CURRICULUM VITAE

Name	:	Ashoke Sen
Birth	:	July, 1956
Field of Specialization	:	High Energy Physics
Designation	:	Professor
Address	:	Harish-Chandra Research Institute Chhatnag Road, Jhusi Allahabad 211019, India.
e-mail	:	ashokesen1999@gmail.com
Fax Number	:	91 532 2569576
Academic records	:	B.Sc. (Physics) Calcutta University (1975) M.Sc. (Physics) I.I.T. Kanpur (1978) Ph.D. (Physics) SUNY at Stony Brook (1982)
Post-doctoral fellowships	:	October 1982 - July 1985

		Fermilab, USA
		August 1985 - February 1988 SLAC (USA)
Other positions held	:	March 1988 - September 1997 Tata Institute of Fundamental Research
Fellowships of Academies (national)	:	Fellow, Indian Academy of Sciences, elected 1991
		Fellow, Indian National Science Academy, elected 1995
		Fellow, National Academy of Sciences, India, elected 1997
Fellowships of Academies (international)	:	Fellow, Royal Society, London elected 1998
		Fellow, Third World Academy of Sciences elected 2004
Awards (national)	:	1994 S. S. Bhatnagar award

		1995 B.M. Birla Science Prize
		1996 G.D. Birla award
		1998 R.D. Birla award
		2001 Padmashri
		2001 Kamal Kumari National award
		2004 INSA S.N.Bose Award lecture
		2005 H.K. Firodia award
		2006 J C Bose Fellowship, DST, Govt of India
		2009 Infosys prize
		2013 Padma Bhushan
		2013 M P Birla award
Awards (international)	:	1989 ICTP prize in honour of H. Yukawa
		1997 Third World Academy of Sciences Prize
		2006 Pius IX Gold Medal
		2012 Fundamental Physics Prize
		2014 Dirac Medal (ICTP)
Honorary degrees	:	D.Sc., University of Calcutta
		D.Sc., Indian Institute of Technology, Kharagpur
		D.Sc., Bengal Engineering and Science University, Shibpur
		D.Sc., Panjab University

D.Sc., Indian Institute of Technology, Kanpur

D.Sc., Indian Institute of Technology, Bombay

D.Litt., Jadavpur University

D.Sc., IISER, Kolkata

D.Sc., Shiv Nadar University, Delhi

D.Sc., Vidyasagar University, Medinipur

Distinguished lectures and visits (international)

- Rothschild Visiting Professor, Feb.-March, 1997 and June 21 - July 20, 2002, Isaac Newton Institute, Cambridge, U.K.
- Morris Loeb Lecturer, April 17-27, 2000, Harvard University, Cambridge, USA
- Walter a. Eva Andrejewski foundation Lecturer, Humboldt University, Berlin, Germany, Mar 4-10, 2002
- James H. Simons lecturer, April 29 - May 10, 2002, SUNY at Stony Brook, New York, USA
- PIMS distinguished chair at the University of British Columbia, The Pacific Institute for the Mathematical Sciences, August 2003
- Dirac lecture, June 20, 2005, DAMTP, Cambridge University, UK
- Morningstar visiting Professor, 2004, 2005, 2007 MIT, Cambridge, USA
- Einstein Colloquium, December 2005, Weizmann Institute, Israel.
- Stanford Institute For Theoretical Physics distinguished lecturer, May 2006.
- Moore Scholar, Caltech, February-March, 2007.
- JC Bose memorial lecture, Royal Society, London, June 11, 2007.

- Blaise Pascal chair, Univ. of Pierre and Marie Curie, Paris, September 2009 - September 2010
- KIAS scholar, KIAS, Seoul, May-June, 2013
- Distinguished Professor, KIAS, Seoul, May-June, 2015, September 2016.
- Run Run Shaw Distinguished Lecture, Stony Brook University, October 2016.

Distinguished lectures and visits (national)

- Saha memorial lecture, November 23, 1998, Saha Institute of Nuclear Physics, Kolkata, India
- Subhashis Nag memorial lecture, December 29, 2003, Institute of Mathematical Sciences, Chennai, India
- Acharya J. C. bose memorial lecture, November 30, 2004, Bose Institute, Kolkata
- S N Bose Memorial Lecture, S N Bose Center for Basis Sciences, Kolkata, December 29, 2008
- Chandrasekhar lecture, ICTS, TIFR, Mumbai, August 10, 2009
- Infosys visiting professor, IISc, Bangalore, February 2020
- Madan Lal Mehta lecture, TIFR, Mumbai, February 2020.

Invited talks at conferences and schools

1. Monopole '83, 6-9 Oct 1983, Ann Arbor, Michigan, USA
2. Workshop On Unified String Theories, 29 Jul - 16 Aug 1985, Santa Barbara, USA
3. Summer Workshop On High-Energy Physics And Cosmology, 30 Jun - 15 Aug 1986, Trieste, Italy
4. International Workshop On Superstrings, Composite Structures And Cosmology, 11-18 Mar 1987, College Park, Maryland, USA
5. CCAST Symposium / Workshop On Fields, Strings And Quantum Gravity, 29 May - 10 Jun 1989, Beijing, China
6. Workshop On Superstrings, 12-14 Jul 1989, Trieste, Italy

7. 5th SERC School on High Energy Physics, November - December 1989, Indian Institute of Technology, Kanpur, India
8. International Colloquium On Modern Quantum Field Theory, 8-14 Jan 1990, Bombay, India
9. 25th International Conference On High-Energy Physics (ICHEP 90), 2-8 Aug 1990, Singapore, Singapore
10. Summer School In High-Energy Physics And Cosmology, 18 Jun - 28 Jul 1990, Trieste, Italy
11. Strings And Symmetries 1991, 20-25 May 1991, Stony Brook, New York, USA
12. Trieste Summer School In High-Energy Physics And Cosmology, 17 Jun - 9 Aug 1991, Trieste, Italy
13. International Conference On Gravitation And Cosmology (ICGC 91), 12-18 Dec 1991, Ahmedabad, India
14. 7th SERC School on High Energy Physics, December 1991, Physical Research Laboratory, Ahmedabad, India
15. Workshop on string theory, 8-19 Apr 1992, Trieste, Italy
16. 16th Johns Hopkins Workshop On Current Problems In Particle Theory, 8-10 Jun 1992, Goteborg, Sweden
17. Trieste Summer School on High-Energy Physics and Cosmology, 15 Jun - 14 Aug 1992, Trieste, Italy
18. Meeting On Bose And 20th Century Physics, 30 Dec 1993 - 5 Jan 1994, Calcutta, India
19. Silver Jubilee Conference Of The Indian Association For General Relativity And Gravitation, 14-18 Feb 1994, Pune, India
20. ICTP Summer School In High-Energy Physics And Cosmology, 13 Jun - 29 Jul 1994, Trieste, Italy
21. 11th DAE Symposium On High-Energy Physics, 28 Dec 1994 - 2 Jan 1995, Shantiniketan, India

22. STRINGS 95: Future Perspectives In String Theory, 13-18 Mar 1995, Los Angeles, California, USA
23. ICTP Spring School On String Theory, Gauge Theory And Quantum Gravity, 27 Mar - 4 Apr 1995, Trieste, Italy
24. International Workshop On Supersymmetry And Unification Of Fundamental Interactions (SUSY 95), 15-19 May 1995, Palaiseau, France
25. ICTP Trieste Conference On S-Duality And Mirror Symmetry, 12-23 Jun 1995, Trieste, Italy
26. Frontiers In Quantum Field Theory In Honor Of The 60th Birthday Of Prof. K. Kikkawa, 14-17 Dec 1995, Toyonaka, Japan
27. 4th International Conference On Supersymmetries In Physics (SUSY 96), 29 May - 1 Jun 1996, College Park, Maryland, USA
28. ICTP Summer School In High-Energy Physics And Cosmology, 10 Jun - 26 Jul 1996, Trieste, Italy
29. European Research Conference On Advanced Quantum Field Theory In Memory Of Claude Itzykson, 31 Aug - 5 Sep 1996, La Londe Les Maures, France
30. Workshop On Frontiers In Field Theory, Quantum Gravity And String Theory, 12-21 Dec 1996, Puri, India
31. 4th Jerusalem Winter School In Theoretical Physics On Dualities And Symmetries, 30 Dec 1996 - 8 Jan 1997, Jerusalem, Israel
32. Duality Symmetries in String Theory II, April 97, ICTP, Trieste, Italy
33. Strings 97 Meeting, 16-21 Jun 1997, Amsterdam, The Netherlands
34. 8th Marcel Grossmann Meeting On Recent Developments In Theoretical And Experimental General Relativity, Gravitation And Relativistic Field Theories (MG 8), 22-27 Jun 1997, Jerusalem, Israel
35. 13th SERC School on High Energy Physics, Feb 10 - Mar 3 98, Shantiniketan, India
36. Strings 98, 22-27 Jun 1998, Santa Barbara, California, USA
37. 29th International Conference On High-Energy Physics (ICHEP 98), 23-29 Jul 1998, Vancouver, British Columbia, Canada

38. 22nd Johns Hopkins Workshop On Novelties Of String Theory, 20-22 Aug 1998, Goteborg, Sweden
39. Strings 99, 19-25 Jul 1999, Potsdam, Germany
40. NATO Advanced Study Institute: TMR Summer School On Progress In String Theory And M-Theory (Cargese 99), 24 May - 5 Jun 1999, Cargese, Corsica, France
41. Advanced School On Supersymmetry In The Theories Of Fields, Strings And Branes, 26-31 Jul 1999, Santiago de Compostela, Spain
42. String Theory at the Millennium, Jan.12-15, 2000, Caltech, USA
43. Lennyfest, May 20-21, 2000, Stanford, USA.
44. 18th International Symposium On Lattice Field Theory (Lattice 2000), 17-22 Aug 2000, Bangalore, India
45. 14th DAE Symposium On High-Energy Physics, 18-22 Dec 2000, Hyderabad, India
46. Strings 2001: International Conference, 5-10 Jan 2001, Mumbai, India
47. 16th SERC School On Theoretical High-Energy Physics, 25 Feb - 16 Mar 2001, Allahabad, India
48. 8th International Symposium On Particle Strings And Cosmology (PASCOS 2001), 10-15 Apr 2001, Chapel Hill, North Carolina, USA
49. Avatars of M-Theory, June 5-8, 2001, ITP Santa Barbara, USA
50. The Duality Workshop: A Math/Physics Collaboration, June 18 - July 13, 2001, ITP, Santa Barbara, USA
51. Les Houches Summer School: Session 76: Euro Summer School On Unity Of Fundamental Physics: Gravity, Gauge Theory And Strings, 30 Jul - 31 Aug 2001, Les Houches, France
52. JHS/60, Nov.3-4, 2001, Caltech, USA
53. Supergravity At 25, 1-2 Dec 2001, Stony Brook, New York, USA
54. 14th Chris Engelbrecht Summer School In Theoretical Physics: Quantum Gravity, String Theory And Cosmology, 23 Jan - 1 Feb 2002, Stellenbosch, South Africa

55. DPF 2002: The Meeting Of The Division Of Particles And Fields Of The American Physical Society, 24-28 May 2002, Williamsburg, Virginia, USA

56. Strings 2002, 15-20 Jul 2002, Cambridge, England

57. International Conference On Theoretical Physics (TH 2002), 22-26 Jul 2002, Paris, France

58. 17th Nishinomiya-Yukawa Memorial Symposium: String Theory, 12-13 Nov 2002, Nishinomiya, Japan

59. 9th International Symposium On Particles, Strings And Cosmology (PASCOS 03), 3-8 Jan 2003, Mumbai (Bombay) India

60. ICTP Spring School On Superstring Theory And Related Topics, 31 Mar - 8 Apr 2003, Trieste, Italy

61. Theoretical Advanced Study Institute In Elementary Particle Physics (TASI 2003): Recent Trends In String Theory, 1-27 Jun 2003, Boulder, Colorado, USA

62. Strings 2003, 6-11 Jul 2003, Kyoto, Japan

63. Summer School On Strings, Gravity And Cosmology: 14-25 Jul 2003, Vancouver, BC, Canada

64. Nobel Symposium 2003: Cosmology And String Theory, 14-19 Aug 2003, Sigtunastiftelsen, Sweden

65. IPM String School And Workshop 2003, 29 Sep - 9 Oct 2003, Caspian Sea, Iran

66. 3rd ICTP Latin American String School (LASS 2003), 1-19 Dec 2003, Sao Paulo, Brazil

67. Spring School on Superstring Theory and Related Topics, 15-23 Mar 2004, Trieste, Italy

68. 18th Nordic String Meeting, May 13 to May 15, 2004, Groningen, The Netherlands

69. Onassis Lectures In Physics: Fields And Strings, 5-9 July 2004, Heraklion, Greece

70. Annual International Conference On Strings, Theory And Applications (Strings 2004), 28 Jun - Jul 2, 2004, Paris, France

71. Fourth Regional Conference of the Physics Academy of the North East(PANE), November 2004, Shilchar, India

72. International Workshop On String Theory (ISM04), 15-23 Dec 2004, Khajuraho, India

73. IPM String School and Workshop (ISS2005), 5-14 Jan 2005, Qeshm Island, Iran

74. ICTP Spring School On Superstring Theory And Related Topics, 14-22 Mar 2005, Trieste, Italy

75. Summer School on Strings, Gravity and Cosmology, Perimeter Institute, June 20 - July 8, 2005, Waterloo, Ontario, Canada

76. Strings 05 Conference, Fields Institute, July 11-16, 2005, Toronto, Canada

77. Workshop On Einstein's Legacy In The New Millennium, 15-22 Dec 2005, Tohsali Sands, Puri, India

78. 23rd Winter School In Theoretical Physics: String Theory: Symmetries And Dynamics, 28 Dec 2005 - 6 Jan 2006, Jerusalem, Israel

79. 12th Regional Conference on Mathematical Physics, 27 Mar - 1 Apr 2006, Islamabad, Pakistan

80. IPM String School And Workshop (ISS2006), 10-19 Apr 2006, Tehran, Iran

81. Strings 2006, 18-24 June, Beijing, China

82. 1st Asian String School, Seoul, Korea, January 8-19, 2007.

83. Prestrings 2007, Granada, June 18-22, 2007.

84. Strings 2007, Madrid, June 25-29, 2007.

85. Eurostrings 2007, Crete, July 1-7, 2007.

86. Indian String Meeting 2007, October 15 October 19, 2007, Allahabad, India.

87. 30 Years of Mathematical Methods in High Energy Physics, March 17-19, 2008 RIMS, Kyoto, Japan.

88. Spring School On Superstring Theory And Related Topics, 27 Mar - 4 Apr 2008, Trieste, Italy.

89. IPM string school, Isfahan, Iran, April 9-17, 2008.
90. Cargese Summer School, June 16 to June 28, 2008, Cargese, France
91. Eurostrings 2008, June 30 - July 4, 2008
92. Prestrings 2008, Zurich, 11-15 August, 2008.
93. Strings 2008, CERN Geneva, 18-23 August, 2008.
94. Indian Strings Meeting 2008, Pondicherry, Dec. 6-13, 2008
95. IISc Centenary conference, December 13-16, 2008, Bangalore, India.
96. IPM string school, April 9-18, 2009.
97. 4th School On Attractor Mechanism: SAM 2009, 29 Jun - 3 Jul 2009, Frascati, Italy.
98. Strings 2009, 22-26 Jun 2009, Rome, Italy.
99. PASCOS 2009, 6-10 Jul 2009, Hamburg, Germany.
100. 12th Marcel Grossmann Meeting On General Relativity (MG 12), 12-18 Jul 2009, Paris, France.
101. ICTS Inaugural Conference, Bangalore, 27-31 Dec, 2009
102. CERN Winter School on Supergravity, Strings, and Gauge Theory, 25-29 January 2010 CERN
103. Iberian Strings 2010, 10-12 Feb 2010, Porto, Portugal.
104. XXII Workshop Beyond the Standard Model, Bad Honnef, March 8 - 11, 2010
105. Strings 2010, 15-19 Mar 2010, College Station, Texas.
106. Solvay Workshop on Symmetries and dualities in gravitational theories, Brussels, May 19-21, 2010
107. 40th International Symposium Ahrenshoop on the Theory of Elementary Particles, Berlin August 23 - 27, 2010.
108. String Theory: Formal Developments and Applications, Cargese, June 21 - July 3, 2010

109. ICHEP 2010, Paris, July 22 to July 28, 2010.

110. Advanced String School, Puri, Oct 4-10, 2010

111. Indian Strings Meeting, Puri, January 2011

112. QFT 2011, Pune, February 2011

113. School & Conference on Modular Forms and Mock Modular Forms, ICTP, Trieste, Feb-Mar 2011

114. Sixth regional meeting in string theory, Milos, Greece, June 2011

115. Strings 2011, Uppsala, Sweden, June 2011

116. 25th Solvay Conference on Physics, Brussels, Belgium, October 2011

117. Asian Winter School on Strings,Particles and Cosmology, Japan, January 2012

118. String Theory: Holography and its application, Jerusalem, Israel, February 2012

119. ICTP Spring School, Trieste, Italy, March 2012

120. N=4 Super Yang Mills, 35 years after, Caltech, Los Angeles, USA, March-April, 2012

121. Progress in Quantum Field Theory and String Theory, Osaka, Japan, April 2012

122. IIP-ICTP School on Gravity and String Theory, Natal, Brazil, May 2012

123. Black Holes and Information, Santa Barbara, USA, May 2012

124. String Math 2012, Bonn, Germany, July 2012

125. The holographic Way: String theory, Gauge theory and Black Holes, Stockholm, Sweden, October 2012

126. Indian Strings Meeting, Puri, India, December 2012

127. Strings 2013, Seoul, South Korea, June 2013

128. GR20, Warsaw, Poland, July 2013

129. Rikkyo Math-Phys 2014, Tokyo, Japan, January 2014

130. Asian Winter School 2014, Puri, India, January 2014
131. Strings 2014, Princeton, USA, June 2014
132. Recent developments in string theory, Ascona, Switzerland, July 2014
133. String field theory and related aspects, SISSA, Trieste, Italy, July-August 2014
134. ICTP 50th Anniversary conference, ICTP, Trieste, October 2014.
135. CERN Winter school, Geneva, Switzerland, February 2015.
136. ICTP Spring School, Trieste, Italy, March-April, 2015.
137. Superstring perturbation theory, Perimeter Institute, Waterloo, Canada, April 2015.
138. String field theory and related topics, Center for Theoretical Physics, Sichuan University, China, May 2015.
139. Advanced String School, ICTS, Bangalore, India, June 2015.
140. Strings 2015, ICTS, Bangalore, India, June 2015
141. National Strings Meeting, Mohali, India, December 2015
142. Indian-Israeli workshop on quantum field theory and string theory, Goa, India, December 2105
143. String-Math 2015, Sanya, China, December 2015 - January 2016.
144. String geometry and BPS state counting, IHP, Paris, April 2016
145. School on Fundamental Aspects of String Theory, Sao Paolo, May, 2016
146. 10th Anniversary Celebration of Galileo Galilei Institute, May 2016
147. VIII workshop on string field theory and related topics, Sao Paolo, May-June, 2016
148. Cargese Summer School, Cargese, June 2016
149. Strings 2016, Beijing, August 2016
150. Workshop on String Theory and Quantum Field Theory, Kyoto, August 2016
151. KIAS 20th Anniversary Symposium, KIAS, Seoul, September 2016

152. YITP at 50, Stony Brook, October 2016
153. Symposium to Celebrate 75th Birthday of John Schwarz, Caltech, November, 2016
154. Indian Strings Meeting, Pune, December 2016
155. School and Workshop on Modular Forms and Black Holes, NISER Bhubaneswar, January 2017
156. CERN Winter School on Strings and Fields, February 2017
157. Advanced String School, Haifa, Israel, June 2017
158. Conference on String Field Theory, Tel Aviv, June 2017
159. Strings 2017, Tel Aviv, June 2017
160. Current Themes in High Energy Physics and Cosmology, Copenhagen, August 2017
161. National String meeting, Bhubaneswar, December 2017.
162. ICTS at Ten, ICTS, Bangalore, January 2018
163. Asian Winter School, ICTS, Bangalore, January 2018
164. 50 years of the Veneziano model, GGI, Florence, May 2018
165. Solvay workshop on Infrared Physics, Brussels, May 2018
166. Cargese Summer School in High Energy Physics and Astrophysics, June 2018
167. Amplitudes 2018, SLAC, Stanford, June 2018
168. Strings 2018, Okinawa, Japan, June 2018
169. New Frontiers in String Theory, YITP, Kyoto, July 2018
170. New Trends in Field Theories, BHU, November 2018
171. String and M-Theory: The New Geometry of the 21st Century, Singapore, December 2018
172. Indian strings meeting, IISER Trivandrum, December 2018
173. String Theory from a Worldsheet Perspective, Galileo Galilei Institute, Florence, April 2019.

174. String Field Theory and String Perturbation Theory, Galileo Galilei Institute, Florence, May 2019.

175. New Pathways in Explorations of Quantum Field Theory and Quantum Gravity Beyond Supersymmetry, ICTP, Trieste, June 2019

176. Strings 2019, Brussels, July 2019

177. The future of GW Astronomy, ICTS, Bangalore, August 2019

178. Precision Gravity: from the LHC to LISA, MIAPP, Munich, September 2019

179. Workshop on Supermoduli, ICTP, Trieste, September 2019

180. NSM 2019, IISER Bhopal, December 2019

181. M-theory and Mathematics, Abu Dhabi, January 2020

182. String field theory workshop, Sao Paolo, June 2020 (virtual)

183. String 2020, Cape Town, 29 June - 5, July 2020 (virtual)

184. Recent Developments in S-matrix theory, ICTS, Bangalore, July 2020 (virtual)

185. Rethinking the Relativistic Two-Body Problem: A Universe of Gravitational Waves, AEI Potsdam, August 2020 (virtual)

186. Recent advances in Mathematics and related areas, Kerala School of Mathematics, Kozhikode, December 2020 (virtual)

187. Kavli Asian Winter School, Beijing, January 2021 (virtual)

188. Workshop on Quantum Gravity, Higher Derivatives and Nonlocality, March 2021 (virtual)

189. Camplitudes 2021, California, March 2021 (virtual)

190. Conference on Gravitational scattering, inspiral, and radiation, Galileo Galilei Institute, Florence, April 2021 (virtual)

191. Quantum Gravity and Modularity, Dublin, May 2021 (virtual)

192. TASI 2021, Boulder, Colorado, June 2021 (virtual)

193. Strings 2021, Sao Paulo, June 2021 (virtual)

194. Amplitudes 2021, Copenhagen, August 2021 (virtual)
195. Workshop on Celestial Amplitudes and Flat Space Holography, Crete, August 2021 (virtual)
196. Workshop on string field theory and related topics, September 2021 (virtual)
197. Strings, Fields and Holograms, Ascona, October 2021 (virtual)

LIST OF RESEARCH PUBLICATIONS

In chronological order

[1] Ashoke Sen, ASYMPTOTIC BEHAVIOR OF THE SUDAKOV FORM-FACTOR IN QCD.

Phys.Rev.D24:3281,1981.

[2] Ashoke Sen, ASYMPTOTIC BEHAVIOR OF THE WIDE ANGLE ON-SHELL QUARK SCATTERING AMPLITUDES IN NONABELIAN GAUGE THEORIES.

Phys.Rev.D28:860,1983.

[3] Ashoke Sen, ASYMPTOTIC BEHAVIOR OF THE FERMION AND GLUON EXCHANGE AMPLITUDES IN MASSIVE QUANTUM ELECTRODYNAMICS IN THE REGGE LIMIT.

Phys.Rev.D27:2997,1983.

[4] Ashoke Sen, CONSERVATION LAWS IN THE MONOPOLE INDUCED BARYON NUMBER VIOLATING PROCESSES.

Phys.Rev.D28:876,1983.

[5] Ashoke Sen, George Sterman, CANCELLATION OF SUDAKOV EFFECTS IN THE DRELL-YAN PROCESS.

Nucl.Phys.B229:231,1983.

[6] Yoichi Kazama, Ashoke Sen, ON THE CONSERVATION OF ELECTRIC CHARGE AROUND A MONOPOLE OF FINITE SIZE.

Nucl.Phys.B247:190,1984.

[7] Ashoke Sen, A LOCALLY SUPERSYMMETRIC SU(6) GRAND UNIFIED THEORY WITHOUT FINE TUNING AND STRONG CP PROBLEMS.

Phys.Rev.D31:900,1985.

[8] Ashoke Sen, ROLE OF CONSERVATION LAWS IN THE CALLAN-RUBAKOV PROCESS WITH ARBITRARY NUMBER OF GENERATION OF FERMIONS.

Phys.Rev.Lett.52:1755,1984.

[9] Ashoke Sen, MONOPOLE INDUCED BARYON NUMBER VIOLATION DUE TO WEAK ANOMALY.

Nucl.Phys.B250:1,1985.

[10] Ashoke Sen, SLIDING SINGLET MECHANISM IN N=1 SUPERGRAVITY GUT.

Phys.Lett.148B:65,1984.

[11] Ashoke Sen, RADIATIVE CORRECTIONS IN GRAND UNIFIED THEORIES BASED ON N=1 SUPERGRAVITY. 1. NONGAUGE THEORIES.

Phys.Rev.D30:2608,1984.

[12] Ashoke Sen, COMPARISON OF THE CANONICAL HAMILTONIAN AND THE HAMILTONIAN OF CALLAN AND RUBAKOV FOR THE MONOPOLE FERMION SYSTEM.

Phys.Rev.D31:433,1985.

[13] Ashoke Sen, RADIATIVE CORRECTIONS IN SUPERSYMMETRIC GAUGE THEORIES.

Phys.Rev.D31:2100,1985.

[14] Ashoke Sen, BARYON NUMBER VIOLATION INDUCED BY THE MONOPOLES OF THE PATI-SALAM MODEL.

Phys.Lett.153B:55,1985.

[15] Ashoke Sen, Hidenaga Yamagishi, LOCALIZATION OF THE DYON CHARGE.

Phys.Rev.D31:3285,1985.

[16] Ashoke Sen, NATURALLY LIGHT HIGGS DOUBLET IN SUPERSYMMETRIC E6 GRAND UNIFIED THEORY

Phys.Rev.Lett.55:33,1985.

[17] Ashoke Sen, RADIATIVE CORRECTIONS IN GRAND UNIFIED THEORIES BASED ON N=1 SUPERGRAVITY. 2. GAUGE THEORIES.

Phys.Rev.D32:411,1985.

[18] L.D. McLerran, Ashoke Sen, THERMODYNAMICS OF QCD IN THE LARGE N LIMIT.

Phys.Rev.D32:2794,1985.

[19] Ashoke Sen, THE HETEROTIC STRING IN ARBITRARY BACKGROUND FIELD

Phys.Rev.D32:2102,1985.

[20] Ashoke Sen, EQUATIONS OF MOTION FOR THE HETEROTIC STRING THEORY FROM THE CONFORMAL INVARIANCE OF THE SIGMA MODEL

Phys.Rev.Lett.55:1846,1985.

[21] Ashoke Sen, LOCAL GAUGE AND LORENTZ INVARIANCE OF THE HETEROTIC STRING THEORY.

Phys.Lett.166B:300,1986.

[22] T. Banks, Dennis Nemeschansky, Ashoke Sen, DILATON COUPLING AND BRST QUANTIZATION OF BOSONIC STRINGS

Nucl.Phys.B277:67,1986.

[23] Ashoke Sen, SUPERSPACE ANALYSIS OF LOCAL LORENTZ AND GAUGE ANOMALIES IN THE HETEROTIC STRING THEORY.

Phys.Lett.174B:277,1986.

[24] Ashoke Sen, (2, 0) SUPERSYMMETRY AND SPACE-TIME SUPERSYMMETRY IN THE HETEROTIC STRING THEORY

Nucl.Phys.B278:289,1986.

[25] Dennis Nemeschansky, Ashoke Sen, CONFORMAL INVARIANCE OF SUPERSYMMETRIC SIGMA MODELS ON CALABI-YAU MANIFOLDS

Phys.Lett.178B:365,1986.

[26] Ashoke Sen, CENTRAL CHARGE OF THE VIRASORO ALGEBRA FOR SUPERSYMMETRIC SIGMA MODELS ON CALABI-YAU MANIFOLDS.

Phys.Lett.178B:370,1986.

[27] Ashoke Sen, HETEROTIC STRING THEORY ON CALABI-YAU MANIFOLDS IN THE GREEN-SCHWARZ FORMALISM

Nucl.Phys.B284:423,1987.

[28] Joseph J. Atick, Ashoke Sen, CORRELATION FUNCTIONS OF SPIN OPERATORS ON A TORUS.

Nucl.Phys.B286:189,1987.

[29] Joseph J. Atick, Ashoke Sen, SPIN FIELD CORRELATORS ON AN ARBITRARY GENUS RIEMANN SURFACE AND NONRENORMALIZATION THEOREMS IN STRING THEORIES.

Phys.Lett.186B:339,1987.

[30] Joseph J. Atick, Ashoke Sen, COVARIANT ONE LOOP FERMION EMISSION AMPLITUDES IN CLOSED STRING THEORIES.

Nucl.Phys.B293:317,1987.

[31] Joseph J. Atick, Lance J. Dixon, Ashoke Sen, STRING CALCULATION OF FAYET-ILIOPOULOS D TERMS IN ARBITRARY SUPERSYMMETRIC COMPACTIFICATIONS

Nucl.Phys.B292:109,1987.

[32] Joseph J. Atick, Ashoke Sen, TWO LOOP DILATON TADPOLE INDUCED BY FAYET-ILIOPOULOS D TERMS IN COMPACTIFIED HETEROTIC STRING THEORIES.

Nucl.Phys.B296:157,1988.

[33] Ashoke Sen, MASS RENORMALIZATION AND BRST ANOMALY IN STRING THEORIES.

Nucl. Phys.B304:403,1988.

[34] Joseph J. Atick, Jeffrey M. Rabin, Ashoke Sen, AN AMBIGUITY IN FERMIONIC STRING PERTURBATION THEORY.

Nucl.Phys.B299:279,1988.

[35] Joseph J. Atick, Gregory Moore, Ashoke Sen, SOME GLOBAL ISSUES IN STRING PERTURBATION THEORY.

Nucl.Phys.B308:1,1988.

[36] Joseph J. Atick, Gregory Moore, Ashoke Sen, CATOPTRIC TADPOLES.

Nucl.Phys.B307:221,1988.

[37] Samir D. Mathur, Sunil Mukhi, Ashoke Sen, CORRELATORS OF PRIMARY FIELDS IN THE SU(2) W Z W THEORY ON RIEMANN SURFACES.

Nucl.Phys.B305:219,1988.

[38] Samir D. Mathur, Sunil Mukhi, Ashoke Sen, DIFFERENTIAL EQUATIONS FOR CORRELATORS AND CHARACTERS IN ARBITRARY RATIONAL CONFORMAL FIELD THEORIES.

Nucl.Phys.B312:15,1989.

[39] Samir D. Mathur, Sunil Mukhi, Ashoke Sen, ON THE CLASSIFICATION OF RATIONAL CONFORMAL FIELD THEORIES.

Phys.Lett.B213:303,1988.

[40] Samir D. Mathur, Sunil Mukhi, Ashoke Sen, RECONSTRUCTION OF CONFORMAL FIELD THEORIES FROM MODULAR GEOMETRY ON THE TORUS.

Nucl.Phys.B318:483,1989.

[41] Samir D. Mathur, Ashoke Sen, DIFFERENTIAL EQUATION FOR GENUS TWO CHARACTERS IN ARBITRARY RATIONAL CONFORMAL FIELD THEORIES.

Phys.Lett.B218:176,1989.

[42] Ashoke Sen, EXACTLY SOLVABLE STRING COMPACTIFICATION ON CALABI-YAU MANIFOLDS IN THE GREEN-SCHWARZ FORMALISM.

Phys.Lett.B224:278,1989.

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Research summary

All scientific papers are based on the work of many others in the past. Mine are no exceptions. However in the summary of my research given below, I'll not add references to the many papers on which my work was based, even though I may mention some of the names. The original references may be found in my papers.

I have not attempted to cover everything that I have worked on. I also have not tried to follow the chronological order in which the work was done. This would have been difficult anyway since some of the topics were studied over many years, often with gaps of several years in between. Instead I have attempted to group together related topics. Even though as a graduated student I started by analyzing high energy behaviour of gauge theory scattering amplitudes, the main theme of my research has been string theory – the theory that attempts to give a unified description of all the constituents of matter and all the forces acting between them, including gravity. I'll first describe my work as a graduate student, then describe the various aspects of string theory that I have worked on. I'll end this summary by a somewhat provocative topic involving the future of our universe.

1 Sudakov form factor in QCD

My work as a graduate student was on the high energy behaviour of scattering amplitudes in gauge theories. In my first paper [1] I analyzed the three point amplitude a highly off-shell photon and a pair of on-shell quarks in non-abelian gauge theories. Working at the leading order in the power series expansion in inverse powers of the photon momentum, I gave a systematic procedure for resumming all the logarithms of the photon momentum to all orders in perturbation theory. These include the logs arising from the infrared, collinear and ultraviolet regions of loop momentum integration. Later I extended the analysis to four point scattering of quarks for large values of the Mandelstam invariants s, t and u [2].

2 String theory and conformal field theory

My first major project in string theory involved studying the relationship between the two dimensional σ-models describing string propagation in a given background field, and the space-time properties of these background fields. My main contribution during this project was to establish the relation between classical equations of motion of massless fields in string theory and conformal invariance of the two dimensional sigma model describing string propagation in background of these massless fields [19,20]. Later similar results were found by Callan, Friedan, Martinec and Perry. Working along this line I also showed that in order to get a string compactification that preserves $N = 1$ space-time supersymmetry, the corresponding two dimensional σ-model should have (2,0) world-sheet supersymmetry [24, 27]. This provided a way of looking for space-time supersymmetric vacua of string theory.

3 Solution generating techniques

I developed a method for generating new classical solutions of string theory from a known classical solution, when the original solution is independent of some of the space-time coordinates [60–62]. Using string field theory I also argued that these solution generating transformations can be extended to the full classical effective action of string theory, going beyond the leading two derivative approximation. Later, I used this method to generate the most general electrically charged rotating black hole solution in four dimensional heterotic string theory [81] and also a string solution carrying charge current that was used to give evidence for the proposal of Hull and Townsend and Witten that type IIA string theory compactified on K3 is dual to heterotic string theory compactified on T^6 [83].

4 Fayet-Iliopoulos term in string theory

In 1987, Dine, Seiberg and Witten used low energy effective field theory to argue that in some four dimensional string theories with U(1) gauge symmetry one loop effects can generate a Fayet-Iliopoulos D-term that can break supersymmetry. In collaboration with J. Atick and L. Dixon I showed how the presence of such a D-term can be verified in an explicit one loop string computation for any string compactification [31]. We also found that for most of the known string theories, the generation of the D-term does not break supersymmetry, since one can find a new supersymmetric vacuum in the space of field configurations. As described in §13, this was later put on a firmer footing using the tools of string field theory.

5 Strong weak coupling duality

One of my main topics of research has been the subject of strong-weak coupling duality or S-duality in string theory and quantum field theory. The original proposal for such a duality was given by Montonen and Olive in the late 70's, and it became clear through the work of Olive and Witten, Osborn and of Font, Ibanez, Lust and Quevedo that the proposal takes a firmer footing in $N = 4$ supersymmetric Yang-Mills theory and heterotic string theory compactified in T^6 which contains the former as its low energy limit. There were many evidences for this *e.g.* the BPS mass formula, symmetry of the equations of motions etc. but there was a general feeling in the community that these are simple consequences of supersymmetry and do not give non-trivial evidence for the strong weak coupling duality. While this is true to some extent, not everything follows from supersymmetry. In particular I argued that the existence of this duality requires a precise relation between charge quantization laws in the theory and the period of the θ-parameter that does not seem to follow from supersymmetry [69]. I summarized these evidences in [280] where I also argued that the duality symmetry leads to some precise prediction for the existence of certain dyonic states in the spectrum that were not known to exist at that time. In [78] I explicitly verified some of these predictions which eventually made the community take the idea of this duality more seriously. This also led to some precise mathematical conjectures on the existence of certain harmonic differential forms in the moduli spaces of monopoles studied earlier by Atiyah and Hitchin. This was then developed and extended by Seiberg and Witten, Vafa and Witten, Hull and Townsend and many others. I also did further work on this subject, finding new examples of dualities in string theory.

6 F-theory and orientifold

In 1996 C. Vafa proposed a new way of compactifying type IIB string theory known as F-theory. These compactifications are not accessible to the standard perturbative analysis, since the coupling constant of the theory becomes large in some regions in the internal space. Nevertheless based on various symmetry arguments Vafa argued that some of these compactifications are dual to more conventional string compactifications. I showed [94] that at least for some of these compactifications, one can take appropriate limits where they reduce to ordinary string compactifications – known as orientifolds – that are amenable to perturbative techniques, and the dualities proposed by Vafa can be understood in terms of more conventional dualities proposed earlier. This method has been used later to find various other dualities involving F-theory, and has also led to the discovery of new string compactifications in the search for duals of F-theory compactification. Extending the method of this paper I later showed [98] how one can take appropriate limit of a general F-theory compactification to map it into an orientifold.

7 Black holes and elementary strings

String theory contains black hole solutions which carry the same quantum numbers as elementary string states. The most general class of such black hole solutions in toroidally compactified heterotic string theory was constructed in [81]. Thus it is natural to ask if the degeneracy of black hole states, as counted by the Bekenstein-Hawking entropy, agrees with the degeneracy of elementary string states. If true, this will indicate that there is no distinction between the black holes and elementary string states, and at the same time, this would provide a statistical interpretation of Bekenstein-Hawking entropy from the counting of microscopic states. The main obstacle to this calculation had been that the degeneracy of elementary string states is calculable only in the weak coupling limit, whereas these states become black holes only for sufficiently large coupling when the gravitational effects are appreciable. I circumvented this problem by looking at the states which preserve part of the space-time supersymmetry (also known as BPS states), since it is known that for such states the degeneracy remains unchanged as we go from the strong to the weak coupling. Comparison of the black hole entropy according to (a stringy modification of) the Bekenstein-Hawking prescription, and the logarithm of the degeneracy of the elementary string states, showed an exact agreement between the two sides as functions of three independent parameters, – the mass and charge of the black hole, and the string coupling constant – up to an overall multiplicative numerical coefficient which could not be calculated explicitly [84]. Later similar agreement was found by Strominger and Vafa and many other authors in many other examples, where the numerical factor could be calculated. The missing numerical factor in my original analysis was calculated much later by Dabholkar, and shown to agree with the degeneracies of elementary string states.

8 Precision counting of black hole microstates

$\mathcal{N} = 4$ supersymmetric string theories typically contain a spectrum of dyon states which preserve 1/4 of the supersymmetries of the original theory. In collaboration with Justin David and Dileep Jatkar I computed the exact spectrum of dyons in a class of such string theories and verified the duality invariance of the spectrum [161, 163, 165, 167, 169]. One surprising feature of our results is that in all the theories, the generating function of the degeneracy / index is given by the inverse of a Siegel modular form. For the specific case of heterotic string theory compactified on T^6 the Siegel modular form is the Igusa cusp form, as conjectured by Dijkgraaf, Verlinde and Verlinde several years earlier. These results were then compared to the contribution from higher derivative and quantum corrections to black hole entropy in a variety of string compactifications that will be described in §9.

9 Stringy and quantum corrections to black hole entropy

The effective action of string theory contains correction to the Einstein-Hilbert action in the form of higher derivative terms in the action. This corrects the black hole solution as well as the black hole entropy. For the latter a general formula was written down by Wald. In 2005 I showed that the analysis simplifies enormously for an extremal black hole. In particular in any theory of gravity coupled to other matter fields with generally covariant higher derivative corrections, the near horizon field configuration of an extremal black hole is obtained by extremizing an ‘entropy function [159, 160]. The entropy function is a function of the parameters characterizing the near horizon geometry of the black hole and there is a well defined algorithm for constructing this function from the Lagrangian density of the theory. Furthermore the entropy itself is given by the value of the entropy function at its extremum. This led to a proof of the ‘attractor mechanism’ in a general higher derivative theory of gravity without invoking supersymmetry. In particular the results show that in a generic situation where the entropy function has no flat directions the near horizon field configuration is determined completely by extremizing the entropy function and hence cannot depend on the asymptotic values of the scalar fields of the theory. On the other hand if the entropy function has flat directions then the near horizon field configuration is not completely determined by extremizing the entropy function and could have some dependence on the asymptotic values of the scalar fields. But the entropy is still independent of the asymptotic data. Although initial studies focussed on spherically symmetric black holes, this analysis was later generalized to black holes carrying angular momentum [162, 166].

As a continuation of this project I also proposed an exact formula – known as the quantum entropy function – that computes the entropy of an extremal black hole after taking into account both stringy corrections and quantum corrections to the black hole entropy [189, 194]. This provides a way to compare the black hole entropy and the degeneracies computed in the microscopic theory to an arbitrary accuracy. This procedure has been used to compute logarithmic corrections to the black hole entropy in N=4 and N=8 supersymmetric string theories [204,211,212], twisted index that computes the degeneracy weighted by $(-1)^F$ times some discrete symmetry generator [202, 203] and the sign of the index [205]. The results are in agreement with the microscopic results. The computation of logarithmic corrections was also generalized to non-extremal black holes [217].

10 Multi-centered black holes and quivers

In supergravity, which is the low energy limit of string theory, we have both single centered and multi-centered black hole solutions. The latter become particularly important for extremal black holes for which the multi-centered black holes can be stable, and contribute to the entropy for a fixed total charge besides the single centered black holes carrying the same charge. It turns out however that as we change the moduli of string compactification, given by the asymptotic values of massless scalars, some of these multi-centered configurations may cease to exist and / or new multi-centered configurations may appear. Therefore the black hole index may jump across codimension one subspaces of the moduli space known as walls of marginal stability. In [172] I classified these walls of marginal stability for a wide class of $N = 4$ supersymmetric string compactification. I also showed that even though the index jumps across the walls of marginal stability, the partition function (generating function of the index) remains unchanged. The same generating function, expanded in different ways, gives the result for the index in different regions of the moduli space. The jumps across the walls, known as the wall crossing formula, are determined by the residues at certain poles of the generating function. I also derived a general form of the wall crossing formula in $N = 4$ supersymmetric theories in [187].

The structure of wall crossing in $N = 2$ supersymmetric string compactification is much more complex. The jumps across the walls was analyzed by Denef and Moore, Kontsevich and Soibelman, Joyce and Song and many others, leading to the wall crossing formula. In [207] with Manschot and Pioline I derived two new versions of the wall crossing formula by analyzing the properties of black hole bound states. These were later shown to agree with each other and with the earlier results of Kontsevich and Soibelman and of Joyce and Song [214]. Later we used these ideas to write down the degeneracies of multi-centered black hole configurations in terms of single centered degeneracies [208] and applied it to derive some results in quiver quantum mechanics [218, 221]. The importance of this work stems from the fact that the microscopic counting of the type described in §8 typically gives the full degeneracy / index without distinguishing between single and multi-centered black holes while the macroscopic analysis based on the quantum entropy function, as described in §9, focuses on the contribution from single centered black holes. Therefore in order to compare the results we need the relation between single and multi-centered black holes.

11 String field theory

The usual formulation of string theory uses a first quantized description, also known as the world-sheet approach. While capable of computing S-matrix elements in a given background, this approach is not very useful for describing a change in the background. A second quantized approach to string theory was proposed by Witten, Zwiebach and others that give a more conventional quantum field theory like formulation of string theory with infinite number of fields. The background independence of the theory however was not manifest. In several papers, some of them in collaboration with Barton Zwiebach, I proved background independence of string field theory for backgrounds that are related by marginal deformation [51, 75, 77].

I returned to the subject of string field theory in the context of tachyon condensation, and superstring perturbation theory, described in §12 and §13 respectively, and again much later for the formulation of superstring field theory. Actually my work on superstring field theory started in the mid 90's in a paper with Saroja where we showed how in principle one could write down a consistent field theory for the NSNS sector of superstring theory by making the picture changing operators move as we vary the moduli of the Riemann surface [65]. It was however not fully clear if we can consistently avoid collision of picture changing operators / spurious poles, thereby avoiding possible singularities. I returned to this problem in 2014 and resolved this issue using the notion of vertical integration [230]. A fully systematic procedure for carrying out vertical integration was given later in a paper with Witten [236]. This was needed not just for the formulation of string field theory, but also for a systematic description of superstring perturbation theory.

While this resolved the problem of constructing string field theory action in the NSNS sector, a full string field theory must also include the NSR, RNS and RR sectors. This had been a stumbling block in the formulation of superstring field theory and the absence of an action for type IIB supergravity, which arises as the low energy limit of type IIB string theory, was a clear signal that one cannot have a conventional action. I resolved this problem by introducing an extra set of string fields in the theory. Even though it seems to double the number of degrees of freedom, one finds that one set of fields decouple in the final theory, and the remaining interacting degrees of freedom precisely produce the perturbative amplitudes [234, 239] of superstring theory. Later I used this formalism to write down an action for type IIB supergravity and other theories with chiral bosons [239]. Using the framework of string field theory I, in various collaborations, also discussed the construction of the Wilsonian effective action by integrating out the heavy modes [228], proof of unitarity of string theory [242] and proof of crossing symmetry of four point amplitudes [259].

12 Non-BPS states and tachyon condensation in string theory

Another of my projects involves study of non-supersymmetric solitons in string theory. Most of the earlier studies on solitons in string theory have been on supersymmetric (also known as BPS) configurations. In a series of papers in 1998 I showed that many string theories have stable non-BPS states and that they can also be used to test various duality conjectures [107, 110, 111].

During this study, I also found a novel construction of non-BPS states in terms of kink solution involving the tachyon field on a brane anti-brane pair. Tachyons have been known to be present in bosonic string theory almost since its birth but are absent in superstring theory. Nevertheless if we consider a system of coincident D-brane and anti D-brane in superstring theory, the spectrum of open strings contain a tachyonic mode indicating that we have a scalar field for which the potential has a maximum at the origin of the field space. An interesting question that had remained unanswered was 'what describes the minimum of the tachyon potential?' The study of non-BPS branes led to a series of conjectures about tachyon potential on the brane-antibrane system and non-BPS D-branes in superstring theory, as well as on D-branes of bosonic string theory [108–110, 112, 117]. Later, in various collaborations with Zwiebach, Berkovits, and Moeller I found evidence for these conjectures in string field theory [118–120, 123]. The analytic solution describing the tachyon vacuum in open bosonic string field theory was constructed by Schnabl a few years later who verified the conjecture on the energy density of the tachyon vacuum. Many of the other conjectures have also been analytically proven by now.

Although initial studies of the non-BPS branes focussed on their static properties, in 2002 I found a set of time dependent solutions describing the 'decay' of these branes [140, 141]. These are among the few time dependent solutions in string theory whose properties have been studied in detail and have been used extensively to build cosmological models out of string theory. Study of these solutions has also led to a new kind of duality conjecture between open and closed string theories [286].

13 Superstring perturbation theory

The original formulation of superstring perturbation theory was based on the world-sheet formulation that expresses the scattering amplitudes as integrals over the moduli spaces of Riemann surfaces. However these integrals often run into divergences from the boundaries of the moduli space where the Riemann surface degenerates. Usually one can deal with these divergences by analytic continuation in the momenta of the external particles – we define the amplitude for the range of momenta where the integrals are finite and then analytically continue the result to other values of the momenta. However this procedure does not always work. By expressing the amplitudes in terms of Feynman diagrams of string field theory one finds that these failures occur precisely when one of more internal propagators in a Feynman diagram is forced to be on-shell due to momentum conservation rules. This is the case for example when we have self energy diagrams on external legs of a Feynman diagram or tadpoles of massless fields. Since in quantum field theory we know precisely how to address these problems – e.g. by mass renormalization in the first case and by finding the correct vacuum in the second case – we can use string field theory to resolve these divergences. We discussed these in a series of papers with Pius and Rudra [226–228]. In [238] I used the technique of string field theory to reanalyze and extend the analysis described in §4 by showing how the broken supersymmetry generated by the one loop Fayet-Iliopoulos term is restored by shift of the string field. In the broken supersymmetric 'vacuum' we have a non-zero cosmological constant but this becomes zero in the supersymmetric vacuum. I also used the notion of vertical integration, mentioned in §11 to give a fully systematic description of superstring amplitudes avoiding spurious poles which otherwise plague the usual formulation of the world-sheet theory [230, 236].

14 D-instanton amplitudes

D-instantons describe classical finite action solutions in euclidean string theory and could give non-perturbative contribution to the scattering amplitudes in string theory. In principle D-instanton contribution to string amplitudes can be computed systematically by summing over world-sheets with boundaries, with D-instanton boundary condition at the boundaries. However the resulting integrals over the moduli spaces of Riemann surfaces often run into divergences from the boundary of the moduli space. Again using the language of string field theory one finds that these divergences can be traced to the presence of internal on-shell open string propagators in the Feynman diagram, with the boundaries of the open string lying on the D-instanton. However in this case the problem is more severe since the open strings on the D-instanton are forced to carry zero momentum along the non-compact directions and hence no analytic continuation is possible.

One again finds that using the language of string field theory one can resolve these problems. The main idea is to remove the open string zero mode contributions from the internal propagators of the Feynman diagram and integrate over the zero modes separately at the end. This procedure successfully resolved various open problems that were present in the earlier analysis, *e.g.* in the work of Green and Gutperle in ten dimensional type IIB string theory and in the work of Balthazar, Rodrigues and Yin in two dimensional bosonic string theory. We applied this procedure to analyze D-instanton contribution to string amplitudes in two dimensional bosonic string theory [264, 267, 270, 271], ten dimensional type IIB superstring theory [272, 273] and type II string theories compactified on Calabi-Yau threefolds [275, 276].

15 Soft theorem

Leading soft photon and soft graviton theorem, discovered by Weinberg in the mid 1960's, express an amplitude with one or more low momentum (soft) graviton or photon in terms of an amplitude without such soft particles. Interest in the soft theorem was revived recently due to the work of Strominger and others on the connection between soft theorems, asymptotic symmetries and memory effect, and also due to the discovery by Cachazo and Strominger of subleading soft theorem for scattering of massless particles. In various collaborations I gave a general proof of the subsubleading soft graviton theorem in any generally covariant quantum theory of gravity [249–251]. Later with Alok Laddha I showed how by taking appropriate classical limit of the soft theorem, one can derive the form of low frequency classical gravitational radiation in a classical scattering process purely in terms of the incoming and outgoing hard particle momenta. This analysis is straightforward in dimensions five or more, but has interesting logarithmic corrections in four dimensions that produce a late and early time tail of the gravitational radiation [257, 258]. A classical proof of this was given later [265] and some interesting properties of this formula were explored in [274].

16 Doublet-Triplet splitting in string inspired GUTS

In conventional SU(5) grand unified theories, the Higgs field belongs to a fundamental representation of SU(5) and it requires a high degree of fine tuning (1 in 10^{15}) to keep its color triplet component heavy (which is required to avoid rapid proton decay) and at the same time the weak doublet Higgs light (so that it can induce symmetry breaking responsible for the mass of the $W^{\pm}$ and Z bosons). In a paper in 1985 [16] I showed how in string theory one might be able to get this mass hierarchy naturally, without the need of any fine tuning.

17 Stringy corrections to the Calabi-Yau metric

In 1986, several groups found a new four loop contribution to the β-function in the σ-model describing string propagation on a Calabi-Yau manifold. This led to the possibility that Calabi-Yau manifolds are not valid backgrounds for string compactification as these would not be solutions of the equations of motion. In collaboration with D. Nemeschansky I showed that it is possible to modify the metric on the Calabi-Yau manifold order by order in string perturbation theory so that it continues to remain solutions of the equations of motion, and hence provides a conformally invariant σ-model [25].

18 Classification of rational conformal field theories

In collaboration with Samir Mathur and Sunil Mukhi, I proposed a way to classify rational conformal field theories by using modular properties of their characters [39]. If the theory has n characters then modular transformations acts as an $n \times n$ matrix on these characters. This in turn implies that there is a modular covariant n-th order ordinary differential equation whose solutions give the characters. For a given value of n, one can start with a general form on the modular differential equation parametrized by some unknown constants and then determine those constants by requiring the solutions to the differential equation properties satisfied by characters *e.g.* integrality of the Fourier expansion coefficients.

19 Matrix theory

In 1996, Banks, Fischler, Shenker and Susskind proposed a non-perturbative definition of eleven dimensional supergravity theory in terms of quantum mechanics of infinite dimensional matrices. I gave a systematic description of this theory when we compactify some of the eleven dimensions [104]. This unified many of the ad hoc descriptions of this theory given earlier.

20 Interpolating function

In string theory and quantum field theories, most expansions are asymptotic. However many string compactifications and quantum field theories have the property that at strong coupling it admits a dual weakly coupled description, thereby admitting a perturbation expansion in inverse powers of the coupling. In [222] I described a general procedure for combining the strong and weak coupling expansion to get an interpolating function. In special cases where the exact result is known, this function gives a better approximation to the exact result than either of the two expansions.

21 The future of our universe

Discovery of the accelerated expansion of the universe in the late 90's has changed our understanding of the future of our universe. We now know that in the far future the universe is going to divide itself into multiple regions which will not be able to communicate with each other even though today we can reach those regions if we try hard enough. Another aspect of our universe is the possibility that we may be living in a metastable vacuum that could decay into a different vacuum by formation of a tiny bubble which would expand at the speed of light and wipe out the whole observable universe. In an essay [235] I suggested that we could in principle increase the chances of survival of our civilization by spreading out in different regions of the universe that are reachable today, but will be out of each others' reach in the far future. In that case if in the future a bubble of more stable vacuum forms in one region, it can wipe out everything that is within its reach, but civilizations settled in other parts of the universe that are out of reach will survive. Detailed calculation of how efficient this process is was performed in a follow up paper with Kashyap, Mondal and Verma [237] where we also calculated how the half-life of our universe changes with time due to the expansion of the universe.