Physics

VIEWPOINT

A Speed Test for Dark Matter

Whether mysterious high-energy photon emissions from our Galaxy come from dark matter or a more mundane source might be resolved by detecting their Doppler shifts along different lines-of-sight.

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Dark matter dominates the large-scale dynamics of the Universe, but what it *is* remains a puzzle. Recent observations of an unexplained x-ray line in the emission from our Galaxy, as well as distant galaxies, suggest we might have detected—at least indirectly—the particles that make up dark matter (see 15 December 2014 Viewpoint). But so far, astrophysicists haven't been able to rule out the possibility that the spectral line comes from ordinary gas. A team of scientists now suggests the signal's origin could be pinned down by observing the emission from our own galaxy and analyzing how the line's frequency shifts when it is observed along different directions with respect to the Galactic Center [1]. The sign of the shift (to higher or lower frequencies) is different for dark matter and ordinary gas particles because of their distinct velocity distributions. Although these frequency changes are too small to detect with current x-ray spectrometers, they should be observable by upcoming missions.

The gravitational effects of dark matter were first uncovered in the 1930s by Fritz Zwicky, who noticed the abnormally high velocities of ordinary matter in galaxy clusters [2]. More than 40 years ago, Vera Rubin's measurements of galactic rotational velocities showed that dark matter is needed to bind galaxies and other structures in the Universe [3]. Today, few physicists doubt dark matter's existence. It is known, from cosmological observations, to make up 25.7% of the Universe (by density) [4], more than 5 times the contribution from ordinary atoms. Researchers also generally agree that dark matter probably consists of a new, but thus far undetected, particle. But beyond its crucial gravitational influence, little is known about dark matter because of its feeble interaction with ordinary matter.

Several well-motivated models predict that dark matter particles can annihilate or decay into photons with a narrow range of energies. Such models have recently received renewed interest because of the detection of a sharp x-ray line, at 3.55 keV [5, 6], in emissions from the center of the Milky Way, the Andromeda galaxy, and galaxy clusters, all of which are believed to be surrounded by a spherical "halo" of dark matter (Fig. 1, inset). One model that explains the emission line assumes the dark matter particle is a "sterile" neutrino with a mass of 7.1 keV, which produces a photon

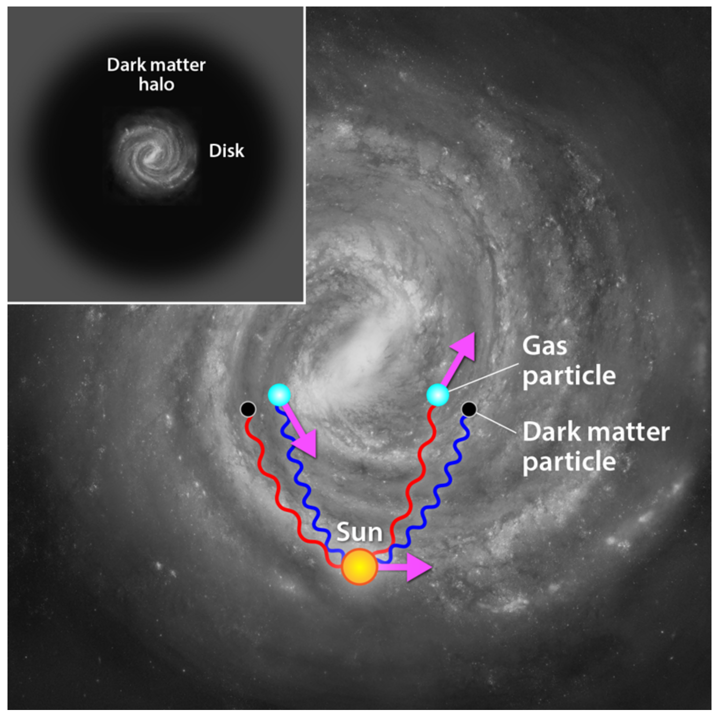

Figure 1: Photon emissions observed in our Galaxy could be produced by dark matter, or they could be from ordinary gas. Speckhard *et al.* propose a way to distinguish the two possible sources. Relative to our Galaxy, dark matter particles have an average velocity of zero, so their emissions should look blueshifted if we look towards the rotation in the Galaxy from the sun ("right" in the figure) and redshifted if we look in the direction opposite the rotation ("left" in the figure). Emissions from gas particles would, however, appear to have the opposite Doppler shift because of the relative velocity these particles have due to their co-rotation with the Galactic disk. (The inset shows the spherical "halo" of dark matter believed to surround our Galaxy.) (Milky Way illustration by Nick Risinger (CC:BY); additional graphics by APS/Alan Stonebraker)

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and a lighter neutrino when it decays [7]. There are, however, other dark matter models, not involving sterile neutrinos, which may also predict a 3.55-keV line (see, for example, Refs. [8, 9]). These models may better account for the noticeable absence of x-ray emissions in spectra from the dark-matter-dominated dwarf galaxies of the Milky Way.

The observation of an unexpected photon line in diffuse emission from galactic halos has long been heralded as a smoking gun for dark matter. However, after much debate, astrophysicists still cannot definitively rule out the possibility that the line has a more mundane origin, coming from strong emission processes involving the excited states of atoms [10]. To quote Carl Sagan, “Extraordinary claims require extraordinary evidence.”

In the new analysis, Eric Speckhard of The Ohio State University, Columbus, and colleagues propose a method to search for such extraordinary evidence in future observations of line emission. Specifically, they argue that a spectral line produced by dark matter will be observed at a slightly different frequency than one resulting from ordinary gas emission (Fig. 1). The reason is that dark matter particles and gas particles have different velocity distributions with respect to the reference frame of the Solar System. The gas particles producing the strongest emission lines corotate with the Galactic disk, and they have a broad velocity distribution, which depends on the temperature and turbulent dynamics of the gas. As shown in Fig. 1, if these particles are observed towards the direction of the Galaxy’s rotation they will appear to be moving away, and their emissions will therefore be redshifted; gas particles that are instead observed in a direction opposite to that of the rotation would appear to be blueshifted. In contrast to gas particles, dark matter particles moving within the Galactic halo are expected to have a more isotropic, nearly Maxwellian distribution. With respect to the Milky Way’s rest frame, their velocities will, on average, be zero. The Doppler shifts from dark matter emissions, due to the motion of the Sun, will have the opposite sign compared to those from gas: blueshifted when looking towards the direction of rotation and redshifted when looking against it. Assuming typical Galactic velocities of 200–300 km/s (roughly 0.1% the speed of light), the authors estimate that spectra would need to be acquired with an energy precision of 0.1% to distinguish a dark matter source from ordinary gas. A similar test could be performed on spectral lines obtained from observing the Andromeda galaxy.

Interestingly, the Astro-H mission’s soft x-ray spectrometer (SXS), scheduled for launch in 2016, has design specifications that are right at this 0.1% level [11]. Assuming an exposure time of just over 23 days for each range of Galactic longitudes, the authors estimate that the spectrometer could detect a large enough signal to confirm or refute a dark matter origin of the 3.55-keV line.

Searching the sky for dark matter is an endeavor fraught with pitfalls. We must not only find a needle in a haystack—the spectrum of the Universe is crowded with emission lines—we must also find it in a haystack filled with crafty astrophysical imposters. Models of dark matter that predict line radiation, especially in the gamma-ray regime, strongly exclude nearly all impostors. But the dark matter velocity spectroscopy proposed by Speckhard *et al.* might go a step further by actively confirming the dark matter provenance of line radiation and by allowing the velocity structure of dark matter to be measured directly.

The 3.55-keV line might ultimately prove to have less profound origins than decaying dark matter or other dark matter physics. But the technique described by Speckhard and colleagues should be a powerful test for the next candidate dark matter line that comes our way. Future x-ray and gamma-ray missions should absolutely try to achieve a relative spectral resolution below 0.1%. Ultimately, if dark matter line radiation is identified and confirmed, we’ll have a means to observe the detailed spatial and velocity structure of dark matter in the Milky Way, in other galaxies, and indeed throughout the cosmos. Such confirmation would usher in a new age of dark matter astronomy where the Universe shines brightly in photons emitted by dark matter. No longer dark and invisible, the halos and large-scale structures of the cosmic web could be directly, and sharply, imaged and mapped. We would have access to the hidden secrets of our dark Universe, which have so far only been glimpsed as murky shadows in the gravitational field.

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