A Proposed Measurement of the Anisotropy of the Cosmic Black-Body Radiation

or

Aether Drift and the Shape of the Universe

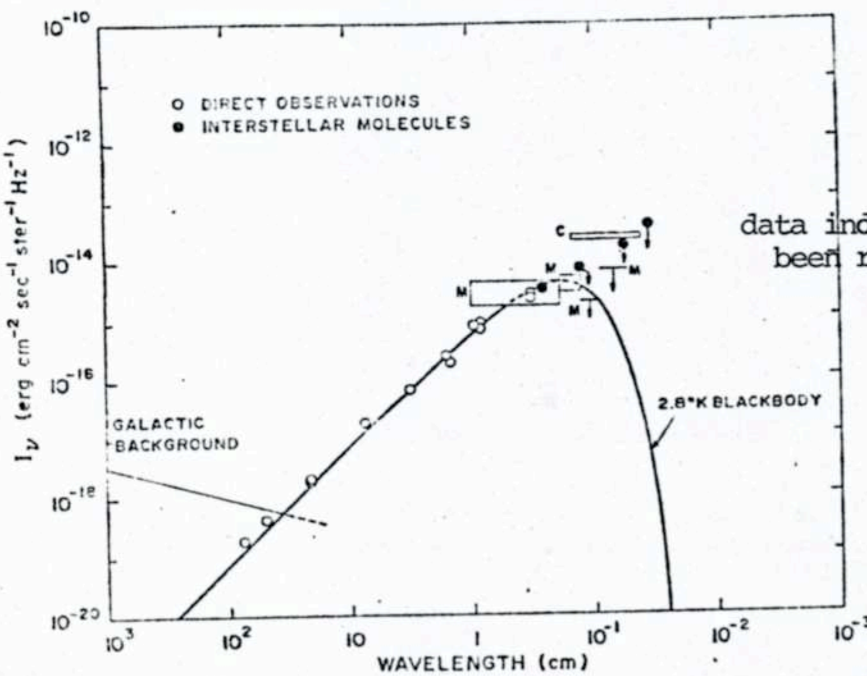
ROUGH DRAFT

Rich Muller, May 16 1973

Cosmic Black-Body Radiation: Aether Drift and the Shape of the Universe

INTRODUCTION

The 2.7^{O}K cosmic black-body radiation discovered by Penzias and Wilson is the strongest evidence that we have in confirmation of the Big Bang Theory. All discrepancies between theory and experiment have ~~ha~~ vanished (i.e. the "8^{O}K" results of Houkkand Harwit, and of Muelhner and Weiss have been retracted by the experimenters). ~~The following plot represents of the measurements of the~~ ~~at~~ Absolute flux measurements from wavelengths of 75 cm down to below 1 cm. agree with the black-body formula, as the following plot shows:



data indicated by "C" has been retracted

The interpretation of ~~this~~ these data easily fills several chapters of modern books on cosmology (such as that by Peebles). Several state-of-the-art experiments are being planned (one by J. Mather, under the supervision of Paul Richards at Berkeley) to fill in ~~the~~ data points on the short wavelength portion of the curve (i.e. on the ~~WEX~~ "Wien fall-off").

Data on polarization ~~and anisotropy~~ can be ~~summarized~~ summarized in one sentence: none has been seen. The upper limit for the amount of polarization present is difficult to find since there is no mention of measurements of the polarization except in Penzias and Wilson's first article on the subject! Fred Hattack at the University of Michigan has assured me that if the black-body radiation were polarized to more than about 1% it would have shown up strongly in their measurements of galacti polarization. He will attempt to define a better limit within a month or so.

Considerable effort in the past several years has gone into looking for anisotropy in the radiation. The work divides into two categories: searches for large scale anisotropies (differences in intensity over large angles, e.g. 45°) ~~as would be caused by the motion of the earth with respect to the radiation, semi-humorously called "Aether drift")~~, and searches for small scale anisotropies (less than 1° in angular size). The latter experiments require radio telescopes with good angular resolution, and will not be further discussed here. (I am currently writing a proposal for such an exp.)

The searches for large ~~scale~~ anisotropy are summarized in the following table from Peebles' book:

ISOTROPY OF THE RADIATION BACKGROUND

Reference	Wavelength	Angular Resolution	$\delta i/i$
Partridge and Wilkinson[18]	3.2 cm	24-hour	$\lesssim 0.0008$
Partridge and Wilkinson[18]	3.2 cm	15°	$\lesssim 0.005$
Conklin and Bracewell[19]	2.8 cm	10'	$\lesssim 0.002$
Conklin[20]	3.75 cm	24-hour	$\cong 0.0006$
Boughn, Fram and Partridge[21]	0.86 cm	24-hour	$\lesssim 0.006$
Epstein[22]	0.34 cm	12'	$\lesssim 0.05$
Penzias, Schraml and Wilson[23]	0.35 cm	2'	$\lesssim 0.02$
Schwartz[24]	0.3-1.6 A	24-hour	$\lesssim 0.01$
Schwartz[24]	0.3-1.6 A	20°	$\lesssim 0.04$

Only Conklin, and also Henry (in a paper done after the above table was made) believe they see an effect. Personally, I don't believe either of their results, for reasons I will get to shortly. Let me first discuss how one would interpret an anisotropy if one saw it. The two major contributors to a large scale anisotropy would be motion of the earth with respect to the center of mass of the radiation (humorously called "Aether drift") and lumpiness of the matter in the universe with which the radiation was once in equilibrium.

There is only one Lorentz frame in which black-body radiation is isotropic: the one for which the walls are at rest. For this experiment, the "walls" are the matter with which the radiation was last in equilibrium. If we look at the radiation from a frame moving with velocity v with respect to this canonical frame, an anisotropy is observed of magnitude

$$dI \cong I \frac{v}{c} \cos\theta$$

where θ is the angle between the angle of observation and v. (The more exact form of this equation includes a second-order time dilation term. Due to the motion of the motion of the sun around the center of the Milky Way (at about 200 km/sec) we expect to see an anisotropy of order:

$$\frac{dI}{I} = \frac{200}{3 \times 10^5} = 0.0007$$

Note that this expected value just coincides with the limits of the previous experiments. The two experiments that claim an effect see the effect in the wrong direction to be accounted for by galactic rotation; in fact it is difficult to account for their numbers within the framework of our understanding of the dynamics of the local group of galaxies. (Of course, disagreement with theory is NOT the reason I don't believe their results!)

Lumpiness in the mass distribution of the universe also results in anisotropy. Suppose there is a fractional variation in the density of the universe dp/p, over a distance in space dL. Let L_0 be the "Hubble Radius" of the Universe (L_0 = c T, where c = speed of light, and T = age of the universe). Then Prof. Ray Sachs (of the Berkeley Physics Department) has shown that variations in the intensity of black-body radiation will result, given approximately by

$$\frac{dI}{I} = \frac{1}{2} \frac{dp}{p} \frac{dL}{L_0}$$

What I consider of most interest here are the numbers that Sachs plugged into these formulas before the current isotropy experiments were done. For large scale anisotropies he used dL = .3 L_0 , dp/p = 0.1, to yield dI/I = 1.5%. The limits are now a factor of twenty lower than this! In fact Peebles argues that the measurements of the isotropy of the black body radiation are the best evidence that we have that the universe is homogeneous and isotropic! If we improve on the current experiments by a factor of ten we may well discover a deviation from spherical symmetry. The first order effect would probably be a quadrapole effect, i.e. the intensity as a function of position angle in the sky would vary as $\cos^2\theta$. Previous experiments have consentrated on the $\cos\theta$ term.

Before proposing an experiment, let me discuss in detail the expected/sources of random and systematic noise.

~~Experimental techniques and limitations~~

SOURCES OF ERROR

Measurements of the black-body are limited by the following sources of random and systematic error:

(1) Noise in the receiver. Receiver noise is generally specified by either its "front end temperature" or by its "noise figure". Front end temperatur is related to noise power by the Rayleigh-Jeans formula:

$$I = \frac{2\,k\,T\,f^2}{c^2} = \text{noise power}$$

Front end temperature is a very convenient number as long as the Rayleigh-Jeans Law holds. For example, if we wish to measure a signal of $3^{\circ}K$, and our front end temperature (or simply, receiver temperature) is $3000^{\circ}K$, then our signal to noise ratio is 10^{-3}. The invention which allows one to work with such small signal to noise ratios is called the "Dicke Radiometer", ~~which will be discussed shortly.~~

The "Dicke Radiometer" operates by chopping the signal(at, say, 100 Hz) but not the noise. The resulting signal is then detected with a phase sensitive detector. The ability of such a detector to see small fluctuations in power levels is given by

$$\frac{dI}{I} = \frac{dT}{T} = \frac{1}{\sqrt{N}} = \frac{1}{\sqrt{df\ t}}$$

where N is the number of effectively intependent measurements, and is given by the integration time t divided by the system coherence time:

$$N = t/t_{coh} = t\,df$$

where df is the system bandwidth. Thus we get:

$$dT = \frac{T}{\sqrt{df\ t}}$$

It is the recent development of parametric amplifiers with small T and of intermediate amplifiers with large df, that make the proposed experiment possible.

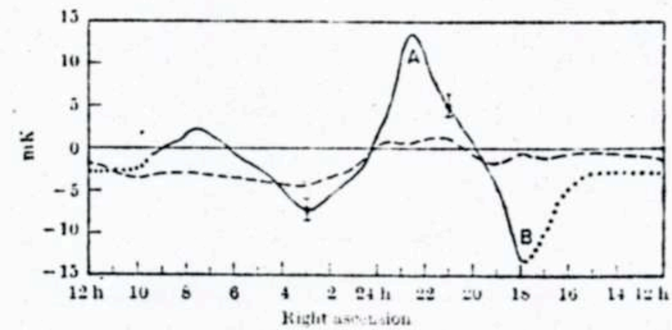
Noise figure is related to noise temperature T by

$$NF = 1 + \frac{T}{300^{\circ}K}$$

Noise figure is usually given in terms of power decibels, so (for example) a noise figure of 3 db means a noise figure of $10^{0.3} = 2$, and a noise temperature of $300^{\circ}K$.

Sources of random and systematic error, continued:

(2) Galactic radiation. The galaxy emits in the frequency range of interest, and is the most important source of systematic error in previous isotropy experiments. In the figure on the first page of this note, the dotted line on the left represents galactic radiation; at wavelengths longer than about 20 cm. it is dominant over the black body radiation. (Note the one data point in the figure at 70 cm.--this was obtained by extrapolating under the noise.) The galactic radiation is highly anisotropic, but it falls off with frequency as $f^{-0.8}$. For absolute intensity measurements this background becomes negligible for wavelengths shorter than 10 cm. But when looking for anisotropy measurements, it is stll significant at 3 cm. Conklin has made the best isotropy measurements; his plot of intensity difference vs. right ascention looks like this:



The solid line represents his measurements of the anisotropy. After "subtracting" the galactic background, he is left with the dotted line. Note that the "background" dominates the signal. The subtraction is done by taking a galaxy map at longer wavelengths, and extrapolating it to shorter wavelengths using a power law. If the residual dotted curve were due to the motion of the earth through the radiation, it would be a pure cosine wave. It isn't, so Conklin derives the amplitude and phase of the first fourier component of the dotted curve, and those two numbers represent his results.

Conklin believes he is seeing the motion of the earth through the radiation (the Aether), but I find it just as plausible that he is observ no more than the residual of a poor extrapolation.

Paul Henry has published a result in confirmation of Conklin, also at 3 cm, but this time from a balloon (to avoid atmospheric problems, discussed next). His residual data, after galactic subtraction, looks like this:

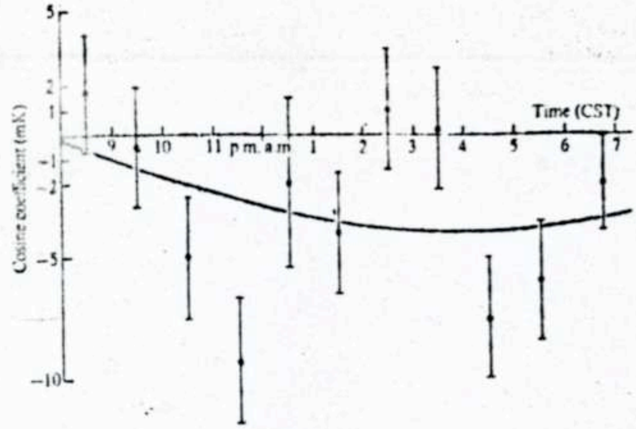


Fig. 1 Hourly averages of cosine coefficients corrected for galactic radiation. The curve is the best fit to a 24 h anisotropy. Error bars represent single standard deviation error limits.

The "fit" to the data is so bad, that it is hard to decide x whether the data conclusion (in confirmation of Cohklin's result) is worth anything at all. Henry had a serious systematic error that he recognized only after this flight (an additional source of noise generated as his detecter rotated in the earth's magnetic field), and although he thought he could eliminate this x noise in the analysis. XXXXXXXXXXXXX To avoid galactic noise, we xxx wish to operate at shorter wavelengths, 1 cm or less.

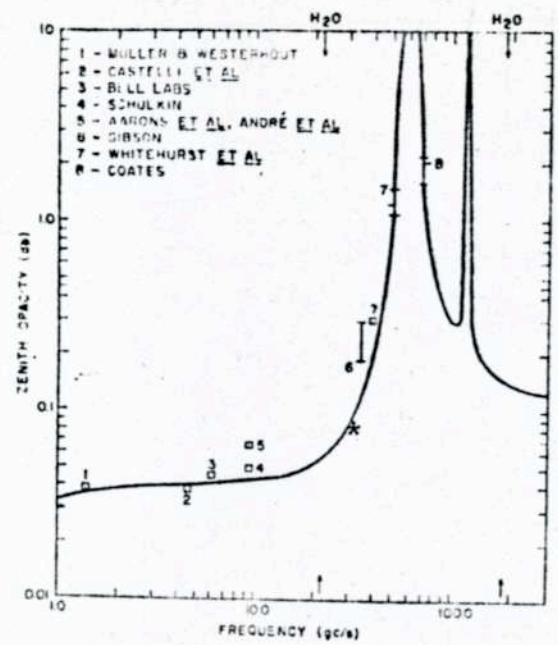
(3) Atmospheric noise. In the region of interest, the main contributors in the atmosphere to microwave radiation are water vapor, oxygen, and ozone. Water vapor is potentially the most troublesome, because it tends to be anisotropic. Thex Oxygen contributes noise, but it should be highly uniform. Likewise xxx ozone is probably uniform (measurements at thisxaccuracyxdon the millidegree accuracy don't exist) although we know it varies from day to day. andxit

The main water lines in the region of interest are: (Burch)

freq. (cm^{-1})	rel. intensity	width
0.74	1.35×10^{-2}	0.087
6.11	$2.26 \times 10^{+0}$	0.11

There are other2x27 lines, but these dominate. If we assume a Lorentzian (i.e. Breit-Wigner) line shape, we find that xthe two lines make equal contributions at $f = 1.1\ cm^{-1}$, although the minimum in intensity lies at $f = 1.6\ cm^{-1}$ (48 GHz). The reduction in noise from $f = 1.1\ cm^{-1}$ (33 GHz) to $f = 1.6\ cm^{-1}$ is only about 33%.

The oxygen emmission lines are shown in the following plot (Meeks,Lil



The positions of the two water lines are shown with arrows at the top of the plot. The main point to be learned from this plot is that we cannot go too high in frequency unless we are willing to go above the atmosphere. The star (*) indicates the zenith opacity (proportional to the zenith emmissivity) at 33 GHz, which is probably the best frequency for this experiment.

The ozone lines form what is practacically a continuum in our frequency range. The following list of them was published by Gora; ~~Th~~ the intensity is somewhat less (?) than the emission of oxygen.

The Rotational Spectrum of Ozone between 0 and 120,000 Mc/sec

Comparison of Calculated and Observed Frequencies

Calculated frequency ν (Mc/sec)	Observed frequency ν_{obs} (Mc/sec)	Transition $\Delta J_{\Delta K}(J_K)$	Centrifugal distortion correction $-\Delta\nu_{C.D.}$ (Mc/sec)	Intensity factor $Y = \mu^2 e^{-W_1/kT}$	Maximum absorption coefficient $\alpha_{max} \times 10^5$ (cm^{-1})
767		$P_R(32_4)$	- 498	0.21	0.001
1,291		$R_p(32_5)$	65	0.18	0.001
9,204	9,201	$R_p(20_3)$	- 130	0.79	0.29
10,225	10,226	$R_p(9_2)$	1	1.51	0.69
10,598		$R_p(34_3)$	-1365	0.05	0.02
11,072	11,073	$R_p(3_1)$	- 2	1.51	0.81
11,898		$R_p(35_6)$	1047	0.04	0.04
14,868	14,866	$P_R(24_3)$	- 159	0.65	0.63
16,158	16,163	$R_p(26_4)$	- 42	0.45	0.53
23,859	23,863	$P_R(19_2)$	135	0.95	2.36
25,290	25,300	$R_p(45_7)$	- 634	0.01	0.03
25,526	25,511	$R_R(39_5)$	- 50	0.05	0.15
25,651	25,649	$P_R(17_1)$	176	0.51	1.48
27,476		$P_R(37_2)$	4614	0.03	0.09
27,863	27,862	$R_p(40_6)$	667	0.04	0.12
28,962	28,960	$P_R(25_3)$	175	0.58	2.1
30,056	30,052	$P_R(16_2)$	17	1.21	4.8
30,182	30,181	$P_R(15_1)$	104	0.69	2.7
30,525	30,525	$P_R(19_1)$	303	0.35	1.5
36,025	36,023	$R_p(22_3)$	- 180	0.62	3.5
37,836	37,832	$R_p(17_3)$	173	1.18	7.4

ν (Mc)	ν_{obs} (Mc)	Transition	$-\Delta\nu_{C.D.}$	Y	$\alpha_{max} \times 10^5$
39,425		$R_p(22_3)$	-2373	0.06	0.5
42,832.6	42,832.6	$P_R(2_0)$	5	0.50	4.0
43,557	43,654	$P_R(13_1)$	70	0.84	7.0
43,582		$P_R(35_5)$	- 145	0.06	0.5
44,867		$P_R(21_1)$	507	0.24	2.1
53,245		$P_R(31_4)$	271	0.25	2.7
51,267		$R_p(34_5)$	393	0.13	1.5
51,956		$R_p(25_4)$	605	0.55	6.5
53,690		$P_R(8_1)$	44	1.17	14.7
55,359		$R_p(24_3)$	- 317	0.46	6.1
58,105		$R_p(28_4)$	51	0.36	5.2
58,403		$R_p(30_3)$	-1577	0.13	1.8
61,364		$P_R(30_4)$	99	0.28	4.6
61,364		$R_p(33_5)$	1251	0.16	2.3
64,931		$P_R(17_2)$	170	1.07	17.9
65,239		$P_R(11_1)$	64	0.93	17.2
66,061		$R_p(26_3)$	- 573	0.32	6.1
67,240		$R_p(28_3)$	- 975	0.91	4.1
67,356		$R_p(5_1)$	9	2.51	50
68,438		$P_R(23_1)$	771	0.15	3
76,404		$P_R(23_3)$	324	0.69	18
76,535		$R_p(11_2)$	69	1.81	46
77,644		$P_R(22_3)$	179	0.76	20

The relative strengths of these lines depends on the details of the local atmosphere. For example, in Berkeley the water vapor lines would completely dominate. White mountain has the advantage of being a relatively dry environment; most of the water carried by the prevailing winds is precipitated in the Sierras. Superior locations would be Antarctica, or a balloon gondola.

In order to put these background problems in perspective, let me give a detailed experimental example: the experiment currently being build by Adrian Webster in the Astronomy department.

ADRIAN WEBSTER'S EXPERIMENT

Webster is building an apparatus that should be operational this summer. He hopes that it will be semi-automatic, so that it will continue to operate on its own for up to a year (Webster is returning to England in a few months). It consists of two collecting horns, aimed at opposite directions from the zenith, with the axis of each making an angle of 30° (I think) from the zenith. He has chosen the wavelength of 0.9 cm since there is less galactic background there than at lower frequencies. In order to avoid noise introduced by amplifier drift (usually identified with the mysterious "1/f noise") he switches his receiver back and forth between the two antennae at a rate of about 100 Hz (with what is called a "Dicke switch"). The switched signal is then fed into a "balanced mixer" in which the signal is non-linearly mixed (with a diode) with a local oscillator. (The local oscillator is a Gunn oscillator; it is what determines the frequency that is observed.) One of the side-bands of the signal is then fed into the intermediate frequency (IF) amplifier. The bandwidth of the system is determined by the bandwidth of the IF amplifier: for Webster's system the bandwidth B is approximately 300 MHz. This wide bandwidth is extremely important, as I shall show presently. The signal is then detected with a phase-sensitive detector, operating at the frequency of the Dicke switch. It is integrated for one second, and recorded on paper tape.

In order to balance out antenna noise, the two horns are slowly rotated, and thus their roles are reversed. (I think Webster's horns rotate once per minute.) In addition, Webster includes a special low noise mechanical switch (which he calls a "Webster Switch") that periodically reverses the terminals of the Dicke switch, and thus tends to cancel out unbalanced switching noise. The inclusion of the Webster

The main limitations on the accuracy of Webster's results will, I believe, come from systematic errors. In order to reduce systematic errors by a truly significant amount, it is first necessary to improve the sensitivity of the receiver by a significant amount. Fortunately, due to advances in microwave technology during the last two years, it is now possible to do just that (although it will cost considerably more than Webster is currently spending).

In order to improve on the sensitivity of the receiver, I propose using a parametric amplifier on the front end, immediately following the Dicke switch. Such amplifiers are not quite "off-the-shelf" but they are "state-of-the-art". John Saarloos has contacted several commercial firms that could build one for us for about \$25000, with a front end temperature of about 300°K, operating at 0.9 cm. wavelength. Alternatively, it could be built at LBL by the group headed by Branko Leskovar. When we include the insertion loss of the Dicke switch, the effective front end temperature of the receiver system would probably be about 400°K. (If we used two parametric amps, we would keep the temperature down near 300°K, and the second amplifier should be considerably cheaper than the first.) Although this would represent only a 1800/400 = 4.5 improvement in the front end temperature of the receiver, remember that the integration time scales as the inverse of the square of the front end temperature, and therefore for the example given previously (dI/I = 0.0007) we require only 20 minutes of observation time (instead of 7 hours) in order to observe a significant effect!

~~1200 seconds = 20 minutes.~~ Being able to reduce statistical errors to a manageable amount in a relatively short integration time gives us the opportunity to tackle systematic errors head on.

The most serious expected systematic error arises from potential blotchiness in the water vapor content of the sky. The easiest way to get a handle on this problem would be to simultaneously monitor the distribution of water vapor, for example by periodically switching (for a very brief period) to a different frequency where water dominates the signal. There are many ways to procede from there. We could either attempt a subtraction, or wait for the times when the water "seeing" was good (i.e. either when it was low in emission, or at least isotropic). Since we could perform a significant experiment in a short period of time, if it is feasable to wait for good seeing.

Lower front end noise even enables us to reduce systematics dxxxxx due to galactic background, in a similar way. As can be seen from Conklin's plot (on page 5 of this memo), the galactic background is highly anisotropic. Since our sensitivity has been improved, we can now afford to avoid those regions of the sky which have the xxx greatest and least uniform galactic emission. The way to do this is first, to reduce the angle between the two receiving horns, and secondly, to concentrate on those sections of the sky where the galactic emmission is either minimal or uniform. The signal from the "Aether drift" would be reduced, but the systematic noise from galactic background (which cannot be reduced by looking for a dx sidereal effect!) could be reduced by an even larger factor.

Of course not all systematic errors are to be anticipated. But I believe as a general principle, that systematic errors are easier to study (and hopefully... remove) in a low noise system.

There are advantages to be gained by flying from a balloon xpxxxxxxxxx (reduction in atmospheric noise) xx or in operating from Antarctica (lower water vapor content), but it any case we would want to have a preliminary experiment operated at White Mountain.