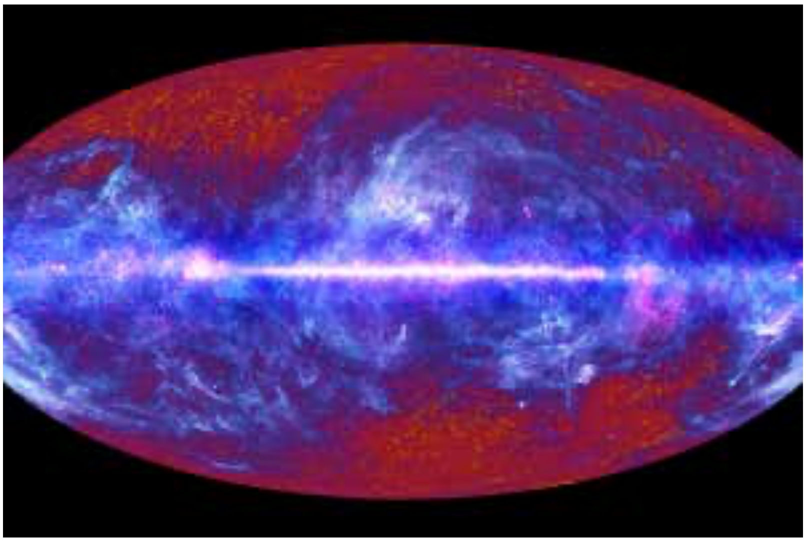
Why the vast emptiness of space isn't really that empty after all

Space-time may seem empty, but the expanse between stars is filled with more interesting stuff than you may think



SPACE-TIME is mostly empty. Though there are at least 100 billion galaxies – each home to around 100 billion stars – and lots of galactic dust, the universe is so vast that there are huge tracts of space-time between every star and more still between every galaxy. Even the nearest star to Earth (the sun) is nearly 150 million kilometres away, meaning the fastest thing in the universe (light) still takes 8 minutes to get from there to here, despite travelling at 300,000 kilometres per second.

It seems like most of what is between Earth and the sun is two other planets – other than that, there isn't much else that we can see. But is space actually completely empty? Not really.

There are a few senses in which we can think of space-time as being teeming with stuff. One is quantum-mechanical in nature. Quantum field theory, the tool we use to study particle physics, says particles flicker in and out of existence, even in a vacuum. In other words, once quantum effects are taken into account, there is no such thing as completely empty space-time. Importantly, these random particles pop in and out of existence quickly and are unable to have a meaningful impact on phenomena that we might notice. And they aren't something big, like a star suddenly appearing and then disappearing.

There is another way in which the universe is fundamentally full of things. For almost 80 years, we have been getting to know an all-pervasive type of light that we scientists call the cosmic microwave background radiation, or CMB. Like many things in science, the CMB was first detected by accident. The first hint was from Andrew McKellar's 1941 observations of the region around a star. He noticed that rather than being a temperature of absolute zero on a Kelvin scale, which is what you might expect from empty space, it was about 2.3 Kelvin, or -271°C. About a decade later, theoretical physics caught up, using simple cosmological models to predict the existence of a radiation that is everywhere in the universe.

Then, in the 1960s, Arno Penzias and Robert Wilson were taking some measurements using a radio telescope when they noticed a background noise in the signal that wouldn't go away. The structure of the signal meant that its wavelength could be associated with a temperature. They found the temperature to be about 3.5 Kelvin, in effect rediscovering McKellar's original measurement. In the decades since that moment, we have launched multiple space telescopes to measure this radio signal more closely, and the CMB has become an incredibly important tool in observational cosmology.

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These instruments include the NASA Cosmic Background Explorer, or COBE, which found that the CMB's temperature is about 2.73 Kelvin and is around the same temperature everywhere in the sky no matter what direction we look in. In other words, the universe is filled with photons from the CMB. COBE also first verified an idea from cosmological theories suggesting there would be extremely small variations in the temperature.

These variations are part of what makes the CMB so important as a tool. Our theories tell us that the CMB originates from a time when the universe was so hot that it was filled with a plasma of light and matter particles. This plasma was so dense that light couldn't travel very far without colliding with a particle. As the universe cooled, the light and particles decoupled and the universe became transparent to the light.

The CMB is that light, stretched over time, providing us with information about what the universe was like when it was only 400,000 years old. The little variations in the temperature are evidence of quantum fluctuations that we expect to be the source of how structures – dust clouds, stars and then galaxies – began to form.

Since COBE became operational in 1989, NASA has launched the Wilkinson Microwave Anisotropy Probe (WMAP), which studied those small fluctuations in more detail until 2010. Most recently, NASA supported the European Space Agency's Planck space observatory, which shared WMAP's mission but completed it with more sensitive instruments.

Today, CMB measurements are important evidence that confirms our theoretical models about the history and timeline of structure formation. The measurements are consistent with our observations of the presence of dark matter and the mysterious dark energy phenomenon too. Importantly, Planck information is also playing a role in the debate about the measurement of the Hubble-Lemaître constant that I mentioned a few columns ago.

As such, it is a good thing that while the universe looks mostly empty to the human eye, it is, in some basic sense, teeming with light – and useful light at that!