RESULTS FROM THE FIRST FLIGHT OF BAM

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Abstract

A new instrument, BAM (Balloon-borne Anisotropy Measurement), designed to measure cosmic microwave background (CMB) anisotropy at medium angular scales was flown for the first time in July of 1995. BAM is unique in that it uses a cryogenic differential Fourier transform spectrometer coupled to a lightweight off-axis telescope. The very successful first flight of BAM demonstrates the potential of the instrument for obtaining high quality CMB anisotropy data.
A new instrument, BAM (Balloon-borne Anisotropy Measurement), designed to measure the optical spectrum of cosmic microwave background (CMB) anisotropies was flown for the first time in July 1995. The instrument is sensitive to anisotropies on angular scales from $3/4^\circ$ to a few degrees, scales just larger than those typically predicted for the first so-called Doppler peak in the anisotropy angular power spectrum [1]. Therefore, measurements made by BAM will be used for a sensitive test of the angular power spectrum of primordial anisotropies. In this paper preliminary results obtained from the first flight are described.

The BAM receiver is a differential Fourier transform spectrometer, previously used for a measurement of the CMB intensity spectrum from a sounding rocket [2], [3], coupled to a lightweight prime-focus telescope. All of the optical elements of the spectrometer are at $\sim 2$ K except for the bolometric detector assembly, which operates at 0.26 K. Rapid scanning of a mirror assembly in the cryostat varies the optical path length difference in the interferometer, and produces interferograms at the bolometers whose amplitudes are proportional to the brightness difference between the two spectrometer inputs. Spectra are obtained \textit{a posteriori} by Fourier transformation of the interferograms with respect to optical delay. Useful anisotropy data are obtained in five spectral channels with central frequencies from $3.1 \text{ cm}^{-1}$ to $9.2 \text{ cm}^{-1}$. Unlike most other instruments designed to measure the CMB anisotropy, which employ an ambient temperature chopping mirror to switch the beam on the sky, BAM obtains a differential measurement with no warm moving optical element; the only moving optical element is the moving mirror assembly located in the cryostat.

A diagram of BAM in cartoon form, adapted from the official decal (in color), is shown on the title page. The two inputs to the differential spectrometer are displaced from each other in a direction perpendicular to the plane of the drawing. The inputs are located near to the optic axis of the 70 cm focal length paraboloidal primary mirror, resulting in two beams $0.7^\circ$ FWHM on the sky separated by $3.6^\circ$. Collimators [4] define the acceptance of the two inputs. The
collimators view the same portion of the primary mirror, thus the instrument is insensitive to thermal gradients across the primary mirror. This was tested late in the flight by heating one side of the mirror to produce a 2 K gradient across the mirror; no change in signal is detected.

The BAM gondola structure is relatively large in order to accommodate the off-axis optical design. The gondola stands 4 m high in the laboratory, and the ground shield is 4.5 m across at the widest point. Nevertheless, the application of aerospace-like design and construction techniques has produced a lightweight gondola. For example, the arm holding the primary mirror is a riveted sheet aluminum structure similar to an airplane wing. The undercarriage of the gondola, which absorbs the impact of landing, is made from aluminum honeycomb panels supported by a frame made from welded chrome-molybdenum steel. The 1.65 m diameter aluminum primary mirror itself is also lightweight, weighing 26 kg. The launch weight of BAM is 660 kg, not including ballast.

BAM was launched from the U.S. National Scientific Balloon Facility in Palestine, Texas at 00:45 UT on 8 July 1995 (sunset on 7 July 1995 local time). An animation of the launch and other images can be viewed at [http://cmbr.physics.ubc.ca](http://cmbr.physics.ubc.ca). The gondola reached a float altitude of 41.4 km approximately five hours after launch; a little over three hours was spent performing the experiment at float. Data acquisition was terminated when the balloon neared the end of telemetry range. The instrument was recovered with only minor damage.

Figure 1 shows a chronology of events during the flight. Just before reaching a stable float altitude the telescope was unlatched and scanned across the planet Jupiter to calibrate the instrument and to confirm the beam shape. The instrument was then rotated to look north and a series of observations was begun near to transit above the north celestial pole. Shortly afterwards a memory chip in the pointing system telemetry electronics became intermittent and then failed, corrupting some parts of the telemetry from the pointing system. As a result, the ground station sent erroneous corrective commands at a rate
Figure 1. Chronology of events during the flight. Jupiter was scanned several times and provides the primary calibration for the instrument. Regions indicated by the dashed lines indicate periods during which data analyzed here were acquired. The disjoint nature of these regions is largely due to the problems encountered by the failure of a memory chip in the pointing system as described in the text.

exceeding the capabilities of the command transmitter, so successful command transmission became unreliable. The telescope remained locked to guide stars and data were collected, but the precise sequence of observations was difficult to control. After understanding the problem a switch was made to a redundant telemetry channel not intended for use during flight, and a software patch for the ground station was developed. As a result, reliable commanding of the gondola was restored for the last half hour of observation.

It had been intended to obtain an interleaved set of double difference measurements by slewing the telescope in azimuth by an angle corresponding to the beam separation every three minutes. We were not entirely successful in this regard. Since slewing is controlled by commands from the ground the memory failure limited the number of double differences obtained. As a result,
preliminary results based on analysis of single differences are presented; single difference measurements were obtained on ten fields on the sky.

The spectrum of the optical signal from the sky is contained in the cosine component of the phase-corrected Fourier transforms of the interferograms. The sine component is orthogonal to signals from the sky and thus provides a monitor of systematic effects in the measurement. Using a likelihood analysis technique and assuming that the sky can be described by a Gaussian autocorrelation function \([5]\), it is found that the 90\% confidence interval for the cosine component is not consistent with zero. Although the peak of the likelihood function for the sine component is not at zero power, the sine amplitude is consistent with zero. The detected optical signal can be expressed as the square root of the band power or \(Q_{\text{flat}}\) (after \([6]\)). It is found that \(Q_{\text{flat}} = 35.9^{+17.7}_{-6.3} \, \mu K\) at an effective spherical harmonic of \(\ell = 74\). Details can be found in \([7]\). Figure 2 shows this result along with the results of other current CMB anisotropy measurements.

Statistically significant fluctuations in the microwave sky have been observed, but not with the sensitivity required to attribute these fluctuations definitively to cosmic origin; in particular it has not been possible to constrain the amplitude of the fluctuations and their optical spectral signature simultaneously. The modest sensitivity obtained in this flight is the result of mechanical and electrical malfunctions, coupled with the short observing time accepted for the initial flight of a new instrument, and it is not the result of any fundamental limitation of the instrument. Avoiding a repeat of these malfunctions poses no serious technical challenge or risk. With a longer flight and some improvements to the receiver, an improvement in the signal-to-noise ratio of at least a factor of five is conservatively anticipated.

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Figure 2. Current measurements of CMB anisotropy. The BAM result is shown as a triangle. Measurements of CMB anisotropy are a measurement of variance and are thus biased away from zero. Thus in regions where there are more measurements one expects a larger scatter as evidenced in this figure. This figure is adapted from [8].

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