# MEASUREMENTS OF THE COSMIC BACKGROUND RADIATION TEMPERATURE AT 6.3 CM

N.MANDOLESI,P.CALZOLARI,S.CORTIGLIONI AND
G.MORIGI
Istituto TESRE/CNR Bologna,Italy

L.DANESE AND G.DE ZOTTI

Istituto di Astronomia Padova,Italy

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N. MANDOLESI, P. CALZOLARI, S. CORTIGLIONI, AND G. MORIGI
Istituto TESRE/CNR, Bologna, Italy

AND

L. DANESE AND G. DE ZOTTI
Istituto di Astronomia, Padova, Italy

## ABSTRACT

We report on new measurements of the cosmic background radiation (CBR) intensity at 4.75 GHz (6.3 cm), made as a part of a large experiment to measure the CBR spectrum between 2.5 and 90 GHz. The present results, $T_{CBR} = 2.70 \pm 0.08$ K, agree with, but are substantially more accurate than, those previously reported by Mandolesi et al. (1984). We also present and discuss careful new observations of the emission from the atmosphere and from the Galaxy.

Subject headings: cosmology - cosmic background radiation

# I. INTRODUCTION

It is well known that energy dissipation occurring at $z > z_1 = 6\cdot 10^4 (H_o/50)^{-1}\Omega_b^{-1/2}$ ($H_o$ = Hubble constant; $\Omega_b$ = baryon density in units of the critical density) results in distortions of the cosmic background radiation (CBR) spectrum, mostly confined to the Rayleigh-Jeans region (Sunyaev and Zeldovich 1970).

Theory predicts the distortion to have a broad maximum at a wavelength depending on $\Omega_b$ and always > 3 cm for $\Omega_b \leqslant 1$ (Illarionov and Sunyaev 1974; Danese and De Zotti 1980). Thus there is a great deal to be learned about the early history of the universe from accurate measurements of the CBR spectrum at cm wavelengths.

We report here on new observations at 6.3 cm (4.75 GHz) carried out in September 1983 as a part of a wide collaborative effort to determine the CBR spectrum over the wavelength range 0.3 - 12 cm (Smoot et al. 1983; 1985). The new observations are a continuation of the work done in summer 1982 and reported by Mandolesi et al. (1984). Taking advantage of the experience gained in the earlier work, the equipment and the experimental technique were improved and a substantially better accuracy was achieved.

# II. CONCEPT AND DESIGN OF THE EXPERIMENT

## a) Instrumental configuration

The intensity of the CBR in the Rayleigh-Jeans region is measured by comparing the antenna temperature of the zenith sky with that of an absolute reference blackbody load kept at liquid helium temperature (we recall that the antenna temperature $T_A$ is related to the radiation brightness $i_\nu$ by the equation: $T_A = i_\nu \lambda^2/2k$).

The difference $\Delta T_A$ between the antenna temperatures measured when the radiometer is pointed at the zenith and when it is pointed at the cold load is:

$$\Delta T_A = T_{A,zenith} - T_{A,CL} - \Delta T_{offset} \qquad (1)$$

where $\Delta T_{offset}$ is a term which allows for changes in radiometer output caused by rotation of the antenna.

The cold load has been described in a previous paper (Smoot et al. 1983). Its antenna temperature $T_{A,CL}$ is computed converting to antenna temperature the liquid helium boiling temperature at the pressure measured in the dewar ( 3663±4 mK) and adding the contribution from windows (5±2 mK) and walls ( 8±7) of the dewar and from the radiometer as reflected by the cold load ( 6±4 mK: cfr. also table 1 in Smoot et al. 1985). Summing up we find:

$$T_{A,CL} = 3.682 \pm 0.010 \text{ K} . \qquad (2)$$

Taking into account that $T_{A,zenith}$ is the sum of contributions of the CBR, the Galaxy, the ground (intercepted by the antenna sidelobes) and the atmosphere, and solving for $T_{A,CBR}$ we find:

$$T_{A,CBR} = \Delta T_A - T_{A,CL} - T_{Gal} - T_{ground} - T_{atm} - \Delta T_{offset} . \qquad (3)$$

The careful experimental strategy (cf. Smoot et al. 1983; 1985) minimizes unwanted radiations entering the receivers and accurately determines residual contributions.

The configuration of the 6.3 cm radiometer as employed in 1982 and described by Mandolesi et al. (1984) was modified to improve the accuracy of the measurements and to make its operation easier . The new configuration (Fig. 1) is similar to that of the 3 cm radiometer used in the collaboration (Friedman et al. 1984). This change has allowed both much better statistics on the zenith-cold load measurements and rapid atmospheric scans. Special care was taken in constructing the rotating part (receiver and antennas) in order to minimize instrumental flip-offsets which represented the largest source of error in the 1982 measurements.

The two antennas, already used in 1982, were corrugated horns with 12°.5 HPBW and very low sidelobes (Bielli et al. 1983). To further reduce the sidelobe reception of ground radiation, ground shields of wire screen were employed around the 45° reflector and, during the atmospheric scans, around the main antenna. The residual contribution of the ground radiation has been computed taking into account the response functions of the antennas and the profile of the ground.

The addition of a reflector, mounted at 45°, redirecting the reference antenna beam toward the zenith, results in a partial linear polarization of the incoming radiation. Since the feed of the antenna accepts only one linear polarization state, there is a modulation of the signal intensity as a function of the radiometer rotation position (cf. Friedman (1984) for a detailed discussion). To correct for this effect a teflon septum was installed in the cylindrical waveguide feed of the antenna. The septum acts as a quarter wave plate converting part of the linear into circular polarization thus reducing the dependence of the reference signal on the position angle. Laboratory tests were made to determine the residual linearly polarized contribution: it turned out to be 22 mK at 45° zenith angle. The appropriate corrections for this effect on the data from zenith angle scans have been taken into account.

In addition, in 1983, a small horn antenna looking at the sky replaced a 300 K load previously matching the third port of the circulator (Fig. 2). This configuration decreases by a factor ≈10 the noise emitted through the main antenna and hence reflections from the cold load calibrator. Thus frequent VSWR measurements were not necessary.

The receiver is of a Dicke type having an overall noise figure of 3 db, corresponding to a system noise temperature $T_{sys}$ = 300 K and a RF bandwidth of 160 MHz: with a 10 second integration time the minimum detectable signal is $\Delta T_{min} = 0.017$ K and the peak to peak noise is $\Delta S = 0.085$ K.

All parts of the receiver were connected together and with the antennas without using unnecessary waveguides or cables and were mounted on a one-piece aluminum slab which guaranteed the necessary mechanical stiffness, a uniform temperature distribution and a proper electrical ground reference. The internal temperature was continuously monitored and was constant to within ± 0.1 K.

Moreover the receiver box was magnetically shielded to reduce by a factor $\simeq 10^4$ the effect of the terrestrial magnetic field on the ferrite components of the receiver during rotation of the receiver and antenna.

The gain of the radiometer, monitored through systematic eccosorb calibrations varied by less than 0.6% during each run. Since the difference between the zenith and the cold load antenna temperatures was small, this caused a negligible error in the final result.

### b) Tests

Several tests were carried out to check the performance of the radiometer and to estimate the unwanted signals entering the antennas.

First, we needed to estimate the changes in the radiometer's output depending on its orientation ("flip offsets"). Flip tests were made placing a liquid nitrogen cooled slab of Eccosorb CW-12 on the main antenna; the result was

$$\Delta T_{offset} = 0. \pm 0.020 \text{ K.} \qquad (4)$$

The data supplied by the factory which built the hornes (CSELT) on the VSWR of the antennas were complemented by measurements made during the experiment with the main antenna pointed towards the zenith and coupled to the liquid He calibrator. The noise reflected back by the absolute calibrator was measured to be 6 ± 4 mK.

As a check on side- and back-lobe pickup, additional screens were alternately introduced and removed and the corresponding variations of the radiometer otput were compared with those predicted by simulations. In this way a residual contribution from the ground of 20 ± 10 mK has been estimated for the case when the main antenna looks at the zenith.

Four temperature sensors were placed along the main antenna, to monitor continuously its thermal condition during the coupling with the liquid He cold load. The temperature along the walls of the antenna was constant to within ± 0.5 K during each measurement run.

Before and after each liquid He run several tests were made using liquid nitrogen to check the linearity of the receiver; deviations from linearity were $\leq 5\%$.

## III. GALACTIC EMISSION

To minimize the galactic contribution care was taken to make the absolute measurements when the zenith direction did not intersect the galactic plane. Away from the plane the expected galactic contribution ($T_{Gal}$) to the zenith antenna temperature at 4.75 GHz is only of a few tens of mK.

To compute $T_{Gal}$ as a function of position on the sky we used the all sky maps produced by Witebsky (1982) which take into account both synchrotron radiation and thermal emission from HII regions (concentrated in the galactic plane). The synchrotron contribution was derived from the 408 MHz all sky survey data of Haslam et al. (1982) assuming a spectral index $\alpha_S = 0.8$. The contribution of HII regions was estimated from a list of such sources compiled by Witebsky (1978); a spectral index $\alpha_H = 0.1$ was used in this case. We convolve the galactic emission with the response function of our antenna.

Witebsky's (1982) results were checked by comparison with those of the radio continuum survey of the northern sky at 1420 MHz by Reich (1982) and with the observations of the galactic transit at 2.5 GHz (Sironi et al. 1984). There was good agreement with both. Assuming $T_{CBR}$ = 2.73 K and a spectral index of 0.7 we found Witebsky's and Reich's results to differ by no more than a few mK for all regions covered by our observations (where HII emission is always negligible). Witebsky's maps also agree to better than 10% with the 2.5 GHz measurements of the galactic profile by Sironi et al. (1984).

As a further check, the profile of the galactic plane at 4.75 GHz was measured in both 1982 and 1983. The results of the former observations were reported by Mandolesi et al. (1984); the 1983 data are shown in Fig. 4.

The two sets of data on the galactic emission at 4.75 GHz do not fully agree with each other. A discrepancy of 50 mK at the peak of the galactic emission is found, to be compared with an estimated experimental uncertainty of 30 mK. The origin of this discrepancy is unclear. We note, however, that Witebsky's model nicely fits our 1983 data (Fig. 3).

As already mentioned, our CBR measurements were made when the position of the Galaxy on the sky was such to ensure a low galactic contribution to the zenith antenna temperature. Table 1 lists days and hours (U. T.) of our 1983 observations together with the average values of $T_{Gal}$ predicted by the model and the associated uncertainties. The latter have been assumed to amount to 100% if $T_{Gal} \leqslant 25$ mK and to 70% otherwise; these are conservative estimates generously allowing for the errors in both the calibration of the data of Haslam et al. (1982) and Reich (1982), and in the spectral indices used to extrapolate the data to our frequency. The resulting average contribution of the galaxy is $T_{Gal} = 30 \pm 25$ mK.

## IV. ATMOSPHERIC CONTRIBUTION

An accurate determination of the atmospheric contribution to the zenith antenna temperature is an essential condition for successsful ground based measurements of the CBR intensity. Even for the high altitude, dry site chosen for oservations and in clear weather conditions the atmosphere is the most important source of the unwanted signal.

In comparison with previous measurements of the CBR spectrum, a substantial improvement in the determination of $T_{atm}$ could be achieved in our collaborative experiment taking advantage of the results of atmospheric scans made by all six radiometers operating at White Mountain, utilising the atmospheric emission theory. In particular, the consistency of the observations at all six wavelengths with each other and with the predictions of the best current atmospheric models corroborates our error estimates and gives us confidence that we are not overlooking important systematic effects. A full discussion of the atmospheric measurements will be presented in a forthcoming paper (Danese et al. 1985).

In our experiment the dominant contribution to the atmospheric emission at 4.75 GHz is, by far, that of $O_2$ ($T_{O_2} = 950$ mK); water vapor contributes only 10 - 20 mK (cf. Partridge et al. 1984). It is well known that $O_2$ can be safely assumed uniformly mixed (Mc Clatchey et al.,1972) . This assumption eases the determination of $T_{atm}$ based on the increase in the observed signal with increasing zenith angles. In deriving $T_{atm}$ we did not use the simple secant law, but took into account the effects of the earth's curvature, and of atmospheric self absorption, and we convolved the beam pattern with the atmospheric profile.

In 1982 our instrument did not easily make fast atmospheric scans.

Mandolesi et al. (1984) adopted a vertical atmospheric antenna temperature, $T_{atm}$ = 1000 ± 100 mK, obtained from an educated extrapolation of the observations at 2.5, 9.5 and 10 GHz. In 1983 measurements were made at 30° and 45° E and W of the zenith. Since, in computing $T_{atm}$, observations at 45° have a much larger statistical weight than those at 30°, it was important to shield the antenna carefully from the ground (see Sect. II).

Our atmospheric scans were made on the same days (September 5 and 6) as the measurements of the CBR temperature. All observations were carried out in clear weather conditions. Measurements with a solar hygrometer during daylight hours and atmospheric measurements at 33 and 90 GHz (where $T_{atm}$ depends strongly on water vapor emission) converge in indicating a precipitable water vapor content ranging from 2.5 to 4 mm in our observing conditions (see Danese et al. 1985). If so, the variable water vapor contribution at our frequency is always negligibly small and it is meaningful to derive an average $T_{atm}$ analyzing all our 101 data points together.

The distribution of these data (Fig. 4) is well represented by a gaussian with $\langle T_{atm} \rangle$ = 997 mK and a standard deviation $\sigma$ = 104 mK; hence the statistical error on the mean is 11 mK. The Kolmogorov-Smirnov test gives a maximum deviation $D_m$ = 1.1, corresponding to a 20% probability of incorrectly rejecting a gaussian data distribution.

The true uncertainty on $T_{atm}$, however is larger than the statistical 11 mK because of the possibility of systematic errors. The largest uncertainty comes from "flip offsets". As mentioned in Sect. II, the flip test yielded an uncertainty in the vertical antenna temperature of 20 mK. This translates into an uncertainty of ≈ 20 mK/(1 − sec 45°) ≈ 50 mK in $T_{atm}$ since the latter is determined essentially on the basis of measurements made at a 45° zenith angle.

An additional instrumental effect was found to be related to the quarter-wave plate. On September 5 we made 29 atmospheric scans with the plate rotated by 90°; the resulting $<T_{atm}>$ turned out to be 40 mK higher than the mean of the other measurements.

Adding in quadature all the above uncertainties we get a total error on $T_{atm}$ of 70 mK. We note, however, that the above is likely to be quite a conservative estimate since part of the flip asymmetry may be due to the quarter-wave plate in the feed of the secondary antenna (Friedman 1984). An extrapolation to 4.75 GHz of the measurements at 2.5, 9.4 and 10 GHz, guided by the atmospheric emission theory, gives $T_{atm}$ = 975 mK, again suggesting that our estimated error in $T_{atm}$ is quite conservative.

Our determination of $T_{atm}$ is very interesting also in connection with atmospheric emission theory. Indeed observations made at our frequency (as well as those made at 2.5, 9.4 and 10 GHz) and with our experimental conditions are ideal to single out the non-resonant continuum emission of $O_2$ (all other contributions to $T_{atm}$ are smaller by at least a factor of 30) and hence to experimentally determine its spectrum (Partridge et al. 1984; Danese et al. 1985).

## V. RESULTS AND CONCLUSIONS

Listed in Table 2 are the results of the 36 independent measurements of the CBR antenna temperature, $T_{A,CBR}$, carried out on September 5 and 6, in clear sky conditions.

Figure 5 shows the histogram of these data, which is well fitted by a gaussian with $<T_{A,CBR}>$ = 2.59 K and a standard deviation $\sigma$ = 0.08 K. The Kolmogorov-Smirnov test gives a maximum deviation $D_m$ = 0.61 and an associated probability of 80% of incorrectly rejecting a gaussian distribution.

Table 3 summarizes our averaged results for all quantities needed to determine $T_{A,CBR}$ (see eq.2), together with their errors, which include both systematic and statistical uncertainties added in quadrature. The final result is $T_{A,CBR} = 2.59 \pm 0.08$ and, in terms of thermodynamic temperature we get

$$T_{CBR} = 2.70 \pm 0.08 \text{ K}. \qquad (5)$$

The remarkable improvement in accuracy, compared with the earlier results $T_{CBR} = 2.73 \pm 0.22$ K (this value slightly differs from $T_{CBR} = 2.71 \pm 0.2$ previously reported by Mandolesi et al. 1984, because of a more accurate estimate of the load contribution), was obtained by a drastic reduction of the flip asymmetry and, hence, of the associated uncertainty, and by an accurate determination of the atmospheric antenna temperature at the zenith.

We stress that further improvements in the accuracy of $T_{atm}$, and hence of $T_{CBR}$, at 6.3 cm appear to be achievable by future measurements. As discussed in Sect. IV, atmospheric variability is not a problem in a high altitude, dry site such as White Mountain. What is needed is a more accurate determination of $\Delta T_{offset}$ and of the effect of the quarter wave plate; also, simply carrying out observations at angles larger than 45° would result in a decrease of the uncertainty in $T_{atm}$, provided, of course, that the radiometer is carefully shielded.

The weighted average of the measurements of all radiometers operating at White Mountain is $T_{CBR} = 2.73 \pm 0.05$ K (Smoot et al. 1985); in other words the CBR temperature in the Rayleigh-Jeans region has been determined to better than 2%. Correspondingly, the constraints on the early thermal history of the universe have been effectively strengthened, forthcoming measurements at and beyond the peak.

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# FIGURE CAPTION

Fig. 1 - A sketch of the 6.3 cm radiometer used in 1983.

Fig. 2 - Schematic layout of the 6.3 cm receiver.

Fig. 3 - 1983 transit scans of the galactic plane at 6.3 cm made at White Mountain (latitude= 37.5°). Observations made on September 5(crosses) and 6 (full dots) are shown with model predictions.During the measurements the main antenna pointed toward the zenith and the reference antenna toward declination $\delta = 82.5°$. The zero point for the data has been fixed by the condition $\Delta T_{Gal} = 0$ for the two points most distant from the galactic plane. Typical observational errors statistical plus systematic added in quadrature) are displayed.

Fig. 4 - Histogram of the atmospheric scan data measured on September 5 and 6. The best fit gaussian having $<T_{atm}> = 997$ mK and $\sigma = 104$ mK is also shown.

Fig. 5 - Histogram of the Cosmic Background Radiation antenna temperature with the best fit gaussian having $<T_{atm}> = 2.59$ K and $\sigma = 0.08$ The data were obtained from four liquid helium runs made on September 4. 5 and 6. 1983.

## TABLE 1

GALACTIC CONTRIBUTIONS TO THE ZENITH ANTENNA TEMPERATURE (mK)

| Run | Day | U. T. | $T_{Gal}$ |
|---|---|---|---|
| I | Sept. 4 | 9:16-10:17 | 15±15 |
| II | Sept. 5 | 2:44- 3:30 | 34±25 |
| III | Sept. 5 | 8:02- 8:45 | 20±20 |
| IV | Sept. 6 | 4:04- 4:42 | 42±30 |

## Table 2

RESULTS OF INDIVIDUAL MEASUREMENTS EXPRESSED AS ANTENNA TEMPERATURES (mK)[a]

| Run I | | Run II | | Run III | | Run IV | |
|---|---|---|---|---|---|---|---|
| $\Delta T_A$ | $T_{A,CBR}$ | $\Delta T_A$ | $T_{A,CBR}$ | $\Delta T_A$ | $T_{A,CBR}$ | $\Delta T_A$ | $T_{A,CBR}$ |
| -115 | 2535 | -131 | 2539 | -12 | 2587 | 34 | 2646 |
| -243 | 2407 | -58 | 2612 | 33 | 2632 | -36 | 2576 |
| -171 | 2479 | -30 | 2640 | -98 | 2501 | -109 | 2503 |
| -213 | 2437 | -28 | 2642 | 131 | 2730 | -81 | 2531 |
| -76 | 2574 | -26 | 2644 | 21 | 2620 | 15 | 2627 |
| -91 | 2559 | 54 | 2724 | 50 | 2649 | 45 | 2567 |
| -95 | 2555 | -32 | 2638 | -4 | 2595 | ... | ... |
| -118 | 2532 | -19 | 2651 | 13 | 2612 | ... | ... |
| ... | ... | 26 | 2696 | 32 | 2631 | ... | ... |
| ... | ... | -58 | 2612 | -28 | 2571 | ... | ... |
| ... | ... | 69 | 2739 | 38 | 2637 | ... | ... |

[a] The atmospheric contribution is, to a good approximation, constant during each run. The average values of $T_{atm}$ are: 997 mK, for run I; 958 mK for run II; 1043 mK for run III; 1008 mK for run IV. The values of $T_{Gal}$ appropriate to each run are listed in Table 1. $T_{ground}$ is 20 mK, $T_{A,CL}$ is 3682 mK.

## Table 3

SUMMARY OF RESULTS EXPRESSED AS ANTENNA TEMPERATURES (mK)

| $T_{A,CL}$ | $\Delta T_A$ | $\Delta T_{offset}$ | $T_{ground}$ | $T_{atm}$ | $T_{Gal}$ |
|---|---|---|---|---|---|
| 3682 | -45 | 0 | 20 | 997 | 35 |
| ±10 | ±13 | ±20 | ±10 | ±70 | ±25 |

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# ADDRESSES OF THE AUTHORS

P. CALZOLARI, S. CORTIGLIONI, N.MANDOLESI, and G. MORIGI: Istituto TESRE/CNR, Via dei Castagnoli, 1 I-40126 Bologna, Italy

L. DANESE and G. DE ZOTTI: Istituto di Astronomia, Vicolo dell'Osservatorio, 5 I-35122 Padova, Italy

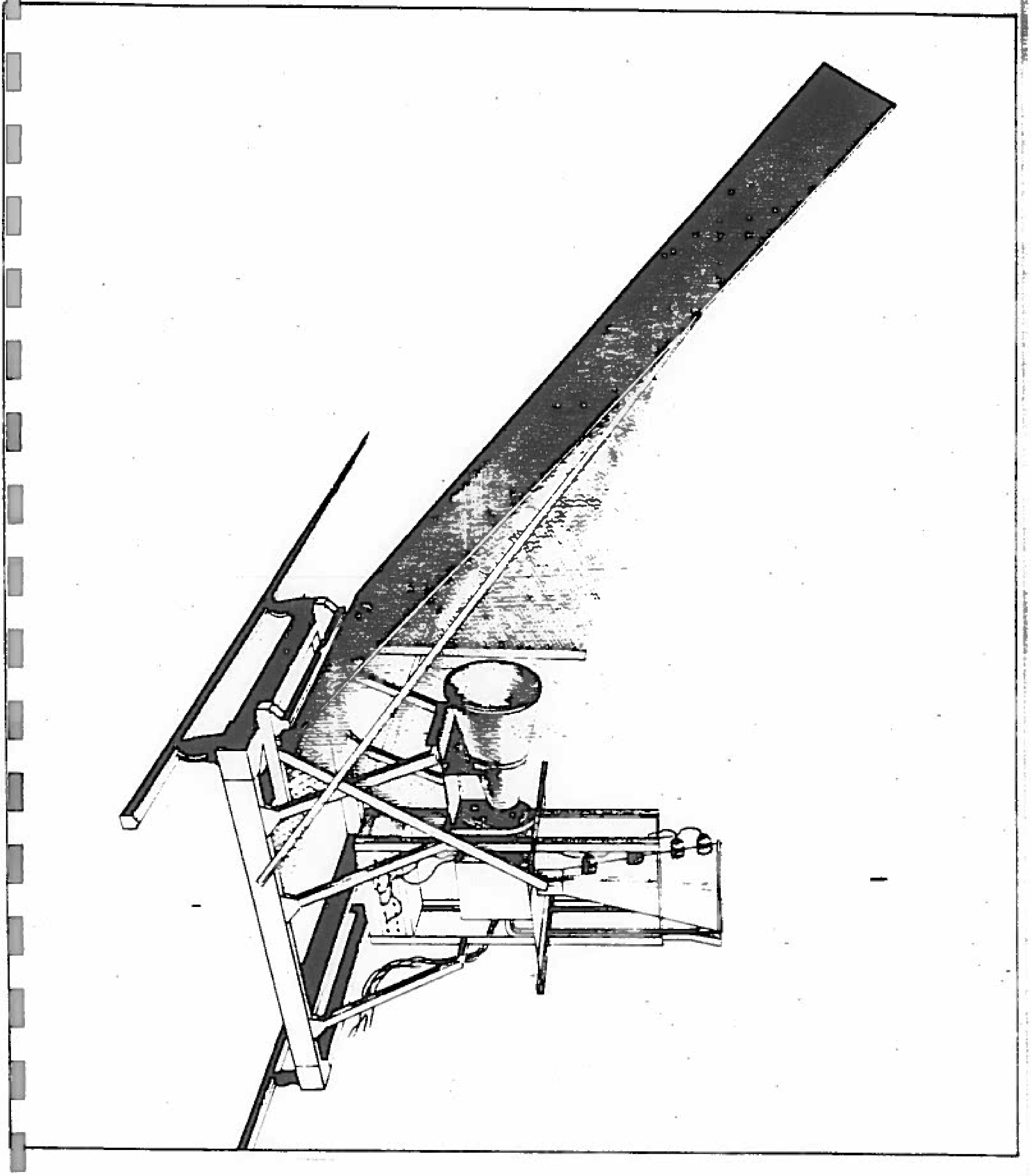

Fig. 1

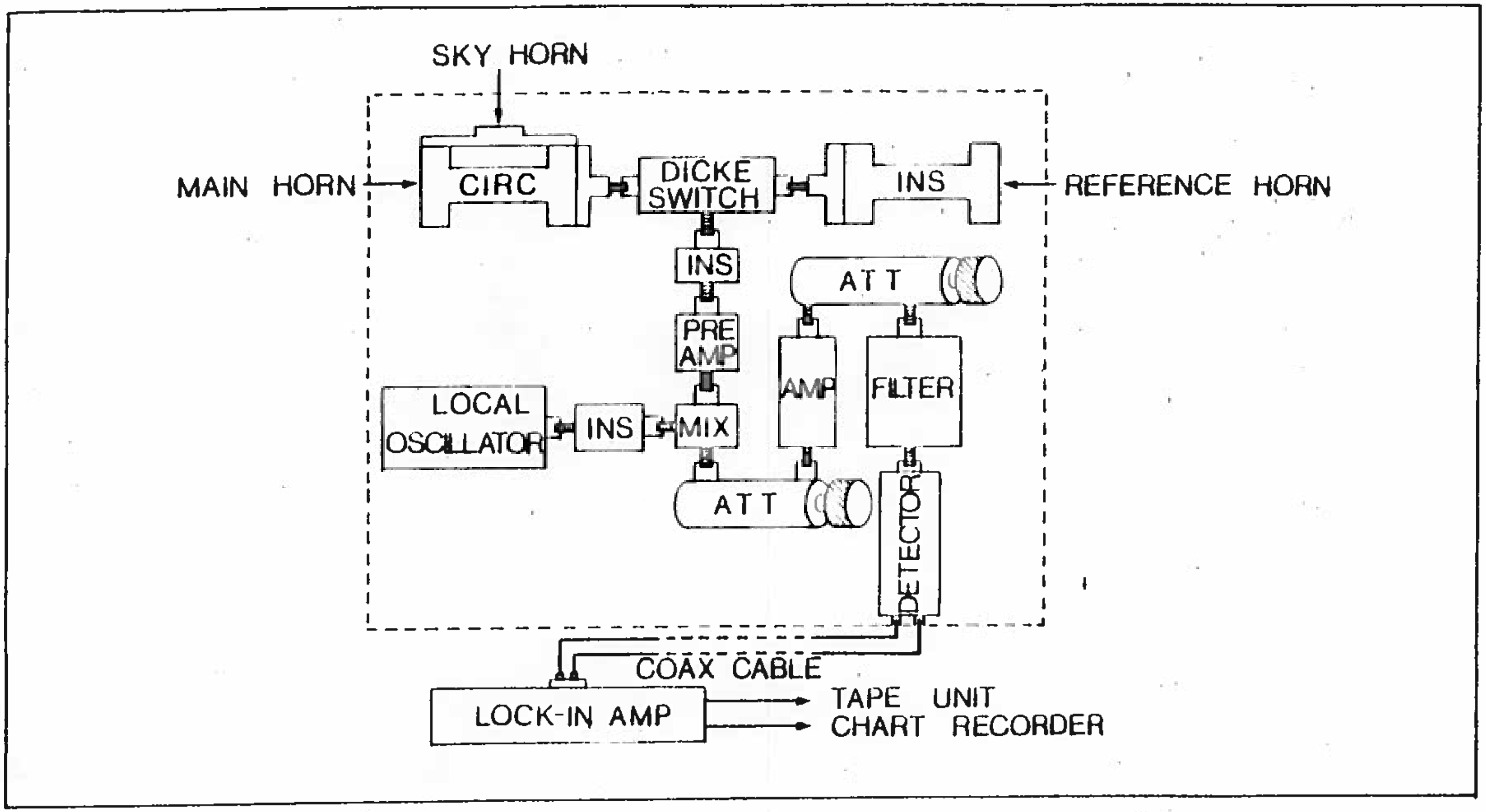
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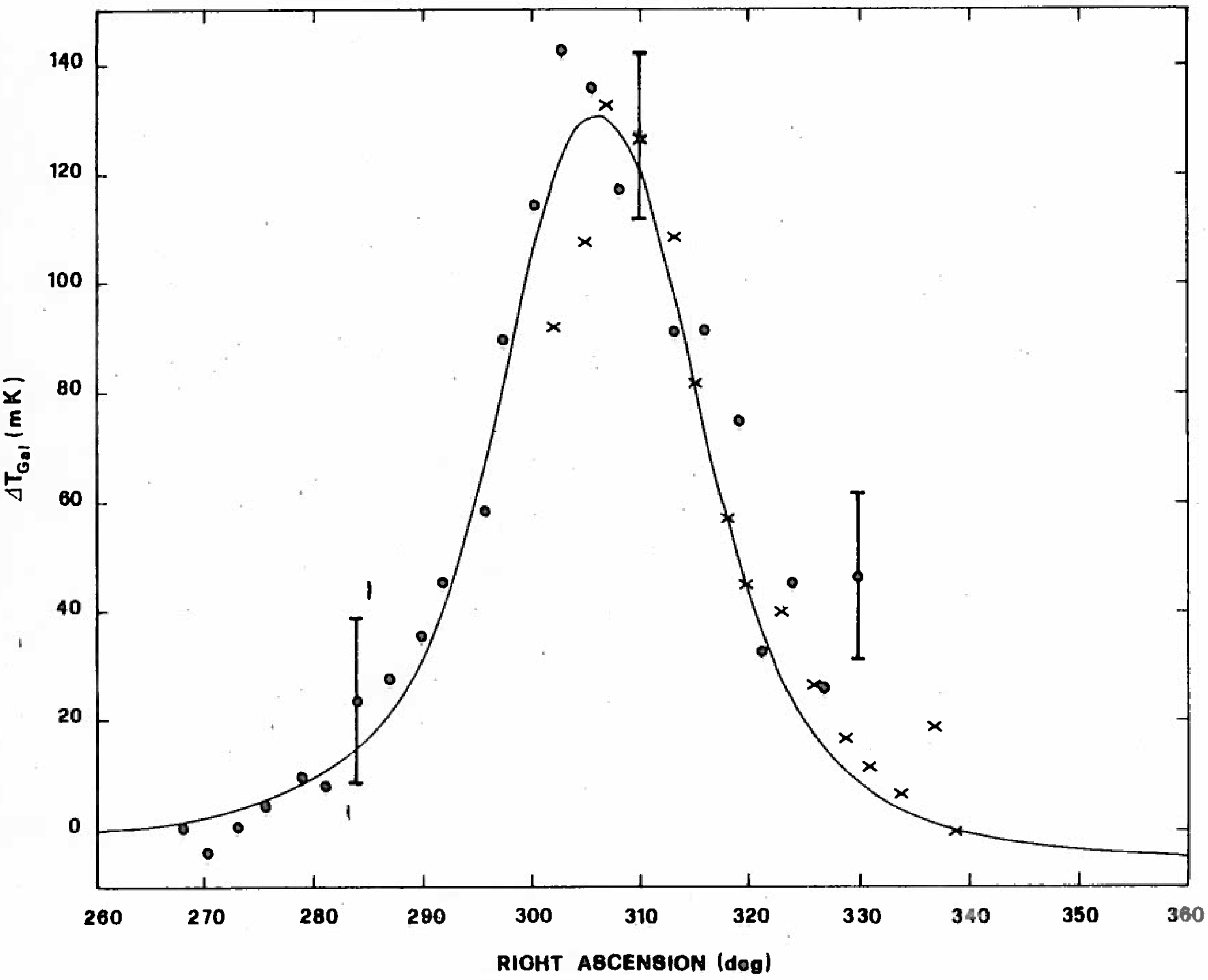
CHART RECORDER

Fig. 2



$\Delta T_{Gal}$ (m K)
0
20
40
60
80
100
120
140
260
270
280
290
300
310
320
330
340
350
360
RIGHT ASCENSION (deg)

Fig. 3

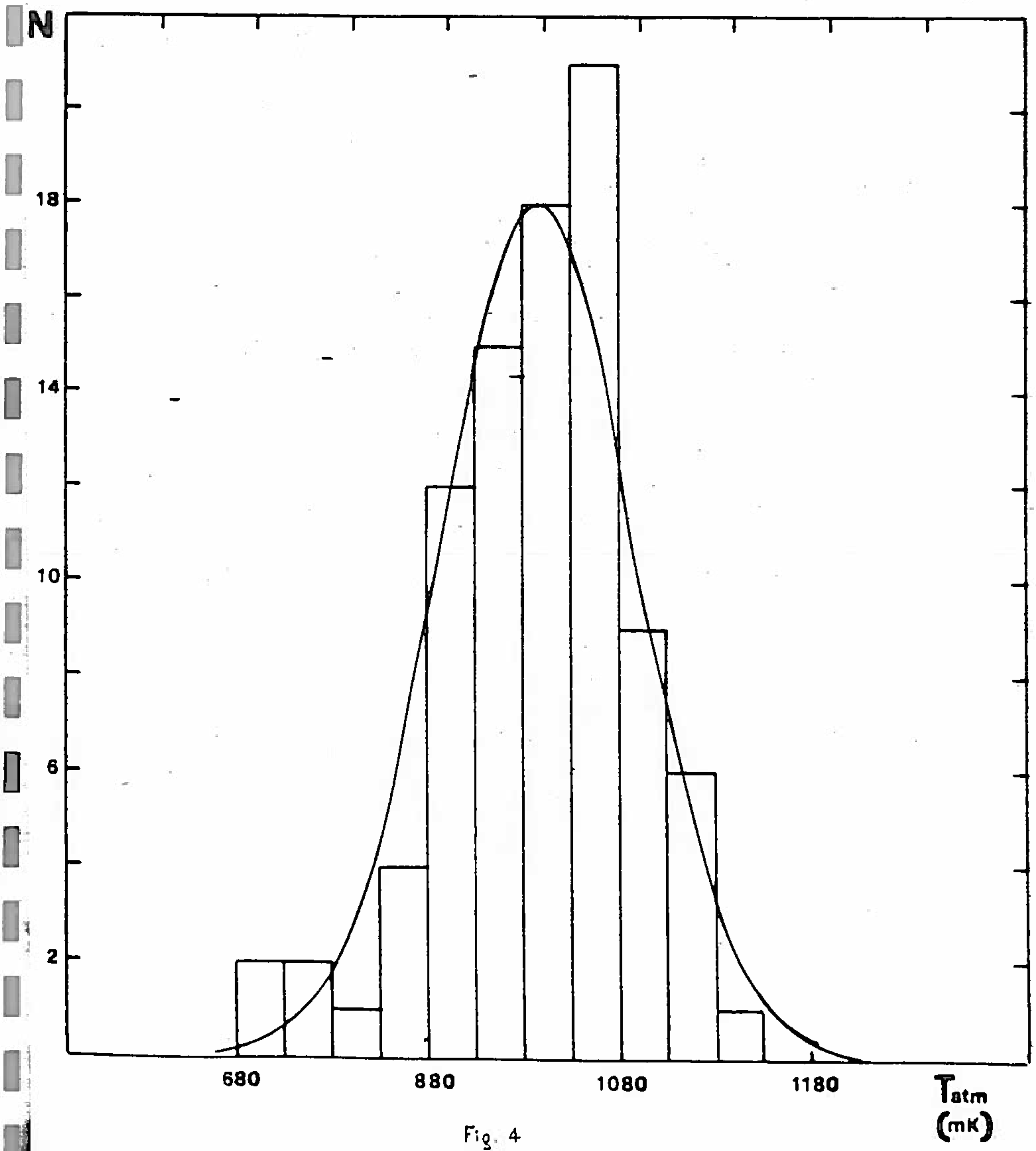


Fig. 4

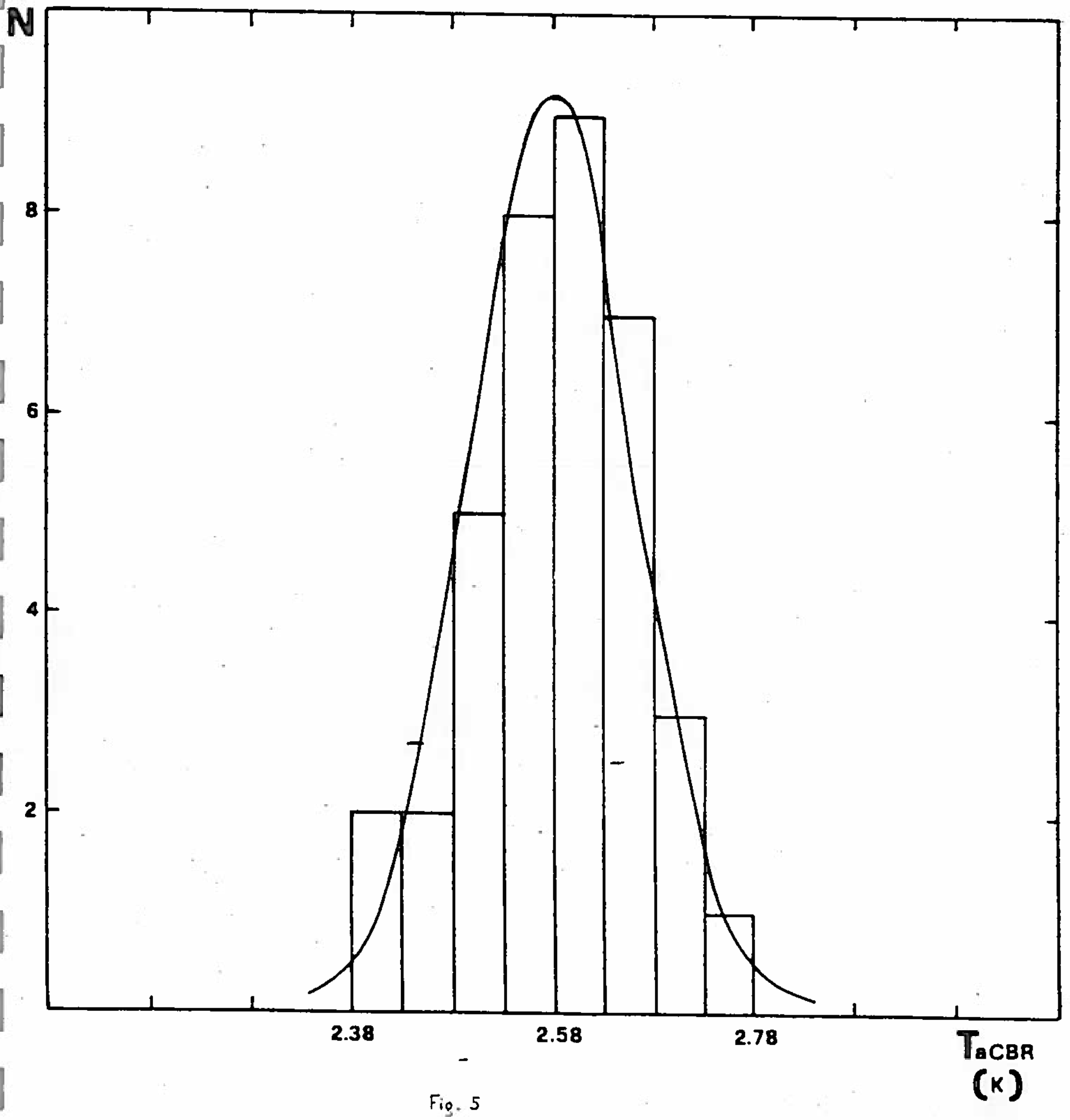


Fig. 5