Black Body Radiation from the early universe

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I showed a graph in class of the spectrum of light from the early universe. This light has the spectrum that physicists and chemists recognize as that of light in full thermal equilibrium with matter, called *blackbody radiation.* It is spectra of this sort which Max Planck "explained" in 1906 by supposing that light is only ever absorbed or emitted in packets of energy

$$E_{light\ packet} = h\nu \quad (1)$$

where h is a universal number, now called Planck's constant, and ν is the frequency of the light.

I realize that this graph raised at least as many questions as it answered, and I will try to address just a few of them here.

What is Blackbody Radiation? If I had a hollow opaque sphere and I heated it until it was red hot or white hot, it must certainly shine at least as much light into the central cavity as it shines outwards, except that the light in the cavity will be reabsorbed by the sphere itself, while the light emitted on the outside goes away from the sphere and heats the room. Because the light inside is constantly emitted and then absorbed, it comes to *thermal equilibrium* with the walls. The light on the outside does not. Poke a small hole into the sphere and measure the intensity and spectrum of the thermal light inside and you will find, as careful scientists did 100 years ago, that the properties of the light are determined by the temperature of the container, but you get exactly the same light no matter what your sphere is made of. The light inside a steel ball is exactly the same as the light inside a porcelain ball at thermal equilibrium. This is called *blackbody* because a small hole in a large hollow cavity will appear to be very black. No light shined onto the hole is returned as a reflection.

What does this have to do with quantum mechanics? By 1900 chemists had made enormous progress understanding classical thermodynamics. They could calculate the spectrum of thermal light they expected, but there was a problem. The spectrum should be

$$I(\nu) \propto 8\pi c^2 k_B T \nu^2 \quad (2)$$

where I is an intensity and k_B is Boltzmann's constant. The average energy of any oscillator, a mass on a spring for example, in thermal equilibrium, is $1/2k_BT$ and Eq 2 amounts to understanding that the effective number of oscillators in the blackbody cavity is proportional to ν^2. Eq. 2 is a very good fit to measurements at low frequencies (long wavelengths). But there is an obvious and very serious problem: the intensity keeps growing at high frequencies and the total predicted intensity is not finite. This problem is called the *Ultraviolet Catastrophe* because the classical model predicts enormous optical power at short wavelengths, which lie in the ultraviolet part of the spectrum. Planck's quantum hypothesis in Eq. 1 fixes the ultraviolet catastrophe because at high frequencies the size of a packet of light becomes very large, too large for atoms in the cavity walls to emit even one. The average energy at high frequency in Planck's model is no longer k_BT, it is nearly zero.

What does this have to do with a rocket? I showed data from a rocket-borne spectrometer which measured light from when the universe was 300,000 years old, and this light is also a blackbody. Like all blackbodies, its spectrum only matches the classical model at low frequencies. This spectrum shows that the universe 'knew about' quantum mechanics more than 10 billion years before people did!

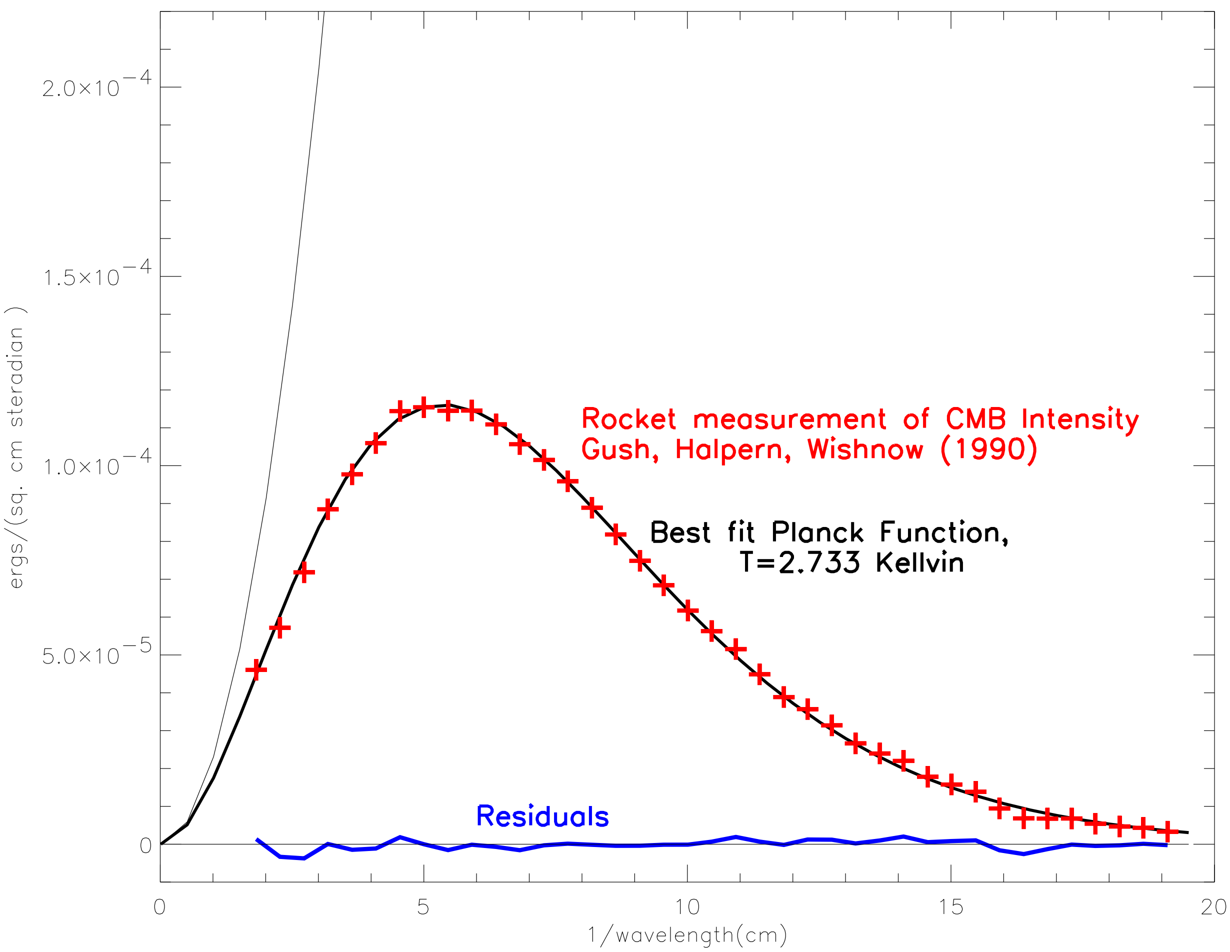

Figure 1: **Spectrum of the Cosmic Microwave Background:** The intensity of the sky at wavelengths of a few mm is plotted versus frequency ($f = c/\lambda$). The data are shown as red plusses. The smooth curve passing near the data is the best fit quantum-mechanical blackbody curve, corresponding to a temperature of 2.733 Kelvin, and the blue line at the base is the temperature minus the fit. The thin black curve rising from the origin as ν^2 is the classical model of Eq. 2 for the same temperature. The match is only acceptable for wavelengths longer than one cm. These data are from a UBC rocket experiment which lasted for 10 minutes on 20 January, 1990.

The early universe was full of blackbody radiation because it was opaque and in thermal equilibrium. It was expanding and cooling, but at any given moment everything was at the same temperature. The radiation cooled as the universe expanded and when the universe cooled to 4300 K it became transparent because the protons and electrons could form neutral hydrogen. The light has travelled undisturbed since then, but has continued to cool because the universe has continued to expand, and now has an apparent temperature below 3 Kelvin.