Future prospects in measuring the CMB power spectrum

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Measurements of the CMB power spectrum promise to revolutionize our understanding of the early universe and the parameters involved. We already have a tentative understanding of the power spectrum from COBE at large angular scales and from ground based and balloon borne experiments at small angular scales. The currently observed spectrum shows a strong rise as we approach sub-degree scales and even a possible fall at smaller scales. The capability now exists to make a precision measurement of the power spectrum from both sub-orbital and orbital platforms in the next 5–10 years. The results of such a measurement will profoundly effect our knowledge of the fundamental parameters that characterize our universe.

1. Introduction

Studies of the Cosmic Microwave Background (CMB) have provided some of the most challenging and fruitful measurements of the fundamental properties of the universe. The fundamental assumptions made over half a century ago about a homogeneous and isotropic universe are still consistent with our current knowledge of the universe. In particular we know from studies of the CMB that the assumption of isotropy is valid to an astonishing level, one which has profoundly affected the theoretical concepts of how we view the very early universe. Indeed during the long march from the discovery of the CMB in 1965 to our first hints of fundamental structure in the CMB in 1991–3, the very fact that we placed increasingly stringent limits on CMB anisotropies was strongly influencing the theoretical framework. This was particularly true regarding inflationary scenarios of the very early universe. We now have a rudimentary knowledge of the CMB power spectrum sufficient to constrain and even make preliminary measurements of the fundamental parameters such as total density, baryon fraction, etc. We now have sufficiently sensitive measurements in selected regions of the sky with degree scale measurements to give confidence that we will be able to map large portions of the sky with enough accuracy to reduce the errors on many fundamental cosmological parameters to the few percent level or better. Combining these maps with maps from other surveys, such as LSS optical and IR surveys, will provide a database we could only dream about even a decade ago. While there are still many potential pitfalls that remain to be crossed towards this goal, we now understand many of the issues of foreground contamination and systematic errors that we worried about in the past from our recent degree scale measurements. We are now very optomistic about the science that will result from the next generation of experiments.

† Parts of this paper are adapted from my other papers.

2. Early Measurements of the Power Spectrum — Prior to COBE

As a historical footnote we now know we had detected degree scale structure and hence had a preliminary measurement of power spectrum prior to 1992 but needed confirmation of what we had measured. Our subsequent (and others) measurements have now shown that these early measurements were correct. Prior to the COBE launch in 1989, our Advanced Cosmic Microwave Explorer (ACME) payload had made two balloon flights and one South Pole expedition making measurements from 0.3 to 3 degrees with SIS and bolometric detectors. Prior to the April 1992 COBE announcement, ACME had flown four times and made two South Pole trips with a total of seven measurements. Our 1988 South Pole trip with ACME outfitted with a sensitive SIS (Superconductor-Insulator-Superconductor) receiver resulted in an upper limit at 0.5° of $\Delta T/T \leq 3.5 \times 10^{-5}$ at 0.5° for a Gaussian sky. This was tantalizingly close to the "minimal predictions" of anisotropy at the time and, as we were to subsequently measure, just barely above the level of detectability. In the Fall of 1989, we had our second ACME flight. This flight used a bolometric detector in place of the SIS detector and was the first in a series (the MAX flights) using bolometric detectors. The third ACME (second MAX) flight was the next summer (1990). This MAX-II flight resulted in structure being detected that was consistent with a cosmological spectrum. The data was taken in a low dust region and showed no evidence for galactic contamination. This data in the Gamma Ursa Minoris region ("GUM data") was first published in Alsop et al. (1992)[3] *prior* to the COBE detections. At the time, our most serious concern was of atmospheric stability, so we revisited this region in the next ACME flight in June 1991. ACME was next shipped to the South Pole for the second time in October 1991 with both SIS and HEMT (High Electron Mobility Transistor) based detectors for additional ground based measurements. This South Pole trip, the so-called SP91 data, resulted in a number of results and still represents the most sensitive per point measurement of the CMB ever made. There were seven strip measured, the most sensitive two of which are referred to as the "9" and "15" point scans, respectively published in Gaier et al. (1992) and Schuster et al. (1993). These data were taken using a broad band HEMT between 25-35 GHz split into four bands. The beam size was about 1.5 degrees but varied from 1.4 to 2.0 degrees over the lowest to the highest frequency bands. Both the 9 and 15 point scans showed significant structure at the level of $\Delta T/T = 1 \times 10^{-5}$. Since the beam size varied with band and since the data were taken in a "step scan" mode, a falling (negative spectral index) spectrum can result if the primary structure is smaller than the beam size and not centered in the beam. The 4 channel added data in both the 9 and 15 point scans shows a very similar level of structure at the 10 ppm level, with a significant negative spectral index in the 9 point data and a less negative (consistent with flat at 2 sigma) in the 15 point. As mentioned one cannot conclude unique spectral information about the source spectrum from these "spectral" indexes due to the beam size variation and scan mode. The fact that they both yield similar amplitude was intriguing. A conservative upper limit was published in Gaier et al. (1992) of the 9 point scan of $\Delta T/T \leq 1.4 \times 10^{-5}$ at 1.2° This upper limit for a Gaussian auto correlation function sky was computed from the highest frequency channel. The four channel co-add (assuming it is of cosmological origin) of this same data set yields a strong detection at a level of $\Delta T/T = 1 \times 10^{-5}$. The 15 point data is even more sensitive and as mentioned yields a strong detection at a similar level of $\Delta T/T = 1 \times 10^{-5}$ and was published in Schuster et al. (1993). Analysis of dust and synchrotron maps from the area of the sky surveyed, with reasonable assumptions about the spectral indices, predict that the signal level we observed is not consistent with expected dust or synchrotron. Indeed the low frequency synchrotron maps do not show similar morphology and would predict an amplitude that is much smaller ($< 7\ \mu$K). No evidence for point source contamination was found either and a recent intensive measurement of the field yielded a negative result for point source contamination (Gundersen et al. 1997). The 1σ error measured per point in the 15 point scan is 14 μK or $\Delta T/T = 5 \times 10^{-6}$. Per pixel, this is the most sensitive CMB measurement to date at any angular scale. Perhaps the most intriguing aspect, and the most confusing at the time, was the strong rise in the power spectrum from 10 ppm at 1.5 degrees from the SP 91 data to 40 ppm in the ACME-MAX-II 0.5 degree data. This was the first indication of a rise in the power spectrum as we approached the (possibly) sub-horizon scale. The fact that these two SP 91 data sets yielded similar amplitudes prompted us to return to the South Pole in 1993 with two HEMT detectors with a larger frequency range, 25-35 and 38-45 GHz in seven bands. We also used a "smooth scan" instead of the "step scan" for these data. These so-called SP93 (or sometimes SP94) data also yielded strong detections. Since the beam size was now ranging from 1 to 2 degrees we could compare with the SP 91 results as well as the ACME-MAX results at 0.5 degrees. The SP 93/94 results measure an amplitude consistent with the SP 91 data but somewhat larger at the smaller beam size of 1 degree.

The relevant measurements just prior to the COBE announcement are summarized in Figure 1. While this early data was quite confusing at the time, particularly the rise in the power spectrum from 1.5 to 0.5 degrees, it is now seen with our (and others) additional measurements to be consistent. Without the large-scale normalization of the COBE data however, it seemed difficult to reconcile the apparently discordant data. This normalization at large angular scales was provided by the COBE data in 1992, and as shown in Fig. 5, our earlier degree-scale measurements are consistent with the COBE detections.

3. Foreground Issues

To make measurements of the CMB at the part per million level we have to contend with sources of radiation from a number of other sources. Included in this are emission from our own galaxy in the form of interstellar dust, Bremsstrahlung and synchrotron radiation. Additional significant radiation from the earth, sun and moon and the atmosphere can be a problem that needs to be considered. The approximate relevant level of the backgrounds is shown in Figure 2. This needs to be interpreted carefully as the real picture is quite complicated depending on the spatial morphology being studied and for the atmosphere on time dependent effects. In any case it is a good guide to discuss the relevant issues. At high frequencies, above 100 GHz the primary galactic contaminant is thermal radiation from interstellar dust grains. The composition and structure of these dusts grains is not well understood and the generic properties are lumped into a description of the effective emissivity and temperature. The emissivity is frequency dependent while the temperature is spatially dependent. Since we are not generally interested in making measurements close to the galactic plane we do not have to deal with the extreme complexities in this region. With the ACME-MAX experiments we have made measurements both on and off the galactic plane of the interstellar dust in a few selected regions. While we cannot claim to have made an exhaustive survey, the results are consistent morphologically with the shorter 100 micron IRAS maps suitably scaled to our wavelengths. This allows us to at least predict the approximate level of expected contamination at shorter wavelengths using the IRAS and DIRBE maps as templates. The good news is that at the 10 ppm level where we have strong detections, there are large regions of the sky that should be relatively uncontaminated as we show in Figure

FIGURE 1. ACME CMB power spectrum data prior to the COBE detection. Theoretical curves are from Steinhardt and Bond (private communication). See KEY in Fig. 5 caption.

3. At lower frequencies, below 50 GHz, the primary contaminant is Bremsstrahlung and synchrotron radiation. Here we rely on a similar comparison using maps at much lower frequencies, notably the 0.4 and 1.4 GHz maps. The synchrotron radiation is generally not expected to be much of a problem due to its steep spectral index (typically -2.9 off the plane). The Bremsstrahlung is more complicated. First we do not know much about the diffuse Bremsstrahlung emission and secondly it does not decrease nearly as rapidly as the synchrotron emission at higher frequencies. We can however measure the H-alpha and related optical emission to constrain or measure it indirectly. Reynolds and other have done selected regions and are planning much more ambitious surveys that will help us in the future. In the end it is the data themselves that will provide the best indicator of contamination or lack thereof. By making measurements over a wide range of frequencies we can distinguish between cosmological and galactic emission.

At all observation frequencies, extragalactic radio sources are a potential concern. Extragalactic radio sources have the disadvantage that there is no well-known spectrum which describes the whole class of sources. For this reason, measurements over a very large range of frequencies and angular scales are required for CMB anisotropy measure-

FIGURE 2. Relevant backgrounds for terrestrial measurements at the South Pole and at balloon altitudes (35 km) where ACME observes. Representative galactic backgrounds are shown for synchrotron, bremsstrahlung, and interstellar dust emission as well as the various ACME (center) wavelength bands.

ments in order to achieve a sensitivity of $\Delta T/T \approx 1 \times 10^{-6}$. As we proceed towards smaller beams sizes the problem becomes progressively more difficult for point source contamination. However as we show in Figures 2 the estimated contribution for 10' beam surveys is still encouraging. We can make an estimate of the portions of the sky that are likely to be contaminated by galactic emission by combining the low and high frequency galaxy maps with our "knowledge" of the spectral indices of the various species. In Fig. 2, we show such an estimate for the fraction of sky uncontaminated by the direct emission from our galaxy. Keep in mind that this is only an estimate based on our present data. While additional galactic surveys would help to determine the galactic component better, it is assumed at the current time that the best data on galactic contamination will come from the future CMB maps themselves. Additional ground based surveys of point sources and H-II emission will be a great aid in CMB studies however. As an example, for our SP '94 data set we have made a point source survey at a number of frequencies to determine the spectra of the brightest point sources in our field (Gundersen et al., 1997). No evidence of significant point source contamination was found for this data set. Ideally such point source surveys could be carried out for the entire sky. Such a task is daunting however considering the number of known, let alone unknown, point sources. For example, in ACME, the sensitivity to point sources is about 47 μK per Jansky at 40 GHz. This is for a 1 degree beam. A 10' beam size experiment will face a point source sensitivity of about 1 mK per Jansky. A 1 ppm per pixel survey of the CMB at 10' resolution will require milli-Jansky point source rejection ability. One of the objectives

Date	Site	Detector System	Beam FWHM (deg.)	Instrument Sensitivity
1988 Sept	Balloon^{P}	90 GHz SIS receiver	0.5	4 mK $s^{1/2}$
1988 Nov-1989 Jan	South Pole	90 GHz SIS receiver	0.5	3.2
1989 Nov	Balloon^{FS}	MAX photometer (3, 6, 9, 12 cm^{-1}) ^3He	0.5	12, 2, 5.7, 7.1
1990 Jul	Balloon^{P}	MAX photometer (6, 9, 12 cm^{-1}) ^3He	0.5	0.7, 0.7, 5.4
1990 Nov-1990 Dec	South Pole	90 GHz SIS receiver	0.5	3.2
1990 Dec-1991 Jan	South Pole	4 Channel HEMT amp (25-35 GHz)	1.5	0.8
1991 Jun	Balloon^{P}	MAX photometer (6, 9, 12 cm^{-1}) ^3He	0.5	0.6, 0.6, 4.6
1993 Jun	Balloon	MAX photometer (3, 6, 9, 12 cm^{-1}) ADR	0.55-0.75	0.6, 0.5, 0.8, 3.0
1993 Nov-1994 Jan	South Pole	HEMT 25-35 GHz	1.5	0.8
1993 Nov-1994 Jan	South Pole	HEMT 38-45 GHz	1.0	0.5
1994 Jun	Balloon	MAX photometer (3, 6, 9, 14 cm^{-1}) ADR	0.55-0.75	0.4, 0.4, 0.8, 3.0
1996 Feb	Balloon	HACME HEMT 38-45 GHz	0.7	0.4, 0.5, 0.8
1996 Jun	Balloon	HACME HEMT 38-45 GHz	0.7	0.4, 0.5, 0.8

TABLE 1. CMB measurements made with ACME.

of the next generation of CMB measurements will indeed be greatly refined galactic and extra-galactic source models and measurements.

4. Atmosphere

For sub orbital missions, balloon borne and ground based, atmospheric emission is a dominant concern. The atmosphere is a complex source being frequency, spatially and temporally dependent. The frequency dependence is actually useful since it allows us to monitor it and allows narrow band instruments to achieve extremely low atmospheric residuals. The emission consists primarily of the molecular transitions of oxygen water and ozone. Except for the effect of pressure waves the oxygen is thought to be very uniformly distributed. Water is known to be very inhomogeneous and ozone appears to have some inhomogeneities as well. For virtually all CMB experiments these are the only relevant species. Below 60 GHz there are no ozone lines of significance and hence at longer wavelengths we only need to contend with oxygen and water. As seen from Figure 2 the atmospheric emission is vastly different depending on the frequency and bandwidth of the observations. This is particularly true at high altitudes (balloons) where the pressure broadening of the molecular lines is less prominent. Here the ratio of peak to valley emission can be as large as a factor of 1000 or more. Hence, judicious choice of wavelength can drastically reduce the atmospheric emission. As an example we can reduce the atmospheric emission for a 40 GHz HEMT based detector from 7 Kelvin at the South Pole to less than 1 milliKelvin at balloon altitudes. At some wavelengths this allows us to operate without worrying about any significant atmosphere.

5. ACME Results

There have been a total of 13 ACME observations/flights from 1988 to 1996. Over 20 articles and proceedings have resulted from these measurements as well as nine Ph.D. theses. ACME-SIS and ACME-HEMT articles by Meinhold and Lubin (1991),[6] Meinhold et al. (1992),[7] Gaier

FIGURE 3. Galactic model estimates for the fraction of sky uncontaminated below a given level. The model includes synchrotron, bremsstrahlung, and dust emission. The synchrotron model is given for two different spectral indices. Far off the galactic plane (where we are most interested in measuring), the steeper spectral index is more appropriate. The dust model is based on the IRAS 100 micron map combined with our dust data from the mu-Pegasus region.

et al. (1992),[4] Schuster et al. (1993),[5] Gundersen et al. (1995),[8] and ACME-MAX articles by Fischer et al. (1992),[9] Alsop et al. (1992),[3] Meinhold et al. (1993),[10] Gundersen et al. (1993),[11] Devlin et al. (1994),[12] Clapp et al. (1994)[13] Tanaka et al. (1996)[15] and Lim et al. (1996)[16] summarize the results to date.

6. Future

As exciting and rewarding as the past five years have been in CMB studies, the next decade truly promises to be profound in its results. We have now made measurements sensitive enough to extract many of the cosmological parameters but lack the sky coverage to reduce the sample and cosmic variance to a reasonable level. We are now at a point, both technologically and in our understanding of the relevant CMB signals and non cosmological backgrounds, that we can seriously contemplate making a precision measurement of the CMB power spectrum. What is needed is not necessarily more sensitivity (though more is always welcome) but more samples

FIGURE 4. Estimated parameter extraction versus sensitivity, assuming 50% sky coverage.

of the sky. Some of the current and past confusion in measurements of the power spectrum are undoubtably due to small statistics. For example, in Figure 4 we show the estimated cosmological parameter extraction precision versus beam size and pixel sensitivity for an experiment that cover 50% of the sky. While the extraction procedures and error estimates are still being debated it appears feasible to get a precision in measuring the various parameters to the percent level within the next decade. This implicitly assumes a cosmological model that is "well behaved" and assumes no additional pathological foregrounds.

7. Mapping Techniques

To date, essentially all the sub degree experiments have been done in a one dimensional scan mode and have not been able to make a "true map". This has been done because of the atmospheric emission restricting us to make one dimensional, constant elevation angle chops. All of the ACME measurements are of this type. An orbital mission does not suffer from this problem, of course. However even then one is making 1-D strips and then "sewing" them together to make a map. The COBE mission was no exception. The only "real maps" so far have been made by interferometers and then a "map" must be carefully scrutinized since the data weighting is far from uniform. With the exception of interferometers, experiments have been either differential or "total" power (this means a direct measure of the flux is made). Virtually all experiments (including our own) have opted for the differential technique as it is less demanding on various system stabilities. Recently experiments have shown that a direct "total" power measurement is possible and the era of sub-degree resolution maps is about to begin. It is easy to see why this is difficult. The typical equivalent noise of a state-of-the-art

FIGURE 5. Recent ACME results (in BOLD) along with results from other groups. Key: a-COBE, b-FIRS, c-Tenerife, d1-SP91 9 pt. 4 channel analysis-Bond '93, d3-SP91 9+13 pt. 4 channel analysis-Bond '93, d5-SP91 9 pt. Gaier et al. '92, e-Big Plate, f-PYTHON, g-ARGO, h-MAX4-Iota Dra, i-MAX4-GUM, j-MAX4-Sig Herc, k-MSAM2, l-MSAM2, m-MAX3-GUM, n-MAX3-mu Peg, o-MSAM3, p-MSAM3, q-Wh. Dish, r-OVRO7, s2-SP94-Q, s3-SP94-Ka, t-SP89, u-MAX2-GUM, many from Steinhardt and Bond by private communication.

detector is 10–30K. This is to be compared to the desired sensitivity of 3–30 micro Kelvin. This requires a system stability of the order of 1–10 ppm.

8. Polarization

The CMB is characterized by the four Stokes parameters I, Q, U and V in each direction and at each frequency observed. I characterizes the overall spectrum (flux) while Q and U give the linear polarization and V the circular polarization. Very little effort has been directed towards the measurement of the polarization of the CMB compared to the effort in anisotropy detection. In part, this is due to the low level of linear polarization expected. Typically, the polarization is only 1–30% of the anisotropy and depends strongly on the model parameters. This is an area which, in theory, can give information about the reionization history, scalar and tensor gravity wave modes, and large-scale geometry effects. It is now possible to measure

Publication	Configuration	Beam FWHM (deg.)	$\Delta T/T \times 10^{-6}$
Meinhold & Lubin '91	ACME-SIS SP '89	0.5	<35
Alsop et al., '92	ACME-MAX-II (GUM)	0.5	45^{+57}_{-26}
Gaier et al., '92	ACME-HEMT SP '91	1.5	<14
Meinhold et al., '92	ACME-MAX-III (μ Peg - upper limit)	0.5	<25
Meinhold et al., '92	ACME-MAX-III (μ Peg - detection)	0.5	15^{+11}_{-7}
Schuster et al., '93	ACME-HEMT SP '91	1.5	9^{+4}_{-2}
Gundersen et al., '93	ACME-MAX-III (GUM)	0.5	42^{+17}_{-11}
Devlin et al., '94	ACME-MAX-IV (GUM)	0.55-0.75	37^{+19}_{-11}
Clapp et al., '94	ACME-MAX-IV (Iota Draconis)	0.55-0.75	33^{+11}_{-11}
Clapp et al., '94	ACME-MAX-IV (Sigma Hercules)	0.55-0.75	31^{+17}_{-13}
Gundersen et al., '95	ACME-HEMT SP '94	1	$15^{+5.7}_{-2.5}$
Lim et al., '95	ACME-MAX-V (μ Peg)	0.5	<13
Tanaka et al., '95	ACME-MAX-V (HR5127)	0.5	12^{+4}_{-3}
Tanaka et al., '95	ACME-MAX-V (Phi Herculis)	0.5	19^{+7}_{-4}

TABLE 2. Recent ACME degree-scale results.

CMB polarization to a sensitivity of better than 1 ppm on limited portions of the sky. In the future, this will be a very fruitful area of inquiry, particularly when combined with overlapping anisotropy measurements. In particular the polarization-anisotropy cross correlation is a very powerful technique in understanding and breaking degeneracies in the parameter extraction. At mm and cm wavelengths dedicated polarization measurements designed to reach a level of sensitivity of 1 ppm or better are feasible to do from the ground since the atmosphere is essentially unpolarized at these wavelengths.

9. Orbital vs Sub Orbital Missions

There are currently several major proposed (and now just started) satellite missions. The European COBRAS/SAMBA proposal is a combined HEMT and bolometer mission, and would cover from about 1 to 10 mm with resolution varying from about 4 to 40 arc minutes depending on the frequency. In the U.S., the Mid-Explorer class MAP mission is a HEMT based mission that will cover from 3 to 15 mm with a beam size from 20 to 80 arc minutes. There are significant differences in technical and programmatic approaches being taken with the European being a more ambitious, and hence, more costly experiment. The U.S. Mid-Explorer mission is designed with more limited objectives, but at a significantly lower price and at a possibly shorter time scale to launch. Either of these missions would provide invaluable data that could revolutionize our understanding about early universe physics. Currently, it can be assumed that these missions will not produce data before 2002 at the earliest for the US mission, and 2006 for the European one, and hence it is to be anticipated that continued vigorous ground-based and suborbital experiments will continue to produce valuable data.

Indeed, per pixel sensitivities with suborbital missions in the μK region are now achievable

FIGURE 6. The ACE Experiment - An ultra long duration balloon experiment.

with current and new technologies, HEMTs, and bolometers over hundreds to hundreds of thousands of pixels and possibly over large portions of the sky. With the HEMT and bolometer array receivers that are being planned now for sub orbital measurements it is quite possible that the integrated sensitivity and resolution of these measurements will exceed that of the US mission. The major issue will be atmospheric stability, control of sidelobes and getting a uniform dataset. Ideally, to reduce systematic effects, full-sky coverage would be best, and this is one area where a space-based measurement will excel. In a number of ways the sub-orbital and orbital missions will be complimentary and allow for a very powerful combined dataset.

9.1. *The ACE Experiment*

The primary limitation at this time is not necessarily more sensitivity but rather increased sky coverage. We now have detections at a S/N of 1 to 10. While more sensitivity is always welcome the primary goal is to increase the statistics of the sky sample. For sub-orbital approaches the primary balance is between increased exposure time from the ground but much larger atmosphere versus much less exposure time with balloons but with much lower atmosphere and increased detector sensitivity. Long duration balloons circumnavigating the arctic for periods of 10-15 days will allow us to significantly extend the conventional balloon exposure. A new approach using ultra long duration balloons with 100 day exposure may allow an excellent low cost alternative to orbital missions in this and other areas. As an example of this approach the ACE experiment is designed to achieve beam sizes of less than 10 arc minutes at 100 GHz and exposure times of 100 days or more. This system will be the equivalent of a small satellite with closed cycle refrigerators to cool the HEMTs to 20K and autonomous control. Figure 6 shows a schematic drawing of this experiment.

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REFERENCES

Lubin, P. *et al.* 1985 *Astrophys. J.* **298**, L1.

Pospieszalski, M. W. *et al.* 1990 *IEEE MTT-S Digest*, 1253.

Alsop, D. C *et al.* 1992 *Astrophys. J.* **317**, 146.

Gaier, T. *et al.* 1992 *Astrophys. J.* **398**, L1.

Schuster, J. *et al.* 1993 *Astrophys. J.* **412**, L47.

Meinhold, P.R. & Lubin, P. M. 1991 *Astrophys. J.* **370**, L11.

Meinhold, P. *et al.* 1992 *Astrophys. J.* **406**, 12.

Gundersen, J. O. *et al.* 1995 *Astrophys. J.* **443**, L57.

Gundersen, J. O. *et al.* 1997 *to be submitted to Astrophys. J.*

Fischer, M. *et al.* 1992 *Astrophys. J.* **388**, 242.

Meinhold, P. *et al.* 1993 *Astrophys. J.* **409**, L1.

Gundersen, J. O. *et al.* 1993 *Astrophys. J.* **413**, L1.

Devlin. M. *et al.* 1994 *Astrophys. J.* **430**, L1.

Clapp, A. *et al.* 1994 *Astrophys. J.* **433**, L57.

Wollack, E. *et al.* 1994 *Astrophys. J.* **419**, L49.

Lim, M. *et al.* 1996 in press.

Tanaka, S. *et al.* 1996 in press.

Smoot, G. F. *et al.* 1992 *Astrophys. J.* **396**, L1.