MATHEMATISCHES FORSCHUNGSINSTITUT OBERWOLFACH

Tagungsbericht 27/1994

Integrable Systems

19.6. bis 25.6.1994

Die Tagung fand unter der Leitung von P. van Moerbeke (Louvain) und W. Nahm (Bonn) statt. Im Mittelpunkt des Interesses standen Fragen der integrablen Hierarchien und ihrer Geometrie, konforme Feldtheorien und physikalische Anwendungen (Phasenübergänge, Quanten-Hall-Effekt).

Vortragsauszüge

P. DI FRANCESCO:
Counting Rational Curves on Projective Spaces

There is only a finite number N_d of rational curves of the projective plane $\mathbf{P}_2$, of degree d, through $3d-1$ fixed points. Such curves must also have $\frac{(d-1)(d-2)}{2}$ double points with distinct tangents. Borrowing ideas from field theory in physics, and following M. Kontsevich and Y. Manin, one can build a certain "free energy" function, generating intersection theory on the moduli space of such curves. In particular, this function plays the role of a potential for some graded integrable deformation of the cohomology ring of $\mathbf{P}_2$. The associativity of the ring translates into "crossing relations" for the free energy, which in turn determine the numbers N_d completely. This procedure can be repeated for any projective space $\mathbf{P}_r$, and also more involved varieties, with more incidence relations to make the numbers of curves finite. The results always take the form of quadratic recursion relations for the numbers of rational curves. Relations to topological field theory (or Kontsevich-type matrix integrals?) should help shed some light on higher genus curve counting as well.

J. FRÖHLICH, E. THIRAN:
Chern-Simons Theory, Integral Lattices and Fractional Quantum Hall Effect

We consider two-dimensional gases of electrons in a strong, unifrom, external magnetic field transversal to the plane of the system. We are interested in the physics of such systems at large distance scales and low frequencies, i. e. , in the scaling limit. It is shown that, in the scaling limit, these systems are described by pure, abelian Chern-Simons theories, provided there is no dissipation in the system ($R_L = 0$). We then review the connection between Chern-Simons theory and the Knizhnik-Zamolodchikov equations and with current (Kac-Moody) algebra. In passing, implications for knot theory are mentioned, but the physically important fact is that solutions of the K-Z equations span the physical state space of C-S theory. Returning to the physics of 2D electron gases, one notices that those solutions of K-Z equations derived from abelian CS-theories that describe physical states of such systems have special monodromy properties described by integral, Euclidean lattices. These lattices are then studied and classified partially, and this leads to the prediction of allowed, rational values of the Hall conduction, fractional charges and statistics of "Laughlin vortices", etc...

J. FELDMAN, E. TRUBOWITZ, H. KNÖRRER:
Riemann Surfaces of Infinite Genus

We introduce a class of Riemann surfaces of infinite genus to which many of the classical results on compact Riemann surfaces extend. They are special cases of "parabolic" surfaces in the sense of Ahlfors - Nevanlinna. So they admit a canonical homology basis $A_1, B_1, A_2, B_2, \ldots$ and a basis $w_1, w_2, \ldots$ of the Hilbert space of square integrabel holomorhic 1-forms such that $\int_{a_i} w_j = \delta_{ij}$. In addition the associated theta function converges on a suitable Bunuel space, and there is an analogue of Riemann's Vanishing Theorem and Torelli's Theorem.

The definiton of the class of Riemann surfaces considered is in terms of glueing "standard pieces". It is explicit enough to be able to verify that Fermi curves of 2-dimensional periodic Schrödinger operators as well as the spectral curves for the periodic KP II equation belong to it. The latter fact is used to prove that the initial value problem for this equation has solutions that are almost periodic in time.

G. FELDER, C. WIECZERKOWSKI:
Conformal Field Theory and Integrable Models on the Torus

The spaces of conformal blocks on the sphere and on the torus are introduced as spaces of invariant linear forms on tensor products of Kac Moody algebra $\hat{g}$ modules under the Lie algebra of meromorphic functions with values in g. These spaces are identified with certain spaces of functions with values on finite dimensional vector spaces. The corresponding KZ equations are derived. The consistency condition on the torus leads to generalizations of the classical Yang-Baxter equation. Its quantization is discussed.

I. M. SIGAL:
Some Mathematical Problem of Non-linear Dynamics

Consider a non-linear Schrödinger or wave equation. Assume a solution exists for as long times as required. The question we address is to describe properties of such a solution, especially its localization in space and time. We addressed the following three topics: I. Periodic solutions, II. Resonances, III. Dynamics of vortices. We describe one of these results. Consider NL Schrödinger and Wave equations which are small perturbations of linear ones. Assume the corresponding linear equations have periodic or quasiperiodic solutions, i. e. (quasi)periodic in time and L^2 in space. Thus

WE: periodic and quasiperiodic solutions are unstable under generic NL perturbations

SE: periodic solutions are stable under all reasonable perturbations while quasiperiodic solutions are unstable under generic perturbations.

K. GAWEDZKI:
Conformal field theory in higher genera

Solution of WZW (and coset) conformal field theory model on a higher genus Riemann surface may be encoded in the scalar product on the space of non-abelian theta functions. The latter are holomorhpic sections of powers of the determinant bundles on the moduli space of holomorhic bundles of rank > 1. The scalar product of non-abelian theta functions is given by a formal functional integral. This integral may be effectively calculated (at least for rank 2 case) and reduces to a finite-dimensional integral expression. As a by-product, one obtains integral expressions for higher genus conformal blocks of WZW conformal model.

H. KNÖRRER, D. LEHMANN, E. TRUBOWITZ, J. FELDMAN:
Two Dimensional Fermi Liquids

Let $\epsilon(\vec{n})\epsilon C^{\omega}$ be the (renormalized) dispension relation, $\mu > 0$ the chemical potential and let $\lambda < k_1, k_2 \mid V \mid k_3, k_4 > \epsilon C^{\infty}$ be the interaction of a many-fermion model in two space dimensions. For simplicity suppose that the model has a fixed ultraviolet cut off and that $F = \{\vec{k} \mid \epsilon(\vec{n}) = \mu\}$ is compact. The main hypotheses are that $\nabla\epsilon(\vec{h}) \neq 0$ for all $\vec{h}\epsilon F$, and that, for all $\vec{g}, F \neq -F + \vec{g} = \{\vec{p} \mid \epsilon(-\vec{p} + \vec{g}) = \mu\}$. Then there is an $\eta > 0$ such that for all $\mid \lambda \mid < \eta$ the thermodynamic limits of the Euclidean Green's functions of the model exist in the sense of distributions and are analytic in λ. The particle number density $N_{\vec{k}}$ is C^{∞} in $\vec{k}$ except that it has a jump discontinuity at every $\vec{k}\epsilon F$.

W. EHOLZER, N.-P. SKORUPPA:
Methods for obtaining closed formulas for conformal characters of rational models of W-algebras

Let c be the central charge and H be the set of conformal dimensions of a rational model of a (bosonic) W-algebra. Then for each $h \in H$, we have its associated conformal character ξ_h = trace of $q^{L_0 - c/24}$ in the representation whose conformal dimension is h. These functions satisfy the following axioms (we set $q = e^{2\pi i \tau}$, where $\tau\epsilon\mathcal{G}$ = complex upper half plane):

1. ξ_h is holomorphic in $\mathcal{G}, \xi_h \neq 0$.
2. The space $\text{span}_{\mathbb{C}}\{\xi_h \mid h \in H\}$ spanned by the ξ_h is invariant under $SL(2,\mathbb{Z})$.
3. $\xi_h = 0(q^{-\tilde{c}/24})$ for $\tau \to i\infty$ where $\tilde{c} = c - 24\min H$ is the effective central charge.
4. $\xi_h q^{-(h-c/24)}$ is invariant under $\tau \to \tau + 1$.
5. The Fourier coefficients of ξ_h are rational.

Then for many pairs (c, H) coming from rational models the following theorem holds true (cf: [Eholzer-Skoruppa, BONN-TH-94-16]):
Theorem: Assume that *6. the ξ_h are invariant under some congruence subgroup of $SL(2,\mathbb{Z})$.*
Then the ξ_h are uniquely determined, i. e.: if $\xi_h (h \in H)$ is any set of functions on $\mathcal{G}$ which satisfy 1. to 6., then each ξ_h is unique up to multiplication by a constant. Thus, roughly speaking, once the central charge and the conformal dimension of a rational model are known, then the conformal characters can be already determined from this data only. Though we proved our theorem only for a part of all known rational models we believe that it works in much more generality. The methods used for the proof of the theorem are also useful for obtaining closed formulas for conformal characters.

N. TUROK, J. W. R. UNDERWOOD, D. OLIVE:
Solution in Affine Toda Field Theories

Affine Toda field theories in two dimensions are integrable and Lorentz invariant deformations of conformally and W-invariant theories. The local conserved charges generate an infinite dimensional Poincaré algebra which turns out to be isomorphic to the principal Heisenberg subalgebra of the associate affine Kac Moody algebra. Thus internal and space time symmetries are coupled, with the consequence that interesting mass patterns and coupling rules are exhibited by the particles which are the quanta of the fundamental fields. General soliton solutions are found when the coupling is imaginary, exploiting the representation theory of the affine Kac Moody algebra. Most physical properties are derived from vertex operators associated with the solitons otained by exponentiating the principal Heisenberg subalgebra. The soliton species are in one to one correspondence with the above mentioned particle species and display similar mass and coupling patterns. Unless identical any pair of solitons attract each other.

D. E. EVANS:

Amenable Operater Algebras

Recent work on the possible classification of amenable C^*-algebras by K-theoretic invariants has helped solve some open problems regarding the approximately finite dimensional algebras (non-commutative zero-dimensional spaces), quantum or non-commutative 2-torus (which may have applications to almost Mattieu operators or Discrete Magnetic Laplacians, and infinite algebras associated to topological Markov chains. This involves input from some dynamical systems e. g. shifts, Rohlin properties of automorphisms, non commutative orbifolds – the latter idea has applications in subfactor theory). This talk describes joint work with Bratteli, Ellwitt, and Kishimoto.

C. A. TRACY, H. WIDOM:

Fredholm Determinants, Differential Equations and Matrix Models

Orthogonal polynomical random matrix Models of N x N hermitian matrices lead to Fredholm determinants of integral operators with kernel of the form

$$\frac{\varphi(x)\psi(y) - \psi(x)\varphi(y)}{x - y}$$

This talk is concerned with the Fredholm determinants of integral operators having kernel of this form and where the underlying set is the union of intervals

$$J = \bigcup_{j=1}^{m} (a_{2j-1}, a_{2j})$$

The emphasis is on the determinants thought of as functions of the end-points a_k.

We show that these Fredholm determinants with kernels of the general form described above are expressible in terms of solutions of PDE's as long as φ and ψ satisfy

$$\begin{aligned} m(x)\varphi'(x) &= A(x)\varphi(x) + B(x)\psi(x) \\ m(x)\psi'(x) &= -C(x)\varphi(x) - A(x)\psi(x), \end{aligned}$$

m, A, B, C polys. in x. The (φ, ψ) paris for the sine, Airy and Bessel kernels satisfy such relations, as do the pairs which arise in the finite N Hermite, Laguerrre, and Jacobi ensembles and in Matrix Models of 2D quantum graivty. Therefore, we are able to write down the systems of PDE's for these ensembles as special cases of the general system.

An analysis of these equations leads in many cases where J is a single interval ($J = (s, \infty)$ included) to explicit representations in terms of Painlevè transcendents.

LEONID A. DICKEY:
Constrained KP hierarchy and symmetries

A few papers were published in the recent time dealing with the so-called "constrained KP hierarchy" (Orlov, Bing Xu, Cheng Y., Oevel, and Strampp). This is a restriction of the KP hierarchy to pseudo-differential operators having integral parts of a very special form involving only two unknown functions, instead of infinitely many of them in the whole hierarchy.

We try to explain the nature of this restriction linking it to generating functions of all symmetries of the KP hierarchy. We also give a new formula for the generating function. It has a form $w(\mu)\partial^{-1}w^*(\lambda)$, an inverse derivative "sandwiched" between the Baker and the adjoint Baker functions taken at different points. This formula generalizes that known before for inner symmetries of the hierarchy where $\mu = \lambda$.

MOTOHIRO MULASE:
Coverings of Riemann Surfaces, Heisenberg Algebras, and Prym Varieties

Consider a triple $A_o \subset A \subset gl(n, D)$, where $D = (\mathbb{C}[[x]])\left[\frac{d}{dx}\right]$ is the ring of ordinary differential operators, A is a maximally commutative subalgebra of $gl(n, D)$ with a monic element, and A_o is a subalgebra described below. By a standard technique of matrix pseudodifferential operators, one can embed $A \rightleftharpoons gl(n, \mathbb{C}((z)))$, where $z = \frac{d}{dx}^{-1}$. (Actually, one takes a zero-th order matrix pseudodifferential operator S so that $S(A_o S \subset gl(n, \mathbb{C}((z)))$.) $A_o \subset A$ is a subalgebra. with these data, one can associate functionally a geometric object containing arbitrary morphisms between arbitrary algebraic curves, and a vector bundle on these curves with vanishing cohomologies. One can visualize the algebra extension $A_o \subset A$ in terms of geometry of algebraic curves. Maximal commutative subalgebras of the formal loop algebras (without nilpotent elements) other than Heisenberg-type ones are presented from analysing singularities of the covering morphism. These commutative algebras act on the Grassmannian of vector valued functions and produce Prym varieties of the covering as finite-dimensions orbits.

This is the non-commutative geometry one can expect from $gl(n, \mathbb{C}((z)))$, or $gl(n, D)$.

As a motivation, a formula due to Kontsevich and myself was presented:

$$X \sim \begin{bmatrix} k_o & & \\ & \ddots & \\ & & k_{n-1} \end{bmatrix}, Z_n(t, f) = \int e^{\sum_{m=1}^{\infty} tr(t_m X^m)} f(x),$$

$$f(x) = f(k_o, \cdots, k_{n-1}) = \frac{det[\phi_i(k_j)]}{\Delta(k_o, \cdots, k_{n-1})}$$

Then $Z_n(t, f)$ is a KP-τ function, and it is a continuum limit of Hirota Soliton solutions. In fact,

$$\phi_i(k) = \sum_{\alpha=1}^{N} C_{i\alpha}\delta(k - \lambda_\alpha) \quad \text{makes} \quad Z_n(t, f)$$

a soliton solution.

BORIS KHESIN, FEODOR MALIKOV:
Drinfeld-Skolov reduction for matrices of complex size

We construct affinization of the algebra gl_λ of "complex size" matrices that contains the algebras gl_n for integral values of the parameter. The Drinfeld-Sokolov Hamiltonian reduction of the algebra $\hat{gl}_\lambda$ results in the quadratic Gelfand-Dickey structure on the Poisson-Lie group of all pseudodifferential operators of fractional order.

This Poisson-Lie group provides a general framework for description of classical W_n-algebras as its Poisson submanifolds, while the (quantum) $W_{1+\infty}$-algebras appears as the dual space to the Lie algebra of that group.

The construction of "λ-deformation" can be extended to the simultaneous deformation of orthogonal and symplectic algebras which produces self-adjoint operators. It has also a counterpart for the Toda lattices with "fractional number" of particles.

LAWRENCE THOMAS, STEPHAN WASSOLL:
Schrödinger operators and classical almost integrability

Let $H = -\Delta + V$ be a Schrödinger operator acting in $L^2(M)$, M either a d-dimensional torus or sphere, V analytic.

For the case of the torus, we construct asymptotic expansions for the eigenfunctions and eigenvalue of H at high energy E, via WKB methods, the expansions in inverse powers of E. the classical action appearing in the eigenfunctions is the solution of a classical Hamilton-Jacobi equation. KAM methods assume that this classical action can be constructed at least for a Cantor set V^∞, whose intersection with the subset $V(E)$ of phasespace with energy $\leq E$ satisfies $|V^\infty \cap V(E)|/|V(E)| \to 1, E \to \infty$. It follows that the dimensions of the subspace of the approximative eigenfunctions corresponding to energy $\leq E$ ist asymptotic to actual dimension of the subspace corresponding to $H \mid \leq E, E \to \infty$.

Similar results are obtained for the case of the 2-sphere, but just to $O(E^{-1})$ (which should be compared to the typical spacing between eigenvalues within an eigenvalue cluster which is $O(E^{-1/2})$). Turning point difficuluties and problems associated with the high eigenvalue degeneracy of the unpertubed operator are addressed by first transforming the operator to a Bargmann space representation.

A theorem of Kac-Spencer, Weinstein, Widom and other states that the l-th cluster of eigenvalues (for H on the sphere) clustered about $E = l(l+d-1)$ has a limiting (probability) distribution $l \to \infty$ equal to the distribution of the Radon transform of V. We gives an example of a (Hölder)-continuous potential V for which the limiting distribution of eigenvalues is singular continuous.

DAVID B. FAIRLIE:
Integrable systems in high dimensions

A set of equations which generalise the Bateman equation $\phi_{xx}\phi_t^2 + \phi_{tt}\phi_x^2 - 2\phi_{xt}\phi_x\phi_t = 0$ is present which admit an infinite number of inequivalent Lagrangian descriptions. These equations are linearised by a Legendre transform, and shown to arise out of the equations for constant flow following the fluid. Extensions of these equations which generalise the two-dimensional Born-Infeld equation are proposed and solved by the same transform. Finally, the general implicit solution to the homogeneous Monge-Ampère equation $det(\frac{\partial^2\phi}{\partial x_i \partial x_j}) = 0$ is constructed using similar methods.

JOHANN VAN DE LEUR:
KdV type hierarchies, the string equation and $W_{1+\infty}$ constraints

To every partition $n = n_1 + \ldots + n_s$ one can associate a vertex operator realization of the Lie algebras a ∞ and gl_n. Using this construction it is possible to obtain reductions of the s-component KP hierarchies, reductions which are associated to these partitions $n = n_1 + \ldots + n_s$. In this way one obtains matrix KdV type hierarchies. Finally, I prove that the following two statements for a KP τ-function are equivalent.

(1) τ is a τ-function of the $[n_1, \ldots, n_s]^{+n}$ reduced (s component) KP hierarchy that also satisfies the string equation $L_{-1}\tau = 0$.

(2) τ satisfies the vacuum constraints of the $W_{1+\infty}$ algebra, i.e., $(W_{q-p}^{p+1} + \delta_{pq}c_{p+1})\tau = 0$ for all $p, q \in \mathbb{Z}_{\geq 0}$.

ALEXEI MOROZOV:
Hirota equations for 0-loop algebras (the case of $SL_q(2)$)

"Generalized τ-functions" can be defined as generating functionals of all the matrix elements of a given group element $g \in G$ in a given representation V. The element set of "time-variables" in general situation is associated with the maximal nilpotent subalgebra of G, not with its Cartan subalgebra. Moreover, in the case of quantum groups such τ-functions are not c-numbers, but take values in the non-commutative ring $\mathcal{A}(\mathcal{G})$. However, despite all these differences from the standard KP and Toda situations, the generalized τ-functions always satisfy the analogue of Hirota bilinear equations. These can be derived by manipulations with intertwinning operators between different representations of G. The simplest example of 0-loop algebra $G = SL(2)$ and its quantum counterpart $G = SL_q(2)$ is considered, but the most interesting examples should be associated with 1-loop affine algebra, especially of level $k > 1$, and their universal enveloping.

F. ALBERTO GRÜNBAUM:
Time and band limiting and symmetries of KP

A Schrödinger operator $L = -\partial^2 x + V(x)$ such that for some family of eigenfunctions, $L_\varphi = \lambda_\varphi$, one has $B(\lambda, \frac{d}{d\lambda})\varphi \equiv \left(\sum_{j=0}^{m} a_j(\lambda)\left(\frac{d}{dx}\right)^j\right)\varphi = \Theta(x)\varphi$ for a finite m and some $a_j(\lambda), \Theta(x)$ is called a bispectral Schrödinger operator. This consists of the cases: $V(x) = c/x^2, \alpha x$ and two families of $V(x)$, i.e., rational solutions of KdV as well as solutions of certain Virasoro flows that are rational functions of x. These are results of Duistermaat-Grünbaum und Magri-Zubelli. I show that if ones forms the integral operator T in $L^2(-G, G)$ with kernel

$$K(k_1, k_2) = \int_0^T \varphi(x, h_1)\varphi(x, k_2)dx$$

then there exists a DIFFERENTIAL OPERATOR D such that

$$TD = DT.$$

This is done so far in all cases except the KdV case and extends classical results of Slepian, Landau, Pollak developed to understand the work of Shannon in communication theory.

LASZLO FEHÉR:
Generalized Drinfeld-Sokolov reductions

A classical W-algebra generalizing the second Gelfard-Dickey Poisson bracket may be associated to every sl_2 subalgebra of a simple Lie algebra G using Drinfeld-Sokolov type Hamiltonian reduction.

One may also generalize the Drinfeld-Sokolov construction of hierarchies using the graded regular elements of the inequivalent graded Heisenberg algebras of $G \otimes (\tau\lambda, \lambda^{-1})$. The Heisenberg algebras are parametrized by the Weyl group of G, and in the case of the simple Lie algebras of type A, B, C, D we find the list of their graded regular elements. For $G = sl_n$, we describe the KdV type hierarchies associated to the graded regular elements of minimal grade, which turn out to be the matrix generalizations of the r-KdV hierarchies, and also include the "reduced KP hierarchies" discussed by L. Dickey at the present meeting.

FRANCO MAGRI:
KP equations without pseudodifferential operators

This talk aims to suggest a geometric point of view in the theory of soliton equations. The belief is that a deeper understanding of the origin of these equations may provide a better understanding of their remarkable properties. According to the geometric point of view, soliton equations are the outcome of a specific reduction process of a bihamiltonian manifold, which is equivalent to, but different from the Drinfeld-Sokolov reduction. Our suggestion is to pay attention also to th "unreduced form" of soliton equations.

In particular, the Gelfard-Dickey's hierarchy is introduced starting from the Casimir's functions of a pencil of (modified) Lie-Poisson brackets, and the KP equations are seen as the evolution equations in the dual of the symmetry algebra.

KANEHISA TAKASAKI, TAKASHI TAKEBE:
Dispersionless integrable hierarchies and higher dimensional generalizations

Dispersionless limits of integrable hierarchies are not only interesting in themselves in applications to topological conformal field theories, but also useful as a toy model to search for new integrable hierarchies (in particular, in higher dimensions). The dispersionless KP and Toda hierarchies inherit many significant properties of the ordinary KP and Toda hierarchies. Of particular interest are the notions of tau functions and $W_{1+\infty}$ symmetries, which play an important role in applications to physics. These notions are shown to be carried out to dispersionless (or quasi-classical) limit. In general, many formulae in the original KP and Toda hierarchies simplify in the dispersionless hierarchies. This allows us to guess their higher dimensional generalizations. Along these lines, a few higher dimensional dispersionless hierarchies have been constructed, and in a special case, the notion of tau function is introduced.

MARK ADLER:
Symmetries, W-algebras and applications

The aim of these talk was to show the robustness of symmetries for a variety of integrable systems, and to show how they are used to derive various geometrical properties of these system. In particular, we consider the KP and Toda symetries and discuss:

1) special solutions of the KdV
2) solving $[L, P] = 1$ and Kontsevich integrals
3) infinite families of symplectic structure for the Gelfard-Dickey equations
4) orthogonal polynomials and matrix integrals and their Virasoro constraints.

T. SHIOTA, P. VAN MOERBEKE:

A Lax pair for the vertex operator and the central extension of W-algebras

The vertex operator can be viewed as a tangent vector field to the space of τ-functions for the KP equation. In joint work with Adler und P. van Moerbeke, I show that this vertex operator has a representation in terms of a Lax pair at the level of symmetry vector fields to the manifold of wave operators. A similar study can be done for the 2-dimensional Toda lattice. This technology has applications to 1-matrix, 2-matrix models and Kontsevich integrals; namely, it provides the constraints for those integrals.

RAIMUND VARNHAGEN:

Topoloy and fractional quantum Hall effect

First we show that the Hall conductance σ_{xy} of a two dimensional layer is proportional to the topological quantity $\frac{c_1}{r}$ $\left(\sigma_{xy} = \frac{e^2}{h}\frac{c_1}{r}\right)$ where c_1 is the first Chern number of a rank r vectorbundle. This vector bundle describes the degenerated ground state of the Hall system.

From Laughlin type wave functions with generalized periodic boundary conditions we explicitly construct these vector bundles and we show that only for the experimentally observed fractions these vector bundles are indecomposable.

In special cases we calculate the fluctuations of the curvature which converge exponentially to zero in the limit of infinite particle number.

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