Physics for the 21st Century

Unit 10: Dark Matter

Doug Finkbeiner and Rick Gaitskell

Most of the matter in the universe is not made up of the normal matter that makes up stars, gas, dust, planets and people.

> RICK GAITSKELL: *It's something else. It's known for want of a better word as dark matter.*

> DOUG FINKBEINER: *What is dark matter? You lose sleep over this stuff.*

Scientists are determined to find out what dark matter is, and much of their research is pointing them towards a particular non-luminous particle.

> RICK GAITSKELL: *I think it's fair to say that the most favored candidate, which seems to be extremely strongly supported by particle theorists that we currently have, is what's known as the WIMP, the weakly interacting massive particle.*

Doug Finkbeiner, of the Harvard-Smithsonian Center for Astrophysics, may have found evidence of WIMPs colliding in the form of an unexplained brightness near the center of the Milky Way, known as the haze.

> DOUG FINKBEINER: *This is the money plot. Do I actually think it's dark matter? Well, just between you and me…*

> RICK GAITSKELL: *Here we go, 4850.*

Rick Gaitskell, of Brown University, is working to design an experiment to be assembled nearly one mile below the ground in an effort to block out enough background noise that they will be able to detect WIMPs interacting with normal matter.

> RG: *We are building what will be the most sensitive dark matter detector in the world and, therefore, if there is a dark matter signal out there, there is every prospect of us seeing it.*

Two scientists, one looking to the cosmos, the other going deep underground, both with the possibility of revealing new information about what the majority of the matter in the universe is made of.

Part I: The Haze

Doug Finkbeiner

In the early 1930s, while observing the 1,000 or so galaxies in the Coma Cluster, astronomer Fritz Zwicky observed that the galaxies at the edge of the cluster were orbiting its center of mass much more quickly than predicted, unless the cluster contained a lot of matter in regions not emitting visible light.

Zwicky suggested that, "further study would be in order."

Zwicky's research lay virtually untouched until the 1970s when astronomers Vera Rubin and Kent Ford, while observing gas clouds around Andromeda and other galaxies, detected similar discrepancies between the expected orbital velocities and the velocities they observed. Rubin and Ford concluded that when studying a single galaxy, astronomers observe only about one tenth of the total mass needed to explain how fast individual objects are rotating around the galactic center.

Scientists now believe the best explanation for this and other observational anomalies in our universe is that there is some other form of invisible or dark matter.

No one has ever directly detected dark matter, but astrophysicist Doug Finkbeiner, like Zwicky, Rubin and Ford before him, may have happened upon a significant clue.

> DOUG FINKBEINER: *Well it's certainly true that the most interesting thing you find is often the thing you weren't looking for. I really wasn't looking for dark matter at all. I wasn't thinking about dark matter. I was looking at the WMAP maps.*

WMAP, which stands for Wilkinson Microwave Anisotropy Probe, is a NASA satellite, which produced the first fine resolution full sky map of the microwave sky.

> DOUG FINKBEINER: *This is the sky as WMAP actually observes it. You see here a map of the whole sky. Red means more emission. Blue means less. And, there's this band across the galactic plain. Since we're sitting in the disc of a galaxy and we look out, we see emission everywhere aligned with that disc, especially in the center of the galaxy here.*

Like looking through a dirty window, foreground emissions from our galaxy, the red stripe across the center of the map, diminish our view of the

oldest light in the universe, the cosmic microwave background, or CMB. Finkbeiner and his colleagues are carefully peeling away the foreground signals of the Milky Way to build a clearer view of the CMB.

> DF: *And so, I was studying these foreground emission mechanisms, trying to understand everything we can about this emission in the galactic plain. Well, everyone else was looking at the extragalactic cosmological signal. And so, this was really just kind of a sanity check to make sure that everything made sense.*

To subtract out the foreground emissions, Finkbeiner uses other full sky maps taken at different wavelengths by different surveys. By using the information on these maps he can calculate the equivalent microwave emissions on the WMAP and subtract them out.

> DF: *This is a map of infrared emission from dust grains all over the sky. So, this is a full sky survey. And, you can see there's dust not just in the galactic plain, where it appeared in the WMAP maps, but at high galactic latitudes away from the plain. So, there's dust everywhere.*
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> *So, this map of dust allows us to subtract the microwave dust emission from WMAP.*

In addition to removing the dust emissions, Finkbeiner also needed to remove emissions from ionized gas.

> DF: *This is a map of ionized gas. We can use this to estimate the microwave emission from ionized gas, which is the other most important component and subtract that from the WMAP maps.*

Once Finkbeiner subtracts out the known emissions of dust and gas from WMAP, he is left with this image, in which most of the emission in the Milky Way is masked out. But there is one more major emission source that needs to be accounted for -- synchrotron radiation

Synchrotron radiation is electromagnetic radiation that is generated as charged particles moving near the speed of light spiral around the lines of a magnetic field.

> DF: *And so, these charges spinning around the magnetic field -- they're essentially vibrating as they go around in the loop, and those vibrating charges are making photons.*

To account for synchrotron radiation, Finkbeiner uses the Haslam map, which is an all sky survey of radio emissions.

DF: *Synchrotron emission can produce electromagnetic radiation of nearly any frequency. It can be visible light, x-rays. It can be anything. But the Haslam map is supposed to trace the ordinary synchrotron emission from ordinary mechanisms like supernova shocks. So now we've taken out the dust, we've taken out the ionized gas. We also have to remove the synchrotron emission.*

By subtracting out the synchrotron emission, Finkbeiner thought that all of the foreground emissions on WMAP would be accounted for and expected to see a zero foreground signal.

Instead, this is what he found.

DF: *So, one of the great things about science is when you're surprised. And, this was definitely a case where I expected the WMAP foregrounds to look like the sum of gas, dust, and synchrotron. And, they don't. Here, we have this excess does not really look like the Haslam map we just looked at. In particular, there's too much down here inside this box.*

And, we call that the WMAP haze. And it's a mystery.

So, I didn't think it could have to do with dust. So my first thought was ionized gas. But there are reasons that that's impossible. The gas would have to be very hot to be able to explain why we didn't see it in the ionized gas map. One possible explanation for this excess is synchrotron emission from dark matter annihilation.

Annihilation is what happens when a particle meets its antimatter partner. For example, when an electron and its anti-matter partner, the positron, collide, they annihilate, creating new particles.

Dark matter particles could be their own antimatter partners; therefore annihilation could occur if two dark matter particles collide.

Greg Dobler is a postdoctoral researcher working with Doug Finkbeiner to better understand the WMAP haze.

GREG DOBLER: *So these are two dark matter particles that we can't see at all, they don't interact with anything. Eventually two of them come in and they hit each other here, and they annihilate through some process that we don't know. And in the end there's e plus and e minus, electrons and positrons. And these electrons and positrons, as soon as they're produced, are in a magnetic field, and so they start spiraling around the magnetic field producing* *synchrotron as soon as that happens. And that synchrotron radiation is what we think we see in the haze.*

DOUG FINKBEINER: *Now, you might wonder why this synchrotron is different from the synchrotron in the Haslam map that we already subtracted. It's very important that this has a harder spectrum.*

The Haslam map measures synchrotron radiation at a radio frequency. From this data, Finkbeiner can infer the brightness of ordinary synchrotron radiation, such as supernovae, across the full microwave spectrum. Finkbeiner compares this level of brightness, or spectrum with WMAP, which measured microwave emissions at 5 different frequencies in the higher range. At these frequencies WMAP shows a higher intensity of synchrotron radiation, or a harder spectrum, that cannot be explained by the Haslam map.

DF: *And so, if you have a harder spectrum from something, it can appear in the WMAP frequencies, but not be very bright at much lower frequencies in the Haslam map. And, that's why subtracting off the Haslam map, we think removes the ordinary synchrotron from supernovae, but would not remove as much the synchrotron from dark matter.*

The next step for Finkbeiner in investigating if dark matter annihilation could be responsible for the haze was to test if a simple model could produce something like he was seeing. He started by considering a candidate for dark matter called a WIMP.

DF: *So, a WIMP is a really cool idea about what the dark matter could be. WIMP stands for weakly interacting massive particle, where weakly here is technical jargon. So, it refers to the weak nuclear force as opposed to the strong nuclear force or electromagnetism or gravity. Those are the forces of nature.*

So, weakly interacting -- massive as if it's -- yes, it's not really light. It's massive, much more massive than a proton say, and then particle.

In order to calculate if WIMP annihilation could produce the haze, Finkbeiner and Dobler need to know the density of dark matter throughout the galaxy, and the rate at which these particles are annihilating.

GREG DOBLER: *On average, annihilation never happens in the universe. It happens very, very, very rarely. The dark matter particles in order to annihilate have to get very close to each other In certain regions like toward the galactic center where the dark* *matter density is thought to be very high. The idea is that this can happen much more often, still not very often, but more often.*

And one of the reasons we think about dark matter is, is because if you take your simplest idea for what the dark matter particle is and your simplest idea for how it's distributed in the galaxy, the resulting synchrotron emission that you get is roughly consistent within a factor of ten or so, with what we observe from WMAP.

So, in the end, what you would expect to see would be a glowing ball of synchrotron towards the galactic center,

DOUG FINKBEINER: *So the haze is not proof of anything. We are not looking at a picture of dark matter here. Dark matter is dark, so you can't see it. This is a picture of microwaves from electrons and positrons that might come from dark matter annihilation.*

Finkbeiner and his colleagues will continue testing the haze model with new data. A new full sky survey from the Planck satellite will give a much more detailed look at microwave emissions than WMAP.

DF: *So then you'd like this to fall off a cliff here…*

And already they are analyzing data from the Fermi Gamma Ray telescope which has provided the first full sky gamma ray picture of the universe.

Extracting the foreground emissions from the Fermi data, is the next step for Finkbeiner in investigating if dark matter annihilation could be responsible for the haze.

DF: *And in these maps what you see is a little white fuzziness at the center. So if there is dark matter annihilation going on, you would expect something to look like this. But there may be other explanations.*

But even as Finkbeiner examines the latest images from telescopes that might give more definitive evidence that dark matter is annihilating at the center of the galaxy, other experiments are still necessary to confirm their existence.

DF: *Approaching this problem of dark matter from the astrophysics first is kind of putting the cart ahead of the horse.*

Right well I think the next big thing to happen is underground detection experiments. If they show WIMPs actually scattering, then we can really start to piece together the whole story.

Part II: Underground WIMP Detector

Rick Gaitskell

One such experiment is being conducted at the abandoned Homestake goldmine near Deadwood, South Dakota. Rick Gaitskell of Brown University is one member of a team of scientists and researchers attempting to strike particle physics gold. He is overseeing a massive operation…actually two massive operations, one above ground and one 4,850 feet below, both working on the construction of the large underground xenon detector, or LUX detector, which hopefully could detect for the first time ever -- a dark matter particle.

> RICK GAITSKELL: *We are building what will be the most sensitive dark matter detector in the world and, therefore, there is every prospect of us, if there is a dark matter signal out there, of our seeing it.*

Above, they are assembling the detector itself, calibrating and testing the instrumentation before the whole thing is moved nearly a mile below ground, where they are preparing an abandoned mine to become a sophisticated particle physics laboratory.

For Gaitskell, detecting dark matter particles has been a career long endeavor.

> RG: *This is an appalling admission because it means for the 20 years I've been working in the same field I actually went, I had done a lot of reading, was aware or became aware of this question of the missing mass of the universe, the dark matter problem, and went straight in as a graduate student developing a detector in order to look directly for dark matter. That, in fact, is where I find myself still 20 years later. And at the time I went into the field, based on the theories we had at that time, we thought we would solve this problem within five years at the outset.*

What has eluded Gaitskell for decades may be the same hypothetical class of matter that Doug Finkbeiner suspects is responsible for the haze: the WIMP.

WIMPS, if they exist, are invisible particles with no charge that rarely interact with ordinary matter. They are expected to have 100 to 1,000 times the mass of a proton.

WIMPS are a good candidate for dark matter because they fit naturally into a model of how our universe formed into its current structure of galaxy

clusters and galaxies.

> RG: *So in order to today have the tremendous wealth of structure we see today in the form of galaxies and galaxy clusters, the quantitative models that we have derived say that you need a thing which is very ready to sort of fall in and make structure as gravity worked its process over the billions of years.*

Structure formed in the early universe as matter fell into slightly over-dense regions under the influence of gravity. WIMPs, because they move relatively slowly compared to the speed of light, and are also massive, would naturally fall into these over dense regions, building up the structures we observe in our universe today.

The problem with WIMPs is that we can't see them.

> RG: *Because these WIMP particles are neutral and, in fact, as the acronym indicates interact only very weakly with other particles, it turns out that it is very possible for this room to be filled with hundreds of millions of particles that we're simply not aware of because they are so weakly interacting and interact so rarely with conventional matter*.

Gaitskell's goal is to document these rare interactions between WIMPs and conventional matter, a task made more challenging by other more commonly occurring signals that can lead to a false detection -- which is why the experiment is using the earth as a natural shield and being conducted underground.

One of the major signals that they are trying to block is the one produced by cosmic rays. Cosmic rays are very high-energy particles coming in from space.

> RG: *Standing here at the surface, if I hold out my hand there are three to four cosmic rays traveling through it every second. If we were to try to operate the dark matter detector at the surface, the signal deposited from these particles would completely screen out the dark matter signal.*

But as you travel down to the depths of 4,850 feet, an elevator ride through nearly a mile of rock that takes over 15 minutes to complete, this changes dramatically.

> RG: *As we stand here now, fewer than two or three cosmic rays are going through my hand every year, that substantial reduction in cosmic rays allows us to eliminate one of the multitude of*

backgrounds that we have to beat down in order to be able to finally discover, or see the dark matter events which are extremely rare.

But the cosmic rays are not the only background signal they are concerned with. Once underground, the natural radioactivity from people, the walls of the laboratory, and the rock itself are enough to make the detector go off hundreds of times a second. To eliminate this radioactivity, Gaitskell and his team will immerse the detector into an eight-meter diameter tank of highly purified water.

This multilayered strategy, of putting the detector below ground and immersing it in water allows for an extremely low background event rate in their detector.

It is one thing to eliminate background signals; Gaitskell now has to figure out how to detect what has thus far been undetectable.

RG: *The challenge with WIMPs is when they interact with conventional material they're moving at hundreds of kilometers a second. They weigh about the same as an atom but that is just a single particle and when it interacts with a target, the amount of energy that deposited is extremely small. So, our challenge was to find a material that, even though the volume of our detector was going to be very large, that we could somehow see the deposition of a small amount of energy in the middle of that detector.*

The material they chose is xenon.

Xenon is less radioactive than other materials they could use, so it has a lower probability of false detections. It also is more sensitive at low energies, so it is better able to detect small interactions.

The LUX team chose to use xenon in its liquid form.

RG: *While we could have done the experiment with xenon gas, the probability of the dark matter particles, the WIMPs, interacting with our target is directly proportional to the amount of mass of the target; the more mass you can get, the more sensitive our detector is for searching for these WIMPs. We realized that in order to sort of most effectively get the most amount of mass in the smallest amount of space, we found that going directly to a liquid, xenon gives us a significant increase in the amount of mass that we see within a certain volume.*

RG: *Are you able to get live signal?*

Another consideration for Gaitskell was the volume of liquid to use.

> RG: *One of the things we realized is that if you take a large volume of xenon in order to look for very rare events, one of the great strengths this kind of detector has is that the outer layers of xenon shield or stop particles, conventional background, from getting in to the central region. So, we are now constructing a detector, which is nearly a third of a ton in mass. And by doing that it means we can, for the first time, really get a level of radioactivity or absence of radioactivity in the xenon, in the core of the xenon that will simply be unparalleled in previous experiments that have taken place.*

Even with a detector that is as quiet as any that have come before, detecting a dark matter particle is not guaranteed. Most WIMPs, because they are neutral and are weakly interacting, will pass right through the liquid xenon without any interaction.

What Gaitskell hypothesizes is that occasionally one will have a very low energy interaction with one of the nuclei in the atoms of the liquid xenon.

> RG: *The nucleus recoils and emits scintillation light, which we detect using photosensitive detectors on the boundaries of the container.*

The photosensitive detectors are photomultiplier tubes, or PMTs. One hundred and twenty-two of them will be arranged above and below the liquid.

At ground level they are preparing and testing each individual tube for use in the detector

> CARLOS HERNANDEZ FAHAM: *So this is what one of our PMTs looks like, and that's where light is detected. We can even measure a single photon. So, imagine that xenon atom over here. We have our detector. Here is the photomultiplier tube looking into the xenon. A particle comes in. It gives us a flash of light and that flash of light we can detect with the PMTs once it hits the photo cathode, which is essentially a sensitive material that likes to emit an electron when a photon interacts with it. And that electron will give us a signal we can actually measure.*

The signature signal of a WIMP is actually not one signal but two. When a WIMP interacts with the xenon, it not only causes an initial burst of light, but it also ionizes the xenon atoms, causing electrons to be released, which creates another signal just microseconds later.

The two signals will look like this on the detector.

> JEREMY CHAPMAN: *So, in – in real time the – the detector is quite quiet. There is no signal in the detector and then the WIMP interacts in the xenon and you get this primary scintillation pulse, and then the electrons are also ionized at this site. And you get this large, called the S2 pulse, the ionization signal.*

This signal is easy to distinguish from one created by a cosmic ray.

> JC: *So, the cosmic ray in the detector will have this long track of light and the detector goes up like a Christmas tree. It's – it's very easy to distinguish WIMP-like low energy events from cosmic rays.*

Gaitskell's team will continue calibrating each individual PMT by simulating WIMP events with LED lights. Eventually they will have the entire detector functioning at ground level.

> MALE VOICE: *And that's 4,100 feet.*

Then they will disassemble the whole thing and bring it down piece, by piece, 4,850 feet below ground where they will reassemble it and start the experiment.

> RICK GAITSKELL: *We could be seeing our first event in the first few days of operation of the detector. But, we may have to wait many months in order to see a dark matter event.*
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> *I think when the first few of those WIMP events come in, it will certainly be an opportunity we're going to have to pinch ourselves after so many years of searching. At that point, we will begin to be able to tell something for the first time about the dark matter WIMP events themselves. We'll be able to tell something about their abundance, something about their mass, which will allow us to plug this back into our overall model of cosmology and better understand how the Universe and our galaxy are put together.*

While Rick Gaitskell waits for data supporting the existence of WIMPs, Doug Finkbeiner examines the latest images from telescopes that might give more definitive evidence that dark matter is annihilating at the center of the galaxy. Both physicists may contribute important research to help answer the question: what is most of the matter in the universe made of?