Dark Matter in the Universe

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Mijnheer de Rector Magnificus, geachte collegas, dames en heren,

You've just heard about our universe from my favourite colleague, and in particular about the puzzles that astronomy is throwing at physicists these days. We're happy to oblige!

Astronomy is an amazing branch of science. It is certainly physics, but unlike the terrestrial branches of the subject, it gets its information solely from distant observations. We astronomers cannot build a laboratory in which we control the conditions of an experiment, to isolate one or other phenomenon. We cannot vary parameters at will, and see how our experimental setup reacts. We cannot even walk around our experiment and look at it from all sides; we cannot get inside it to see how things work. We often cannot even control exactly what we measure. And many important processes happen so slowly that we cannot watch them happen directly.

A nice example is a galaxy. Galaxies consist of 100s of 1000s of millions of stars, and most have the shape of a rather thin disk of stars, about 10x thinner than its diameter. A bit like this frisbee, but much much bigger. (I could have brought a nice spanish potato omelette instead, but unfortunately my usual supplier was busy).

The stars in a galaxy all attract each other gravitationally, so the galaxy would like to collapse inwards. It does not because it is rotating. Just like the moon orbits around the earth rather than falling onto it, the stars orbit around in a galaxy disk. The timescales are very different though: while the moon completes an orbit in about a month, the stars in a galaxy take 100s of millions of years per revolution.

That is the model, our idea of how galaxies are. But that is not what we see. What we see is a projection of this disk onto the sky: so instead of seeing a round disk, we see a more-or-less flattened shape on the sky, depending on where you observe from. [demonstrate with a frisbee] While my colleagues on the side there see a rather round disk, you in the middle see a thin line; or it could be the reverse.

We also cannot wait many millions of years to watch a star complete a revolution (particularly since the Rector insists that Ph.D students finish their thesis on time). But we CAN measure the speeds with which stars move towards us or away from us, using the Doppler effect. (remember the ambulance siren in Ana's talk --- though I prefer to use the sound of a Formula 1 car as an example). Light gets slightly redder or bluer depending on the speed of the source towards us. So we can see the effect of the rotation as a redshift of the light on one side of the disk, and a blueshift on the other. The effect is quite small (60x smaller than a semi-tone), but clearly measurable with spectrographs. We can only see the motion along our line of sight this way; the motion across the sky we need to imagine.

So that is what we observe: a lot of elliptical sources, of varying shapes, where one side appears to move towards us, and the other side away. No information on the distance down the line of sight (no perspective), or about the motions in the plane of the sky, which are far too slow to detect. Our picture of circular, rotating disks only emerges once we add physical intuition, some general assumptions about random orientations, equilibrium, gravity, etc.

This was just a simple example of how we need to INTERPRET what we see: I could instead have picked double stars, our sun (we only see the surface, but have good reason to think we understand the physics all the way into the center), supernova explosions, etc etc. In the case of galaxy disks we can be pretty sure that the global picture is correct, but in more complicated objects, particularly ones with important structure on scales too small to see directly, or ones that are far from equilibrium, the limitations of our `experiments' can be quite severe. The line between imagination and fantasy can be a thin one!

In astronomy all we can do is look, and interpret. It is as if we hear an orchestra, and, only through listening carefully, we try to deduce all we can about it: the kind of instruments, their number, how they work, the acoustics of the room, the temperature, the composition of the air in the room, how far away the orchestra is, etc etc, all the way to the proverbial colour of the conductor's eyes. One can push this analogy quite far. Hearing is a decomposition of sound waves into many different frequencies, and this spectrum is what gives sound its `colour' . Depending on the shape of an instrument, and the way it is played, a different colour of sound emerges. On its way to us this sound is further modified: it refracts around corners, reflects off surfaces, gets partially absorbed, provokes resonances, and mixes with noise from all kind of different sources. Finally, once it gets to our ear, the sound is detected, and the spectrum registered somehow by our brains. Our brains have been trained to recognize a violin from a bassoon, a harpsichord from a piano, a trumpet from a flute; and with experience even very subtle differences between instruments, such as the material a violin's strings are made from, the way a piano has been tuned, or the voice of a particular soprano, can be recognized.

Astronomical observations are quite analogous.

Of course the point of music is not to listen to it so analytically; fortunately also astronomical observations can give esthetic pleasure in addition to their cold analytic function! I am only sorry not to be able to show you some pictures here today. Astronomy is fortunate in that it is a very appealing science to the public at large. Even in the cloudy Netherlands, people know and wonder about the planets, the stars, the sky, life beyond the earth, etc etc. Spectacular pictures of celestial objects easily spark the imagination and stimulate curiosity, and not a week goes by without some new discovery that makes it into the newspapers.

This week is no different.

Right now, about 1.5 thousand million km away two fantastically sophisticated robots are surveying perhaps the most spectacular and the most enigmatic objects in the Solar System, the planet Saturn and its biggest moon Titan. Titan is about three times as small as the Earth, and has a dense atmosphere. Because it is much further from the sun it is a lot colder, which has slowed down its chemical evolution. It is therefore of particular interest, as it may resemble the early earth.

The climax of the mission should have just happened. If all has gone well, the Huygens probe, built by the European Space Agency and named after the man who discovered Titan 350 years ago, has just parachuted down through Titan's atmosphere. It should now be sitting somewhere on the surface. The data it has collected should be arriving about now. Unfortunately we're all here in this aula, and so we don't yet know what happened; but it's fascinating.

By the way, those who are interested may want to go to the lectures tonight in the Lipsius building, or go to the old observatory to see Saturn through the telescopes there.

Let me turn now to a description of some of my own research.

My main interest is in the distribution of dark matter in the universe. In the coming years I will mostly concentrate on studying this with a new instrument, OmegaCAM, using the technique of gravitational lensing. So let me tell you a little about dark matter, about OmegaCAM, and about gravitational lensing.

First, dark matter.

Dark matter is matter that does not shine (for once astronomers have chosen clear terminology!). Since the 1980s it has been clear that galaxies exert much stronger gravity than you would expect if you simply count how many stars they contain. This is particularly true in the outskirts. One obvious explanation is that there is an extra source of gravity, which we cannot see: hence the concept of dark matter. Because the discrepancy is greater in the outer parts, the dark matter would have to be located around the galaxies, and not so much inside them: so we talk of giant dark halos inside which the galaxies we see are embedded. In our own galaxy we can trace the disk out to some 60.000 lightyears from the center; the dark halo extends 10 times further at least, and is about 10 times as massive as the visible part. This frisbee, which represents the stars that you see, is thus surrounded by a huge ball of dark matter, several meters across.

In astronomy, the first encounter with dark matter was the discovery by Galle of the planet Neptune in 1846. Neptune's existence had been predicted as an explanation for a small deviation in the orbit of Uranus: so its gravitational effect was detected first. It is still the only case of dark matter that has been identified.

Incidentally, while I was a student at Cambridge I frequently used the beautiful, historical Northumberland telescope, a 6-m long wooden 12-inch refractor telescope dating back to 1838. It sits in a huge dome on the lawns of the institute of astronomy there, and is still regularly used by the student amateur astronomy club at the university. It played a bittersweet role in the discovery of Neptune [1]. In 1846, after it had become clear that the orbit of Uranus deviated a bit from its predicted orbit, both Adams in England and Le Verrier in France calculated that the pull by a new planet, orbiting about twice as far as Uranus around the sun, could be the explanation. Both figured out roughly where this new planet should be. In England Adams asked Challis, then head of Cambridge observatory, to search for the new planet in the predicted place on the sky, and Challis reluctantly agreed, later writing that

"It was so novel a thing to undertake observations in reliance upon merely theoretical deductions; and that while much labour was certain, success appeared very doubtful."

(those of you who have served on telescope time allocation panels will recognize the sentiment)

The technique was simple: search the sky near where the new planet should lie, and look for an object which moves from one night to the next (a planet should move; stars not). Challis observed on four nights that summer, and to test his methods he compared the positions of some stars on the various nights. His method appeared to work, but for some reason he did not finish the job; looking over his records, we now know that he did observe Neptune, and had he completed the analysis he would have found it.

In September, Challis and the Northumberland telescope did it again. Le Verrier had published a paper explaining that the planet should be so big that it would look like a little disk in a good telescope. This meant that it could be identified directly -- no need to compare positions night by night. On September 29 Challis observed again, and soon noticed that one `star' appeared like a small disk --- but before claiming the discovery he wanted to repeat the observations on another night to see whether this object indeed moved, as it should if it were a planet. This caution cost him the discovery: meanwhile Galle in Berlin had also read Le Verrier's paper, started observing with his own telescope, and very quickly found the new planet. Before Challis could observe again, the discovery was announced in the Times.

If Challis was annoyed and frustrated at having missed his chance at eternal fame, and comes across as a scientist without what we would today call the killer instinct, the same cannot be said for another astronomer of the period, John Herschel. He was the son of the great William Herschel, the discoverer of Uranus in 1781. As soon as John Herschel saw the announcement of Neptune's discovery, he contacted William Lassell, an amateur astronomer who had recently completed a large telescope, and told him to

"Look out for satellites with all possible expedition."

Ten nights later, the biggest moon of Neptune (Triton) was discovered.

I have included this tale for its obvious lessons (don't be afraid to test new theories; pick your collaborators wisely; analyse your data; go for success), and to illustrate that the search for dark matter is an old, hard, and painful one.

But now, back to the galaxies.

By studying the speed with which stars and gas clouds move around in galaxies, it is possible to deduce how strong the force is that causes this motion (just as the orbit of Uranus revealed how strong that planet was being pulled by Neptune). Simply put, if stars move around very fast in a galaxy, then that galaxy needs to pull quite hard to stop the stars from escaping; hence it must be heavy. On the other hand, if the motions are very slow then the mass of the galaxy cannot be too high or all the stars would quickly sink into the middle.

It is now clear that galaxy clusters (studied by Zwicky in Harvard in the 30s) and spiral galaxies (particularly from the work in the 1980s at the Kapteyn Institute) are embedded in very extensive massive halos of dark matter. The same is now known to be true also of elliptical galaxies, galaxy groups, etc etc --- in fact it appears that everything in the universe that is bigger than a few thousand lightyears contains a lot of dark matter.

We have very little idea what the dark matter is made of. The most plausible candidate is a kind of particle that pervades space but barely interacts with anything else, and so is very hard to detect in any way except via its gravity. Ever-more sophisticated laboratory searches have been going on for decades, but nothing has been found yet. It's still a mystery, and an important one: not only may it point the way to a new sector of particle physics, but the dark matter is also a crucial ingredient in the formation of galaxies. The dark haloes form first, and these then determine through rather messy physics how the galaxies form inside them. In order to understand how galaxies form, therefore, we need to know what the halos are like: what are their masses, shapes, sizes. This is what we intend to study with OmegaCAM.

The OmegaCAM project, which I lead, is building a very large digital camera for what is called wide-field astronomy: taking pictures of large parts of the sky. Where a normal commercial digital camera will use a detector with some 4 million pixels, OmegaCAM has 268 million, super-sensitive, pixels. Each image will occupy 1000 MB of data, more than can be held on a single compact disk. If you were to display an image at 2 pixels per mm, similar to TV resolution, you would need a wall of 8m wide and 8m high!

OmegaCAM will operate on a new telescope being built for the European Southern Observatory, arguably the most sophisticated astronomical observatory on Earth, in northern Chile. Each OmegaCAM image will reproduce a square piece of the sky that measures a degree on a side.

If you go to a planetarium, you see the sky projected onto a dome, maybe 5m in radius. Each OmegaCAM image corresponds to an area of about 10x10cm of that dome - what I have been calling large is in reality still quite a small piece of the sky! It requires 40,000 images, one next to the other, to cover the whole sky.

The sensitivity is such that after an hour's exposure, each image will contain about 100,000 different sources, from nearby stars that are part of our own galaxy (10s to 1000s of lightyears away), to relatively nearby galaxies (up to 100 million lightyears away), and all the way out to the edge of the observable universe, some 13000 million lightyears from us. Such huge images are a gold-mine of information, but they also present a formidable data handling problem, which particularly the Dutch part of the OmegaCAM team has been working hard to solve. It is a tribute to the current state of computer science that it is even possible to contemplate working with such a huge dataset, and `mining' it for astronomy. Let me give you an example of what we will be able to do.

Most of the stars in the galaxy are intrinsically very faint, and of lower mass than the sun. Some of them are so light-weight, more than twelve times lighter than the sun, that their centers do not get hot enough to ignite the nuclear reactions that make the stars shine brightly. Such objects are called 'brown dwarfs' (I told you that nomenclature in astronomy is not always very clear). They may well be quite numerous, but they are very hard to see because they are so faint (they are more than 1000 times fainter than the sun, and look much redder). Only the ones that are very nearby can be seen at all. Now, the sky is full of very faint sources, but most of these are intrinsically quite bright galaxies, that just look faint because they are at enormous distances. How can you weed these few faint brown dwarfs out of 100s of thousands of sources?

One method is to use colour, and select the reddest sources. Unfortunately brown dwarfs are not the only red objects in the sky, and they are rare enough that most of the red sources will be something else entirely. In fact, some of those can be very interesting in their own right: the most distant and luminous quasars in the universe also look very red!

The trick is to turn the faintness of the brown dwarfs to an advantage. Any brown dwarf we can detect at all must be quite nearby, no more than a few 100 lightyears. All stars move in the galaxy, (typical speeds of about 30 km/s), and this makes them shift their position very slowly on the sky. For distant objects this change in position is immeasurably small, but the closer an object is, the faster it appears to move across the sky: think of an aeroplane which creeps slowly across the sky when it cruises far overhead, but appears to move very fast when you're watching it from close to the runway. So we can pick out the nearby objects by looking for things which move. It turns out that over a couple of years, anything within a distance of a few 100 lightyears will move by a measurable amount. So comparing two images, taken two years apart, is all that is needed. It is Challis's method again!

We expect to find a brown dwarf in about 10% of all OmegaCAM images. To collect a useful sample of 100 brown dwarfs then requires 1000 images.

To find these one-in-a-million sources requires advanced computer techniques. Clearly it is not possible to look through 1000 pairs of these huge images yourself: instead all needs to be computer-analysed, so that a list of moving sources can be generated quasi-automatically. In such a huge data processing task, quality control is vitally important: we want to be sure that each `brown dwarf' that we discover is not one of the millions of other sources in which there was a problem with measuring the position! So one of the key elements of the system we're developing is a very close integration between the database where all images are stored (Terabytes and Terabytes of them), and the sophisticated data processing pipeline that is used to analyse the images, so that all stages of the data processing can be easily checked.

So much for OmegaCAM. The instrument, which has been built and financed by a team of people in Germany, Italy and the Netherlands, is at the moment sitting in a lab at ESO in Munchen, undergoing testing. It is expected to be shipped to Chile later this year, and to start operating early in 2006.

My main use of OmegaCAM will be to make a large gravitational lensing map of several 1000 square degrees, a project which I have called KIDS (Kilo-Degree Survey). With this project it will be possible to measure accurately how the galaxies that we see are surrounded by dark matter. Let me try to explain how this works.

Gravitational lensing is the effect that light rays are bent by gravity. If I shine a light beam past your head, the light feels the effect of your head's mass, and is slightly attracted towards it. (illustrate with beret?) As a result the lightbeam changes direction slightly, bending towards you. If you have a heavy head, the attraction is stronger; on the other hand if you have a big head, the effect is weaker (big empty heads are the worst). Now, in high school physics we've all learned about lenses: they deflect light beams, and focus them. By analogy we call the light deflection due to gravity 'gravitational lensing'. If you do the calculation, you find that your head has a focal length of about 1000 million lightyears (use this at parties if you want to impress someone).

If you observe a distant galaxy that lies behind a gravitational lens, then the light that was originally aimed at you will be deflected, and will not reach your eye or telescope; on the other hand, light that was aimed a bit further away from the lens, and would have missed you, is now deflected by the lens back towards you. The effect is therefore that you see everything slightly further away from the lens than you would have expected. It is as if the lens pushes the images of the background sky away. Along with that push comes a squeeze: the lens distorts the sky, and so alters the apparent shapes of the background sources a little bit, tending to form a pattern of little arcs around the lens. The best demonstration of the effect is to look through the foot of a wine glass --- we¥ll give you your experimental apparatus in a few minutes.

Stars like the sun act as gravitational lenses, and so do galaxies, groups of galaxies, in fact any concentration of matter will have the tendency to deflect light that passes. In the KIDS project, the idea is to map a large part of the sky, and divide the many sources that we see into a set of nearby galaxies (the foreground lenses) and a set of more distant ones (the background galaxies).

The game then will be to find systematic distortions of the background sky near foreground galaxies --- basically to look statistically for the systematic pushing away of the background sources due to the lensing effect, and the associated squeezing of the source shapes. I will not try to explain how that is done, but a quite beautiful mathematical formulation underlies this technique. If it works, then we will be able to say what the masses, shapes, and sizes of the dark haloes around different types of galaxies are. We'll learn how much of the dark matter in the universe sits in dark haloes, and how much floats in between the galaxies. We can even literally make maps of the dark matter --- we will have brought it to light!

The project will start next year, and should be very competitive with similar ones going on elsewhere in the world. A lot of people are already involved, and we're always looking for more: in Challis's words, much labour is certain, but I do not think that success is doubtful. It will be exciting!

But now for something completely different.

Yesterday I heard a news item on the BBC world service about the start of the world year of physics, which celebrates the 100th anniversary of three of Einstein's most important papers. It included an interview with Frank Wilcek, one of last year's physics nobel prize winners. He was asked to describe the importance of Einstein's work, which he did very well, in laymens' terms. However, as often happens after science stories, before turning to the next item the presenters could not resist a little comment to each other, making fun of themselves for not understanding him, while implying this was not important.

Unfortunately this is symptomatic. In educated circles it is socially unacceptable to be unread, not to know the great philosophers, composers, painters or authors, or not to know your history; but being scientifically illiterate can be shrugged off with an "I was never good at maths" or an "ooo, that is all far too difficult for me". Scientists are all too often seen as men (or women) in white coats, working anonymously in laboratories. Often a news report on a new discovery will simply say "Scientists have discovered..." without even mentioning the name of the people involved, or the institute at which they work. Can you imagine a news story that says "A politician has announced new plans for a wind park", or "An orchestra performed a symphony last night", let alone "A football player succeeded in scoring a hat-trick in Amsterdam yesterday" ?

Another frequent problem is a poor understanding of the scientific method. During the Mad Cow Disease crises a few years ago, there was a period where it was not clear how dangerous BSE was for humans. Many press interviewers seized on the point that `experts disagreed'. But science advances precisely in this way, by confronting experts who honestly disagree, and then figuring out new arguments, tests or experiments from which to learn more. Research consists not of collecting `facts', but of posing question after question --- the best researchers are not those with the best answers, but those with the best questions.

Sadly the media rarely succeed, in my view, to convey the true excitement of scientific discovery, and this is tragic. The story of scientific discovery can be entertaining, but it is so much more than entertainment. All too often these days a documentary about the latest discoveries out of CERN, the Hubble Space Telescope, or whatever, is dramatized to the extent that the only thing missing to make it a good Hollywood B-film is the love story! (and perhaps that is only because of the shortage of women in the physical sciences?). Is this how children are to be encouraged into the sciences?

Honestly, the real stories of discovery are exciting enough that they can be told without embellishments, particularly in astronomy.

I am coming to the end of my lecture. Time for some words of thanks.

In the gravitational dynamics first worked out by Newton over 300 years ago, the orbits that two bodies describe around each other are perfectly regular: both describe periodic orbits around a fixed point, without ever touching or getting too far away from each other. Such a dynamical system is a rather poor analogy to the typical life of an academic couple! Rather than being perfectly predictable and regular, the 2-academics system behaves chaotically: small differences in the initial conditions can cause dramatic differences in the future evolution of the system, and can even lead to its total dispersion. Fortunately this is not the only possible outcome. Sometimes it evolves apparently chaotically for a while, but then settles down to making mostly small oscillations around a fixed point, with the occasional large excursion. In this configuration it is even possible to add little satellites that remain part of the system, for a while anyway.

We are fortunate indeed to have found in Leiden such a fixed point, and to have put a rather chaotic phase in our lives behind us. I'd like here to thank all those that helped make our simultaneous appointments possible, and those in Groningen and Bilbao for their understanding when we left. I also hope that our example is encouraging to those who are now in the situation we found ourselves in a few years ago...

Happily research is not a lonely business, and I am grateful to acknowledge the collegiality, help, wisdom, insight and experience of many friends and colleagues with whom I have worked over the years, particularly at the Institute of Astronomy in Cambridge, at the Canadian Institute for Theoretical Astrophysics in Toronto, at the Harvard-Smithsonian Center for Astrophysics in the other Cambridge, at the Dept of Theoretical physics at the University of the Basque Country in Bilbao, at the Kapteyn Institute in Groningen, and now here at the Sterrewacht in Leiden. It has been, and still is, a particular pleasure to work with a series of bright undergraduate and graduate students, and to feed off their enthousiasm. Long may it last.

The final words of thanks, however inadequate they are, go to my parents and to Ana. You have always worked to create an atmosphere of support and encouragement. This is very easy to take for granted, but it would be terrible to have to do without it. I will always be grateful.

We still owe you the answer to the riddle posed by Ana at the beginning of her lecture: we'll be glad to reveal it over a glass of something at the reception next door, to which you are all warmly invited.

Ik heb gezegd.

Reference:
[1]   J J O'Connor and E F Robertson, http://www-groups.dcs.st-and.ac.uk/~history/HistTopics/Neptune_and_Pluto.html