Bringing light to a dark Universe

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One of the biggest challenges facing cosmologists today is to explain how the Universe came to look the way it does. To appreciate the size of this task, consider our local star, the Sun. This is just one of the many billions that form the vast collection we call the Milky Way Galaxy. As we look up into the night sky we know there are at least as many galaxies as there are stars in the Milky Way. Galaxies are the building blocks of the Universe.

The key to understanding how the Universe evolved into the beautiful place we see today is being able to explain how galaxies are born and how they change with time. A number of questions spring to mind immediately: Why do galaxies come in a range of sizes and brightness's, with different abundances? Why do galaxies have a variety of shapes? Did galaxies all begin to form at the same time in the past, or is the formation process more complicated than this? Do galaxies change their appearance over time, perhaps as the result of close encounters or even collisions with other galaxies?

The basic recipe for making a galaxy is deceptively simple; take a huge cloud of gas, mix in the force due to gravity and wait. Despite the simplicity of this scheme the physics of galaxy formation remains poorly understood. This is because the processes thought to be important in the formation of galaxies, such as the cooling of gas and the formation of stars from the cold gas, are complex. A further difficulty is that galaxies are very big, very remote and have probably evolved over billions of years: unlike other scientific disciplines, astronomers cannot set up a simple experiment in the laboratory to test their ideas about galaxy formation. Moreover, we cannot go to a neighbouring galaxy to poke and prod at it to see how it is put together.

Instead, a new way of doing physics, using mathematical algorithms for computer simulations, is required[1] (Fig. 1). Here a prescription for building a

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[1] Using mathematical algorithms for computer simulations one can follow the formation of a single structure or a huge volume that covers a significant fraction of the observable Universe. Supercomputers like the Cosmology Machine shown in Figure 1 at the Institute for Computational Cosmology, University of Durham,

Fig. 1. Cosmology Machine at the Institute for Computational Cosmology, University of Durham

galaxy is designed and translated into a set of instructions that tells the computer how we think the model galaxy should build up. Running the simulation over the equivalent of some cosmological timescale puts this prescription to the test. If the end product looks anything like a real galaxy, then we have learned something about how galaxies are constructed. If not, then arguably we have learned even more about galaxy formation because we have to go back to the drawing board to reshape our ideas.

In addition to not having a perfect grasp of the physics behind galaxy formation, there is an added complication that we need to worry about. The ordinary matter that we see using telescopes is only a fraction of the material that makes up the Universe around us; the rest of the mass in the Universe is made of invisible "dark matter". Although we can't see it, we know it is there through the effects of the extra gravitational force it contributes in galaxies and on larger scales; dark matter controls the structure and destiny of the Universe. Recent theoretical work suggests that much of the dark matter may come in the form of new subatomic particles. To date, no one has isolated a particle of dark matter in the laboratory, though several experimental cam-

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are needed to tackle such computationally intensive calculations: a typical calculation can take anything from a week to several months on a hundred or more processors. The largest calculation to date followed the evolution of large scale structure over the history of the Universe using 1 billion particles to represent the mass of the Universe. (Institute for Computational Cosmology, University of Durham.)

paigns are underway, including one by the UK Dark Matter Collaboration based at the Boulby Potash Mine in North Yorkshire.

As if dark matter, made up of invisible, as of yet undetected exotic elementary particles was not hard enough to swallow, astronomers now believe that the Universe is an even stranger place. Observations of distant exploding stars suggest that we live in a Universe in which the rate of expansion is actually speeding up. This is exactly the opposite of what one would expect if mass were the only influence, with gravity acting as a brake on the expansion. Instead, the accelerating expansion of the Universe suggests that space is filled with a mysterious, sinister sounding “dark energy”.

However, the added burden of having to model the dark side of the Universe, the dark matter and dark energy, is not too taxing. It turns out that we have a pretty good idea of the initial conditions that should be fed into the computer for simulations. (Fig. 2).

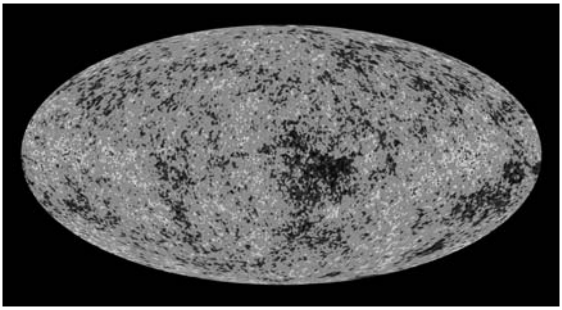

Fig. 2. The image shows the results from the first year of observations by the NASA Wilkinson Microwave Anisotropy Probe; the temperature ripples have amplitudes of order tens of micro Kelvin around a mean temperature of 2.726 Kelvin above absolute zero. (Courtesy NASA/WMAP Science Team.)

After that, the evolution of the distribution of dark matter, in a Universe in which dark energy can set the rate of expansion, is much more straightforward to model than the evolution of the luminous material that we can see. In the case of dark matter we only have to consider the force of gravity. The initial conditions come from observations of the cosmic microwave background radiation - the “heat” left over from the Big Bang that fills the Universe[2].

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[2] The cosmic microwave background radiation is a fossil relic from the Big Bang. The early Universe was much hotter and denser than it is today. Up to a few hundred thousand years after the Big Bang, the mass in the Universe was ionised: no neutral atoms existed, as the radiation that filled the Universe was energetic enough to dislodge the electron from hydrogen atoms as quickly as they formed. The distribution of radiation mirrored that of the mass in the Universe. By around 380,000 years after the Big Bang, the expansion of the Universe had cooled the radiation so that it became too feeble to knock electrons out of hydrogen. The

The pattern of temperature fluctuations seen in the microwave background radiation tells us about early structure in the density of the Universe. We can think of these patterns as a "baby picture" of the Universe. The microwave light we record set off around 380,000 years after the Big Bang, which occurred over 13 billion years ago; the equivalent of taking a picture of an 80 year old person on the day of his birth.

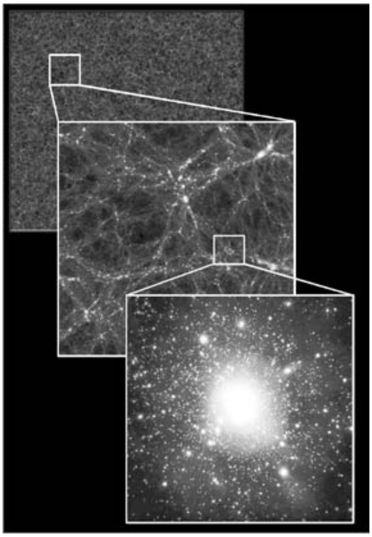

Fig. 3. Computer simulations of the formation of structure in the dark matter. (Simulations courtesy of the Virgo Consortium for Cosmological Simulations.)

The results from a computer simulation, set up to model the evolution of the dark matter in a large volume of the Universe starting from just after the Big Bang, are shown in Figure 3. The initially small irregularities in the density of dark matter grow due to the force of gravity attracting nearby material[3]. By the present day, the model Universe has a filamentary structure

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matter and radiation stopped interacting, but the radiation retained an imprint of the distribution of mass in the Universe at that early time. This imprint is seen as tiny fluctuations in the temperature of the cosmic microwave background radiation.

[3] Initially small density fluctuations grow through a process called gravitational instability. The intensity of the shading in Figure 3 indicates the density of dark matter. The top panel shows the present day output from the "Hubble Volume" simulation, which covers a large fraction of the observable universe. This simulation followed the formation of the large scale structure in the Universe using one billion particles to represent the dark matter. The middle panel shows a simulation of a smaller region of the universe with much higher mass resolution. Typically this class of simulation employs around 100 million particles and is

that has been dubbed the "cosmic web". This pattern looks similar to that of the distribution of galaxies seen in the biggest map made to date of the local Universe made by the 2dFGRS team (Fig. 4).

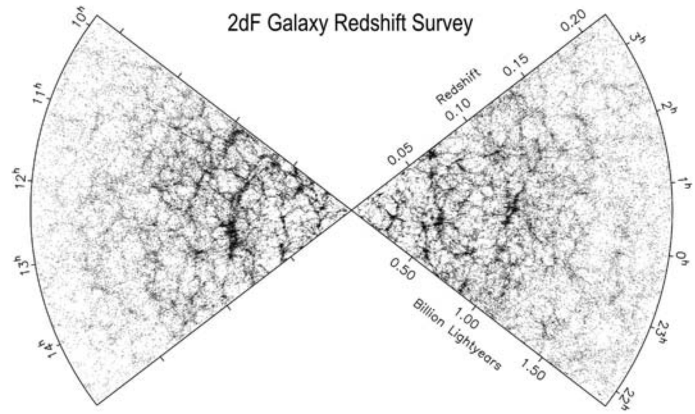

Fig. 4. The two-degree field galaxy redshift survey (2dFGRS). (Courtesy the 2dF-GRS team.)

The image shows the galaxy distribution projected in the declination direction on the sky; the scale at the fat end of the wedges gives the right ascension on the sky. The survey covers two regions on the sky, one in the Southern Galactic Pole and one towards the Northern Galactic Pole. The filamentary pattern of galaxies is similar to the so-called "cosmic web" apparent in the simulation pictures. The 2dF Galaxy Redshift Survey was undertaken by a collaboration of over 30 astronomers from more than a dozen institutions in Australia, the UK and the USA. The survey was completed in April 2002. Despite the similarity between these two images Figure 4 and Figure 3, one of the real Universe and one of a computer generated counterfeit, it must be remembered that we are comparing the measured distribution of galaxies with a simulated distribution of the unseen dark matter. How do we know what the distribution of galaxies should look like in the theoretical model? To answer this question one of us, (Carlton Baugh and Carlos Frenk), along with Shaun Cole and Cedric Lacey at the Institute for Computational Cosmology in Durham, and Andrew Benson at Caltech, performed a powerful computer

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used in combination with models of galaxy formation. Finally the bottom panel shows an ultra-high mass resolution simulation of the formation of an individual structure or halo in the dark matter. The formation of the dark matter halo could be followed with 10-100 million particles. The halo is quite lumpy; these are the cores of the ancestors of the halo that have been accreted or cannibalised through the force of gravity.

simulation that was able to follow the formation and evolution of galaxies in a model universe containing both dark matter and dark energy (Fig. 5).

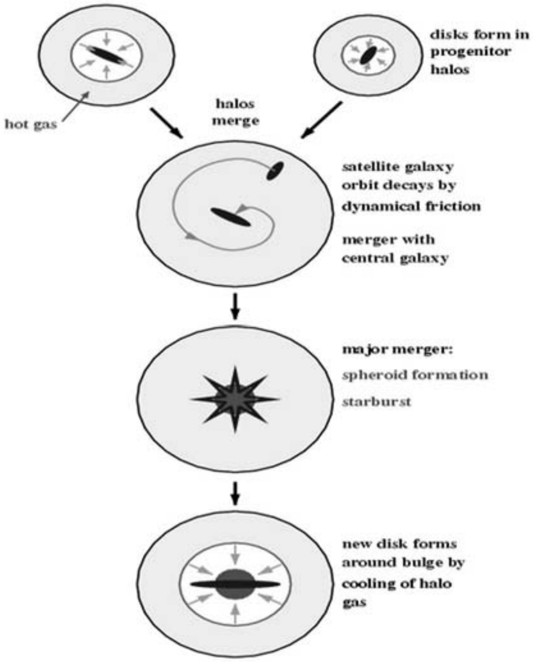

Fig. 5. How a model of galaxy formation works. (Courtesy Cedric Lacey.)

Computer simulations of structure formation in the dark matter can be used to reconstruct the family history or merger tree of a dark matter halo, showing the ancestors or fragments of the structure at an earlier time. The complex physics thought to be important in galaxy formation is then encoded in a semi-analytic model of galaxy formation using this tree. The model of Figure 5 describes how gas cools, how this gas turns into stars and how the star formation process is regulated by events such as supernova explosions. This cartoon illustrates the formation of a galactic bulge from the merger of two disk galaxies.

A prediction of where the galaxies should appear in this dark universe is shown in Figure 6. The model predicts that the size or brightness of a galaxy is related to the mass of the structures in the dark matter: big, bright galaxies are more likely to form in regions where the most massive dark matter structures are found. A fundamental consequence of this model prediction is that the clumpiness of the galaxy distribution should increase as the brightness of the model galaxies is increased.

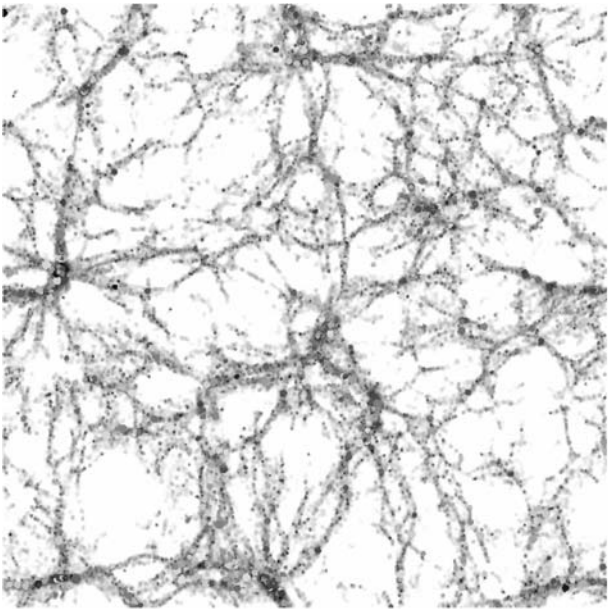

Fig. 6. The distribution of galaxies predicted by the semi-analytic model of galaxy formation. The size of the box is approximately 200 Mpc across; the slice shown is approximately 11 Mpc thick. (Courtesy Andrew Benson.)

Observationally, this effect had been searched for in a number of earlier surveys of the local Universe. However, the relatively small number of galaxies measured in these surveys meant that no clear consensus was reached; some teams reported trends of clumpiness in the distribution of galaxies increasing with brightness, others found no effect. The 2dFGRS team made measurements for ten times more galaxies than any other survey completed in the last millennium. The opportunity was there to resolve this issue once and for all. The 2dFGRS team, led by Peder Norberg (at the time a PhD student in Durham and now a Zwicky Fellow at the ETH in Zurich), examined how well the predicted behaviour of the model galaxies matched that of the real galaxies. Amazingly, the 2dFGRS galaxies showed exactly the same trend of clumpiness increasing with brightness that was predicted in the computer simulations.

This encouraging success for the galaxy formation model shows that the theorists may be working along the right lines, despite being kept in the dark about what most of the Universe is made of.