

Astrophysics 405 Homework Assignment 3

The Cosmic Microwave Background Radiation Temperature

Work in groups of 2-4.

Due 1999 April 15

Consult Fred Babbott (SB 518; 220-5411) for observing assistance.

In this laboratory exercise, you will use the radio telescope on the roof of Science B to measure the intensity of the Cosmic Microwave Background Radiation (CMBR). The standard Big Bang model explains the CMBR as redshifted thermal radiation that decoupled from the matter in the Universe when temperatures dropped far enough for hydrogen atoms to become neutral. For their discovery of the CMBR in 1964, Arno Penzias and Robert Wilson were awarded the 1978 Nobel Prize for Physics.

The CMBR is isotropic to a very high degree (one part in 10^3). At wavelengths in the cm range, it is brighter than other forms of radiation when averaged over the sky. At longer wavelengths, the synchrotron radiation from the Galaxy dominates, while at shorter wavelengths, the Earth's atmospheric emission is much stronger than the CMBR. You will make your measurements in the middle of this window, at a wavelength of 7 cm. Cloudy weather is no great concern for this experiment, but nighttime observations are desirable to minimize solar interference.

The Radio Telescope and Brightness Temperature

The radio telescope consists of a 3.1-meter parabolic reflector and a receiver system tuned to 7 cm wavelength radiation. For a detailed description of the instrumental setup, see the radio telescope project web page at www.ras.ucalgary.ca/radiotel. The telescope responds to radiation within a "beam" (field of view) of about 1.8° diameter, centered on the pointing direction of the antenna. The receiver produces a voltage at the output that is proportional to the intensity of radiation within this beam.

Radio astronomers often measure intensities in units of brightness temperature. If I is the radiation intensity, the brightness temperature is given by

$$T_b = \frac{\lambda^2}{2k} I .$$

For an optically thick blackbody radiator with temperature T , it is easily shown that $T_b = T$. The emergent intensity for an isothermal source is given by the solution of the radiative transfer equation

$$I_\nu = B_\nu (1 - e^{-\tau_\nu}) ,$$

where B_ν is the Planck Function and τ_ν is the optical depth. In the case where the Planck function can be written in the form of the Rayleigh-Jeans approximation, this equation becomes

$$I_\nu = \frac{2kT}{\lambda^2} (1 - e^{-\tau_\nu}) ,$$

which, from the definition of brightness temperature, can be written

$$T_b = T (1 - e^{-\tau_\nu}) .$$

It therefore follows that for an optically thick source ($\tau_\nu \gg 1$), $T_b = T$. Since for a fixed wavelength the brightness temperature changes linearly with intensity, the voltage output of the telescope is proportional to the brightness temperature of the source of radiation being observed. You will use this fact to measure the brightness temperature of the sky at $\lambda = 7$ cm. The measurement will consist of two parts:

1. the calibration of the brightness temperature response of the antenna
2. the measurement of the brightness temperature of the sky

The concept of this measurement is very simple. The challenge is in taking careful measurements to minimize the error on the result.

Calibration

The response of the radio telescope is read via a voltmeter attached to the output port of the detector system. The calibration problem consists of relating the output voltage to the brightness temperature of the source. This is done by placing two optically thick sources of precisely known temperature in the reception pattern of the receiver. These sources consist of two buckets filled with microwave absorbing material: one at ambient temperature and one at liquid nitrogen temperature.

Use these measurements to derive a relationship between the output voltage ($V - V_0$) and the brightness temperature of the source. You will find that there is still a significant output voltage even when the brightness temperature of the source is 0 K. This residual output power arises from noise generated from the receiver electronics; its temperature equivalent is called the receiver temperature, T_{rec} . The output of the telescope in temperature units when looking at a source of brightness temperature T_{source} is thus $T_{sys} = T_{rec} + T_{source}$.

You should perform the calibration twice, once before and once after observing the sky, to check for any drift in calibration, and to assess the precision of the technique.

The Sky Temperature

The radio antenna acts as a mirror at $\lambda = 7$ cm, reflecting the radiation from a 1.8° patch of the sky. The output of the telescope when pointing at the sky will then be

$$T_{sys} = T_{rec} + T_{sky} .$$

The temperature of the sky can in principle arise from two sources, radiation from the atmosphere and radiation from outer space (the CMBR). The brightness of the sky will be given by

$$T_{sky} = T_{atm} (1 - e^{-\tau_{atm}}) + T_{CMBR} .$$

In the case $\tau_{atm} \ll 1$, we can write $T_{sky} = T_{atm}\tau_{atm} + T_{CMBR}$. Assuming a plane-parallel atmosphere with $\tau_{atm} = \tau_0 \sec(z)$, where z is the zenith angle of the pointing direction of the radio telescope beam, we have

$$T_{sky} = T_{atm}\tau_0 \sec(z) + T_{CMBR} .$$

Thus one should be able to solve for and remove the atmospheric contribution by carefully measuring the telescope response as a function of zenith angle, leaving only the CMBR brightness temperature.

In practice, this correction is difficult to achieve with the telescope we have, because of contamination from “stray” radiation entering the feed through sidelobes in the telescope’s sensitivity pattern vs. angle, much as off-axis scattered light can contaminate optical telescope photometry. Stray radiation can come from the Sun, the Milky Way, the walls of the building, or even your lab partners. Experiments comparing the signal received with the full telescope and that with the feed detached from the reflector suggest the stray contribution from building walls may be a few degrees K, depending on pointing direction. (By itself, the feed acts as an antenna with a much broader beam, but with minimal sidelobes.) Significant contamination from the Sun and the inner Milky Way, near each other in the sky at this time of year, is also present during daylight hours.

Celestial stray radiation can be minimized by observing after sunset. Take measurements at a variety of zenith angles, and try fitting the temperature as a function of $\sec(z)$ to find the atmospheric contribution. Comment on whether you think terrestrial stray radiation contamination is still a problem. The best direction for measurements is toward the northwest, which avoids most contamination from satellites, an increasing problem in radio astronomy. Even so, building walls become a serious issue for $z \geq 60^\circ$.

Hand in your measurements, calculations, and the final result with estimated error. Comment on what you think are the main sources of uncertainty or contamination, and how the experiment might be improved.