + (1-s)\omega$ . This is a symplectic form for all  $0 \leq s \leq 1$ . It is clearly closed and is symplectic since it tames  $J_t$ . We note that  $\Delta$  is symplectic for all  $\omega_s$  and, if  $t = 0$  or  $t = 1$ ,  $L_t$  is Lagrangian with respect to all  $\omega_s$ . Hence by an application of Moser's theorem we can find a diffeomorphism  $\psi_t$  of  $S^2 \times S^2$  such that  $\psi_t^*(\omega) = \phi_t^*(\omega)$ . The  $\psi_t$  can be chosen to vary smoothly with  $t$ , to fix  $\Delta$  and such that  $\psi_0 = \text{id}$  and  $\psi_1$  fixes  $L$ . To see this, we recall that Moser's method involves writing  $\omega_s = \omega_0 + d\alpha_s$  and studying the flow of the vectorfield  $X_s$  defined by  $X_s \lrcorner \omega_s = \frac{d\alpha_s}{ds}$ . The definition implies that  $\mathcal{L}_{X_s} \omega_s = d(\frac{d\alpha_s}{ds}) = \frac{d\omega_s}{ds}$ . We have the freedom in this construction to add any smooth family of exact 1-forms  $\beta_s$  to the  $\alpha_s$ . These  $\beta_s$  can be chosen such that  $\alpha_s + \beta_s$  vanishes on the symplectic normal bundle to  $\Delta$  and, if  $t = 0$  or  $t = 1$ , on the tangent bundle to  $L_t$ . Then the flow fixes  $\Delta$  and, if  $t = 0$  or  $t = 1$ , also fixes  $L_t$ .

Thus  $\psi_t(L_t)$  is a Lagrangian isotopy from  $L$  to  $\overline{\Delta}$  inside  $S^2 \times S^2 \setminus \Delta$  as required.

To show that the space  $\mathcal{L}$  of Lagrangian spheres is contractible, by applying a result of R. S. Palais [24] it suffices to show that  $\pi_k(\mathcal{L}) = 0$  for all integers  $k \geq 0$ . Thus Theorem 2 reduces to the following.

**Theorem 17** *Given a family of Lagrangian spheres  $L_p \subset S^2 \times S^2 \setminus \Delta$  for  $p \in S^k$  there exists a family of Hamiltonian isotopies of  $S^2 \times S^2$  which fix  $\Delta$  and map  $L_p$  onto  $\overline{\Delta}$ .*

This follows exactly as Theorem 1 for  $T^*S^2$  by applying the full parameterized version of Theorem 10 once we establish the analogue of Lemma ??, that is, we need to show the following.

**Lemma 18** *There exists a family of tame almost-complex structures  $J_p$  on  $S^2 \times S^2$  such that each curve in the corresponding foliations  $\mathcal{F}_0$  and  $\mathcal{F}_1$  intersects  $L_p$  transversally in a single point. The almost-complex structures  $J_p$  can be taken to agree with  $J_0$  near  $\Delta$ .*

**Proof of lemma 18** We briefly recall the construction of the almost-complex structures in [16]. Associated to each  $p \in S^k$  and positive integer  $N$  there exists a tame almost-complex structure  $J_{p,N}$  on  $S^2 \times S^2$  which corresponds to stretching the neck to length  $N$  along the boundary of a small tubular neighborhood of  $L_p$ . It is easy to arrange that the  $J_{p,N}$  vary smoothly with  $p$ . For fixed  $p$  it was shown in [16] that after taking a subsequence as  $N \rightarrow \infty$  reparameterizations of  $J_{p,N}$ -holomorphic spheres in the corresponding foliations  $\mathcal{F}_0$  and  $\mathcal{F}_1$  converge smoothly to finite energy planes in  $T^*L_p$ . For a suitable choice of the  $J_{p,N}$  these finite energy planes must be transverse to  $L_p$ , in particular the  $J_{p,N}$  holomorphic foliations  $\mathcal{F}_0$  and  $\mathcal{F}_1$  are transverse to  $L_p$  for  $N$  sufficiently large. We claim that there exists an  $N$  such that the  $J_{p,N}$ -holomorphic foliations are transverse to  $L_p$  for all  $p$ , thus establishing the lemma.

Suppose that the claim is false. Then for all  $j$  there exists a point  $q_j \in S^k$  and a  $J_{q_j,j}$ -holomorphic sphere  $C_j$  tangent somewhere to  $L_{q_j}$ . A subsequence of  $\{q_j\}$  will converge to some  $p \in S^k$ . Now, there exist diffeomorphisms  $a_j : S^2 \times S^2 \rightarrow S^2 \times S^2$  such that  $a_j(L_{q_j}) = L_p$  and  $a_j$  is an  $(J_{q_j,j}, J_{p,j})$ -biholomorphism on the tubular neighborhood of  $L_{q_j}$ . Furthermore, after taking the subsequence, the  $a_j$  can be chosen to converge  $C^\infty$  uniformly to the identity and so  $I_j = a_{j*}(J_{q_j,j})$  is a sequence of almost-complex structures on  $S^2 \times S^2$  agreeing with  $J_{p,j}$  near  $L_p$  and which are tame for  $j$  large. We apply the compactness theorem from [2] exactly as in [16] to the  $I_j$ -holomorphic foliations  $\mathcal{F}_0$  and  $\mathcal{F}_1$ . The same proof shows that reparameterizations converge to finite energy planes in  $T^*L_p$  transverse to  $L_p$ . But this gives a contradiction as required since the  $I_j$

holomorphic spheres  $a_j(C_j)$  are tangent to  $L_p$ .

## 4 Manifolds with 1-handles

We will now consider the class of convex symplectic manifolds constructed by adding 1-handles to the unit cotangent bundle  $T^1S^2$  in order to establish Theorem 1 in this case. Our first observation is that any such manifold  $M$  can be symplectically embedded in  $(S^2 \times S^2, \omega)$ , after perhaps scaling the symplectic form. This follows from the methods of [9]. We can arrange that the zero-section in  $T^1S^2$  again becomes identified with  $\overline{\Delta}$  and the boundary of  $M$  is a smooth hypersurface  $\Sigma$  of contact-type in  $S^2 \times S^2$ . More precisely one can think of  $M$  as a Stein manifold having a bounded plurisubharmonic exhaustion function which is zero on the zero-section in  $T^*S^2$  and whose other critical points are nondegenerate and have Morse index 1. The symplectic form on  $M$  is the Kähler form of the plurisubharmonic exhaustion. Now, as in [6] or [7], 2-handles can be added to  $M$  to cancel the 1-handles and produce a Stein manifold symplectomorphic to  $T^1S^2 = S^2 \times S^2 \setminus \Delta$ . We will later use the fact that  $\Sigma$  is now a level-set of a plurisubharmonic exhaustion on  $S^2 \times S^2 \setminus \Delta$ .

We plan to find families of almost-complex structures  $J_t$  on  $S^2 \times S^2$  and diffeomorphisms  $f_t : \Delta \rightarrow \Delta$  such that the  $J_t$ -holomorphic curves in  $\mathcal{F}_0$  through points  $x$  and the  $J_t$ -holomorphic curves in  $\mathcal{F}_1$  through  $f_t(x)$  intersect on embedded spheres  $L_t \subset M$  with  $L_0 = \overline{\Delta}$  and  $L_1 = L$ . The almost-complex structures can be constructed by deforming  $J_0$  in a neighbourhood of  $\Sigma$  and, for  $t$  close to 0 or 1, also in a neighbourhood of  $\overline{\Delta}$  or  $L$ .

Suppose that we perform the operation of stretching-the-neck along  $\Sigma$ . That is, we symplectically identify a neighbourhood of  $\Sigma$  in  $S^2 \times S^2$  with  $((-\epsilon, \epsilon) \times \Sigma, d(e^t \alpha))$ , where  $\alpha$  is a fixed contact form on  $\Sigma$ . We can then produce a manifold  $A_N$  by replacing this neighbourhood by  $(-N, N) \times \Sigma$ . Our original almost-complex structure can be extended over  $(-N, N) \times \Sigma$  to be translation invariant and the symplectic form can be extended over  $(-N, N) \times \Sigma$  such that  $A_N$  is symplectomorphic to  $(S^2 \times S^2, \omega)$  via a symplectomorphism equal to the

identity outside  $(-N, N) \times \Sigma$  (for this see [21]). Under this symplectomorphism we can think of stretching the neck as studying a family of almost-complex structures  $J_N$  on  $S^2 \times S^2$  which degenerate along  $\Sigma$  as  $N \rightarrow \infty$ .

At the same time, we can deform the almost-complex structure along the boundary of tubular neighborhoods  $U_0$  or  $U_1$  of  $L_0 = \bar{\Delta}$  or  $L_1 = L$  respectively. Stretching to length  $N_1$  and  $N_2$  on the contact hypersurfaces  $\Sigma$  and  $\partial U_i$  respectively we obtain almost-complex structures  $J_{N,0}$  and  $J_{N,1}$ , where  $N = (N_1, N_2)$ . There exist smooth families of almost-complex structures  $J_{N,t}$  connecting  $J_{N,0}$  and  $J_{N,1}$  which are fixed on the tubular neighborhoods of  $\Sigma$  and in the complement of  $M$ .

Following the work of H. Hofer, K. Wysocki and E. Zehnder, see [21] (and see below), and as in [16], after taking suitable subsequences of  $N = (N_1, N_2)$  in which both entries tend towards infinity, for  $i, j = 0, 1$  families of  $J_{N,i}$ -holomorphic curves in  $\mathcal{F}_j$  will converge to unions of finite energy curves as  $N \rightarrow \infty$ . The limiting finite energy curves can be chosen to extend to foliations of three symplectic manifolds with cylindrical ends, namely the completion  $W$  of the complement of  $M$  in  $S^2 \times S^2$  with an end symplectomorphic to the negative symplectization of  $\Sigma$ , that is  $((-\infty, 0) \times \Sigma, d(e^t \alpha))$ , the completion of  $U_i$ , which will be a copy of  $T^*S^2$ , and the completion of  $M \setminus U_i$  with two ends symplectomorphic to the positive symplectization of  $\Sigma$  and the negative symplectization of the boundary of  $U_i$ . A priori these foliations will depend upon the subsequence  $(N_1, N_2) \rightarrow \infty$ . Similarly we can let just  $N_1$  or  $N_2$  tend towards infinity. In the first case we produce foliations of  $W$  and the completion of  $M$ . In the second case we produce foliations of the completions of  $U_i$  and  $S^2 \times S^2 \setminus U_i$ . For the relevant compactness result here see [2]. Taking a diagonal subsequence this result produces finite energy curves through a dense set of points in each of the three symplectic manifolds, and another application of the compactness result finds finite energy curves through every point. These curves either coincide or are distinct by positivity of intersection, see [22], since we are taking limits of foliations, and hence the limit is also a foliation. Further facts about finite energy curves, such as definitions, asymptotic convergence to Reeb orbits and

Fredholm properties can be found in the series of papers [18], [19], [20]. A brief summary containing the facts we need here appears in section 2 of [16].

The foliations of the completion of  $U_i$  were determined in [16], Lemma 10. For  $U_i$  and its almost-complex structure suitably chosen, the Reeb flow on  $\partial U_i$  is foliated by closed orbits, and exactly one curve in each foliation is asymptotic to each closed orbit. Also, each curve in the foliation from  $\mathcal{F}_0$  intersects in a single point each curve in the foliation from  $\mathcal{F}_1$  provided that the curves have different asymptotic limits. Another result coming from the analysis in [16], see Lemmas 8 and 9, is that the curves in both foliations are transverse to the zero-section, and it follows that the curves in the foliations of  $S^2 \times S^2$  are transverse to  $L_i$  for  $N$  sufficiently large.

We now look at the foliations of  $W$  coming from restricting curves in  $\mathcal{F}_0$  or  $\mathcal{F}_1$  to  $W$  as  $N_1 \rightarrow \infty$ . It will be important for us that in any stretch  $N_1 \rightarrow \infty$  the corresponding two foliations of  $W$  will coincide. Moreover this foliation is independent of the almost-complex structure on  $M$  (assuming that this almost-complex structure is the result of stretching, perhaps to length infinity, along  $U_i$  complex structures lying in a compact set).

First, to see that the foliations coincide when the almost-complex structure on  $M$  has  $N_2 = \infty$ , suppose that a curve in the limiting  $\mathcal{F}_0$  foliation intersects one in the limiting  $\mathcal{F}_1$  foliation but that the curves do not have identical images. Then, by the positivity of intersections, any intersections of limiting finite energy curves must also be seen as intersections of holomorphic spheres in the foliations  $\mathcal{F}_0$  and  $\mathcal{F}_1$  of the complement of  $U_i$  when  $N_1$  is large. By the positivity of intersections again, intersections are stable under perturbation and so we may assume that the curves have distinct asymptotic limits on  $\partial U_i$ . But this gives a contradiction since for  $N_2$  large we would see one intersection point near our point in  $W$  and another inside  $U_i$ , each contributing positively, while the topological intersection number is 0.

Next, to see that the foliations are independent of the almost-complex structure on  $M$ , fix two almost-complex structures  $J_0$  and  $J_1$  and study the limits of curves through a generic point  $x \in \Delta$ . In other words, the deformation index of

the curve  $C$  passing through the point  $x$  in one of the resulting foliations is 2, or its constrained index (to pass through  $x$ ) is 0. Suppose that there are two different limits through this point. Then by considering a family of almost-complex structures  $J_t$  connecting  $J_0$  and  $J_1$  (and fixed on  $W$ ) and the corresponding family of  $J_t$ -holomorphic curves through  $x$ , we can find a limiting curve  $C'$  in  $W$  passing through  $x$  which is arbitrarily  $C^\infty$  close to  $C$  on a compact subset of  $W$  but does not coincide with  $C$ . Then, if the almost-complex structure on  $W$  is regular,  $C'$  must have positive constrained deformation index (as  $C$  itself will be isolated amongst curves of constrained index 0) or unconstrained index at least 3. But, following the analysis of M-L. Yau, see [30], for a suitable choice of contact form on  $\Sigma$  the Reeb orbits (of a bounded period) correspond either to Reeb orbits on a perturbed  $T^1S^2$ , or are multiple covers of orbits lying entirely in the 1-handles. In any case, they have Conley-Zehnder index at least 1 and therefore the components in  $M$  all have nonnegative deformation index. It follows that the components in  $W$  have deformation index bounded by 2 (as the sum of the deformation indices in our limits is equal to the deformation index of the original curves) and so we have a contradiction.

A further consequence of these arguments is that we can find an  $N_1$  such that if the complex structure is stretched to length  $N_1$  along  $\Sigma$  then (independently of the almost-complex structure on  $M$ ) we may assume that the curve in either  $\mathcal{F}_0$  or  $\mathcal{F}_1$  through a point  $x \in \Delta$  lies  $C^\infty$   $\epsilon$ -close to the corresponding curve in the limiting foliation restricted to a compact subset of  $W$ . Otherwise, letting  $N_1 \rightarrow \infty$ , we reach a contradiction. In particular, if we stretch to length at least  $N_1$  then curves through points  $x, y \in \Delta$  which are distance order  $\epsilon$  apart do not intersect in the fixed compact subset of  $W$ .

The following is the key proposition for the proof of Theorem 1.

**Proposition 19** *There exists a family of almost-complex structures  $J_t$  and diffeomorphisms  $f_t$  of  $\Delta$  such that the spheres  $L_t$  given by intersecting the  $J_t$ -holomorphic sphere in  $\mathcal{F}_0$  through points  $x \in \Delta$  with the  $J_t$ -holomorphic sphere in  $\mathcal{F}_1$  through  $f_t(x) \in \Delta$  lie in  $M$ . Also,  $L_0 = \overline{\Delta}$  and  $L_1 = L$ .*

**Proof** Letting  $N_2 = \infty$ , for  $i = 0, 1$  we have two foliations of  $U_i$  and a single foliation of  $S^2 \times S^2 \setminus U_i$  coming from limits of curves in  $\mathcal{F}_0$  and  $\mathcal{F}_1$ . We can define diffeomorphisms  $f_i$  of  $\Delta$  as follows. Each  $p \in L_i$  lies on a unique plane  $P_0$  in the foliation of the completion of  $U_i$  coming from limits of  $\mathcal{F}_0$ . Similarly,  $p$  lies on a unique plane  $P_1$  in the completion of  $U_i$  coming from limits of  $\mathcal{F}_1$ . There is a unique plane  $Q_0$  in  $S^2 \times S^2 \setminus U_i$  whose negative asymptotic limit corresponds to the positive limit of  $P_0$ , and there is a unique plane  $Q_1$  in  $S^2 \times S^2 \setminus U_i$  whose negative asymptotic limit corresponds to the positive limit of  $P_1$ . If we denote the intersection of  $Q_0$  with  $\Delta$  by  $x$  then  $f_i(x)$  can be defined to be the intersection with  $\Delta$  of  $Q_1$ .

By construction the  $f_i$  are fixed-point free, therefore by Theorem 3 they can be connected by a family of fixed-point free diffeomorphisms  $f_t$  of  $\Delta$ . Assume that for any  $x \in \Delta$  and  $t \in [0, 1]$  the points  $x$  and  $f_t(x)$  are at least  $\epsilon$  apart, and choose a corresponding  $N_1$  as above such that when we stretch to length  $N_1$  along  $\Sigma$  the sphere in  $\mathcal{F}_0$  through  $x$  does not intersect the sphere in  $\mathcal{F}_1$  through  $f_t(x)$  for any  $x, t$ .

We can find a family of almost-complex structures  $J_t$  on  $S^2 \times S^2$  such that if  $t < \delta$  then  $J_t$  is stretched to length  $N_2$  along  $\partial U_0$ ; if  $t > 1 - \delta$  then  $J_t$  is stretched to length  $N_2$  along  $\partial U_1$ ; if  $\delta \leq t \leq 1 - \delta$  then  $J_t$  is stretched to length  $N_1$  along  $\Sigma$ . Then we claim that if  $N_2$  is chosen sufficiently large the spheres  $L_t$  are all disjoint from  $W$  as required. This follows by taking a limit as  $N_2 \rightarrow \infty$ . If the claim were false for  $t < \delta$  then we could find an  $x \in \Delta$  such that the curve in the foliation of  $S^2 \times S^2 \setminus U_0$  coming from  $\mathcal{F}_0$  passing through  $x$  intersects in the curve in the foliation of  $S^2 \times S^2 \setminus U_0$  coming from  $\mathcal{F}_1$  through  $f_t(x)$ , a contradiction as these two foliations coincide.

We remark that for a fixed large, but finite,  $N_2$  this construction gives  $L_0$  and  $L_1$  only  $C^\infty$  close to  $\bar{\Delta}$  and  $L$  respectively, but this can easily be corrected with a small adjustment of the  $f_t$  and Proposition 19 is established.

Using Proposition 19, we now complete the proof of Theorem 1. Following the method of section 3, we can find a family of symplectic forms  $\omega_t$  on  $S^2 \times S^2$  such that  $L_t$  is Lagrangian with respect to  $\omega_t$ . The  $\omega_t$  restrict to exact symplectic

forms on  $M$ , say  $\omega_t = d\alpha_t$ , which tame  $J_t$ . In a tubular neighborhood  $V = (-\epsilon, 0) \times \Sigma$  of the boundary  $\Sigma = \{0\} \times \Sigma$  of  $M$ , define a function  $\chi : V \rightarrow [0, 1]$  such that  $\chi(r, y)$  is an increasing function of  $r$ ,  $\chi(r, y) = 0$  for  $r$  close to  $-\epsilon$  and  $\chi(r, y) = 1$  for  $r$  close to 0. Then, first scaling  $\alpha_t$  if necessary, we can replace it by  $\beta_t = (1 - \chi)\alpha_t + \chi e^r \alpha$  in  $V$ . The new form  $\omega_t = d\beta_t$  will still be symplectic and tamed by  $J_t$  (for  $\alpha_t$  suitably scaled) but now agrees with  $\omega$  near  $\Sigma$ . Assuming  $V$  to be disjoint from all  $L_t$ , the submanifolds  $L_t$  will still be Lagrangian with respect to  $\omega_t$ .

We now apply Moser's method as in section 3 to find a symplectomorphism between  $(M, \omega_t)$  and  $(M, \omega)$  and thereby isotope the  $L_t$  into Lagrangian submanifolds of  $(M, \omega)$ . As before, this can be arranged to fix  $L_0$  and  $L_1$  and now also the neighborhood  $V$ . Thus it gives our Lagrangian isotopy as required.

## 5 Proof of Theorem 4

In this section we study the symplectic manifold  $W$ , which is a plumbing of two copies of  $T^*S^2$ . Namely we take two copies of  $T^*S^2$  and identify the cotangent fibers projecting to a disk  $D$  in  $S^2$  with a product  $D \times E$  in each copy. We then identify the two copies of  $D \times E$ , preserving the product structure but reversing the factors. Alternatively  $W$  can be realized as a Stein manifold by adding a 2-handle to a disk bundle  $T^1S^2$  along the boundary of one fiber, a Legendrian curve for the natural choice of contact structure.

In any case,  $W$  is naturally a symplectic manifold with symplectic form  $\omega_0$  and contains two Lagrangian spheres  $L_1$  and  $L_2$  corresponding to the two zero-sections. We will think of its non-compact end as a copy of  $[0, \infty) \times M$  where  $M$  carries a contact structure with contact form  $\alpha$  and the symplectic structure on the end is given by  $\omega = d(e^t \alpha)$ .

The manifold  $M$  is a Lens space  $L(3, 2)$ . The contact form can be described as follows.

Let  $S$  be the 3-sphere given by

$$S = \{(z_1, z_2) \in \mathbb{C}^2 | H(x) = 1\}$$

where

$$H(x) = |z_1|^2 + \frac{1}{r^2} |z_2|^2$$

and equipped with the contact form  $\lambda|_S$  where

$$\lambda = \frac{i}{4} \sum_{j=1}^2 (z_j d\bar{z}_j - \bar{z}_j dz_j).$$

Let  $r^2 > 1$  and irrational, and periodic orbits  $p_0 = \{z_2 = 0\} \cap S$  and  $p_1 = \{z_1 = 0\} \cap S$ .

**Lemma 20** (see [17] Lemma 1.6) *The associated Reeb vectorfield possesses precisely two periodic orbits  $p_0$  and  $p_1$ . They are nondegenerate and have Conley-Zehnder indices  $\mu(p_0) = 3$  and  $\mu(p_1) = 2n + 1$  where  $n < r^2 + 1 < n + 1$ .*

Now we observe that  $S$  and  $\lambda|_S$  are invariant under the map  $\sigma : (z_1, z_2) \mapsto (e^{\frac{2\pi i}{3}} z_1, e^{\frac{4\pi i}{3}} z_2)$  and so project to  $L(3, 2)$  to give the contact form  $\alpha$ . The orbits  $p_0$  and  $p_1$  triple cover periodic orbits  $x_0$  and  $x_1$  on our  $L(3, 2)$ . Let  $X$  be the corresponding Reeb vectorfield.

Our proof will proceed as follows. On  $[0, \infty) \times M$  we choose a tame almost-complex structure  $J$  which is translation invariant, preserves the contact planes on  $M$  and satisfies  $J(\frac{\partial}{\partial t}) = X$ . Throughout the proof we will fix this almost-complex structure. It can be extended to a tame almost-complex structure  $J$  on  $W$  and for each extension we will describe a foliation of  $W$  by finite energy planes asymptotic to multiple covers of  $x_0$ . Let  $L \subset W$  be a Lagrangian sphere homotopic to  $L_1$ . Then we pay specific attention to the pattern of the foliation relative to  $L$  when we change  $J$  by stretching the neck near  $L$ . This is all done in section 5.1.

In section 5.2, using our holomorphic foliations we can construct plurisubharmonic exhaustion functions on  $W$ . These functions will have exactly one

minimum and two critical points of index 2. It will turn out that after stretching the neck along  $L$ , the unstable manifold of one critical point will be disjoint from  $L$ .

All such plurisubharmonic exhaustions give isotopic symplectic structures on  $W$ . The final part of the proof, in section 5.3, will use these isotopies to construct the symplectomorphism needed for our theorem. Of course Theorem 1 will also be used, in a form which says that a Lagrangian sphere disjoint from the unstable manifold of one critical point is Hamiltonian isotopic to the stable manifold of the other critical point.

## 5.1 Finite energy holomorphic curves in $W$

### 5.1.1 Finite energy foliations

As stated above,  $W$  admits a foliation by finite energy planes. More specifically the following is true.

**Theorem 21** *For any tame extension  $J$ , the almost-complex manifold  $(W, J)$  can be foliated by finite energy planes. Exactly three planes in the foliation,  $E_0, E_1, E_2$ , are asymptotic to  $x_0$ . The other finite energy planes are all asymptotic to  $3x_0$ . After choosing orientations for  $L_1$  and  $L_2$  we may assume that  $E_i \bullet L_j = -\delta_{ij}$  and  $E_0 \bullet L_j = 1$  for  $i, j = 1, 2$ .*

#### **Proof**

This is very similar to the proof in [14], (which of course is heavily reliant on the series of papers [18], [19], [20]) but the arrangement of finite energy planes is different to the situation covered there. In fact, [14] described finite energy foliations of Stein manifolds diffeomorphic to disk bundles over  $S^2$  whose boundaries are the Lens spaces  $L(p, 1)$ . The basic case of the foliation of  $T^*S^2$  with boundary  $\mathbb{R}P^3$  was worked out earlier in [13]. The proofs, and this one, follow the same path in that they start with the finite energy planes in  $\mathbb{R} \times S^3$  constructed in [17] (using the method of filling by holomorphic disks) and project these to get finite energy planes in  $W$  which are topologically trivial relative to

the boundary but appear in a 2-dimensional family. A process of elimination using index and area inequalities then determines the behaviour of the family of curves as they propagate into  $W$ .

More precisely, this reasoning, originating in the works of H. Hofer, K. Wysocki and E. Zehnder, [17], Theorem 5.1, implies that there is a 2-dimensional moduli space of unparameterized disjoint embedded finite energy planes asymptotic to  $3x_0$ . An  $S^1$  family of these planes lie in  $[0, \infty) \times M$  and each plane in the family touches  $\{1\} \times M$  in a single point. Choosing  $R$  large, this  $S^1$  family will intersect  $\{R\} \times M$  in an  $S^1$  family of circles, a 2-torus, which bounds a solid torus  $U$  containing the periodic orbit  $x_0$ . Let  $B$  be the intersection of the  $S^1$  family of finite energy planes with  $[0, R] \times M$ . Then a small perturbation of  $B \cup U$  is a pseudoconvex hypersurface bounding a domain  $V$  Stein homotopic to  $W$ . In fact the perturbation of  $B \cup U$  can be isotoped into  $\{R\} \times M$  through a family of pseudoconvex hypersurfaces.

We are interested in an extension of our moduli space to a family of finite energy planes foliating  $V$ . After the perturbation of  $B$  we may suppose that our  $S^1$  family intersects  $B$  in a circle  $\gamma$  of complex tangencies. Other finite energy planes in our moduli space will intersect  $B$  in circles linking  $\gamma$ , see for example Figure 2 in [14]. Since  $M$  is an  $L(3, 2)$ , after choosing coordinates on  $U$  we may assume that the finite energy planes intersecting  $\partial U$  do so in  $(3, 1)$  curves, where the first component represents the class of a longitude homotopic to  $x_0$ .

The planes in the moduli space intersecting  $U$  do not form a compact set. In fact, as in [14], Lemma 3.2, bubbling occurs and sequences of finite energy planes asymptotic to  $3x_0$  will converge to three finite energy planes  $E_0, E_1, E_2$  asymptotic to  $x_0$ . (The topology of  $V$  implies that we now get bubbling into three planes, energy considerations imply that they are all asymptotic to  $x_0$ .) We call these rigid planes since the moduli space of finite energy planes asymptotic to  $x_0$  modulo reparameterization has dimension 0. Together with the finite energy planes asymptotic to  $3x_0$  the rigid planes complete our foliation.

We notice as in [14] that  $V$  is homotopic to the intersections of the three rigid planes with  $V$ , after identifying their boundaries in  $U$ . (This implies that

there is no further bubbling.) To check the intersection numbers, we can choose a convenient almost-complex structure  $J$  since the numbers are independent of the choice. In fact there is an  $S^1$  subgroup of symplectomorphisms of  $W$  which on each cotangent bundle corresponds to the extension via differentials of the rotations of  $L_j$  about the axis through the intersection point  $q \in L_1 \cap L_2$ . Let  $q_1$  and  $q_2$  be the antipodal point of  $q$  in  $L_1$  and  $L_2$  respectively. If the almost-complex structure is invariant under these symplectomorphisms, then so are the rigid planes (as they appear only in dimension 0). Stokes' Theorem implies that holomorphic planes cannot intersect our Lagrangians in circles (since they are symplectic and the symplectic form on  $W$  is exact) and so the rigid planes must intersect the two Lagrangians in fixed points of the  $S^1$ -action. A plane disjoint from the Lagrangians is homotopic to a plane in  $[0, \infty) \times M$  where the asymptotic limit  $x_0$  is not contractible. Therefore each rigid plane does indeed intersect a Lagrangian and we can order our planes so that  $E_0 \cap L_j = \{q\}$ ,  $E_1 \cap L_1 = \{q_1\}$  and  $E_2 \cap L_2 = \{q_2\}$ . Choosing orientations for  $L_1$  and  $L_2$  gives the theorem as required.

Topologically the intersections of our finite energy planes with  $U$  can be visualized as follows. We note however that this is an idealized picture. In practice holomorphic curves can have quite complicated tangencies with pseudoconvex hypersurfaces. In the next section we will use the technique of filling by holomorphic disks to ensure that the pattern we describe here does indeed occur.

We look at a cross-section  $A$  of  $U$ . The interior of  $A$  has three special points corresponding to the intersection of  $A$  with the rigid planes. By taking  $R$  sufficiently large, the rigid planes can be assumed to intersect  $U \subset \{R\} \times M$  transversally. A finite energy plane intersecting  $\partial U$  hits  $\partial A$  in three points. Choosing a path from one of these points to one of the special points determines a 1-parameter family of finite energy planes intersecting the path. The intersections of these planes with  $A$  generate two more paths from our points in  $\partial A$  to the remaining special points. Conversely a path in our moduli space

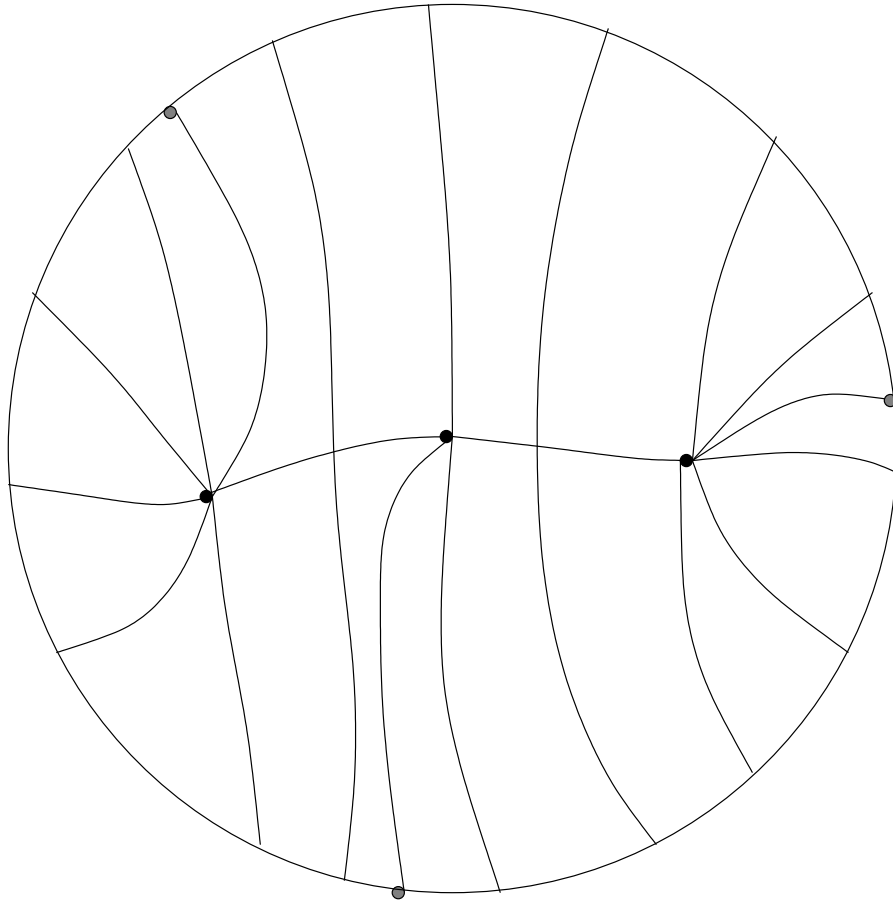


Figure 1: flowlines in the cross-section  $A$

starting from a plane intersecting  $\partial U$  and converging to the bubbled planes generates three paths in  $A$ . Starting with other planes intersecting  $\partial U$  we can generate a vector field on  $A$  with elliptic points corresponding to the rigid planes. The vector field will necessarily have hyperbolic points corresponding to tangencies of finite energy planes with  $U$ . Assuming that there are no more elliptic points (which could occur if a finite energy plane became tangent to  $U$  from the outside) there must be two hyperbolic points and the various integral curves are illustrated in Figure 1. The three marked points on the boundary are the intersections of a typical finite energy plane with  $\partial A$ . With our choice of subscripts the central special elliptic point in Figure 1 corresponds to  $E_0$ . Notice that the same picture is obtained in each cross-section  $A_\theta$  of  $U$  for  $\theta \in S^1$  and we can continuously choose coordinates in each  $A_\theta$  so that the elliptic points lie in the same position. But then the points on  $\partial A_\theta$  corresponding to a fixed finite energy plane will rotate through  $\frac{2\pi}{3}$  in these coordinates as  $\theta$  moves once around. The integral curves leaving our points on  $A_\theta$  can be chosen so that they correspond to the same family of finite energy planes for each  $\theta$ . These integral curves will encounter a hyperbolic point for two values of  $\theta$ , corresponding to a 1-parameter family in the moduli space becoming tangent to  $U$  twice before bubbling. Topologically this means that two curves in the plane must contract to the boundary and that the plane will bubble into three components.

### 5.1.2 Stretching the neck

In this subsection we consider which finite energy planes in the foliation will intersect  $L$  if we perform a stretching-the-neck operation to deform  $J$  along the boundary of a tubular neighborhood of  $L$ . The result is the following.

**Lemma 22** *There exist tame extensions  $J$  on  $W$  such that with such almost-complex structures the rigid planes  $E_0$  and  $E_1$  intersect  $L$  transversally in a single point each and  $E_2$  is disjoint from  $L$ . The nonrigid planes intersecting  $L$  contain an  $S^1$  family with the property that the planes in the family intersect  $U$  in two disjoint circles. The union of the first  $S^1$  family of circles form a torus*

enclosing  $E_0 \cap U$  and  $E_1 \cap U$ ; the union of the second  $S^1$  family of circles form a torus enclosing  $E_2 \cap U$ .

**Proof** The almost-complex structure is replaced by other almost-complex structures  $J_N$  as in section 4 where  $\Sigma$  is now the boundary of a tubular neighborhood  $Z$  of our Lagrangian  $L$ , which of course is diffeomorphic to  $\mathbb{R}P^3 = L(2, 1)$ . We fix a contact form on  $\Sigma$  as above, now quotienting  $S^3$  by the map  $\sigma : (z_1, z_2) \mapsto (-z_1, -z_2)$ . Denote by  $y_0$  and  $y_1$  the corresponding Reeb periodic orbits on  $\Sigma$ . Note that this form and the corresponding Reeb vector field are nondegenerate unlike the Morse-Bott type form on  $\partial U_i$  used in section 4.

The stretching-the-neck procedure in section 4 applies again here to produce a finite energy foliation of the completed tubular neighborhood of  $L$  which is now identified with  $T^*L = T^*S^2$ . Since  $y_1$  has large Conley-Zehnder index the finite energy curves must be asymptotic to  $y_0$ . The resulting foliation was first described in [13], (see Theorem 2.1, or alternatively, for a description entirely in terms of finite energy planes, rather than disks, Theorem 2.3 in [14]). There are two finite energy planes asymptotic to  $y_0$  and the remaining planes are asymptotic to  $2y_0$ . The planes asymptotic to  $y_0$  have intersection number  $\pm 1$  with  $L$ . They are rigid in the sense that the corresponding moduli space has dimension 0.

Taking limits of finite energy planes in the holomorphic foliations of  $(W, J_N)$  also results in a collection of finite energy curves lying in a completion of  $W \setminus Z$  and the symplectization of  $\Sigma$  equipped with suitable almost-complex structures. After taking subsequences and additional limits we also obtain finite energy foliations of  $W \setminus Z$ .

Suppose that an embedded finite energy curve  $u$  in  $W \setminus Z$  has one positive asymptotic limit  $mx_0$  and  $k$  negative asymptotic limits asymptotic to  $n_i y_0$ ,  $1 \leq i \leq k$ . The virtual dimension of the moduli space of finite energy curves containing  $u$  modulo reparameterization is given by

$$\text{index}(u) = -(2 - 1 - k) + \mu(mx_0) - \sum_{i=1}^k \mu(n_i y_0)$$

where the  $\mu$  are Conley-Zehnder indices with respect to a suitable trivialization giving  $c_1(TW) = 0$ . For  $m, n_i$  not too large  $\mu(mx_0) = m$  and  $\mu(n_i y_0) = \lfloor \frac{n_i}{2} \rfloor + n_i$  where  $\lfloor z \rfloor$  denotes the greatest integer less than or equal to  $z$ . Hence

$$\text{index}(u) = m - 1 - \sum_{i=1}^k (\lfloor \frac{n_i}{2} \rfloor + n_i - 1).$$

Our assumption is that  $L$  is homotopic to  $L_1$ . Thus the limits of the  $J_N$  holomorphic rigid planes  $E_0$  and  $E_1$  must contain rigid planes in  $T^*L$ . The components of the limits in  $W \setminus Z$  must have positive and negative asymptotic limits asymptotic to  $x_0$  and  $y_0$  respectively. It will turn out later that these curves coincide for  $E_0$  and  $E_1$ . Meanwhile, we next observe that the limiting curves corresponding to  $E_2$  have no component in  $T^*L$ . To see this, we note that for the component of the limit in  $W \setminus Z$  to have nonnegative index, since  $m = 1$  its negative asymptotic limit can cover  $y_0$  only once. Therefore any components in  $T^*L$  are rigid curves. But then the component of the limit of  $E_2$  must coincide with a component of the limit of  $E_0$  or  $E_1$ . In either case this implies that for  $N$  sufficiently large  $E_2$  will intersect non-rigid  $J_N$ -holomorphic planes which intersect  $L$  close to  $E_0$  or  $E_1$ , a contradiction. Therefore, crucially for us, the  $J_N$ -holomorphic rigid planes  $E_2$  are disjoint from  $L$  for  $N$  sufficiently large.

We now look at a limit of  $J_N$ -holomorphic finite energy planes passing through a point  $p \in L$  disjoint from the rigid planes. We claim that the limiting curve has a single component in  $T^*L$  asymptotic to  $2y_0$  and two components in  $W \setminus Z$ , one a double cover of the component of the limits of  $E_0$  or  $E_1$  and the other the limit of the rigid planes  $E_2$ .

To justify the claim, we note that one component of the limit in  $T^*L$  must be a plane asymptotic to  $2y_0$ . The sum of the positive asymptotic limits of the limiting components in  $W \setminus Z$  is  $3x_0$  and as in section 4, the negative asymptotic limits of components of a limiting curve in  $W \setminus Z$  cover  $y_0$  at least as many times as the positive asymptotic limits of the corresponding limit curve in  $T^*L$ . Suppose that a component of the limit in  $W \setminus Z$  with negative asymptotic limit  $2y_0$  is embedded and the almost-complex structure is generic so the curve has

nonnegative index. Then by the above formula the positive asymptotic limit must cover  $x_0$   $m = 3$  times and index = 0. Thus such curves are isolated. But taking a limit as our initial point  $p \in L$  approaches a rigid plane, such limits must approach the limits of the  $E_i$ , which is impossible. Therefore the limiting components in  $W \setminus Z$  with negative asymptotic limit  $2y_0$  are multiple covers of the limits of  $E_0$  and  $E_1$ , which must therefore coincide. (We recall that by positivity of intersections [22] a limit of embedded holomorphic curves is either embedded or a multiple cover.) There is another component of the limit in  $W \setminus Z$  with positive asymptotic limit  $x_0$ . Since such curves are again isolated we see that this must coincide with the limit of the  $E_2$  as required.

The claim implies that for  $N$  sufficiently large the nonrigid planes intersecting  $L$  will intersect  $U$  in two disjoint circles, one close to the intersection of  $U$  with  $E_0$  and  $E_1$  and homotopic to  $2x_0$ , the other close to the intersection with  $E_2$ . This establishes Lemma 22.

## 5.2 Plurisubharmonic exhaustion functions

In this section we produce a filling (or foliation) of  $V$  by holomorphic disks with boundary on the perturbation of  $B \cup U$  and use it to construct a plurisubharmonic exhaustion for  $V$ . The key property is that  $L$  will be disjoint from the unstable manifold of one of the two index 2 critical points.

**Theorem 23** *For any extension  $J$  as in Lemma 22, the almost-complex manifold  $(V, J)$  admits a plurisubharmonic exhaustion function with three critical points, one a minimum and the others of index 2. The Lagrangian  $L$  is disjoint from the unstable manifold of one of the index 2 critical points.*

It would be convenient simply to use the intersections of  $V$  with finite energy planes as our filling. Unfortunately it seems hard to control the tangencies of such planes with  $U$ . Therefore we singularly foliate  $U$  with surfaces, each of which in turn can be singularly foliated by the boundaries of holomorphic disks. Together with the finite energy planes intersecting  $B$  these will complete the filling.

**Proof** There exist  $S^1$  families of  $J_N$ -holomorphic finite energy planes which divide the finite energy planes in the moduli space intersecting  $L$  from those lying entirely in some  $[R, \infty) \times M$ . As  $N$  approaches infinity the planes in this family can each be chosen to converge to a union of curves having a component in  $T^*L$ . Thus the planes in the family will converge to the curve in  $W \setminus Z$  which is a double-cover of the limit of the  $J_N$ -holomorphic  $E_0$  and  $E_1$  and to the limit of  $E_2$ . Therefore, since the family is compact, for  $N$  sufficiently large the curves in the family will intersect  $U$  transversally in two families of circles, one homotopic to  $2x_0$  and the other to  $x_0$ . The first family will foliate a torus  $I$  enclosing  $(E_0 \cup E_1) \cap U$  and the second will foliate a torus enclosing  $E_2 \cap U$ .

We define vector fields on each  $A_\theta \subset U$  looking exactly as described in the previous section, but not necessarily corresponding to the intersections of the  $A_\theta$  with finite energy planes. The integral curves of our vector field converging to the intersection of a particular curve  $C$  with  $\partial U$  will form a surface diffeomorphic to a sphere with four disks removed. The four boundary components are the intersections of  $U$  with  $C$ ,  $E_0$ ,  $E_1$  and  $E_2$ . Now, it is easy to adjust our vector field such that each of these surfaces intersect the torus  $I$  in the boundary of one of the finite energy planes in our  $S^1$  family.

Next we use the theory of filling by holomorphic disks, see [5], [1], [7], [12] (Theorem 1 in [12] unifies a lot of the previous work) to singularly foliate each of the surfaces above by boundaries of holomorphic disks in  $V$ . The foliation extends the boundaries of  $C$  and the  $E_i$  and is unique, therefore it includes the intersection of the surface with  $I$ . The filling looks approximately as in Figure 2. In particular since it includes the disk through  $I$  the arrangement of the singular (hyperbolic) points  $p$  and  $q$  is as shown.

We construct a plurisubharmonic function by following [7], see also [13], [14]. We start by defining a function  $g$  which is constant on the holomorphic disks in our filling. We now fix  $J = J_N$  for  $N$  suitably large. Recall that  $\gamma$  is the circle of complex tangencies in  $B \subset \partial V$  and let  $T_1, T_2$  be tori in  $U$  formed by the boundaries of holomorphic disks passing through the hyperbolic points  $p$  and let  $S_1, S_2$  be tori in  $U$  formed by the boundaries of holomorphic disks passing

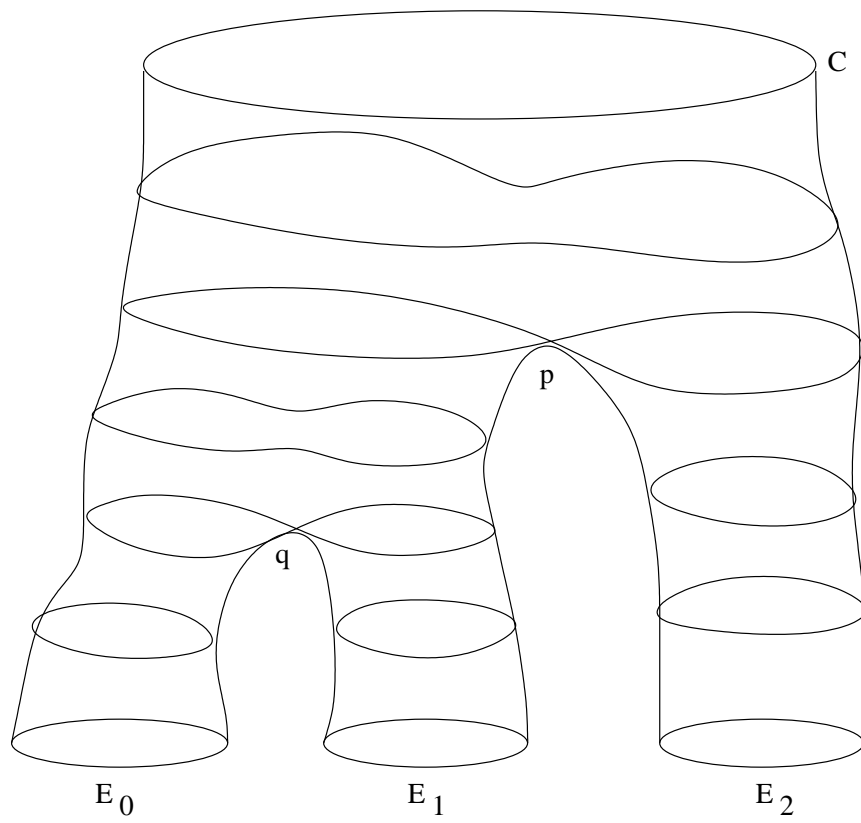


Figure 2: holomorphic disks filling a surface

through the points  $q$ . We label things so that the inside of  $T_1$  in  $U$  encloses  $S_1$  and  $S_2$ . We define  $g$  to be a Morse function on  $\gamma$  with a single minimum at 0 and a single maximum at 1. As in [13] we define  $g$  to be constant on families of holomorphic disks converging to points on  $\gamma$ . These families of disks can be chosen to be parameterized either by an interval with the disks converging to the points  $g^{-1}(t) \in \gamma$  for  $t \leq \frac{1}{4}$  or  $t \geq \frac{3}{4}$  or alternatively by an interval with one end converging to a point  $g^{-1}(t) \in \gamma$  for  $\frac{1}{4} < t < \frac{3}{4}$  and the other to a cusp-disk with boundary on  $T_1 \cup T_2$ . This defines  $g$  on the disks passing through the complement of the insides of  $T_1$  and  $T_2$ .

Inside  $T_2$  we simply define  $g$  to be constant on 1-parameter families of disks connecting the disks on which  $g = t$ . Inside  $T_1$  we again define  $g$  to be constant on families of disks connecting the disks on which  $g = t$  and  $\frac{1}{4} < t < \frac{3}{8}$  or  $\frac{5}{8} < t < \frac{3}{4}$ . We also let  $g = t$  on intervals of disks connecting disks with  $g = t \in [\frac{3}{8}, \frac{5}{8}]$  on one side and cusp-disks with boundary on  $S_1 \cup S_2$  on the other. Inside  $S_1$  and  $S_2$  we extend  $g$  to be constant on the 1-parameter families of disks connecting the disks on which  $g = t$  as before. Altogether this defines a function  $g$  whose level-sets are foliated by holomorphic disks.

Now, as in [7], see also [13], [14], the level-sets of  $g$  are Levi flat (foliated by holomorphic curves) but we can perturb  $g$  such that they become pseudoconvex. One way to do this is to choose a function  $\psi$  on  $W$  which satisfies  $dd^c\psi(X, JX) \gg |d\psi|$  for any unit vector  $X$  tangent to the foliation (with respect to any fixed metric). Then we can replace  $g$  by  $g + \psi$ . Recall that the level-sets of a function  $f$  are pseudoconvex if  $-dd^c f$  is positive on the complex tangencies  $d^c f = 0$ . (Before the perturbation  $-dd^c g$  vanishes on this subspace.) We then have that  $dd^c(g + \psi)$  is positive on the complex tangencies of the level-sets of  $g$ , but the tangencies to the level-sets of  $g + \psi$  differ only by order  $|d\psi|$  and so the same is true for these subspaces. Next, composing  $g$  with a sufficiently convex function  $\phi$  on  $\mathbb{R}$  with  $\phi'' \gg \phi' > 0$  it then becomes strictly plurisubharmonic. (To see this, we compute  $-dd^c(\phi \circ g) = -d(\phi' d^c g) = -\phi' dd^c g + \phi'' d^c g \wedge dg$  and observe that the first term is positive on complex tangencies to the level sets of  $g$  while the second term vanishes, but on sufficiently transverse com-

plex planes the second term is positive and overwhelms the first.) Next set  $f = \max(g, h)$  where  $h$  is a function increasing rapidly towards  $\partial V$ . The function  $f$  can be smoothed to give a plurisubharmonic exhaustion. Investigating the pattern of holomorphic disks as in [13], section 3, we see that it has three critical points. There is an index 0 critical point near the minimum of  $g$  on  $\gamma$  and there are index 2 critical points near the maxima of  $g$  on  $S_1 \cap S_2$  and  $T_1 \cap T_2$ . We call these points  $a$  and  $b$  respectively. The construction ensures that  $f(b) > f(a)$ . Furthermore  $f < f(b)$  on all disks lying inside the hypersurface formed by the holomorphic disks intersecting  $I$ . Therefore  $L$  is disjoint from the unstable manifold of  $b$  as required, as it lies inside this hypersurface.

We close this section by remarking that since  $f$  provides a plurisubharmonic exhaustion of  $W$  (or more precisely an almost-complex manifold  $V$  Stein homotopic to  $W$ ), we can adjust  $f$  near its minimum such that the stable manifolds of the two critical points are embedded spheres intersecting transversally at the minimum.

### 5.3 Symplectomorphisms

The plurisubharmonic function  $f$  from the previous section gives a symplectic form  $\omega = -dd^c f$  on  $W$  where  $d^c f = df \circ J$ . This in turn gives us a vector field  $v = \text{grad} f$  defined by  $v \lrcorner \omega = d^c f$ . By a suitable choice of  $f = h$  near  $\partial V$  we may assume that  $v$  is complete in the sense that its positive integral flow exists for all time.

The stable manifolds of the two critical points are Lagrangian spheres with respect to the form  $\omega$ . By Weinstein's Lagrangian neighborhood theorem applied to a pair of transversally intersecting Lagrangians, a neighborhood of these two stable manifolds is symplectomorphic to a neighborhood of  $L_1 \cup L_2 \subset (W, \omega_0)$ . We then use [9] to imply the following.

**Lemma 24**  *$(W, \omega)$  and  $(W, \omega_0)$  are symplectomorphic via a symplectomorphism  $\psi$  taking the stable manifolds of the critical points  $a$  and  $b$  of  $f$  onto  $L_1$  and  $L_2$  respectively.*

After perhaps adjusting  $f$  the following is also true. As above  $L$  denotes the Lagrangian sphere homotopic to  $L_1$ .

**Lemma 25** *There exists a symplectomorphism  $\phi$  from  $(W, \omega_0)$  to  $(W, \omega)$  taking  $L$  onto a Lagrangian sphere disjoint from the unstable manifold of the critical point  $b$  of  $f$ .*

Lemmas 24 and 25 together imply our Theorem 4. For, the one-parameter group of diffeomorphisms generated by  $-v = -\text{grad}f$  give an isotopy (which is necessarily Hamiltonian) of  $\phi(L)$  to a Lagrangian sphere in a tubular neighborhood of the stable manifold of the critical point  $a$ . Since this tubular neighborhood can be taken to be symplectomorphic to a unit cotangent bundle of  $S^2$ , Theorem 1 implies that a further Hamiltonian diffeomorphism maps the image of  $\phi(L)$  onto the stable manifold of  $a$  itself. We denote the Hamiltonian diffeomorphism mapping  $\phi(L)$  onto the stable manifold of  $a$  by  $\chi$ . Then  $\psi \circ \chi \circ \phi$  is the symplectomorphism required by Theorem 4.

**Proof of Lemma 25**

By choosing  $f = h$  carefully near  $\partial V$ , now identified with the noncompact end of  $W$ , we may assume that  $\omega = \omega_0$  outside of a compact subset of  $W$ . In fact, both forms are exact and we can write  $\omega - \omega_0 = d\alpha$  where the 1-form  $\alpha$  is identically zero outside of a compact set. Furthermore, since  $\omega$  and  $\omega_0$  tame the same almost-complex structure,  $\omega_t = (1-t)\omega_0 + t\omega$  is a symplectic form on  $W$  for all  $t$ .

Using Moser's method, we observe that the compactly supported time-dependent vector field  $X_t$  defined by  $X_t \lrcorner \omega_t = \alpha$  satisfies  $\mathcal{L}_{X_t} \omega_t = \frac{d}{dt} \omega_t$  and so its flow generates a symplectomorphism from  $(W, \omega_0)$  to  $(W, \omega)$ .

We are interested in the image of  $L$  under such a symplectomorphism, we recall that  $L$  is initially disjoint from the unstable manifold of  $b$  and we want to ensure that this remains the case under the flow of  $X_t$ . We will adjust  $f$  so that this will be the case.

Assume that a fixed tubular neighborhood  $Z$  of  $L$  is disjoint from the unstable manifold of  $b$ . Given the construction in Theorem 23 we may assume that

$f \geq 0$  and  $Z \subset f^{-1}([0, r])$  for some  $r < f(b)$ .

The composition of  $f$  with an increasing function  $s : [0, \infty) \rightarrow [0, \infty)$  remains plurisubharmonic provided that  $\frac{s''}{s'} \gg 1$ . We choose  $s$  (and its derivatives) to be very small on  $[0, r]$  but then to increase rapidly on  $(r, \infty)$ . Thus we can replace  $f$  by another nonnegative plurisubharmonic exhaustion, still denoted by  $f$ , and having the property that  $f|_Z < 1$ . Further we arrange that  $\omega(X, JX) \ll \omega_0(X, JX)$  on  $f^{-1}([0, 1])$  for all tangent vectors  $X$ , while  $\omega(X, JX) \gg \omega_0(X, JX)$  on  $f^{-1}([2, 3])$  for all  $X$  and now  $f(b) > 3$ . We observe that for reasonable choices of functions  $s$  the Moser flow will still exist for all time. Alternatively we can adjust  $\omega_0$  near  $\partial V$  also such that the flow still has compact support.

On the tubular neighborhood  $Z$  we have that  $\omega$  and  $d^c f$  are now uniformly small. Thus the length of  $X_t$  (relative to the Riemannian metric defined by  $\omega_0$  and  $J$ ) remains bounded on this neighborhood for  $t < \frac{1}{2}$  say. Therefore there exists a uniform  $\epsilon$  (depending only upon  $\omega_0$ ,  $J$  and  $Z$ ) such that the flow of  $L$  remains in  $Z$  for  $t < \epsilon$ . But for  $t > \epsilon$  we can suppose that on  $f^{-1}([2, 3])$  the vector field  $X_t$  is closely approximated by  $-\frac{1}{t} \text{grad} f$ . Hence the flow of  $L$  remains in  $f^{-1}([0, 3])$  for all  $0 \leq t \leq 1$  and so the symplectomorphism generated by  $X_t$  can indeed be arranged to leave  $L$  disjoint from the unstable manifold of  $b$  as required.

## 6 Lagrangian isotopies and Dehn twists

In this section we use the analysis of section 5 to deduce Theorem 5.

First of all, by Weinstein's Theorem a Lagrangian 2-sphere has self-intersection  $-2$ , thus Lagrangian spheres in  $W$  are homologous to either  $L_1$ ,  $L_2$  or  $L_1 \sharp L_2$ . Up to Hamiltonian isotopy  $L_1 \sharp L_2 = \tau_{L_2}(L_1)$  and so it suffices to prove the result assuming that  $L$  is homologous to  $L_1$ .

Using the notation from the previous section, we recall that Theorem 20 constructed a finite energy foliation of  $(W, J)$  with respect to any tame almost-complex structure  $J$  which is standard outside of a compact set. In fact the

finite energy foliation is described quite explicitly, in particular in terms of the intersection of the finite energy planes with a level  $\{R\} \times M$ , for  $R$  large. The rigid planes  $E_i$  intersect  $\{R\} \times M$  transversally in a certain tubular neighborhood  $U$  of the Reeb orbit  $x_0$ . The boundary of  $U$  is foliated by circles in an  $S^1$ -family of finite energy planes and this family divides  $W$  into two pieces. We assume that the piece foliated by planes disjoint from  $U$  is disjoint from all of the Lagrangian spheres, and when we vary  $J$  it will always be fixed in this region.

In section 5.2, the finite energy foliation with respect to particular choices of  $J$  was used as the starting point to construct a plurisubharmonic exhaustion function  $f$  of a Stein domain  $V \subset W$  with  $\partial V = B \cup U$ . The plurisubharmonic function has three critical points, one of index 0 and two of index 2. With respect to the Kähler structure associated to the plurisubharmonic function the two stable manifolds form Lagrangian spheres intersecting in a single point.

Such a plurisubharmonic exhaustion function can in fact be constructed for any of the almost-complex structures we consider, in a manner continuous over 1-parameter families, if we neglect the requirement of unstable submanifolds avoiding a Lagrangian. The rigid planes  $E_i$  and the finite energy foliation are determined by a given almost-complex structure  $J$ . However there are still ambiguities in the construction of the plurisubharmonic function in Theorem 23. First we must choose families of surfaces in  $U$  diffeomorphic to a sphere with three disks removed. One boundary of such a surface should coincide with the intersection of a finite energy plane with the boundary of  $U$  and the other three boundaries with the intersections of the  $E_i$  with  $U$ . It can be seen that  $U$  can be singularly foliated by such surfaces, the foliation being smooth away from the  $E_i$ . Now, the surfaces themselves can be chosen in an essentially canonical way (so that they intersect cross-sections as in Figure 1) given the position of the  $E_i \cap U$  and a choice of embedded curve in a cross-section  $A$  traveling from  $E_1$  to  $E_2$  through  $E_0$ . To do this, we simply map the cross-section to the model picture in Figure 1, mapping rigid planes to the special points in the figure and the curve to the corresponding curve in the figure, and pull-back the foliation there. This is well-defined up to a homotopy fixing the rigid planes and the path (but

not necessarily the boundary). It is a consequence of the existence of different homotopy classes of such paths that there exist different Hamiltonian isotopy classes of Lagrangian spheres. Anyway, after the foliating surfaces are chosen we can construct a plurisubharmonic function with the required properties as follows, and do this canonically modulo a contractible set of choices.

This is done in a similar manner to Theorem 23. We first fill each of the surfaces by holomorphic disks, however for a general choice of almost-complex structure  $J$  we no longer have a torus  $I$  dividing the families of filling disks. Therefore the pattern of holomorphic disks in the filling is no longer necessarily that of Figure 2, that is, starting with a boundary in  $\partial U$ , the family may reach the hyperbolic complex tangency  $q$  before reaching  $p$ . Nevertheless we can construct a plurisubharmonic exhaustion in a canonical way by perturbing a function  $g$  constant on the holomorphic disks filling  $V$ . We define  $g$  as before on disks with boundary on  $B$ . To extend  $g$  to  $U$  we proceed as follows. Parameterize the boundaries of holomorphic disks on  $\partial U$  by  $\psi \in S^1$  and thus the foliating surfaces starting from these boundaries. On each of the surfaces we can find a smooth function  $h_\psi$  which is constant on the boundaries of holomorphic disks, is equal to 1 on  $\partial U$ , and is equal to 0 on  $\partial E_i$ ,  $i = 0, 1, 2$ . The  $h_\psi$  can be chosen to vary continuously with  $\psi$  and such that  $h_\psi$  has critical points only at the hyperbolic points of the surfaces. Then we can define a map  $P : U \rightarrow D^2 = \{x^2 + y^2 \leq 1\}$  by assigning to a point in  $U$  the point in  $D^2$  with polar coordinates  $(h_\psi, \psi)$ . By adjusting the parameterization we may assume that  $g|_{\partial U} = P^*L$  where  $L = \frac{y+2}{4}$  and thus extend  $g$  to  $U$  by the same formula. After taking the maximum  $f$  of  $g$  and a function  $h$  increasing rapidly towards  $\partial V$  and smoothing appropriately, exactly as in Theorem 23, we see that as before  $f$  will have only three critical points, a minimum on the circle of complex tangencies in  $B$  and two index 2 critical points close to the hyperbolic points on the surface extending the maximum circle of  $g$  on  $\partial U$ .

We will identify our symplectic structure  $\omega_0$  on  $W$  with the Kähler structure coming from a  $J_0$ -plurisubharmonic function, where  $J_0$  is a fixed almost-complex structure. Then the stable manifolds of the index 2 critical points correspond

to  $L_1$  and  $L_2$ . Suppose that  $J$  is another almost-complex structure tamed by  $\omega_0$ . Let  $\omega_1$  be the symplectic form corresponding to a  $J$ -plurisubharmonic function. Then there are two natural symplectomorphisms from  $(W, \omega_1)$  to  $(W, \omega_0)$ . Since both  $\omega_0$  and  $\omega_1$  tame the same almost-complex structure, convex linear combinations of the two forms are also symplectic and so by Moser's theorem we can generate a symplectomorphism between them. On the other hand, given a plurisubharmonic exhaustion its gradient flow is conformally symplectic with respect to the corresponding symplectic form. Therefore we get another symplectomorphism by first identifying neighborhoods of the stable manifolds using Weinstein's Theorem and extending this to a global symplectomorphism using the gradient flows (see [9] for these ideas). Composing this symplectomorphism with the inverse of the Moser diffeomorphism gives a symplectomorphism of  $(W, \omega_0)$  determined by a tame almost-complex structure  $J$ . If  $J = J_0$  and the surfaces in  $U$  are chosen in the same way then we may assume that this map is the identity.

Now let  $L$  be a Lagrangian sphere in  $W$  homologous to  $L_1$ . It was shown in section 5 that there exists an almost-complex structure  $J$  satisfying the requirements above such that the corresponding unstable manifold of one of the index 2 critical points is disjoint from  $L$ . Furthermore, under the Moser map  $(W, \omega_0) \rightarrow (W, \omega_1)$  the Lagrangian  $L$  can be arranged to stay disjoint from this unstable manifold. Therefore by Theorem 1, composing with a Hamiltonian diffeomorphism we may assume that the Moser map takes  $L$  to one of the stable manifolds. Thus the symplectomorphism of  $(W, \omega_0)$  described above maps  $L$  onto  $L_1$ .

Now suppose that we choose a family of almost-complex structures  $J_t$ ,  $0 \leq t \leq 1$  with  $J_1 = J$ . Choosing a smooth family of foliations of  $U$  and corresponding plurisubharmonic exhaustion functions we get a family  $\phi_t$  of symplectomorphisms of  $(W, \omega_0)$  with  $\phi_1(L) = L_1$ . If this could be done in such a way that the foliation corresponding to  $J_0$  is the standard one then  $\phi_0$  would be the identity and one would in fact construct a Hamiltonian isotopy from  $L$  to  $L_1$  (any smooth isotopy of Lagrangian spheres can be realized by a global Hamiltonian

flow).

As explained above, a family of surfaces foliating  $U$  can be essentially determined by the rigid planes  $E_i$  and an embedded path in a cross-section  $A$  from  $E_1$  to  $E_2$  through  $E_0$ . We are prevented from choosing a family of foliations which matches the required ones for  $t = 0$  and  $t = 1$  if the relative positions of the  $E_i \cap U$  rotate for  $0 \leq t \leq 1$ . This is the only obstruction.

Suppose now that we carry out this procedure starting with  $\tau(L)$  rather than  $L$ , where  $\tau$  is a composition of Dehn twists. Actually we can assume that  $\tau$  is a composition of even powers of Dehn twists, so it is isotopic to the identity. In this case we can choose  $J_1 = \tau(J)$  and connect this to  $\tau(J_0)$  through the family  $\tau(J_t)$  since  $\tau$  will be a compactly supported symplectomorphism. We observe that the intersection of  $\tau(J_t)$  finite energy planes with  $U$  are exactly the same as the intersections of the  $J_t$  finite energy planes. Therefore to understand the new family of intersections  $E_i \cap U$  it suffices to understand the intersections  $E_i \cap U$  for a family of tame almost-complex structures connecting  $\tau(J_0)$  and  $J_0$ .

First consider  $T^*S^2$  with its standard symplectic form. This again can be thought of as a Stein manifold with open end symplectomorphic to  $[0, \infty) \times N$  where  $N = \mathbb{R}P^3$  with its standard contact form. The Reeb flow here can be identified with the geodesic flow on  $S^2$ . We fix a tame almost-complex structure  $J$  invariant under the natural action of  $\text{Isom}(S^2)$ . Then as described in [13], and used in [14] and [16],  $T^*S^2$  admits a finite energy foliation with all planes asymptotic to multiples of a Reeb orbit  $y_0$  corresponding to, say, the equator on  $S^2$ . The foliation now contains two rigid planes  $E_i$  asymptotic to the single orbit  $y_0$  and all other finite energy planes in the foliation are asymptotic to  $2y_0$ . The rigid planes will project to opposite hemispheres on the  $S^2$ . Now rotation about the axis perpendicular to the equator preserves  $y_0$  and  $J$  and so also the rigid finite energy planes. It follows that each intersects the zero-section at either the north or south pole and intersects the tubes of radius  $r$ , denoted  $T^r S^2$ , in circles projecting to parallels on  $S^2$ . The square  $\tau^2$  of the symplectic Dehn twist about the zero-section can be thought of as the Hamiltonian flow of  $H = \frac{1}{2}|p|^2$  if the cotangent vector has length  $|p| \leq 2\pi$  and the identity

if  $|p| \geq 2\pi$ . (In other words, the tubes are preserved and for  $r < 2\pi$  the diffeomorphism of  $T^r S^2$  is the time- $r$  geodesic flow.) This map  $\tau^2$  is isotopic to the identity through (non-compactly supported) symplectomorphisms  $\tau_t^2$  where  $\tau_t^2$  is equal to the Hamiltonian flow of  $H(tp)$  for  $|p| \leq \frac{2\pi}{t}$  and the identity for  $|p| \geq \frac{2\pi}{t}$ . We observe that  $\tau_t^2(J)$  for  $0 < t \leq 1$  give a family of tame almost-complex structures converging to  $J$  as  $t \rightarrow 0$ . In fact, for  $R$  sufficiently large,  $\tau_t^2(J)|_{T^{\geq R} S^2}$  is approximately equal to  $J$  for all  $t$  since  $\tau_t^2$  acts as the geodesic flow on a fixed level (which we can assume to preserve the relevant CR structure) and is approximately translation invariant for  $R$  large. Therefore after a small adjustment we will think of  $\tau_t^2(J)$  as a compactly supported variation of  $J$ . In a level  $T^R S^2$  let us choose coordinates  $(x, y)$  in a cross-section  $A$  transverse to our Reeb orbit at  $(0, 0)$  such that our rigid  $J$ -holomorphic planes intersect in points  $(\pm\epsilon, 0)$ . Then we observe that for  $0 < t \leq 1$  the positions of  $\tau_t^2(E_i) \cap A$  perform one complete rotation. Since the space of almost-complex structures is contractible, any family connecting  $\tau^2(J)$  and  $J$  will have the same effect on the intersections.

Returning to our original situation, a family of almost-complex structures  $J_t$  on  $W$  connecting  $\tau_{L_1}^2(J_0)$  and  $J_0$  can be chosen to be fixed away from a neighborhood of  $L_1$ , in particular near the rigid curve  $E_2$ . So in following this path the position of  $E_2$  remains unchanged and we claim that  $E_0$  and  $E_1$  rotate their position once.

To justify the claim, we again follow the methods of section 5. We stretch the neck a length  $N \rightarrow \infty$  along the boundary of a tubular neighborhood  $V$  of  $L_1$ , symplectomorphic to a tubular neighborhood  $T^{\leq r} S^2$  of the zero-section in  $T^* S^2$ . We suppose the the  $J_t = J_0$  outside of  $V$  for all  $t$ . In the limit as  $N \rightarrow \infty$  we have complex structures  $J_{t,\infty}$  on  $T^* S^2$  and our  $J_t$ -holomorphic finite energy foliations of  $W$  converge to  $J_{t,\infty}$ -holomorphic finite energy foliations of  $T^* S^2$ . These foliations may be taken to be exactly those described in the model case, in particular the limits of the rigid planes rotate positions once for  $0 \leq t \leq 1$ . We recall also that the limits of the rigid planes  $E_0$  and  $E_1$  in the completion of  $W \setminus V$  converge to the same finite energy cylinder. We look at the intersections of our

$E_i$  with a 1-parameter family of surfaces intersecting this cylinder transversally. The surfaces can be chosen to be tangent to a cross-section  $A$  in  $U$  at one end and tangent to a tube  $T^r S^2$  at the other. Then for  $N$  sufficiently large our finite energy planes  $E_i$  will intersect these surfaces transversally and so their relative rotation will be the same in each. But by uniform convergence the rotation of the  $E_i$  in a  $T^r S^2$  will be the same as that of the limits with respect to the  $J_{t,\infty}$ , in other words they rotate once. Our claim follows.

In conclusion, for a suitable choice of  $\tau$ , a family of almost-complex structures connecting  $\tau(J_0)$  and  $J_0$  can produce any relative movement of the  $E_i \cap U$  up to homotopy. So given a  $J_1$ , we can find a  $\tau$  such that a family of almost-complex structures  $J_t$  connecting  $\tau(J_1)$  and  $J_0$  produces no relative movement of the  $E_i \cap U$ . This allows us to find a smooth family of foliations of  $U$  which is standard at  $t = 0$  but corresponds to a plurisubharmonic function having an unstable manifold disjoint from  $L$  at  $t = 1$ . Then  $\tau(L)$  will be Hamiltonian isotopic to  $L_1$  as required.

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