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Statement of Research

The main areas of my research interest have been in Cosmology, Radio Astronomy, Gravitational Waves, Artificial Intelligence and high performance computing (HPC). In cosmology, I have been mostly working on problems related to the Large Scale Structure (LSS) of the Universe and Cosmic Microwave Background (CMB) which are two of the most active research areas of cosmology. In LSS my primly concern has been understanding the limitations of Cosmological N-Body codes due to finite box size, and mode coupling in the non-linear gravitational clustering. In radio astronomy my involvement has been in developing software pipelines for the Giant Meter Wave Radio Telescope (GMRT) data (automatic flagging and calibration pipeline, transient search pipeline) and studying 21-cm line of Hydrogen. My CMB research has been mainly focused on developing new methods of cosmological parameter estimation and probing the early universe by reconstructing the Primordial Power Spectrum (PPS) using non-linear methods like Maximum Entropy Method (MEM). At present the main theme of my research work is optimization under which I am investigating a few problems in CMB and gravitational wave data analysis. In particular I am working on techniques which can be used to map the stochastic gravitational wave background using a pair of LIGO detectors.

A detail summary of the problems I have been working or I have worked on is given below in a reverse chronological order.

A. Cosmological Parameter Estimation

A typical Cosmic Microwave Background Radiation (CMBR) data analysis pipeline consists of reducing time-order data into maps, which are further reduced into power spectra and from which cosmological parameters can be estimated using Bayesian analysis i.e., maximum likelihood (ML) methods. Due to the massive volume of data produced by precision instruments like WMAP and Planck, computation at every stage in CMB data analysis is challenging and we not only need high performance computing system there is a demand for robust, efficient and accurate codes which can meet the demand of precision instruments like WMAP and Planck.

With **Prof. Tarun Souradeep** at IUCAA I have developed a code `COSMOPSO` for cosmological parameter estimation which is based on Particle Swarm Optimization (PSO) algorithm. The code we developed is is not only better equipped to deal with a large parameter space and/or with multiple local maxima, it is completely insensitive also to the starting point and does not require any other quantity like covarianace matrix as is the case for commonly used Markov-Chain Monte Carlo (MCMC) methods and have a very few design parameters. A detail description of the code and few applications are discussed in (Prasad & Souradeep, 2012).

In PSO, a team of particles (computational agents) is a launched in the multi-dimensional parameter space and each member of the team changes its position based on its own experience and that of the others. Experience of a PSO particle is represented by a point called "Pbest" (personal best) in the parameter space at which the particle has found the maximum value of the cost function (in our case the likelihood function) and that of all the members is represented by a point called "Gbest" (global best), which is nothing but the best (with the highest value of the cost function) among all the Pbests.

Since the "jump size" of particles in PSO depend on their distance from the global maximum i.e., it is smaller when particles are closer to the global maximum than when they are far and as a result of that we always get more number of sampled points closer to the global maximum and less far away. In a recent work (manuscript is preparation) we have shown that multiple realization of PSO can sample the parameter space quite fairly to the extent that we were able to reproduce not only the best fits cosmological parameters from the WMAP nine year, we were also able to get the error bars using PSO sampled points which are quite close to what we get from commonly used MCMC samples (using `COSMOMC`).

Extending the program of cosmological parameter estimation we have developed a parameter estimation code which is based on the Downhill Simplex method of Nelder and Mead. Unlike PSO, the downhill simplex method is a geometrical method in which we begin with an initial simplex i.e., set of $(n+1)$ points in n dimensional parameter space, and replace the worst point (with the highest value of cost function) with a new point which we get after carrying out four different type of geometric operations named reflection, expansion, contraction and shrinking. The detail of our code and its comparison with `COSMOPSO` and few other methods like Powell's method and MCMC will be presented in a future publication (manuscript in preparation). One of the main findings of our study is that although Downhill simplex method and Powell's method are computationally faster than PSO however, they are quite sensitive to the starting point and have poor success rate as compared to PSO. Like MCMC methods, PSO not only gives the best fit point (the point at which the cost function is minimum/maximum) multiple realizations of it give sample points also from which we can probability distribution also.

B. Probing the Early Universe

The temperature and polarization anisotropies in the observed CMB sky directly give us a snapshots of the physical conditions of an epoch of the early Universe called the "last scattering" (roughly a few hundred thousand years after the big bang). Before the last scattering the photons, which we see around us in the form of CMB, were tightly coupled to the matter (baryons) and as the temperature of the Universe dropped (due to expansion) photons decoupled from the matter. At the time of decoupling there were density fluctuations in the matter (created in an earlier process of exponential expansion called inflation) which grew due to gravitational instability and lead to formation of galaxies and other large scale structure in the Universe. Constraining the primordial density perturbations (fluctuations) from CMB data is one of the most important problems in cosmology.

With one of my collaborators **Gaurav Goswami** at IUCAA, I demonstrated that in order to deconvolve the Primordial Power Spectrum (PPS) from the CMB angular power spectrum (which we get from the WMAP data) some form of "regularization" is needed. We use Maximum Entropy Method (MEM) to regularize the PPS which basically penalizes a PPS with features and avoid the over-fitting of the data. The results of our study have been published in (Goswami & Prasad, 2013). The study we have done was with the binned temperature data only and in future we plan to generalize our method for unbinned data as well as polarization also.

The main motivation behind considering a power spectrum with features has been to explain the shortage of power at the large angular scales (small multipoles) in the WMAP and Planck data. With my collaborators **Gaurav Goswami** and **Prof. Raghavan Rangarajan** at Physical Research Laboratory, Ahmedabad and **Suratna Das** at IIT Kanpur, I am exploring a scenario in which the inflationary era is preceded by a radiation dominated pre-inflationary era which will have unique signatures on the CMB angular power spectrum. This study is in its advance stage of completion.

From the WMAP, Planck, BICEP2 and many other CMB experiments now we have a very high precision data available to constrain the models of the Early universe, in particular models of PPS with features. With **Prof. Tarun Souradeep** at IUCAA and **Dr. Manzoor Malik** and **Asif Iqbal** at the University of Kashmir I have also been involved in a comprehensive study which aims to constrain a large number of models of PPS against the observational data.

C. Mapping Stochastic Gravitational Wave Background

The Universe may be filled with Stochastic Gravitational Wave Background (SGWB) originated in the Early universe or in the present Universe. Direct detection and measurement of this radiation may not only provide strong observational support to Einstein's theory of general relativity, it may also be used as a probe of the early Universe, like Cosmic Microwave Background(CMB), or may open up a new window of astronomy. Due to the fact that a gravitational wave detectors like Laser Interferometric Gravitational Wave Observatories (LIGO) have very poor pointing accuracy (around 90 degree for a LIGO detector) resolving a gravitational wave source on the sky or making a map of sky is challenging. It has been argued that SGWB can be extracted from cross-correlating the signals from two LIGO detectors assuming that the noise at two (LIGO) detectors will be un-correlated and the signal will be common. In the present work we consider mopping SGWB as an optimization problem and use Particle Swarm Optimization (PSO), which is population based search procedure used in artificial intelligence, to reconstruct the map of SGWB sky for lower harmonic multipoles from the cross-correlated output of two detectors. In the present work we show that it may be not be possible to resolve higher harmonics from a pair of Ligo detectors but lower harmonics can be successfully recovered.

This project is in final stage of its completion.

D. Radio Astronomy

I have worked on some projects in Radio Astronomy when I pursued a post-doc in Computational Astronomy at the National Centre for Radio Astrophysics (NCRA-TIFR) Pune, India., with **Prof. Jayaram Chengalur**. With Prof. Chengalur I developed a software package named `FLAGCAL` for flagging and calibration of the Giant Meter Radio Telescope (GMRT) data. This package can be used to remove the data corrupted due to Radio Frequency Interference (RFI), instrumental problems or other issues. Written in a very user friendly way and supported by documentation and publication, `FLAGCAL` can flag and calibrate a large volume of data in a short period of time on a multi-core platform. It can find its use in other projects also apart from those for which it was developed. The details of the package can be found in (Prasad & Chengalur, 2012).

A short summary of some other projects I have been involved in and have used `FLAGCAL` for data analysis at some stage is as follows.

(1) Detection of Fast transients with Radio Interferometric arrays

Involving a team of members from India and Australia and headed by **N. D. R. Bhat** from the Centre for Astrophysics & Supercomputing, Swinburne University, Australia and **Prof. Yashwant Gupta** from the National Centre for Radio Astronomy Pune, India, the aim of this project was to develop a software pipeline for real-time fast radio transient detection for the GMRT. In this project, my primary role was to carry out analysis and simulations for noise statistics and contribute in the imaging part of the pipeline using `FLAGCAL`. The project is complete and a summary of the project is given below.

We developed a transient detection system for GMRT that will function in a commensal mode with other observing programs. It capitalises on the GMRT's interferometric and sub-array capabilities, as well as the versatility of the new software backend. We carried out a pilot survey to aid the software development effort. This survey was conducted at 325 and 610 MHz, and covered 360 deg^2 of the sky with fairly short dwell times. It provides oodles of real data for testing the efficacies of algorithms and observing strategies applicable for transient detection. We present several examples illustrating the methodologies of detecting short-duration transients, including the use of sub-arrays for higher resilience to spurious events of terrestrial origins, localisation of candidate events via imaging and phasing in software toward the direction of target for improved detection. In addition to the general goal of demonstrating the use of interferometric arrays for fast transient exploration, thereby marking important steps in the road map toward SKA-era science, our efforts lay a foundation on which to build a more sophisticated and sensitive system that will become necessary as the GMRT is upgraded with wider bandwidth instruments in the near future. A detail description of the pipeline and the results of the pilot survey are published in (Bhat et al., 2013).

(2) Characterizing foreground for redshifted 21 cm radiation: 150 MHz Giant Metrewave Radio Telescope observations

Foreground removal is a major challenge for detecting the redshifted 21-cm neutral hydrogen (HI) signal from the Epoch of Reionization (EoR). We have used $150\,\mathrm{MHz}$ GMRT observations to characterize the statistical properties of the foregrounds in four different fields of view. The measured multi-frequency angular power spectrum $C_\ell(\Delta\nu)$ is found to have values in the range $10^4\ \mathrm{mK}^2$ to $2\times10^4\ \mathrm{mK}^2$ across $700 \le \ell \le 2\times10^4$ and $\Delta\nu \le 2.5$ MHz, which is consistent with model predictions where point sources are the most dominant foreground component. The measured $C_\ell(\Delta\nu)$ does not show a smooth $\Delta\nu$ dependence, which poses a severe difficulty for foreground removal using polynomial fitting.

The observational data was used to assess point source subtraction. Considering the brightest source $(\sim 1\ \mathrm{Jy})$ in each field, we find that the residual artifacts are less than 1.5% in the most sensitive field (FIELD I). Considering all the sources in the fields, we find that the bulk of the image is free of artifacts, the artifacts being localized to the vicinity of the brightest sources. We have used FIELD I, which has a rms noise of $1.3\ \mathrm{mJy/Beam}$, to study the properties of the radio source population to a limiting flux of $9\ \mathrm{mJy}$. The differential source count is well fitted with a single power law of slope -1.6. We find there is no evidence for flattening of the source counts towards lower flux densities which suggests that source population is dominated by the classical radio-loud Active Galactic Nucleus (AGN).

The diffuse Galactic emission is revealed after the point sources are subtracted out from FIELD I . We find $C_\ell \propto \ell^{-2.34}$ for $253 \le \ell \le 800$ which is characteristic of the Galactic synchrotron radiation measured at higher frequencies and larger angular scales. We estimate the fluctuations in the Galactic synchrotron emission to be $\sqrt{\ell(\ell+1)C_\ell/2\pi} \simeq 10\,\mathrm{K}$

at $\ell = 800$ ($\theta > 10'$). The measured C_ℓ is dominated by the residual point sources and artifacts at smaller angular scales where $C_\ell \sim 10^3\ \mathrm{mK}^2$ for $\ell > 800$.

The results of the study are published in (Ghosh et al., 2012).

E. Structure formation in the universe

This section summarizes the work which I have done for my Ph.D thesis at the Harish-Chandra Research Institute Allahabad, under the supervision of Prof. J. S. Bagla.

Galaxies, clusters of galaxies and other cosmological structures in the universe are believed to have formed due to gravitational amplification of the primordial density fluctuations which are imprinted in the CMBR sky. The growth of structures in the universe from the primordial fluctuations to the present can be studied analytically as long as the fluctuations are small, since in this case they grow independently at different scales i.e., the linear regime. However, when the fluctuations become large, mode coupling makes it impossible to use analytical methods and cosmological N-body simulations are generally used. Two of the main problems I have worked on are mode coupling in non-linear gravitational clustering and the finite box size effects in cosmological N-body simulations. A short summary of these is as follows:

In the Cold Dark Matter (CDM) dominated universe, structure formation takes place hierarchically, in the sense that structures at small scales form first and lead the formation of structures at larger and larger scales subsequently. In this scenario it becomes important to understand how the presence of structures at small scales (substructure) affects the formation of structures at larger scales. It is well known that the transfer of power in a nonlinear gravitational cluster is mainly from large to small scales, and so there is no effect of substructure on the collapse of fluctuations at large scales at the level of the power spectrum. In a series of two publications (Bagla et al., 2005; Bagla & Prasad, 2009) we tried to understand the role of substructure in hierarchical gravitational clustering using indicators other than the power spectrum.

In order to understand the role of substructure, in one of the projects we studied the collapse of a plane wave, which represents a large scale perturbation, in the presence and absence of substructure or small scale perturbations (Bagla et al., 2005). We found that the plane wave collapses to a thin sheet (pancake) which gets thinner when small scale perturbations are introduced isotropically. We conclude that the scattering between clumps (formed due to the collapse of small scale perturbations) helps in the dynamical relaxation of the plane wave and the pancake becomes thinner. Apart from this, we also tried to model the effects of small scale perturbations in the form of artificial viscosity. Applying Burger's equation, we found that it is possible to find a common value of viscosity for every multistream region which forms due to the collapse of the plane wave. The details of this work can be found in (Bagla et al., 2005).

In another project, we studied the role of substructure in gravitational clustering using a set of cosmological N-body simulations (Bagla & Prasad, 2009) for a general class of models. We simulate the collapse of a pure power law model ($n = -1$) and considering it as the reference model, we also simulate two other models in which we either suppress or enhance the power at small scales. We analyze our results using visual comparison (slices), two point correlation function, Skewness and number density of haloes. We find that the effects of substructure on the collapse of perturbations at larger scales are not as significant in a general case as they are in the case of planar collapse. The detailed results of this study can be found in (Bagla & Prasad, 2009).

Cosmological N-body simulations play an important role in understanding the gravitational clustering of matter in the universe. However, they are not free from the limitations of numerical modeling. One of the main limitations of cosmological N-body simulations arises from the finite range of scales considered depending on the grid size and the size of the simulation box. In cosmological N-body simulations, fluctuations at scales smaller than the grid scale and larger than the box size are ignored. Due to the fact that power transfer in non-linear gravitational clustering is mainly from large to small scales, effects of perturbations at sub-grid scales can be ignored, but this is not the case for the perturbations at scales larger than the simulation box. In a series of three publications (Bagla & Prasad, 2006; Prasad, 2007; Bagla et al., 2009) we have presented a prescription for estimating the effects of finite box size in cosmological N-body simulations on various physical quantities like two point correlation function, skewness, mass functions and formation and destruction rates of haloes. We have found that the absence of power at large scales due to finite box size suppresses the power at all scales and leads to the suppression of the number density of larger haloes and enhancement of that of smaller ones. The detail results of the study can be found in (Bagla & Prasad, 2006; Prasad, 2007; Bagla et al., 2009).

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