Hi this is Steve Nerlich from Cheap Astronomy www.cheapastro.com and this is *Fun with photons*

1. *Photons are particles, but massless particles*

Photons don't have mass, but they do have energy – which has a certain mass-equivalence, even though it isn't *really* mass. For example, imagine you explode a hydrogen bomb in a very strong box that is sitting on a large set of scales. Immediately after the explosion, the mass of the box and its contents would not change in the slightest, even though a fair proportion of the matter inside the box has been converted to energy. The box would only begin to lose mass when heat begins to escape from it in the form of photons.

So are those photons carrying mass away from the box? Well no, they are just carrying energy away. When photons were in the box they contributed to the box's total mass, but once out of the box they just contribute a certain mass- energy equivalence to the wider universe.

To bring this idea home, imagine that you microwave a cup of coffee for 60 seconds. Irradiating it with photons, will very slightly increase the cup of coffee's mass. Having given it that additional mass, you can then sit the cup of coffee on a table and it will slowly lose that mass again, as heat radiates away from the cup in the form of photons. So, photons can add and subtract mass even though they themselves never have mass.

2. *Despite being massles, photons do have momentum.*

Anyway, it really is true that photons don't have mass. What they do have is momentum – which is a form of energy. The momentum of photons can be best understood by thinking about solar sails. A photon that strikes a solar sail transfers its momentum to that sail. So a photon with momentum p, gives up that momentum p to the sail when the photon is absorbed.

Remember that momentum is energy, something that is always conserved – it can neither be created, nor destroyed, just transformed. But we haven't finished with the solar sail story yet.

If you have a highly-reflective solar sail, when a photon strikes it, the photon imparts its momentum to the sail and the sail is accelerated forward. But with a highly reflective sail another photon is reflected back in the opposite direction to the sail's motion. Does that mean the sail just loses the momentum that it initially gained? Well no, quite the opposite.

If you imagine the sail as a catcher floating in microgravity, the catcher will be forced backwards as she or he catches the photon. But if the photon is reflected, it's like the catcher is throwing that caught photon back to where it came from. This means that the catcher is once again forced backwards in accordance with Newton's third law of equal and opposite reactions. So a photon hits the reflective sail with a momentum of p, and another photon is reflected backwards with momentum p which delivers a total momentum to the sail of 2p.

The trouble with solar sails is that they can only effectively sail near a powerful source of photons, like the Sun. This is because, as the distance a photon travels increases, that photon loses some of its pushing power, in accordance with the inverse-square law.

3. Intensity and the inverse square law

The power of photons, or the power of light is what is known as intensity. It's easy enough to experience intensity with visible light and it's easy enough to experience the inverse square law too. Up close a bright light is – well, bright. As you double your distance away from the light, it dims not to a half, but to a quarter of its initial intensity. This is best understood by thinking of light as a wave. A circular wave produced by a pebble dropped into a pond declines in amplitude as the radius of the circular wave produced grows outwards. Indeed, that amplitude declines by the inverse square law – until it eventually peters out altogether.

We could just as well say that your retina receiving high amplitude light waves (high intensity) or low amplitude light waves (less intensity), but the convention is that we don't talk about amplitude in relation to light. In fact, we still talk about the amplitude of radio light – and we talk about amplitude modulation – which is also known as AM radio.

4. The Doppler effect.

We know that intensity (which is also amplitude, but what the heck) decreases with distance. But within the same inertial frame of reference, wavelength doesn't change at all. So a light source with a red wavelength, looks like intense red up close and it looks like dim red at a distance – the key point is, it's always red.

But if you are in motion relative to a light source, the wavelength of that light source does change. If you are moving towards it, the light gets blue-shifted. If you are moving away, the light gets red-shifted. And if you come to a halt relative to that light source, the wavelength goes back to being what it originally was.

Of course, that's the Doppler effect. A similar effect, though a bit weirder, is seen when we measure the red shift of distant astronomical objects which are moving away from us due to the expansion of the universe. Since they are moving away, the light from them is red-shifted.

But here we have to stop and think whether this is a simple Doppler effect. The observed motion (indeed the acceleration) of those distant objects isn't because they are moving *through* space-time, but because new space-time is being created between us and them, which is what makes them more and more distant as time goes on. The standard explanation for this red-shift effect is that the expansion of the Universe stretches out a ray of light from a distant source, so that its wavelength is shifted to red.

This is not exactly like the Doppler effect because it's no longer possible to come to a halt relative to that distant light source to enable its wavelength goes back to what it was. In an expanding universe there is no absolute frame of reference against which you can consider yourself to have come to a halt.

5. The end

Indeed, the whole universe seems to be conspiring to make rays of light lose energy over large distances so that eventually the whole universe will grow totally dark and totally cold – and also totally empty after all the baryons decay into more photons which are also stretched into nothingness. So, just as the universe started *from* nothing, the universe will end *with* nothing – never being anything more than just an unusually-protracted vacuum fluctuation.

And that was fun with photons.

Thanks for listening. This is Steve Nerlich from Cheap Astronomy, www.cheapastro.com. Cheap Astronomy offers an educational website where we try to make light of some heavy stuff. No ads, no profit, just good science. Bye.