Hi this is Steve Nerlich from Cheap Astronomy www.cheapastro.com and this is *Light: Wibbly-wobbly, spacey-timey stuff.*

This is the second in a series of two podcasts on light.

Last episode we reviewed how light waves propagate through an electromagnetic field – a bit like how water and sound waves propagate through a physical medium – although the key words there are 'a bit like'. What's different about light waves is their ability to move through a vacuum – a feature also common to gravity waves. To explain this we say that light propagates through a field – you could even say a continuum – of electromagnetism, while gravity waves propagate through a continuum of space-time. There's no immediate reason to think these continuums (continua?) have any underlying sameness.

For example, light bends along the curvature of space-time when passing close to a massive object, but it's not obviously affected when passing by a strong magnet – which is presumably bending the local electromagnetic field in a similar fashion. Also, mass and charge seem to be largely independent properties of matter.

What we are dealing with here is some of the intrinsic properties of apparently empty space. A perfect vacuum might not have any protons or electrons in it, but it's still something to the extent that there really was nothing before the Big Bang.

On the other hand, we can go all philosophical here and say that empty space is just an illusion. After all, from a photon's perspective no time passes between it being emitted from the Sun's surface and it reaching the Earth's surface. And nor does any time pass between it leaving a quasar formed in the early universe and then arriving at our telescopes an apparent 13 billion years later.

Arguably, light is just nature's way of staying in touch with itself within a universe of declining energy density – so that both time and distance are just representations of the universe's increasing entropy. Anyway, I think what this really means is that we've discussed as much of the movement of light through a vacuum that can be of any immediate usefulness – and so far we've mostly about light moving as a wave. All that starts going a bit off the rails when we look at interactions between light and matter.

Black body radiation is essentially the intrinsic radiation generated by a chunk of matter – as opposed to radiation that might be reflected off it – or radiation passing through it from behind. So really, black body radiation is just a consequence of the temperature of that body – where a warm body with gently oscillating atoms radiates at longer redder wavelengths and a very hot object with violently oscillating atoms radiates at short blue wavelengths. And an object at zero Kelvin with none of its atoms moving, radiates nothing at all.

There's a problem with all this when you start collecting the data though. The mathematical relationship between wavelength and energy output that is apparent at longer redder wavelengths starts calculating infinite energy outputs once you get up towards ultra-violet wavelengths, a problem in classical physics referred to as the ultraviolet catastrophe.

For example if you heat a black body, it radiates heat and looks red, heat it even more it radiates even more intensely and looks blue. At the red end of the spectrum there is a certain relationship between the wavelength and the heat output - which roughly equals the square of the wavelength frequency. But if you use this relationship to try and predict the energy output of a blue-hot object, you start calculating ridiculous heat output values – since, by the square law, output per unit frequency would approach infinite as frequency continues to increase.

In reality collected data shows that energy output from a hotter body radiates with a progressive change in the peak wavelength of its total radiative output – so a warm black body radiates across all wavelengths but with a peak at red and a quite hot black body radiates across all wavelengths but with a peak at blue. In this way, black body radiation could be explained without needing the energy output to increase to infinite. And having that shift in the peak radiation - from red to yellow to blue - accounts for the observable colour change that is seen in progressively heated black bodies.

The mathematics of black body radiation and a solution to the ultraviolet catastrophe was derived by Max Planck. He found he could restrict the range of wavelengths available for energy output from a black body using his Planck's constant in a formula that fit the data perfectly. His formula, of energy equals frequency times Planck's constant – still allows a close relationship between energy and wavelength, but only up to a point.

Planck suggested that the meaning of his formula was that although you do create an electromagnetic wave by jiggling a charge – it seems there are only a discrete number of levels of oscillation at which that charge can be jiggled. His formula also showed that any radiative output of a black body was always the multiple of a small number – representing a very small and discrete bit of energy – later to be named a quanta. And since he had derived his formula from an area of mathematics known as statistical mechanics – well, you can see where all this is going.

Einstein then appeared on the scene – and had a number of different things to say about light. But here we are just going to look at his Nobel-prize winning paper on the photoelectric effect. The photoelectric effect was yet another problem with classical physics. If you set up an experiment where light is shone on a metal, you can measure electrons being knocked out by the light – and you will find that the energy level that those emitted electrons carry is determined by the wavelength of the light and not its intensity.

This is somewhat intuitive since we know you can shine a really, really bright light on a radio – and it still won't start playing music. The radio will only respond to electromagnetic radiation in the radio frequency. With the photoelectric effect – it's only when you hit the right frequency (or frequencies) that electrons start flying off the metal. If you then increase the intensity of the light at that wavelength – a greater number of electrons do start flying off, so intensity is not irrelevant. What's interesting though – is that at a particular wavelength all the electrons that get knocked out have the same energy level. It's only when you step up to a higher frequency that you start knocking out electrons at a higher energy level.

Einstein explained all this by pointing to Planck's work – which had already hinted at radiative energy being composed of discrete quanta. If light can only carry energy within a discrete set of energy levels – which are related to its wavelength – then light can only impart the set energy level it is carrying regardless of how intense the light is at that set wavelength.

The photo-electric effect is sometimes pointed to as proof of light having a particle nature – but this is not a mandatory conclusion to draw. Arguably, the photo-electric effect is more an indication of the strangeness of electrons which have their own quantum nature – where they only absorb energies above a particular threshold – at which point they suddenly leap to a higher energy level, literally by a quantum leap – that is a leap without any intervening gradations. This explains both the photoelectric effect and blackbody radiation.

A better case for light's particle-like nature is the Compton effect, where high frequency X-rays and gamma rays have so much energy that they are not fully absorbed by a metal's electrons, but instead bounce back after knocking out an electron. When this happens, it's found that the wavelength of the scattered light is longer – because it's lost the energy the electron has gained – but more importantly the light has been deflected at an angle, like a billiard ball that's hit another billiard ball. This outcome just can't be explained if light acts like a wave – even though it usually does – indicating that light does seem to have little billiard ball-like things which we call photons.

Mind you electrons can occasionally act like waves – for example in the double slit experiment, which was originally used in the eighteenth century to demonstrate that light was made of waves. Ironic, huh?

Thanks for listening. This is Steve Nerlich from Cheap Astronomy, www.cheapastro.com. Cheap Astronomy offers an educational website where we can even confuse ourselves sometimes. No ads, no profit, just good science. Bye.