ICTS
INTERNATIONAL CENTRE for THEORETICAL SCIENCES
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Scientific Contributions of Spenta Wadia

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String Theory: Past and Present

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ICTS, Bengaluru

Graduate studies (1973-78)

Ph.D. degree from City University of NY

Advisor: Sakita

Thesis: *Canonical Quantization Of Non-Abelian Gauge Theory In The Schrodinger Picture: Applications to Monopoles and instantons*

Theme: Quantization of gauge theories, correct treatment of surface terms in a gauge independent manner, gauge-fixing problems

This is the first paper to discuss the role of asymptotic gauge transformations in a non-abelian gauge theory.

- *The Surface Term in Gauge Theories*, Jean-Loup Gervais, B. Sakita, S.R. Wadia, Phys.Lett. 63B (1976) 55

Discussion of the theta-vacuua in different gauges. It also contained the first discussion of the degeneracy of gauge fixing conditions in non-Abelian gauge theories, an issue which is now familiar to us as the Gribov ambiguity! (Gribov's paper appeared almost a year later)

- *The Role of Surface Variables in the Vacuum Structure of Yang-Mills Theory*, T. Yoneya, S.R. Wadia, Phys.Lett. 66B (1977) 341-345

Post doctoral research (1978-82)
University of Chicago

At Chicago, I know that Spenta's thinking was mainly influenced by Nambu and Kadanoff. Spenta carried the influences from New York and Chicago with him to India, and these were to continue to shape his future scientific work.

Theme: non-perturbative properties of gauge theories, especially confinement, using lattice gauge theory, large-N methods, etc.

His first attempt to derive string equations on lattice (following the works of Nambu and Gervais and Neveu).

- *Variational Approach and Duality in Strong Coupling QCD*, T. Eguchi, S.R. Wadia, Phys.Rev.Lett. 43 (1979) 665.

A unified approach to large N limit in various problems and gave exact loop equations on the lattice. The latter paper has a careful treatment of intersections in loops.

- *On the Dyson-Schwinger Equations Approach to the Large N Limit: Model Systems and String Representation of Yang-Mills Theory*, Spenta R. Wadia, Phys. Rev. D24 (1981) 970.

His next work explored connection of electric-magnetic duality with quark confinement, e.g. for SU(3) a plasma of an octet of monopoles confines the fundamental representation quarks. (This work corrected an error in Polyakov's classic paper on confinement in 2+1 dims, which claimed that half-integer charged monopoles confine integer charged quarks in SU(2) gauge theory!).

- *Topology of Quantum Gauge Fields and Duality. 1. Yang-Mills Higgs System in (2+1)-dimensions*, S.R. Das, S.R. Wadia, Phys.Lett. 106B (1981) 386, Erratum: Phys.Lett. 108B (1982) 435.

Next came the third order transition in large-N QM, which we now know as Gross-Witten-Wadia (GWW) transition. A decade later, it became the basis for double scaling limit in c=1 matrix model.

- *N = Infinity Phase Transition in a Class of Exactly Soluble Model Lattice Gauge Theories*, Spenta R. Wadia, Phys.Lett. 93B (1980) 403-410.

(An earlier study of a similar large N transition in 2-dim gauge theory was published years later:

- *A Study of U(n) Lattice Gauge Theory in 2-dimensions*, S.R. Wadia, EFI preprint, 1979 and arXiv:1212.2906 [hep-th])

For the four post-doc years (1978-82) at Chicago, Spenta was working on some of the most important problems of the times – some of them, like confinement, are still with us today. I think it is here that he was acquiring, without realizing it, the skills, and the courage, to take on bigger responsibilities.

These came soon after he joined TIFR as faculty in 1982, where, except for the initial couple of years, he largely worked on String Theory.

1982-84

NJL model as a phenomenological model for chiral symmetry breaking in QCD.

Work inspired by Witten's beautiful papers on topological aspects of the Wess-Zumino term. A confining gauge theory has a mass gap. Hence integrate out the gauge fields to obtain effective non-linear local Lagrangian for fermions.

How does one get the anomalous WZW term?

- *The Nambu-Jona-Lasinio Model: An Effective Lagrangian for Quantum Chromodynamics at Intermediate Length Scales*, A. Dhar, S.R. Wadia, Phys.Rev.Lett. 52 (1984) 959; A. Dhar, R. Shankar, S.R. Wadia, Phys.Rev. D31 (1985) 325.

- *Large N Baryons: Collective Coordinates of the Topological Soliton in SU(3) Chiral Model*, S. Jain, S.R. Wadia, Nucl.Phys. B258 (1985) 713.

1984 onwards - Research primarily in String Theory

Worked on a few different themes:

Conformal invariance as an underlying principle of string theory; exactly solvable models to understand principles of string theory; black hole puzzles ; AdS/CFT correspondence

1. Conformal invariance as an underlying principle of string Theory:

These papers showed that vanishing of conformal anomaly is a necessary requirement for consistent string propagation and that Virasoro gauge conditions imply the string equations of motion.

- *Conformal Invariance and String Theory in Compact Space: Bosons*, S. Jain, R. Shankar, S.R. Wadia, Phys.Rev. D32 (1985) 2713.

- *Virasoro Conditions, Vertex Operators and String Dynamics in Curved Space*, S. Jain, G. Mandal, S.R. Wadia, Phys.Rev. D35 (1987) 778.

In non-critical strings, conformal invariance is enforced by integrating over the 2-dim metric.

Interpretation of the Liouville mode as a space-time direction!

- *Quantization of the Liouville Mode and String Theory*, S.R. Das, S. Naik, S.R. Wadia, Mod.Phys.Lett. A4 (1989) 1033.

This was confirmed in the light-cone gauge using the operator methods of KPZ to show that D=25 string coupled to 2-d gravity indeed gives rise to closed string amplitudes.

- *The Role of Quantized Two-dimensional Gravity in String Theory*, A. Dhar, T. Jayaraman, K.S. Narain, S.R. Wadia, Mod.Phys.Lett. A5 (1990) 863.

2-d gravity dressed bgd. fields satisfy classical equations of motion

- *Critical Behavior in Two-dimensional Quantum Gravity and Equations of Motion of the String*, S.R. Das, A. Dhar, S.R. Wadia, Mod.Phys.Lett. A5 (1990) 799.

2. Study of exactly solvable models to understand principles of string theory:

Matrix models: First discussion of double trace operators and change of critical behavior

- *New Critical Behavior in d=0 Large N Matrix Models*, S.R. Das, A. Dhar, A.M. Sengupta, S.R. Wadia, Mod.Phys.Lett. A5 (1990) 1041-1056.

c=1 matrix model: exact treatment in terms of non-relativistic fermions

- *Excitations and interactions in d = 1 string theory*, A.M. Sengupta, S.R. Wadia, Int.J.Mod.Phys. A6 (1991) 1961-1984.

- *Interactions and scattering in d = 1 string theory*, G. Mandal, A.M. Sengupta, S.R. Wadia, Mod.Phys.Lett. A6 (1991) 1465-1478

Discovery of W_∞ algebra

- *Gauge theory formulation of the c=1 matrix model: Symmetries and discrete states*, S.R. Das, A. Dhar, G. Mandal, S.R. Wadia, Int.J.Mod.Phys. A7 (1992) 5165-5192.

Exact bosonization of c=1 matrix model and showed the approximate nature of collective field theory

- *Nonrelativistic fermions, coadjoint orbits of W_∞ and string field theory at c = 1*, A. Dhar, G. Mandal, S.R. Wadia, Mod.Phys.Lett. A7 (1992) 3129-3146.

3. Black hole puzzles

c=1 matrix model is unitary and `dual' to 2-dim string theory, where the Liouville mode becomes a space dimension. So if there is a black hole solution in 2-dim string theory, then we can address some of the important problems of black hole physics.

- *Classical solutions of two-dimensional string theory,*
  G. Mandal, A.M. Sengupta, S.R. Wadia, Mod.Phys.Lett. A6 (1991) 1685-1692.

However, 2-dim dilaton gravity is probably too simple.

Further success came in higher dimensions. Strominger and Vafa presented a calculation of black hole entropy using D-brane microstates and Boltzmann's formula. Next, a calculation of Hawking radiation from near extremal black holes gave the correct answer (modulo proportionality constant). This work did a calculation of absorption cross-section and showed that it also agreed with the classical calculation.

- *Absorption versus decay of black holes in string theory and T symmetry*, A. Dhar, G. Mandal, S.R. Wadia, Phys.Lett. B388 (1996) 51-59.

These works confirmed the D-brane modeling of a near extremal black hole and Hawking radiation and played a role in arriving at Maldacena's AdS/CFT correspondence.

This work was followed by a series of papers which made precise the microscopic modeling of near extremal black holes in the context of a 2-d gauge theory. The efforts culminated in a comprehensive review.

- *D-brane black holes: Large N limit and the effective string Description*, S.F. Hassan, S.R. Wadia, Phys.Lett. B402 (1997) 43-52.

- *Gauge theory description of D-brane black holes: Emergence of the effective SCFT and Hawking radiation*, S.F. Hassan, S.R. Wadia, Nucl.Phys. B526 (1998) 311-333

- Absorption and Hawking radiation of minimal and fixed scalars, and AdS / CFT correspondence, J.R. David, G. Mandal, S.R. Wadia, Nucl.Phys. B544 (1999) 590-611.

- Microscopic formulation of black holes in string theory, J.R. David, G. Mandal, S.R. Wadia, Phys.Rept. 369 (2002) 549-686

4. AdS/CFT correspondence

This paper demonstrated the existence of an infinite number of non-local charges in $AdS_5 \times S^5$ theory in the light-cone gauge.

- *Aspects of semiclassical strings in $AdS_5 \times S^5$*, G. Mandal, N.V. Suryanarayana, S.R. Wadia, Phys.Lett. B543 (2002) 81-88.

Small black hole ↔ string states transition in the bulk corresponds to the 3rd order GWW transition in the gauge theory

- *Finite temperature effective action, AdS_5 black holes, and 1/N expansion*, L. Alvarez-Gaume, C. Gomez, Hong Liu, S.R. Wadia, Phys.Rev. D71 (2005) 124023.

- *Black hole / String Transition for the Small Schwarzschild black hole of $AdS_5 \times S^5$ and Critical Unitary Matrix Models*, L. Alvarez-Gaume, P. Basu, M. Marino, S.R. Wadia, Eur.Phys.J. C48 (2006) 647-665.

What can AdS/CFT say about stirred turbulent flows?

- *Forced Fluid Dynamics from Gravity*, S. Bhattacharyya, R. Loganayagam, S. Minwalla, S. Nampuri, S.P. Trivedi, S.R. Wadia, JHEP 0902 (2009) 018.

The following work showed that the non-Relativistic Navier-Stokes equations are universal limit of relativistic hydrodynamics

- *The Incompressible Non-Relativistic Navier-Stokes Equation from Gravity*, S. Bhattacharyya, S. Minwalla, S.R. Wadia, JHEP 0908 (2009) 059.

Recent work - 2+1 dim Chern-Simons matter theories:

A series of papers uncovered remarkable dualities: level-rank duality of CS theory implies fermion-boson duality.

- *Chern-Simons Theory with Vector Fermion Matter*, S. Giombi, S. Minwalla, S. Prakash, S.P. Trivedi, S.R. Wadia, Xi Yin, Eur.Phys.J. C72 (2012) 2112.

A complex phase structure is implied by the `discreteness' of the eigenvalues of the zero mode of the holonomy matrix

- *Phases of large N vector Chern-Simons theories on* $S^2 \times S^1$, S. Jain, S. Minwalla, T. Sharma, T. Takimi, S.R. Wadia, S. Yokoyama, JHEP 1309 (2013) 009.

The bosonic and fermionic S-matrices (of CS coupled to bosonic or fermionic matter) map to each other under the bose-fermi duality after a level-rank transposition. However, the S-matrices have unusual structural features; they include a non-analytic piece localized on forward scattering (due to the `magnetic flux' carried by the `charged particles' as a consequence of Gauss's law), and obey modified crossing, also required by unitarity.

- *Unitarity, Crossing Symmetry and Duality of the S-matrix in large N Chern-Simons theories with fundamental matter*, S. Jain, M. Mandlik, S. Minwalla, T. Takimi, S.R. Wadia, S. Yokoyama, JHEP 1504 (2015) 129

Congratulations!