Research Proposal Submitted to the National Aeronautics
and Space Administration

by

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An Educational Organization

A NOVEL APPLICATION OF FOURIER TRANSFORM SPECTROSCOPY WITH HEMT AMPLIFIERS AT MICROWAVE FREQUENCIES

August 1991

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Endorsements:

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Table of Contents

Abstract

We propose to develop a low noise, cryogenic 90 GHz high electron mobility transistor (HEMT) amplifier and apply it to one of the fundamental problems in physics - the anisotropy of the cosmic microwave background radiation (CMB). Lower frequency versions of these devices are quiet, broadband, electronically and thermally stable, and have become the detectors of choice for radio astronomy. We plan to push this technology to the high-frequency/low-noise limit to take advantage of the window of minimum Galactic foreground emission near 90 GHz. With a set of amplifiers covering the 25-50 GHz range, the low frequency Galactic components can be mapped to their natural limits, modeled and subtracted from the region of minimum contamination. The long term goal is to make a map of $\Delta T_{CMB}/T_{CMB}$ to an accuracy of $1 - 2 \times 10^{-6}$ on an angular scale of 1°.

The need for coarse spectral information motivates the novel application of Fourier transform spectroscopy which we propose. The exceedingly wide bandwidth of HEMT amplifier make the FTS a useful and relatively simple technique between 25 and 110 GHz. The instrument is the microwave equivalent of COBE's FIRAS experiment. Other important features of the HEMT-based radiometers we have in mind are: high-sensitivity, simplicity and reliability, relatively simple cooling requirements, ability to produce multiple beams (arrays), and excellent gain stability. These properties make HEMT radiometers very attractive for making precise maps of the CMB anisotropy from balloon and satellite platforms.

I. Science Overview and Goals

NASA's highly successful COBE[1] satellite has, by exceeding most of its design goals, answered several key cosmological questions. The CMB has an accurate thermal spectrum from $\lambda = 1\ cm$ to $\lambda = 0.5\ mm$, as predicted by the Big Bang model. At large angular scales the radiation is very isotropic, except for a dipole effect due mostly to the Galaxy's peculiar velocity. The infrared background from the first stars and galaxies that form is smaller than the flux from foreground sources, zodiacal and Galactic dust. Ongoing analysis continues to search deeper into the data, but one vital issue in cosmology could not be addressed by COBE due to the state of microwave receiver technology at the time it was designed and built. Anisotropy in the CMB at angular scales of $5'$ to $5°$ carries the imprint of density fluctuations which eventually led to large-scale mass structure – clusters of galaxies; sheets, and voids. The standard model predicts fluctuations at a level of $\Delta T/T \approx 10^{-5}$, only a factor of two or so below current experimental limits. While ground-based or balloon experiments may detect anisotropy within the next few months or years, the real scientific payoff will come from multi-frequency maps of the CMB anisotropy, showing the angular spectrum and character of the intrinsic CMB fluctuations. For the first time we will have direct measurements of the physical conditions in the early universe, well before structure started to form.

There are two main problems with making these maps. (1) Instrument sensitivity has been the main limitation to date. The CMB temperature is only 2.735 K (according to COBE) so to clearly see the expected anisotropy the error per map pixel should be ± 3 μK or less. The most promising technologies for reaching this level are bolometers for $\lambda \leq 2\,mm$ and high electron mobility transistor (HEMT) amplifiers at longer wavelengths. (2) Foreground radiation sources from Galactic electrons and dust will ultimately limit the accuracy of CMB anisotropy measurements. The Galactic window is around $\lambda = 3\,mm$ (100 GHz), but even here it will be necessary to subtract Galactic emission to reach the desired sensitivity. Therefore, course spectral information is needed in any high precision anisotropy project.

Another important idea that is being pursued by several groups is to develop a multi-beam observing system. Since integration times are long (hours) for even the lowest-noise instruments, having an array of detectors is a huge advantage for a mapping project. Bolometers and HEMTs show considerable promise for elements of arrays and several groups are working on this. Finally, since remote observations (South Pole, balloons, satellites) are involved in CMB isotropy experiments, system simplicity and reliability are important considerations. Here HEMTs have a significant advantage over other low-noise mm-wave detectors.

Most observations of CMB anisotropy at angular scales below 5° have been made from the ground. The atmosphere seriously degrades these measurements in two ways: (1) lumpy water vapor emission creates a large noise signal on most days, and (2) the smooth component of atmospheric emission increases system noise – the main limitation on ΔT for most well-designed experiments. Cold sites, balloons, and satellites are currently being used. To us (and to the Soviets) it is clear that a satellite at the solar L2 point is the ultimate platform for an anisotropy experiment. No atmosphere, greatly reduced Earth and Sun emission, simplified pointing, and long integration time are important advantages of a remote satellite.

The work proposed here is part of a program to capitalize on recent and expected advances in high-frequency, cryogenic HEMT technology. Viewed from the perspective of the problems mentioned above, HEMT amplifiers are very promising for high-precision mapping of the CMB anisotropy. We plan to help NRAO engineers to evaluate HEMTs for use at 90 GHz, and simultaneously to build radiometers using available 30 GHz and 40 GHz amplifiers. These radiometers will be evaluated on the ground and from balloons, with the ultimate goal a proposal to NASA for a Small Explorer mission to map the CMB anisotropy in the Galactic polar regions.

II. Project Description

HEMTs

HEMT amplifiers have become the detectors of choice for frequencies between 1 and 45 GHz wherever low noise, broadband, and stable amplifiers are required. They are relatively cheap and rugged devices well suited to satellite or remote observing applications. Their combined sensitivity, simplicity, and stability make them ideal for measurements needing extended integration times. With a set of amplifiers covering from 25 to 110 GHz, the long wavelength portion of the CMB could be mapped to the limits imposed by Galactic foregrounds.

Marian Pospieszalski[2] at NRAO has recently completed a Q band (38-45 GHz) amplifier which, when operated at 20 K, has a mean noise temperature T_n of 45 K over the 7 GHz bandwidth; the bandwidth can be increased. We plan on assisting NRAO in extending this range up to 110 GHz. By scaling the noise from low frequency devices, $T_n \propto \nu$, one predicts a W band (70-110 GHz) amplifier will have $T_n \approx 90$K. Although HEMT chips exist which have been tested at room temperature up to 100 GHz, none have been tested cold; chip manufactures generally lack the expertise or incentive for cryogenic testing. Experience shows that the warm chip characteristics have little to do with the cryogenic ones but that once a good HEMT batch is found, all the chips in that batch will be good.

It is useful to compare bolometers and SIS mixers to HEMT amplifiers. To do this we compare the rms noise in measuring the temperature difference between two points on the sky in one second for systems that have made CMB measurements, $\Delta T_{rms} = \sqrt{2}T_{sys}/\sqrt{\Delta\nu_{rf}} = \sqrt{2}\,NET$. Although bolometers are theoretically more sensitive than HEMT, even in the single mode limit, they are much more difficult to use because of the need for very low operating temperatures. Currently, the most sensitive bolometric systems (MIT[3] and Berkeley[4]) operate at $\approx$ .3 K and can measure the difference in temperature between two points on the sky with $\Delta T_{rms} \approx 700\mu$K (The MIT system measures the difference between the sky and a reference load with $\Delta T \approx 630\mu$K.) This requires more than one mode, and the lowest frequency is $\approx$ 160 GHz. These systems took years to develop. The up-coming generation of bolometric systems (Berkeley, Goddard and Princeton) operate at .1K and promise better detector sensitivity; the Princeton group (Dragovan and Peterson) will attempt a single mode measurement at 90 GHz and expect to get $\Delta T_{rms} \approx 880\mu$K. SIS mixers have very low noise but the bandwidth is limited by the IF amplifier. A Princeton group[5] achieved a $\Delta T_{rms} \approx 2200\mu$K at 38 GHz. This radiometer used a mixer with $T_{rec} = 30$ K, the atmosphere contributes roughly 20 K; NRAO [6] has recently made significant advances in SIS technology. The Santa Barbara group[7] recently used a K_A band (25-36 GHz, single mode) HEMT operating near 4.2K at the South Pole and achieved a sensitivity of $\Delta T_{rms} \approx 400\mu$K ($T_{sys} = 30$ K). The heart of this system was assembled just months before the expedition. The projected ΔT_{rms} for a single 90 GHz HEMT amplifier with $\Delta\nu_{rf} = 20$ GHz operating under $T_{atm} = 20$ K is 1100 μK, in a balloon this becomes 900 μK.

Even though the sensitivity of the single HEMT is not as good as the bolometer sensitivity, HEMT's are particularly alluring because of their simplicity and stability. As measurements of the CMB push to new levels, the importance of these qualities cannot be overstated. Other attributes include the following:

1) They operate between 4K and 20K – lower temperatures do not significantly enhance the sensitivity – so mechanical refrigerators can be used.

2) They are microphonically insensitive. At NRAO, we witnessed a (successful) noise test of an amplifier on top of a running pump station – this would be impossible with a bolometer.

3) Their rf bandwidth, ν_{rf}, may be split into sub-bands (see below) to gain frequency resolution. There are no problems with out-of-band radiation leaking through bandpass filters.

4) They are only sensitive to radio frequency interference (RFI) in their amplification band; out-of-band signals are strongly rejected.

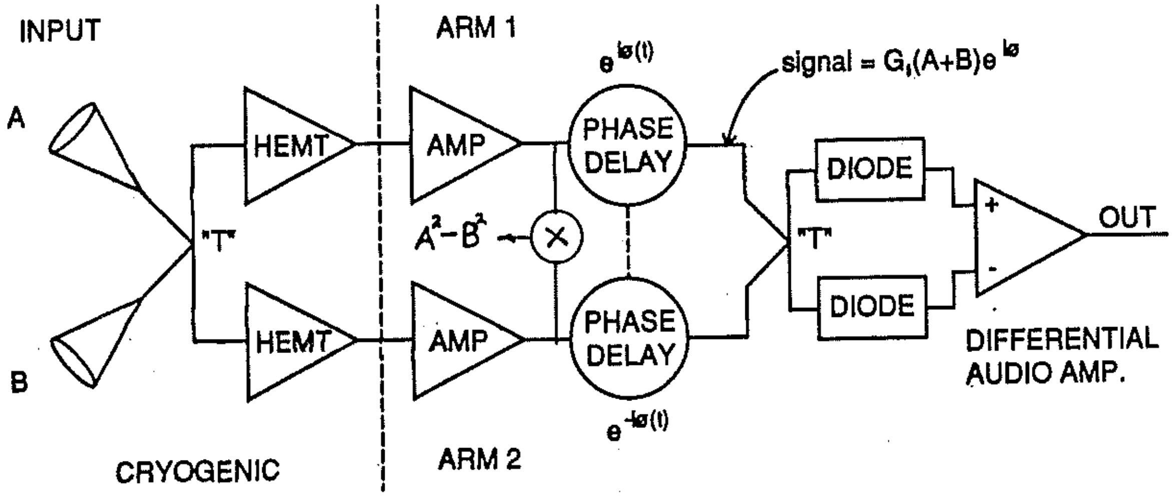
5) They use single mode optics which are easier to understand and design than multimode optics.

6) They have very little low frequency gain fluctuation so beam switching is greatly simplified. In tests of a 1.4 GHz HEMT at Princeton, the 1/f knee is below .001 Hz.

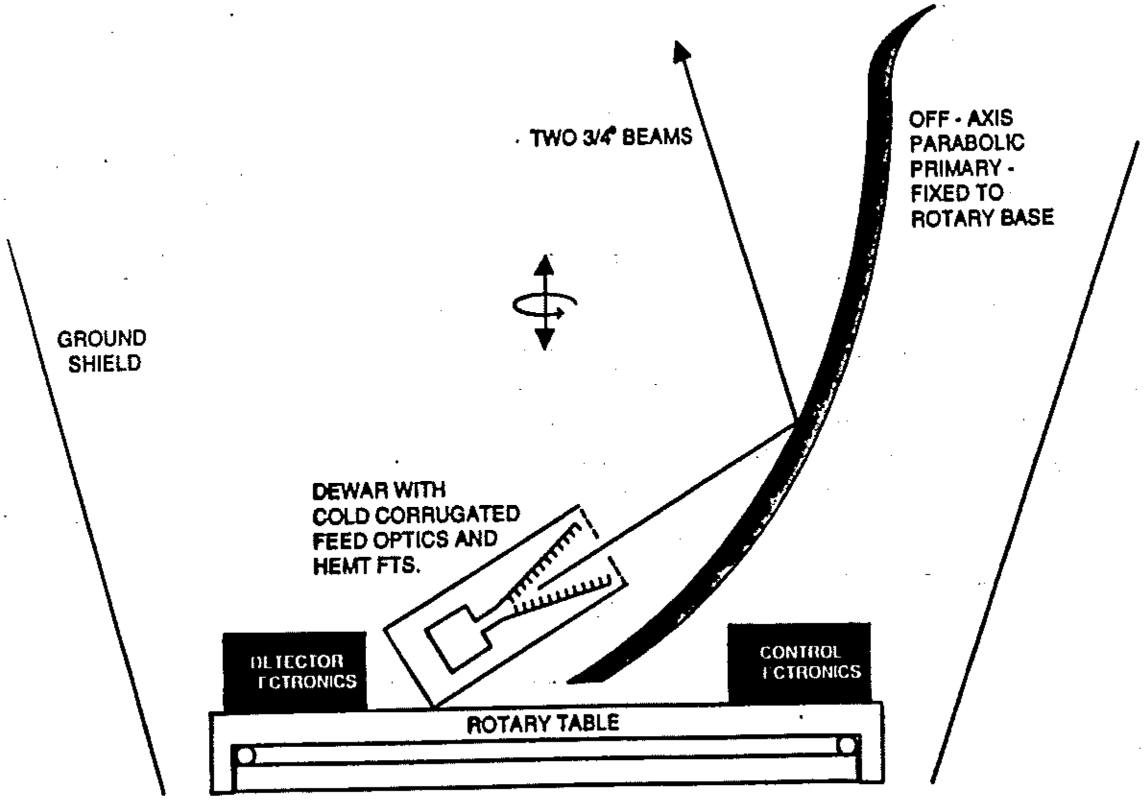
Effectively Using The HEMT Bandwidth – A Novel FTS

Measurements of the CMB anisotropy require a moderate level of frequency resolution but nothing like what is needed for line work. It is desirable to split the HEMT bandwidth to identify and remove Galactic signal. In some applications splitting the band is even necessary because fullband microwave components do not yet exist. Both the Santa Barbara and Princeton groups have done this with a variety of schemes to good effect. We plan to build and test a new scheme for subdividing the passband.

As an extension of Fourier transform spectroscopy, a method used with great success by COBE's FIRAS instrument, we propose the single-mode, low-frequency version, a schematic of which is shown in Figure 1. In the waveguide version, the radiation can be amplified by a wideband HEMT. Two input horns feed the E and H arms of a "magic T " which combines the input signals. The radiation in each of the output arms is amplified by cold HEMTs and then passes through coupled phase delays. These may be realized with a moving sliding short common to two separate magic Ts; an electronic phase delay would be desirable, but we don't yet know how to do that over a wide bandwidth. At the output of the phase shifter in arm 1, the field is given by $G_1(A+B)\exp(i\phi(t))$ where G_1 is the arm gain and ϕ is the phase shift, and the output of arm 2 is $G_2(A-B)\exp(-i\phi(t))$. After combining the fields in another T and square law detecting, we get $constant \pm 4\,G_1G_2(A^2-B^2)\cos(2\phi(t))$ for the symmetric (+) and antisymmetric (−) outputs. These outputs are differenced by an audio amplifier and the result is $8\,G_1G_2(A^2-B^2)\cos(2\phi(t))$. Because of the dispersion introduced by the wave guide, the output must be de-dispersed. The Fourier transform is then taken to yield the power spectrum of the difference in radiation from the two inputs. In summary, the HEMT FTS output gives the spectral difference between the two horns for each cycle of the phase shifters, analogous to the output of FIRAS – a much more complicated instrument.



HEMT FTS
FIGURE 1



OBSERVING CONFIGURATION
FIGURE 2

This system has a number of nice features. All the parts necessary to implement it (except the HEMTs) are common off-the-shelf microwave components, even at 90 GHz, and there are fewer of them than for a comparable filter bank system. In a design of the phase delay element, we can obtain 16 resolution bins (for 90 GHz) with 7 cm of sliding short travel. This would be an incredible diagnostic tool. Also, the resolution may easily be adjusted by changing the travel of the sliding shorts. The fullband sensitivity may be recovered by summing over the bins and if a couple were tainted with RFI they could be exorcised and the remaining bins summed with little loss of signal to noise. In a realistic system, there will have to be isolators and roughly 30 dB more gain than is drawn in Figure 1. The additional amplifier in each arm could be a second HEMT. Though there are a number of ways to implement the basic HEMT FTS idea, the output in Figure 1 is to first order insensitive to gain variations in the arms. We are also considering a correlation technique which would replace the rightmost T in Figure 1 with a multiplier. Another multiplier ahead of the phase shifters would give a broadband high-sensitivity measurement of $A^2 - B^2$.

The noise analysis for this instrument is different than for the standard Martin-Puplett FTS (eg. FIRAS) but the fundamental result still holds[8]. That is, the post detection bandwidth is $\propto 1/\tau$, where τ is the cycle time of the phase delay, *for each resolution element*. This result is independent of the number of resolution elements and is responsible for the "multiplex advantage." Thus, a HEMT FTS with n resolution bins is the same, in terms of noise, as a HEMT system that has a filter bank with n filters. Unlike FIRAS, the resolution bins may be added up to recover the the fullband signal. Essentially this occurs because the detection process is noiseless; all the amplification and "detection" has occurred before the signal is divided into frequency bins.

A HEMT FTS system for measuring the CMB anisotropy

It has been recognized for years that the optimal place to look for the CMB anisotropy is near 90 GHz. At lower frequencies, variations in the intensity and spectral index of Galactic synchrotron radiation confound observations. Indeed an early report of a detected anisotropy at 20 GHz turned out to be just this[9]. At frequencies too far above 90 GHz, intensity variations in Galactic dust emission can mask anisotropy in the CMB. This is the case for the analysis of the 180 GHz channel of the MIT radiometer[3]. For ground-based experiments, one is also constrained by atmospheric emission lines near 60 and 120 GHz. In addition to selecting propitious frequencies, observations should be made near the regions of low Galactic contamination[10] near RA = 200°, DEC = +65° and RA = 0°, DEC = −60°.

We will use a HEMT FTS system in a very simple configuration. The two cooled corrugated horns in Figure 1 will receive radiation from a large off-axis parabolic primary to produce two .75° beams with a separation on the order of 1.5°. Figure 2 shows a schematic of the layout. The beams will be scanned on the sky or "wobble" with a rotary base. The system is versatile enough so that a number of optical and scanning schemes may be tried. To simplify the data analysis, the wobble frequency is much slower than the time it takes the phase shifter to make a full cycle. In order to minimize the atmospheric contribution, the azimuthal rotation axis would be adjustable. The primary will be large enough so that additional high frequency amplifiers may be piggybacked as they are developed.

The HEMT FTS sensitivity for the full band is $\Delta T_{rms} \approx 300\mu K$, $\approx 450\mu K$, and $\approx 920\mu K$ for K_A, Q, and W band radiometers. These estimates are based on the following known or expected system parameters: $T_{atm} = 10, 20, 30K$; $\Delta\nu_{rf} = 10, 20, 20$ GHz; and $T_{rec} = 20, 45, 100K$ respectively. These are conservative estimates given the history of HEMT development. To reach $\Delta T_{rms} = 3\mu K$ would take 2.5 hr, 4 hr, and 1 day the the K_A, Q, and W bands; in balloons and satellites the time is reduced because $T_{atm} \approx 0$ at these wavelengths.

III. Project Implementation

The proposed project is divided into two parts. In the first, which will span three years, a detector system using a HEMT FTS idea and capable of making significant advances in the measurement of the CMB is built and operated. We will begin by building a K_A band 'lab' FTS and will work with higher frequency HEMT's as they become available. The two principle optical components, the large parabolic reflector and a fast precise rotary base have already been developed at Princeton in the labs of Prof. Dragovan and Prof. Peterson. The initial tests will be done on the roof of the physics building, when a successful radiometer is complete we will take it to a better site for preliminary scientific observations. We would plan to come on line with a Q-band HEMT FTS in the second year. This would be Ed Wollack's PhD experiment.

In the second part, which is concurrent and will take two years, we would work with Marian Pospieszalski to find chips for frequencies between 50 and 110 GHz. He plans to begin work on the W-band amplifiers in January 1992. The relationship would be informal involving only the exchange of information. We will set up a bench top test apparatus at Princeton with a mechanical refrigerator to measure the cryogenic S-parameters and noise of promising HEMT devices. Wollack would begin work on this immediately.

IV. Relevance to NASA Objectives

History shows clearly that the planning and execution of major NASA missions draws heavily on a background of research and development at university labs. COBE is a prime example. Not only were the instruments developed over years of work in groups at Berkeley, JPL, MIT, and Princeton; but many of the NASA scientists who played key roles in COBE came out of those same groups.

In the COBE example, and in many others, the role of the NSBF cannot be emphasized too strongly. Conditions at balloon altitudes are as close as we can get to those in space, and many of the subtle effects on instruments cannot be found in the lab or even in environmental test chambers. COBE instrument tests never approximated space as well as the old balloon-borne experiments. The many configurations and detector types that were used on balloon experiments were essential in choosing the optimum design for COBE's instruments.

The important problem of mapping the primeval fluctuations in the CMB is a natural one for NASA to address. Clearly, the ultimate experiment will be done in remote space where instruments can have unperturbed weeks to achieve the necessary integration times to reach microkelvin sensitivity over hundreds of pixels. The best Soviet group reached this conclusion several years ago and designed the RELICT experiments which have excellent orbits but noisy instruments. A few years ago the best groups in Europe failed to convince ESA to start a CMB anisotropy mission, primarily because of COBE's potential and the state of detector technology. If HEMT-based radiometers can be developed which improve on COBE's DMR sensitivity by a factor of 50, then someone will surely launch a small satellite to do it. The work proposed here is intended to do the development and testing (from balloons and cold dry sites) of HEMT-based radiometers to determine whether a small, single-purpose satellite could extend COBE's sensitivity and angular resolution enough to produce (at last) a map of the CMB anisotropy. NASA would then have the choice of whether or not to do the mission.

In addition, the radiometers we propose to develop could be used as part of already planned NASA missions. Although cryogenic HEMT's are not part of the EOS program, the HEMT FTS might be useful. Sensing the earth does not require the high HEMT sensitivity but one does want the stability. The HEMT FTS provides a way to get moderate frequency resolution with a simple and robust system. For absolute measurements, one of the input horns could be replaced with a variable temperature load and the other occasionally switched to a reference. This is microwave version of the scheme so successfully used with COBE's FIRAS.

V. Qualifications and Experience of Key Personnel

David Wilkinson and collaborators at Princeton have been making measurements of the anisotropy and the absolute temperature of the CMB at radio frequencies since 1965. Because anisotropy measurements are limited by instrument noise, it is important to anticipate the next receiver technology and to work with other groups who have the needed device expertise. Starting with commercially available cm-wave mixers, the Princeton work progressed to a maser (with JPL), and SIS mixers (with NBS and Goddard Space Science Institute). We hope to follow this successful pattern by working with NRAO on the development of 90 GHz, cryogenic HEMT amplifiers. Our special expertise has been in the area of radiometer and experiment design. To measure sky temperature differences of a few microkelvin in the presence of 300 K Earth and a noisy atmosphere requires special attention to details. Radiometer design emphasizes sensitivity, stability and reliability, while experimental techniques focus on reducing the effects of ground, atmospheric and Galactic emission. For example, the Princeton group was the first to do CMB anisotropy (and temperature) measurements from a balloon platform, and Wilkinson was among the original proposers of the COBE. Princeton anisotropy experiments have ranged in angular scale from 2′ (using the Green Bank 140′ telescope) to full sky mapping with 7° beams (using a maser-based radiometer and several balloon flights).

Most of the techniques needed to accomplish the work described in this proposal have been used at one time or another in the Princeton group. Even the novel microwave Fourier transform spectrometer is a natural evolution of the two channel correlation radiometer which this group has been using for 15 years. In the full-band radiometer a simple phase switch (± 90°) is used instead of the continuous phase shifters shown in Fig. 1, and the output is synchronously detected instead of Fourier transformed. However, the technical challenges and risks of the FTS technique should not be underestimated, especially for large bandwidth at 90 GHz.

Lyman Page has been involved in three separate measurements of the CMB anisotropy as a graduate student, post-doc, and instructor. All three use broadband cryogenic bolometric radiometers covering frequencies between 3 cm^{-1} (90 GHz) and 22.5 cm^{-1} (675 GHz). The passbands were characterized using Fourier transform spectroscopy. The observing programs cover both large and small angular scales from balloon platforms and ground based systems.

The first experiment used a balloon-borne radiometer with bolometers cooled to .24K to map the sky in four spectral bands near the peak of the CMB (200 GHz) with an angular resolution of 4°. The radiometer was flown three times and scientific information was obtained from each flight. In the first flight (Oct. 88), we found that the galaxy emitted more at 180 GHz than was previously expected[11]. COBE's FIRAS has substantiated these results. With a preliminary analysis of only a fraction of the data from the second and third flights (Oct. 89 and May 90) Page and his collaborators (Steve Meyer at MIT and Ed Cheng at NASA GSFC) have placed the most stringent limit on the amplitude parameter a_2 for a Harrison-Zel'dovich perturbation spectrum normalized to the quadrupole, namely $\Delta T/T \leq 1.3\times10^{-5}$ with 95% confidence. In addition the experiment has placed the lowest limits on the CMB anisotropy at 10° angular scales, exceeding the current limits set by COBE's DMR.

A second experiment with an angular resolution of 1° was done at the United States South Pole station with Mark Dragovan of Princeton and Bob Pernic of Yerkes Observatory. A radiometer built at MIT in the early 80's, similar to the one described above, was overhauled and optimized for a telescope at the South Pole with a resultant five fold improvement. This high and dry site allows for more integration time than a balloon flight with little degradation of the signal due to atmospheric fluctuations. The data are only partially analyzed but we can tell that the atmosphere is stable enough for future ground based anisotropy work at 150 GHz.

A third experiment, in collaboration with a team headed by Bob Silverberg at NASA GSFC and Steve Meyer at MIT, is underway and is expected to fly this Fall. It uses the above mentioned balloon borne radiometer in the focal plane of a pointing off-axis 1.5 meter Cassegrain telescope. The goal is the search for anisotropies and the Sunyaev-Zel'dovich effect with a 1° beam.

VI. Training of Professionals

The physics department at Princeton has a strong commitment to the training of young physicists at all levels, from young faculty members to undergraduates. In the Gravity/Cosmology group there are currently 3 senior faculty members and 5 non-tenured faculty, 7 thesis graduate students, 5 pre-generals graduate students, and 4 undergraduate research assistants. Two postdoctoral fellows will soon be joining the group to work with Dragovan and Peterson on bolometer systems for use at the South Pole. Many alumni of the group are actively persuing scientific careers in astrophysics. Of direct interest to NASA are the following people who work on COBE: Ed Cheng, David Cottingham, Dale Fixsen, Mike Hauser, Phil Lubin (1 year visit), Steve Meyer, and Rai Weiss (1 year visit). We consider the training of young scientists a vital part of our mission.

The funds requested in this proposal are primarily intended to support the research of Dr. Lyman A. Page, Jr. who started an Assistant Professorship at Princeton in July, 1991. Page studied with Professor S. Meyer at MIT, receiving his Ph.D. in 1989. He wishes to continue his work on the CMB anisotropy by employing the new HEMT technology at longer wavelengths . The bolometer-based instrument that he built and flew (with E. Cheng and S. Meyer) for his Ph.D. thesis at MIT works at short wavelengths and has record sensitivity.

A graduate student, Ed Wollack, would do his Ph.D. thesis on the proposed project. He has finished his general exams and is starting to set up a cryogenic test station for evaluating HEMT chips for possible use at 90 GHz. He would work closely with Page and Wilkinson on the design, testing, and field operation of the proposed HEMT-based radiometers. He has been working in our group for the past two years assisting a current thesis student (Suzanne Staggs) with a measurement of the CMB temperature at $\lambda = 21cm$. Ed designed, built, and tested several pieces of microwave hardware used in that project. The proposed budget includes support for two undergraduate students, full time during the summer and part-time during the school year. We have found that experience in a research lab is often the most important element in a students decision to stay in science after graduation. Also, working in the lab gives students an independence and self confidence that are hard to get otherwise; they are much more comfortable going off to graduate school knowing that they have some useful research skills. We find too that undergraduates, properly supervised, can be very productive. The department has special courses in electronics and machine shop practice that we encourage undergraduates to take.

VII. References

[1] For an overview of the mission see "The Cosmic Background Explorer" by Gulkis, Lubin, Meyer, and Silverberg, Sci. Am. Jan. 1990. A number of the recent experimental results are contained in "After the First Three Minutes," eds. Holt, Bennett, and Trimble, American Institute of Physics Conference Proceedings 222, 1991.

[2] Pospieszalski, IEEE MTT, 37:1340,1989. Pospieszalski in the "Advance Space VLBI Mission Technology Workshop" Feb. 12-13, 1991, BDM International, Columbus, MD. Pospieszalski *et al.*, IEEE MTT, 36:552,1988.

[3] Meyer, Cheng, and Page, Ap. J. 371:L7-L9, 1991.

[4] "After the First Three Minutes" (cited above) pg. 123.

[5] Jarosik, Timbie, and Wilkinson, *in preparation*

[6] Preprint from Pan, Kerr *et al.*. Submitted to IEEE MTT, 1990.

[7] Measurement done by Gaier *et al.* from the University of California at Santa Barbara. It was reported at the Aspen Center for Physics, July 5, 1991 by P. Meinhold.

[8] Martin, D. H., Chapter 2: *Polarizing (Martin-Puplett) Interferometric Spectrometers for the Near- and Submillimeter Spectra*, in *Infrared and Millimeter Waves, Vol 6*, Academic Press, 1982.

[9] Davies *et al.*, Nature, 326:462, 1987.

[10] Masi *et al.*, Ap. J., 366:L51, 1991.

[11] Page, Cheng, and Meyer, Ap. J. 355:L1-L4, 1990.

IX. Bibliographies

Lyman A. Page, Jr.

Birth:	September 24, 1957 San Francisco, CA
Degrees:	BA (High Honors in Physics) Bowdoin College 1978 Ph.D. (Physics) MIT 1989
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Selected Recent Publications:

Page, L.A., Cheng, E.S., and Meyer, S.S., "A Large-Scale Cosmic Microwave Background Anisotropy Measurement at Millimeter and Submillimeter Wavelengths," Ap. J. **355**:L1-L4, 1990.

Meyer, S.S., Cheng, E.S., and Page, L.A., "A Measurement of the Large-Scale Cosmic Microwave Background Anisotropy at 1.8 Millimeter Wavelength," Ap. J. **371**:L7-L9, 1991.

David T. Wilkinson

Birth:	May 13, 1935 Hillsdale, Michigan
Degrees:	BSE (Eng. Physics), University of Michigan 1957 MSE (Nuclear Physics), University of Michigan 1959 Ph.D. (Physics), University of Michigan 1957
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Selected Recent Publications:

P. T. Timbie and D. T. Wilkinson, Low-Noise Interferometer for Microwave Radiometery, Rev. Sci. Instru. **59**:914-920, 1988.

J. M. Uson and D. T. Wilkinson, The Microwave Background Radiation, Chapter 14, GALACTIC AND EXTRAGALACTIC RADIO ASTRONOMY, eds. G. L. Verschuur and K. I. Kellermann with the assistance of E. Bouton, 2nd Edition, Springer-Verlag, pp. 603-639, 1988.

P. T. Timbie and D. T. Wilkinson, A Search for Anisotropy in the Cosmic Microwave Radiation at Medium Angular Scales, Ap. J. **353**:140-144, 1990.

J. C. Mather *et al.*, A Preliminary Measurement of the Cosmic Microwave Background Spectrum by the Cosmic Background Explorer (COBE) Satellite, Ap. J. Letters, **354**:L37-L40, 1990.

G. Smoot *et al.*, COBE Differential Microwave Radiometers: Instrument Design and Implementation, Ap. J., **360**:685-695, 1990.

X. Current Support

Lyman A. Page, Jr.	*none*		
David T. Wilkinson	Research on Gravitation, Relativity, and Cosmology. (co-PI with P.J.E. Peebles)	NSF	12/31/92
	Science Validation and Cosmological Studies of Data from COBE.	NASA	12/31/91
	High Sensitivity Radiometers for Post-COBE Measurements of Anisotropy in the 2.7 K Cosmic Background Radiation.	NASA	12/31/91