Shining Light on Dark Matter

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Scientists have long faced the challenge of studying objects and phenomena they can't see with their unaided eyes. Astronomers developed telescopes to see stars and galaxies; biologists developed microscopes to examine cells and their contents; many scientists have exploited vast swaths of the electromagnetic spectrum, from gamma rays to radio waves, invisible to our eyes.

Those challenges, though, seem small compared with the efforts by astronomers and physicists to study something that eludes detection: dark matter. Its presence can be inferred by the gravitation effects it has—the first hints of its existence came from studies of the rotational curves of galaxies, indicating that the visible galaxies were embedded in giant halos of matter than couldn't be seen—but it can't yet be directly detected by instruments big or small across the spectrum.

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"'Dark matter' is really a misnomer," said Joseph Lykken of Fermilab in a talk about dark matter detection efforts at the annual meeting of the American Association for the Advancement of Science (AAAS) in Chicago earlier this month. "It's really transparent matter."

The AMS-02 experiment, seen here shortly before being launched to the ISS in 2011, still needs to collect at least two more years of data before project scientists believe they have enough to confirm or rule out the existence of a proposed type of dark matter particle. (credit: NASA/KSC)

At the AAAS meeting, though, scientists argued that we are, perhaps, closer than ever before to being able to detect dark matter, with the possibility that some major announcements in those efforts could come later this week at the Dark Matter 2014 conference at UCLA.

To detect dark matter, it's helpful to have an idea of what you're looking for. Scientists have proposed many ideas for what dark matter might be, but most now think it's in a form known as weakly interacting massive particles, or WIMPs. As the name suggests, these particles could be heavy, yet rarely interact with other articles beyond gravity.

"It's a relic of the first fraction of the second of the universe," explained Rocky Kolb of the University of Chicago during a half-hour talk at the AAAS meeting. "A few hundred million are in this room at this instant, flying around at a million kilometers per hour, and about 10^{12} [one trillion] will pass through you during this talk."

WIMPs had won out among most scientists over an alternative concept, massive compact halo objects, or MACHOs. (If you've ever doubted scientists' sense of humor, those dueling acronyms should set you at ease.) MACHOs would be ordinary matter, but condensed in forms not easily seen: black holes, dwarf stars, and even rogue exoplanets. "Observations in the last decade or so have ruled out the possibility of MACHOs being the dark matter in our galaxy and other nearby galaxies," Kolb said.

A few scientists have even argued that dark matter doesn't even exist at all, and that phenomena linked to it could be explained by changes to fundamental dynamics, something called Modified Newtonian Dynamics, or MOND. Kolb, though, is among the majority of scientists skeptical of MOND. "Recent observations have shown that this probably isn't the answer, and in terms of explaining dark matter, it seems that Newton and Einstein got it right," he said.

If dark matter is made of WIMPs, how do you go about proving it? One approach is not to try to directly detect WIMPs themselves, but particles created when WIMPs collide with and annihilate one another. That's the technique used by scientists involved with the Alpha Magnetic Spectrometer (AMS) experiment on the International Space Station. WIMP annihilation should create an excess of positrons with a specific profile as a function of energy: increasing at higher energies, then dropping off sharply beyond a threshold energy of about 500 billion electron volts (GeV).

Last April, the AMS team published its first results, which showed—at least to them—tantalizing hints of a dark matter signature (see "Revisiting exoplanets and dark matter", The Space Review, April 8, 2013.) The positron ratio increased in the data from 0.5 to 350 GeV, but the slope of the increase flattened at those higher energies. To the AMS team, it looked like what they would expect from the annihilation of WIMPs. But other scientists noted that the acceleration of particles by pulsars could also explain the AMS data.

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One way to resolve this is to collect data at higher energies: if the positrons are linked to pulsars, the ratio should not drop at energies above about 500 GeV, while it should drop dramatically if it's caused by WIMP annihilation. Collecting that data with AMS will take time, though, cautioned Paolo Zuccon, assistant professor of physics at MIT and a member of the AMS team, at the AAAS meeting.

"In going to higher energies, there are two kinds of problems. One is statistics," he said: there are fewer events detected by AMS at higher energies, thus is takes more time to detect a statistically significant number of them. In addition, at higher energies it's more challenging to distinguish among different types of particles.

"We need probably five years total of data before publishing something that is significant" in terms of the shape of the positron excess curve at higher energies, Zuccon said. The AMS has already collected nearly three years of data, as it was installed on the station in May 2011. "There's still two years to go."

While AMS orbits the Earth looking for particles that can be traced to WIMPs, others are going deep into the Earth to try and detect WIMPs directly. Sensitive detectors, buried inside mountains and abandoned mines to be shielded from more ordinary particles and radiation, try to detect the "nuclear recoil" in those rare cases when a WIMP does collide with the nucleus of an atom.

Those experiments press detection technology to its limits. "You're trying to detect WIMPs, who make these nuclear recoils, and you're doing it in an absolute sea of normal matter particles," said Dan Bauer of Fermilab at AAAS. Radioactivity is another major challenge to these experiments, he added. That drives experiments deep underground, but also requires shielding from radiation and a detector sensitive enough to detect WIMPS “but has to actively reject all the other interactions that normal matter produces.”

Those efforts have, so far, failed to make a definitive detection of WIMPs. One detector located inside Italy’s Gran Sasso mountain, DAMA/LIBRA, has detected what some scientists claim to be an annual variation of detected events that would be consistent with the variation expected as the Earth rotates around the Sun, moving through the “WIMP wind.” Many others, though, including Bauer, are skeptical of those claims.

“It’s very nice to see a signature like that,” he said, “but there are many experimental variations that could also do just that.” The inability of the DAMA/LIBRA team to eliminate those other potential causes of the annual variation in the data makes the conclusions unconvincing for him. “The problem with these experiments is that they run out of explaining power. They see an effect, but they can’t assure it isn’t in their experiment.”

Other experimental physicists, undaunted by those challenges, are planning ever more sophisticated detectors to try and detect WIMP signatures. Elena Aprile, professor of astrophysics at Columbia University, discussed at the AAAS meeting efforts with one experiment, called XENON100, which is also located inside Gran Sasso; it uses liquid xenon as the detector. Even as they continue to study data collected by this experiment, they’re working on another, larger one, XENON1T, that’s slated to begin observations in 2017.

A similar experiment that also uses liquid xenon is the Large Underground Xenon (LUX) experiment, located in the former Homestake gold mine in South Dakota. Thomas Shutt, professor of physics at Case Western Reserve University, said at the AAAS meeting that the experiment is now collaborating with another on an effort called LUX-ZEPLIN that uses new technology to reduce background signals. “We can do an extraordinarily good job in suppressing external backgrounds,” he said.

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Can these experiments finally detect evidence of the WIMPs thought to comprise dark matter? Some are doubtful. Juan Collar of the University of Chicago said that a WIMP detection requires something like performing a triple jump: first you have to show that any detected events are not electron recoils, then show they are indeed the designed nuclear recoils, and then show that recoils are from dark matter interactions.

“I consider this triple jump a very tall order,” he said. “I don’t know of any dark matter detector technique able to do a flawless triple jump.”

“We are in a business that’s too damn close, if you ask me, to the Popperian definition of pseudoscience, which is something you can never falsify because there are always some knobs that you can turn and run away from constraints,” he said. “There are too many uncertainties.”

Those involved in some of the dark matter experiments, though, are more sanguine about the prospects of finding something soon—or else ruling out the existence of WIMPs and sending theorists back to the drawing boards. “We’re making a lot of progress and seeing hints of signals,” Bauer said. “We think we might be able to see it soon.”

“Given the nature of the dark matter problem, given how fundamental it is, even though WIMPS, at some level, are a shot in the dark, it would behoove us to do everything we can to probe all of the standard parameter space,” Shutt said. “I think a nearly complete probe of the accessible space is in reach.”

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