

# HILBERT FLAG VARIETIES AND THEIR KÄHLER STRUCTURE

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ABSTRACT. In this paper we introduce the infinite-dimensional flag varieties associated with integrable systems of the *KdV*- and *Toda*-type and we discuss the structure of these manifolds. As an example we treat the Fubini-Study metric on the projective space associated with a separable complex Hilbert space and we conclude by showing that all flag varieties introduced before possess a Kähler structure .

## 1. INTRODUCTION

Apart from the fact that flag varieties play a central role in the representation theory of Lie groups, they are also prominent geometric objects in various parts of mathematical physics. In the finite dimensional case e.g. a double fibration of flag varieties is the central object in the Penrose transform and its generalizations, see [BE89].

For soliton equations of KdV-type, infinite dimensional Grassmannians form the geometric structure, see e.g. [SS83] and [SW85], that yield solutions of these equations and the towers of equations, so-called hierarchies, linked to them. Associated to these planes are so-called  $\tau$ -functions in which the solutions of the soliton hierarchies can be expressed. These functions can be given a geometric description in terms of the determinant bundle over this variety. In the same context finite chains of subspaces in the Grassmann manifold correspond to so-called modified equations of these hierarchies and to Darboux transformations, see resp. [HH94] and [HvdL01a]. Infinite chains of subspaces occur naturally at Toda-type hierarchies, as one can read off from e.g. [AHvM93] and [FH91].

These varieties also turn up in quantum field theory. We mention a few instances. E.g. in quantum field theory in two space-time dimensions, the possible boundary conditions for the Dirac operator give you a point in a Grassmannian, see [Wit88]. By using the structure of the determinant bundle over this variety, Witten arrived at so-called multiplicative Ward identities. In [KNTY88], the relevant moduli space for conformal field theories over Riemann surfaces were embedded in a Grassmannian, which enabled an explicit calculation of a priori provided quantities, like the current and energy-momentum tensor, in terms of the moduli. Moreover, it led to a characterization of the image by a system of differential equations for the corresponding  $\tau$ -functions. From a Grassmannian description of the theory Fukuma, Kawai and Nakayama deduced in [FKN92] the  $W_{1+\infty}$ -symmetry of 2-dimensional quantum gravity and obtained the reduction of the tower of constraints to the lowest level. Also the conjectures of Witten that link the partition function of 2-dimensional quantum gravity to  $\tau$ -functions of integrable hierarchies support the central character of this geometric structure.

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The foregoing examples underline the importance of a good knowledge of the structure of infinite flag varieties. Here we present an analytic category of flags that contains the Grassmann manifolds of all subspaces of a fixed finite dimension and that is at the same time a natural extension of the Grassmannians from [SW85]. We describe their manifold structure and show that they all possess a Kähler structure. This last fact can be used at the Hamiltonian description of the integrable systems alluded to above.

The precise content of the various sections is as follows: the second section describes the type of flags that we will consider and gives two infinite dimensional Lie groups that act transitively on the space  $\mathfrak{F}$  of these flags. In the third section we present useful decompositions of a number of open subsets in these Lie groups and the manifold structure of  $\mathfrak{F}$ . The connected components of the variety  $\mathfrak{F}$  are described in the fourth section. Next we treat as an example the Fubini-Study metric on projective Hilbert space. The final section is devoted to the description of the Kähler structure on  $\mathfrak{F}$ .

## 2. THE FLAG VARIETY

First we will discuss the form of the flag varieties that will be considered. We start out with a separable complex Hilbert space  $H$  equipped with an inner product  $\langle \cdot, \cdot \rangle$  and a decomposition

$$(1) \quad H = \bigoplus_{-N-1 < i < M+1} H_i, \quad \text{where } H_i \perp H_j \text{ for } i \neq j \text{ and } H_i \text{ is closed.}$$

Here, as in the rest of this paper, the direct sum of a number of Hilbert spaces is meant to be the Hilbert direct sum, as soon as it is infinite. This will be assumed from now on without further mentioning. We have no restriction on the dimension of the spaces  $H_i$ , in other words  $m_i = \dim(H_i)$  satisfies  $1 \leq m_i \leq \infty$ . For convenience, we write  $I = \{j \mid -N-1 < j < M+1\}$  for the collection of indices of the decomposition (1). W.r.t. the decomposition (1) we consider for each  $i, i \in I$ , the subspace

$$(2) \quad H(i) = \bigoplus_{-N-1 < j \leq i} H_j$$

and this gives rise to the so-called *basic flag*  $F^{(0)}$ , which will be the leading example of a flag and which consists of the chain of subspaces

$$H(-N-1) = 0 \dots \subset H(i-1) \subset H(i) \subset \dots \subset H = H(M).$$

More generally, we consider inside  $H$  flags  $F = \{F(i) \mid i \in I\}$ , that is to say chains of closed subspaces of  $H$ ,

$$\{0\} = F(-N-1) \dots \subset F(i) \subset F(i+1) \dots \subset F(M) = H.$$

To any such a flag  $F$  is associated an orthogonal decomposition of  $H$ ,

$$H = \bigoplus_{i \in I} F_i, \quad \text{where } F_i = F(i) \cap F(i-1)^\perp.$$

We will denote the flag  $F$  both by  $F = \{F(i) \mid i \in I\}$  as well as  $F = \{F_i \mid i \in I\}$ . The choice of the Hilbert space and the relevant decomposition depends of the process one wants to describe as the following examples show

*Example 2.1.* In quantum field theory the states of the system are vectors in a Fock space. In the fermionic case, this space is built up from the splitting of a basic Hilbert space into positive and negative energy states. E.g., at the Dirac theory for a one dimensional particle of mass  $m \geq 0$ , one considers, see [CR87], the Dirac Hamiltonian

$$D = \begin{pmatrix} -i & 0 \\ 0 & -i \end{pmatrix} \frac{d}{dx} + \begin{pmatrix} 0 & m \\ m & 0 \end{pmatrix}.$$

It acts on the Hilbert space  $H = L^2(\mathbb{R})^2$  and the relevant decomposition of  $H$  for the Fock space representation is  $H = H_+ \oplus H_-$ , where  $H_+$  is the subspace of  $H$  corresponding to the positive spectrum of  $D$  and  $H_-$  the one corresponding to the negative spectrum of  $D$ . In general, see [Mick], Dirac operators are associated to a number of geometric data, like a spin bundle over an oriented Riemannian manifold, another vector bundle over this manifold and a connection. A similar splitting of the square-integrable extended Dirac spinors is the starting point for the construction of a representation of an extension of the group of gauge transformations, see [Mick].

*Example 2.2.* In the case of the KP-theory and its many subsystems, the relevant space  $H$  is the Hilbert space

$$L^2(S^1, \mathbb{C}) = \left\{ \sum_{n \in \mathbb{Z}} a_n z^n, a_n \in \mathbb{C}, \sum_{n \in \mathbb{Z}} |a_n|^2 < \infty \right\}$$

with the inner product

$$\left\langle \sum_{n \in \mathbb{Z}} a_n z^n \mid \sum_{n \in \mathbb{Z}} b_n z^n \right\rangle = \sum_{n \in \mathbb{Z}} a_n \bar{b}_n.$$

Decompositions that play a role in this context can be described as follows: consider a finite  $M$  and  $N$  and let  $\underline{s} = (s_{-N}, \dots, s_{M-1})$ , where  $s_i \in \mathbb{Z}$  and  $s_{i+1} < s_i$ . Then we take the basic flag defined by

$$H(i) = \left\{ \sum_{n \geq s_i} a_n z^n \in H \right\}, \quad -N \leq i \leq M-1,$$

which is complemented with  $H(-N-1) = \{0\}$  and  $H(M) = H$ . For matrix versions of the KP-hierarchy, one uses the Hilbert space  $L^2(S^1, \mathbb{C}^n)$  with similar decompositions.

The class of flags under consideration here, have, first of all, the same length as the basic flag  $F^{(0)}$ . Secondly, the components of the flag have the same “size” as the corresponding components of  $F^{(0)}$ , i.e. for all  $i, i \in I$ ,

$$\dim(F_i) = \dim(H_i)$$

and finally we require our flags not to differ too much from the basic flag. This last property is specified in the definition below. Before that we introduce some notations. Let  $p_i, i \in I$ , be the orthogonal projection of  $H$  onto  $H_i$ . The decomposition (1) induces also one for linear operators on  $H$

*Notation 2.3.* If  $g$  belongs to  $\mathcal{B}(H)$ , the space of bounded linear operators from  $H$  to  $H$ , then  $g = (g_{ij}), i \in I$  and  $j \in I$ , denotes the decomposition of  $g$  w.r.t. the  $\{H_i \mid i \in I\}$ . That is to say  $g_{ij} = p_i \circ g \mid H_j$ . If  $g \in \mathcal{B}(H)$  and  $i_0, i_0 \in I$ , then we write suggestively  $g_{\geq i_0}$  for

$\sum_{i \geq i_0} p_i g | \oplus_{i \geq i_0} H_i$  in  $\mathcal{B}(\oplus_{i \geq i_0} H_i)$  and  $g_{\leq i_0}$  for  $\sum_{i \leq i_0} p_i g | \oplus_{i \leq i_0} H_i$  in  $\mathcal{B}(\oplus_{i \leq i_0} H_i)$ . Finally, if we have operators  $u_i \in \mathcal{B}(H_i)$ ,  $i \in I$ , then we write

$$\text{diag}(u_i) := \begin{pmatrix} \ddots & \ddots & \ddots & \ddots & \ddots \\ \ddots & u_{i+2} & 0 & 0 & \ddots \\ \ddots & 0 & u_{i+1} & 0 & \ddots \\ \ddots & 0 & 0 & u_i & \ddots \\ \ddots & \ddots & \ddots & \ddots & \ddots \end{pmatrix}.$$

**Definition 2.4.** Let  $\mathfrak{F}$  be the collection of flags  $F = \{F_i | i \in I\}$ , satisfying three properties. First of all, the equality  $\dim(F_i) = \dim(H_i)$  should hold for all  $i \in I$ . Next the operator  $\sum_i \sum_{j \neq i} p_j | F_i : H \rightarrow H$  is required to be a Hilbert-Schmidt operator. Finally, the operator  $\sum_{i \in I} p_i | F_i$  in  $\mathcal{B}(H)$  that maps each subspace  $F_i$  to  $H_i$  should be a Fredholm operator of order zero. We call  $\mathfrak{F}$  the *flag variety* corresponding to the decomposition (1).

*Remark 2.5.* If there are only a finite number of components in the decomposition (1), then these flag varieties are exactly the ones introduced in [HH94]. The need for infinite chains of subspaces comes up naturally in the context of *Toda*-type hierarchies, see e.g. [HvdL01b]. If there are only a finite number of components and only one  $m_i$  is infinite, then the Hilbert-Schmidt condition is superfluous. Hence the present class of flag varieties includes both the Grassmann variety  $Gr(k, H)$  of all  $k$ -dimensional subspaces of  $H$  as well as the Grassmann variety  $Gr(H)$  introduced by Pressley and Segal in [PS86]. As is well-known by now this last manifold is the Hilbert variety from which a rich collection of solutions for the *KP*-hierarchy could be constructed. The flag varieties of finite length in this last category occur naturally in the context of the *KP*-hierarchy at considering modified equations and Darboux transformations, see e.g. [HH94] and [HvdL01a].

*Remark 2.6.* Since  $H = \oplus_i H_i = \oplus_i F_i$ , the condition that the operator  $\sum_i p_i | F_i$  is Fredholm of index zero implies that each  $p_i | F_i$  is Fredholm and that the index of all but a finite number of these Fredholm operators is zero.

Like the finite dimensional flag varieties also the space  $\mathfrak{F}$  is a homogeneous space for several groups. First of all there is the analogue for  $\mathfrak{F}$  of the general linear group. Its Lie algebra is formed by

**Definition 2.7.** A *restricted endomorphism* of  $H$  is a  $u = (u_{ij})$  in  $\mathcal{B}(H)$  such that  $u - \text{diag}(u_{ii})$  is a Hilbert-Schmidt operator. We denote the space of all restricted endomorphisms of  $H$  by  $\mathcal{B}_{\text{res}}(H)$ .

The algebra  $\mathcal{B}_{\text{res}}(H)$  becomes a Banach algebra if we equip it with the norm  $\|\cdot\|_2$  defined by

$$\|u\|_2 = \|u\| + \sum_{i \neq j} \|u_{ij}\|_{\mathcal{HCS}},$$

where  $\|\cdot\|$  denotes the operator norm and  $\|\cdot\|_{\mathcal{HCS}}$  the Hilbert-Schmidt norm. If one chooses an orthogonal basis  $\{e_k(i) | 0 \leq k < m_i\}$  of each  $H_i$ , then one can describe basic operators in

$\mathcal{B}_{\text{res}}(H)$  as follows: for each  $i$  and  $j$ ,  $i \in I$ ,  $j \in I$ , and all integers  $k$  and  $l$ , with  $0 \leq k < m_i$  and  $0 \leq l < m_j$ , we define the operator  $E_{(k,i)(l,j)}$  in  $\mathcal{B}_{\text{res}}(H)$  by

$$E_{(k,i)(l,j)}(e_l(s)) = \delta_{li} \delta_{js} e_k(i).$$

The  $\{E_{(k,i)(l,j)} \mid 0 \leq k < m_i \text{ and } 0 \leq l < m_j\}$  form a Hilbert basis of the space  $\mathcal{HS}(H_j, H_i)$  of Hilbert-Schmidt operators from  $H_j$  to  $H_i$ .

*Remark 2.8.* The Lie algebra  $\mathcal{B}_{\text{res}}(H)$  varies with the decomposition (1) one considers. It is a significant enlargement of the Lie algebra  $\mathcal{HS}(H, H)$  in order to have a wider range of generators for the flows that preserve the manifold. An example of this situation are the commuting flows for the  $KP$ -hierarchy from example (3.6).

As for graded properties of the Lie algebra  $\mathcal{B}_{\text{res}}(H)$ , it possesses various Lie subalgebras like loop algebras e.g. that have a  $\mathbb{Z}$ -grading with finite dimensional homogeneous components, but none of them is dense in  $\mathcal{B}_{\text{res}}(H)$ , so that they are all significantly smaller components of the algebra. This property can be seen from the fact that  $\mathcal{B}_{\text{res}}(H)$  contains in general subspaces that are the bounded linear operators on a Hilbert subspace of  $H$ . The decomposition (1) induces a  $\mathbb{Z}$ -grading only on a dense subalgebra of  $\mathcal{B}_{\text{res}}(H)$  and as such it does not fit into the category of Lie algebras as considered in [RS97] or [LS92]. Namely, if we introduce for  $k \in I$ , the subspace

$$(3) \quad \mathcal{B}_k := \{b = (b_{ij}) \in \mathcal{B}_{\text{res}}(H), b_{ij} \text{ is non zero only if } j = i + k\}$$

and, if we put  $\mathcal{B}_l = 0$ , for  $l \in \mathbb{Z} - I$ , then

$$(4) \quad \mathcal{B}_{\text{fin}} = \sum_{k \in \mathbb{Z}} \mathcal{B}_k$$

is a dense  $\mathbb{Z}$ -graded Lie subalgebra of  $\mathcal{B}_{\text{res}}(H)$ .

The next step will be the introduction of the Lie group corresponding to  $\mathcal{B}_{\text{res}}(H)$ . If  $\text{GL}(H)$  denotes the group of invertible elements in  $\mathcal{B}(H)$ , then we have

**Definition 2.9.** The *restricted linear group*,  $\text{GL}_{\text{res}}(H)$ , consists of the group of invertible elements of  $\mathcal{B}_{\text{res}}(H)$ .

By definition  $\text{GL}_{\text{res}}(H)$  is a natural Banach Lie group with Lie algebra  $\mathcal{B}_{\text{res}}(H)$ . From the two facts that the Hilbert-Schmidt operators form a two-sided ideal in  $\mathcal{B}(H)$  and that a bounded operator is Hilbert-Schmidt as soon as the product of this operator with a Fredholm operator is Hilbert-Schmidt, one deduces that the group  $\text{GL}_{\text{res}}(H)$  is equal to  $\text{GL}(H) \cap \mathcal{B}_{\text{res}}(H)$ .

Next we discuss a property of the group  $\text{GL}_{\text{res}}(H)$  if  $N$ ,  $M$  or both are infinite. If  $g \in \text{GL}_{\text{res}}(H)$ , then  $g - \text{diag}(g_{ii})$  is Hilbert-Schmidt. Hence it is compact and therefore  $\text{diag}(g_{ii})$  is a Fredholm operator of order zero. In particular all the  $g_{ii}$  are Fredholm operators and if  $M = \infty$  resp.  $N = \infty$ , then there is a  $i_0$  resp.  $j_0$  such that for all  $i \geq i_0$  resp. all  $j \leq j_0$  the operator  $g_{ii}$  resp.  $g_{jj}$  is invertible. For  $M = \infty$  and  $i$  tending to infinity, the Hilbert Schmidt norm of the off-diagonal part of  $g_{\geq i}$  tends to zero and the same holds the off-diagonal part of  $g_{\leq j}$  for  $j$  tending to  $-N - 1 = -\infty$ . Since the operator norms of the  $\{g_{ii} \mid i \geq i_0\}$  and the  $\{g_{jj} \mid j \leq j_0\}$  are bounded away from zero, this leads to

**Lemma 2.10.** *Let  $g \in \text{GL}_{\text{res}}(H)$ , where  $M$  resp.  $N$  is infinite. Then there exists an  $i_0$  resp.  $j_0$  such that for all  $i \geq i_0$  resp. all  $j \leq j_0$  the operator  $g_{\geq i}$  resp.  $g_{\leq j}$  is invertible.*

The analogue of the unitary group  $U(H)$  in this context is:

**Definition 2.11.** The *restricted unitary group*,  $U_{\text{res}}(H) = \text{GL}_{\text{res}}(H) \cap U(H)$ .

Both  $U_{\text{res}}(H)$  and  $\text{GL}_{\text{res}}(H)$  are natural generalizations of the restricted unitary and general linear group, introduced in chapter 6 of [PS86]. If  $A^*$  denotes the adjoint of an operator  $A \in \mathcal{B}(H)$ , then the Lie algebra of  $U_{\text{res}}(H)$  consists of

$$\mathfrak{u}_{\text{res}}(H) = \{X \mid X \in \mathcal{B}_{\text{res}}(H), X^* = -X\}.$$

This is a real Lie subalgebra of  $\mathcal{B}_{\text{res}}(H)$  and the Lie algebra  $\mathcal{B}_{\text{res}}(H)$  can be written as

$$\mathcal{B}_{\text{res}}(H) = \mathfrak{u}_{\text{res}}(H) \oplus i \cdot \mathfrak{u}_{\text{res}}(H).$$

In other words  $\mathcal{B}_{\text{res}}(H)$  is the complexification of  $\mathfrak{u}_{\text{res}}(H)$ . On the group level this corresponds to the fact that the group  $\text{GL}_{\text{res}}(H)$  possesses a ‘‘polar decomposition’’ of which  $U_{\text{res}}(H)$  forms the unitary component. For, consider the sets

$$\begin{aligned} P(H) &= \{A \mid A \in \text{GL}(H), A = A^* \text{ and } A > 0\} \quad \text{and} \\ P_{\text{res}}(H) &= \mathcal{B}_{\text{res}}(H) \cap P(H). \end{aligned}$$

On  $P_{\text{res}}(H)$  we put the topology induced by  $\mathcal{B}_{\text{res}}(H)$ . Since the map  $A \mapsto \sqrt{A}$  from  $P_{\text{res}}(H)$  to  $P(H)$  is locally given by a convergent power series in  $A$ , this map is in fact a continuous map from  $P_{\text{res}}(H)$  to itself. Thus we get

**Proposition 2.12.** *The map  $(u, p) \mapsto up$  from  $U_{\text{res}}(H) \times P_{\text{res}}(H)$  to  $\text{GL}_{\text{res}}(H)$  is a homeomorphism.*

*Proof.* The inverse of this map is

$$g \longmapsto (g\sqrt{g^*g}^{-1}, \sqrt{g^*g})$$

and we have just seen that it is continuous. □

With each  $g \in \text{GL}_{\text{res}}(H)$  we can associate the flag  $g.F^{(0)}$  given by

$$g(H(-N-1)) = 0 \subset \dots \subset g\left(\bigoplus_{j \leq i} H_j\right) \subset \dots \subset g(H(M)) = H.$$

From the way the group  $\text{GL}_{\text{res}}(H)$  is defined it is clear that this flag belongs to  $\mathfrak{F}$ .

The group  $U_{\text{res}}(H)$  acts already transitively on  $\mathfrak{F}$ . Let  $F = \{F_i, i \in I\}$  belong to  $\mathfrak{F}$ . From the definition of  $\mathfrak{F}$  we know that there is for each  $i, i \in I$ , an isometry  $u_i$  between  $H_i$  and  $F_i$ . If we put  $u = \bigoplus_i u_i$ , then the condition defining  $\mathfrak{F}$  implies that  $u$  belongs to the group  $U_{\text{res}}(H)$  and that  $F = u(F^0)$ .

The stabilizer in  $\mathrm{GL}_{\mathrm{res}}(H)$  of the basic flag is the parabolic subgroup

$$P = \left\{ g = \begin{pmatrix} \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\ \ddots & g_{mm} & \cdots & \cdots & g_{ml} & \ddots \\ \ddots & 0 & \ddots & & \vdots & \ddots \\ \ddots & \vdots & \ddots & \ddots & \vdots & \ddots \\ \ddots & 0 & \cdots & 0 & g_{ll} & \ddots \\ \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \end{pmatrix} \in \mathrm{GL}_{\mathrm{res}}(H), \text{ with } g_{ii} \in \mathrm{GL}(H_i) \text{ for all } i \right\}$$

Since the group  $U_{\mathrm{res}}(H)$  acts also transitively on  $\mathfrak{F}$  and the stabilizer of the basic flag in this group is:

$$P \cap U_{\mathrm{res}}(H) = \{u \mid u \in U_{\mathrm{res}}(H), u = \mathrm{diag}(u_{ii}), \text{ with } u_{ii} \in U(H_i)\},$$

one can see  $\mathfrak{F}$  both as  $\mathrm{GL}_{\mathrm{res}}(H)/P$  and as  $U_{\mathrm{res}}(H)/P \cap U_{\mathrm{res}}(H)$ .

Let  $\tau : \mathrm{GL}_{\mathrm{res}}(H) \rightarrow \mathfrak{F}$  be the projection  $\tau(g) = g \cdot F^{(0)}$ . On  $\mathfrak{F}$  we will put a Hilbert manifold structure that makes  $\tau$  into an open submersion. This will be discussed in the next section.

### 3. THE MANIFOLD STRUCTURE

In this section we discuss the Hilbert manifold structure on  $\mathfrak{F}$  and some decompositions of open subsets in  $\mathrm{GL}_{\mathrm{res}}(H)$ . From the definition of the parabolic group  $P$  one sees directly that the Lie algebra of  $P$  is given by

$$L(P) = \{g \mid g = (g_{ij}) \in B_{\mathrm{res}}(H), g_{ij} = 0 \text{ for all } i < j\}$$

and that a complement of  $L(P)$  in  $B_{\mathrm{res}}(H)$  is the Hilbert space  $(E, \|\cdot\|_{\mathcal{HS}})$  with

$$E = \bigoplus_{\substack{i \in I \\ i < j}} \mathcal{HS}(H_j, H_i).$$

From section 6.1 in [Bou98], we know then that the homogeneous space  $\mathfrak{F} = \mathrm{GL}_{\mathrm{res}}(H)/P$  carries an analytic  $E$ -manifold structure for which  $\tau$  is a submersion and for which the action  $L_g$  of  $g \in \mathrm{GL}_{\mathrm{res}}(H)$  on  $\mathfrak{F}$  by left translation is analytic.

Next we give descriptions of some open subsets in  $\mathrm{GL}_{\mathrm{res}}(H)$  that will be needed later on and occur also at the construction of solutions of related integrable systems. Consider for each  $k, k \in I$ , the set  $\Omega(\geq k)$  in  $\mathrm{GL}_{\mathrm{res}}(H)$  given by

$$\Omega(\geq k) = \left\{ g \in \mathrm{GL}_{\mathrm{res}}(H) \mid g_{\geq i} = \begin{pmatrix} \ddots & \ddots & \ddots & \ddots \\ \ddots & g_{rr} & \cdots & g_{ri} \\ \ddots & \vdots & & \vdots \\ \ddots & g_{ir} & \cdots & g_{ii} \end{pmatrix} \in \mathrm{GL}_{\mathrm{res}}(\bigoplus_{j \geq i} H_j) \text{ for all } i \geq k \right\},$$

and its counterpart  $\Omega(\leq k)$  defined by

$$\Omega(\leq k) = \left\{ g \in \mathrm{GL}_{\mathrm{res}}(H) \mid g_{\leq i} = \begin{pmatrix} g_{ii} & \cdots & g_{ir} & \cdots \\ \vdots & & \vdots & \ddots \\ g_{ri} & \cdots & g_{rr} & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{pmatrix} \in \mathrm{GL}_{\mathrm{res}}(\oplus_{j \leq i} H_j) \text{ for all } i \leq k \right\}.$$

Further we use the notations  $\Omega_+(H)$  resp.  $\Omega_-(H)$  for the intersection of all members of each collection, i.e.

$$\Omega_+(H) = \Omega_+ := \bigcap_{k \in I} \Omega(\geq k) \quad \text{and} \quad \Omega_-(H) = \Omega_- := \bigcap_{k \in I} \Omega(\leq k).$$

By using lemma 2.10 and the fact that the invertible operators are open in the space of Fredholm operators one sees that the sets  $\Omega(\geq k)$ ,  $\Omega(\leq k)$ ,  $\Omega_+$  and  $\Omega_-$  are open and we discuss here their decomposition in terms of subgroups of  $\mathrm{GL}_{\mathrm{res}}(H)$ . Inside this group we introduce the Lie subgroups  $U_-(\geq k)$  and  $P(\geq k)$  defined by respectively

$$U_-(\geq k) = \left\{ g = (g_{ij}) \in \mathrm{GL}_{\mathrm{res}}(H) \mid \begin{array}{l} g_{ii} = \mathrm{Id}_{H_i} \text{ for all } i \\ g_{ij} = 0 \text{ for } i > j \\ g_{ij} = 0 \text{ for } i < j \text{ and } j < k \end{array} \right\},$$

$$P(\geq k) = \{g = (g_{ij}) \in \mathrm{GL}_{\mathrm{res}}(H) \mid g_{ij} = 0, \text{ if } i < j \text{ and } j \geq k\}.$$

If  $u \in U_-(\geq k)$  and  $p \in P(\geq k)$  and  $g = up$ , then it is a direct verification that for all  $l \geq k$  there holds  $g_{\geq l} = u_{\geq l}p_{\geq l}$ , hence  $g$  belongs to  $\Omega(\geq k)$ . The union of all the groups  $U_-(\geq k)$  is again a group and we denote it as follows

$$U_- = U_-(H) = \bigcup_{k \in I} U_-(\geq k).$$

For the counterpart  $\Omega(\leq k)$  we introduce similarly the groups  $U_-(\leq k)$  and  $P(\leq k)$  given by

$$U_-(\leq k) = \left\{ g = (g_{ij}) \in \mathrm{GL}_{\mathrm{res}}(H) \mid \begin{array}{l} g_{ii} = \mathrm{Id}_{H_i} \text{ for all } i \\ g_{ij} = 0 \text{ for } j < i \\ g_{ij} = 0 \text{ for } i < j \text{ and } i > k \end{array} \right\}$$

and

$$P(\leq k) = \{g = (g_{ij}) \in \mathrm{GL}_{\mathrm{res}}(H) \mid g_{ij} = 0, \text{ if } i < j \text{ and } i \leq k\}.$$

If we take now an  $u \in U_-(\leq k)$  and  $p \in P(\leq k)$  and we put  $g = pu$ , then there holds for all  $l \leq k$  that  $g_{\leq l} = p_{\leq l}u_{\leq l}$ . Hence  $g$  belongs to  $\Omega(\leq k)$ . Clearly  $P(\geq k) \cap U_-(\geq k) = \{\mathrm{Id}_H\} = P(\leq k) \cap U_-(\leq k)$  and this gives you the injectivity of both the following maps

**Proposition 3.1.** *The map  $(u, p) \mapsto up$  from  $U_-(\geq k) \times P(\geq k) \rightarrow \mathrm{GL}_{\mathrm{res}}(H)$  determines a homeomorphism between  $U_-(\geq k) \times P(\geq k)$  and  $\Omega(\geq k)$ . Likewise, the map  $(p, u) \mapsto pu$  from  $P(\leq k) \times U_-(\leq k) \rightarrow \mathrm{GL}_{\mathrm{res}}(H)$  is a homeomorphism between  $P(\leq k) \times U_-(\leq k)$  and  $\Omega(\leq k)$ .*

*Proof.* We merely have to reconstruct in an analytic way for an element  $g \in \Omega(\geq k)$  resp.  $\Omega(\leq k-1)$  the elements  $u_1 \in U_-(\geq k)$  and  $p_1 \in P(\geq k)$  resp.  $u_2 \in U_-(\leq k-1)$  and  $p_2 \in P(\leq k-1)$  such that  $g = u_1 p_1$  resp.  $g = p_2 u_2$ . First we decompose these elements w.r.t.  $H = (\oplus_{j \geq k} H_j) \oplus (\oplus_{j < k} H_j)$  respectively as follows

$$g = \begin{pmatrix} g_{\geq k} & g_{>(k)} \\ g_{<(k)} & g_{\leq k-1} \end{pmatrix} = \begin{pmatrix} Id & 0 \\ g_{<(k)} g_{\geq k}^{-1} & Id \end{pmatrix} \begin{pmatrix} g_{\geq k} & g_{>(k)} \\ 0 & g_{\leq k-1} - g_{<(k)} g_{\geq k}^{-1} g_{>(k)} \end{pmatrix}$$

$$g = \begin{pmatrix} g_{\geq k} & g_{>(k)} \\ g_{<(k)} & g_{\leq k-1} \end{pmatrix} = \begin{pmatrix} g_{\geq k} - g_{>(k)} g_{\leq k-1}^{-1} g_{<(k)} & g_{>(k)} \\ 0 & g_{\leq k-1} \end{pmatrix} \begin{pmatrix} Id & 0 \\ g_{\leq k-1}^{-1} g_{<(k)} & Id \end{pmatrix}.$$

This reduces the problem for  $\Omega(\geq k)$  to decomposing an element  $\tilde{g} := g_{\geq k} \in \Omega_+(\oplus_{j \geq k} H_j)$  as  $\tilde{g} = \tilde{u} \tilde{p}$ , where  $\tilde{u} \in U_-(\oplus_{j \geq k} H_j)$  and  $\tilde{p} \in P(\oplus_{j \geq k} H_j)$  and for  $\Omega(\leq k-1)$  to the decomposition of an element  $\hat{g} := g_{\leq k-1} \in \Omega_-(\oplus_{j < k} H_j)$  as  $\hat{g} = \hat{p} \hat{u}$ , where  $\hat{u} \in U_-(\oplus_{j < k} H_j)$  and  $\hat{p} \in P(\oplus_{j < k} H_j)$ . Each of these decompositions is found by a step by step procedure, where we use the decomposition of  $\tilde{g}$  w.r.t.  $\oplus_{j \geq k} H_j = (\oplus_{j > k} H_j) \oplus H_k$  and that of  $\hat{g}$  w.r.t.  $\oplus_{j \leq k-1} H_j = H_{k-1} \oplus (\oplus_{j < k-1} H_j)$  given by

$$\tilde{g} = \begin{pmatrix} g_{\geq k+1} & g_+ \\ g_- & g_{kk} \end{pmatrix} = \begin{pmatrix} Id & 0 \\ g_- g_{\geq k+1}^{-1} & Id \end{pmatrix} \begin{pmatrix} g_{\geq k+1} & g_+ \\ 0 & g_{kk} - g_- g_{\geq k+1}^{-1} g_+ \end{pmatrix},$$

$$\hat{g} = \begin{pmatrix} g_{k-1k-1} & g_2 \\ g_1 & g_{\leq k-2} \end{pmatrix} = \begin{pmatrix} g_{kk} - g_2 g_{\leq k-2}^{-1} g_1 & g_2 \\ 0 & g_{\leq k-2} \end{pmatrix} \begin{pmatrix} Id & 0 \\ g_{\leq k-2}^{-1} g_1 & Id \end{pmatrix}.$$

Continuing in this fashion this procedure finishes for  $\Omega(\geq k)$  resp.  $\Omega(\leq k)$  in a finite number of steps if and only if  $M < \infty$  resp.  $N < \infty$  and yields you then the required decomposition. In the infinite case the increasing product of elements in  $U_-(\oplus_{j \geq k} H_j)$  resp.  $U_-(\oplus_{j < k} H_j)$  converges to an element in these groups respectively, since the operator norms of the  $\{g_{\geq l}, l \geq k\}$  and the  $\{g_{\leq l}, l < k\}$  are bounded away from zero and the sum over the Hilbert-Schmidt norms of the off-diagonal components is finite. This proves the lemma.  $\square$

Next we consider the open subsets  $\Omega_+$  and  $\Omega_-$ . From the foregoing results it follows that  $U_- P \subset \Omega_+$  and  $P U_- \subset \Omega_-$ . Note that we have already shown equality here in the cases that  $M$  or  $N$  is finite. So what remains is the case  $M = N = \infty$ . To show equality in this case, we take a  $g \in \Omega_+$  and an  $h \in \Omega_-$ . Thanks to Proposition 3.1 we may assume that  $g \in P(\geq k)$  and  $h \in P(\leq k-1)$ . These operators are then reduced to the required form again by a step by step procedure. For, decompose both operators w.r.t.  $H = (\oplus_{j \geq k} H_j) \oplus H_{k-1} \oplus (\oplus_{j < k-1} H_j)$ , then we have respectively

$$g = \begin{pmatrix} g_{\geq k} & * & * \\ 0 & g_{k-1k-1} & * \\ 0 & p_4 & * \end{pmatrix} = \begin{pmatrix} Id & 0 & 0 \\ 0 & Id & 0 \\ 0 & p_4 g_{k-1k-1}^{-1} & Id \end{pmatrix} \begin{pmatrix} g_{\geq k} & * & * \\ 0 & g_{k-1k-1} & * \\ 0 & 0 & * \end{pmatrix},$$

$$h = \begin{pmatrix} * & * & * \\ q_2 & h_{k-1k-1} & * \\ 0 & 0 & h_{\leq k-2} \end{pmatrix} = \begin{pmatrix} * & * & * \\ 0 & h_{k-1k-1} & * \\ 0 & 0 & h_{\leq k-2} \end{pmatrix} \begin{pmatrix} Id & 0 & 0 \\ h_{k-1k-1}^{-1} q_2 & Id & 0 \\ 0 & 0 & Id \end{pmatrix}$$

Continuing in this fashion one finds all the components of the  $U_-$ -component of  $g$  resp.  $h$ , which are the limits of the increasing products of elements in  $U_-$  due to the step by step procedure. Their convergence is based on the same argument as above. We thus have found a Gauss type decomposition for the sets  $\Omega_+$  and  $\Omega_-$  and resume this result in a

**Corollary 3.2.** *Inside  $\text{GL}_{\text{res}}(H)$ , we have  $U_-P = \Omega_+$  and  $PU_- = \Omega_-$ . In particular we see that  $\Omega_+ = \Omega_-^{-1}$ .*

From this corollary follows that the restriction of  $\tau$  to  $U_-$  gives you a diffeomorphism  $u \mapsto uF^{(0)}$  between  $U_-$  and the open neighborhood  $\tau(\Omega_+)$  of  $F^{(0)}$ . Clearly the group  $U_-$  is diffeomorphic to the Hilbert space  $E$ . Note that from the definition of  $\Omega_+$  one can conclude directly that

$$\tau(\Omega_+) = \left\{ F = (F_i) \in \mathfrak{F} \mid \bigoplus_{j \leq l} p_j : \bigoplus_{j \leq l} F_j \rightarrow \bigoplus_{j \leq l} H_j \text{ is a bijection for all } l \in I \right\}.$$

This characterization of  $\tau(\Omega_+)$  tells you how to choose around a general point of  $\mathfrak{F}$  a concrete neighborhood diffeomorphic to  $E$ . This requires, however, the introduction of the following notation.

*Notation 3.3.* If  $W$  is closed subspace of  $H$ , then we denote the orthogonal projection on  $W$  by  $p_W$ .

Consider a  $F = (F_i)$  in  $\mathfrak{F}$ . Then the analogue of  $\tau(\Omega)$  for  $F$  is

$$U_F = \left\{ V = (V_i) \text{ in } \mathfrak{F} \mid \bigoplus_{i \leq l} p_{F_i} : \bigoplus_{i \leq l} V_i \rightarrow \bigoplus_{i \leq l} F_i \text{ is a bijection for all } l \in I \right\}.$$

Since  $\mathfrak{F} = U_{\text{res}}(H) \cdot F^{(0)}$ , we have for all  $F$  and  $G$  in  $\mathfrak{F}$  that the map  $\sum_j \sum_{i \neq j} p_{F_i} | G_j$  is a Hilbert-Schmidt operator. Hence, if  $V$  belongs to  $U_F$ , then there is a unique operator  $A$  in  $\bigoplus_{\substack{j \in I \\ i < j}} \mathcal{HS}(F_j, F_i)$  such that for all  $i$ ,  $-N - 1 \leq i \leq M + 1$ ,

$$V(i) = \{x + A(x) \mid x \in F(i)\}.$$

This is why we call  $V$  also the graph of  $A$  and we write  $V = \text{graph}(A)$ .

It is convenient to have a special name for the flags in  $U_F$ .

**Definition 3.4.** A flag  $V$  in  $U_F$  is called *transversal* to  $F$ .

Let  $g_F$  be an element of  $U_{\text{res}}(H)$  such that  $g_F \cdot F^{(0)} = F$ . Instead of the big cell  $\Omega_+$  in  $\text{GL}_{\text{res}}(H)$  with respect to the decomposition  $H = \bigoplus_i H_i$ , we could also have introduced a big cell with respect to  $H = \bigoplus_i F_i$  and it will be clear that this set can be written as

$$g_F U_- P (g_F^{-1}).$$

Consequently, we get for  $U_F$  that

$$U_F = \left\{ g_F u p (g_F)^{-1} F \mid \text{with } u \in U_- \text{ and } p \in P \right\} = \tau(g_F U_- P).$$

Then we can define for each  $F$  in  $\mathfrak{F}$  a diffeomorphism  $\varphi_F: U_F \rightarrow E$  by

$$\varphi_F(g_F u F^{(0)}) = u - \text{Id}.$$

Each  $(U_F, \varphi_F)$  is a concrete chart around  $F$  for the  $E$ -manifold structure on  $\mathfrak{F}$ .

We have obtained now a concrete description of the manifold structure on  $\mathfrak{F}$ :

**Proposition 3.5.** *The  $(U_F, \varphi_F)$  are the charts of the analytic  $E$ -manifold structure on  $\mathfrak{F}$ .*

*Proof.* It is sufficient to show for each  $U_{F(1)}$  and  $U_{F(2)}$  with  $U_{F(1)} \cap U_{F(2)} \neq \emptyset$  that

$$\varphi_{F(2)} \circ \varphi_{F(1)}^{-1} : \varphi_{F(1)}(U_{F(1)} \cap U_{F(2)}) \rightarrow \varphi_{F(2)}(U_{F(1)} \cap U_{F(2)})$$

is an analytic map. From the step by step decomposition described in Proposition 3.1 follows that the  $U_-$ -component of  $(g_{F(2)})^{-1} g_{F(1)} u$  actually depends analytically on  $u$ . This proves the proposition.  $\square$

We conclude this subsection with describing the role the flag varieties corresponding to the example 2.2 play for the KP-hierarchy and its subsystems.

*Example 3.6.* Recall that the KP hierarchy consists of a tower of nonlinear differential equations in infinitely many variables  $\{t_n | n \geq 1\}$ . It is named after the simplest nontrivial equation in this tower, the Kadomtsev–Petviashvili equation:

$$(5) \quad \frac{3}{4} \frac{\partial^2 u}{\partial t_2^2} = \frac{\partial}{\partial t_1} \left( \frac{\partial u}{\partial t_3} - 3u \frac{\partial u}{\partial t_1} - \frac{1}{4} \frac{\partial^3 u}{\partial t_1^3} \right),$$

which is a two dimensional generalization of the  $KdV$ -equation. We consider solutions of these equations that belong to a commutative ring of functions  $R$ , which is stable under the operators  $\partial_n = \frac{\partial}{\partial t_n}$ . The compact form in which one usually presents the equations of the hierarchy, is the so-called Lax form. This is an equality between operators in the privileged derivation  $\partial = \partial_1$  of a specific nature. This simple way to present the equations requires that one extends the ring  $R[\partial] = \{\sum_{i=0}^n a_i \partial^i | a_i \in R\}$  and adds suitable integral operators to the ring. Then it becomes possible to take the inverse and roots of certain differential operators. E.g. the square root  $\mathcal{L}^{\frac{1}{2}}$  of the Schrödinger operators  $\mathcal{L} = \partial^2 + 2u$  is well-defined in this extension. Thus one arrives at the ring  $R[\partial, \partial^{-1}]$  of pseudodifferential operators with coefficients in  $R$ . It consists of all expressions

$$\sum_{i=-\infty}^N a_i \partial^i \quad , \quad a_i \in R \quad \text{for all } i,$$

that are added in an obvious way and multiplied according to

$$\partial^j \circ a \partial^i = \sum_{k=0}^{\infty} \binom{j}{k} \partial^k(a) \partial^{i+j-k}.$$

Each operator  $P = \sum p_j \partial^j$  decomposes as  $P = P_+ + P_-$  with  $P_+ = \sum_{j \geq 0} p_j \partial^j$  its differential operator part and  $P_- = \sum_{j < 0} p_j \partial^j$  its integral operator part. An operator  $L \in R[\partial, \partial^{-1}]$  of the

form

$$(6) \quad L = \partial + \sum_{j < 0} \ell_j \partial^j, \quad \ell_j \in R \quad \text{for all } j < 0.$$

carries the name *Lax operator*. We call a Lax operator a *solution the KP hierarchy* if and only if it satisfies the system of equations

$$(7) \quad \partial_n(L) = \sum_{j < 0} \partial_n(\ell_j) \partial^j = [(L^n)_+, L], \quad n \geq 1.$$

They are called the *Lax equations* for  $L$ . As such they are a generalization of the so-called Lax equations of the  $m$ -th Gelfand-Dickey hierarchy, which is the following system of equations for a differential operator  $\mathcal{L} = \partial^m + \sum_{i \leq m-2} l_i \partial^i$  in  $R[\partial]$ ,

$$(8) \quad \partial_n(\mathcal{L}) = [(\mathcal{L}^{\frac{n}{m}})_+, \mathcal{L}], \quad n \geq 1.$$

E.g. for  $m = 2$  this operator  $\mathcal{L}$  will be the Schrödinger operator  $\partial^2 + 2u$  and the case  $n = 3$  of the Lax equations 8 is then equivalent to the property that  $u$  is a solution of the *KdV*-equation. A similar situation occurs in the *KP*-case. First one shows that the Lax equations of the *KP*-hierarchy are equivalent to the following infinite set of conditions for the Lax operator  $L$  :

$$(9) \quad \partial_n(L^m)_+ - \partial_m(L^n)_+ = [(L^n)_+, (L^m)_+], \quad m, n \geq 1.$$

The case  $n = 3$  and  $m = 2$  of the system 9 implies then that the coefficient  $\ell_{-1}$  of  $L$  is a solution of the *KP*-equation.

The equations of the *KP*-hierarchy possess a rich collection of solutions besides the trivial one  $L = \partial$ . In [SW85], they considered the Hilbert space from example 2.2 with the decomposition corresponding to  $\underline{s} = (0)$ . On the associated Grassmann manifold  $Gr(H)$  acts the group of the commuting flows

$$\Gamma_+ = \{\gamma(t) := \exp\left(\sum_{i \geq 1} t_i z^i\right) \mid t_i \in \mathbb{C}, \sum_{i \geq 1} |t_i| N^i < \infty \text{ for some } N > 1\}.$$

By transferring an arbitrary plane  $W$  in  $Gr(H)$  with this group  $\Gamma_+$  into the open cell  $\Omega_+$  and using the Gauss decomposition from corollary 3.2, they constructed for each  $W$  in  $Gr(H)$  a solution  $L_W$  of the *KP*-hierarchy. We will refer to this set of solutions of the *KP*-hierarchy as the Segal-Wilson class. The coefficients of the Lax operators thus constructed turned out to be meromorphic functions on the group  $\Gamma_+$ . Besides the construction of this extensive class of solutions, Segal and Wilson also gave a geometric characterization of the solutions in  $Gr(H)$  that are the  $m$ -th root of a monic differential operator of order  $m$ , i.e. solutions of the  $m$ -th Gelfand-Dickey hierarchy. That are precisely the planes  $W$  satisfying  $z^m W \subset W$ . A geometric description of a generalization of this subsystem, the so-called vector constrained *KP*-hierarchy, was given in [HvdL98]. Similar constructions can be made for other groups of commuting flows, see e.g. [HP93].

Note that, if  $L$  is a Lax operator in  $R[\partial, \partial^{-1}]$ , then for all monic  $P$  in  $R[\partial]$  the operator  $PLP^{-1}$  is again a Lax operator. In view of the foregoing results a natural question is: given a solution  $L$  in  $R[\partial, \partial^{-1}]$  of the *KP*-hierarchy in the Segal-Wilson class, determine operators  $P$  in  $R[\partial]$  such that  $L_P = PLP^{-1}$  belong again to the Segal-Wilson class and describe these transformations geometrically in the context of the Grassmanian. This type of transformation

for Schrödinger operators already occurred in the work of Darboux. Therefore these transformations and their inverses carry his name. The raised question was settled in [HvdL01a]. There it was shown that if  $V$  and  $W$  belong to  $Gr(H)$  and  $V$  is a subspace of codimension  $n$  in  $W$ , then there is an explicit monic differential operator  $P$  in  $R[\partial]$  such that

$$L_V = PL_W P^{-1}$$

In other words the flag variety corresponding to  $\underline{s} = (n, 0)$  describes the Darboux transformations of order  $n$ . Moreover, refinements of these flags, i.e. chains looking like the basic flag of type  $\underline{s} = (n, \dots, s_i, \dots, 0)$ , correspond to specific decompositions of the differential operator  $P$ . Similar questions can be raised for the subsystems mentioned above, we refer to [HvdL01a] for the answer.

#### 4. THE CONNECTED COMPONENTS OF $GL_{\text{res}}(H)$

Let  $g = (g_{ij})$  be an element of  $GL_{\text{res}}(H)$ . Recall that we have shown already that all diagonal components  $g_{ii}$  of  $g$  are Fredholm operators. The collection of Fredholm operators on a Hilbert space  $K$  is an open part of the space  $\mathcal{B}(K)$ . Its connected components are given by the index, which is defined as

$$\text{ind}(B) = \dim(\ker(B)) - \dim(\text{coker}(B)),$$

where  $B$  is a Fredholm operator on  $K$ . Since the off-diagonal part of  $g$  is Hilbert-Schmidt and hence compact, the operator  $\text{diag}(g_{II})$  is a Fredholm operator of index zero. Moreover, we saw in Lemma 2.10 that for sufficiently large  $|i|$  the  $g_{ii}$  are invertible. Hence we have that the indices of the  $\{g_{ii} \mid i \in I\}$  satisfy

$$\sum_{i \in I} \text{ind}(g_{ii}) = 0 \quad \text{and} \quad \text{ind}(g_{kk}) = 0 \quad \text{if} \quad m_k < \infty \quad \text{or} \quad |k| \gg 0.$$

These relations lead to the introduction of the subgroup  $Z$  of  $\mathbb{Z}^I$  defined by

$$Z = \left\{ z = (z_i) \in \mathbb{Z}^I \mid \sum_{i \in I} z_i = 0, z_k = 0 \quad \text{if} \quad m_k < \infty \quad \text{or} \quad |k| \gg 0 \right\}.$$

On  $Z$  we take the discrete topology. The standard properties of the index imply that the map  $i : GL_{\text{res}}(H) \rightarrow Z$ ,

$$g \mapsto \{\text{ind}(g_{ii})\},$$

is a continuous group homomorphism. Hence the sets

$$GL_{\text{res}}^{(z)}(H) = \{g \mid g \in GL_{\text{res}}(H), i(g) = z\}, \quad \text{with } z \in Z,$$

are open. In fact, they are exactly the connected components of  $GL_{\text{res}}(H)$ , for

**Proposition 4.1.** *For each  $z \in Z$ , the set  $GL_{\text{res}}^{(z)}(H)$  is non-empty and connected.*

*Proof.* Let  $z = (z_i)$  be in  $Z$ . To see that  $GL_{\text{res}}^{(z)}(H)$  is non-empty, one has to consider only a finite number of the components  $\{H_i\}$ , since only a finite number of the  $\{z_i\}$  are nonzero. That case has been shown in [HH94] and by extending the operator found there with the identity, one

obtains an element in  $\mathrm{GL}_{\mathrm{res}}^{(z)}(H)$ . As for the connectedness it suffices to show that  $\mathrm{GL}_{\mathrm{res}}^{(0)}(H)$  is connected. First one notes that, since  $P$  is homeomorphic to

$$\prod_{i \in I} \mathrm{GL}(H_i) \times \prod_{j < i} \mathcal{HS}(H_j, H_i)$$

and all the  $\mathrm{GL}(H_i)$  are connected, (see [Kui65]), the group  $P$  is connected. If we can show that each element of  $\mathrm{GL}_{\mathrm{res}}^{(0)}(H)$  can be joined by a continuous path to an element of  $P$ , then this proves that  $\mathrm{GL}_{\mathrm{res}}^{(0)}(H)$  is connected. Also this we reduce to the case of a finite number of components  $\{H_i\}$ , which has been treated in [HH94]. Assume  $M = \infty$ , if it would be finite then one can proceed directly to the second step in the following reduction. For any element  $g \in \mathrm{GL}_{\mathrm{res}}^{(0)}(H)$  we know from Lemma 2.10 that there is a sufficiently large  $k_0$  such that  $g \in \Omega(\geq k_0)$ . Hence  $g = up \in U_{-}(\geq k_0)P(\geq k_0)$ . Then the map  $t \mapsto \{\mathrm{Id} + (1-t)(u - \mathrm{Id})\}p$  joins  $g$  with  $p$ . If  $N$  is finite, then we have w.r.t.  $H = (\oplus_{j \geq k_0} H_j) \oplus (\oplus_{j < k_0} H_j)$

$$p = \begin{pmatrix} p_{\geq k_0} & * \\ 0 & g_{\leq k_0-1} \end{pmatrix}, \text{ where } g_{\leq k_0-1} \in \mathrm{GL}_{\mathrm{res}}^{(0)}(\oplus_{-N-1 < j < k_0} H_j).$$

According to [HH94], the element  $g_{\leq k_0-1}$  is linked by a continuous path with a  $p(k_0) \in P(\oplus_{-N-1 < j < k_0} H_j)$  and we are done. If  $N = \infty$ , then there is a sufficiently small  $l_0$  such that  $p \in \Omega(\leq l_0)$ . Decomposing  $p$  w.r.t.  $H = (\oplus_{j \geq k_0} H_j) \oplus (\oplus_{l_0 < j < k_0} H_j) \oplus (\oplus_{j \leq l_0} H_j)$ , results in

$$p = \begin{pmatrix} p_{\geq k_0} & * & * \\ 0 & g(0) & * \\ 0 & p(1) & p_{\leq l_0} \end{pmatrix} = \begin{pmatrix} p_{\geq k_0} & * & * \\ 0 & g(0) & * \\ 0 & 0 & p_{\leq l_0} \end{pmatrix} \begin{pmatrix} \mathrm{Id} & 0 & 0 \\ 0 & \mathrm{Id} & 0 \\ 0 & p_{\leq l_0}^{-1} p(1) & \mathrm{Id} \end{pmatrix} =: p_1 u_1.$$

The map  $t \mapsto p_1 \{\mathrm{Id} + (1-t)(u_1 - \mathrm{Id})\}$  links  $p$  with  $p_1$ . From Proposition 3.1, we know that  $p_{\leq l_0} = p(2)u(2)$ , with  $p(2) \in P(\oplus_{j \leq l_0} H_j)$  and  $u(2) \in U_{-}(\oplus_{j \leq l_0} H_j)$ . Hence we can decompose  $p_1$  further as

$$p_1 = \begin{pmatrix} p_{\geq k_0} & * & * \\ 0 & g(0) & * \\ 0 & 0 & p_{\leq l_0} \end{pmatrix} = \begin{pmatrix} p_{\geq k_0} & * & * \\ 0 & g(0) & * \\ 0 & 0 & p(2) \end{pmatrix} \begin{pmatrix} \mathrm{Id} & 0 & 0 \\ 0 & \mathrm{Id} & 0 \\ 0 & 0 & u(2) \end{pmatrix} =: p_2 u_2.$$

By shrinking  $u_2$  to the identity as we did before with similar operators, one links  $p_1$  continuously with  $p_2$ . From [HH94] we know that  $g(0)$  can be linked to a  $p(0) \in P(\oplus_{l_0 < j < k_0} H_j)$  and this concludes the proof of the Proposition.  $\square$

This Proposition is the extension to flag varieties of Proposition 6.2.4 in [PS86].

Since the parabolic group  $P$  is connected, we see that

**Corollary 4.2.** *The connected components of  $\mathfrak{F}$  are given by*

$$\mathfrak{F}^{(z)} = \left\{ g \cdot F^{(0)} \mid g \in \mathrm{GL}_{\mathrm{res}}^{(z)}(H) \right\}, \quad z \in Z.$$

*Remark 4.3.* Let  $H$  be the Hilbert space from example 2.2. Then the connected components of  $Gr(H)$  are labeled by the integers. It is clear that for each  $m \in \mathbb{Z}$  and each  $W \in Gr^{(n)}(H)$ , the space  $z^m W$  belongs to  $Gr^{(n-m)}(H)$ . The construction method in [SW85] of solutions of the  $KP$ -hierarchy is such that we have  $L_W = L_{z^m W}$ . Hence, for the set of solutions one could

restrict to one component, but at Darboux considerations the other components are needed as well.

*Example 4.4.* Again we take the Hilbert space from example 2.2 and consider the Grassmannian  $Gr(H)$ . If we have for each  $n \in \mathbb{Z}$  a plane  $W_n \in Gr^{(n)}(H)$  and if these subspaces form an infinite flag

$$(10) \quad \cdots \subset W_{n-1} \subset W_n \subset W_{n+1} \subset W_{n-2} \subset \cdots,$$

then we know from [HvdL01b] that this renders you a solution of the 1-Toda lattice hierarchy. There it is also shown that an infinite chain

$$\cdots \subset W_{n-1} \subset W_n \subset W_{n+1} \subset \cdots \subset W_0 = \left\{ \sum_{n \geq 0} a_n z^n \in H \right\},$$

yields systems of orthogonal polynomials occurring in Matrix models. This illustrates that infinite flags are important as well.

## 5. THE FUBINI-STUDY METRIC

In this section we take the example of projective Hilbert space  $\mathbb{P}^1(H)$ , i.e. the manifold of all complex lines in  $H$  and equip it with a Kähler structure that is the analogue of the finite dimensional case and for which its expression in local coordinates is not a notational disaster. Let  $H$  be

$$(11) \quad H = \left\{ \sum_{i \geq 0} \alpha_i e_i \quad \middle| \quad \sum_{i \geq 0} |\alpha_i|^2 < \infty \right\}.$$

As the orthogonal decomposition corresponding to  $\mathbb{P}^1(H)$  we take

$$(12) \quad H = \{\alpha_0 e_0, \alpha_0 \in \mathbb{C}\} \oplus \left\{ \sum_{i > 0} \alpha_i e_i \in H \right\} := H_0 \oplus H_1.$$

Each  $\sum_{i \geq 0} \alpha_i e_i \neq 0$  in  $H$  determines an element of  $\mathbb{P}^1(H)$  that we denote by  $[\alpha_i]$ . The space  $\mathbb{P}^1(H)$  is covered by the open subsets  $U_j$ ,  $j \geq 0$ , given by

$$U_j = \{[\alpha_k], \alpha_j \neq 0\}.$$

The local complex coordinates on  $U_j$  are the  $z_k(j) = x_k(j) + iy_k(j) := \frac{\alpha_k}{\alpha_j}$ ,  $k \neq j$  and instead of the real ones  $x_k(j), y_k(j)$ ,  $k \neq j$ , it is convenient to take the  $z_k(j)$  and  $\overline{z_k(j)}$ ,  $k \neq j$ . For  $s \neq j$ , we have on  $U_j \cap U_s$  that

$$z_k(s) = \frac{z_k(j)}{z_s(j)}, \text{ for } k \neq s \text{ and } k \neq j, \quad z_j(s) = \frac{1}{z_s(j)}.$$

This defines the biholomorphic coordinate transformation  $\varphi_{s,j}$  on  $U_j \cap U_s$ . On each  $U_j$  we have the vector fields

$$\frac{\partial}{\partial z_k(j)} := \frac{1}{2} \left( \frac{\partial}{\partial x_k(j)} - i \frac{\partial}{\partial y_k(j)} \right) \text{ and } \frac{\partial}{\partial \overline{z_k(j)}} := \frac{1}{2} \left( \frac{\partial}{\partial x_k(j)} + i \frac{\partial}{\partial y_k(j)} \right).$$

Hence any vector field  $X$  on  $U_j$  can be written as

$$(13) \quad X_u = \sum_{k \neq j} a_k(u) \frac{\partial}{\partial x_k(j)} + i \sum_{k \neq j} b_k(u) \frac{\partial}{\partial y_k(j)} = \sum_{k \neq j} \alpha_k(u) \frac{\partial}{\partial z_k(j)} + \sum_{k \neq j} \overline{\alpha_k(u)} \frac{\partial}{\partial \overline{z_k(j)}},$$

where  $\alpha_k(u) = a_k(u) + ib_k(u)$ . Since  $\mathbb{P}^1(H)$  is a complex manifold, it has a canonical complex structure  $J$  that satisfies in each  $u \in U_j$

$$(14) \quad J_u \left( \frac{\partial}{\partial x_k(j)} \Big|_u \right) = \frac{\partial}{\partial y_k(j)} \Big|_u \text{ and } J_u \left( \frac{\partial}{\partial y_k(j)} \Big|_u \right) = - \frac{\partial}{\partial x_k(j)} \Big|_u.$$

We have seen that in each  $u \in U_j$  the  $\{ \frac{\partial}{\partial z_k(j)} \Big|_u \text{ and } \frac{\partial}{\partial \overline{z_k(j)}} \Big|_u, k \neq j \}$  form a Hilbert basis of the tangent space at  $u$  considered as a real Hilbert space. Dual to these derivations are the elements  $(dz_k(j))_u$  and  $(d\overline{z_k(j)})_u$  in the cotangent space at  $u$ , giving rise to the sections  $dz_k(j)$  resp.  $d\overline{z_k(j)}$  of the complexified cotangent bundle  $T^* \mathfrak{Y} \otimes \mathbb{C}$  over  $U_j$ . The first span the subspace  $T^{1,0}$  of complex-linear cotangent vectors and the second the space  $T^{0,1}$  of complex-antilinear cotangent vectors. This splitting of the complex-valued 1-forms on  $U_j$  also extends to the complex-valued  $k$ -forms  $\Omega^k(U_j, \mathbb{C})$  on  $U_j$ . They are a direct sum of the spaces  $\Omega^{(l,m)}(U_j, \mathbb{C})$ ,  $l+m=k$ , of differential forms of type  $(l, m)$ , which are by definition the sections of the  $(\Lambda^l T^{1,0}) \wedge (\Lambda^m T^{0,1})$ . By composing the exterior derivative  $d$  with the projections on the factors  $(\Lambda^l T^{1,0}) \wedge (\Lambda^m T^{0,1})$ , one gets the operators  $\partial$  and  $\bar{\partial}$

$$\partial : \Omega^{(l,m)}(U_j, \mathbb{C}) \rightarrow \Omega^{(l+1,m)}(U_j, \mathbb{C}) \text{ and } \bar{\partial} : \Omega^{(l,m)}(U_j, \mathbb{C}) \rightarrow \Omega^{(l,m+1)}(U_j, \mathbb{C})$$

that are on the level of  $C^\infty$ -functions given by

$$\partial(f) = \sum_{k \neq j} \frac{\partial}{\partial z_k(j)}(f) dz_k(j) \text{ and } \bar{\partial}(f) = \sum_{k \neq j} \frac{\partial}{\partial \overline{z_k(j)}}(f) d\overline{z_k(j)}.$$

The sum of the operators  $\partial$  and  $\bar{\partial}$  is equal to the exterior derivative and they share with the exterior derivative the property  $\partial^2 = 0 = \bar{\partial}^2$ . Therefore they satisfy  $\bar{\partial}\partial = -\partial\bar{\partial}$ . On each  $U_j$  we have the function

$$K_j([\alpha_s]) := \ln \left( \sum_{k \neq j} |z_k(j)|^2 + 1 \right) = \ln \left( \sum_{k \neq j} z_k(j) \overline{z_k(j)} + 1 \right) =: \ln(V_j).$$

On the intersection  $U_j \cap U_s$  these functions are linked by the relation

$$(15) \quad \varphi_{s,j}^* K_s = K_s \circ \varphi_{s,j} = K_j - \ln(|z_s(j)|^2) = K_j - \ln z_s(j) + \ln \overline{z_s(j)} \pmod{2\pi i \mathbb{Z}}.$$

To  $K_j$  is associated the  $(1, 1)$ -form  $\omega_j$  on  $U_j$  given by

$$(16) \quad \begin{aligned} \omega_j &:= i \bar{\partial} \partial(K_j) = i \sum_{\substack{k \neq j \\ r \neq j}} \frac{\partial^2 K_j}{\partial z_k(j) \partial \overline{z_r(j)}} dz_k(j) \wedge d\overline{z_r(j)} \\ &= i \sum_{\substack{k \neq j \\ r \neq j}} \frac{\delta_{kr} V_j - z_r(j) \overline{z_k(j)}}{V_j^2} dz_k(j) \wedge d\overline{z_r(j)}. \end{aligned}$$

Next we use the fact that the pullback by the holomorphic map  $\varphi_{s,j}$  commutes with  $\partial$  and  $\bar{\partial}$  and we insert relation (15) to get

$$(17) \quad \varphi_{s,j}^* \omega_s = i \partial \bar{\partial} \varphi_{s,j}^* K_s = i \partial \bar{\partial} K_j = \omega_j.$$

Hence the  $\{\omega_j\}$  compose to a global  $(1, 1)$ -form  $\omega$  on  $\mathbb{P}^1(H)$ . The form  $\omega$  is closed, for locally on  $U_j$  we have

$$d\omega = (\partial + \bar{\partial})\omega = i(\partial + \bar{\partial})(\omega_j) = i(\partial + \bar{\partial})\partial\bar{\partial}K_j = 0 + i\bar{\partial}\partial\bar{\partial}K_j = -i\partial\bar{\partial}^2K_j = 0.$$

From the local formula one deduces directly that for all vector fields  $X$  and  $Y$ , there holds  $\omega(JX, JY) = \omega(X, Y)$ , i.e.  $J$  is compatible with  $\omega$ . With  $\omega$  we also associate a metric  $g$ . For 2 vector fields  $X$  and  $Y$  it is given by  $g(X, Y) = \omega(X, JY)$ . To see that it is positive-definite, we decompose a vector field  $X$  locally on  $U_j$  as in formula 13, we write  $\alpha(u)$  resp.  $z$  for the sequences  $\{\alpha_k(u)\}$  resp.  $\{z_k(j)\}$  and we use the notation

$$\langle (\gamma_k), (\delta_k) \rangle_j := \sum_{k \neq j} \gamma_k \bar{\delta}_k,$$

for square summable sequences. Then we get that for a nonzero vector field  $X$

$$(18) \quad \begin{aligned} \omega(X, JX) &= \sum_{\substack{k \neq j \\ r \neq j}} \frac{\delta_{kr} V_j - z_r(j) \overline{z_k(j)}}{V_j^2} \alpha_k(u) \overline{\alpha_r(u)} dz_k(j) \wedge \overline{dz_r(j)} \\ &= \langle \alpha(u), \alpha(u) \rangle_j (1 + \langle z, z \rangle_j) - \langle \alpha(u), z \rangle_j \langle z, \alpha(u) \rangle_j > 0, \end{aligned}$$

because of the Cauchy-Schwarz inequality. This metric we call, analogously to the finite dimensional case, the *Fubini-Study metric* on projective Hilbert space, Thus we have put a Kähler structure on  $\mathbb{P}^1(H)$  and one way to proceed in the general case, would be to make a complex embedding of  $\mathfrak{F}$  into some  $\mathbb{P}^1(\mathcal{H})$ . This would require the construction of holomorphic line bundles over  $\mathfrak{F}$  with sufficiently many global sections. This approach is too cumbersome and we will present a more direct one in the next section. We conclude with an example from the *KP*-theory, where these homogeneous coordinates in a Hilbert space play a role.

*Example 5.1.* For the Hilbert space from example 2.2 we consider the Grassmannian  $Gr(H)$ . For  $n \in \mathbb{Z}$ , let  $\Sigma(n) = \{m \in \mathbb{Z}, m \geq -n\}$ . If  $H_{\Sigma(n)}$  is the Hilbert span of the  $\{z^s \mid s \in \Sigma(n)\}$ , then it belongs to the component  $Gr^{(n)}(H)$ . Other basic examples in this component of  $Gr(H)$  are the subspaces corresponding to subsets of  $\mathbb{Z}$  comparable to  $\Sigma(n)$ . More precisely, consider

$$(19) \quad \mathfrak{g}(n) = \{\Sigma = (s_i) \mid s_i \in \mathbb{Z}, i \geq -n, s_{i+1} > s_i, s_i = i \text{ for } i >> 0\}$$

and let  $H_\Sigma$  be the Hilbert span of all the  $z^s, s \in \Sigma$ . All these spaces belong to  $Gr^{(n)}(H)$ . For each  $\Sigma = (s_i)$  from  $\mathfrak{g}(n)$  we denote the orthogonal projection of  $H$  onto  $H_\Sigma$  by  $p_\Sigma$  and we write  $\sigma_\Sigma$  for the isomorphism between  $H_{\Sigma(n)}$  and  $H_\Sigma$  determined by  $\sigma_\Sigma(z^i) = z^{s_i}, i \geq -n$ . From the way  $Gr(H)$  is defined, one deduces that any plane  $W$  in  $Gr^{(n)}(H)$  is the image of an embedding  $w : H_{\Sigma(n)} \mapsto H$ , satisfying two properties. The first is that the component  $w_+ := p_{\Sigma(n)} \circ w$  is of the form "Identity + trace-class" so that  $\det(w_+)$  is well-defined. The second property is that the other component  $w_- := (Id - p_{\Sigma(n)}) \circ w$  is a Hilbert-Schmidt

operator. We denote the space of this type of embeddings by  $\mathcal{P}_n$ . Two embeddings  $w_1$  and  $w_2$  in  $\mathcal{P}_n$  have the same image if and only if  $w_1 = w_2 \circ t$  with  $t$  in the group

$$(20) \quad \mathcal{T}_n = \{t \in \text{Aut}(H_{\Sigma(n)}) \mid t - Id \text{ is trace class } \}.$$

Consider the product space  $\mathcal{P}_n \times \mathbb{C}$  and the equivalence relation on it given by

$$(w_1, \lambda_1) \sim (w_2, \lambda_2) \Leftrightarrow w_1 = w_2 \circ t, \quad \text{with } t \in \mathcal{T}_n \quad \text{and } \lambda_1 = \lambda_2 \det(t).$$

The equivalence class of  $(w, \lambda)$  we denote by  $[w, \lambda]$ . The quotient under this equivalence relation defines the line bundle  $\text{Det}^*$  over  $Gr^{(n)}(H)$ . Note that for each  $\Sigma = (s_i) \in \mathcal{J}(n)$  we have the holomorphic section

$$\text{Image}(w) \mapsto [w, \det(\sigma_{\Sigma}^{-1} \circ p_{\Sigma} \circ w)]$$

of this bundle. Now for each  $v$  and  $w \in \mathcal{P}_n$  the operator  $v^* \circ w - Id$  is equal to  $(v_+)^* w_+ + (v_-)^* w_- - Id$  and thus is a trace class operator. For the determinant of this product of a  $\mathbb{Z} \times \mathcal{J}(n)$ -matrix and a  $\mathcal{J}(n) \times \mathbb{Z}$ -matrix we have a formula similar to the one for the product of an  $k \times m$ -matrix and a  $m \times k$ -matrix. There holds namely

$$\det(v^* \circ w) = \sum_{\Sigma \in \mathcal{J}(n)} \det(v^*|_{H_{\Sigma}} \circ \sigma_{\Sigma}) \det(\sigma_{\Sigma}^{-1} \circ p_{\Sigma} \circ w).$$

It can be derived by approximating  $w_+ - Id$  and  $w_-$  with operators with a finite dimensional range. In particular one sees that the sequence  $(\det(\sigma_{\Sigma}^{-1} \circ p_{\Sigma} \circ w))_{\Sigma \in \mathcal{J}(n)}$  belongs to  $\ell^2(\mathcal{J}(n))$  and then one verifies that the map

$$W = \text{Image of } w \mapsto [(\det(\sigma_{\Sigma}^{-1} \circ p_{\Sigma} \circ w))]$$

defines an embedding of  $Gr^{(n)}(H)$  into the projective space of the Hilbert space  $\ell^2(\mathcal{J}(n))$ . The homogeneous coordinates  $(\det(\sigma_{\Sigma}^{-1} \circ p_{\Sigma} \circ w))_{\Sigma \in \mathcal{J}(n)}$  are called the *Plücker coordinates* of the plane  $W$ , as they are the analogue in the present setting of the finite dimensional notion.

The Plücker coordinates also turn up at the so-called  $\tau$ -functions for the  $KP$ -hierarchy. Solutions  $L$  of the  $KP$ -hierarchy are usually meromorphic expressions in a single  $\tau$ -function and its derivatives w.r.t. the privileged variable  $t_1$  and these functions are determined up to a constant by  $L$ . For the solutions  $L_W$ ,  $W \in Gr(H)$ , we can describe them concretely. The group  $\Gamma_+$  from example 3.6 acts on each component  $Gr^{(n)}(H)$ . If we decompose the action of  $\gamma(t)^{-1}$  w.r.t.  $H = H_{\Sigma(n)} \oplus H_{\Sigma(n)}^{\perp}$  as  $\begin{pmatrix} a & b \\ 0 & d \end{pmatrix}$ , then the  $\tau$ -function associated with  $w \in \mathcal{P}_n$  is given by  $\tau_w(\gamma(t)) := \det(w_+ + a^{-1}bw_-)$ . The same formula for the determinant as above gives you the decomposition of  $\tau_w$

$$(21) \quad \tau_w(\gamma(t)) := \det(w_+ + a^{-1}bw_-) = \sum_{\Sigma \in \mathcal{J}(n)} \det(\sigma_{\Sigma}^{-1} \circ p_{\Sigma} \circ w) \tau_{\sigma_{\Sigma}}(\gamma(t)).$$

in the  $\tau$ -functions of the planes  $H_{\Sigma}$ ,  $\Sigma \in \mathcal{J}(n)$ . As it is shown in [SW85], these are the Schur functions corresponding to the partition  $(i - s_i)_{i \geq -n}$

6. THE KÄHLER STRUCTURE ON  $\mathfrak{F}$ 

Now that we know the manifold structure on  $\mathfrak{F}$  we can discuss its tangent bundle and put a global hermitian structure on it. Its imaginary part renders a global 2-form on  $\mathfrak{F}$  that can be shown to be closed. Thus we will obtain the Kähler structure on  $\mathfrak{F}$ . Hence, here the positive definiteness is automatic and the closedness requires a proof, while it was the other way around in the foregoing section.

Since the exponential map is an analytic isomorphism from  $E$  to the group  $U_-(H)$ , we also have the isomorphism

$$Y \mapsto \exp(Y).F^{(0)}$$

between  $E$  and the neighborhood  $\tau(\Omega_+)$  of  $F^{(0)}$ . In particular we see that the small perturbation of this map

$$Y \mapsto \exp(Y - Y^*).F^{(0)} = \{\exp(Y - Y^*) \exp(Y^*) \exp(-Y)\} \exp(Y).F^{(0)}$$

is an isomorphism from a neighborhood of 0 in  $E$  to a neighborhood  $V^{(0)}$  of  $F^{(0)}$  in  $\mathfrak{F}$ . Moreover, the tangent space in  $F^{(0)}$  can be identified with  $E$  by associating with each  $X \in E$  the derivation

$$f \mapsto X_{F^{(0)}}(f) := \left. \frac{d}{dt} \right|_{t=0} f(\exp(tX).F^{(0)}),$$

where  $f$  stands for an arbitrary  $C^\infty$ -function around  $F^{(0)}$ . For each  $F = g_F.F^{(0)}$  in  $\mathfrak{F}$ , with  $g_F \in U_{\text{res}}(H)$ , a trivialization of the tangent bundle  $T\mathfrak{F}$  on the open set  $g_F.V^{(0)}$  is given by

$$(22) \quad (g_F \exp(Y - Y^*), X) \mapsto d(L_{g_F \exp(Y - Y^*)})(F^{(0)})X_{F^{(0)}}.$$

Since each  $\exp(Y - Y^*)$ ,  $Y \in E$ , belongs to  $U_{\text{res}}(H)$ , we note that if we choose different trivializations and we have  $g_{F_1} \exp(Y_1 - Y_1^*).F^{(0)} = g_{F_2} \exp(Y_2 - Y_2^*).F^{(0)}$ , then there holds

$$g_{F_1} \exp(Y_1 - Y_1^*) = g_{F_2} \exp(Y_2 - Y_2^*)u, \text{ with } u = \text{diag}(u_{ii}),$$

with each  $u_{ii} \in U(H_i)$ . Hence another choice of trivialization of the form 22 induces merely the following transformation on  $E$ :

$$X \mapsto uXu^{-1}, \text{ with } u \in U_{\text{res}}(H) \cap P.$$

Consider now any point  $F = g_F.F^{(0)}$  in  $\mathfrak{F}$  and two arbitrary elements  $X_F$  and  $Y_F$  in the tangent space  $T\mathfrak{F}_F$ . They can, once that  $g_F$  has been chosen, uniquely be written as  $X_F = d(L_{g_F})(F^{(0)})X$  and  $Y_F = d(L_{g_F})(F^{(0)})Y$  with  $X$  and  $Y \in E$ . However, there is on the tangent space  $T\mathfrak{F}_F$  a hermitian form in which this dependence of  $g_F$  does not play a role anymore. Recall that the product of two Hilbert-Schmidt operators is an operator of trace class. Then we can define on  $T\mathfrak{F}_F$  the form

$$(23) \quad B_F(X_F, Y_F) := \text{trace}(Y^*X) = \sum_{i \in I} \text{trace}\left(\sum_{k \in I} (Y^*)_{ik} X_{ki}\right)$$

$$(24) \quad = \sum_{i \in I} \sum_{k < i} \text{trace}((Y^*)_{ik} X_{ki}),$$

since  $Y_{ik}^* = 0$ , unless  $k < i$ . The form  $B_F$  is independent of the choice of  $g_F$ , since we have for each  $u \in U_{\text{res}}(H) \cap P$  the relation

$$\text{trace}((uYu^{-1})^*(uXu^{-1})) = \text{trace}(uY^*Xu^{-1}) = \text{trace}(Y^*X),$$

and it is clearly hermitian. Note that this form is constant on  $\mathfrak{F}$ . Thus we have put a hermitian structure on  $T\mathfrak{F}_F$ . The associated strong Riemannian metric is obtained by taking the real part of  $B_F$

$$(25) \quad g(X_F, Y_F) = \frac{1}{2}(B_F(X_F, Y_F) + B_F(Y_F, X_F))$$

$$(26) \quad = \sum_{i \in I} \sum_{k < i} \frac{1}{2}(\text{trace}((Y^*)_{ik} X_{ki}) + \text{trace}((X^*)_{ik} Y_{ki})).$$

Since  $B_F$  is hermitian, its imaginary part defines an antisymmetric form  $\Phi_F$  on  $T\mathfrak{F}_F$  that is equal to

$$(27) \quad \Phi(X_F, Y_F) := g(X_F, iY_F)$$

$$(28) \quad = \sum_{i \in I} \sum_{k < i} \frac{1}{2i}(\text{trace}((Y^*)_{ik} X_{ki}) - \text{trace}((X^*)_{ik} Y_{ki})).$$

The forms  $\Phi_F$  determine the so-called *fundamental 2-form*  $\Phi$  on  $\mathfrak{F}$  by

$$\Phi(X_1, X_2)(F) := \Phi_F((X_1)_F, (X_2)_F),$$

for all vector fields  $X_1$  and  $X_2$  on  $\mathfrak{F}$ . It is well-known, see e.g. [AMR88], that on a Hilbert manifold as  $\mathfrak{F}$  the exterior derivative of an  $k$ -form  $\omega$  is well-defined and is given by

$$(29) \quad d\omega(X_0, \dots, X_k) = \sum_{l=0}^k (-1)^l \mathfrak{L}_{X_l}(\omega(X_0, \dots, \hat{X}_l, \dots, X_k)) +$$

$$(30) \quad \sum_{0 \leq i < j \leq k} (-1)^{i+j} \omega(\mathfrak{L}_{X_i}(X_j), X_0, \dots, \hat{X}_i, \dots, \hat{X}_j, \dots, X_k)$$

Here  $\hat{X}_i$  denotes that  $X_i$  is deleted. Further, the  $X_0, \dots, X_k$  are vectorfields on  $\mathfrak{F}$  and  $\mathfrak{L}_{X_i}$  denotes the Lie derivative w.r.t.  $X_i$ .

The manifold  $\mathfrak{F}$  is called a *Kähler manifold* if the 2-form  $\Phi$  is closed, i.e.  $d\Phi=0$ . The form  $\Phi$  is also called a *Kähler form* then. Since the 2-form  $\Phi$  is constant on  $\mathfrak{F}$ , all the expressions  $\mathfrak{L}_{X_l}(\Phi(X_i, X_j))$  in the exterior derivative of  $\Phi$  are zero. For the remaining expressions in  $d\Phi$ , we use again that  $\Phi$  is completely determined by  $\Phi_{F(0)}$  and obtain then from (29) the following condition for the closedness of  $\Phi$

**Proposition 6.1.** *The 2-form  $\Phi$  is closed if and only if  $\Phi_{F(0)}$  is a Lie algebra 2-cocycle, that is to say it satisfies for all  $X, Y$  and  $Z \in E$  the relation*

$$(31) \quad \Phi_{F(0)}(X, [Y, Z]) + \Phi_{F(0)}(Y, [Z, X]) + \Phi_{F(0)}(Z, [X, Y]) = 0.$$

Note that for  $M + N = 1$ , i.e. in the case of the Grassmannian, the commutators in the cocycle condition are all zero, so that the statement is trivially true. To show that  $\Phi_{F(0)}$  possesses the cocycle property, we prove the relation for  $X, Y$  and  $Z \in E$  equal to any of the basic operators  $E_{(k,i)(l,j)}$  in  $E$  and, since they form a Hilbert basis of  $E$ , the fact that  $\Phi_{F(0)}$  is continuous gives the general result. Let  $X = E_{(k_1, i_1)(l_1, j_1)}$ ,  $Y = E_{(k_2, i_2)(l_2, j_2)}$  and  $Z = E_{(k_3, i_3)(l_3, j_3)}$ , then there holds for  $l = 1, 2$  and  $3$  that  $i_l < j_l$ . This restricts the possible outcomes of the commutator of  $Y$  and  $Z$  to

$$[Y, Z] = 0, \text{ if } (l_2, j_2) \neq (k_3, i_3) \text{ and } [Y, Z] = E_{(k_2, i_2)(l_3, j_3)} \text{ if } (l_2, j_2) = (k_3, i_3).$$

If  $(l_2, j_2) = (k_3, i_3)$ , then we get

$$\Phi_{F^{(0)}}(X, [Y, Z]) = \frac{1}{2i} \text{trace}(E_{(l_3, j_3)(k_2, i_2)} E_{(k_1, i_1)(l_1, j_1)} - E_{(l_1, j_1)(k_1, i_1)} E_{(k_2, i_2)(l_3, j_3)}).$$

For  $(k_2, i_2) = (k_1, i_1)$ , there holds either  $\text{trace}(E_{(l_3, j_3)(l_1, j_1)}) = \text{trace}(E_{(l_1, j_1)(l_3, j_3)}) = 0$  or  $E_{(l_3, j_3)(l_1, j_1)} = E_{(l_1, j_1)(l_3, j_3)}$ , so that  $\Phi_{F^{(0)}}(X, [Y, Z]) = 0$  for these  $X, Y$  and  $Z \in E$ . The same reasoning holds for the other terms and thus we have obtained the final result

**Theorem 6.2.** *The 2-form  $\Phi$  is closed and  $\mathfrak{F}$  is a Kähler manifold.*

Since  $\mathfrak{F}$  is modeled on a Hilbert space the 2-form  $\Phi$  is a symplectic form. As the hermitian structure on  $T\mathfrak{F}$  is invariant under left translations from  $U_{\text{res}}(H)$ , we see that

**Corollary 6.3.** *The group  $U_{\text{res}}(H)$  acts by symplectomorphisms on the symplectic variety  $\mathfrak{F}$ .*

This result can be applied at Hamiltonian aspects of  $KP$ - and *Toda*-type integrable systems.

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