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DARK MATTERS

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Most of the universe is dark. Its nature is a mystery, despite intensive efforts to detect it either directly or indirectly. Let's begin with dark energy. Einstein told us that mass has energy. This explains why the sun shines, because the mass of a helium atom of atomic mass 4 is 0.7% less than the mass of four hydrogen atoms. The mass deficit powers the sun. The converse is just as true. Energy has mass. Astronomers have found that the universe is accelerating. This is due to a form of dark energy, which acts as antigravity. We can't see it but we can effectively weigh it. Dark energy accounts for three quarters of the mass of the observable universe.

Dark Energy

We don't know the nature of this dark energy. We didn't expect to find it. Its discovery two decades ago was an accident. Two teams of astronomers were in a race to discover the fate of the universe. Would it expand forever? Or was it destined to collapse? They exploited a cosmic measuring rod, a certain type of supernova which achieved a limiting luminosity. The host star exploded and the peak in the light from the explosion was found to be constant, from galaxy to galaxy. So if one sees an explosion in a distant galaxy, one can deduce the distance of the galaxy. This property allowed supernovae to be used as precision measures of distance.

The result was a surprise. The most distant supernovae were too dim. The effect was relatively large, by about 20 percent. It could not be due to measurement error. One possibility is that supernovae change with epoch. However while the distant supernovae might be intrinsically fainter, they do seem to be perfect beacons of light that are spectroscopically indistinguishable from their local counterparts. If they were different, we would expect to find some independent evidence of this. We haven't found this. Intrinsic differences are therefore an unlikely explanation.

There was only one plausible explanation. The distant supernovae were inferred to be more distant than our simple model of the universe allowed them be. Only if the universe is accelerating could they be more distant at a given look-back time. The acceleration of the universe had been measured for the first time.

The cause of the acceleration could only be due to some density of energy in space that acted like a pressure. Normally pressure in a strong gravity field acts to enhance gravity. Its energy is a source of mass. It squeezes space, like matter: space contracts as matter attracts. But physics allows the possibility of negative pressure. This acts in the opposite way to gravity. As it pushes on space, space expands. This results in acceleration as the universe expands and the density of ordinary matter decreases.

Negative pressure is a common phenomenon. It acts repulsively, like antigravity. The lower the density the greater the force. Here is one analogy. Stretch an elastic band. The restoring force increases the more one stretches the elastic, as the elastic density decreases.

The phenomenon that causes acceleration of the universe is not unknown to physics. But what is a great puzzle is its strength, today, when the cosmos is cold and dilute. The observed acceleration is a very weak force. Why is

it manifesting itself around now, in the recent past? And how did it emerge from the Big Bang, an incredibly hot and energetic environment at the beginning of time?

Dark Energy: The Greatest Puzzle in Physics

There is indeed a natural time for negative pressure early in the history of the universe. It is very early indeed and is due to a change in the state of matter. There is a sudden injection of negative pressure about 10^{-36} second after the Big Bang. We can think of this as latent heat that is released as the phase change of the matter occurs. Why is this like a negative pressure? Because it acts against gravity. Thermal, that is positive pressure, simply acts as extra gravitational energy. That's what Einstein tell us: all energy is a source of gravity. Negative pressure acts like antigravity, however.

As the universe expands, the pressure of the matter decays, and can't resist gravity. The source of gravity is reduced, and the expansion of the universe slows down. But the constant pressure that comes from the latent heat does not decay. Indeed it dominates and so dilutes the density of matter. It has a constant density of energy, and effectively counters the reduction in density due to the expansion of space. Thanks to this sudden injection of energy, the expansion of the universe actually speeds up. There is a huge acceleration of the universe, that we refer to as inflation.

Inflation doesn't last long as it's not stable, the energy field that drives inflation oscillates and decays into radiation. The inflationary phase occurred only 10^{-36} second after the Big Bang. In turn, this decay reheats the universe, which initially cooled down dramatically as inflation occurred because of the rapid expansion. Soon space is filled with thermal energy. The normal expansion resumes. It is back to the usual Big Bang. The universe was incredibly dense at this point in time. This means that the density of the energy that causes inflation must also be incredibly high.

Much later, that is now, the universe has recently begun accelerating again. This is due to dark energy, which also has a constant density that just overcomes the density of matter at the present time. Indeed this current phenomenon is also inflation, but a new phase that is beginning very recently. Some call this recent acceleration the beginning of the run-away universe. The difference with very early inflation is that the value of the density of dark energy now is much less that that at the epoch of inflation. The difference is more than a hundred factors of 10, that is 10 multiplied together a hundred times. So if we required that the same fundamental physics that explained very early inflation would be operating today to account for late inflation, the estimated value of dark energy would be too large by a really huge factor. This prediction has been said to be one of the worst predictions in all of physics.

Dark Matter

For most astronomers, dark matter is as tangible as stars. Astronomers routinely map dark matter by its effects on the propagation of light. Light paths are curved by the presence of intervening matter. Lumps of dark matter act like gravitational lenses.

We conceive of galaxies as blobs of dark matter with dabs of luminous material. One of the big revelations from the age of computer simulations of galaxies was that the dark halos that are known to surround galaxies are not uniform. In fact they are highly inhomogeneous, having formed over time from a long history of mergers of small satellites. And indeed gravitational lensing generates blobby arcs of background galaxies that directly image this substructure.

We understand the formation of cosmic structure, as well as the evolution of the universe as a whole, in terms of dark matter. Yet a decade of sophisticated searches has failed to detect the material directly. We see the shadow it casts, as stars orbit in halos of dark matter. We have a global understanding of dark matter and how it affects the

dynamics of stars and galaxies. But we are completely unaware of what the dark side of the universe may contain in any detailed sense.

Dark Matter: What Is It?

Our best bet for dark matter is that it is made up of weakly interacting fundamental particles. Weakly interacting, because otherwise it would be glowing like starlight. And a fundamental particle because that seems the most natural and simple hypothesis that is motivated by cosmology. All fundamental particles once existed in the very early universe. One survivor would be the dark matter particle. Because it is so weakly interacting, it is a relic from very long ago, and has subsequently been like a fossil from the past..

Look Deep Underground

It certainly isn't any ordinary object or particle—that has long since been ruled out. Theoretical prejudice favors a novel type of particle that interacts only weakly with ordinary matter. Vast numbers of these particles should be flowing through our planet all the time, and by rights you'd expect some of them to leave a mark. Physicists have grown crystals and filled cryogenic vats, hauled them deep underground to screen out run-of-the-mill particles, and watched for tiny pulses of heat and flashes of light that would betray the passage of something never before seen. The results so far are not encouraging. In Lead, South Dakota, the LUX experiment operates one mile underground in an abandoned gold mine. It has found nothing. In China, the PandaX experiment in the Jin-Ping underground laboratory in Szechuan operates in a tunnel under 2.4 kilometers of rock. It has found nothing. In a road tunnel near Fréjus in the French Alps, the EDELWEISS experiment, at a depth of 1.7 km, has found nothing. And the list goes on.

The null results are rapidly squeezing the regions of parameter space where dark matter might lurk. Confronted by the drought of data, theoretical physicists have conjectured about more exotic particles, but the vast majority of these candidates would be even harder to detect. One could instead hope to produce dark-matter particles at a particle accelerator, so that we could infer their presence by default: by checking whether energy seemed to go missing in particle collisions. But the Large Hadron Collider has tried precisely this and noticed nothing so far. Some theorists suspect dark matter doesn't exist and our theory of gravitation—Einstein's general theory of relativity—has led us astray. General relativity tells us that galaxies would fly apart if not held together by unseen matter, but perhaps the theory is wrong. Yet general relativity has passed all other observational tests, and all rival theories have seemingly fatal flaws.

Eighty-five percent of all matter is unknown. Our greatest fear is that it will always remain so. Although most experiments have come up short, two do claim to have spotted dark matter. Both claims are highly controversial, for different reasons. These outliers may well be wrong, but they deserve a closer look. If nothing else, these cases illustrate the difficulty of spotting dark matter amid all the other detritus of the cosmos.

The DAMA/LIBRA particle detector at the Gran Sasso Laboratory, installed in a tunnel 1.4 km below a mountain in northern Italy, looks for flashes of light caused by dark-matter particles scattering off the atomic nuclei in a crystal of sodium iodide. It has been collecting data for over 15 years and has seen a very peculiar thing. There are possible light signals. They could be due to various backgrounds in the rock but the rate of detections waxes and wanes with the seasons, with a maximum in June and a minimum in December. There is no denying that DAMA/LIBRA detects a seasonal modulation with a very high statistical significance.

That is exactly what you expect from dark matter. Dark matter is thought to form a vast cloud enveloping the Milky Way galaxy. Our solar system as a unit is moving through this cloud. But individual planets move through the cloud at varying speeds because of their orbital motion around the sun. Earth's speed relative to the putative cloud peaks in June and bottoms out in December. That would determine the rate at which dark-matter particles flow through an Earth-based detector.

But many other sources of particles also vary with the seasons, such as groundwater flows (which affect the background level of radioactivity) and the production of other particles, such as muons, in the atmosphere. At last count, some five other experiments around the world claim limits that are inconsistent with DAMA's claim. This has led to a certain amount of skepticism. The only way to be sure is to replicate the experiment with the same type of detector at one or more different locations, and several such experiments are now underway. One will be at the South Pole, where local seasonal effects are out of phase and very different from those in Italy.

Look in Space

A second intriguing hint of dark matter comes from indirect experiments, which do not look for the elusive particles per se, but for the secondary particles they would produce when they collide with one another and mutually annihilate. In 2008 an Italian-Russian satellite called PAMELA (Payload for Antimatter/Matter Exploration and Light-nuclei Astrophysics) observed an unexpectedly high number of positrons, the antimatter version of the electron, emanating from deep space. The observation was recently confirmed by the Alpha Magnetic Spectrometer onboard the International Space Station.

Dark matter particles run into each other in the depths of space and annihilate. They produce pairs of matter and antimatter particles, most notably positrons and electrons. The observed energetic protons could be produced by dark matter. However, the positrons don't match the signature of viable dark-matter candidates. But there is a more conventional explanation.

The positron observations might be explained by outflows of electrons and positrons predicted to come from rapidly rotating neutron stars known as millisecond pulsars. To settle the case, we need to check whether the positrons tend to be coming from the direction of known neutron stars. Here we seem to be converging. New observations by the High-Altitude Water Cerenkov Observatory in Puebla, Mexico at an altitude of 13400 feet indeed find positrons towards two nearby pulsars.

Gamma rays are another byproduct of dark matter particle annihilations. The Fermi gamma ray telescope is on a satellite that orbits the earth at an altitude of 340 miles. It has mapped the sky in gamma rays and discovered thousands of sources as well as a diffuse glow from the Milky Way galaxy. Some sources are galactic, including supernova remnants and pulsars, others are far away, supermassive black holes seen as the active nuclei of galaxies.

The diffuse glow of gamma rays mostly comes from the interaction of cosmic rays with interstellar gas clouds. These interactions produce gamma rays. But towards the centre of our galaxy, there is a residual glow in gamma rays that cannot be accounted for by any known process. The excess gamma ray light extends up to around 20 degrees from the center of our galaxy.

The gamma ray excess could be due to a new population of gamma ray sources. These might be binary stars, in which one component is a black hole. We detect luminous x-ray and gamma ray binaries, but there could be a large population of fainter binaries. That's one explanation.

The central gamma ray glow has just the shape expected from dark matter: symmetrical about the galactic center, with an intensity that rises towards the centre of the galaxy. It also has the expected strength from annihilations of the dark matter particles that are hypothesized if we take the WIMP miracle seriously. And it even has the expected distribution of gamma ray energies. This almost seems too good to be true.

Fluctuations in the gamma ray distribution on the sky already tend to favor the option of many weak and unresolved pulsar sources near the galactic center. Also, if the gamma rays were coming from dark matter, astronomers should detect a similar signal from nearby small dwarf galaxies, which have a proportionately greater amount of dark matter than our own galaxy. No such signal has yet been detected.

Look in the Early Universe

Most of our search efforts have focused on the simplest candidate particles, known as WIMPs: weakly interacting massive particles. The word "weakly" is a double entendre: the interaction is feeble, and it occurs via the so-called weak nuclear force. Such particles are a natural extension of the Standard Model of particle physics. Even without knowing the details, the adverb "weakly" provides enough information to calculate how many such particles should suffuse the universe. In the hot primordial soup of the big bang, particles are naturally created and destroyed. As the universe expands, the temperature drops, and one by one, different types of particles cease to form, depending on their mass. Particles can still be destroyed at a rate that depends on their interaction strength, until they are too diffusely spread out to collide with one another.

Given the interaction strength that WIMPs should have, one can run the numbers, and deduce that the cauldron of the early universe should have created the observed amount of dark matter. The resulting particles should weigh in at hundreds of proton masses. In sum, there is a natural sweet spot for particle dark matter, dubbed the "WIMP miracle." But maybe this is a case of a beautiful hypothesis slain by ugly facts as our experimental efforts are increasingly frustrated.

Physicists are becoming increasingly desperate, exploring options that they use to consider second-best possibilities. The elusive particles could be very heavy or very light. In either case, detection is more challenging.

Perhaps the dark-matter particles are exceedingly massive. There is a basic tradeoff, though. The more massive the particle is, the fewer of them are needed to account for the total mass in dark matter that astronomers observe, and there might be so few that our detectors would miss them in direct searches. Physicists would need to find some completely alternative search strategy. Maybe one could use stars as detectors. Stars do trap dark matter particles. If the star is very cold, such as an old neutron star, one might expect a residual and unexpected glow of heat. So far, this strategy has not panned out.

Look in the Sun

Going in the other direction, the dark-matter particle might be too light in weight to leave much of a mark in our detectors. To search for it, physicists might need to make use of a detector that nature has already provided for us: the sun. The sun sweeps up particles as it moves through the galactic dark matter cloud. These particles could scatter off protons in the sun and modify its temperature profile. This would affect the turbulent motions of gas eddies that rise, fall, and swirl in the sun's upper layers. And we should be able to see these effects through the science of helioseismology, which studies disturbances that propagate inside the sun and their effect on the surface, much as we study terrestrial earthquakes by seismology. It indeed turns out that there are unexplained helioseismological anomalies that are difficult to reconcile with our standard model of the sun. But again, there are more conventional explanations, involving more conventional but uncertain stellar physics than appeal to a new type of particle

If dark-matter particles collect in the sun, they may also annihilate in the core. That would produce energetic neutrinos that detectors such as Super-Kamiokande in central Japan and the IceCube observatory at the South Pole could see. So far no candidate events have been reported. The most extreme example of an ultra-lightweight particle is the axion, a hypothesized weakly interacting particle with a trillionth or less of the mass of a proton. It would not be completely dark, but would interact electromagnetically and could generate microwave photons inside strong magnetic field cavities. Experiments aimed at detecting axions have been operating since the 1980s, with as little success so far as WIMP detectors.

Look Elsewhere

Perhaps the dark particle is not even a particle, but an "unparticle," as dubbed by one theorist. Unparticles are distant cousins of the electromagnetic field whose energy does not come in discrete packages. They could leave

an indirect trace in collider data. Perhaps the identity of dark matter has no single solution. After all, ordinary matter is also composed of many types of particles. Dark matter could likewise have several contributors, rendering the search more difficult by diluting the putative signature of any specific particle candidate. Perhaps dark matter does not interact at all, except gravitationally. This would make the experimentalist's life even more of a nightmare.

In a sense, we are in the situation that approaches every scientist's dreams Old ideas aren't working: new ones are needed. These might come from exploring novel types of particles, or we might discover a fully consistent new theory of gravity that dispenses entirely with dark matter.

The nagging worry is that nature has put the new physics in a place where we can't find it. Although we haven't completely exhausted the search for WIMPs, there's only so much more that experiments can do. As they become more sensitive to dark matter, they also become more sensitive to detector noise or garbage particles, irrelevant to dark matter, and they cannot always discriminate between these effects. At the present rate of improvement, within a decade, terrestrial dark matter detectors will be blinded by neutrinos emitted either by the sun or by cosmic rays colliding with the Earth's atmosphere.

New Telescopes, New Particle Accelerators

At this point, despite the increasing frustration, we must still pursue indirect means of detection. One of the most promising is the Cherenkov Telescope Array, an assembly of more than 100 telescopes under construction in Chile and in La Palma, which, among other goals, will look for gamma rays produced by annihilation of dark-matter particles in our galaxy and others. But eventually this search strategy will run into another problem: cost. For now, dark matter detectors are among the most economical of major physics experiments, but if we need to keep increasing their size, sensitivity, and sophistication, their price tag could rival behemoths such as the Large Hadron Collider (LHC: nearly $7 billion to build) and the James Webb Space Telescope (around $8 billion) to be launched in 2021, with no guarantee of success—a very hard sell for politicians.

The strongest tool for discovery of dark-matter particles would be a new particle collider. Fast-forwarding some three to four decades from now, physicists plan to build a collider with ten times the power of the LHC. Studies are underway both in China and in Europe. Such a machine could search for particles of mass tens of TeV, or ten thousand proton masses. This approaches the limit of what the WIMP miracle allows.

Crudely scaling up from the LHC, such a behemoth would cost $70 billion in today's dollars. Shared among nations and spread over the decades, that might just be feasible. But it is probably the limit. Even if physicists had unlimited resources, there would be no point in building anything larger to search for even higher masses. At this point, any unknown particle would have to be so massive that, were the particle produced in the same way as its lighter counterparts, the Big Bang would most likely not have produced it in sufficient quantity.

Despite these immense efforts, we may not find any signals. That would be a gloomy prospect. Maybe there is no dark matter. We keep looking for deviations from general relativity. So far we have found none. On the contrary, the first detection of a black hole in 2015 by gravitational waves has bolstered Einstein's theory—and its corollary, the existence of dark matter.

But look on the bright side. There could be immense mysteries and revelations about the dark side of nature that we will never glimpse unless we search. For now, we keep looking for particles. We can do nothing else but press on until we run out of funds or ideas.