Basic concepts in CMB detectors for poets and theorists

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Advanced Technology Group

A strategy for your research life

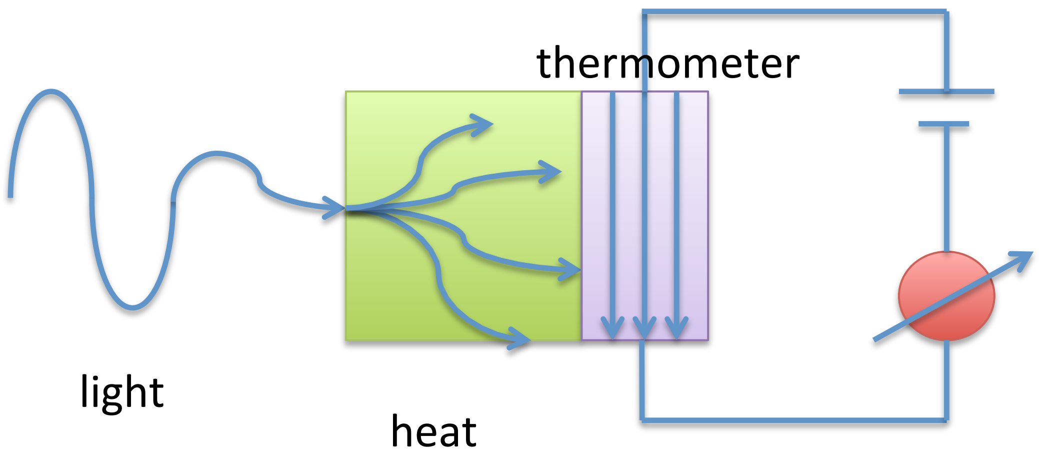
- Any new project → **OPPORTUNITY**
- Science led → historically **VERY EFFECTIVE**
- Blue Sky Research → **NEW SCIENCE, NEW TECHNOLOGIES**
- Find a hard science question → **NEW TECHNOLOGIES**
- Blue sky vs "Established" → problem for young researchers

"The best papers to write are those that are the first in their field or those that are the last in their field". [Tom Phillips]

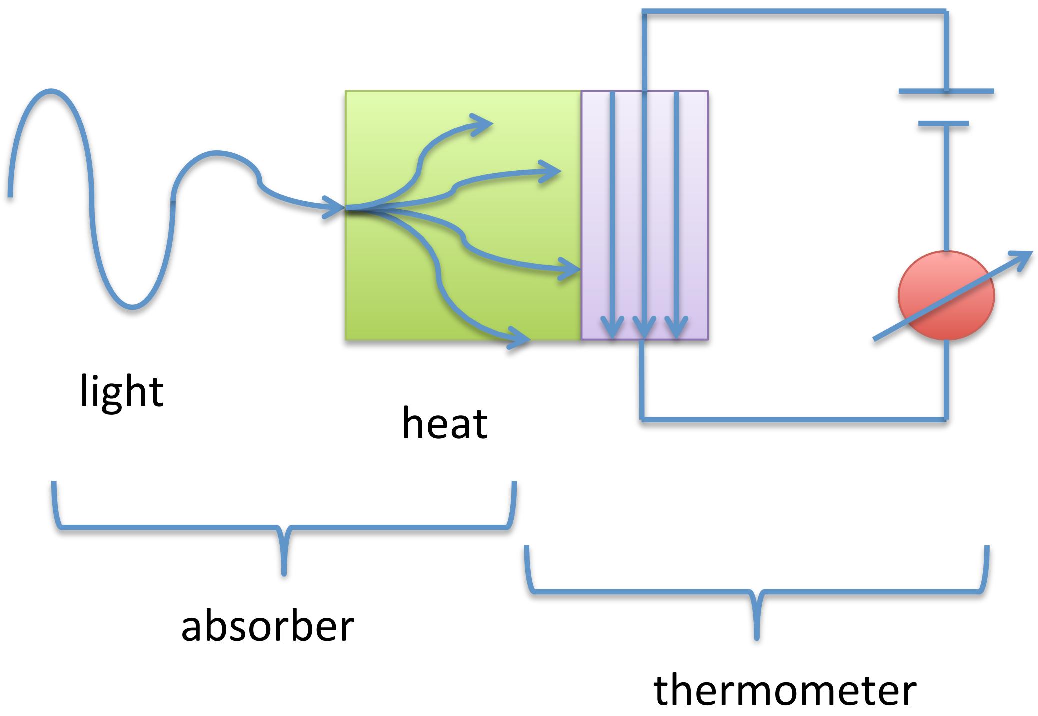
Collection of concepts/ideas/projects useful in CMB

1. Bolometers [today]
2. HEMT [tomorrow]
3. Comparison Bolo/HEMT [tomorrow]
4. Possibly some more material [tomorrow]

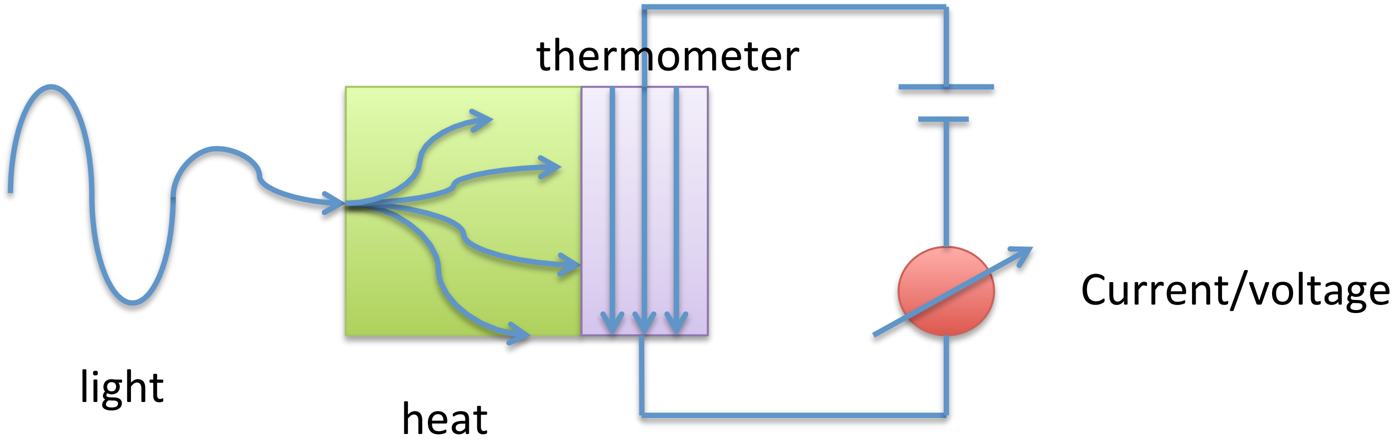
1. Bolometers in CMB research



1. Bolometers in CMB research



1. Bolometers in CMB research

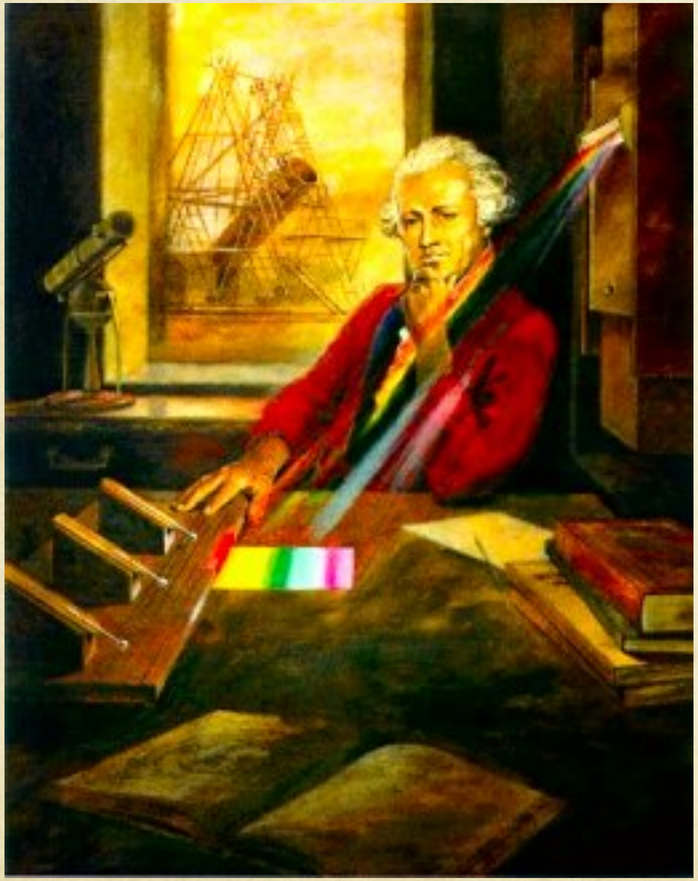


Notice that the bolometer has lost all the information about the PHASE of the incoming photon. It is good and bad.

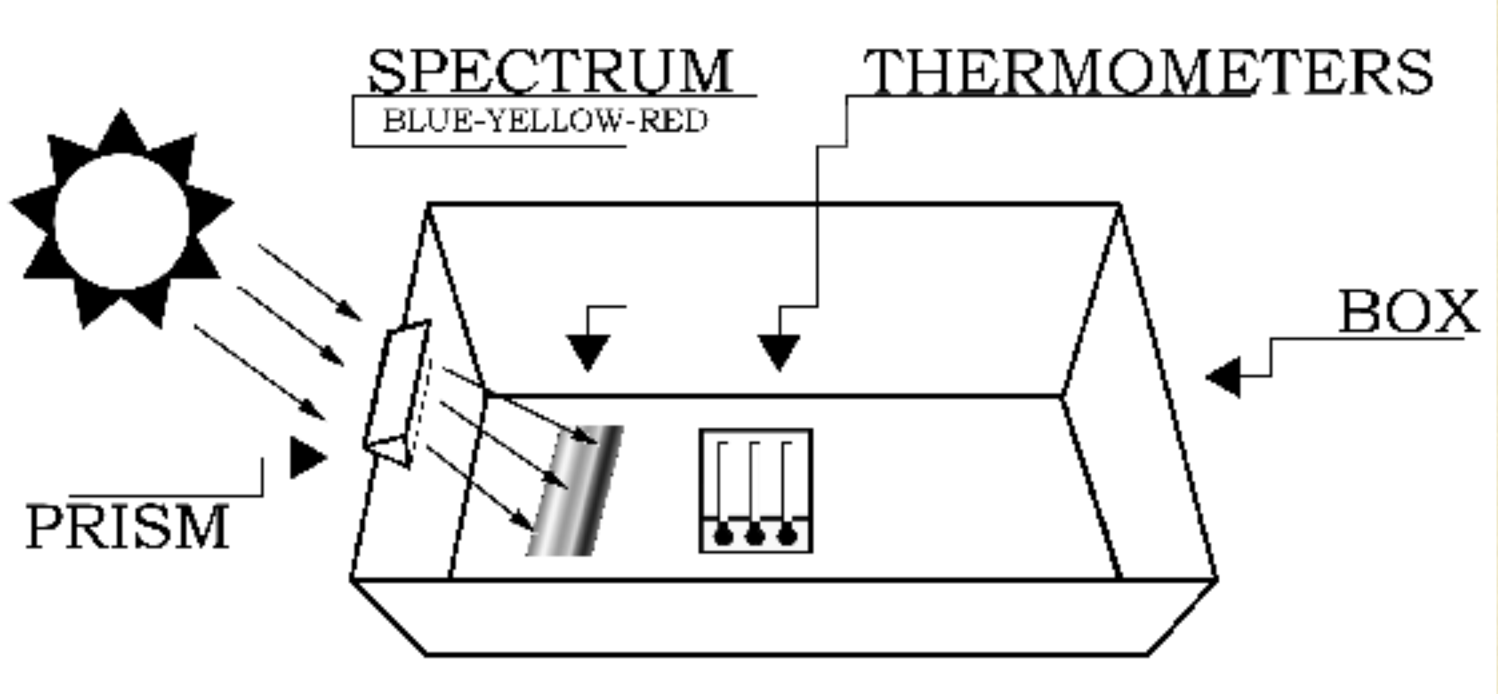
Light to heat

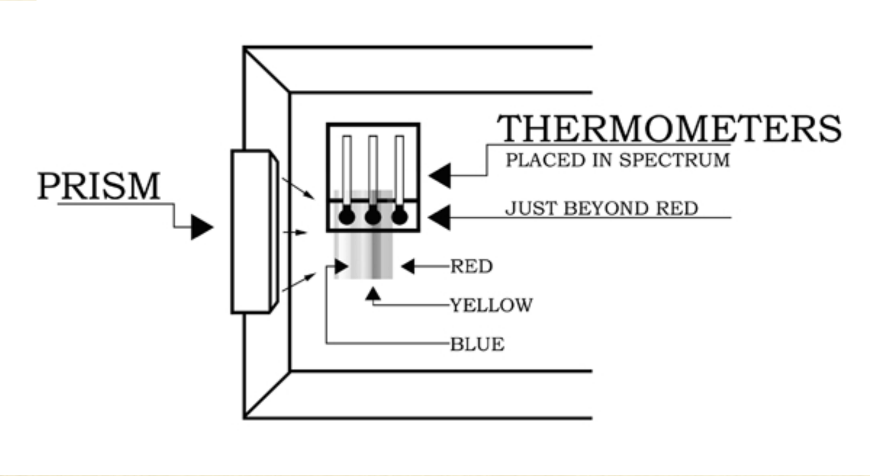
- First were the Greeks and the Incas
  - Archimedes is said to have used mirrors to concentrate sunlight onto Roman warships during the siege of Syracuse (214-212 BC) to have set them on fire; while the veracity of this story has long been in dispute, the Greeks were certainly aware of the heat content of sunlight, and this is mentioned by Aristophanes in his play The Clouds of 424 BC
  - At the Feast of Raymi, a fire was ignited by using a concave metal mirror focused onto cotton wool; the failure of the sun, a key deity of the Incan religion, to ignite said fire was taken as an ill omen

Sir Frederick William Herschel astronomer & composer (1738-1822)



He played the cello and harpsichord in addition to the oboe and later the organ. He composed numerous musical works, **including 24 symphonies** and **many concertos**, as well as some church music. Six of his symphonies are available in excellent recordings made in 2003 by the London Mozart Players, conducted by Matthias Bamert (Chandos 10048)

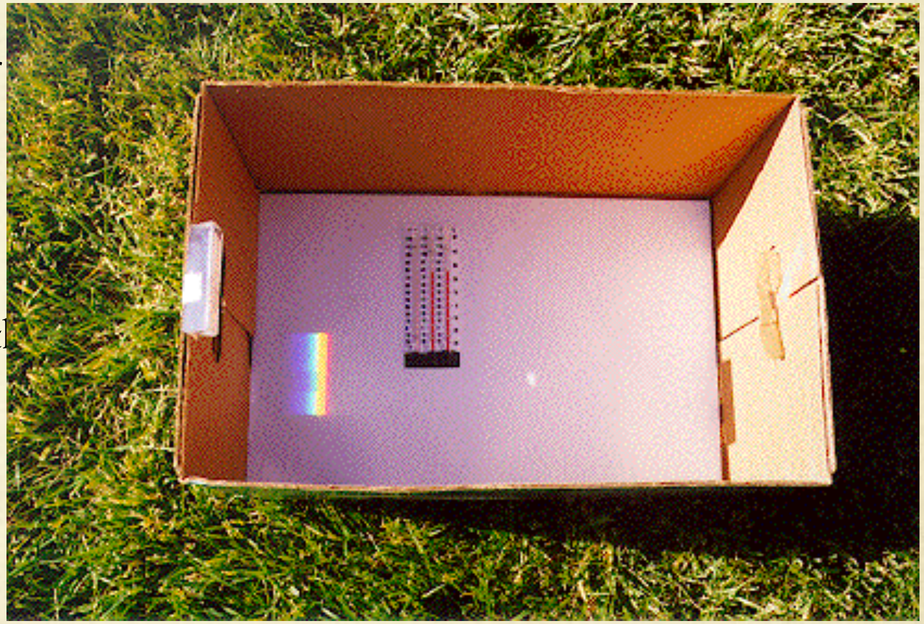




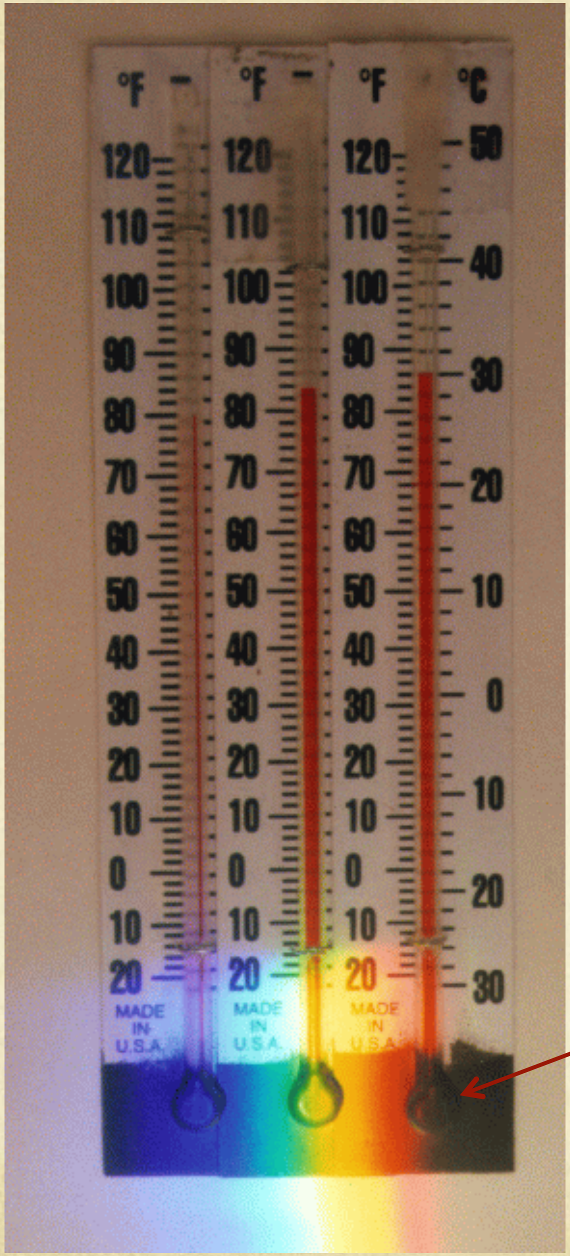
- ✓ Herschel wanted to measure the "heat" of light. He discovered IR radiation while calibrating…
- ✓ Herschel is the first to use a thermometer to measure the total amount of energy in a beam of light!

Do it yourself!

MATERIALS: One glass prism (plastic prisms do not work well for this experiment), three alcohol thermometers, black paint or a permanent black marker, scissors or a prism stand, cardboard box (a photocopier paper box works fine), one blank sheet of white paper.



PREPARATION: You will need to blacken the thermometer bulbs to make the experiment work effectively. One way to do this is to paint the bulbs with black paint, covering each bulb with about the same amount of paint. Alternatively, you can also blacken the bulbs using a permanent black marker. (Note: the painted bulbs tend to produce better results.) The bulbs of the thermometers are blackened in order to better absorb heat. After the paint or marker ink has completely dried on the thermometer bulbs, tape the thermometers together such that the temperature scales line up http://coolcosmos.ipac.caltech.edu/cosmic_classroom/ir_tutorial/discovery.html



Highest temperature in the IR!

First bolometer

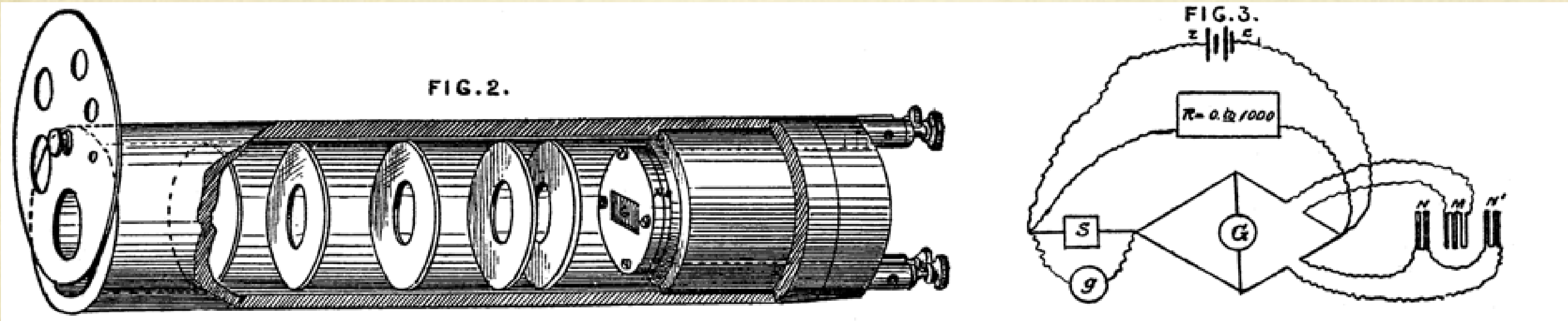
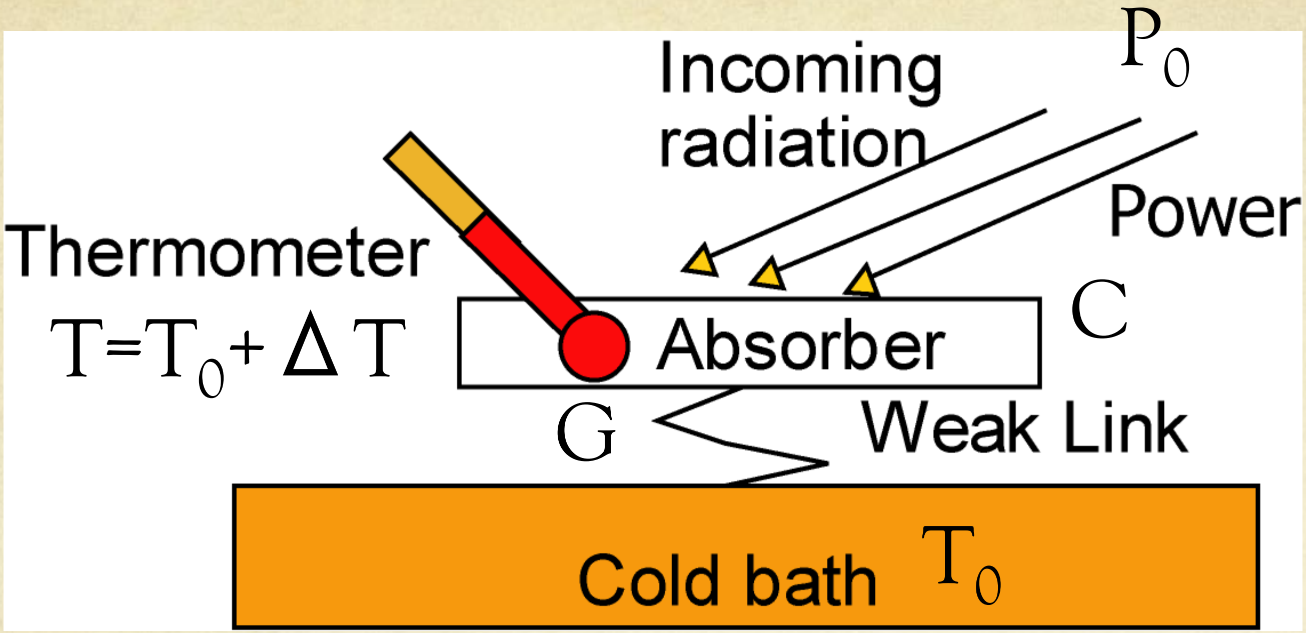


Figure 1. Bolometric instrument of S.P. Langley.

The next major advances in bolometry keep the core of Langley’s original principles: an absorber converting light into heat, and a thermistor converting heat into an electrical signal.



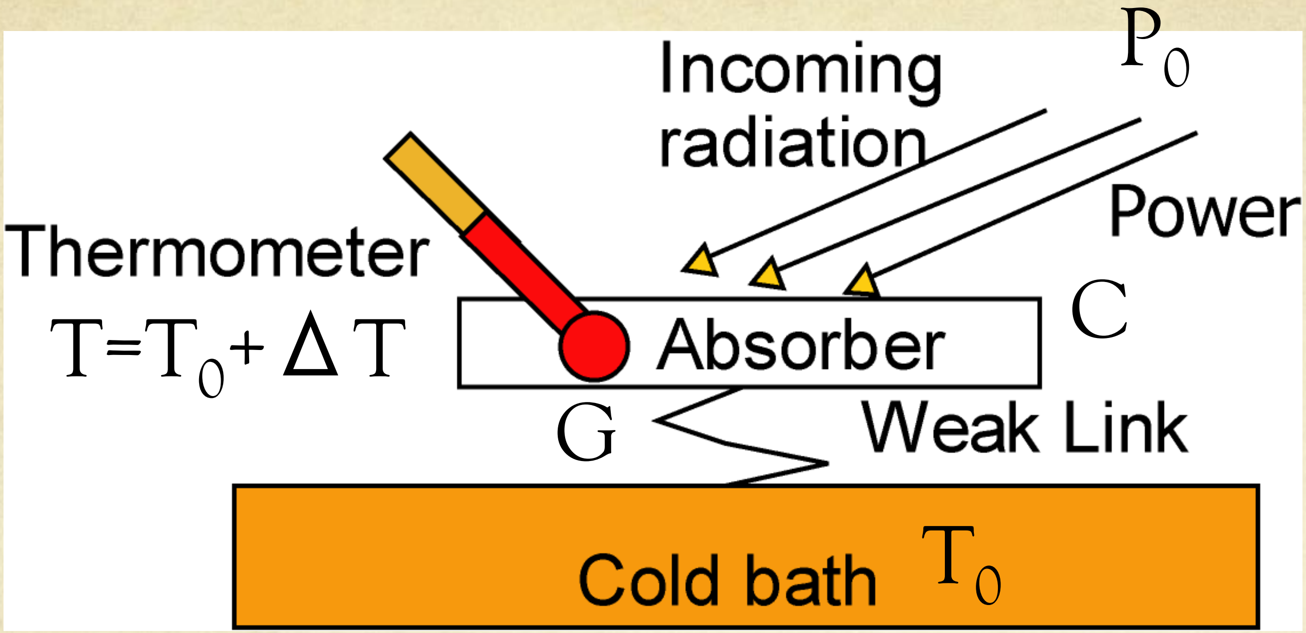
$$C\frac{d\Delta T}{dt}+G\Delta T=P$$

Bolometer equation

$$C\frac{d\Delta T}{dt}=0$$

When P = const

$$\Delta T=\frac{P}{G}$$



$$C\frac{d\Delta T}{dt}+G\Delta T=P$$

Bolometer equation

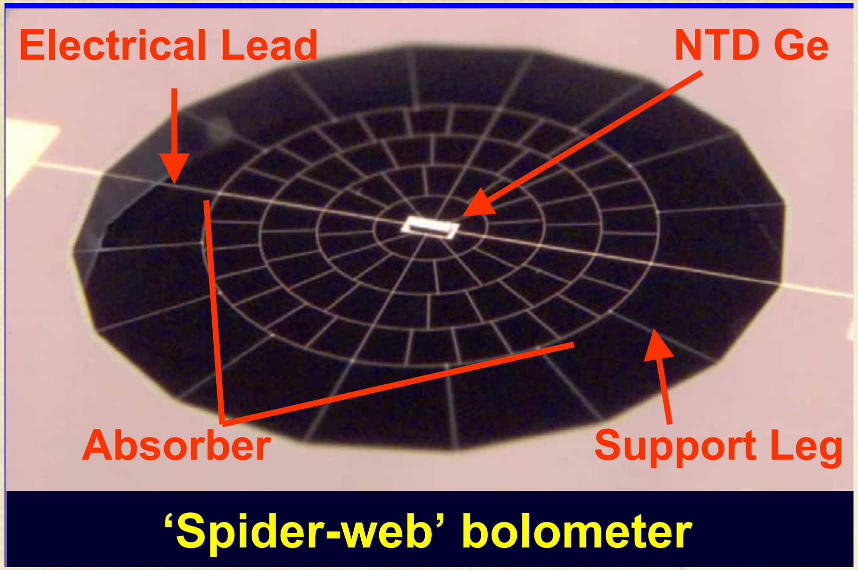
$$\Delta T=\frac{P}{G}e^{-\frac{t}{\tau}}$$

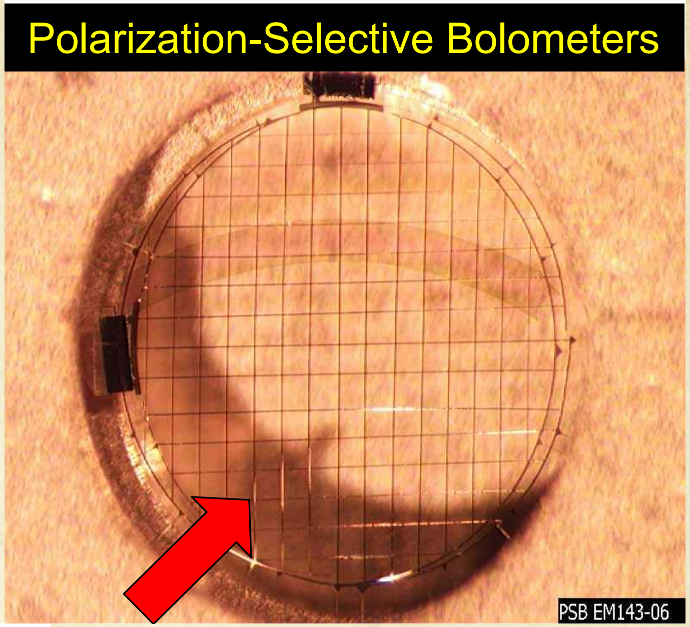
If you stop the flux P

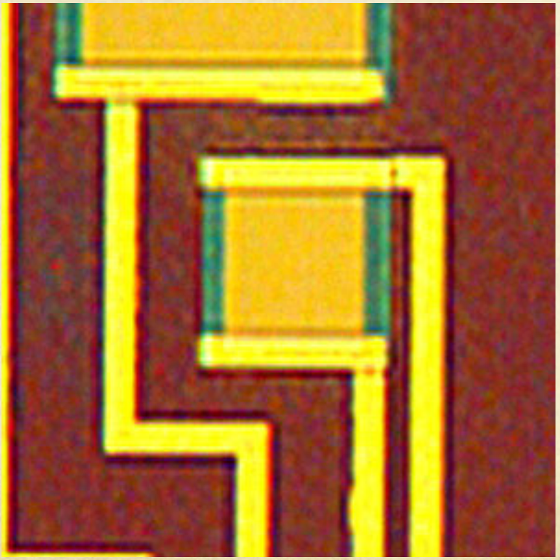
$$\tau=\frac{C}{G}$$

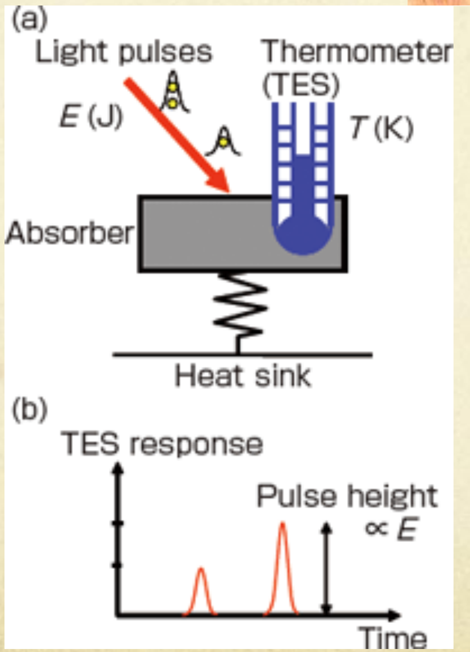
What does a bolometer do?

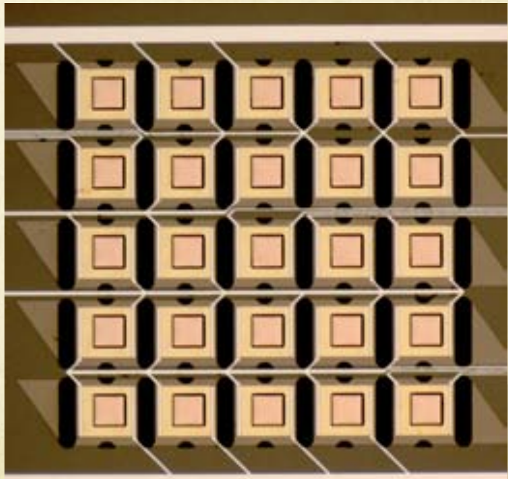
- Thermal (classical) detector
- It tries to go to thermal equilibrium with whatever it is looking at
- If looking at the CMB it is actually trying to establish thermal equilibrium with the LSS!!!
- Radiative heating → that's why bolometers need to be at very low temperatures: the sky is damn cold


Electrical Lead
NTD Ge
Absorber
Support Leg
‘Spider-web’ bolometer


Polarization-Selective Bolometers
PSB EM143-06




(a)
Light pulses
Thermometer (TES)
E (J)
T (K)
Absorber
Heat sink
(b)
TES response
Pulse height ∝ E
Time



Optimizing bolometers

- There are 4 parameters:
  - NEP (Noise Equivalent Power) [W/√Hz] → it adds in quadrature
  - Responsivity S [V/W]
  - Conductance G [W/K]
  - Time constant τ [seconds]

NEP, τ minimized

R maximized

NEP

- **Noise Equivalent Power** can be interpreted as *the input signal power that produces a signal-to-noise ratio of unity at the output of a given detector at a given data-signaling rate or modulation frequency, and effective noise bandwidth; it is the minimum detectable power per square root bandwidth.*

- *Why W/√Hz?*
  - *S/N=1 in 1 Hz output bandwidth equivalent to 0.5 seconds integration time (you need to samples to define a frequency). The S/N improves with the square root of the integration time or, equivalently, inversely with the square root of the bandwidth. You improve the NEP by a factor of 10 if you integrate for 50 seconds!*

Optimizing bolometers

$$NEP \propto \sqrt{\text{bolometer size}} \propto 1/R$$

Small bolometer

$$S \propto \frac{d(\text{Resistance})}{dt} \propto \frac{1}{G}$$

Large responsivity, made of metal or semiconductor with strong Res=Res(T). **G minimized.**

$$\tau \propto \frac{1}{G} \propto \text{bolometer size}$$

G maximized

Some optimization is needed

Noise

1. Johnson noise

2. Phonon noise

3. Photon noise

Johnson noise

- Random thermal agitation of **electrons** in a resistor
- With a simple experiment we can determine:
  - Boltzmann constant
  - Value of temperature in C of absolute zero
- Johnson in his paper gave a determination of k within 8%

JULY, 1928 *PHYSICAL REVIEW* *VOLUME 32*

THERMAL AGITATION OF ELECTRICITY IN CONDUCTORS

BY J. B. JOHNSON

ABSTRACT

Statistical fluctuation of electric charge exists in all conductors, producing random variation of potential between the ends of the conductor. The effect of these fluctuations has been measured by a vacuum tube amplifier and thermocouple, and can be expressed by the formula $\bar{I}^2=(2kT/\pi)\int_0^\infty R(\omega)|Y(\omega)|^2d\omega$. I is the observed current in the thermocouple, k is Boltzmann's gas constant, T is the absolute temperature of the conductor, $R(\omega)$ is the *real* component of impedance of the conductor, $Y(\omega)$ is the transfer impedance of the amplifier, and $\omega/2\pi=f$ represents frequency. *The value of Boltzmann's constant* obtained from the measurements lie near the accepted value of this constant. *The technical aspects of the disturbance* are discussed. In an amplifier having a range of 5000 cycles and the input resistance R the power equivalent of the effect is $\bar{V}^2/R=0.8\times10^{-16}$ watt, with corresponding power for other ranges of frequency. The least contribution of *tube noise* is equivalent to that of a resistance $R_c=1.5\times10^5 i_p/\mu$, where i_p is the space current in milliamperes and μ is the effective amplification of the tube.

JULY, 1928 PHYSICAL REVIEW VOLUME 32

THERMAL AGITATION OF ELECTRIC CHARGE IN CONDUCTORS*

By H. Nyquist

Abstract

The electromotive force due to thermal agitation in conductors is calculated by means of principles in thermodynamics and statistical mechanics. The results obtained agree with results obtained experimentally.

Dr. J. B. Johnson[1] has reported the discovery and measurement of an electromotive force in conductors which is related in a simple manner to the temperature of the conductor and which is attributed by him to the thermal agitation of the carriers of electricity in the conductors. The work to be resported in the present paper was undertaken after Johnson's results were available to the writer and consists of a theoretical deduction of the electromotive force in question from thermodynamics and statistical mechanics.[2]

$$\langle V^2 \rangle = 4kTR\Delta\nu \quad [\text{V/sqr(Hz)}]$$

$$NEP_J^2 = \frac{\langle V^2 \rangle}{S^2} \quad [\text{W/sqr(Hz)}]$$

$$NEP_J^2 = \frac{4kTR\Delta\nu}{S^2}$$

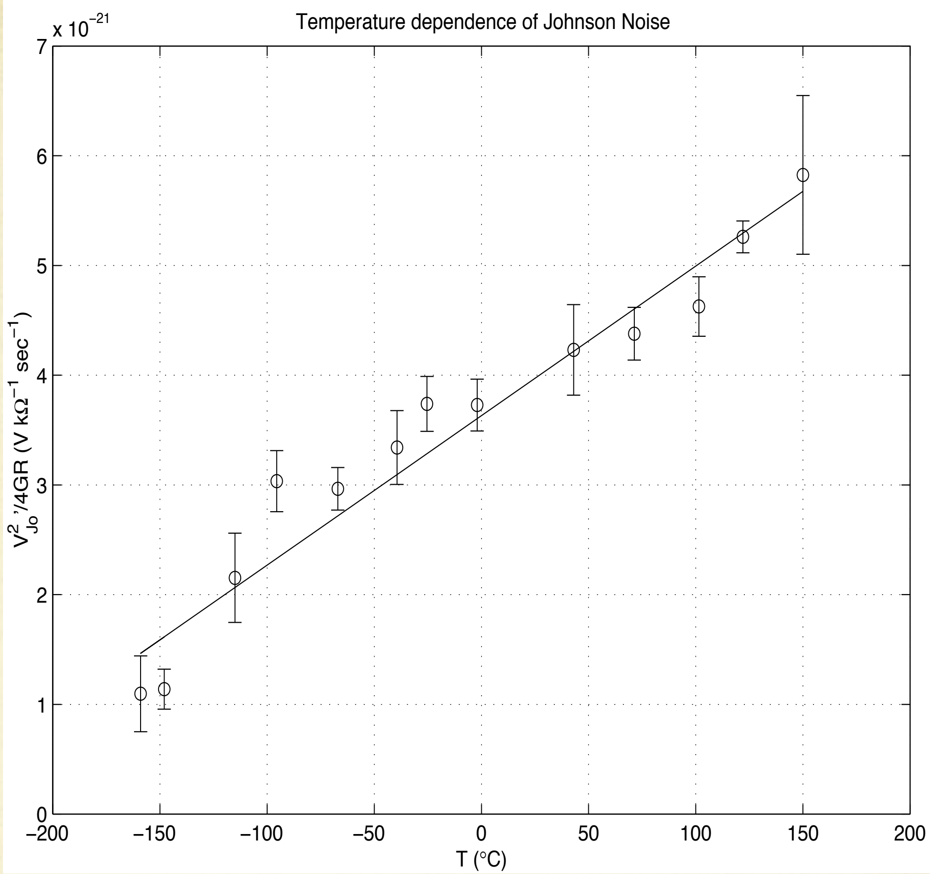


FIG. 10. Temperature dependence of Johnson Noise V'_{Jo}.

$k = 1.37 \pm 0.06 \times 10^{-23}$ J/K

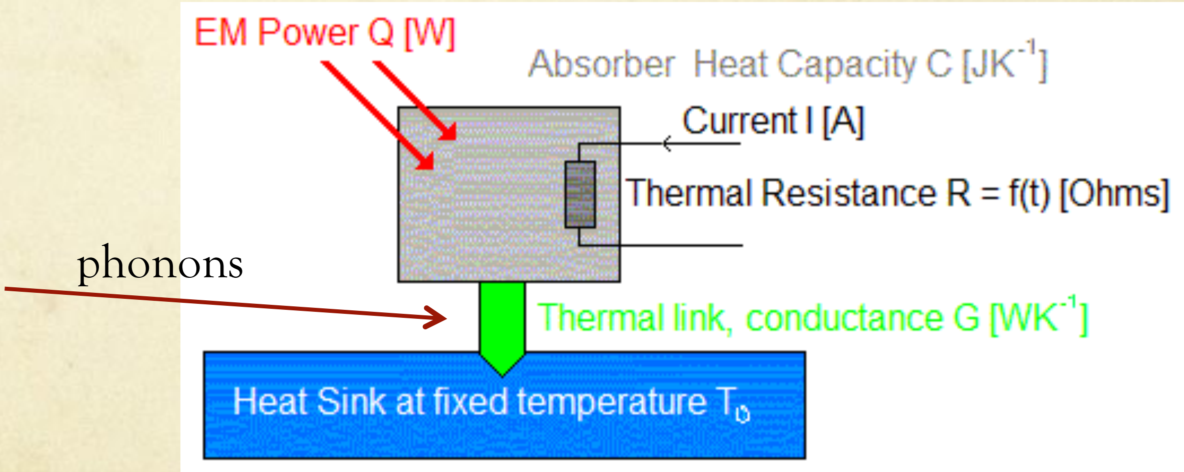
$T_0 = -265.5 \pm 6.9$°C

Phonon noise

- Quantization of the flow of heat to the heat sink: phonons
- Phonons: quantized lattice vibrations

$$NEP_J^2 = 4kT^2G$$

[W/sqr(Hz)]



Photon noise

- Extremely interesting!
- Intrinsic "natural" variation of the incident photon flux
- If the source is a black body:

$$n = \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

$$\langle \Delta n_{\mathrm{rms}} \rangle^2 = n^2 + n$$

Photon bunching $h\nu \ll kT$

$h\nu \gg kT$ poisson

Discussion about Noise Equivalent Power and its use for photon noise calculation.

Samuel Leclercq. 2007-03-02.

Abstract.

The Noise Equivalent Power (NEP) is a concept often used to quantify the sensitivity of a detector or the power generated by a source of noise on a detector. But the literature offers different definitions and different ways to calculate it. I recall here these definitions and the results of calculations from several authors, for the particular case of photon noise from background source illuminating a detector. In the second part of the document, starting from bases of mathematical description of random processes, I show the link between the different definitions of the NEP. In the third part, starting from the fundamental properties of boson I calculate the most general expression for the photon NEP, allowing to link the various expressions found in the literature, and understand the assumptions made for each case.

Must be read by experimentalists and theorists!!!!

Photon noise

$$NEP^2 = \frac{1}{t_m \Delta f}\left(\int_{\Delta\nu} h\nu \frac{\gamma_b(\nu)}{(\gamma_s(\nu))^2} P_\nu(\nu)\, d\nu + \int_{\Delta\nu} \frac{(1+p^2)\Delta_s(\nu)}{2} \left(\frac{\gamma_b(\nu)}{\gamma_s(\nu)} P_\nu(\nu) \right)^2 d\nu \right)$$

Where: t_m : Measuring time

Δf : Post-detection bandwidth

$P_\nu d\nu = n \frac{h\nu}{t_m}$: Power spectral density

γ_s : Ratio between incident photons and dissipated power

γ_b : Ratio between incident photons and detected photons

$\gamma_s \geq \gamma_b$

p : Polarization $0 \leq p \leq 1$

$\Delta_s(\nu)$: Spatial coherence factor

Practical photon noise

- Under reasonable assumptions:
  - $\Delta_s = \lambda^2/A\Omega$ (spatial coherence)
  - $1/t_m d\nu$ (time coherence)
  - Atmosphere gives $kT \gg h\nu$ (but also optics…)

$$NEP^2 = \int \frac{1}{\Delta_s(\nu)} \frac{4\varepsilon(\nu)}{\eta_{MB}^2\, \alpha\left(1-\varepsilon(\nu)\right)^2} kT\, h\nu \left[1+\varepsilon(\nu)\,\alpha\,\frac{kT}{h\nu}\right] d\nu$$

$$NEP_{ph}^2 \approx 2Q(h\nu + \eta\varepsilon kT)$$

Photon noise to make independent measure of temperature/emissivity of the CMB

ON THE MICROWAVE BACKGROUND SPECTRUM AND NOISE

P. DE BERNARDIS and S. MASI
Istituto di Fisica dell'Università di Roma, Rome, Italy

Received 28 July 1982

We show that the combined measurement of the cosmic background radiation (CBR) intensity and noise can provide direct information on the temperature and the emissivity of the source responsible for the CBR.

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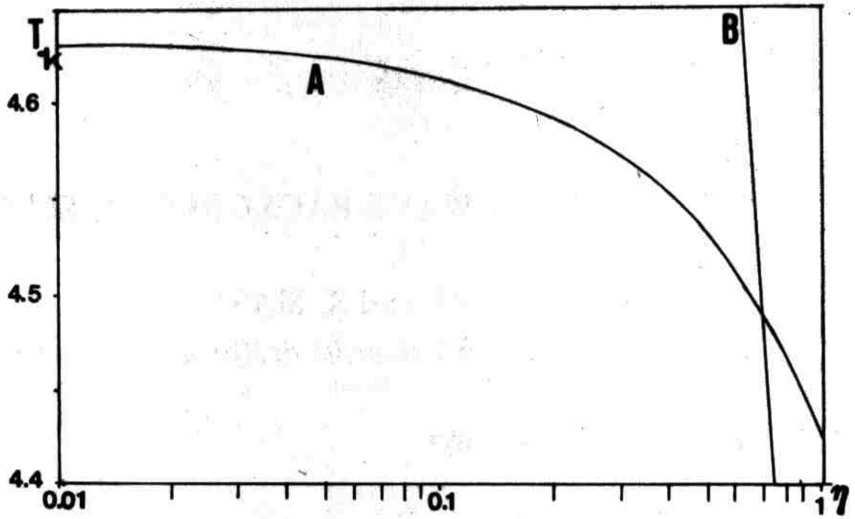

Fig. 2. A noise and intensity measurement gives two relations between T and η: A is eq. (12) and B is eq. (11) for $T = 4.5\ K$ and $\eta = 0.7$. The intersection gives T and η.

$$I = 2\pi \frac{(kT)^4}{h^3c^2}\left(\eta \int_{x_1(T)}^{x_2(T)} \frac{x^3\,\mathrm{d}x}{\mathrm{e}^x - 1}\right). \qquad (11)$$

$$N^2/kI = 2T(3.84 + 0.179\eta)\,. \qquad (12)$$

Two measurables containing temperature and emissivity

Total noise

$$NEP_{TOT}^2 = 4kT^2G + \frac{4kTR\Delta\nu}{S^2} + 2Q(h\nu + \eta\varepsilon kT)$$

Lowering T is good

BLIP bolometers are those for which the 3rd term dominates over the first two. Today is achieved relatively easily.

END – part one