Cover Page for Proposal Submitted to the National Aeronautics and Space Administration	**NASA Proposal Number** **07-ASMCS07-0012**

NASA PROCEDURE FOR HANDLING PROPOSALS

SECTION I - Proposal Information

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Chicago	**IL**	**60637-1433**	**US**

Proposal Title : **A study for a CMB Probe of Inflation**

Proposed Start Date	Proposed End Date	Total Budget	Year 1 Budget	Year 2 Budget	Year 3 Budget
02 / 01 / 2008	**01 / 31 / 2009**	**1643035.00**	**1643035.00**	**0.00**	**0.00**

SECTION II - Application Information

NASA Program Announcement Number	NASA Program Announcement Title
NNH07ZDA001N-ASMCS	**Astrophysics Strategic Mission Concept Studies**

For Consideration By NASA Organization *(the soliciting organization, or the organization to which an unsolicited proposal is submitted)*
NASA , Headquarters , Science Mission Directorate , Astrophysics

Date Submitted	Submission Method	Grants.gov Application Identifier	Applicant Proposal Identifier
11 / 20 / 2007	**Electronic Submission Only**		

Type of Application	Predecessor Award Number	Other Federal Agencies to Which Proposal Has Been Submitted
New		

International Participation	Type of International Participation
No	

SECTION III - Submitting Organization Information

DUNS Number	CAGE Code	Employer Identification Number (EIN or TIN)	Organization Type
005421136	**5E688**	**362177139**	**ZZ**

Organization Name (Legal Name)	Company Division
UNIVERSITY OF CHICAGO, THE	
Organization DBA Name	Division Number

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CHICAGO	**IL**	**606375418**	**USA**

SECTION IV - Proposal Point of Contact Information

Name	Email Address	Phone Number
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SECTION V - Certification and Authorization

Certification of Compliance with Applicable Executive Orders and U.S. Code

By submitting the proposal identified in the Cover Sheet/Proposal Summary in response to this Research Announcement, the Authorizing Official of the proposing organization (or the individual proposer if there is no proposing organization) as identified below:

- certifies that the statements made in this proposal are true and complete to the best of his/her knowledge;
- agrees to accept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal; and
- confirms compliance with all provisions, rules, and stipulations set forth in the two Certifications and one Assurance contained in this NRA (namely, (i) the Assurance of Compliance with the NASA Regulations Pursuant to Nondiscrimination in Federally Assisted Programs, and (ii) Certifications, Disclosures, and Assurances Regarding Lobbying and Debarment and Suspension.

Willful provision of false information in this proposal and/or its supporting documents, or in reports required under an ensuing award, is a criminal offense (U.S. Code, Title 18, Section 1001).

Authorized Organizational Representative (AOR) Name	AOR E-mail Address	Phone Number
Theresa Rainer	**TerryR@ura.uchicago.edu**	**773-702-8605**

AOR Signature *(Must have AOR's original signature. Do not sign "for" AOR.)* **Date**

PI Name : **Stephan Meyer**

Organization Name : **UNIVERSITY OF CHICAGO, THE**

NASA Proposal Number

07-ASMCS07-0012

NASA Proposal Number

Proposal Title : **A study for a CMB Probe of Inflation**

SECTION VI - Team Members

Team Member Name	E-mail Address	Phone Number	Organization Name	Team Member Role	International Participation	U.S. Government Agency Participation	U.S. Government Agency	Total Funds Requested
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Kent Irwin	irwin@boulder.nist.gov	303-497-5911	NIST	Co-I	No	Yes	National Institute of Standards & Technology (NIST)	100000.00
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U.S. Government Agency Participation	U.S. Government Agency	Total Funds Requested
No		**0.00**

Team Member Name	E-mail Address	Phone Number
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Organization Name	Team Member Role	International Participation
NASA Goddard Space Flight Center	**Co-I**	**No**

U.S. Government Agency Participation	U.S. Government Agency	Total Funds Requested
Yes	**NASA Goddard Space Flight Center**	**100000.00**

Team Member Name	E-mail Address	Phone Number
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Organization Name	Team Member Role	International Participation
Jet Propulsion Laboratory	**Co-I**	**No**

U.S. Government Agency Participation	U.S. Government Agency	Total Funds Requested
No		**0.00**

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Organization Name	Team Member Role	International Participation
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U.S. Government Agency Participation	U.S. Government Agency	Total Funds Requested
No		**0.00**

Team Member Name	E-mail Address	Phone Number
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Organization Name	Team Member Role	International Participation
Jet Propulsion Laboratory	**Co-I**	**No**

U.S. Government Agency Participation	U.S. Government Agency	Total Funds Requested
No		**0.00**

Team Member Name	E-mail Address	Phone Number
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Organization Name	Team Member Role	International Participation
University of California Irvine	**Co-I**	**No**

U.S. Government Agency Participation	U.S. Government Agency	Total Funds Requested
No		**0.00**

Team Member Name	E-mail Address	Phone Number
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Organization Name	Team Member Role	International Participation
Princeton University	**Co-I**	**No**

U.S. Government Agency Participation	U.S. Government Agency	Total Funds Requested
No		**0.00**

Team Member Name	E-mail Address	Phone Number
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Organization Name	Team Member Role	International Participation
Harvard University	**Co-I**	**No**

U.S. Government Agency Participation	U.S. Government Agency	Total Funds Requested
No		**0.00**

PI Name : **Stephan Meyer**

Organization Name : **UNIVERSITY OF CHICAGO, THE**

NASA Proposal Number

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Proposal Title : **A study for a CMB Probe of Inflation**

SECTION VII - Project Summary

This is a proposal to formulate a program of technology and instrument development for a future definition of a Beyond Einstein Inflation Probe using the polarization of the cosmic microwave background anisotropy signal (CMBPol).

Inflation explains the apparent flatness of the universe, the small amplitude of CMB anisotropy on large scales, and provides a natural explanation for the seeds of structure. The CMB polarization anisotropy has imprinted on it a signal predicted to be sourced by these same inflationary era seed fluctuations. This signal is one of the few direct observational handles on the physics of inflation.

Detection of inflation with CMB polarization is difficult because 1) The signal is at most 100 nanoKelvin so high sensitivity is needed. 2) Other polarization and temperature anisotropy is many times bigger. Current instruments do not have the required level of rejection. 3) Astrophysical and local foregrounds are large and their properties are poorly known making rejection difficult.

It is not known what is needed to make a definitive, high signal-to-noise B-mode measurement. The proposed work will develop a plan to implement the program called for in the "Task Force on Cosmic Microwave Background Research" report. We will summarize systematics mitigation and foreground rejection methods in current experiments. We will develop estimates for the cost of two template missions and the cost and schedule of maturing promising detector and optics technologies. We will summarize today's scan strategies, foreground models and rejection methods, and identify the most promising directions for further advances. We will summarize the theoretical underpinnings, the lensing signal and other sceondary anisotropy. We will show the richness of the ancillary science that would result from a CMBPol mission. The resulting report will be delivered to NASA and the Decadal Survey of the National Research Council.

PI Name : **Stephan Meyer**	**NASA Proposal Number**
Organization Name : **UNIVERSITY OF CHICAGO, THE**	**07-ASMCS07-0012**
	NASA Proposal Number

Proposal Title : **A study for a CMB Probe of Inflation**

SECTION VIII - Other Project Information

Proprietary Information

Is proprietary/privileged information included in this application?

Yes

International Collaboration

Does this project involve activities outside the U.S. or partnership with International Collaborators?

No

Principal Investigator	Co-Investigator	Collaborator	Equipment	Facilities
No	**No**	**No**	**No**	**No**

Explanation :

NASA Civil Servant Project Personnel

Are NASA civil servant personnel participating as team members on this project (include funded and unfunded)?

Yes

Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year
2008				
Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs
10				

PI Name : **Stephan Meyer**	NASA Proposal Number
Organization Name : **UNIVERSITY OF CHICAGO, THE**	**07-ASMCS07-0012**
	NASA Proposal Number

Proposal Title : **A study for a CMB Probe of Inflation**

SECTION VIII - Other Project Information

Environmental Impact

Does this project have an actual or potential impact on the environment?	Has an exemption been authorized or an environmental assessment (EA) or an environmental impact statement (EIS) been performed?
No	**No**

Environmental Impact Explanation:

Exemption/EA/EIS Explanation:

PI Name : **Stephan Meyer**	**NASA Proposal Number**
Organization Name : **UNIVERSITY OF CHICAGO, THE**	**07-ASMCS07-0012**
	NASA Proposal Number

Proposal Title : **A study for a CMB Probe of Inflation**

SECTION VIII - Other Project Information

Historical Site/Object Impact

Does this project have the potential to affect historic, archeological, or traditional cultural sites (such as Native American burial or ceremonial grounds) or historic objects (such as an historic aircraft or spacecraft)?

No

Explanation:

PI Name : **Stephan Meyer**

Organization Name : **UNIVERSITY OF CHICAGO, THE**

NASA Proposal Number

07-ASMCS07-0012

NASA Proposal Number

Proposal Title : **A study for a CMB Probe of Inflation**

SECTION IX - Program Specific Data

Question 1 : Short Title:

Answer: CMBPol Study

Question 2 : Strategic Mission Class:

Answer: Large (significantly greater than $600M)

Question 3 : Desired NASA Center Partner:

Answer: Jet Propulsion Laboratory

Question 4 : Institution Type:

Answer: Educational institution

Question 5 : Does this proposal include the use of NASA-provided high end computing?

Answer: No

Question 6 : Research Category:

Answer: 11) Development of Future Mission Concepts

Question 7 : Team Members Missing From Cover Page:

Answer:

Nils Halversen, University of Colorado, Boulder, Colorado
Jason Glenn, University of Colorado, Boulder, Colorado
Clive Dickenson, JPL
Brian Keating, CalTech
Manoj Kaplinghat, UC Irvine
Huan Tran, UC Berkeley

Question 8 : This proposal contains information and/or data that are subject to U.S. export control laws and regulations including Export Administration Regulations (EAR) and International Traffic in Arms Regulations (ITAR). I have identified the export controlled material in this proposal. I acknowledge that the inclusion of such material in this proposal may complicate the government's ability to evaluate the proposal.

Answer: No

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1 Summary

This is a proposal to formulate a program of technology and instrument development for a future definition of a Beyond Einstein Inflation Probe using the polarization of the cosmic microwave background anisotropy signal (CMBPol).

Inflation explains the apparent flatness of the universe, the small amplitude of CMB anisotropy on large scales, and provides a natural explanation for the seeds of structure. The CMB polarization anisotropy has imprinted on it a signal predicted to be sourced by these same inflationary era seed fluctuations. This signal is one of the few direct observational handles on the physics of inflation.

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It is not known what is needed to make a definitive, high signal-to-noise B-mode measurement. The proposed work will develop a plan to implement the program called for in the "Task Force on Cosmic Microwave Background Research" report. We will summarize systematics mitigation and foreground rejection methods in current experiments. We will develop estimates for the cost of two template missions and the cost and schedule of maturing promising detector and optics technologies. We will summarize today's scan strategies, foreground models and rejection methods, and identify the most promising directions for further advances. We will summarize the theoretical underpinnings, the lensing signal and other sceondary anisotropy. We will show the richness of the ancillary science that would result from a CMBPol mission. The resulting report will be delivered to NASA and the Decadal Survey of the National Research Council.

2 Science Justification

The past three decades have seen several revolutions in our thinking about how the Universe evolved. Inflation, Dark Matter, Dark Energy are concepts which did not exist 30 years ago and each is a major upheaval in our thinking. Yet out of those decades, a robust, quantitative model for the early evolution of the Universe has emerged.

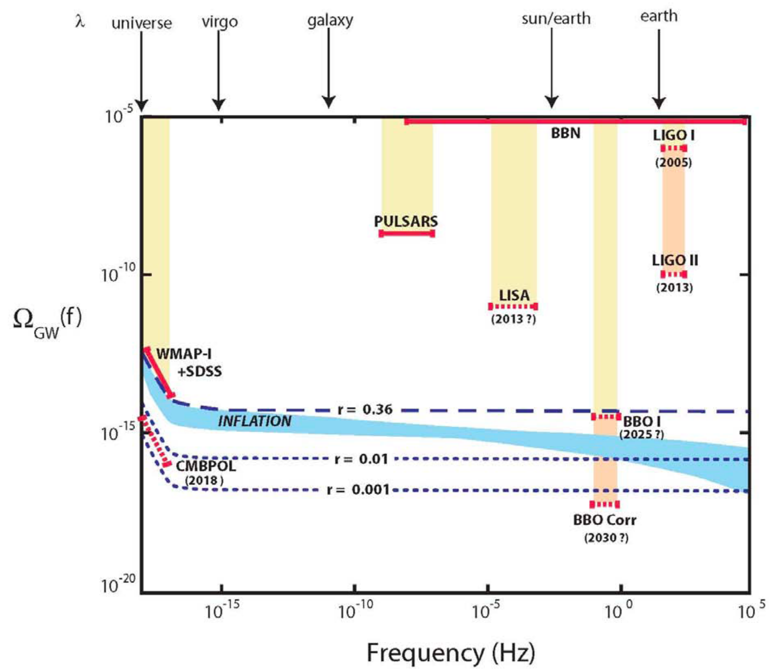

Figure 1: The plot shows the expected amplitude of gravitational waves as a function of frequency for several values r, the tensor-to-scalar ratio. WMAP constrains $r < 0.36$. The CMBPol mission sensitivity is for the Weiss Report sensitivity of 10 times more sensitive than the Planck mission. Also shown are the sensitivities of other measurements and their expected completion data. Only the Big Bang Observer, a distant future direct gravitational wave detector, has the sensitivity to see primordial gravity waves at the same level as the CMBPol mission. (Figure taken from the Weiss Report)

A remarkable interplay between new, ever more sensitive measurements, and an evolving theoretical understanding of their consequences has left us with a picture of an expanding Universe, its dynamics driven by forms of matter and energy which we have yet to discover directly, and large-scale structure thought to be the consequence the of gravitational collapse from initial seeds formed during an inflationary period. The period of inflation is one of exponential expansion with a constant density during which the size of the Universe grew by many orders of magnitude and left us with the matter, energy and expansion we see today.

Inflation itself is the first of these revolutions in thinking and is an extremely attractive model of what happened in the earliest times because it explains so much of what we see.

- Inflation solves the “flatness problem.” Space grows more flat during inflation and less flat afterwards, so that without inflation, generic initial conditions would predict curvature growing over time and the density rapidly approaching either zero or infinity. The universe today is measured to be very close to flat.

- Inflation solves the "horizon problem". Regions we see in two opposing directions in a CMB map would never have been in causal contact without an inflationary era and we would have no explanation for their nearly identical temperatures as measured by the CMB anisotropy experiments.
- Inflation solves the "monopole problem" by diluting away unobserved relics from phase transitions in the early Universe.
- Inflation provides a natural way to generate the initial seeds of later structure formation by predicting that quantum fluctuations with nearly constant fluctuation power per decade of scale will be produced.

These explanations for the classic problems of cosmology of the 1960's are compelling and make it extremely important that the idea be explored by direct measurement.

Quite aside from the cosmological interest, inflation, if correct, has enormous consequences for fundamental physics. Inflation is modeled as being caused by a scalar field rolling slowly down a potential with a kinetic energy that acts as a "cosmological constant" which causes the exponential expansion. The dynamics of the field ends inflation and gives a prediction for the spectrum of fluctuations departing slightly from scale invariant.

Unfortunately, there are very few direct inflationary observables with which to test the physics of inflation. One of the most powerful observational handles would the detection of the gravitational radiation predicted because of the quantum fluctuations occurring during inflation. Measuring the gravitational wave power spectrum would provide a direct measurement of the cosmic density history while it remains relatively constant during inflation. The measurement would not only demonstrate that something akin to inflation actually happened, but would also give tantalizing information about physics on energy scales vastly exceeding those accessible in laboratories.

The inflationary gravitational waves are expected to be produced in a scale invariant spectrum from at least the size of our Hubble length and below. As illustrated in Figure 1, current and currently planned gravitational wave detectors are 5 to 10 orders of magnitude too insensitive to measure this signal directly. In the very distant future, the Big Bang Observer may have sufficient sensitivity for a direct detection.

The Cosmic Microwave Background (CMB) Radiation provides an independent way to detect the gravitational waves from inflation because of the effect they have on the polarization pattern of the anisotropy of the CMB. As seen in Figure 1 the fiducial CMBPol mission of the Weiss Report (a factor of 10 more sensitive than the Planck mission) has the ability to detect primordial gravity waves to a level of $r < 0.01$ where r is the ratio of tensor-to-scalar perturbations.

Figure 2 illustrates how close WMAP has already come in sensitivity to constraining models of inflation. Indeed, there is a hint of departure from scale invariance which would be an indicator of inflation physics being probed (Spergel et al., 2007). The Planck mission which launches in 2008 is to be able to set a constraint of $r = 0.1$. Models with zero or one degree of fine tuning are within the black curve of Figure 2 and would be detected by the fiducial Weiss Report mission, whose sensitivity is shown by the red horizontal line at $r = 0.01$ (Boyle et al., 2006).

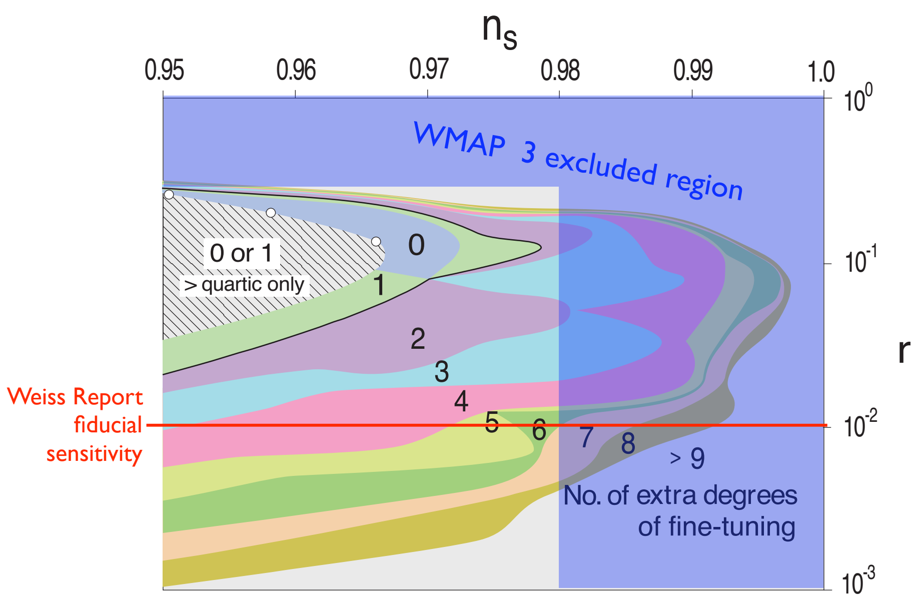

Figure 2: Predictions for the fluctuation power law slope, n_s, and tensor-to-scalar ratio, r, for minimally tuned inflation models. Over plotted are the excluded regions from WMAP three year data in purple (Spergel et al., 2007), and the red sensitivity line for the fiducial Weiss Report mission at $r = 0.01$. Figure is modified from Boyle et al. (2006).

This is a proposal to carry out a Mission Concept Study and develop a program for the study of technology and instrumentation leading to the definition of a Beyond Einstein Inflation Probe. The Probe would use the CMB B-Mode anisotropy to determine the amplitude of primordial gravitation waves. This measurement will provide unique insight to the existence and nature of an inflationary era in the early universe. The measurement addresses question 1 in the astrophysics science area of the NASA 2007 Science Plan: "Understand the origin and destiny of the universe, phenomena near black holes and the nature of gravity" (NASA, 2007).

3 Proposal Context

The roadmap "Beyond Einstein: From the Big Bang to Black Holes" recommended that an Inflation Probe be launched to "Detect the imprints left by quantum effects and gravitational waves at the beginning of the Big Bang" (Structure and Evolution of the Universe Roadmap Team, 2003). Three mission concepts based on CMB B-Mode polarization measurements were developed (Bock et al., 2006b). Several members of this proposal team were part of those mission studies. This proposed work builds on those studies.

The four national agencies, NASA, NSF, DoE and NIST involved in CMB research, combined to charge an interagency "Task Force on Cosmic Microwave Background Research" to published a report in 2005 (Weiss Report) (Bock et al., 2006a). The report emphasized the importance and fundamental nature of the CMB B-Mode research and presented a program of technology and instrument development, data analysis work and theory.

This last summer, the Beyond Einstein Program Assessment Committee (BEPAC) has made it clear that the Inflation Probe is not likely to be started in the next several years (Kennel, 2007). However, the importance of carrying out the mission was reaffirmed by the BEPAC for the reasons outlined in Section 2. As pointed out in the Weiss Report, the mission will require a number of new developments beyond the current state of the art in technology, instrument characterization, knowledge of foregrounds, and analysis. The BEPAC also reaffirmed that ongoing funding for research and technology development was a requirement for the success of the missions after the first two. The needed research to arrive at a point where an optimal mission can be started must start now.

The NASA Primordial Polarization Program Definition Team (PPPDT) (Hanany et al., 2007) was formed to shepherd the activities called out in the Weiss Report . Their recommendation was that the entire CMB community should combine to submit a single response to the Astrophysics Mission Concept Study Program. The study should carry out an Inflation Probe mission costing exercise. In addition to a report for NASA, a goal is to make the results available for the 2010 Astrophysics Decadal Survey committees.

This proposal team has found that there are sufficient questions about the nature of a future B-Mode experiment that a more in-depth review of the current technology, techniques and experiments, of our understanding of foregrounds and systematics is necessary. In addition there are several major mission design questions which are not yet answered. For example, should the Inflation Probe be aimed at only angular scales above one degree be built which permits a smaller and probably cheaper mission? Or should a mission with much higher resolution enabling the study of weak lensing of the CMB (a possible foreground) in addition to the primordial signal be the goal? Questions of foregrounds, systematics, instrument and spacecraft cost and ancillary science are all tied up in this fundamental question. These questions should be examined carefully before proposing a final mission design.

4 Proposed Work

This proposed study is designed to gather input from a broad sector of the scientific community doing research related to studying the CMB. In addition to fully costing two template mission for a CMB polarization probe of the physics of inflation, it will summarize the current state of experimental and theoretical research and outline the current technologies. The structure of the proposed work and the management is designed to permit a broad range of community input with a range of time commitment levels.

Part of the proposed work is to carry out two complete but interrelated costing exercises for two“Template Missions.” The studies will examine the characteristics and costs of a satellite with angular resolution of one degree or greater and a small beam telescope satellite with resolution of a few arcminutes. It will also study the two main focal plane detector technologies, bolometers and amplifiers. These studies will develop complete mission against which the other theoretical, systematic, and data analysis study elements of this proposed work will be tested. It is likely that the cost of the small beam mission which will require a 3m telescope would exceed $800M. It is however also possible that the outcome of this study will be that the smaller mission, with one degree beams or larger is the correct approach. It may be that the best approach is a mission in combination with larger ground-based telescopes. The answer to this question will depend on a careful balancing of cost, capability, science and risk. We propose to carry out that analysis.

Because of the BEPAC recommendation to start JDEM and LISA before the Inflation Probe, it may be that the technology detailed in our template costing studies for this proposal will not be the best possible solution by the time the actual mission is developed. We will therefore also examine in detail the current state of promising detector, optics and cooling technology for CMB research. We will assess the Technology Readiness Level (TRL) of and the cost and schedule to develop that technology to the point where a mission can be confidently defined.

Since the time of the Weiss Report, advances have been made in the techniques for analyzing foregrounds together with primordial signal. Other advances in the characterization of systematics have occurred. A numerical simulation of the template missions with primordial signal, foreground and systematics will be run. A detailed study of what is known about millimeter foregrounds and what is still needed in terms of foreground emission characteristics will be part of the report. We will carry out a survey of the primary science papers in the literature and how they couple to measurement sensitivity as a function of angular scale. The template missions will also be measured against the primary science goals.

An additional study we plan to carry out is an overview of current CMB experiments, both polarization and temperature measurements. We will look carefully at the methods each of these experiments use to reduce foregrounds and systematics in an effort to gather together the information about where the tchnology and instrumentation is now and what direction will be most promising for the future.

The report written for NASA and the Decadal Survey will develop what is learned from these studies to make a concrete costing estimate for the Inflation Probe mission. It will also present a plan with schedule and estimated costs for the research needed to enable the final definition of a mission concept within the next decade.

As shown in Figure 7 and listed below, eight detailed studies will be carried out. Two are the mission costing studies. The other studies carry out investigations of key questions experimental or technical nature that span the issues to be investigated to come to a complete understanding of the CMBPol mission. These studies will be organized to provide input to the Workshops which are described below.

The key to the success of the work outlined in this proposal is a great deal of carefully channeled input from a broad cross-section of the CMB community. This input will come from two sources: individual contributions to the workshops from investigators in the community whose research overlaps CMBPol questions, and from the detailed studies. All workshop contributions will have an oral and written component and contributers will be considered proposal collaborators.

4.a Workshops

Three workshops, all meeting in the summer of 2009 are planned. The workshop topics are

1. Theory, ancillary science and foregrounds

2. Systematic errors, observing strategies and template missions

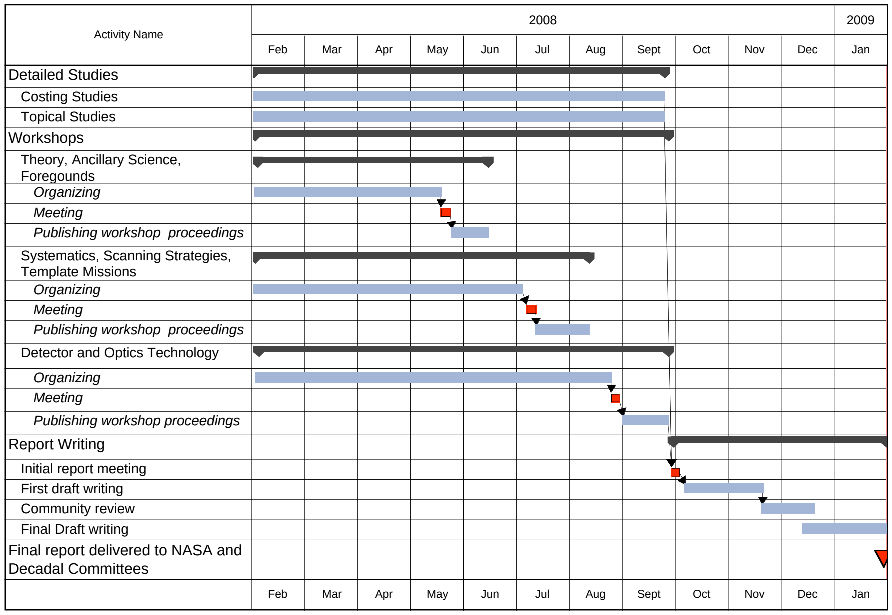

Figure 3: The CMBPol Mission Concept Study centers on the workshops. The topical and costing studies will provide major input to the workshops. Members of the community will be asked to contribute to the workshops and will be study collaborators. Each workshop generates a proceedings which includes not only written versions of the presentations, but also an analysis of the topics covered in the workshops. These are then gathered for an initial report writing meeting in early October 2008. The last quarter is devoted to writing the report and obtaining community review.

3. Focal plane and optics technology definition and costs

The first of these will be at the end of May 2008 at Fermilab. The second in June or July of 2008 near Goddard Space Flight Center. The third will be in August 2008 at NIST in Boulder. Each workshop will be led by a proposal Co-Investigator. They will be 4 to 5 days long with each day consisting of presentations in the morning followed by afternoon and evening subgroup meetings. Each subgroup will explore one of the topics or a set of topics covered in the presentation. The sub-group develops a report which summarizes the topic.

Much of the effort of the workshop organizers will be in the planning of the workshops. This planning is essential for success and is organized by the by the workshop lead. Choosing the topics for the presentations and subgroups is the first step. Choosing the presenters and formulating the make up of the subgroups and their topics will determine the productivity of the meeting. It is likely that many of the presenters will also be members of the subgroup summarizing the topic of the presentation. The presenters will be made up of co-investigators who have lead detailed studies, members of the CMB community who have been asked to present at the workshop, and also members of the community who volunteer to contribute and are willing to contribute a written part to their presentation.

Once the subgroups have met they will be responsible for writing the topical summary. The goal of the summary is to capture the consensus of the presentations and the subgroup participants. This consensus may be just a summary of what has been agreed upon. On the other hand it may be an outline of points of disagreement among the presenters or subgroup members. In this case, a synthesis of the main points of disagreement will be formulated.

Following the workshop, a proceedings, which includes the presentations, the written version of each presentation, the subgroup written findings, and a workshop summary outlining the final findings and results will be compiled. These proceedings will be published on the study website.

All presenters in workshops are considered collaborators (or are co-investigators) and are responsible for a written version of their presentation (not just the slides). The subgroups are responsible for developing the topical summary. The workshop lead will write the overall workshop summary and compile the proceedings.

All travel and room and board for the summer workshops will be supported for contributing participants. The workshop lead will have control of a workshop budget which can include relevant support staff salaries and a month of summer support for the study lead or collaborator. The workshops are open to all. Non-contributers must support their travel with other funds.

4.b Detailed Studies

A number of detailed studies will be undertaken. Each is lead by a co-investigator and results in a presentation in at one of more of the workshops. Ideally, most of the study work would be complete by the time the workshop meets. Figure 3 shows the approximate timing of the studies and workshops. The study will result in a report written by the study lead which may be the written contribution to the workshop. There will be no restriction to otherwise publishing the results of these studies in journals and the authors retain the intellectual property rights. The only requirement for this work is that a document appropriate for this study is written. The topics of the detailed studies is as follows. Additional topics may be required as the study develops.

1. A costing and template missions study for an amplifier focal plane based mission. This study will include the complete spacecraft, optics, cooling system, pointing system, control and telemetry.
2. A costing and template mission study for a bolometer focal plane based mission. This study will include the complete spacecraft, optics, cooling system, pointing system, control and telemetry.
3. Foreground removal methods study .
4. Scanning strategy study.
5. Horn optics study.
6. Weak lensing study.
7. Optical system study.
8. Systematics study.

The first two items are mission costing studies. They are to be carried out by a co-investigators lead. Because these studies are difficult and must be carried out in a rather short time, the lead will be supported by engineers and other co-investigators of this proposal. In the case of the amplifier focal plane study, some initial work has already been done on a similar study. In the case of the bolometer focal plane, this study is an amplification and continuation of a previous CMBPol mission concept study.

The other studies are on particular topics that proposal co-investigators will undertake. In all cases these studies will work in close consultation with the workshop leads, the mission costing studies, each other, and the PI. Of particular interest is that these other studies provide the needed input for the mission costing studies and support them when needed.

4.c Two Mission Costing Studies

Two mission costing studies will be carried out. Because this proposal incorporates input from the whole community, these can be carefully coordinated so that a number of possible mission architectures and capabilities may be evaluated together. Taken together, they will explore the two major detection methods, amplifiers and bolometers, and two types of experiments, a low-resolution mission aimed at seeing the B-Mode signal at angles above 1 degree, and a high-resolution mission which covers both the large and the small angular scales.

The mission studies will be coordinated in their goals but carried out independently. Their characteristics will be used to make the two "Template Missions" against which all the detailed studies will be investigated. The templates will also provide the test cases for all three workshops. This will permit the strengths of each mission to be tested against the scientific goals and the difficulties introduced by foregrounds, non-ideal experimental characteristics, and systematics.

4.c.1 Bolometer Mission Concept

Requirements for Bolometers and Technological Readiness For future space-borne polarization measurements, bolometers offer the highest sensitivity and the possibility of covering all frequency bands of interest, from 30 Ð 300 GHz. The sensitivities achievable per detector with a cryogenic space-borne telescope are clearly within reach. As shown in Table 4.1, these sensitivities are a modest factor of 2.5 lower than the goal sensitivities of Planck. In fact, laboratory instrument tests of the Planck HFI bolometric focal plane demonstrate sensitivities significantly better than the Planck goals (Bock et al., 2006a), though the in-flight sensitivities will only be demonstrated after the launch of Planck, expected in late 2008. We anticipate that CMBPol will need a raw sensitivity advantage of a factor of greater than 10 over Planck, and that most of this advantage will come from operating large arrays of order 2000 detectors. Covering the required spectral bands in a single technology provides technical simplification, avoiding the systems difficulties in combining HEMTs and bolometer technologies into a single focal plane.

In order to achieve readiness for CMBPol, the two main technical hurdles for bolometers will be developing large-format arrays, and extending the frequency coverage to low frequencies. Instruments using SQUID-multiplexed TES bolometer arrays (SCUBA2,

Freq (GHz)	NET[1]				NEP[2]	
	CMBPol[3]		Planck/HFI[4]		CMBPol	Planck/HFI
	Req'd	Goal	Goal	Meas.	Goal	Goal
30	80	57	-		4	
40	71	50	-		5	
60	60	42	-		5	
90	52	37	102	67	6	14
135	49	35	83	48	7	16
200	54	38	135	68	7	17
300	92	65	400	224	7	20

[1]Noise Equivalent Temperature per polarized detector in $\mu K_{CMB}\sqrt{s}$
[2]Noise Equivalent Power at the detector detector in $aW/\sqrt{Hz}$
[3]Assumes TES bolometers with single-mode linear polarization, 40% optical eficiency, 30% fractional badnwidth, 10mK base temperature, 2K optics, and a 40K baffle with 0.3% coupling.
[4]Planck bands are shifted slightly to match the closest CMBPol band. Measured data taken from ground-based instrument-level tests, channel average.

Table 4.1: Detector Sensitivities for CMBPol Bolometer and Planck/HFI

Frequency Bands	30-300 GHz	**Orbit**	L2 Halo
Resolution	0.9° at 90 GHz	**Inflow Data Rate**	1260kbps
Detectors	2366 TES bolometers	**Total Mass (CBE)**	1320 kg
Design Lifetime	2 years	**Total Power (CBE)**	875 W
Optics	Six 30 cm refractors	**Delta-V**	215 m/s

Table 4.2: Summary of EPIC low-resolution mission configuration

ACT, and SPT) are now coming to into the field, with formats as large as 10,000 bolometers. While further development may be required on key aspects, e.g. array uniformity, low-frequency noise stability, and magnetic field susceptibility, the pace of development indicates that large arrays will be at TRL = 6 prior to the start of CMBPol. Bolometers to date have operated at frequencies greater than 90 GHz, due limits on suspended absorber size in classical bolometers. New antenna-coupled bolometers, currently being developed by several groups in the US, avoid this limitation and can be naturally extended to operate at lower frequencies. Individual antenna-coupled bolometers have been fully demonstrated, sub-orbital experiments are now in development based on arrays of these devices, and on track to demonstrate technological readiness in a matter of a few years.

Scan-Imaging Bolometric Polarimeters We plan to further develop point bolometric mission configurations based on a previous NASA study, the Experimental Probe of Inflationary Cosmology. EPIC developed two instrument concepts based on drift-scanned bolometric polarimeters, the approach successfully demonstrated by several sub-orbital experiments and planned for the upcoming Planck mission. Scan-imaging

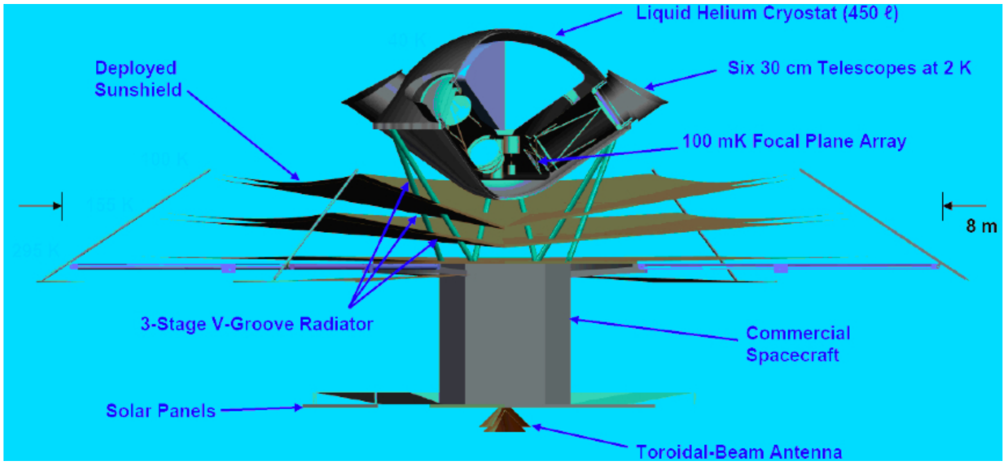

Figure 4: Low-resolution EPIC mission configuration, using multiple 30 cm cryogenic refracting telescopes operating arrays of 100 mK bolometers in bands between 30 Ð 300 GHz. The instrument is cooled to 2 K by a long-duration liquid helium cryostat, the outer shell of which is passively cooled to 40 K. The experiment scans the sky with a spinning and precessing scan strategy covering more than half the sky in a 24 hour period with a high degree of uniformity and angular coverage. A deployed shield keeps radiation from the sun, earth, and moon from entering the optics or causing thermal disturbances.

polarimeters are now producing maps with sensitivity $< 1\ \mu K_{RMS}$ in 1 degree^2 pixels on small regions of sky, demonstrating the basic technique but at 20 times lower sensitivity than will ultimately be required over the entire sky. The EPIC study developed a low-resolution mission configuration, based on multiple 30-cm refracting telescopes similar to the optics used in the BICEP experiment, and a high-resolution mission configuration, based on a 3-m Gregorian-Dragone reflecting telescope similar to the optics developed for the EBEX and Polarbear experiments.

We propose to expand the work of the EPIC study to assess the scientific tradeoffs in the choice of frequency bands and aperture diameter(s). The understanding of systematic error control is critical, and we propose to extend the current analysis to quantify in particular the impact of 1/f noise, scan strategy, and control of main beam mismatches. The large 3-m mission option opens the possibility for strong ancillary science, and we will investigate alternate optical configurations that could reduce the mass and cost of this configuration.

4.c.2 Amplifier Mission Concept

Amplifier focal planes provide a number of advantages for a CMBPol mission. Among these is the possibility of obtaining all Stokes parameters for each pixel of the focal plane continuously, the fact that the focal plane can be run at 20K rather than at sub-Kelvin temperatures, the ability of using of a correlation receiver which permits differencing inputs before the detection process. The disadvantages are the lower sensitivity due to the “amplification noise” which is a fundamental noise introduced with amplification, and higher power operation of the focal plane.

As with the bolometer mission study, the amplifier mission concept study will expand on an earlier study, in this case an Explorer Class mission. The challenges unique to the amplifier focal plane are the cooler and the sensitivity. In the previous study, three

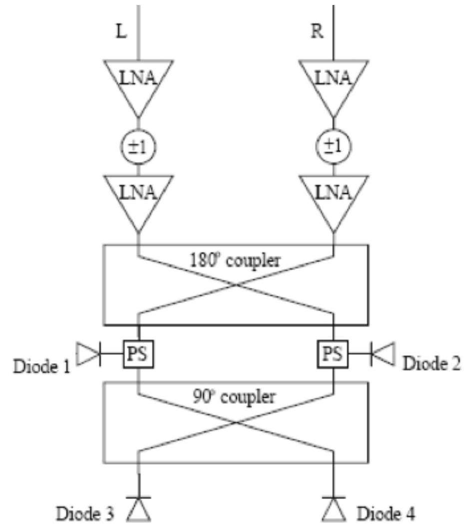

Figure 5: An schematic of the polarimeter components on the integrated circuit module of QUIET. Left- and rightcircularly-polarized radiowaves enter from the top, both fed from the same input horn which is one pixel in the focal plane. Phase switches in each arm (indicated by ±1) are operated one at a time and provide the Dicke-switching which separates the polarized signal from the total power. The signals pass through low noise amplifiers (LNA) , and then enter a series of hybrid couplers, detailed in the text. PS indicates power splitters. The demodulated outputs of detector diodes 1 and 2 are proportional to the Stokes parameter Q while diodes 3 and 4 encode U after demodulation. Filters have been omitted for clarity.

cooler options were appraised, a staged pulse tube cooler, a two stage Stirling cooler, and a Sorption Cooler. These will each be reevaluated in the light of this mission.

The amplifier sensitivity and power requirements are another element of this study. The current generation use InP amplifiers, which achieve the lowest system temperatures available for these large bandwidths at frequencies below 100 GHz. Low noise amplifiers at 40 GHz and 90 GHz with greater than 20% bandwidth and state of-the-art noise performance have been demonstrated by members of this team. A 90-GHz four-stage amplifier was developed for radio astronomy applications and has been used in CAPMAP, SZA, SEQUOIA, AMiBA, JPL's Deep Space Network and at the Effelsberg Telescope. The noise measured for this design is between 40 and 50 K when cooled to 20 K as shown in Figure 6.

4.d Final Report

After the three summer workshops, the core team of investigators (the co-investigators and the PI) will meet at Chicago to organize the writing of the final report. During the meeting the leads of the workshops and the detailed reports will present their summaries. This information will be used to formulate the report.

Figure 3 shows the schedule of the final report activity. After a first version of the report is completed, we will solicit comment from the community on the report and its conclusions. This input will be used to make any necessary modifications. The final report will be ready at the end of January 2009. The report will be delivered to the NASA

Starting September 2008, with the reports from the studies and the workshops in hand, the final writing of the report would begin. The PI and the CoIs would be responsible for the final report. Everything in the study including the final report and

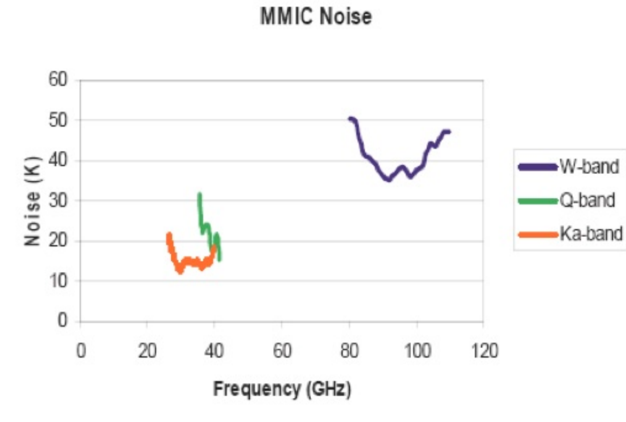

Figure 6: noise curves of one of our MMIC amplifiers. Two dozen of the 90 GHz amplifiers are currently operating in CAPMAP with a typical receiver noise of 50 K. The 40 GHz amplifiers have 20 K typical noise and are also operating in CAPMAP. We have demonstrated similar band-average performance in the QUIET modules.

the workshop and detailed study report will be public. The final report, the study and workshop reports and the workshop presentations will be a useful resource to the community following the completion of the report.

4.e Webpage

Throughout the proposed period of activity and for a period thereafter a study webpage will be maintained. The webpage will announce study activities and workshops. It will be an open repository for the detailed studies, the workshop proceedings, study conclusions and final report. The webpage will be accessible to all and a mechanism for sending comments will be provided. In addition we will maintain a small outreach webpage explaining the activity of the study and the relevant science at a level aimed at the gerneral public.

We plan to organize the material on the webpage so that it will be useful as a reference for the community in addition to being aimed at the decadal survey committees and other NASA committees. The final report and all the underlying reports and materials will be in a single, organized location.

5 Management

The CMBPol study will bring input from as wide a group as possible. It also must converge within the one year study period. This requires a carefully constructed management structure.

The PI has overall responsibility for the timely completion of the study and writing of the report. In this he is assisted by the Co-Investigators who each have responsibility for one of two activities: a workshop or a detailed study.

The workshops are the mechanism which brings collaboration from a large part of the interested community into the study. Careful planning before the workshops will be needed and is the responsibility of the co-investigator in charge of the workshop. The workshop, consisting of presentations followed by analysis of specific topics by subgroups will result in a proceedings which is the responsibility of the workshop lead. The workshop title and leads are shown in Figure 7. The workshop lead will also organize

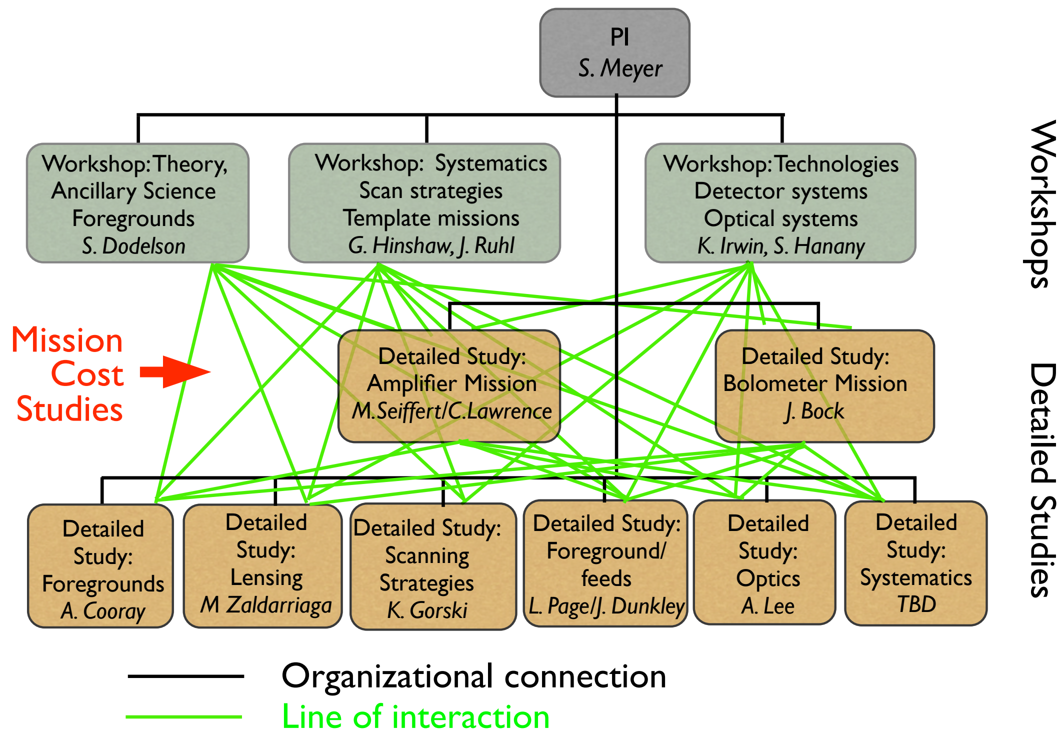

Figure 7: The CMBPol Mission Concept Study is organized around two activities. Workshops which bring in the opinions and ideas of the community and detailed studies which look at specific issues for a CMBPol mission. The detailed studies are a major input to the workshops themselves. As the chart indicates, interactions between nearly all studies with each other and the workshops will tie the study together. Two mission cost studies will be carried out and the results will be presented in two of the three workshops.

the topics, designate a subgroup chair and ensure that each topic is fully developed within the subgroup. The subgroups will be responsible for a summary of their topic and the generation of a written set of conclusions. Anyone contributing a presentation and written contribution to one of the workshops will be considered a collaborator. The subgroups will consist of both collaborators and CoIs.

Another set of co-investigators will carry out detailed studies on particular topics. These include costing studies as well as the studies on scanning, foregrounds, and instrumentation. The study results will be presentated at one of more of the workshops and a written report will be folded into the final proposed report.

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  - Associate Director, Kavli Institute for Cosmological Physics
  - Associate Director, South Pole Telescope Project
  - Member WMAP Science Team
  - Director, Center for Astrophysical Research in Antarctica (CARA). 1997 - 1999
  - Member COBE Science Working Group
- Associate Professor of Physics, Astronomy and Astrophysics, and Enrico Fermi Institute (University of Chicago) 1993-1997
- Assistant Professor of Physics (MIT) 1984 - 1992
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Scientific Editor, Journal of Cosmology and Astroparticle Physics

Selected Invited Reviews

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- S. Dodelson, "CMB-Cluster Lensing," *Phys. Rev. D* **70**, 023009 (2004)
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- W. Hu and S. Dodelson, "Cosmic Microwave Background Anisotropies," *Ann. Rev. Astron. Astrophys.* **40**, 171 (2002)

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Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Implications for Cosmology
D. N. Spergel, R. Bean, O. Dore, M. R. Nolta, C. L. Bennett, **J. Dunkley**, G. Hinshaw, N. Jarosik, E. Komatsu, L. Page, H. V. Peiris, L. Verde, M. Halpern, R. S. Hill, A. Kogut , M. Limon, S. S. Meyer, N. Odegard, G. S. Tucker, J. L. Weiland, E. Wollack, E. L. Wright, 2007 ApJS, **170**, 377.

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J. Dunkley, M. Bucher, P. G. Ferreira, K. Moodley, C. Skordis, 2005, Monthly Notices of the Royal Astronomical Society, **356** 925.

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Advanced Education

1993	Ph.D., Physics, Columbia University "On Photoemission with Polarized X-rays" (Advisor: Prof. R. Novick)

Appointments

2003 – 2005	Associate Professor, Weizmann Institute of Science, Israel
2002 – Present	Associate Fellow, Minnesota Supercomputing Institute
2002 – Present	Associate Professor, University of Minnesota/Twin Cities
1999 – 2002	Assistant Professor, University of Minnesota/Twin Cities
1996 – 1998	Research Physicist, University of California, Berkeley
1993 – 1996	Center Research Fellow, The Center for Particle Astrophysics University of California, Berkeley

Honors and Awards (abbreviated)

2003	'Best Professor in Physics', Institute of Technology Student Board, University of Minnesota
2000-2003	Land-McKnight Professorship, University of Minnesota
2000	Results first authored by Hanany et al. called by *science* "one of the 10 most important science breakthroughs of the year"
1993	Center Research Fellow, The Center for Particle Astrophysics University of California, Berkeley

Membership: American Physical Society, American Astronomical Society, Sigma Xi

Recent Funded Projects (abbreviated)

- EBEX (PI): A balloon borne experiment to measure the polarization of the cosmic microwave background radiation.
- EPIC (Co-I): A study for a NASA satellite mission that will study the polarization of the cosmic microwave background radiation.
- Magnetic Bearing/Anti-Reflection Coatings (PI): Development of a superconducting magnetic bearing and anti-reflection coatings for cosmic microwave background polarization measurements.
- MAXIPOL (PI): An experimental program to measure the polarization anisotropy in the cosmic microwave background radiation.
- Archeops (Co-PI): A European balloon borne cosmic microwave background anisotropy and polarization experiment.
- MAXIMA (Co-I): An experimental program to measure the temperature anisotropy in the cosmic microwave background radiation.

Community Service (abbreviated)

- Lead organizer, American Astronomical Society Meeting Special Session, "The Cosmic Microwave Background Radiation", January 2007
- Editor, Journal of Cosmology and Astro-Particle Physics, 2000 – present
- Chair, Local Organizing Committee, 'The cosmic microwave background and its polarization', March 2003, University of Minnesota/Twin Cities
- Peer review panels for NSF, NASA, and Lawrence Livermore National Laboratory

Recent Relevant Publications

- *'MAXIPOL: Cosmic Microwave Background Polarimetry Using a Rotating Half Wave Plate'*, B. R. Johnson et al., ApJ 2007, Vol. 663, in print, astro-ph/0611394,
- *'A Millimeter-Wave Achromatic Half Wave Plate* S. Hanany, et al. Applied Optics, 2005, Vol. 44, Pgs. 4666-4670, physics/0503122
- *'Temperature and polarization angular power spectra of Galactic dust radiation at 353 GHz as measured by Archeops,* N. Ponthieu, et al. 2005, A&A, Vol. 444, Pg. 327, astro-ph/0501427
- *'Cosmological Constraints from Archeops'* A. Benoit, et al., 2003, Astronomy and Astrophysics, Vol. 399, L25-L30, astro-ph/0210306
- *'A Cosmic Micorwave Background Radiation Polarimeter Using Superconducting Bearings'*, S. Hanany, et al. , 2003, IEEE Trans. Appl. Supercond., Vol. 13, pg. 2128, astro-ph/0304312
- *'Comparison of Designs of Off-Axis Gregorian Telescopes for Millimeter-Wave Large Focal Plane Arrays'* S. Hanany, D. Marrone, 2002, Applied Optics, Vol. 41, #22, 4666. astro-ph/0206211
- *'MAXIMA-1: A Measurement of the Cosmic Microwave Background Anisotropy on Angular Scale of 10 arcminutes to 5 degrees'* S. Hanany, et al. 2000, ApJ, Vol. 545L, 5, astro-ph/0005123

Biographical Sketch

Gary Hinshaw (Co- Investigator)

<u>Education:</u>

Ph.D.	Physics,	1988	Harvard University
AB	Physics,	1981	University of California, Berkeley

<u>Present Position:</u>

Astrophysicist
Code 665, Observational Cosmology Laboratory
NASA Goddard Space Flight Center

Dr. Hinshaw of GSFC has 17 years of experience in CMB satellite data analysis with the COBE-DMR and WMAP missions. He has been a lead author or co-author on all of the significant COBE-DMR and WMAP anisotropy publications. He presently serves as Data Analysis Lead for NASA's successful Wilkinson Microwave Anisotropy Probe. He played a key role in defining the WMAP mission by developing a scientific mission simulator that allowed for a wide range of trade studies to be performed in the early stages of the mission development. The code has been expanded over the life of the mission and is currently used extensively in the analysis of flight data from WMAP. Dr. Hinshaw presently also serves as director of the Legacy Archive for Microwave Background Data Analysis (LAMBDA) which serves CMB data to the scientific community. Last year he won the John C. Lindsay Memorial Award for Space Science, Goddard's highest scientific honor, for his work on WMAP.

<u>Recent Publications:</u>

- Hinshaw, G., Nolta, M.R., Bennett, C.L., Bean, R., Dore, O., Greason, M.R., Halpern, M., Hill, R.S., et. al., "Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Temperature Analysis", ApJS, submitted, 2006.
- Page, L., Hinshaw, G., Komatsu, E., Nolta, M.R., Spergel, D.N., Bennett, C.L., Barnes, C., Bean, R., et. al., "Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Polarization Analysis", ApJS, submitted, 2006.
- Spergel, D.N., Bean, R., Dore, O., Nolta, M.R., Bennett, C.L., Hinshaw, G., Jarosik, N., Komatsu, E., et. al., "Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Implications for Cosmology", ApJS, submitted, 2006.
- Hinshaw, G., Barnes, C., Bennett, C.L., Greason, M.R., Halpern, M., Hill, R.S., Jarosik, N., Kogut, A. Limon, M., et. al., "First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Data Processing Methods and Systematic Errors Limits", ApJS, 148, 63, 2003.
- Hinshaw, G., Spergel, D.N., Verde, L., Hill, R.S., Meyer, S.S., Barnes, C., Bennett, C.L., Halpern, M., Jarosik, N., et. al., "First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: The Angular Power Spectrum", ApJS, 148, 135, 2003.
- Bennett, C.L., Halpern, M., Hinshaw, G., Jarosik, N., Kogut, A., Limon, M., Meyer, S.S., Page, L., Spergel, D.N., et. al., "First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Maps and Basic Results", ApJS, 148, 1, 2003.
- Jarosik, N., Bennett, C.L., Halpern, M., Hinshaw, G., Kogut, A., Limon, M., Meyer, S.S., Page, L., Spergel, D.N., et. al., "First Year Wilkinson Microwave Anisotropy

Kent D. Irwin

National Institute of Standards and Technology	(303) 497-5911 (office)
M.S. 817.03, 325 Broadway	(303) 497-3042 (fax)
Boulder, CO 80305	irwin@nist.gov

Present Position

NIST Fellow	Adjoint Professor
Leader, Quantum Sensors Project	Astrophysics and Planetary Sciences
Quantum Electrical Metrology Division	University of Colorado, Boulder
National Institute of Standards and Technology	

Education

1988 B.S., Physics, California Institute of Technology

1995 M.S., Physics, Stanford University

1995 Ph.D., Physics, Stanford University

Selected Awards

- Samuel Wesley Stratton Award, NIST, 2007
- Keithley Award, American Physical Society, 2007
- Flemming Award, George Washington University, 2006
- Applied Research Award, NIST, 1999
- Department of Commerce Gold Medal, 1999

Selected Publications

Seeing With Superconductors, K. D. Irwin , Scientific American 295, 86-94, November 2006.

Transition-Edge Sensors, K. D. Irwin and G. C. Hilton, in *Cryogenic Particle Detection*, C. Enss (Ed.), Springer-Verlag Berlin Heidelberg, 2005.

Microwave SQUID multiplexer, K. D. Irwin and K. W. Lehnert, Appl. Phys. Lett. 85, 2107 (2004).

An application of electrothermal feedback for high resolution cryogenic particle detection, K. D. Irwin, Appl. Phys. Lett. 66, 1998 (1995).

Spider Optimization: Probing the Systematics of a Large Scale B-Mode Experiment Scales, C. J. MacTavish, P. A. R. Ade, E. S. Battistelli, S. Benton, R. Bihary, J. J. Bock, J. R. Bond, J. Brevik, S. Bryan, C. R. Contaldi, B. P. Crill, O. Doré, L. Fissel, S. R. Golwala, M. Halpern, G. Hilton, W. Holmes, V. V. Hristov, K. Irwin, W. C. Jones, C. L. Kuo, A. E. Lange, C. Lawrie, T. G. Martin, P. Mason, T. E. Montroy, C. B. Netterfield, D. Riley, J. E. Ruhl, A. Trangsrud, C. Tucker, A. Turner, M. Viero, D. Wiebe **arXiv:0710.0375** (October 2007)

Review: SQUID Multiplexers for Transition-Edge Sensors, K.D. Irwin, Physica C 368: 203-210, 2002.

Quantum Calorimetry, Stahle, C.K.; McCammon, D.; Irwin, K.D., Physics Today, 32-37, Aug 1999

Superconducting Multiplexer for Arrays of Transition Edge Sensors, Chervenak, J.; Irwin, K.; Grossman, E.; Martinis, J.; Reintsema, C.; Huber, M., Appl. Phys. Lett. 74(26): 4043-4045, Jun 28, 1999

Thermal-Response Time of Superconducting Transition-Edge Microcalorimeters, Irwin, K.D.; Hilton, G.C.; Wollman, D.A.; Martinis, J.M., J. Appl. Phys. 83(8): 3978-3985, Apr 1998

CHARLES R. LAWRENCE

EDUCATION

1983 Ph. D. in Physics, Massachusetts Institute of Technology.

1970 B. S. with Distinction, Honors in Physics, University of Michigan, Ann Arbor.

EMPLOYMENT

2000– Principal Scientist, Astrophysics Element, JPL

1993–2000 Research Scientist, Astrophysics Element, JPL

1991–1993 Senior Research Associate, California Institute of Technology

1986–1991 Senior Research Fellow, California Institute of Technology

1983–1986 Research Fellow, California Institute of Technology

1978–1983 Research Assistant, Massachusetts Institute of Technology

PROFESSIONAL ACTIVITIES

2003– Lead, JPL Center for Longwavelength Astrophysics

1998– Deputy Project Scientist for SIRTF

1998– Survey Scientist for Low Frequency Instrument on Planck,

1997– Project Scientist, US Planck Project

1997– PI, US Low Frequency Instrument team on Planck

1996– Instrument Scientist for the SIRTF Infrared Spectrograph

SELECTED PUBLICATIONS

Joint Bayesian Component Separation and CMB Power Spectrum Estimation H. K. Eriksen, J. B. Jewell, C. Dickinson, A. J. Banday, K. M. Górski, C. R. Lawrence 2007, *Ap. J.*, in press

Spitzer Observations of 3C Quasars and Radio Galaxies: Mid-Infrared Properties of Powerful Radio Sources K. Cleary, C. R. Lawrence, J. A. Marshall, L. Hao, and D. Meier 2007, *Ap. J.*, **660**, 117

CMB Component Separation by Parameter Estimation H. K. Eriksen, C. Dickinson, C. R. Lawrence, C. Baccigalupi, A. J. Banday, K. M. Gorski, F. K. Hansen, P. B. Lilje, E. Pierpaoli, M. D. Seiffert, K. M. Smith, and K. Vanderlinde 2006, *Ap. J.*, **641**, 665

The Spitzer Space Telescope Mission M. W. Werner, T. L. Roellig, F. J. Low, G. H. Rieke, M. Rieke, W. F. Hoffmann, E. Young, J. R. Houck, B. Brandl, G. G. Fazio, J. L. Hora, R. D. Gehrz, G. Helou, B. T. Soifer, J. Stauffer, J. Keene, P. Eisenhardt, D. Gallagher, T. N. Gautier, W. Irace, C. R. Lawrence, L. Simmons, J. E. van Cleve, E. L. Wright, M. Jura, and D. P. Cruikshank 2004, *Ap. J. Suppl.*, **154**, 1

The Planck Mission C. R. Lawrence 2002, SPIE conference *Large Telescopes in Space*

Separation of Foreground Radiation from Cosmic Microwave Background Anisotropy Using Multi-frequency Measurements W. N. Brandt, C. R. Lawrence, A. C. S. Readhead, J. Pakianathan, and T. Fiola 1994, *Ap. J.*, **424**, 1.

Observations of the Isotropy of the Cosmic Microwave Background Radiation A. C. S. Readhead and C. R. Lawrence 1992, *Ann. Rev. Astro. Astrophys.*, **30**, 653.

A Limit on the Anisotropy of the Microwave Background Radiation on Arc Minute Scales A. C. S. Readhead, C. R. Lawrence, S. T. Myers, W. L. W. Sargent, H. E. Hardebeck, and A. T. Moffet 1989, *Ap. J.*, **346**, 566.

Curriculum Vitae of Adrian T. Lee

Professional Preparation:

Columbia University, Physics, B.A. 1986
Stanford University, Physics, Ph.D., 1993
University of California, Berkeley, Postdoctoral Fellow in Experimental Astrophysics, 1994-2000

Appointments:

Associate Professor, Department of Physics, University of California, Berkeley, 2004-present
Assistant Professor, Department of Physics, University of California, Berkeley, 2000-2004
Postdoctoral Fellow, Center for Particle Astrophysics and Dept. of Physics, University of California, Berkeley 1994-2000
- Balloon-borne measurements of the Cosmic Microwave Background anisotropy and development of Voltage-biased Superconducting Bolometer (VSB).

Postdoctoral Fellow, Dept. of Radology, Stanford University, 1993-1994
- Mapping of human visual cortex function with Nuclear Magnetic Resonance Imaging.

Doctoral Candidate, Dept. of Physics, Stanford University, 1986-1993
- Search for non-baryonic dark matter. Adviser: Blas Cabrera

Publications related to proposal:

A High Spatial Resolution Analysis of the MAXIMA-1 Cosmic Microwave Background Anisotropy Data, A.T. Lee , P. Ade, A. Balbi, J. Bock, J. Borrill, A. Boscaleri, P. De Bernardis, P.G. Ferreira, S. Hanany, V.V. Hristov, A.H. Jaffe, P.D. Mauskopf, C.B. Netterfield, E. Pascale, B. Rabii, P.L. Richards, G.F. Smoot, R. Stompor, C.D. Winant, J.H.P. Wu, Astrophysical Journal Letters, 561:L1-L5, Nov. 2001, astro-ph/0104459

"MAXIMA-1: A Measurement of the Cosmic Microwave Background Anisotropy on Angular Scales of 10' to 5 degrees," S. Hanany, P. Ade, A. Balbi, J. Bock, J. Borrill, A. Boscaleri, B. P. Crill, P. De Bernardis, H. Del Castillo, P. Ferreira, K. Ganga, V. Hristov, A. H. Jaffe, A. E. Lange, A.T. Lee, P. Mauskopf, C. B. Netterfield, S. Oh, E. Pascale, B. Rabii, P. L. Richards, J. Ruhl, G. F. Smoot, C. D. Winant, Submitted to ApJ Letters, astro-ph/0005123

"Cosmology from Maxima-1, Boomerang and COBE/DMR CMB Observations," A.H. Jaffe, P.A.R. Ade, A. Balbi, J.J Bock, J.R. Bond, J. Borrill, A. Boscaleri, K. Coble, B.P. Crill, P. de Bernardis, P. Farese, P.G. Ferreira, K. Ganga, M. Giacometti, S. Hanany, E. Hivon, V.V. Hristov, A. Iacoangeli, A.E. Lange, A.T. Lee, L. Martinis, S. Masi, P.D. Mauskopf, A. Melchiorri, T. Montroy, C.B. Netterfield, S. Oh, E. Pascale, F. Piacentini, D. Pogosyan, S. Prunet, B. Rabii, S. Rao, P.L. Richards, G. Romeo, J.E. Ruhl, F. Scaramuzzi, D. Sforna, G.F. Smoot, R. Stompor, C.D. Winant, J.H.P. Wu, submitted to Physical Review Letters, astro-ph/0007333

"A Superconducting Bolometer with Strong Electrothermal Feedback," A.T. Lee, P.L. Richards, S.-W. Nam, B. Cabrera, and K.D. Irwin, Appl. Phys. Lett. 69, 1801 (1996).

"Voltage-biased superconducting transition-edge bolometer with strong electrothermal feedback operated at 370 mK," S-F Lee J. M. Gildemeister, W.A. Holmes, A.T. Lee, and P.L. Richards, Applied Optics, Vol. 37, No. 16, pp 3391-3397 (1998).

Collaborators (48 months)

P. Ade (QMWC), A. Balbi (Rome), J. Bock (JPL), J.R. Bond, J. Borrill (LBNL), A. Boscaleri (IROE-CNR), B. Cabrera (Stanford), B. Crill (CIT), P. DeBernardis (Rome), G. DeGasparis (Rome), G. DeTroia (Rome), H. Del Castillo (JPL), J. Clarke (UCB), P. Farese (UCSB), P. Ferreira (Oxford), K. Ganga (IPAC), M. Giacometti (Rome), J. Gildemeister (UCB), S. Hanany (Minn), W. Holmes (JPL), W. Holzapfel (UCB), E. Hivon (CIT), V. Hristov (CIT), I. Iacoangeli (Rome), K.D. Irwin (NIST), A. Jaffe (UCB), A. Lange (CIT), S. Lee (Seagate), L. Martinis (Rome), S. Masi (Rome), P. Mauskopf (UMass), A. Melchiorri (Oxford), L. Miglio (Rome), T. Montroy (UCSB), M. Myers (UCB), S.-W. Nam, C. Netterfield (Toronto), S. Oh (UCB), E. Pascale (IROE-CNR), F. Piacentini (Rome), D. Pogosyan (CITA), S. Prunet (CITA), B. Rabii (UCB), S. Rao (CIT), P. Richards (UCB), G. Romeo (Rome), J. Ruhl (UCSB), F. Scaramuzzi (Rome), D. Sforna (Rome), H. Spieler (LBNL), R. Stompor (UCB), G. Smoot (UCB), C. Winant (UCB), P. Wu (UCB), J. Yoon (UCB).

CURRICULUM VITAE
LYMAN ALEXANDER PAGE JR.

January, 2007

Department of Physics, Princeton University
Princeton, New Jersey 08544-0708
Phone: (609) 258-5578, Email: Page@Princeton.edu

Education

Massachusetts Institute of Technology, Cambridge, MA	Ph.D. 1989 (Physics)
Thesis Advisor: Stephan S. Meyer	
Bowdoin College, Brunswick, ME	B.A. 1978 (Physics)

Honors and Awards

Member of the National Academy of Sciences	2006
Philips Lectureship	2006
Fellow of the American Academy of Arts & Sciences	2004
Marc Aaronson Lectureship & Prize	November 2003
Primakoff Lectureship	March 2003
David and Lucile Packard Fellowship	September 1994
Princeton Engineering Council Teaching Award	May 1994 & 1992
Research Corporation Cottrell Scholar	May 1994
National Science Foundation NYI Award	August 1993
NASA Graduate Student Researchers Program Fellowship	1987-1989

Employment and Research History

- Henry DeWolf Smyth Professor of Physics at Princeton — July 2005 - Present
- Professor of Physics at Princeton — July 1998 - July 2005
- Associate Professor of Physics at Princeton — July 1995 - June 1998
- Assistant Professor of Physics at Princeton — July 1991 - June 1995
    - Page's primary research is on measurements of the cosmic microwave background (CMB) from ground-based, balloon-borne, and satellite platforms with HEMT amplifiers, SIS mixers, and bolometers. Page is one of the original co-investigators on the *WMAP* satellite and is the director of the ACT project.
- Instructor of Physics at Princeton — July 1990 - July 1991
- Postdoctoral Research Fellow at MIT — October 1989 - July 1990
- Graduate Student at MIT — September 1983 - September 1989
- Self employed — February 1980 - September 1983
    - Rebuilt a 37' wooden ketch and sailed about the Caribbean and East Coast of the United States. To support myself and my boat, I worked as a painter, carpenter, rigger, and cabinet maker in various ports of call. In the nine months before graduate school, I was based in Boston.
- Research Technician, Bartol Research Foundation, Newark, DE, McMurdo Antarctica, and South Pole, Antarctica. — September 1978 - January 1980

JOHN E. RUHL

Affiliation:	Physics Department Case Western Reserve University 10900 Euclid Ave. Cleveland, OH, 44106-7079	
Education:	1993	Ph.D. (Physics), Princeton University
	1989	M.A. (Physics), Princeton University
	1987	B.A. (Physics), University of Michigan
Employment:	2002-present	Professor of Physics, Case Western Reserve University
	2001-2002	Associate Professor of Physics, UC Santa Barbara
	1995-2001	Assistant Professor of Physics, UC Santa Barbara
	1993-95	Postdoctoral Fellow, U. Chicago, Advisor: Stephan Meyer
	1987-93	Grad. Student, Princeton Univ, Advisor: Mark Dragovan
Awards:	2005	American Physical Society Fellow
	1996	UC Regents Faculty Fellowship
	1993-95	McCormick Postdoctoral Fellowship
	1990-93	NASA GSRP Fellowship
	1987	Phi Beta Kappa

Research Efforts:

1987-1994: "Python" (PhD thesis): CMB anisotropy from the South Pole with a 4-element 90 GHz bolometric array.

1993-1995: MSAM (Postdoctoral work): balloon-borne bolometric measurement of degree scale CMB anisotropies. Tophat: design and planning for Long Duration Balloon instrument.

1996-present: Boomerang (*with Caltech/JPL, U. Rome, U. Toronto, Cardiff*): Long Duration Balloon-borne instrument, which made resolved, high signal-to-noise maps of the CMB, and the first high-signal-to-noise detection of the first acoustic peak in the CMB angular power spectrum. Reflown as a CMB polarimeter in 2003, detected polarization in the CMB.

1998-2002: Compass (*with UCSB, U. Wisconsin*): 30GHz correlation receiver mated to a 2.6m primary mirror telescope at U. Wisconsin, set upper limit on CMB polarization.

1999-present: Acbar (*with UC Berkeley, Carnegie-Mellon, Caltech/JPL*): Millimeter-wave 16-element bolometer array for the 2 meter diameter Viper telescope at the South Pole, to study fine-scale anisotropies in the CMB.

2001-present: South Pole Telescope (*with U. Chicago, UC Berkeley, Harvard-Smithsonian*): A 10 meter off-axis telescope at the South Pole with large-format bolometer arrays. SZ effect cluster census to trace the history structure growth, and thus Dark Energy. Future goals include small scale temperature and polarization CMB measurements.

2003 – present: Development of Polarization and Frequency Selective bolometers, a concept for multiplexing both color and polarization in each pixel in the focal plane.

2005 – present: SPIDER (*with Caltech, U. Toronto, NIST, U. British Columbia*): A balloon-borne instrument to measure large angular scale polarization in the CMB.

Michael D. Seiffert
Research Scientist, Jet Propulsion Laboratory
M/S 169-327, 4800 Oak Grove Dr
Pasadena, CA 91109

Relevant Experience

Dr. Seiffert has over 15 years experience in experimental cosmology and the design of new instruments to meet observational needs. His work has a heavy emphasis on the development of new instruments, observing techniques, and control of systematic error and has authored more than 25 refereed scientific papers.

Education

Ph.D., Physics, University of California, Santa Barbara, 1994
B.S. with Honors, Physics, Stanford University, 1986

Present Position

2004-present: Group Supervisor for Cosmology, Jet Propulsion Laboratory, California Institute of Technology
2005-present: Visiting Associate, California Institute of Technology

Selected Relevant Publications

"An upper limit to polarized submillimetre emission in Arp 220**",**
Michael Seiffert, Colin Borys, Douglas Scott, Mark Halpern, *Monthly Notices of the Royal Astronomical Society*, 374, 409 (2007).

"The Cosmic Microwave Background Temperature and Galactic Emission at 8.0 and 8.3 GHz",
J. Singal, D. Fixsen, A. Kogut, S. Levin, M. Limon, P. Lubin, P. Mirel, M. Seiffert, and E. Wollack, *Astrophysical Journal*, 653, 835 (2006)

"Bayesian foreground analysis with CMB data",
H.K. Eriksen, C. Dickinson, C.R. Lawrence, C. Baccigalupi, A.J. Banday, K.M. Górski, F.K. Hansen, E. Pierpaoli, M.D. Seiffert, *New Astronomy Reviews*, 50, 861 (2006)

"The Background Emission Anisotropy Scanning Telescope (BEAST): Instrument Description and Performances", J. Childers et al., *Astrophysical Journal Supplement*, 158, 124 (2005)

"An Instrument to Measure the Temperature of the Cosmic Microwave Background Radiation at Centimeter Wavelengths", A. Kogut, D. J. Fixsen, S. Levin, M. Limon, P. M. Lubin, P. Mirel, M. Seiffert, E. Wollack, *Astrophysical Journal Supplement,* 154, 493 (2004).

"1/*f* Noise and other Systematic Effects in the Planck-LFI Radiometers", Michael Seiffert, Aniello Mennella, Carlo Burigana, Nazzareno Mandolesi, Marco Bersanelli, Peter Meinhold, Phil Lubin, *Astronomy and Astrophysics*, **391**, 1185 (2002) [astro-ph/0206093]

"Cosmic Microwave Background Observations in the Post-Planck Era",
J. B. Peterson, J. E. Carlstrom, E. S. Cheng, M. Kamionkowski, A. E. Lange, M. Seiffert, D. N. Spergel, A. Stebbins [astro-ph/9907276]

Matias Zaldarriaga

Harvard University
Astronomy & Physics Departments
Email: mzaldarriaga@cfa.harvard.edu

Awards:

2006 McArthur Fellowship
2005 Gribov Medal, European Physical Society
2004 Sloan Fellowship
2003 Helen B. Warner Prize, American Astronomical Society
2001 David and Lucile Packard Fellowship
1998 Hubble Fellowship
1996 Barret Prize (MIT) for originality in astrophysics research.

Education:

1998 PhD Massachusetts Institute of Technology.
1994 Licenciado en Ciencias Fisicas University of Buenos Aires.

Positions:

Professor of Astronomy & Physics, Harvard University 7/2004-
Associate Professor in Astronomy & Physics, Harvard University 1/2003- 7/2004
Assistant Professor, New York University, 1/2001-2002
Keck Visiting Professor, Institute for Advanced Study, 9/2001-12/2002
Long-term member, Institute for Advanced Study, 9/1998-1/2001

Publications:

1. **"A general solution to the E-B mixing problem"**
   K. M. Smith and M. Zaldarriaga
   arXiv:astro-ph/0610059
2. **"Benchmark parameters for CMB polarization experiments"**
   W. Hu, M. M. Hedman and M. Zaldarriaga
   Phys. Rev. D **67**, 043004 (2003) [arXiv:astro-ph/0210096]
3. **"Gravitational Lensing Effect on Cosmic Microwave Background Polarization"**
   M. Zaldarriaga and U. Seljak
   Phys. Rev. D **58**, 023003 (1998) [arXiv:astro-ph/9803150]
4. **"Signature of gravity waves in polarization of the microwave background"**
   U. Seljak and M. Zaldarriaga
   Phys. Rev. Lett. **78**, 2054 (1997) [arXiv:astro-ph/9609169]
5. **"A Line of Sight Approach to Cosmic Microwave Background Anisotropies"**
   U. Seljak and M. Zaldarriaga
   Astrophys. J. **469**, 437 (1996) [arXiv:astro-ph/9603033]

University of Chicago Statement of Work

The University of Chicago will be the overall manager of the Mission Concept study. Including the following elements:

1. **The planning of the detailed studies.** The detailed studies will need to be coordinated with each other. Particular attention must be paid to how the theoretical and systematics studies coordinate with the Mission Costing studies. In addition it will be important that the studies mesh both in timing and topic with the workshops. Chicago will be involved in the planning and execution of each of the detailed studies.

2. **The planning of the workshops.** Because the workshops are the main method of getting input from the community and for synthesizing the summaries of each major topic, good workshop organization is key. Chicago will work closely with the workshop organizers to ensure broad input and coordinated execution. Chicago will also work with the workshop leads to generate each of the workshop proceedings.

3. **Final Workshop.** The final report writing workshop will be held in Chicago to initiate and organize the writing of the final report. This is a workshop of co-investigators and highly involved collaborators. Chicago will host this meeting.

4. **Webpage.** Chicago is responsible for generating and maintaining the study webpage. This includes an internal page for collaborative writing and co-investigator and collaborator interaction, and a public part to provide access to the activities and intermediate and final results of the Mission Concept Study.

5. **Final Report**. Chicago will be responsible organizing the co-investigators for writing the final report. The publication of the final report and delivery to NASA and to the Decadal Survey will be the responsibility of the PI.

- Webserver computer – We request $4,000 for the purchase of a webserver computer to facilitate the web publication of the study and study activities and to enable communications among the collaborators and gathering of workshop results.

SUBAWARDS

We request funding for six subawards to the following universities: Case Western Reserve University; Princeton University; Harvard University; University of California at Berkeley; University of California at Berkeley; and the University of Minnesota. Each subaward recipient will host a workshop at their respective institution on CMB-Pol topics. A statement of work and detailed budget with justification has been provided for each in their respective sections of this proposal. We are also requesting funding for a seventh subaward for a yet "to be named" university with its budget and statement of work similar in scale to the subaward requested for Harvard. Once named, we will seek final approval from NASA before awarding these funds.

OTHER DIRECT COSTS

The following four federally funded institutions will also participate in the study: Fermi National Accelerator Laboratory; Goddard Space Flight Center; Jet Propulsion Laboratory; National Institute of Standards and Technology in Boulder, Colorado. Two of the institutions, Fermilab and NIST, Boulder will host workshops. JPL will carry out most of the two costing studies. A statement of work and detailed budget with justification has been provided for each in their respective sections of this proposal. Their costs are included in this proposal budget but it is understood that their funding will be awarded directly to them.

INDIRECT COSTS

Per our rate agreement dated 03/15/07 with our cognizant federal agency, the Department of Health and Human Services, a rate of 53.5% is applied to Modified Total Direct Costs (i.e., Total Direct Costs less D. Equipment) for University of Chicago activities. For the six subawards, a rate of 53.5% is applied to the first $25,000 of payments made by the University to subaward recipient. No overhead is assessed on any payments to the federally funded institutions.

A Study for a CMB Probe of Inflation

Task Statement
Case Western Reserve University

The overall proposal to NASA, of which this subcontract is a part, seeks to gather information from the CMB community relevant to a long-term program of instrument development and testing leading to a future satellite mission. A report, written to NASA, will be the end-product of this proposal. Several workshops will be sponsored to gather and develop the material which will go into that final report.

This proposal funds work by the Case PI (Prof. John Ruhl) during the grant period (2/1/2008 to 1/31/2009) to help coordinate a workshop on systematic effects relevant to measurements of CMB polarization anisotropies, especially with regard to a potential future satellite mission. Prof. Ruhl will work with the lead PI (Prof. Stephan Meyer at U. Chicago) and other members of the team both to coordinate that workshop, and to write a report based on that workshop that will serve as input to the final report for this project to NASA. Funding for the workshop itself is not included in this subcontract. Prof. Ruhl will also work with Prof. Meyer and collaborators to write the final report to NASA.

A Study for a CMB Probe of Inflation
Fermi National Accelerator Laboratory
Scott Dodelson, Principal Investigator

Statement of Work: Theory, ancillary science and foregrounds CMB Workshop

Scott Dodelson will lead and be responsible for this workshop. It will take place over 4 days in May, 2008. A number of people at Fermilab have agreed to help as well, including Albert Stebbins, who wrote the initial papers on E/B decomposition. There will be presentations in the morning followed by afternoon and evening subgroup meetings. Each subgroup has a topic or set of topics which they are to develop into a report which summarizes the topic.

Here is an outline of the initial work that will be done to set up this workshop:

1) Identify and recruit co-organizers (December 31, 2007)
2) Decide on a set of dates (January 15, 2008)
3) Invite participants (January 31, 2008)
4) Send out preliminary announcement (February 15, 2008)
5) Design/mail poster (February 29, 2008)
6) Organize sessions and subtopics (March 31, 2008)

Following the workshop, a proceedings including the written versions of the presentations, the subgroup written findings and a workshop summary outlining the findings and results of the workshop will be compiled. Dodelson will write the workshop summary and compile the proceedings.

A webpage of the activities and progress will be maintained. It will contain streaming video of all talks, the reports, the workshop proceedings and the drafts of the report as it develops. Access to the webpage will be open.

The Conference Office at Fermilab has vast experience organizing workshops of this scale. The office handles of order 25 conferences and workshops every year. Personnel in the Conference Office will:

- Provide with all the necessary equipment and staff
- Assist in planning menus for all food and beverage events

- Arrange for all the food and beverage services
- Contract with outside services (banquet facilities, buses, poster printer, equipment rental, etc.)
- Send out a poster to our specified distribution list
- Prepare and process purchase orders for supplies and equipment
- Contract for purchasing proceedings of the meeting
- Set up and manage on-line registration database (collect money and checks, process payments, make deposits, process credit card purchases, process project/task transfers, name badges, visitors passes, process information for non-U.S. citizens approval for site access, companion badges, etc.)
- Make arrangements for supported people
- Process payment or reimbursement of travel costs
- Set up project/task numbers as required, managing those project/task accounts, tracking funding and billing and seeing that appropriate funds are used for allowable and unallowable costs
- Provide links to general information pertinent to the meeting (driving directions, maps, hotel rate information, participants list, etc.)

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland
20771

Reply to Attn: Dr. Gary Hinshaw / Code 665

November 14, 2007

A Study for a CMB Probe of Inflation
Statement of Work

Gary Hinshaw is a Co-Investigator on a proposal to NASA titled "A Study for a CMB Probe of Inflation." The proposal is submitted by Stephan Meyer of the University of Chicago. John Ruhl (Case Western Reserve University) and Gary Hinshaw (NASA/Goddard) will lead a workshop titled 'Systematic Error Mitigation for a CMB Probe of Inflation'. The purpose of the workshop is to gather community input and distill it into a coherent systematic error budget that will guide the implementation of a future Probe of Inflation. The workshop will take place in Baltimore in June or July of 2008. Ruhl and Hinshaw will select the participants, set the program, and task the participants to provide preparatory material, give presentations, and write papers. They will organize task forces that will discuss sub-topics during the workshop. They will transform the reports of the task forces, the presentations, and the papers into a report. The report will become a chapter in a more comprehensive report that is anticipated to be one of the outcomes of the NASA grant. In addition, Hinshaw will oversee the organization of the conference venue. For this work, NASA/Goddard will receive a subcontract that will pay fees associated with the organization and use of the conference venue, and travel support for Hinshaw to attend the other workshops that are taking place as part of this grant.

Statement of Work

PI: Matias Zaldarriaga
Harvard College Observatory
NASA ROSES 2007
NNH07ZDA001N - ASMCS

Sponsor: University of Chicago (NASA Prime)
University of Chicago PI: Stephan Meyer

A Study for a CMB Probe of Inflation

Period of Performance: 2/1/08 - 1/31/09

The full academic year salaries of members of the Faculty of Arts and Sciences are paid by Harvard University with the understanding that they will ordinarily teach and conduct research freely and flexibly and not make substantial, specific quantified commitments of time and effort to specific organized research projects.

As part of this proposal the PI will study theoretical questions connected to the design choices for a mission to probe inflation using the B modes of the CMB polarization. One of the main contaminants for such studies are B modes generated by gravitational lensing. These B modes are expected to dominate on small angular scales but depending on the strength of the gravitational wave background, can also degrade measurements on large angular scales.

The lensing contamination can be cleaned if precise measurements of the temperature and polarization on small angular scales are available. Together with a graduate student we will study whether it is feasible to use ground based measurements of the anisotropies (such as those that will become available with SPT and ACT) to clean the lensing signal from the B modes measured using lower resolution but higher sensitivity maps produced by a satellite mission. Could such a strategy allow one to improve the sensitivity to inflationary B modes while still having a mission with relatively low resolution and thus lower cost? What are the requirements on the ground based observations for this to be possible? What fraction of the sky should be covered from the ground in order for this strategy to be effective? The PI and the student will also study how such mixed strategy might affect other ancillary science goals of a future polarization mission.

JET PROPULSION LABORATORY
A Study for a CMB Probe of Inflation

Statement of work for amplifier-based CMBpol mission:

We plan to investigate the system configuration, implementation, requirements, and cost of a CMB polarization mission based on HEMT amplifier technology. Specific tasks include:

1) Develop a baseline focal plane design that includes total number of detectors, distribution among frequencies, estimated sensitivity per frequency channel, and total active power dissipation. We will construct several versions of the sensitivity estimate based on today's amplifier technology and extending to anticipated future developments. Our starting assumptions include active cooling of a 4 W load to 20K operating temperature. A focal plane with 160 detector elements at 70 GHz could provide a sensitivity of 111 nK per 1 deg square pixel in a 4 year mission, assuming modest improvements in amplifier technology. The amplifier technology would be based on High Electron Mobility Transistors (HEMTs). Several HEMTs are combined to form an amplifier in a Monolithic Microwave Integrated Circuit (MMIC), which are then combined with other components in a compact polarimeter module. Such modules are currently under development for the QUIET (Q/U Imaging ExperimenT) project, a ground-based CMB polarization measurement to be deployed in the Atacama desert later this fiscal year. Dr. Seiffert will lead this aspect of the work.

2) Develop a baseline active and passive cooling configuration, including type of cooler, estimated cooling power at a variety of temperatures, required thermal stabilization of the cold end stage, amount of heat that would need to be radiated at various stages, overall electrical power consumption, and cooling system mass. Three configurations appear viable:
    a. A high capacity staged pulse tube, which could provide 2 W of cooling at 35 K, and 19 W at 85 K. The cooler would consume 500-700 W power at would have a compressor mass of approximately 20 kg. Such a system would feature a compressor with very high reliability, but drawbacks include difficult system integration and a cold-head redesign to provide greater cooling capacity.
    b. A two-stage stirling cryocooler. An existing model manufactured by Ball provides 0.8 W cooling at 35 K and 2.5 W cooling at 115 K with a power input of 110 W and a mass of ~ 10 kg. Several such coolers could be operated in parallel. This cooler has the best efficiency, has a compressor with very high reliability, but again system integration may be difficult and a cold-head redesign may be required.
    c. Sorption cooler. A model based on the JPL-designed Planck 20K cooler could provide 4 W cooling at 20 K, with 950 W of input power and 90 kg

mass. Advantages include no geometrical and mechanical constrains for the integration (compared to pulse tube and stirling) and 20 K cold-end temperature. Disadvantages include the need for 2 W of pre-cooling @ 50 K, and a need for a redesign of the liquid vapor heat exchangers (currently addressed by a technology program).

Dr. Lawrence will lead this aspect of the work.

3) Derive a mechanical configuration of components and subsystems. The components and subsystems include the detector modules, feed horn array, fore-optics, polarizing elements, and the cooler subassembly. The design for many of these elements can be taken from on-going ground-based CMB experiments. Dr. Seiffert will supervise this aspect of the work, which will be performed by an experienced JPL instrument engineer.

4) Provide preliminary mission requirements including instrument mass, instrument power, telemetry requirements, and pointing requirements. Dr. Seiffert will collect the inputs from the various instrument aspects and summarize in a table.

5) The mission requirements will be used as input for a baseline mission design, which will be performed by JPL Team-X.

6) Use the above information to perform a cost estimate for the mission. This activity will be performed by the JPL costing office in coordination with a Team-X study at JPL.

Statement of work for scanning strategy investigation:

We will focus on analysis of the impact of the scanning strategy on the quality of measurements of CMB polarization. Important issues to be clarified include: the choice of partial vs. full sky coverage of observations, smoothness of the distribution of integration time on the sky, uniformity of coverage of polarimeter orientation angle at each pixel on the sky, and the impact of all these factors on separability of the E and B polarization modes.

Designing a system that provides optimal coverage of polarimeter orientations (for all detectors) at all sky pixels will require extensive interaction with the hardware design teams.

This work will be led by Dr. Gorski.

Statement of work for component separation investigation:

We will investigate the design requirements placed on a CMB polarization mission by the need to separate the CMB signals from confusing foregrounds. We will focus on two questions:

1. What is the optimum range of frequencies to observe?

2. What relative noise level per frequency gives optimum separation of foregrounds? The answer to this, coupled with the relative sizes and noise levels of feeds/detectors as a function of frequency, determines how the focal plane area available to an experiment should be divided.

The main tool for this investigation will be simulations based on a model of the polarized sky developed by the Planck mission that includes synchrotron, free-free, dust, anomalous dust, and discrete source components, and a method or methods of foreground separation that allow direct comparison of the effect of different designs on the angular power spectrum and cosmological parameters.

This work will be led by Dr. Dickinson, with assistance from Dr. Lawrence.

UNIVERSITY OF MINNESOTA

Twin Cities Campus

Shaul Hanany
Associate Professor of Physics
School of Physics and Astronomy
Institute of Technology

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November 8, 2007

A Study for a CMB Probe of Inflation
Statement of Work

Shaul Hanany is a Co-Investigator on a proposal to NASA titled 'A Study for a CMB Probe of Inflation'. The proposal is submitted by Stephan Meyer of the University of Chicago.

Hanany and Kent Irwin (NIST, Boulder) will lead a workshop titled 'Technology Development for a CMB Probe of Inflation'. The purpose of the workshop is to assess the technology development that must take place before a future NASA inflation probe can be implemented. The workshop will take place in Boulder in August or September of 2008. Hanany and Irwin will select the participants, set the program, and task participants with preparing presentations, preparatory material, and papers. They will organize task forces that will discuss technology sub-topics during the workshop. They will transform the reports of the task forces, the presentations, and the papers into a report. The report will become a chapter in a more comprehensive report that is anticipated to be one of the outcomes of the NASA grant.

For this work Hanany will receive a subcontract that supports one month of summer salary, travel support to attend the several workshops that are taking place as part of this grant, and 6 months of salary for a post-doc who will assist in the preparation toward the workshop and in assembling the material afterwards.

UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
325 Broadway
Boulder, Colorado 80305-3328

Nov. 12, 2007

A Study for a CMB Probe of Inflation
Statement of Work

Kent Irwin is a Co-Investigator on a proposal to NASA titled "A Study for a CMB Probe of Inflation." The proposal is submitted by Stephan Meyer of the University of Chicago.

Shaul Hanany (University of Minnesota) and Kent Irwin (NIST, Boulder) will lead a workshop titled 'Technology Development for a CMB Probe of Inflation'. The purpose of the workshop is to assess the technology development that must take place before a future NASA inflation probe can be implemented. The workshop will take place in Boulder in August or September of 2008. Hanany and Irwin will select the participants, set the program, and task participants with preparing presentations, preparatory material, and papers. They will organize task forces that will discuss technology sub-topics during the workshop. They will transform the reports of the task forces, the presentations, and the papers into a report. The report will become a chapter in a more comprehensive report that is anticipated to be one of the outcomes of the NASA grant. In addition, Irwin will oversee the organization of the conference venue, working with NIST's conference program manager.

For this work, NIST will receive a subcontract that will pay fees associated with the organization and use of the conference venue, and travel support for Irwin to attend the several workshops that are taking place as part of this grant. Dr. Irwin's salary while working on the workshop will be paid by funding that NIST has provided to support the community in developing a CMB polarimeter mission.

NIST

Princeton University Statement of Work

"A Study for a CMB Probe of Inflation"

We propose to study two aspects of a CMB Probe of Inflation. The first and dominant one will be aimed at helping to assess the current state of what we know about polarized foreground emission. The second one will be aimed at a detailed study of a key element for a future mission, a high gain 150 GHz corrugated feed. The group at Princeton has extensive experience in both of these areas.

I) Polarized Foreground Emission.

The tell tail signature of the B-modes from an inflationary epoch are found at large angular scales. There are two characteristic features, one at $l \sim 5$ that results from reionization of the universe by the first stars and the other at $l \sim 90$ that results from the decoupling process. With the recent release of the WMAP all sky polarization maps it was seen that at 30 degrees angular scales ($l=5$) polarized synchrotron and dust emission dominate over an $r=0.3$ B-mode signal by a factor of ~5 (in temperature) at the least contaminated frequency near 65 GHz. Thus it is clear that we will have to be able to model and subtract foreground emission to see the $l=5$ feature. The situation at 2° angular scales ($l=90$) is less clear. There are likely region of sky where a $r=0.3$ B-mode signal exceeds the foreground level by an order of magnitude. The basic reason for the discrepancy at the two angular scales is that thermal dust emission is mostly confined to regions near the galactic plane.

We see four areas that need study.
1) Bring the assessment of the levels of foreground contamination in the Weiss report up to date. At the time of the Weiss report, the WMAP result had not been released and thus accurate forecasts could not be made. We now know much more about polarized synchrotron emission and somewhat more about polarized dust emission. Over the next year we will learn still more but the core of what we know will be rooted in WMAP. For the report that results from this study, we will include an up to date assessment.
2) Estimate errors in CMB maps (and cosmological parameters) due to foregrounds at large angular scales. We will develop and improve tools for propagating errors in the polarized Galactic foregrounds through to CMB polarization maps. We have already implemented a method for

marginalizing over the synchrotron and dust foreground components using Gibbs sampling, at a level applicable for WMAP. An extension of this method will be ideal for forecasting the performance of future experiments given different foreground behaviors. The goal would be to find the frequencies and sensitivities required to measure a given tensor-to-scalar ratio.

3) Determine whether external data are useful for foreground removal, or whether the CMBPol maps must be used alone.

4) Search the space of sky coverage and frequency coverage to see if there is an optimum for measuring both the l=5 and l=90 B-mode signature. The two people that will lead this are Joanna Dunkley and Lyman Page. They will work with students. David Spergel will play an advisory role.

II) Corrugated feeds for a polarization mission.

One of the key elements of a potential future mission is the optics. An attractive possibility is a mission with optics based solely on corrugated feeds. The advantage is that one can compute the beam and its polarization properties to high accuracy. However, no one knows if a simple feed with high enough gain (~35 dBi) can be built. The second part of this proposal will be aimed at designing such a feed for 150 GHz. This part of the proposal will be led by Lyman Page and advised by Prof. Suzanne Staggs. Page and Staggs have designed and/or led the design of numerous feeds including the ones on WMAP

University of California, Berkeley
A Study for a CMB Probe of Inflation
Statement of Work

Professor Adrian Lee is a co-investigator and Dr. Huan Tran is a collaborator in the proposal to NASA entitled "A Study for a CMB Probe of Inflation" with Professor Stephan Meyer as Principal Investigator. Lee and Tran plan to carry out a technical study of a "high resolution" option for CMBPOL, the Einstein Probe. The current "low resolution" option has a resolution of 0.5˚ to 1˚, but it is scientifically interesting to study a higher resolution option with 4 to 10 arc-minute resolution which would be able to study the gravitational lensing of the polarized CMB.

The Berkeley team will study instrument designs centered around telescopes with the required angular resolution. The emphasis will be on producing a design that will result in a cost-efficient mission. We will produce several candidate designs and perform detailed optical simulations of them. These simulations will look at the ray-limit optical performance as well as the polarization performance. Costing of these optical designs will be done in collaboration with the JPL group led by Jamie Bock.

UC Irvine (Co-I Institution) Work Statement for "A Study for a CMB Probe of Inflation"

Dr. Asantha Cooray is a Co-I of a one-year NASA Mission Concept Study (ASMCS07) on the CMB Inflation Probe led by Dr. Stephan Meyer at University of Chicago as the overall PI. For this study, UC Irvine is tasked with a Foreground method study to address the effects of galactic and extragalactic polarized foregrounds (synchrotron, dust, radio point sources and galaxy cluster signals, and lensed background signals and sources) on primary goal of the CMB Inflation Probe involving a detection of the primordial B-modes generated by inflationary gravitational waves (IGWs). The UC Irvine-led foreground study will also address the tradeoffs between angular resolution, frequency coverage, and the sensitivity at each channel to optimally reduce the confusion from foregrounds and various possible options for the Inflation Probe (in the form of a low frequency 30 to 100 GHz, a high frequency 150 to 300 GHz, and a mission that has both low and high frequency coverage) will be studied.

The main research tasks of our foregrounds study is

(1) A survey strategy in terms of resolution, frequency coverage, sensitivity, and the sky coverage, to obtain maximal information on the IGWs with sensitivity limited only by residual astrophysical foregrounds. To describe foregrounds, we will make use of WMAP 3-year (and potentially WMAP 5-year) maps and other foreground maps to create tools to optimize the Inflation Probe (or any other CMB experiment that attempt to detect primordial B-modes) in terms of its frequency channels and sky coverage. We will vary the spectral indices of any modeled foregrounds or extrapolated signals from existing data and study various cross-correlations and residual signals to establish the best and worst-case scenarios for residual foreground level. Our study will address the sensitivity level of the Inflation Probe that would be helpful to reach for a IGW B-mode detection by quantifying, for example, when sensitivity improvement is moot due to limitations imposed by foregrounds. We will implement both Fourier-space and pixel-based techniques to remove foregrounds. Any tools resulting from this work will be made public.

(2) Combine UC Irvine-led foreground study with the parallel scan method and systematic study for the template Inflation Probe to study the effects of imperfect removal of spurious signals due to the beam optics on both the IGW induced B-modes at degree angular scales and lensing induced B-modes at few arcminute angular scales.

(3) In light of investigations in (1) and (2) clearly discuss the science goals, both IGWs and secondary goals, for both a low-resolution and a high-resolution polarization mission. In particular, for the high-resolution mission, we will study the effect of foregrounds on lensing measurements and parameterize the variance of the deflection angle in terms of a degradation parameter. This will be a useful way to show the effect of foregrounds on reconstructing lensing with the high resolution Inflation Probe mission. The two forms of the Inflation Probe are under discussion in this overall study and we will connect science goals of the two mission options with residual foregrounds and systematics that might limit certain planned science studies. We will crticially

assess the benefits and will make a recommendation in favor or against a high-resolution experiment.

Time Line:

During the first three months, we will complete Task (1). This is possible to achieve because of WMAP3 polarized maps. The second three months we will complete Task (2) in collaboration with the systematic and scan study team. The final 6 months will be used to combine results from both Tasks (1) and (2) to address the science case for the high-resolution version of the Inflation Probe. During this year, we will also make our results available to the team through our attendance at the three planned workshops.

Team:

The research team at UC Irvine for this foreground study will be led by Co-I Asantha Cooray (Associate Professor), who is also responsible for all activities at UCI and day-to-day management of the work by the postdoctoral fellow that will be supported for this study. *He will draw one month of summer salary to coordinate and to complete the writing of the Irvine foreground report to the study team.*

The team includes unfunded Collaborators Dr. Manoj Kaplinghat (Assistant Professor) and Dr. Alexandre Amblard (Project Scientist). Previously, this team has worked together with concept study design of the Experimental Probe of Inflationary Cosmology (EPIC) that was led by James J. Bock at JPL as the PI. The preliminary work related to foreground impact resulting from that study is described in Amblard, Cooray & Kaplinghat, Phys. Rev. D. 75, 083508 (2007). The team also includes a new postdoctoral fellow (who will be joining UC Irvine in 2008) Rajib Saha. Dr. Saha has worked on topics related to CMB foregrounds and data analysis for his PhD thesis. *He will be paid 6 months of his salary next year from support under this study to investigate the impact of foregrounds on both primary and secondary science goals.*

Other Budget Items:

Co-I Cooray and Postdocotral Fellow Saha will travel to work with other collaborating study teams on the systematics to combine results on the residual foregrounds from UC Irvine study with estimates of the residual systematics to establish the science goals of the Inflation Probe. We have budgeted for two trips at $1250/each to Fermilab and to University of Chicago. We have also included $1800 for publication of results from our study in the Astrophysical Journal.