Indian J. Pure Appl. Math., **50**(3): 705-717, September 2019

DOI: 10.1007/s13226-019-0350-7

ALGEBRAIC TOPOLOGY IN INDIA

Goutam Mukherjee* and Parameswaran Sankaran**

**Indian Statistical Institute, 203 B T Road, Kolkata* 700 108, *India*

***The Institute of Mathematical Sciences (HBNI), CIT Campus, Taramani,*
Chennai 600 113, *India*

e-mails: goutam@isical.ac.in; sankaran@imsc.res.in

We highlight some of the major contributions to algebraic topology in India since the dawn of the 21st century, classified broadly under three heads, namely, manifolds and cell complexes, equivariant topology and deformation theory.

Key words : Manifolds; equivariant topology; deformation theory.

1. INTRODUCTION

Algebraic topology has flourished and grown in many different directions in the last forty years. The driving force behind these developments had largely been understanding topology of manifolds. In the last fifteen years, two major achievements stand out, namely: (a) The resolution of Poincaré conjecture and the geometrization conjecture due to Perelman, using and developing along the way new techniques in differential geometric and analytic methods. (b) The solution to the Kervaire conjecture due to Hill, Hopkins, and Ravenel [*Ann. Math.*, **184** (2016), 1-262] which involved, among other things, stable homotopy theory, equivariant homotopy theory, complex cobordism and formal group law, etc.

There had been active research in several branches of algebraic topology in India. The second half of the twentieth century saw major contributions to the subject by B. L. Sharma, A. Mukherjee, A. R. Shastri, K. K. Mukherjea, and K. Varadarajan. They also helped develop strong research groups in the subject at various institutions and universities.

We highlight some of the major contributions to algebraic topology in India since the dawn of the 21st century, classified broadly under three heads, namely, manifolds and cell complexes, equivariant topology and deformation theory.

2. MANIFOLDS AND CELL COMPLEXES

Several strands of research were followed and many new results have been obtained in the study of manifolds and cell complexes. Mukerjee [55-57], computes the sets of topological and PL structures on Wall, Milnor, and Dold manifolds. Ramesh [71] has constructed manifolds homeomorphic but not diffeomorphic to complex projective space of (real) dimensions 14, and 16. Earlier Aravinda and Farrell [2] constructed such exotic structures on closed manifolds with universal cover a quaternionic hyperbolic space in dimensions 8, 16, or 20. See also [1, 3]. In the same theme of exotic structures, Deo [23] has shown that a certain combinatorial 8-manifold which is a cohomology quaternionic plane does not embed in $\mathbb{R}^{12}$. Non-existence of complex structures on a product $\mathbb{S}^{2m} \times P(\mathbb{C}^n)$ $(n > 1)$ was proved by Charkaborty and Thakur [19].

Bagchi and Datta have done extensive work on combinatorial and enumerative topology. In particular, they made significant contributions to minimal triangulations of such spaces as the real and complex projective spaces, product of spheres, homology spheres, sphere bundles over circles, etc. See [4-6]. See also [8]. Basak and Sarkar [9] constructed vertex-minimal equilibrium triangulations of some 3-dimensional manifolds by considering small covers with orbit space triangular prism.

There have been important contributions to topology of complex manifolds and algebraic varieties. The early work on this theme had been due to Ramanujam [*Ann. of Math. (2)*, **94** (1971), 69-88] who gave a topological characterization of the complex affine plane. Gurjar and Shastri [33] studied, the fundamental group at infinity of affine surfaces (over $\mathbb{C}$) and applied it to give a topological characterization of certain finite quotient singularities of the affine plane [34]. Gurjar, Prateep and Shastri studied rationality questions for affine complex varieties which have trivial reduced rational homology. See [35, 69]. Hsiang and Pati [36] had verified a conjecture of Cheeger-Goresky-MacPherson showing that for normal projective surfaces the intersection cohomology (with middle perversity) is isomorphic to the L^2-cohomology (with respect to the metric induced from the projective variety) of its non-singular part. Sankaran and Thakur [75] have studied the topology and geometry of certain complex manifolds which are topologically $\mathbb{S}^1 \times \mathbb{S}^1$-bundles over smooth complex projective varieties. The manifolds considered by them contain, as special cases, the Calabi-Eckmann manifolds. An orbifold is a singular space that locally looks like a quotient of an open subset of Euclidean space by an action of a finite group. Ganguli and Poddar [30] have introduced the notions of pseudo-holomorphic blowdown construction, and the notion of crepant maps, analogous to those in the realm of algebraic geometry, in the context of quasitoric 4-folds which admit almost complex structure and showed the so called McKay correspondence, namely, the invariance of Betti numbers for rational Chen-Ruan cohomology under crepant pseudo-holomorphic blowdowns for 4-dimensional quasi-toric orbifolds admitting torus invariant almost complex structures. See also Poddar [66]. Poddar and Sarkar [67] studied topology of quasitoric orbifolds, determined orbifold fundamental group, rational homology and cohomology. They proved existence of stable almost complex structure on quasitoric orbifolds and developed tools to decide whether a given quasitoric orbifold arises as the quotient of smooth quasitoric manifold by a finite group. In [68] Poddar and Sarkar studied a class of smooth torus manifolds whose orbit space has the combinatorial structure of simple polytopes with holes, proved several important properties of theses spaces and gave combinatorial formulas to determine topological invariants. Sarkar [83] constructed orbifolds with quasitoric boundary and proved that they have stable almost complex structure. Moreover, he proved that a quasitoric orbifold is complex cobordant to finite disjoint copies of complex orbifold projective spaces. For quasitoric manifold over a simplex, he gave some computations related to Chern numbers in the complex cobordism ring.

Sankaran and Sarkar [74] obtained results on non-existence of non-zero degree maps between complex Grassmann manifolds. This extends earlier work by Ramani and Sankaran [70]. Basu and Sarkar have obtained complete results concerning the same problem when the homogeneous manifolds are of the form $I_{2n,k} := U(n)/SO(k) \times U(n-k)$. Chakraborty and Sankaran [18] have shown that certain assumptions on the parameters, any continuous map between complex Grassmannians $G_{m,l} \to G_{n,k}$ is rationally null homotopic. Similar results when $m = n$ have been obtained by Chakraborty and Masuti [17]. Recently possible degrees of maps between compact manifolds whose universal covers are irreducible non-compact globally symmetric spaces of higher rank have been obtained by Mondal and Sankaran [51].

In K-theory, the main contribution has been computations, in terms of generators and relations, for specific class of spaces. The K-ring of a quasi-toric manifolds was determined by Sankaran and Uma [77]. The same problem for a certain class of *torus* manifolds which includes smooth complete toric varieties was settled in [73]. Earlier work K-theory concerned oriented Grassmann manifolds and related spaces [79, 80]. Using Stiefel-Whitney classes a new (homotopy) invariant $uchar(M)$ has been introduced extensively studied Korbaš, Naolekar and Thakur [45]. Naolekar and Thakur have studied the problem of realizing cohomology classes as characteristic classes of vector bundles; see [61-64].

The question of possible immersions of real projective spaces in Euclidean space has led to deep advances in algebraic topology. The last two of the papers uses computations using the second real Johnson-Wilson theory. Banerjee [7] has extended the computations of Kitchloo and Wilson to obtain new non-immersion results: if $\alpha(m)$ is the number of ones in the dyadic expansion of m, and if $(m, \alpha(m)) \equiv (6, 2)$ or $(1, 0)$ modulo 8, then $\mathbb{R}P^{2(m+\alpha(m)-1)}$ does not immerse in $\mathbb{R}^{2(2m-\alpha(m)+1)}$.

The first new result obtained is that $\mathbb{R}P^{2^{13}-2}$ does not immerse in $\mathbb{R}^{2^{14}-59}$.

The vector field problem which asks for determination of span (or stable span) has been another driving force behind much of the development of algebraic topology. It is a far reaching generalization of the problem of deciding whether a smooth manifold is parallelizable (or stably parallelizable). Sankaran and Zvengrowski [79, 80] had studied the vector field problem and (stable) parallelizability problem for partially oriented (real) flag manifolds and (real) projective Stiefel manifolds. More recently Gondhali and Sankaran [31] and Gondhali and Subhash [32] have studied these problems for certain quotients of the complex projective Stiefel manifolds. Khare [40, 41] has studied the vector field problem for Dold, Milnor and Wall manifolds.

3. Equivariant Topology

In recent years contributions of Indian mathematician in equivariant topology have been significant. Their works mainly centered around stable homotopy theory, equivariant homotopy, equivariant cobrdism, equivariant (co)homology and homotopy theory of manifolds.

Singh [22, 37, 65] and his collaborators have studied of cohomology of orbit spaces for the action of the circle and the cyclic group on specific manifolds such as product of projective spaces, lens spaces, and spheres etc. Singh [85, 86, 89] has obtained interesting results on topology of group actions of certain manifolds and finite CW complexes. He also obtained a Borsuk-Ulam theorem for free $\mathbb{Z}/p\mathbb{Z}$-action on spheres and a parametrized version for $\mathbb{Z}/2\mathbb{Z}$ action [87, 88]. Earlier, Koikara and Mukerjee [43] had obtained Borsuk-Ulam type results for equivariant maps from a product of two spheres to a manifold. See also [44]. The free p-rank of symmetry of a topological space X for a prime p, denoted by $frk_p(X)$, is the largest r such that $(\mathbb{Z}/p)^r$ acts freely on X. For example, it follows from Smith theory that $\mathbb{Z}/p \times \mathbb{Z}/p$ cannot act freely on a sphere and thus one may determine the free p-rank of a sphere. Singh [89] has determined the free 2-rank of a product of complex Milnor manifolds.

Datta and Pandey [20] studied equivariant Morse theory for semifree action of finite groups G on compact manifolds and proved that G-CW structure of such manifolds can be described by Morse polynomial of a Morse function. By an early work of Wassermann [*Toplogy*, **8** (1969), 127-150], followed by the work of Costenoble and Warner [*Michigan Math. J.*, **39**(2) (1992), 325-351], one has a cellular homology of G-spaces graded by virtual representations of equivariant fundamental groupoid. For a closed Riemannian G-manifold where G is a finite group, Datta and Pandey [21] generalized classical Morse theory in the equivariant context and proved that if Wasserman's decomposition corresponds to a vertual representation of the fundamental groupoids, then the generalization of the Morse relations with respect to the above homology are valid. The authors focused attention to the special case $G = \mathbb{Z}_2$, to explain their general result in more precise terms.

There has been continued interest in cobordism theory. Basu, Mukherjee, and Sarkar [14] have produced indecomposable elements in the ring $Z_*(G)$ of G-equivariant cobordisms with finite stationary point sets, using Milnor manifolds when G is an elementary abelian 2-group. Earlier Mukherjee and Sankaran [58] had identified a polynomial subalgebra of $Z_*(G)$ using the certain natural action of G on real flag manifolds. The paper [78] studied the equivariant cobordism of complex flag manifolds with circle actions. See also [24, 38, 39, 42].

Santhanam [82] proved the category of G-equivariant Γ-spaces is Quillen equivalent to the category of G-equivariant E_∞-spaces and provided a construction of units of a G-equivariant E_∞-ring spectrum as a special Γ-space. Thom spectra are useful for detecting ring structures of units of ring spectra and for such rings, Basu and others observed that the topological Hochschild homology may be written as a Thom spectrum. Using this idea, Basu [11] has made complete computations of the topological Hochschild homology of K/p as a $K_p^\wedge$-module, first by expressing K/p as a Thom spectrum over $K_p^\wedge$ and then using the identification above to compute the topological Hochschild homology.

In [52], the authors introduced Bredon-Illman cohomology with local coefficients to develope equivariant obstruction theory for extending equivariant sections of G-fibrations for a topological group G and discussed their representation in the homotopy category. Mukherjee and Pandey [53] gave an alternative description of this cohomology for a discrete group G, generalizing a result of Moerdijk and Svensson [*Proc. Amer. Math. Soc.*, **118**(1) (1993), 263-278]. In [54], Mukherjee and Pandey proved that the Bredon-Illman cochain complex admits a homotopy Gerstenhaber algebra structure which leads to a B_∞-algebra structure on the cochain complex. Mukherjee and Sen [59] have used equivariant simplicial sets to prove further results about representing Bredon cohomology with local coefficients. The authors further constructed Steenrod operations for Bredon cohomology in [60]. Blanc and Sen [16] have used a filtration on the orbit category to prove a spectral sequence for Bredon cohomology. Basu and Sen [15] have further extended the representability results using modern notions of parametrized G-spectra and equivariant crossed complexes.

The Topological Tverberg conjecture which states that for $N = (n+1)(r-1)$ and a map $f : \Delta^N \to \mathbb{R}^n$ there are r disjoint faces of Δ^N whose images have a non-trivial intersection. This conjecture was proved by Bárány, Shlosman and Szücs in 1981 for prime r and by Ozaydin in 1987 for prime powers r. Recently for non-prime powers counterexamples were obtained by Frick. Pertinent question is therefore to determine an optimal value of N for non-prime powers. The main technique to prove such a theorem has been to reduce the problem to an obstruction theory problem in Σ_r-equivariant homotopy theory (and thus for also subgroups of Σ_r). The proofs for the prime power case rely on the restriction to cyclic subgroups and elementary abelian subgroups and the results are similar to the Borsuk-Ulam Theorem [84]. Basu and Ghosh [13] ruled out the possibility of obtaining results for any N using cyclic or elementary abelian groups in the non-prime power case and explored the Borsuk-Ulam properties of representations for these groups.

Basu and Basu [12] have proved several results about a simply-connected closed 4-manifold M with second Betti number k. The first result says that its homotopy groups are the same as those of the $(k-1)$-fold connected sum of $S^2 \times S^3$. The second says that its stable homotopy groups are the same as those of k-copies of S^2 plus one of S^4 if $w_2(M) = 0$, while if $w_2(M) \neq 0$, they equal those of $(k-1)$-copies of S^2 plus one of $\mathbb{C}P^2$. The third result gives for $j \geq 2$, an explicit polynomial P_j of degree j such that the rank of $\pi_{j+1}(M)$ equals $P_j(k-1)$. The fourth result states that, if $k \geq 3$, for a generic metric on M the number of geometrically distinct periodic geodesics of length $\leq l$ grows at least exponentially with l.

Basu [10] used explicit calculations of Sullivan (minimal) models, Massey products, and Pontryagin products to distinguish between several interesting H-spaces, for examples, ΩLS^{2l} and $\Omega(S^{2l} \times \Omega S^{2l})$ have the same homotopy type but as H-spaces they are distinct, on the other hand $\Omega L\mathbb{C}P^n$ and $\Omega(\mathbb{C}P^n \times \Omega\mathbb{C}P^n)$ are rationally homotopy equivalent as H-spaces if $n \geq 2$. He proved $L_{7,1}$ and $L_{7,2}$ are homotopically equivalent but not homeomorphic; on the other hand the configuration space of two points $F_2(L_{7,1})$ and $F_2(L_{7,2})$ are not homotopically equivalent. Again it is known that the functor ΩF_2 preserves homotopy equivalences but Basu showed that $\Omega F_2(L_{7,1})$ and $\Omega F_2(L_{7,2})$ are not equivalent as H-spaces.

4. DEFORMATION OF ALGEBRAS

Deformation theory dates back at least to Riemann's 1857 memoir on abelian functions in which he studied manifolds of complex dimension one and calculated the number of parameters (called moduli) upon which a deformation depends. The modern theory of deformations of structures on manifolds was developed extensively by Frolicher-Kodaira-Nijenhuis-Nirenberg-Spencer. Gerstenhaber in a series of papers in Annals of Mathematics adopted Frolicher-Kodaira-Nijenhuis-Nirenberg-Spencer-theory to study deformations of algebraic structures using cohomological technique. He introduced formal one parameter deformation theory for associative algebras. Later, his theory was extended to Lie algebras by Nijenhuis and Richardson [*Bull. Amer. Math. Soc.*, **72** (1966), 1-29].

Any deformation theory should have the following features: A class of objects within which deformation takes place and a cohomology theory associated to those objects which control the deformation in the sense that infinitesimal deformation of a given object can be identified with the elements of the second cohomology group with coefficients in an adjoint representation. A theory of obstruction to the integration of an infinitesimal deformation where obstructions to the prolongability are controlled by the third cohomology and a notion of rigid objects.

For example, for Gerstenhaber theory, objects are associative algebras and the natural candidate for the cohomology is the Hochschild cohomology and for Nijenhuis-Richardson theory, objects are Lie algebras and the associated cohomology is Chevalley-Eilenberg cohomology.

Loday [*Enseign. Math.*, **39** (1993), 269-293] while studying periodicity phenomena in algebraic K-theory, introduced a new class of equationally defined algebras called *Loday algebras*. Examples are Leibniz algebras–a non anti-symmetric version of Lie algebras, di-associative dialgebras, dendiform and Zinbiel algebras.

In recent time, when deformations of various algebraic objects are being studied, it is felt that it is desirable to have a theory of deformations over more general base, not merely, over formal power series ring. The main problem in deformation theory is to describe all non-equivalent deformations of a given object. The right approach to address this question is to develop a theory of deformation over a local algebra base, or more generally, over a complete local algebra base and to construct the so called 'versal deformation'– a deformation which induces all non-equivalent ones, in the sense that, any deformation is equivalent to a deformation obtained as a push out of versal deformation. Over the last few years, significant progress has been made by Indian mathematicians to understand algebraic deformation theory of some of theses Loday algebras. The first such contribution was initiated with the work of Naolekar (née, Majumdar) and Mukherjee [46, 47]. The biggest difference in this work with the classical theory of Gerstenhaber is that it has to deal with several relations and planar binary trees to construct the deformation theory. Further contributions on deformation theories of Loday algebras were made and explicit construction of versal deformations were given by Ashis Mandal, Anita Naolekar (née, Majumdar), Goutam Mukherjee and Alice Fialowski in [26-28, 48-50]. As an application of the above developments, Mandal jointly with Magnin and Fialowski gave a complete description of the Leibniz (and Lie) universal infinitesimal deformation of 4-dimensional diamond Lie algebra, used in the WZW model, and studied the case of its 5-dimensional analogue by computing Massey products [25].

Having studied algebraic deformation theory of various equationally defined algebras and having thorough knowledge of the corresponding versal deformations, it was felt that it is desirable to develop versal deformation theory of algebras over any quadratic operad which would include the theories for any equationally defined algebras as particular cases. A complete and satisfactory such theory has been developed recently in [29].

REFERENCE

1. C. S. Aravinda and F. T. Farrell, Exotic negatively curved structures on Cayley hyperbolic manifolds, *J. Differential Geom*., **63**(1) (2003), 41-62.
2. C. S. Aravinda and F. T. Farrell, Exotic structures and quaternionic hyperbolic manifolds, *Algebraic groups and arithmetic*, 507-524, *Tata Inst. Fund. Res*., Mumbai, 2004.
3. C. S. Aravinda and F. T. Farrell, Nonpositivity: Curvature vs. curvature operator, *Proc. Amer. Math. Soc*., **133**(1) (2005), 191-192.
4. Bhaskar Bagchi and Basudeb Datta, Combinatorial triangulations of homology spheres, *Discrete Math*., **305**(1-3) (2005), 1-17.
5. Bhaskar Bagchi and Basudeb Datta, Minimal triangulations of sphere bundles over the circle, *J. Combin. Theory Ser. A*, **115**(5) (2008), 737-752.
6. Bhaskar Bagchi and Basudeb Datta, A triangulation of $\mathbb{C}P^3$ as symmetric cube of $\mathbb{S}^2$, *Discrete Comput. Geom*., **48**(2) (2012), 310-329.
7. Romie Banerjee, On the $ER(2)$-cohomology of some odd-dimensional projective spaces, *Topology Appl*., **160**(12) (2013), 1395-1405.
8. Biplab Basak and Basudeb Datta, Minimal crystallizations of 3-manifolds, *Electron. J. Combin*., **21**(1) (2014), Paper 1.61, 25 pp.
9. Biplab Basak and Soumen Sarkar, Equilibrium and equivariant triangulations of some small covers with minimum number of vertices, *J. Ramanujan Math. Soc*., **30**(1) (2015), 29-50.
10. Samik Basu, Of Sullivan models, Massey products, and twisted Pontrjagin products, *J. Homotopy Relat. Struct*., **10** (2015), 239-273.
11. Samik Basu, Topological Hochschild homology of K/p as a $K_p^\wedge$-module, *Homology, Homotopy Appl*., **19**(1) (2017), 253-280.
12. Samik Basu and Somnath Basu, Homotopy groups and periodic geodesics of closed 4-manifolds, *Internat. J. Math*., **26** (2015), 34 pp.
13. Samik Basu and Surojit Ghosh, On equivariant maps related to the topological Tverberg conjecture, *Homology, Homotopy Appl*., **19**(1) (2017), 155-170.
14. Samik Basu, Goutam Mukherjee, and Swagata Sarkar, Some computations in equivariant cobordism in

relation to Milnor manifolds, *Topology Appl.*, **172** (2014), 1-9.

15. Samik Basu and Debasis Sen, Representing Bredon cohomology with local coefficients, *J. Pure Appl. Algebra*, **219** (2015), 3992-4015.

16. David Blanc and Debasis Sen, A spectral sequence for Bredon cohomology, *J. Homotopy Relat. Struct.*, **8** (2013), 279-305.

17. Prateep Chakraborty and Shreedevi Masuti, Rational homotopy of maps between certain complex Grassmann manifolds, *Math. Slovaca*, **68**(1) (2018), 181-196.

18. Prateep Chakraborty and Parameswaran Sankaran, Maps between certain complex Grassmann manifolds, *Topology Appl.*, **170** (2014), 119-123.

19. Prateep Chakraborty and Ajay Singh Thakur, Nonexistence of almost complex structures on the product $\mathbb{S}^{2m} \times M$, *Topology Appl.*, **199** (2016), 102-110.

20. Mahuya Datta and Neeta Pandey, Morse theory on G-manifold, *Topology Appl.*, **123**(2) (2002), 351-361.

21. Mahuya Datta and Neeta Pandey, Equivariant Morse relations, *Homology Homotopy Appl.*, **9**(1) (2007), 467-483.

22. Ronald M. Dotzel and Tej B. Singh, Cohomology ring of the orbit space of certain free Zp-actions, *Proc. Amer. Math. Soc.*, **123**(11) (1995), 3581-3585.

23. Satya Deo, Combinatorial 8-manifolds having cohomology of the quaternionic projective plane and their nonembeddings, *New Zealand J. Math.*, **44** (2014), 15-20.

24. Sanghita Dutta and S. S. Khare, Independence of bordism classes of Milnor manifolds, *J. Indian Math. Soc. (N.S.)*, **68** (2001), 1-16.

25. Alice Fialowski, L. Magnin, and Ashis Mandal, About Leibniz cohomology and deformations of Lie algebras, *J. Algebra*, **383** (2013), 63-77.

26. Alice Fialowski and Ashis Mandal, Leibniz algebra deformations of a Lie algebra, *J. Math. Phys.*, **49**(9) (2008), 093511, 11pp.

27. Alice Fialowski, Ashis Mandal, and Goutam Mukherjee, Versal deformations of Leibniz algebras, *J. K-Theory*, **39**(2) (2009), 327-358.

28. Alice Fialowski and Anita Majumdar, Miniversal deformations of dialgebras, *Commun. Contemp. Math.*, **11**(3) (2009), 413-432.

29. Alice Fialowski, Goutam Mukherjee, and Anita Naolekar, Versal deformation theory of algebras over a quadratic operad, *Homology, Homotopy Appl.*, **16**(1) (2014), 179-198.

30. Saibal Ganguli and Mainak Poddar, Almost complex structure, blowdowns and McKay correspondence in quasitoric orbifolds, *Osaka J. Math.*, **50**(4) (2013), 977-1005.

31. Shilpa Gondhali and Parameswaran Sankaran, Vector fields on certain quotients of complex Stiefel manifolds, *Math. Slovaca*, **63**(4) (2013), 883-896.

32. Shilpa Gondhali and B. Subhash, Vector fields on right-generalized complex projective Stiefel manifolds, *Proc. Roy. Soc. Edinburgh Sect. A*, **143**(6) (2013), 1237-1242.

33. R. V. Gurjar and A. R. Shastri, The fundamental group at infinity of affine surfaces, *Comment. Math. Helv.*, **59**(3) (1984), 459-484.

34. R. V. Gurjar and A. R. Shastri, A topological characterization of $\mathbb{C}^2/G$, *J. Math. Kyoto Univ.*, **25**(4) (1985), 767-773.

35. R. V. Gurjar, C. R. Pradeep, and Anant R. Shastri, On rationality of logarithmic Q-homology planes, II, *Osaka J. Math.*, **34**(3) (1997), 725-743.

36. W.-C. Hsiang and V. Pati, L^2-cohomology of normal algebraic surfaces, I, *Invent. Math.*, **81** (1985) 395-412.

37. Jaspreet Kaur, Hemant Kumar Singh, and Tej Bahadur Singh, Circle group action on the product of two projective spaces, *Topology Proc.*, **48** (2016), 163-172.

38. S. S. Khare, Finite group action and equivariant bordism, *Pacific J. Math.*, **116**(1) (1985), 39-44.

39. S. S. Khare, On Dold manifolds, *Topology Appl.*, **33**(3) (1989), 297-307.

40. S. S. Khare, Span of Milnor manifolds, *J. Indian Math. Soc. (N.S.)*, **75**(1-4) (2008) (2009), 47-57.

41. S. S. Khare, Span of the Wall manifolds, *J. Indian Math. Soc. (N.S.)*, **79**(1-4) (2012), 73-80.

42. S. S. Khare and A. K. Das, Which Milnor manifolds bound? (English summary), *Indian J. Pure Appl. Math.*, **31**(11) (2000), 1503-1513.

43. Basil Shaju Koikara and Himadri Kumar Mukerjee, A Borsuk-Ulam type theorem for a product of spheres, *Topology Appl.*, **63**(1) (1995), 39-52.

44. Basil Shaju Koikara and Himadri Kumar Mukerjee, A Borsuk-Ulam theorem for maps of fibre bundles with manifolds as fibres, *Arch. Math. (Basel)*, **66**(6) (1996), 499-501.

45. Július Korbaš, Aniruddha C. Naolekar, and Ajay Singh Thakur, Characteristic rank of vector bundles over Stiefel manifolds, *Arch. Math. (Basel)*, **99**(6) (2012), 577-581.

46. Anita Majumdar and Goutam Mukherjee, Deformation theory of dialgebra, K*-Theory*, **27**(1) (2002), 33-60; Errata: *K-Theory*, **35**(3-4) (2005), 395-397.

47. Anita Majumdar and Goutam Mukherjee, Dialgebra cohomology as a G-algebra, *Trans. Amer. Math. Soc.*, **356**(6) (2004), 2443-2457.

48. Ashis Mandal, Deformation of Leibniz algebra morphisms, *Homology, Homotopy Appl.*, **9**(1) (2009), 439-450.

49. Ashis Mandal, An example of constructing versal deformations for Leibniz algebras, *Comm. Algebra*, **36**(6) (2008), 2233-2253.

50. Ashis Mandal and Goutam Mukherjee, Deformation of Leibniz algebra morphisms over commutative local algebra base, *Comm. Algebra*, **37**(7) (2009), 2246-2266.

51. Arghya Mondal and Parameswaran Sankaran, Degrees of maps between locally symmetric spaces, *Bull. Sci. Math.*, **140**(5) (2016), 488-505.

52. Amiya Mukherjee and Goutam Mukherjee, Bredon-Illman cohomology with local coefficients, *Quart. J. Math. Oxford Ser. (2)*, **47** (1996), 199-219.

53. Goutam Mukherjee and Neeta Pandey, Equivariant cohomology with local coefficients, *Proc. Amer. Math. Soc.*, **130**(1) (2002), 227-232.

54. Goutam Mukherjee and Neeta Pandey, Homotopy G-algebra structure on Bredon-Illman cochain complex, *Topology Appl.*, **144**(1-3) (2004), 51-65.

55. Himadri Kumar Mukerjee, Classification of homotopy Dold manifolds, *New York J. Math.*, **9** (2003), 271-293.

56. Himadri Kumar Mukerjee, Classification of homotopy real Milnor manifolds, *Topology Appl.*, **139**(1-3) (2004), 151-184.

57. Himadri Kumar Mukerjee, Classification of homotopy Wall's manifolds, *Topology Appl.*, **153**(18) (2006), 3467-3495.

58. Goutam Mukherjee and Parameswaran Sankaran, Elementary abelian 2-group actions on flag manifolds and applications, *Proc. Amer. Math. Soc.*, **126**(2) (1998), 595-606.

59. Goutam Mukherjee and Debasis Sen, Equivariant simplicial cohomology with local coefficients and its classification, *Topology Appl.*, **157** (2010), 1015-1032.

60. Goutam Mukherjee and Debasis Sen, Steenrod's operations in simplicial Bredon-Illman cohomology with local coefficients, *Homology, Homotopy Appl.*, **13** (2011), 273-296.

61. Aniruddha C. Naolekar, Realizing cohomology classes as Euler classes, *Math. Slovaca*, **62**(5) (2012), 949-966.

62. A. C. Naolekar and A. S. Thakur, Vector bundles over iterated suspensions of stunted real projective spaces, *Acta Math. Hungar.*, **142**(2) (2014), 339-347.

63. A. C. Naolekar and A. S. Thakur, On trivialities of Chern classes, *Acta Math. Hungar.*, **144**(1) (2014), 99-109.

64. Aniruddha C. Naolekar and Ajay Singh Thakur, Note on the characteristic rank of vector bundles, *Math. Slovaca*, **64**(6) (2014), 1525-1540.

65. Pedro L. Q. Pergher, Hemant K. Singh, and Tej B. Singh, On 2 and 1 free actions on spaces of cohomology type (a, b), *Houston J. Math.*, **36**(1) (2010), 137-146.

66. Mainak Poddar, Orbifold cohomology group of toric varieties, *Orbifolds in mathematics and physics* (Madison, WI, 2001), 223-231, *Contemp. Math.*, 310, *Amer. Math. Soc.*, Providence, RI, 2002.

67. Mainak Poddar and Soumen Sarkar, On quasitoric orbifolds, *Osaka J. Math.*, **47**(4) (2010), 1055-1076.

68. Mainak Poddar and Soumen Sarkar, A class of torus manifolds with nonconvex orbit space, *Proc. Amer. Math. Soc.*, **143**(4) (2015), 1707-1811.

69. C. R. Pradeep and Anant R. Shastri, On rationality of logarithmic Q-homology planes, I, *Osaka J. Math.*, **34**(2) (1997), 429-456.

70. Vimala Ramani and Parameswaran Sankaran, On degrees of maps between Grassmannians, *Proc. Indian Acad. Sci. Math. Sci.*, **107**(1) (1997), 13-19.

71. Kasilingam Ramesh, Farrell-Jones spheres and inertia groups of complex projective spaces, *Forum Math.*, **27**(5) (2015), 3005-3015.

72. Parameswaran Sankaran, A coincidence theorem for holomorphic maps to G/P, *Canad. Math. Bull.*, **46**(2) (2003), 291-298.

73. Parameswaran Sankaran, K-rings of smooth complete toric varieties and related spaces, *Tohoku Math. J. (2)*, **60**(4) (2008), 459-469.

74. Parameswaran Sankaran and Swagata Sarkar, Degrees of maps between Grassmann manifolds, *Osaka J. Math.*, **46**(4) (2009), 1143-1161.

75. Parameswaran Sankaran and Ajay Singh Thakur, Complex structures on product of circle bundles over complex manifolds, *Ann. Inst. Fourier (Grenoble)*, **63**(4) (2013), 1331-1366.

76. P. Sankaran and V. Uma, Cohomology of toric bundles, *Comment. Math. Helv.*, **78**(3) (2003), 540-554.

77. Parameswaran Sankaran and V. Uma, K-theory of quasi-toric manifolds, *Osaka J. Math.*, **44**(1) (2007), 71-89.

78. P. Sankaran and K. Varadarajan, Group actions on flag manifolds and cobordism, *Canad. J. Math.*, **45**(3) (1993), 650-661.

79. P. Sankaran and Peter Zvengrowski, K-theory of oriented Grassmann manifolds, *Math. Slovaca*, **47**(3) (1997), 319-338.

80. Parameswaran Sankaran and Peter Zvengrowski, Stable parallelizability of partially oriented flag manifolds, II, *Canad. J. Math.*, **49**(6) (1997), 1323-1339.

81. Parameswaran Sankaran and Peter Zvengrowski, Upper bounds for the span of projective Stiefel manifolds, *Recent developments in algebraic topology*, 173-181, *Contemp. Math.*, **407**, *Amer. Math. Soc.*, Providence, RI, 2006.

82. R. Santhanam, Units of equivariant ring spectra, *Algebr. Geom. Topol.*, **11** (2011), 1361-1403.

83. Soumen Sarkar, Complex cobordism of quasitoric orbifolds, *Topology Appl.*, **194** (2015), 386-399.

84. K. S. Sarkaria, Tverberg partition and Borsuk-Ulam theorems, *Pacific J. Math.*, **1**96 (2000), 231-241.

85. Mahender Singh, $\mathbb{Z}_2$ actions on complexes with three non-trivial cells, *Topology Appl.*, **155**(9) (2008), 965-971.

86. Mahender Singh, Orbit spaces of free involutions on the product of two projective spaces, *Results Math.*, **57**(1-2) (2010), 53-67.

87. Mahender Singh, A simple proof of the Borsuk-Ulam theorem for $\mathbb{Z}p$-actions, *Topology Proc.*, **36** (2010), 249-253.

88. Mahender Singh, Parametrized Borsuk-Ulam problem for projective space bundles, *Fund. Math.*, **211**(2) (2011), 135-147.

89. Mahender Singh, Free 2-rank of symmetry of products of Milnor manifolds, *Homology Homotopy Appl.*, **16**(1) (2014), 65-81.