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Spectrum of the Microwave Background Radiation [and Discussion]

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Spectrum of the microwave background radiation

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A review is given of the present status of measurements of the spectrum of the microwave background. Factors that limit experimental accuracy are discussed with particular reference to high-frequency measurements. A selection of the available measurements yields a data set that is reasonably consistent with the black-body spectrum for a temperature of 2.9 K. A simple statistical analysis suggests either that there are errors in the data set, or that deviations from a black-body spectrum exist. The difficulties inherent in properly averaging the results from different observers are described. Prospects for improved measurements are summarized.

Introduction

Measurements of the spectrum of the cosmic microwave background (c.m.b.) have challenged the skills of experimenters for 17 years. The spectrum has been successfully measured over more than three orders of magnitude in frequency from 408 MHz to 720 GHz. The experimental spectrum is approximately that of a 3 K black body, with a peak at *ca.* 180 GHz. Measurements of the spectrum of the c.m.b. have been reviewed recently by Danese & De Zotti (1977) and by Weiss (1980). Lists of experimental results and references appear in many places in the literature (Danese & De Zotti 1978; Woody & Richards 1981).

This paper will begin with a general discussion of the ways in which measurements of the spectrum of the c.m.b. are made. A selected set of measured results will then be discussed. Finally, a description will be given of several experiments now in progress that may improve our knowledge of the spectrum of the c.m.b.

Measurements of the spectrum of the c.m.b. at frequencies below *ca.* 90 GHz have generally used single-mode microwave heterodyne radiometers. The flux in a single mode of the c.m.b. is essentially independent of frequency over this range. Each measured point depends on an independent absolute calibration of the flux received. For frequencies above *ca.* 90 GHz, constant throughput infrared spectrometers have been used to measure the flux in a number of modes which increases as frequency squared. The spectral bandwidth measured with one instrument can then be wide compared with the peak in the constant throughput flux of the c.m.b. In this case some benefit has been obtained from a comparison of measured parameters at neighbouring frequencies.

The anisotropy of the c.m.b. is not large enough to influence the present generation of spectral measurements. No dark region of the sky is expected that can help with the calibration. Thus it is not possible to chop on and off the source. A practical consequence has been that all successful spectral measurements have made use of a liquid helium cooled black-body calibrator, or cold load.

The sensitivity of microwave heterodyne radiometers of the type developed for more conventional radio astronomy is adequate for measurements of the c.m.b. Although the early far-infrared experiments were severely limited by detector noise, modern infrared detectors such as liquid ^{3}He cooled composite bolometers now have adequate sensitivity for typical measurements.

One of the major problems with measurements of the c.m.b. arises from the need to subtract the contributions of unwanted signals, which come both from the apparatus and from the sky. Unwanted signals from within the apparatus can in principle be cancelled by the use of a properly designed Dicke radiometer. A schematic diagram showing some of the necessary features appears as figure 1. The sky signal is compared with the signal from the calibrator when the latter is operated at two different temperatures. Although there can be very severe practical problems with the design of the calibrator and the beam switch, the effects of signals arising within the apparatus are cancelled if the response of the system is linear and if it is stable over the period required for switching the beam. Since the switch is not usually fast enough to avoid inverse frequency detector noise, microwave radiometers use heterodyne down-conversion, while infrared radiometers chop (or interference modulate) the beam against a stable internal reference temperature.

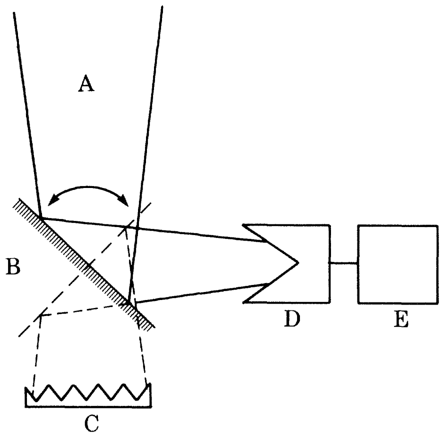

FIGURE 1. Schematic diagram of a Dicke radiometer. A, incoming beam from sky; B, mirror operated in two positions; C, black-body source operated at two temperatures; D, antenna to select mode or modes to be measured; E, receiver.

Thermal radiation from the apparatus and the environment plays an important role in measurements of the c.m.b. At microwave frequencies the ratio of the signal from a 300 K black body to that from a 3 K black body is $T_{300}/T_3 = 10^2$. The dynamic range of microwave receivers is sufficiently large for experiments to be done with room temperature receivers and beam switch, but with a cold load. Because of the exponential cut-off of the Planck spectrum for high frequencies, however, this ratio grows to $kT_{300}\{\exp(h\nu/kT_3)-1\}/h\nu = 6\times10^2$ near the peak of the 3 K spectrum at 180 GHz and 1.5×10^5 at 600 GHz. For far-infrared measurements at and beyond the peak, therefore, all optical elements that contact the primary beam must be cooled to liquid-helium temperatures.

Since the c.m.b. is essentially isotropic, spectral measurements do not require high angular resolution, and relatively small antennas can be used. It is essential, however, that the side- and back-lobe response of the antenna be controlled, so that thermal radiation from the horizon or the Earth does not contribute to the measurement. The 300 K Earth subtends a much larger solid angle than the central lobe of the antenna pattern on the *ca.* 3 K sky. To avoid contamination from earthshine, therefore, the antenna response at the horizon must be reduced by a factor significantly larger than $kT_{300}\{\exp(h\nu/kT_3)-1\}/h\nu$. This condition can be met with modern ridged-horn antennas at microwave frequencies. At infrared frequencies where multi-mode response is often required over a broad frequency bandwidth, apodized antennas have been developed which make use of cold conical reflectors or cold mirrors, along with warm earthshine shields. If these are properly designed, the very stringent requirements of high-frequency measurements can be met.

The design of an adequate low-temperature beam switch and calibrator for far-infrared experiments has proved to be a difficult problem. The reflectivity of practical multi-mode black bodies is of order 10^{-2} to 10^{-3}. This is too large to permit adequate calibration in the presence of room temperature radiation. As a consequence, all successful far-infrared experiments so far have been calibrated by inserting a low-temperature black body into a cold region of the cryostat in the laboratory before or after the measurement, or both. For this procedure to be valid, the operating conditions of the apparatus during the measurement must be reproduced precisely at the time of calibration, or any differences must be measured and corrections applied. In practice this is not too difficult for the primary optical elements. However, even small amounts of warm radiation entering the optical path from objects (such as the warm top of the cryostat) whose temperature is not well controlled can compromise the calibration. The presence of such problems can often be detected by a quantitative analysis of data obtained with low calibrator temperatures.

A problem that can arise from the broad bandwidth of infrared detectors is the possibility of imperfect spectroscopy. A Fourier spectrometer can have cross-talk between the channels. Band-pass filters can have out-of-band leakage. These effects can be minimized by careful design and by avoiding the use of high calibrator temperatures whose spectrum is very different from that of the sky.

Measurements of the spectrum of the c.m.b. are strongly influenced by unwanted signals from the sky. Low-frequency measurements (below *ca.* 1 GHz) suffer from confusion with galactic synchrotron radiation. The lowest frequency measurements available thus far are those of Howell & Shakeshaft (1967). They made measurements of the total signal at both 408 and 610 MHz in a direction away from the galactic pole to identify the spectral index of the interfering radiation. The measured spectral index was then used to subtract the unwanted contribution from measurements made at the galactic pole.

The emission from galactic dust will interfere with spectral measurements of the c.m.b. at sufficiently high frequencies, but has not yet been important for experiments that avoid the galactic plane.

A very important source of confusion for the present generation of high-frequency experiments comes from atmospheric line emission. The density and strength of the emission lines increases very rapidly with frequency. Below *ca.* 90 GHz it is possible to make narrow-band observations through atmospheric windows from high mountain sites. The atmospheric contribution is identified by observing the sky temperature as a function of zenith angle and subtracting the component that varies in proportion to the atmospheric path. Although the accuracy of such corrections is limited by the temporal stability of the atmosphere and any angular dependence of the response of the apparatus, useful data have been obtained for conditions under which the atmospheric signal was many times larger than the c.m.b.

For frequencies higher than *ca.* 90 GHz it is necessary to observe from a higher site such as an aircraft, a balloon, a rocket or a satellite. Aircraft have not been used for spectral measurements, probably because of the lack of control of the experimental environment. Our present knowledge of the spectrum above *ca.* 90 GHz comes from balloon measurements. The flexibility of gondola design, the availability of hours of observing time and the relatively low cost have proved attractive to experimenters who wished to develop the novel types of apparatus required for high-frequency spectral measurements. The disadvantages of the balloon platform arise from the residual atmosphere. Large corrections for atmospheric emission become necessary above *ca.* 360 GHz.

Rocket experiments have the great advantage of the complete absence of both atmospheric emission and atmospheric contamination of cold optical surfaces. Relative to balloons, however, there is a significant sacrifice in both observing time and in the flexibility of the experimental environment. Rocket measurements so far have not been as successful as balloon experiments. Eventually the nearly ideal environment of a space satellite will almost certainly provide the best high-frequency measurements of the spectrum of the c.m.b.

An indirect technique has been used for measuring the temperature of the c.m.b., which involves an optical determination of the excitation temperature of CN molecules in cool molecular clouds (Thaddeus 1972; Hegyi *et al.* 1974). The errors involved in this experiment are perhaps easier to evaluate than for direct experiments, so that the measurements should provide firm upper limits for the temperature of the c.m.b. at frequencies given by the ground-state energy level separations of CN. Corrections can be made for local heating of the molecules, but these require an intimate knowledge of the conditions in the molecular cloud. Measurements of this type in principle provide information about the homogeneity of the c.m.b. They were important in establishing the black-body character of the spectrum at high frequencies.

EXPERIMENTAL RESULTS

A selection of measurements of the spectrum of the c.m.b. is shown in figure 2 as a thermodynamic temperature plotted as a function of the logarithm of the frequency. Essentially all of the reported microwave results are shown. Most of these results were obtained rather quickly after the discovery of the c.m.b. by Penzias & Wilson (1965). Except for the use of a liquid helium cooled cold load, the microwave techniques used were essentially conventional. A recent description has been given by Wilkinson (1980) of the evolution of a second generation of microwave experiments to provide accurate data at the high-frequency end of the microwave range.

The history of far-infrared spectral measurements is very different from that of the microwave experiments. Because the importance of thermal emission increases rapidly with frequency, antennas with better sidelobe rejection are required, and more of the apparatus has to be cold. Balloon or rocket platforms are required to avoid the increased atmospheric emission. Most important, the technology to solve these problems had to be developed. Despite heroic efforts, the early experiments were usually incompletely characterized, and sometimes gave obviously erroneous results. Many of these early experiments, however, pioneered techniques that were more successfully used later. This technology development and reasons for favouring certain infrared experiments have been discussed elsewhere by the author (Richards 1980).

Since that discussion, a report has appeared of a new rocket experiment by Gush (1981). The results of this experiment are not included in figure 2 because in my opinion the instrument does not appear to be well characterized. Difficulties that arose because of the appearance of the warm rocket motor in the field of view are well discussed by Gush. Other problems not sufficiently analysed include the accuracy with which the emissivity of the stainless steel calibrator is known, the possibility that radiation from the warm neck of the cryostat could enter the spectrometer during calibration (or during flight), and the apparent presence of such warm radiation in the calibration data.

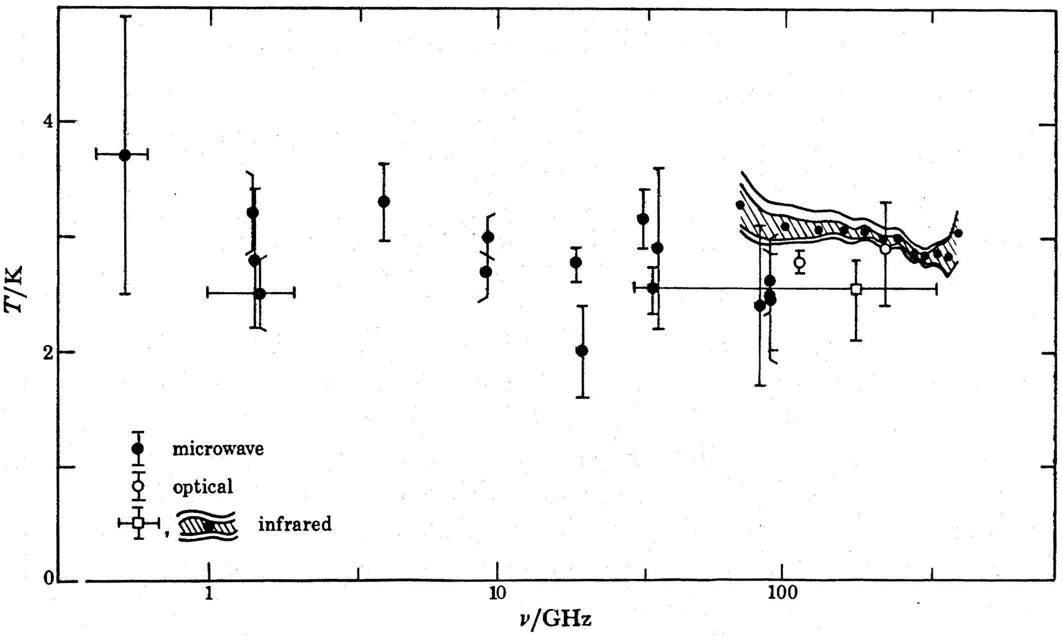

FIGURE 2. A selection of existing measurements of the effective temperature of the c.m.b. as a function of the logarithm of the frequency. The error limits are to be interpreted as ± 1σ. To a first approximation the data can be fitted to a temperature of *ca.* 2.9 K.

Data from only two infrared experiments are included in figure 2. The balloon experiment of Muehlner & Weiss (1973*a*, *b*) used low-pass filters to isolate broad spectral bands. Temperature data are shown for the frequency range from 30 to 300 GHz. This measurement was relatively unaffected by uncertainties in the atmospheric emission, so has narrow error limits. The balloon experiment of Woody & Richards (1981) used a Fourier transform spectrophotometer and thereby obtained 12 data points from 71 to 405 GHz separated by the resolution width of *ca.* 30 GHz. Upper limits were also obtained at points extending to 720 GHz. This experiment shows clearly that the spectrum of the constant-throughput flux of the c.m.b. has a peak at *ca.* 180 GHz and falls at higher frequencies to less than 10 % of the peak value (Woody & Richards 1981). Since the complete data set was obtained simultaneously, certain sources of error are strongly correlated across the spectrum. An error in the overall calibration factor, for example, would shift the entire data set up or down. Other sources of error such as detector noise are uncorrelated from point to point. One point could be shifted up or down relative to its neighbours. The data from this experiment are plotted in figure 2 as a set of points with ± 1σ error limits. The uncorrelated errors are indicated by the shaded region. Correlated errors could have the effect of shifting the shaded region up or down within the limits set by the solid lines.

The data set in figure 2 fits fairly well to a single temperature somewhat below 3.0 K. To a first approximation the spectrum of the c.m.b. is clearly that of a black body. It is tempting to make a detailed statistical analysis of these data. It is important to realize, however, that the new information that can be extracted from such an analysis is very limited. The accuracy of the data may well be strongly affected by systematic errors. The procedures used to set error limits vary from one experimenter to another, especially for experiments of different types. Computing weighted averages is therefore a very subjective process.

Table 1. Various measurements of the c.m.b.

frequency/GHz	temperature/K	technique	reference
0.515–90	$2.77^{+0.13}_{-0.15}$	averaged microwave	Woody & Richards (1981)
114	$< 2.93 \pm 0.06$	excitation of CN	Thaddeus (1972)
30–300	$2.55^{+0.25}_{-0.45}$	infrared filter	Muehlner & Weiss (1973*b*)
227	$< 2.9^{+0.4}_{-0.5}$	excitation of CN	Hegyi *et al.* (1974)
71–405	$2.96^{+0.13}_{-0.08}$, 2.90	infrared spectrophotometer	Woody & Richards (1981)

The set of microwave data was obtained by similar techniques by experimenters with a common tradition. Thus it can be argued that an average of these data weighted by the experimenters' error limits adjusted to $\pm 1\sigma$ should not be seriously in error. The result of this procedure is a fit to temperatures in the range 2.62–2.90 K with normalized χ^2 less than unity. The best fit temperature is 2.77 K (Woody & Richards 1981). This result should be compared with the selection of non-microwave results shown in table 1. The general impression from this comparison and from figure 2 is of a scatter in the high-frequency data that is somewhat larger than would be expected from the stated error limits.

The infrared experiment of Woody & Richards (1981) produced data over a significant spectral range that can be tested for consistency with a best-fit black-body curve. The fit is rather poor. Assuming that the errors are statistical, there is only a 0.3% chance that the data are consistent with a 2.90 K black body. Because of this lack of agreement, the temperature deduced depends on the fitting procedure used. To indicate the range of this variation, the results of two different procedures are given in table 1.

The form of the deviation from a 2.96 K black-body curve is an excess of flux at the peak, but a deficit at higher frequencies. This form is unlikely to arise from experimental problems such as radiation from warm objects or imperfect correction for atmospheric emission. One tantalizing aspect of the data is the fact that arbitrarily reducing the overall calibration factor by 30% brings the data into excellent agreement with a black-body curve at the temperature of 2.77 K given by the weighted average of the microwave data (Woody & Richards 1979). Although no reason for such a large change in calibration factor has been found, the suspicion has arisen that the calibration factor might have been incorrectly measured, or that it might have been different in flight from the laboratory value (Weiss 1980).

The laboratory value of the calibration factor was confirmed from the strength of the atmospheric O_2 lines measured in flight (Woody & Richards 1981), but this confirmation was not entirely convincing for several reasons. These included uncertainties in the theoretical model used for the Zeeman splitting of the O_2 lines, uncertainties in the molecular line parameters, and uncertainties in the instrumental transmission function on a frequency scale comparable with the width of the atmospheric lines. A recent measurement (Pickett *et al.* 1981) of the pressure-broadened width of the 125 GHz O_2 line (when combined with the effects of Zeeman splittings) increases the theoretical estimate of the line strength by 11%. This new estimate of line strength changes the fitted value of the O_2 column density from $1.09 \pm 0.15 \times 10^{22}$ to $0.97 \pm 0.15 \times 10^{22}$ cm^{-2}, which is still consistent with the value 1.03×10^{22} cm^{-1} estimated from the zenith angle, mixing ratio and pressure (Woody & Richards 1981). If a calibration factor based on atmospheric line measurements is used, the effect of the new parameter value is to increase the measured flux of the c.m.b. and thus to increase the discrepancy between these data and the average temperature deduced from the microwave measurements.

Deviations from a black-body spectrum

As has been discussed above, the Woody–Richards (1981) experiment deviates from a black-body spectrum by more than is expected from the known experimental uncertainties. The deviation is in the form of excess radiation near the peak of the spectrum. Depending on the weighting assumed, the averaged results of all experiments can be interpreted in terms of an excess in this same region. Deviations from the Planck curve are expected at some level, and their observation is of highest importance for the refinement of cosmological models.

Compton scattering of the c.m.b. by 'hot' electrons, radiation damping of turbulence, and annihilation of matter and antimatter are some of the mechanisms that could lead to deviations from a black-body spectrum (Zel'dovich *et al.* 1972). The net result of these mechanisms is to scatter low-energy photons to higher energy and hence to shift the peak in the spectrum to higher frequencies. These models do not fit the data as well as a simple Planck curve (Woody & Richards 1981).

Models of the c.m.b. that do not involve establishing complete thermal equilibrium, or which use frequency-dependent emission processes, are relatively unconstrained and can be made to fit the observations. Rowan-Robinson *et al.* (1979) have carried out calculations by using the red-shifted dust features from a pre-galactic generation of stars to increase the c.m.b. in the 3–8 cm^{-1} frequency range relative to that on either side of this range. They obtained a satisfactory fit to at least one plausible weighted average of the observations by this theory.

The fact that a fit can be obtained should not be interpreted as theoretical evidence for the suggested deviation. The question of a deviation must be answered experimentally. The evidence so far available should be regarded as suggestive, but not conclusive.

New experiments

Although the general black-body character of the c.m.b. is now well established, experimental interest in measurements of the spectrum remains high. A new generation of experiments is being developed to search for deviations from a black-body spectrum at both microwave and infrared frequencies.

Mountain-top microwave observations are being planned at frequencies of 2.5, 5, 10, 30 and 100 GHz by a collaboration involving groups from Milan, Bologna, Haverford and Berkeley. Balloon experiments are planned by the Princeton group at microwave frequencies for which mountain-top atmospheric emission is important.

A new infrared experiment is being developed at Berkeley which is designed to be significantly different from the Woody–Richards experiment. Instead of a Fourier spectrometer, band-pass filters will be used at frequencies of 90, 150, 210, 270 and 300 GHz. The residual atmospheric emission at balloon altitude will be removed by scanning zenith angle, rather than by fitting calculated atmospheric spectra. Most important, calibration will be done during the flight with a Dicke switch and a reference black body whose temperature can be varied from 2 to 15 K. A 250 K reference will also be available in flight.

A Far Infrared Absolute Spectrophotometer (FIRAS) has been designed at the Goddard Space Flight Center for the Cosmic Background Explorer Satellite (COBE) which is expected to be launched in 1988. This experiment uses identical pairs of Winston light concentrators as antennas at both inputs of a symmetrical Michelson polarizing interferometer. One input views the sky, the other a reference black body. Since the output of the interferometer is proportional to the difference between the two inputs, it acts as a Dicke switch to provide absolute calibration. Additional calibration is provided by a cold black body, which can be deployed in front of the sky horn. In one year the instrument is designed to map the sky over the frequency range from 30 GHz to 3 THz with a 7° field of view.

At Queen Mary College a balloon experiment is being constructed that also uses a Michelson polarizing interferometer as a Dicke switch to compare signals from the sky with those from a black enclosure. Two microwave ridged-horn antennas are used back-to-back to limit the beam entering the spectrometer to a single electromagnetic mode. The frequency coverage will be restricted to the neighbourhood of the peak of the c.m.b.

With this high level of experimental activity our knowledge of the spectrum of the c.m.b. is expected to improve dramatically in the next 5–7 years.

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REFERENCES

Danese, L. & De Zotti, G. 1977 *Nuovo Cim.* **7**, 277–363.
Danese, L. & De Zotti, G. 1978 *Astron. Astrophys.* **68**, 157–164.
Gush, H. P. 1981 *Phys. Rev. Lett.* **47**, 745–748.
Hegyi, D. J., Traub, W. A. & Carleton, N. P. 1974 *Astrophys. J.* **190**, 543–544.
Howell, T. F. & Shakeshaft, J. R. 1967 *Nature, Lond.* **210**, 1318–1319.
Muehlner, D. & Weiss, R. 1973*a* *Phys. Rev.* **D7**, 326–344.
Muehlner, D. & Weiss, R. 1973*b* *Phys. Rev. Lett.* **30**, 757–760.
Penzias, A. A. & Wilson, R. W. 1965 *Astrophys. J.* **142**, 419–421.
Pickett, H. M., Cohen, E. A. & Brinza, D. E. 1981 *Astrophys. J. Lett.* **248**, L49–L51.
Richards, P. L. 1980 *Physica Scr.* **21**, 610–613.
Rowan-Robinson, M., Negroponte, J. & Silk, J. 1979 *Nature, Lond.* **281**, 635–638.
Thaddeus, P. 1972 *A. Rev. Astr. Astrophys.* **10**, 305–334.
Weiss, R. 1980 *Rev. Astr. Astrophys.* **18**, 489–535.
Wilkinson, D. T. 1980 *Physica Scr.* **21**, 606–609.
Woody, D. P. & Richards, P. L. 1979 *Phys. Rev. Lett.* **42**, 925–929.
Woody, D. P. & Richards, P. L. 1981 *Astrophys. J.* **248**, 18–37.
Zel'dovich, Ya. B., Illarionov, A. F. & Sunyaev, R. A. 1972 *Zh. eksp. teor. Fiz.* **62**, 1217–1227. (English transl. in *Soviet Phys. JETP* **35**, 643–648 (1972).)

Discussion

R. FABBRI (*Istituto di Fisica Superiore, Università di Firenze, Italy*). I do not understand why it may be argued that Professor Richards's experiment does not provide a substantial number of really independent data points.

P. L. Richards. Certain sources of error, such as detector noise, affect individual data points independently. Other sources of error, such as the overall calibration factor, affect all data points in the same way. Therefore a correct statistical analysis of our data must treat these two types of error differently, as was done in our paper in the *Astrophysical Journal*.