Slim and beautiful: Galaxies too good to be true

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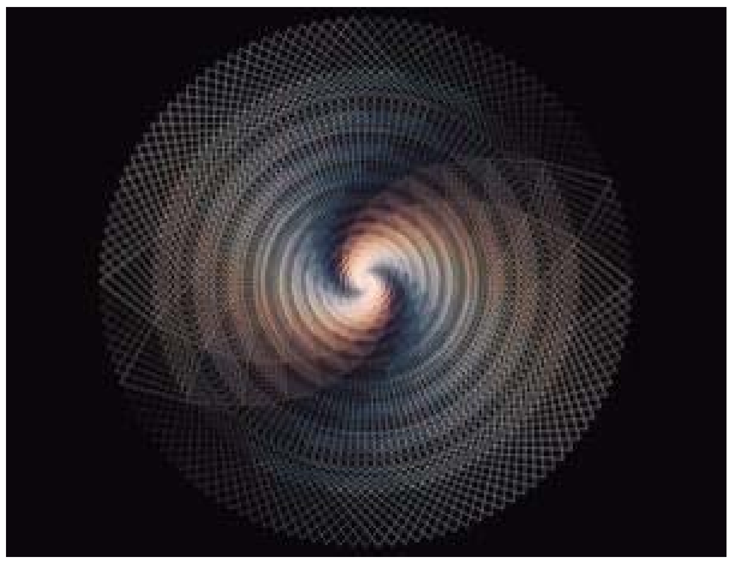
Pristine spiral galaxies are some of the most stunning sights in the night sky – so perfect that they have cosmologists scratching their heads



Battle of the bulge (Image: Andy Gilmore)

THEY are the pin-ups of the cosmos - elegant, luminous spiral swirls that whisper to us the word "galaxy". It's how we think our Milky Way would appear if we could look down on it from above. Other captivating examples are not far away: our nearest large galactic neighbour, Andromeda, for instance, or the evocatively named Pinwheel galaxy.

Easy as these spiral beauties are on the eye, for cosmologists they are becoming something of a headache. As we survey the spiral galaxies around us more closely, nagging doubts are creeping in that some of the largest, most luminous examples in fact look rather too perfect. What's more, many of them seem to be in entirely the wrong place.

There could still be a simple explanation, in some unanticipated twist in the tale of how these galaxies formed. But as the evidence stacks up it is beginning to look like our favoured theory of the cosmos is due for a makeover - and with it our conception of the unseen "dark matter" that controls it.

In a cosmos like ours that consists largely of very little, galaxies are a not-so-minor detail that demands explanation. Any working theory of the universe's development must unravel how these huge agglomerations of matter formed from the featureless, homogeneous universe created in the big bang some 13.7 billion years ago.

Over time a convincing story has evolved, one known as the hierarchical model of galaxy evolution. Its starting point is quantum fluctuations in the matter density of the primordial cosmos, and in particular the doings of dark matter. This invisible substance is thought to account for three-quarters of all the universe's mass, or thereabouts. As the universe expanded and cooled, tufts of it began to condense, forming areas where gravity exerted a greater pull, sucking in more dark matter and also normal gas. Guided by the unseen hand of gravity, these clumps began to mingle, merge and combine over millions of years. That process set them spinning and flattened them out into ever-larger rotating discs of matter - the first galaxies.

This is not a pretty process. Across the universe today, we can see evidence of these violent events in action: sensational collisions between grown-up galaxies, and smaller ones ruthlessly shredded and consumed by their larger counterparts.

Where two mature galaxies combine, gas and stars are tossed this way and that, disrupting or destroying the original pristine, rotating discs and creating a huge spherical jumble. The near-featureless elliptical galaxies dotted around the present-day cosmos are the products of such mergers.

The basic spiral form can survive the smaller-scale events that punctuate most galaxies' histories, but clashes create a central "bulge" of upset stars that do not orbit neatly in one plane, but swarm almost randomly about the disturbed galaxy's core. About 70 per cent of the galaxies in our local universe have this characteristic shape - flat, spiralling arms radiating away from a central, spherical bulge.

That, at least, is what we thought. John Kormendy has long had a sneaking suspicion that this couldn't be the whole story. An astronomer at the University of Texas at Austin, Kormendy has racked up 30 years studying galaxy evolution. In that time, he and others have spotted oddly pristine spiral galaxies that seemingly have no bulge at their cores. They were isolated examples, however, and not enough to set alarm bells ringing. "They could be explained away as the relatively few, relatively weird galaxies that happened not to have merged a lot," he says.

Then, in 2004, Kormendy teamed up with Ralf Bender of the Max Planck Institute for Extraterrestrial Physics in Munich, Germany. Their groups started to examine detailed images of large nearby spiral galaxies taken by the Hubble Space Telescope, backing them up with spectral observations from the University of Texas's Hobby-Eberly Telescope. The results, published in November last year, were something of a shock. Of 19 large nearby spirals, at least 11 seemed to have no bulge, indicating that violent mergers didn't feature in their past. Among them were the seemingly exemplary Pinwheel galaxy - and the Milky Way (*The Astrophysical Journal*, vol 723, p 54).

What these galaxies do have is a bright central concentration of stars all crowded together. To a casual observer it looks like a bulge, but the orderly trajectory of the stars, plus areas of active star formation characteristic of quietly rotating discs, indicate that these stellar swarms do not in fact protrude from the galaxy's plane. It is a nicety that is easy to overlook if we don't have the luck of seeing a galaxy edge-on. "For many decades, they were misidentified as classical bulges," says Kormendy.

And this huge number of slimline, pristine spirals has morphed into a big problem for the hierarchical picture. To get as large as they are, they must have merged, yet "we don't know how to prevent bulge formation when galaxies grow big via mergers", says Kormendy. Jim Peebles, a cosmologist at Princeton University, agrees. "It is wildly unexpected in the standard model," he says.

It's not the only odd thing about these galaxies, either. Twenty years ago, Kormendy was among the first to propose that supermassive black holes play a significant part in galaxy evolution. We think that these black holes exist at the heart of most galaxies because matter near their cores seems to be whirling around a vastly dense agglomeration of mass. In the 1990s, Kormendy and others noted that bigger bulges tend to go hand-in-hand with bigger black holes, suggesting that the two develop in tandem.

The story runs something like this: as large amounts of new material fall into the centre of a galaxy during a merger, the black hole consumes some of it, growing in quick bursts.

In the pristine, bulge-free spirals, there are no mergers to feed the black hole in this way. And it seems there is also no connection between the mass of the central black hole and that of the galaxy's bright central regions, blowing apart the idea that a black hole evolves in lockstep with its environment (*Nature*, vol 374, p 469). Some slimline galaxies seem to have tiny central black holes. The Pinwheel's, for example, is as little as one-thousandth the mass of the black holes of bulging galaxies of the same size. That leaves us with a rather messy picture. "Galaxies are complicated and we don't really understand how they form," says Peebles. "It's really an embarrassment."

Galaxy zoo

So what conclusions can we draw? The simplest, yet least satisfying, message is that the galactic past is inscrutably messy. Jonathan Feng, a particle physicist and cosmologist at the University of California, Irvine, thinks we may have to accept that there is no "one size fits all" explanation for how galaxies come to be. "Like people, galaxies have a wide variety of weird and wonderful histories, and these are reflected in the zoo of observed galaxy shapes and features," he says. Kormendy and his colleagues are now hoping to explain those histories by looking at large clusters of galaxies, where as far as we can see all large galaxies do have bulges. If confirmed, that fact might indicate that it is a galaxy's gravitational environment - whether it exists in the crowded confines of a galaxy cluster or in a wide-open space between clusters that is the crucial determinant of its development.

Peebles, though, wonders whether there might be more to it than that. He suggests that some central tenets of the hierarchical model must be abandoned or weakened.

The key, he says, is to allow for some mechanism that enables galaxies to assume something approaching their final form quickly; far more quickly and smoothly than the bumpy hierarchical process with its continual collisions and mergers allows. If a galaxy merger occurs well into the galaxy's life, when many stars have had a chance to form, those stars get thrown around like pinballs, making a messy bulge inevitable. But if the gaseous structure of a spiral galaxy assembles through early mergers, before a great number of stars have had a chance to ignite, this gas can easily form into a pure, pristine disc.

What you end up with is a two-track picture. Collisions and mergers play their part in constructing some of the large spirals, those with large bulges. Bulge and black hole regulate one another, explaining the observed correlation between their masses. But a significant number of large spirals - perhaps even the majority - form quickly and then evolve, in Peebles's words, as "nearly isolated island universes". A corollary is that their central black holes grow in a slower, weaker process, pulling material in a little bit at a time. That explains the apparent lack of correlation between their properties and those of the galaxy that hosts them.

While we didn't expect this complication, it has something else going for it. It might also explain why the pristine spirals we see are where they are.

There are 562 known galaxies between 3 million to 26 million light years from the centre of our galactic neighbourhood. Oddly, nearly all of these galaxies crowd into just two-thirds of the volume available to them. The other third is a vast region called the Local Void, which contains just two or three galaxies. Trouble is, simulations based on the standard theory predict that the Local Void should contain about 19 galaxies, perhaps more.

Our galaxy and its neighbours are among those gathered like wallflowers along the edge of the void in a structure known as the Local Sheet. Yet three of the 10 biggest, brightest galaxies lie 6 million light years away from this structure. That's also a problem for the standard picture, which says they should appear in more crowded regions. Peebles and his colleague Adi Nusser from the Technion in Haifa, Israel, have calculated that the odds of finding the configuration that we do are well below 1 per cent (*Nature*, vol 465, p 565).

That problem is resolved if some galaxies can evolve into their final forms faster. These rapidly forming galaxies would have sucked the area surrounding them dry of matter. With less matter within it to pull it together gravitationally, as the universe expanded following the big bang, this empty area would have expanded more rapidly, becoming ever bigger and emptier and eventually creating the Local Void with the galaxies collected around it that we see today.

But while the picture of fast-evolving galaxies has some compelling evidence to back it up, we still don't know the answer to a fundamental question: what is it that allows these galaxies to assemble so fast?

That might come down to dark matter's crucial role in fostering galaxies. The greatest concentrations of dark matter cradled the brightest galaxies and galaxy clusters. But if dark matter possessed different properties, that could have had dramatically changed how galaxies turned out, Peebles says.

The standard model of cosmology stands on the foundation of cold dark matter, which consists of a sea of particles that move around very little, if at all. That naturally produces a hierarchical picture, as such matter first gathers in small clumps, gradually merging to form large galaxies. It would be hard to conjure up something bigger straight off.

But it is not the only possibility. "If you want to consider alternatives to conventional cold dark matter, there is no shortage of possibilities," says Feng. If the stuff were a little warmer and faster-moving, for example, it would have a harder time converging into compact bundles, and would naturally form larger clumps, making mergers less essential - and possibly explaining how some galaxies could have grown without them.

One possible basis for warm dark matter is a "sterile" neutrino, a cousin of the elusive neutrino particles that we occasionally spy as they fly through the Earth without stopping. Neutrino-hunting experiments have in recent years seen ambiguous traces of these particles, which would be almost as light, and just as fleet of foot, as regular neutrinos but subject only to the force of gravity, making them even more difficult to pin down. Beyond sterile neutrinos, another possibility is that dark matter is created when heavier particles decay explosively, producing fast-moving, warm particles.

If dark matter comes in a different guise there will be consequences, though, Feng warns. "Since it is moving more quickly, it makes it harder to form small, dense regions," he says. That means there should be fewer smaller galaxies than the standard cosmology permits. That could tally with recent observations that the Milky Way has fewer satellite dwarf galaxies that we expect (*New Scientist*, 22 August 2009, p 37) - although that could be just because we have not yet spotted them all. Besides, the existence of dwarf galaxies in itself implies we don't have a free hand in determining how dark matter looks, says Feng. "The fact there are some of them limits how much you can modify dark matter properties to explain other things," he says.

All that means we are left rather in the dark. "We need some measurements, some tests, of the nature of dark matter," says Peebles - until we do, we won't have any idea of its true influence on galaxy formation. That is one reason why so many astronomical eyes are fixed on the Large Hadron Collider at CERN near Geneva, Switzerland. Most models of dark matter predict particles that should be produced in its highly energetic collisions.

While we wait for new insights, the true life story of the pristine spirals eludes us. Only one thing is certain: it will probably have more twists than we had assumed. That might not be a bad thing, says Peebles. After all, our current prescriptions for things like dark matter are pretty basic. "Why shouldn't it be more complicated?" he asks.

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