background sheet

The physics behind *Measuring time*

Associate Professor Andre Luiten was awarded a PhD in 1996. For his PhD project he built the world's best clock based on a cryogenically cooled sapphire crystal. The performance of the clock means that it will only be in error by a second over 100 million years. The Australian Institute of Physics awarded him the 1997 Bragg Medal for Physics for this research. In 1998 he built the world's best atomic clock in collaboration with the Observatory of Paris. Comparisons between his sapphire and atomic clocks have yielded the most sensitive tests ever performed on Einstein's special theory of relativity.

The following text is a transcript of the video, *Measuring time*, in which Andre describes motivations for his research.

Superscript numbers in the text (eg relativity[1]) refer to the explanatory notes that follow.

Measuring time

There are two great theories of physics today: general relativity[1], which describes the universe on a grand scale; and quantum mechanics[2], which describes the universe on a microscopic scale.

The remarkable thing is that these two theories are fundamentally contradictory[3]. When we try to explain things where they both apply, they just refuse to work together. In addition, as we've learnt more and more about the universe it seems to be getting still more complicated. Dark matter[4], dark energy[5] and a whole host of hundreds of fundamental particles[6], and no way to put it all together. I think that most of us are convinced that there is a new level of understanding which will unify all these laws and phenomena. The problem is how to break through into this new level of understanding.

So you may ask how we research these fundamental laws of physics. Well, one could just sit, and think, in a room. And, if you're very smart, then perhaps the truth will come to you. In our case we're not smart enough to do this, and anyway we'd get lonely sitting in a room alone. So what we've done is join together in a big team to try and make extremely accurate measurements to find where Einstein went wrong[7], for example, or to find out where our understanding of the world of atoms is incorrect.

For example, here we are at Winthrop Tower at UWA. Einstein has told us that, up here, time should flow around 30 billionths of a second [per year] faster, because gravity is a little weaker[8]. Well that's pretty difficult to measure. What we want to do is put our clock onto the International Space Station where time should differ by about a millisecond per year. That's easy for us to measure, because our clock is capable of measuring just a few billionths of a second. In my laboratory we are building several different types of clocks, so that we can test the laws of physics.

The first type of clock[9] we're building is based on a piece of sapphire crystal about the size of your fist, cooled down to 40 °C above absolute zero. With this clock we can measure time with an accuracy of just one second in three hundred million years. But for us this still isn't good enough. So now we're trying to build a new type of clock based on light and atoms that have been cooled to within a few millionths of a degree of absolute zero. We predict that we should be able to measure time with an accuracy of ten to a hundred times better than with the sapphire crystal.

But you might ask why we're building these super accurate clocks. Well, they find use in systems like communications, radar and global positioning satellites systems, all of which could be improved if they incorporated our super accurate clock. At a more fundamental level we're interested in subjecting the laws of physics to the greatest scrutiny that they've ever been put under. For example, I told you earlier about how there was a conflict between relativity and quantum mechanics. One of the outcomes of that conflict is that the laws of physics might not be the same depending on where you are when you make the measurements, or in which direction you make the measurements. Using our clocks and comparing the time kept by the various types of clock we can actually find evidence of this next level of understanding of the universe.

Explanatory notes

1. General relativity

Einstein realised that the 'gravity' we feel is just acceleration we experience as we move through spacetime. This is known as the equivalence principle, and is the basis of Einstein's general theory of relativity. Previously, Einstein's special theory of relativity proposed that time and distance are not absolutes, and measurements of them will differ for different observers.

So if gravity is equivalent to acceleration, and motion affects both time and space, then it follows that gravity also affects time and space. This means that masses will distort spacetime around them and time will progress at different rates in different parts of a gravitational field! As strange as they are, these predictions have been verified by observation.

2. Quantum mechanics

Quantum mechanics describes interactions between energy and matter at the atomic and sub-atomic scale, such as electron transitions between energy levels of an atom. The effects of quantum mechanics are only observable at atomic and sub-atomic scales.

3. The two theories are fundamentally contradictory

General relativity describes physics on a grand scale (ie the Universe). It describes a continuum of space and time. Predictions made on the basis of relativity focus on 'cause and effect' relationships.

Quantum theory describes a world in which some states are allowed and others are prohibited (for example, electrons can only exist in certain energy levels in the Bohr-Rutherford atom). Predictions made on the basis of quantum theory focus on the probability of an event occurring.

General relativity and quantum mechanics have both been verified experimentally. However, when we try to explain situations in which both theories apply, they don't work together! Andre Luiten and other researchers are striving to resolve differences between these theories.

4. Dark matter

About 75 years ago astrophysicists observed a galactic cluster that appeared to have much more gravitational force than expected from the mass of its visible stars. Dark matter was proposed to explain the 'missing' mass.

Dark matter is so called because it doesn't interact with light. It makes up an estimated 23% of the mass-energy of the Universe[a]. Dark matter is thought to be composed of sub-atomic particles that interact only weakly with ordinary matter. Neutrinos, which have little interaction with normal matter, could account for a small proportion of dark matter.

5. Dark energy

In the 1990s, astrophysicists observed supernovae in an effort to study the expansion of the Universe over relatively recent times. They were surprised to discover that the expansion appeared to be speeding up, rather than slowing down!

In 2003, scientists determined that dark energy accounts for 72% of the mass-energy of the Universe[a]. We know little about dark energy, but it is thought to be a gravitationally repulsive force that causes the Universe to expand at an ever-increasing rate.

The remaining 5% of the total mass-energy of the observable Universe is made up of ordinary atoms[a]. These are the building blocks that make up visible matter such as stars, planets, moons and you.

Think about it, only 5% of the Universe is visible. How amazing is that!

6. Fundamental particles

Fundamental particles are those that do not contain smaller particles. Protons, neutrons and electrons were once thought to be fundamental particles that make up all matter. We now know protons and neutrons are composed of smaller particles, but we do not yet know if electrons are fundamental particles.

The current theory of matter, called the Standard Model, tells us that all matter is made up from six quarks and six leptons held together by forces carried by particles called bosons[b].

Gluons, photons, and W and Z bosons are particles that carry the strong, electromagnetic, and weak forces, respectively.

7. Einstein went wrong

Andre's statement is deliberately provocative. We have no evidence that Einstein's theories are wrong, but we do know that they can't be the complete picture. Throughout scientific history, we have overlooked things or made errors when explaining observations and we are still discovering how limited some of our understandings are. We have already seen how the GPS system could easily have failed if the effect of gravity on time had not been considered.

8. Time is faster because gravity is weaker

The general theory of relativity tells us that time slows down more in stronger gravitational fields. A clock at the top of Winthrop Tower will run faster because it is further from the centre of the Earth, and therefore in slightly weaker gravity than at ground level.

But wait; there's more! The special theory of relativity tells us that time runs slower when objects travel faster. The clock at the top of the tower moves at a slightly faster speed than one at ground level because it has to travel further each time the Earth rotates. This extra speed has the opposite effect and makes the clock at the top of the tower run slower.

9. Sapphire clock

All time measurement is based on a repetitive element, such as the swing of a pendulum in a grandfather clock. Since the 1960s, atomic clocks have used the natural oscillations of radiation emitted by caesium atoms.

A sapphire clock uses repetitive bouncing of microwaves pumped inside a sapphire crystal. When the artificially grown sapphire crystal is kept at a very low temperature, the number of 'bounces' of the microwaves within the crystal can be used for very accurate time keeping. Andre Luiten's team at UWA has made the world's most accurate clock, measuring to within one second in 300 million years.

References

a) NASA/WMAP Science Team. 2008. *Content of the Universe*. Retrieved 27 Oct 2009 from http://wmap.gsfc.nasa.gov/news/

b) Lawrence Berkeley National Laboratory. 2009. *The particle adventure*. Retrieved 27 Oct 2009 from http://particleadventure.org