Insignificance

Dark matter and dark energy: they might be more abundant than the stuff we are made of, but are they any more interesting?

Sean Carroll

Humans seem to be extremely unimportant in the grand scheme of the Universe. This insight is often associated with Copernicus, who suggested (although not for the first time) that the Earth was not the centre of the Solar System. A bigger step towards calibrating our insignificance was taken by Edwin Hubble, who determined that astrophysical nebulae are really separate galaxies in their own right. We now think there are about one hundred billion such galaxies in the observable Universe, with perhaps one hundred billion stars per galaxy.

But a metaphysically distinct blow to our importance came with the introduction of the idea of dark matter — we are not even made of the same stuff that comprises most of the Universe. The need for dark matter, in the sense of 'matter we cannot see', was noticed in 1933 by Fritz Zwicky, when studying the dynamics of the Coma cluster of galaxies. When galaxies are orbiting each other, their typical velocities will depend on the total mass involved, but when we observe clusters of galaxies, the velocities are consistently much higher than we would expect from the mass we actually see in stars and gas. Vera Rubin and others have driven the point home by examining individual galaxies. As we move away from the central galactic region, the velocity of orbiting gas becomes systematically higher than it should be. These observations imply the existence of an extended, massive halo of dark matter. Indeed, the picturesque galaxies we see in astronomical images are really just splashes of visible matter collected at the bottom of these more substantial, yet invisible, halos.

Of course, the air we breathe is invisible and transparent, just like dark matter. A sensible first guess might be that the extra mass we infer is ordinary matter, just in some form we cannot see. But we have independent ways to measure the amount of ordinary matter, through its influence on the early-Universe processes of primordial nucleosynthesis and the evolution of density perturbations. These constraints imply that ordinary matter falls far short of what is needed to explain galaxies and clusters (perhaps one-fifth of the total). Not only is dark matter 'dark', it is a completely new kind of particle — something outside the standard model of particle physics, something not yet detected in any laboratory here on Earth.

In *Insignificance* (1985), the surreal meeting of Einstein and Monroe explores relativity and our place in the Universe.

And we have not even mentioned dark energy — the mysterious form of energy that is smoothly distributed throughout space and (at least approximately) constant through time. Independent observations of high-redshift supernovae, the microwave background radiation and the distribution of large-scale structure all require the existence of dark energy. The featureless, persistent nature of dark energy convinces us that it is not even a particle at all. About 70% of our current Universe is dark energy and 25% is dark matter. This leaves all the stuff we have directly observed at a paltry 5% of the whole Universe.

We infer the existence of dark matter and dark energy indirectly, through the influence of their gravitational fields on the ordinary matter that we can see. A famous example of such an inference is the discovery of Neptune, whose existence had been postulated to explain the motion of Uranus. But there is a famous failure, as well — an inner planet 'Vulcan' was once postulated to explain the discrepant motion of Mercury. The correct explanation is that our understanding of gravity was flawed — replacing Newtonian gravity with Einstein's general theory of relativity accounts perfectly for Mercury's orbit. Could a modification of Einstein's theory account for dark matter or dark energy? Perhaps, but constructing such a theory has resisted the attempts of even the most ambitious theorists.

A minimal model of dark matter and dark energy — no noticeable interactions between each other or with ordinary matter — fits the data very well. But if 95% of the Universe is in the form of unseen substances, does this not mean that there is the possibility of hidden structure? Might the dark sector be a fascinating place, with its own intricate interactions — perhaps even a kind of intelligent life? Is there a 'dark light' that we do not see, radiating and absorbing in the dark Universe?

Probably not. If dark matter particles interacted in a way analogous to ordinary matter, they would also behave analogously. In particular, they would collide and cool, settling into the central regions of galaxies, rather than dispersing into extended halos. If the dark energy were coupled to matter of any sort, it would tend to give rise to unseen forces. Although it is hard to absolutely rule out any kind of interesting physics in the dark sector, it is an impressive fact that the minimal model fits a broad variety of phenomena with high precision. More often than not, adding new interactions makes the fit worse rather than better.

Still, it is worth keeping an open mind. The minimal model has some apparent discrepancies, for example, substructure in galaxies and the concentration of dark matter near galactic centres seem to be less than we would predict. Perhaps this is because of new interactions. More likely, our current ability to make accurate predictions is not very good in these regimes.

Sometimes 'most' does not imply 'most interesting'. If human pride is wounded by the revelation of our secondary status in the cosmic inventory, we can take some solace in the recognition that the Universe of dark matter is a cold, quiet place indeed. ■

Sean Carroll is in the Department of Physics, University of Chicago, 5640 S. Ellis Avenue, Chicago, Illinois 60637, USA.

FURTHER READING

Krauss, L. *Quintessence: The Mystery of the Missing Mass* (Basic Books, New York, 2001).
Peebles, P. J. E. *From Precision Cosmology to Accurate Cosmology* online at http://arxiv.org/abs/astro-ph/0208037.
Rees, M. *Our Cosmic Habitat* (Princeton Univ. Press, Princeton, 2003).