1.2 Modern Mathematical Physics

Many aspects of Modern Mathematical Physics (MMP) are connected to Superstring Theory (SST). Being right or wrong, nobody can deny that SST is the most creative theory in modern physics, and most ambitious. In particular, SST has posed and is attempting to solve many difficult problems in other domains of MMP (and even in pure mathematics). These include Supersymmetry (SUSY) and Supergravity (SUGRA), Quantum Gravity (QG) and Mathematical Cosmology, Integrable Systems and Quantum Groups (or Noncommutative Theory). Recently, SST generated new hopes for finding some new approaches to nonperturbative Yang - Mills theory. Although significant results were obtained only in Supersymmetric Yang - Mills theories (SYM), the hopes gradually go stronger that SYM will teach us important lessons that will finally be used in QCD. The hopes are based on recent successes of different dualities, the oldest of which relate solitons that are strongly nonlinear ('nonperturbative') objects to simple particle states of a field theory. SST uncovered new solitons and soliton-like structures in rather an unusual environment, like compactified higher dimensional supergravity theories. The idea that some higher dimensions may lead to real physical, observable effects in gravity and cosmology provokes curiosity of both theorists and experimentalists. From MMP point of view this is also a challenge that requires developing mathematical concepts and tools adequate to new physical and geometrical objects. On the other hand, the new solitons stimulated renewal of interest in low - dimensional integrable models that, in fact, may describe complex higher - dimensional phenomena. Of special interest in this connection are supersymmetric integrable hierarchies as well as various multi-soliton states.

SST is one of the sources of noncommutative quantum field theories. Although big expectations of this new development were not quite achieved, various aspects of noncommutative physics and mathematics are still worth of pursuing and may eventually produce significant progress in physics and mathematics. For example, there exist hopes that introducing noncommutative coordinates may shed new light on the most difficult and persistent problem of quantizing gravity. Even if these hopes will prove to be not justified, developing such nonstandard ideas is certainly useful. More generally, the present state of affairs in quantum gravity and cosmology requires reconsidering many commonly accepted concepts and literally cries for 'crazy' ideas and methods. Our small community working in some of the mentioned directions of MMP is trying to respond to challenges of new physics and mathematics as much as possible.

A.T. Filippov

BRAID GROUP SYMMETRY IN NONCOMMUTATIVE GEOMETRY AND IN INTEGRABLE MODELS

P.N. Pyatov

Discrete symmetries manifest themselves in many instances in modern physics (e.g., in models with sets of identical objects, in crystals etc.) and mathematics (regular polytopes, Weyl groups, theory of symmetric functions etc.). As a rule, they are suitably realized through an action (of an appropriate quotient) of the braid group. The simplest but very important example of such a realization is given by permutation matrices acting on either a set of objects or tensor powers of vector space. A very deep and fruitful generalization of the permutation matrix was elaborated during the last three decades in the framework of the Quantum Inverse Scattering Method. This is a notion of an R-matrix. Nowadays the R-matrix formalism provides a ”covariant” realization of the braid group symmetry in integrable models treated with QISM and in the theory of Quantum Groups.

A principal aim of our research is to develop an R-matrix formalism in its full generality using the last decade advances in a representation theory of finite dimensional quotients of the braid group (such as Hecke and Birman-Murakami-Wenzl algebras). The final goal here is an application of the formalism for investigation of specific integrable models and for construction of noncommutative, quantum group covariant differential geometry.

Naturally enough, constructing the R-matrix formalism is going in parallel to understanding an algebraic and geometric meaning of newly introduced notions. Thus, our strategy is to develop the R-matrix techniques while investigating *structure theory and spectral values of quantum matrix algebras* (joint research project with D.I. Gurevich, A.P. Isaev, O.V. Ogievetsky, and P.A. Saponov). This program of finding a general context for the notion of matrices, their eigenvalues, matrix multiplication and their characteristic identities is further developed in [1–3]. From the physical viewpoint this program is aimed at constructing a natural set of commuting variables (q-matrix eigenvalues interpreted either as integrals of motion, or as angle variables) for a family of models treated by means of the QISM.

In [1], the Cayley-Hamilton identities are derived for the quantum supermatrices of $GL(m|n)$ type. In [2], a necessary R-matrix technique is developed for the case of quantum orthogonal and symplectic matrices. It is shown, in particular, that orthogonal/symplectic type R-matrices carry information about invariant pairing on their corresponding vector spaces. In [3], a structure theory of the $GL(n)$- type quantum matrices is applied for investigation of an algebra of zero modes of the chiral $SU(n)$ WZNW model.

Another but closely related direction of our research is understanding and exploiting a *hidden braid group symmetry in statistical loop models, in the models of stochastically growing interfaces, and in the open Heisenberg spin chains* (joint research with J.de Gier and V.Rittenberg) [4,5]. It is well known that the evolution operator of all three above-mentioned models can be defined in terms of the $GL(2)$-type Drinfeld-Jimbo R-matrix. Our strategy is to go one level higher: from the language of R-matrices up to the level of (appropriately extended) Temperley-Lieb algebras which they represent. In this way, we can see a mathematical (but not physical!) equivalence of all three models and adopt methods developed for each of these models to other cases.

A unifying description for the open spin=1/2 XXZ chain and for a family of Raise and Peel Models (RPM) of a one-dimensional fluctuating interface is developed in [4]. Combinatorial properties of the stationary states of three particular RPM’s are analyzed and compared in detail and explicit formulas for the weights of various stationary configurations for these models are given. It is shown that these weights satisfy a series of bilinear recurrent equalities – the Pascal's hexagon relations. Interestingly enough, Pascal's hexagon also gives solutions to Hirota's difference equation. In [5], the Hamiltonian of the Temperley-Lieb loop model with open boundaries is diagonalized using a coordinate Bethe Ansatz calculation. The spectrum of the loop model contains that of the open spin-1/2 XXZ chain with nondiagonal boundary conditions. Thus, a recently conjectured solution of the complete spectrum of this XXZ chain is derived.

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TOWARDS HIGHER N SUPERSYMMETRIC QUANTUM MECHANICS

E. Ivanov, S. Krivonos

Supersymmetric quantum mechanics (SQM) [1] provides deep insights into supersymmetric field theories in diverse dimensions, as well as into string theory. In particular, superconformal quantum mechanics (SCQM) has profound implications in the AdS_2/CFT_1 and black holes stuff. Taking into account these and some other uses, the construction and analysis of new SQM and SCQM models is an urgent and interesting task. For the last two years, an essential progress was achieved in understanding extended SQM models with $N = 4$ and $N = 8$, $d = 1$ supersymmetries [2]–[9]. Previously, only SQM models with $N \leq 4$ were basically explored (e.g. in [10]).

In recent papers [2, 4, 5], an efficient method of deducing $d{=}1$ off-shell multiplets and relevant superfields originally proposed in [11] was further advanced and applied to $N = 4, 8$ SQM models. It is based on nonlinear realizations of the finite-dimensional superconformal groups in $d{=}1$. The irreducible superfields representing one or another off-shell $d{=}1$ supermultiplet come out as the Goldstone superfields parametrizing one or another coset manifold of the proper $d{=}1$ superconformal group. This method automatically specifies the superconformal properties of the involved supermultiplets which is of importance when setting up the conformal SQM models. The complementary method of constructing off-shell actions of various $N{=}4, d{=}1$ multiplets was developed in [3] within the $N{=}4, d{=}1$ harmonic superspace formalism.

In [4], the full set of off-shell $N{=}4$ supermultiplets with **4** physical fermions (and a finite number of auxiliary fields) was deduced proceeding from nonlinear realizations of the most general $N{=}4, d{=}1$ superconformal group $D(2,1;\alpha)$. The results obtained can be summarized in the Table below.

multiplet	content	R symmetry coset	dilaton	α	superfield
“old tensor”	**(1,4,3)**	–	yes	any	u
chiral	**(2,4,2)**	central charge	yes	$0,-1$	$\phi,\bar{\phi}$
nonlinear chiral	**(2,4,2)**	$su(2)/u(1)$	no	any	$\Lambda,\bar{\Lambda}$
tensor	**(3,4,1)**	$su(2)/u(1)$	yes	any	V^{ij}
nonlinear	**(3,4,1)**	$su(2)$	no	any	N^{ia}
hypermultiplet	**(4,4,0)**	$su(2)$	yes	any	q^{ia}

The application of the same method to the so far unexplored case of $N{=}8, d{=}1$ supersymmetry was initiated in [5]. There, nonlinear realizations of the $N{=}8, d{=}1$ superconformal group $OSp(4^\star|4)$ in its two different cosets were constructed and it was shown that two interesting $N{=}8, d{=}1$ multiplets, with the off-shell field contents **(3, 8, 5)** and **(5, 8, 3)**, naturally come out as the corresponding Goldstone multiplets. Superconformally invariant actions for these multiplets in $N{=}4, d{=}1$ superspace were constructed for all possible splittings of them in terms of $N{=}4$ off-shell multiplets. Thus, the new models of superconformal quantum mechanics were set up.

An exhaustive list of off-shell $N{=}8$ supermultiplets with 8 physical fermions and the relevant constrained $N{=}8, d{=}1$ superfields were derived in [6]. These findings can be considered as preparatory to considering nonlinear realizations of all known $N{=}8$ superconformal groups in their various cosets and identifying various $N{=}8$ multiplets with the relevant Goldstone superfields, similarly to what has been done for $N{=}4$ supermultiplets in [2, 4]. In the $N{=}8$ case this task is much more complicated in view of the existence of many nonequivalent $N{=}8$ superconformal groups ($OSp(4^\star|4)$, $OSp(8|2)$, $F(4)$ and $SU(1,1|4)$ with numerous coset manifolds. The field contents of *linear* off-shell multiplets of $N{=}8, d{=}1$ supersymmetry with **8** physical fermions was found to range from **(8, 8, 0)** to **(0, 8, 8)** with the intermediate multiplets corresponding to all possible divisions of **8** bosonic fields into physical and auxiliary ones. The results obtained in [6] are summarized in the Table below.

Multiplet	$N{=}8$ Superfields	$N{=}4$ splittings
(0, 8, 8)	$\Psi^{aA}, \Xi^{i\alpha}$	$(\mathbf{0},\mathbf{4},\mathbf{4})\oplus(\mathbf{0},\mathbf{4},\mathbf{4})$
(1, 8, 7)	$\mathscr{U}$	$(\mathbf{1},\mathbf{4},\mathbf{3})\oplus(\mathbf{0},\mathbf{4},\mathbf{4})$
(2, 8, 6)	$\mathscr{U}, \Phi$	$(\mathbf{1},\mathbf{4},\mathbf{3})\oplus(\mathbf{1},\mathbf{4},\mathbf{3})$ $(\mathbf{2},\mathbf{4},\mathbf{2})\oplus(\mathbf{0},\mathbf{4},\mathbf{4})$
(3, 8, 5)	$\mathscr{V}^{ij}$	$(\mathbf{3},\mathbf{4},\mathbf{1})\oplus(\mathbf{0},\mathbf{4},\mathbf{4})$ $(\mathbf{1},\mathbf{4},\mathbf{3})\oplus(\mathbf{2},\mathbf{4},\mathbf{2})$
(4, 8, 4)	$\mathscr{Q}^{a\alpha}$	$(\mathbf{4},\mathbf{4},\mathbf{0})\oplus(\mathbf{0},\mathbf{4},\mathbf{4})$ $(\mathbf{3},\mathbf{4},\mathbf{1})\oplus(\mathbf{1},\mathbf{4},\mathbf{3})$ $(\mathbf{2},\mathbf{4},\mathbf{2})\oplus(\mathbf{2},\mathbf{4},\mathbf{2})$
(5, 8, 3)	$\mathscr{U}, \mathscr{V}^{a\alpha}$	$(\mathbf{1},\mathbf{4},\mathbf{3})\oplus(\mathbf{4},\mathbf{4},\mathbf{0})$ $(\mathbf{3},\mathbf{4},\mathbf{1})\oplus(\mathbf{2},\mathbf{4},\mathbf{2})$
(6, 8, 2)	$\mathscr{V}^{ij}, \mathscr{W}^{ab}$	$(\mathbf{3},\mathbf{4},\mathbf{1})\oplus(\mathbf{3},\mathbf{4},\mathbf{1})$ $(\mathbf{4},\mathbf{4},\mathbf{0})\oplus(\mathbf{2},\mathbf{4},\mathbf{2})$
(7, 8, 1)	$\mathscr{V}^{ij}, \mathscr{Q}^{a\alpha}$	$(\mathbf{3},\mathbf{4},\mathbf{1})\oplus(\mathbf{4},\mathbf{4},\mathbf{0})$
(8, 8, 0)	$\mathscr{Q}^{aA}, \Phi^{i\alpha}$	$(\mathbf{4},\mathbf{4},\mathbf{0})\oplus(\mathbf{4},\mathbf{4},\mathbf{0})$

These results consitute a basis for a more detailed study of the $N{=}8$ SQM models associated with the supermultiplets considered. In particular, it would be interesting to explore a possible relation of the corresponding $N=8$ SCQM models to the physics of branes and black holes, e.g. along the line pursued for the $N=4$ case in [12, 13], where the equivalence between the $N=4$ superparticles describing near-horizon geometry of the Reissner-Nordström black holes and $N=4$ SCQM was proven. The intriguing questions are whether some dynamical models with higher $N>8, d=1$ supersymmetry can be constructed by combining some of the $N=8$ multiplets considered in [6] and how the latter are related to multiplets with an infinite number of auxiliary fields, which naturally appear in various versions of *harmonic* $N=8, d=1$ superspace (see e.g. [14, 8]). Some important algebraic and geometric aspects of the SQM models associated with the multiplet $(\mathbf{4},\mathbf{8},\mathbf{4})$ and two closely related to each other multiplets $(\mathbf{3},\mathbf{8},\mathbf{5})$ and $(\mathbf{2},\mathbf{8},\mathbf{6})$ were a subject of recent papers [7, 8, 9].

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NON - ANTICOMMUTATIVE SUPERSPACE

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Recently it was discovered that certain string backgrounds in the low-energy limit give rise to supersymmetric field theories living on superspaces with nonanticommuting Grassmann coordinates. In particular, a specific four-dimensional compactification of the type IIB string in the presence of a constant self-dual graviphoton background $F^{\alpha\beta}$ yields superspace whose odd coordinates obey the Clifford algebra

$$\{\theta^{\alpha},\theta^{\beta}\} = \alpha'^{2}F^{\alpha\beta}\,, \tag{1}$$

rather than the standard Grassmann algebra [1]. This superspace and supersymmetry realized in it must be of Euclidean signature since a real field strength cannot be self-dual in Minkowski space. This deformation breaks the original $N{=}(\frac{1}{2},\frac{1}{2})$ supersymmetry down to $N{=}(\frac{1}{2},0)$ but preserves the important notion of chirality. The basic technical device of constructing the corresponding superfield theories is the Moyal-Weyl star product generalized to Grassmann coordinates [2].

The main motivation for studying such nonanticommutative (or nilpotently deformed) supersymmetric field theories comes from the desire to better understand the symmetry and geometric structure of various effective low-energy limits of string theory. They can also have phenomenological implications. In particular, such deformations could provide a new geometric mechanism of soft supersymmetry breaking.

A natural step beyond the analysis of non-anticommutative $N{=}(\frac{1}{2},\frac{1}{2})$ superspace in [1] is the study of analogous nilpotent chiral deformations of Euclidean $N{=}(1,1)$ superfield theories. This study was initiated in [3, 4] and then continued in our papers [5]-[8]. Both the D-type and Q-type deformations were considered with either spinor covariant derivatives D^{i}_{α} or supersymmetry generators Q^{i}_{α} as the building blocks of the bi-differential Poisson operator specifying the relevant star products.

The Q-deformations generically break the $N{=}(1,1)$ supersymmetry by half, but preserve both chirality and anti-chirality. The simplest $N{=}(1,1)$ Q-deformation is the singlet one ('QS-deformation') based on the Poisson operator

$$P_{s} = -I\overleftarrow{Q}^{i}_{\alpha}\overrightarrow{Q}^{\alpha}_{i}\,, \qquad \text{with} \quad (P_{s})^{5} = 0\,, \tag{2}$$

where I is a real parameter and Q^{i}_{α} are the left-handed supersymmetry generators. While breaking half the supersymmetry, it preserves the internal SU(2)$_R\times$Spin(4) symmetry. The QS-deformation can be given a stringy interpretation like the Q-deformation considered in [1]. Namely, such a non-anticommutative $N{=}(1,1)$ superspace naturally arises for the $N{=}4$ superstring coupled to a complex axion background. The Q-deformations and their QS-subclass preserve Grassmann harmonic analyticity which is the fundamental notion in theories with manifest extended supersymmetry.

The detailed superfield and component structure of the QS-deformed $N{=}(1,1)$ U(1) and U(n) gauge theories was explored in [6]. In particular, an analog of the Seiberg-Witten (SW) map to quantities with undeformed gauge and supersymmetry transformation laws was explicitly worked out. The component Lagrangian of the deformed U(1) gauge theory is related to the standard undeformed free $N{=}(1,1)$ gauge theory Lagrangian by a simple field-dependent rescaling [6]

$$L_{g} = (1+4I\bar{\phi})^{2}[-\frac{1}{2}\varphi\,\Box\bar{\phi} + \frac{1}{4}f^{2}_{mn} + \frac{1}{8}\varepsilon_{mnrs}f_{mn}f_{rs} - i\psi^{\alpha}_{k}\partial_{\alpha\dot{\alpha}}\bar{\psi}^{\dot{\alpha}k} + \frac{1}{4}(d^{kl})^{2}]\,, \tag{3}$$

where $f_{mn} = \partial_m a_n - \partial_n a_m$ and $\varphi, \bar{\phi}, a_m, \psi^\alpha_k, \bar{\psi}^{\dot{\alpha}k}$ and d^{kl} are component fields of the vector multiplet. In [6], we also gave an analogous deformed Lagrangian for a non-Abelian theory.

An important class of $N{=}(1,1)$ theories is that including matter hypermultiplets interacting with themselves and with gauge multiplets. The theory of self-interacting hypermultiplets yields, in the bosonic sector, Euclidean versions of hyper-Kähler sigma models. The hypermultiplets coupled to $N{=}(1,1)$ gauge multiplets could be of relevance from the phenomenological point of view. The system of a gauge superfield minimally coupled to a hypermultiplet in the adjoint representation of the gauge group provides an off-shell $N{=}(1,1)$ superfield formulation of $N{=}(2,2)$ supersymmetric gauge theory which is the Euclidean analog of the renowned $N{=}4$ super Yang-Mills theory.

In [3], we gave general recipes of how to construct Q-deformations of the superfield hypermultiplet actions. In [7, 8], we considered QS-deformation of simple concrete actions with the hypermultiplet and U(1) gauge superfields.

A notable feature of the two considered hypermultiplet models is that there are only two inequivalent ways to realize the deformed U(1) gauge transformations on the hypermultiplet superfields. Our first example is the coupled system of an $N{=}(1,1)$ U(1) gauge superfield and a neutral hypermultiplet. In terms of the undeformed fields related to the deformed ones by a kind of SW-transform the action is radically simplified, though there remains a non-trivial interaction between the fermionic fields of the hypermultiplet and the gauge field. Besides the manifest unbroken $N{=}(1,0)$ supersymmetry, the resulting action possesses one more hidden on-shell $N{=}(1,0)$ supersymmetry and thus describes a QS-deformed $N{=}(2,2)$ gauge theory with the residual $N{=}(2,0)$ supersymmetry.

We also analysed the QS-deformation of a charged hypermultiplet in the minimal interaction with a U(1) gauge multiplet. In the undeformed case, this interacting system possesses no extra supersymmetry besides the manifest $N{=}(1,1)$ one. The QS-deformation breaks the latter down to $N{=}(1,0)$. We analyzed the component action of this deformed $N{=}(1,1)$ electrodynamics and the corresponding scalar field potentials and mass terms. The relevant SW-transformation to the undeformed fields was explicitly constructed.

There remain many open problems to be explored in this new area of research. It is worth distinguishing among them a further analysis, at the classical and quantum levels, of QS-deformations of gauge theory with extended $N{=}(2,2)$ supersymmetry in various superfield formulations, the study of possible modifications of hyper-Kähler geometries of deformed $N{=}(1,1)$ supersymmetric sigma models, and generalization to the case of generic (nonsinglet) Q-deformations. These and related studies are now under way.

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FERMIONIC TODA LATTICE HIERARCHIES

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The two-dimensional Toda Lattice (2DTL) hierarchy has far-reaching applications in modern mathematical physics. Its relevance to conformal and topological field theory and string theory permanently stimulates a subsequent investigation of the 2DTL hierarchy from both physical and mathematical aspects, including the formulation and study of its supersymmetric extensions.

At present, two different nontrivial supersymmetric extensions of the 2DTL hierarchy are known - the $N=(2|2)$ and $N=(0|2)$ supersymmetric Toda lattice hierarchies. Actually, besides a different number of supersymmetries they have different bosonic limits which are decoupled systems of two infinite bosonic Toda lattice hierarchies and single infinite bosonic Toda lattice hierarchy, respectively.

In [1], the Sato equations of the $N=(2|2)$ supersymmetric Toda lattice hierarchy were extended by two new infinite series of fermionic flows, and it was demonstrated that the algebra of the flows of the extended hierarchy is the Borel subalgebra of the $N=(2|2)$ loop superalgebra.

In [2], starting with the zero-curvature representation

$$[\partial_1+L^-,\partial_2-L^+]=0,\quad (L^-)_{i,j}=\rho_i\delta_{i,j+1}+d_i\delta_{i,j+2},\quad (L^+)_{i,j}=\delta_{i,j-2}+\gamma_i\delta_{i,j-1}+c_i\delta_{i,j}$$

we introduced the 2D generalized fermionic Toda lattice equations and investigated their symmetries and reductions for different boundary conditions. Two reductions related with the $N=(2|2)$ and $N=(0|2)$ supersymmetric Toda lattice equations were described. At the reduction to the 1D space the zero-curvature representation can identically be rewritten in the form of the Lax-pair representation. The bi-Hamiltonian structure of the 1D generalized fermionic Toda lattice hierarchy was constructed and its bosonic and fermionic Hamiltonians were found as supertraces of the Lax operators.

In [2], we also considered the 1D N=4 and N=2 supersymmetric Toda lattice hierarchies and constructed their bi-Hamiltonian structures, investigated their fermionic symmetries, and studied a transition to the canonical basis which spoils a number of supersymmetries.

The supersymmetric Toda lattice hierarchies with periodic boundary conditions were considered in [2, 3]. The $(2m\times 2m)$-matrix zero-curvature representation with the spectral parameter was constructed for the $2m$-periodic 2D generalized fermionic Toda lattice hierarchy and the bi-Hamiltonian structure of its one-dimensional reduction was obtained. It was shown that in 1D space this hierarchy had an alternative description in terms of the (4×4)-supermatrix Lax operators $\partial\mathfrak{L}_j(\lambda)=\mathfrak{U}_{j+1}(\lambda)\mathfrak{L}_j(\lambda)-\mathfrak{L}_j(\lambda)\mathfrak{U}_j(\lambda)$,

$$\mathfrak{L}_j(\lambda)=\begin{pmatrix}-\gamma_j & -\rho_j & \lambda-c_j & -d_j\\ 0 & 0 & 1 & 0\\ 1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\end{pmatrix},\quad \mathfrak{U}_j(\lambda)=\begin{pmatrix}0 & -d_{j+1} & -\rho_{j+1} & 0\\ 1 & c_{j-1}-\lambda & \gamma_{j-1} & 0\\ 0 & -\rho_j & 0 & -d_j\\ 0 & \gamma_{j-2} & 1 & c_{j-2}-\lambda\end{pmatrix}$$

which allowed one to investigate its integrability properties. Thus, its r-matrix and monodromy matrix were calculated and analyzed, and their spectral curves were constructed. The periodic 1D $N=2$ Toda lattice hierarchy which has the (3×3)-supermatrix Lax pair representation was discussed in the same approach.

In [4], using the generalized graded bracket introduced in [5] we proposed a new 2D fermionic (K,M)-TL hierarchy in terms of the Lax-pair representation

$$D_s^{\pm} L^{\alpha}_{\Omega^{\alpha}} = \mp\alpha(-1)^{s\Omega^{\alpha}\Omega^{\pm}}[(((L^{\pm}_{\Omega^{\pm}})^s_*)_{-\alpha})^{*(\Omega^{\alpha})}, L^{\alpha}_{\Omega^{\alpha}}\}, \quad \alpha=+,-, \quad \Omega^+=K, \quad \Omega^-=M,$$
$$(L_{\Omega^{\alpha}})^{2s}_* \equiv (L^{*(\Omega^{\alpha})}_{\Omega^{\alpha}} L_{\Omega^{\alpha}})^s, \quad (L_{\Omega^{\alpha}})^{2s+1}_* \equiv L_{\Omega^{\alpha}}(L_{\Omega^{\alpha}})^{2s}_*, \quad s\in\mathbb{N},$$
$$L^+_K = \sum_{k=0}^{\infty} u_{k,i} e^{(K-k)\partial}, \quad L^-_M = \sum_{k=0}^{\infty} v_{k,i} e^{(k-M)\partial}$$

and constructed the algebra of its flows. All known up to now 2D TL equations can be derived from this hierarchy as subsystems. The reduction of the 2D fermionic (K,M)-TL hierarchy to the 1D space reproduces the 1D generalized fermionic TL equations [2] as the first flow of the reduced hierarchy with additional constraint imposed.

Although the Hamiltonian representations of different 1D Toda hierarchies have been known for a long time, the problem of constructing the Hamiltonian structures for the bosonic 2D Toda lattice hierarchy was solved only quite recently. It was carried out in the framework of the R-matrix method. In [4], this method was generalized to the case of Z_2-graded operators in order to derive the bi-Hamiltonian structure of the 2D fermionic (K,M)-TL hierarchy. Defining the R-matrix on the associative algebra $\mathfrak{g}$ of the Z_2-graded difference operators $\mathbb{O}$ and using the generalized graded bracket we constructed two Poisson brackets for the functionals on $\mathrm{g}^{\dagger} = \mathrm{g}$.

$$\begin{aligned}\{f,g\}_1(\mathbb{O}) &= 1/2 < (-1)^{d_{\nabla g} d_{\mathbb{O}}} R(\nabla g)^{*(d_{\mathbb{O}})}[\mathbb{O}^{*(d_{\nabla g})}, (\nabla f)^{*(d_{\nabla g})}\} - [\mathbb{O}, \nabla g\} R((\nabla f)^{*(d_{\nabla g})}) >,\\ \{f,g\}_2(\mathbb{O}_B) &= -1/4 < [\mathbb{O}_B, \nabla g\} R((\nabla f)^{*(d_{\nabla g})} \mathbb{O}_B^{*(d_{\nabla f}+d_{\nabla g})} + \mathbb{O}_B^{*(d_{\nabla g})}(\nabla f)^{*(d_{\nabla g})})\\ &\quad - R(\nabla g \mathbb{O}_B^{*(d_{\nabla g})} + \mathbb{O}_B \nabla g)[\mathbb{O}_B^{*(d_{\nabla g})}, (\nabla f)^{*(d_{\nabla g})}\} > .\end{aligned}$$

The properties of the Poisson brackets are provided by the properties of the generalized graded bracket. For Z_2-graded difference operators of odd (even) parity this bracket defines odd (even) first Poisson structures.

In this approach, the Hamiltonian description of the 1D and 2D fermionic (K,M)-TL hierarchies was constructed [4]

$$D_s^{\pm}\begin{pmatrix} u_{n,i} \\ v_{n,i}\end{pmatrix} = \{\begin{pmatrix} u_{n,i} \\ v_{n,i}\end{pmatrix}, H^{\pm}_{s+1}\}_1 = \{\begin{pmatrix} u_{n,i} \\ v_{n,i}\end{pmatrix}, H^{\pm}_s\}_2, \quad H^+_s = \frac{1}{s} str(L^+_N)^s_*, \quad H^-_s = \frac{1}{s} str(L^-_M)^s_*.$$

Applying the R-matrix which acts nontrivially on the space of the direct sum of two difference operators we derived two different Hamiltonian structures of the 2D fermionic (K,M)-TL hierarchy. The first Hamiltonian structure was obtained for both even and odd values of (K,M) while the second one was established for even values of (K,M) only.

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INTEGRABLE LOW DIMENSIONAL MODELS FOR BLACK HOLES AND COSMOLOGIES

A.T. Filippov

It is well known that 1+1 dimensional dilaton gravity coupled to scalar matter fields is a reliable model for some aspects of high dimensional black holes, cosmological models and branes. The connection between high and low dimensions has been demonstrated in different contexts of gravity and string theory and in some cases allowed one to find a general solution or special classes of solutions in high dimensional theories. These solutions may describe interesting physical objects - spherical static black holes, simplest cosmologies, etc. However, when the scalar fields, which presumably play a significant cosmological role, are not constant, a few exact solutions of high dimensional theories are known. Correspondingly, the two - dimensional models of dilaton gravity coupled to scalar matter are usually not integrable in any sense.

In 2001-2002 we proposed a class of integrable models of 1+1 and 1-dimensional dilaton gravity coupled to scalar fields. The models can be derived from high dimensional supergravity theories by dimensional reductions. The equations of motion of these models reduce to systems of the Liouville equations endowed with energy and momentum constraints which constitute the most difficult part of the problem. In 2003–2004 we constructed the explicit general solution of the 1+1 dimensional problem in terms of chiral moduli fields and established its simple reduction to static black holes (dimension 0+1), and cosmological models (dimension 1+0). In addition, we have recently found wave - type solutions that describe scalar matter waves that may be localized in space. These new solutions may be of importance for understanding both the evolution of black holes and cosmology.

The three basic types of solutions of the gravity coupled to matter (static states, cosmological models, and gravity - matter waves) are usually treated quite differently. We argued that there existed an approach to dimensional reduction in which they could be naturally related. This relation was studied in some detail for static states and cosmologies and can be considered as a sort of ‘static–cosmology’ duality (SC-duality). In the integrable models transitions between static and cosmological states are possible and, moreover, the waves play a significant role in these transitions. This observation, which does not actually require integrability, may open a way to study real physical connections between these apparently diverse objects.

The results are published in [1], [3], [2]

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BLACK HOLE PHYSICS: QUANTUM AND CLASSICAL ASPECTS

D.V. Fursaev

It is a common belief now that the explanation of the microscopic origin of the Bekenstein-Hawking entropy of black holes should be available in quantum gravity theory, whatever this theory will finally look like. Calculations of the entropy of certain black holes in string theory do support this point of view. In the last few years there is also much hope that an understanding of black hole entropy may be possible even without knowing the details of quantum gravity. The thermodynamics of black holes is a low-energy phenomenon, so only a few general features of the fundamental theory may be really important. The review [1] describes some of the proposals in this direction and the results obtained.

One of such proposals is related to induced gravity models. In [2], a derivation of the entropy of black holes in induced gravity models was given on the basis of conformal properties of induced gravity constituents near the horizon. The four-dimensional (4D) theory was first reduced to a tower of two-dimensional (2D) gravities such that each 2D theory is induced by fields with certain momentum p along the horizon. It was demonstrated that in the vicinity of the horizon constituents of the 2D induced gravities are described by conformal field theories (CFT) with specific central charges depending on spin and nonminimal couplings and with specific correlation lengths depending on the masses of fields and on the momentum p. This enabled one to use CFT methods to count partial entropies $s(p)$ in each 2D sector. The sum of partial entropies correctly reproduced the Bekenstein-Hawking entropy of the 4D induced gravity theory. The results of [2] indicate that earlier attempts at the derivation of the entropy of black holes based on a near-horizon CFT may have a microscopic realization.

The most dramatic predictions of scenarios with large extra dimensions is a possibility of creation of mini black holes in future collider experimenters. In the general case, such black holes are rotating. When bulk gravitons are emitted, the black holes also acquire an angular momentum in the bi-plane not lying within the brane. Classical interaction of rotating higher dimensional black holes with a brane in space-times with large extra dimensions was studied in [3],[4]. It was shown that a rotating black hole attached to a brane can lose bulk components of its angular momenta. A stationary black hole can have only those components of the angular momenta which are connected with Killing vectors generating transformations preserving a position of the brane. It was proved that in a final stationary state the null Killing vector generating the black hole horizon is tangent to the brane. The characteristic time when a rotating black hole with the gravitational radius r_0 reaches this final stationary state is $T \sim r_0^{p-1}/(G\sigma)$, where G is the higher dimensional gravitational coupling constant, σ is the brane tension, and p is the number of extra dimensions.

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HAMILTONIAN DESCRIPTION OF LAGRANGE SYSTEMS WITH GIVEN CONSTRAINTS

B.M. Barbashov

The Dirac method [1] of constructing the Hamiltonian formalism for degenerate Lagrange systems is well known and it is widely used in elementary particle physics and quantum field theory. This method involves a quite cumbersome procedure of classifying the Hamiltonian constraints as the primary and secondary constraints and, at the same time, as the first and the second class constraints with substituting the Poisson brackets by the Dirac brackets. At a sight, one could infer that this method is probably the only possible way for treating the constrained systems. However, there are situations where the Dirac method does not work at least in the straightforward way. The simplest example of such dynamical systems is the standard electrodynamics with the Lorentz gauge condition. In this case, one cannot replace all the velocities involved in the gauge condition by the respective canonical momenta because the Lagrangian is singular. Such constraints are referred to as 'noncanonical constraints'. Recently, Faddeev and Jackiw [2] have proposed a clear and convenient method for treating the constrained systems, the so-called 'first order formalism' which is close to the Dirac formalism.

Less known is another way for constructing the Hamiltonian description of constrained systems that may involve constraints following from the initial singular Lagrangian as well as the constraints given 'by hand' from the very beginning. The method was proposed in 1974 by F.A. Berezin [3]; however, this paper did not become well known among physicists. The development of the Berezin approach and its application to a series of models was accomplished in paper [4]. The starting point of this approach is the construction of the generalized Lagrange function which includes the initial one and the given constraints with the respective Lagrange multipliers. By making use of this Lagrangian the generalized canonical momenta are introduced in the standard way. Further, the velocities and the Lagrange multipliers should be expressed in terms of the canonical momenta and canonical coordinates by making use of the initial constraints and the definition of the canonical momenta. In this framework, the following systems are considered: a special Lagrangian linear in velocities, relativistic particle in proper time gauge, relativistic string in orthonormal gauge, Maxwell field and vector massive field in the Lorentz gauge. An appealing feature of this approach is, in particular, a nonvanishing identically canonical Hamiltonian in the case of singular Lagrangians. The relation of this approach to the Dirac method is elucidated and the problems that should be investigated here are revealed.

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INTEGRAL EQUATIONS FOR HEAT KERNEL IN COMPOUND MEDIA

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The heat kernel technique [1, 2] is widely used for constructing quantum field theory in he gravitational background and with allowance for nontrivial boundary conditions. Of particular interest is the asymptotic expansion of the heat kernel it terms of the evolution parameter for its small positive values. The coefficients of this expansion pertain to divergences and anomalies in the relevant quantum field theory models. Proceeding with this one can develop, in particular, the renormalization procedure needed. However, there are no universal methods for constructing the heat kernel and its asymptotic expansion. The development of different approaches to this problem is the subject of many works (see, for example, the reviews [1, 2, 3] and references therein).

The initial definition of the heat kernel is the Green function of the heat-conduction equation with an elliptic operator under study. In many physical problems it is worth going from the differential equation, defining the solution to be found or the relevant Green function, to the equivalent integral equation. In the dynamical evolution problems the integral equations manifestly show the reason-consequence relations governing the physical process under study. Reducing the problem to the integral equation, as a rule, allows one to develop the method of successive approximations(perturbation theory).

On analogy with the Laplace equation the potential theory was also developed for the heat conduction equation in classical mathematical physics (A.N. Tikhonov and his school). However, the heat potential technique is not well known among physicists unlike the Newtonian potentials. In paper [4], by making use of the potentials of the heat conduction equation, the integral equations are derived which determine the heat kernel for the Laplace operator $-a^2\Delta$ in the case of compound media. In each of the media the parameter a^2 acquires a certain constant value. At the interface of the media the conditions are imposed which demand the continuity of the ‘temperature’ and the ‘heat flows’. The integration in the equations is spread out only over the interface of the media. As a result the dimension of the initial problem is reduced to 1. In the case of compound media the standard methods for the investigation of heat kernel do not work because in this case the principal part of the elliptic operator in question is not smooth.

The perturbation series for the integral equations derived are nothing else but the multiple scattering expansions for the relevant heat kernels. Thus, a rigorous derivation of these expansions is given. In the one-dimensional case the integral equations at hand are solved explicitly (Abel equations) and the exact expressions for the regarding heat kernels are obtained for diverse matching conditions. Derivation of the asymptotic expansion of the integrated heat kernel for compound media is considered by making use of the perturbation series for the integral equations obtained. The method proposed is also applicable to the configurations when the same medium is divided by a smooth compact surface into internal and external regions, or when only the region inside (or outside) this surface is considered with appropriate boundary conditions.

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THEORY OF ELLIPTIC HYPERGEOMETRIC FUNCTIONS

V.P. Spiridonov

Elliptic hypergeometric functions represent a radically new class of special functions of mathematical physics. Such functions first appeared in the form of a very peculiar series of hypergeometric type describing elliptic solutions of the Yang-Baxter equation (I.B. Frenkel and V.G. Turaev, 1997) and particular solutions of the Lax pair equations for a new discrete-time integrable chain (V.P. Spiridonov and A.S. Zhedanov, 1999). The next important development consisted in the discovery of the one dimensional elliptic beta integral depending on two basic variables q and p (V.P. Spiridonov, 2000). This integral and its multivariable generalizations to the C_n root system (J.F. van Diejen and V.P. Spiridonov, 2001) were the first representatives of a new class of exactly computable contour integrals. During the last two years these results were extended further on and analysis of many aspects of the general theory of the elliptic hypergeometric functions were completed.

In [2], a general theory of theta hypergeometric integrals was developed. Under some restrictions connected with the double periodicity property of elliptic functions, these integrals reduce to elliptic hypergeometric integrals with the elliptic beta integrals being their very special subcases. In particular, theta functional and elliptic analogs of the Meijer functions were built in this way (a new type of the q-Meijer functions was introduced as well). Another important result of [2] consists in the discovery of the modified elliptic gamma function which is well defined when one of the basic parameters lies on the unit circle, say $|q| = 1$, in contrast to the standard elliptic gamma function.

The set of elliptic beta integrals was extended to a large extent. In [2], a new such C_n integral related to the Warnaar's determinant was proved. Also there were introduced two different types of such integrals associated with the A_n root system reducing in the $p \to 0$ limit to a Gustafson and Gustafson-Rakha integrals. In [7], an A_n elliptic beta integral was found which appeared to be new even at the q- and plain hypergeometric levels. In [1, 5], the modified versions of most known elliptic beta integrals valid for $|q| \leq 1$ was described. The $p \to 0$ limit in modified elliptic beta integrals leads to new q-beta integrals expressed in terms of the double sine function. In [3], an integral analog of the Bailey chains was built for the first time and an infinite binary tree of identities for elliptic hypergeometric integrals of different multiplicities was derived.

In [2], a full description is given of biorthogonal functions on elliptic grids expressed in terms of elliptic hypergeometric series and having an absolutely continuous part of measure determined by the univariate elliptic beta integral. These functions generalize Askey-Wilson orthogonal polynomials and Rahman-Wilson biorthogonal rational functions and have various properties of classical special functions: difference equation, three term recurrence relation, self-duality, etc. They have also intrinsically new features like two-index biorthogonality. Poisson algebras for the corresponding generalized eigenvalue problems were discussed in [9]. Some new results in the general theory of biorthogonal rational functions were derived in [8], where the most general known terminating continued fraction expressible in terms of hypergeometric type functions was derived as well. In [4], an attempt was made to generalize elliptic results to Riemann surfaces of arbitrary genus. However, only a relatively simple elliptic summation formula appeared to be generalizable so far. The most important results in the theory of elliptic hypergeometric functions were summarized in the habilitation thesis [6]. In particular, there it was indicated how elliptic hypergeometric integrals appear in the theory of relativistic Calogero-Moser type equations with elliptic potentials. All elliptic beta integrals are expected to lead to some elliptic integrable systems, and so far only one of them (associated with the BC_n root system) has been investigated in detail.

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