Dark Matter

2. Dark Matter in the Universe

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In Part 1[1] of this article we learnt that there are compelling evidences from dynamics of spiral galaxies, like our own, that there must be non-luminous matter in them. In this second part we will see that even clusters of galaxies must harbour dark matter. As if this was not enough, it turns out that if our knowledge of the universe is not completely wrong, then the universe as a whole has to contain dark matter and that it must be of some exotic type.

Before we discuss the evidences for dark matter in clusters of galaxies, let us point out that it is not just spiral galaxies which are thought to contain dark matter, although the evidences from them are the strongest. Other types of galaxies, like elliptical galaxies, are often seen to be shrouded by a hot halo of gases, which are hot enough to emit X-rays, and understanding this requires the existence of more matter in the galaxies than is seen in the form of stars.

Going beyond individual galaxies, recent studies of the dynamics of small satellite galaxies around large galaxies have shown that the luminous part of galaxies must be immersed in a huge halo of non-luminous matter, much larger than what the studies from rotation curves of spiral galaxies would suggest (see Part 1 of this article). These studies essentially use the same arguments as in the case of spiral galaxies and use the motion of satellites (instead of gas and stars inside the galaxies) to determine the required mass.

Masses of Clusters

An important result from classical mechanics states that for a system of particles the total potential energy (W) is related to the

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[1] Part 1. What You See Ain't What You Got, *Resonance*, Vol.4, No.9, 1999.

total kinetic energy (T) when the particles reach a state of equilibrium. This is analogous to (1) of Part 1 which applies to a single particle in a gravitational field. In this case of an ensemble of particles, the potential arises from the interactions of all particles. To be precise, in this case, one has $W+2T=0$ for such a system. Here, W is proportional to M_t/R where M_t is the total mass and the mean separation between the particles is R (actually it is the harmonic mean, but such details are not necessary for the argument below), and T is proportional to v^2 where v is the mean random velocity of the particles. So, $W=-2T$ means that $M_t \propto Rv^2$. For a given mass, the total size of the system is proportional to the mean separation. Therefore larger the random velocity of particles, larger must be the total mass of the system (for the same size of the system). This is roughly what happens in the case of stars as well. The larger the mass, or the smaller the radius, the higher is the central temperature ($T \propto v^2$) of a star.

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This result, called the virial theorem, has been applied to clusters of galaxies which often contain as many as thousands of galaxies. Observations of the Doppler shift in the spectrum of galaxies can be used to infer the radial velocities of galaxies, and averaging over a number of galaxies, one can find the average three-dimensional velocity of galaxies in a cluster. The separations between the galaxies can also be easily observed and the clusters are thought to have evolved for a considerable time and are in a state of equilibrium. Therefore one can apply the virial theorem to clusters. The total mass estimated from the virial theorem shows an excess of mass which is about ten times that seen in visible galaxies.

Another interesting way to estimate the total mass in clusters uses the result from Einstein's theory of relativity that mass can cause light rays to bend. Images of galaxies at large distances compared to those of clusters and which appear as background objects behind clusters of galaxies are often seen to be distorted. The amount of distortion, from relativity theory is a measure of the distribution of mass in the foreground. One can then calcu-

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late the mass in foreground clusters from such distortion and this estimate is consistent with that obtained from the virial theorem.

Over a larger length scale, there are indications of a large scale distribution of dark matter from the motions of galaxies. Although the galaxies are known to be receding from us because of the expansion of the universe, there are some extra movements superposed on this expansion. This is believed to be caused by the fact that the universe is not homogeneous when sampled at length scales of clusters or a system of few clusters. Clumps of matter can cause galaxies in the vicinity to deviate a bit from the motion due to the expansion of the universe. These deviations can be observed and used to determine the distribution of mass, which can be compared to the distribution of visible galaxies in the universe. There is again a mismatch and non-luminous matter is required to explain the motions of galaxies. The exact amount of dark matter is, however, uncertain and depends on details of how galaxies actually form, and to some extent on the total mean mass density of the universe as a whole. There are indications though that the mean mass density of the universe needs to be larger than a certain value to explain the observations.

Critical Density

In Einstein's theory of relativity, the dynamics of the universe can have three possibilities and is decided by the mean mass density of the universe. If the density is larger than a critical value, called the critical density, then the universe expands for some time and then collapses back due to gravity. This is a closed universe. If the density is less than the critical density, then the universe expands forever. A universe with the mean density equal to the critical density (called a flat universe for reasons to do with the geometry of spacetime in such a universe) hovers perennially between these two possibilities and its speed of expansion decreases all the time. These possibilities are analogous to the three types of orbits in Newtonian theory. A closed universe corresponds to a bound orbit, an open universe to a hyperbolic orbit and a flat universe to a parabolic orbit. Just as the orbits depend on the energy of the particle, the fate of the universe depends on its mean mass density.

The ratio of the mean mass density to the critical density is therefore a useful number to label different universes. If this ratio, called Ω, is larger than unity, then it is a closed universe, and so on. (To be precise, there can be an added complication, if there is what Einstein called the cosmological constant, but we need not worry about it here.)

We can now quantify the results of the observations of large scale motions of galaxies in terms of Ω. It seems that the match between theoretical prediction of motions of galaxies and observations requires a value of $\Omega > 0.2$–0.3. Many theorists, however, believe that the actual value of Ω is much larger. At any rate, do we have this much of mass in the universe in luminous form? The answer is again a resounding 'no'. To appreciate the answer we need to discuss the past history of the universe, which will show us that the amount of normal matter in the universe could not have been much.

Big Bang Nucleosynthesis

Although there are three possibilities for the future of the universe, the past is relatively more certain. As one goes back in time the universe becomes smaller in size and there is no escape from its extent having been only a point at some point of time. This is the Big Bang model and this has been supported by a variety of astronomical observations. (One can actually contrive theories to avoid such a history of the universe but modern observations do not support them.) According to this model, as the universe expands, its mean density decreases and it cools down. In other words, the universe was denser and hotter earlier.

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It is not only matter but radiation can also be an important constituent of the universe. It is well known that when matter and radiation are in equilibrium (that is, when matter absorbs as much energy from radiation as it radiates) the radiation has a particular spectrum, called the black body spectrum. In the early hot universe, matter was so dense that one expects the radiation to have been in equilibrium with it. So the radiation in the early universe is expected to be of black body type.

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This radiation then cools as the universe expands, by which one means that the frequency of radiation is shifted to a lower value (just as the radiation from hot iron is shifted from blue to red as the iron cools). One therefore expects a pervading radiation of low frequency corresponding to a low temperature, in the present universe. Just such a radiation was discovered in 1964, with a temperature of around 3 K, by Penzias and Wilson and it is one of the most important supports for the Big Bang model.

These ideas were worked out initially by a maverick physicist named George Gamow in the 1940s, who had predicted this cosmic radiation in the Big Bang model. He had also worked out some other consequences of the universe being hot and dense in its early phase. One of them has to do with the synthesis of heavy elements from nuclear interactions. Gamow had earlier worked out the physics of nuclear interactions inside the hot core of the Sun. The case of the early universe is a bit more complicated because the universe is expanding all the time, and the density is decreasing. The interaction rate between particles therefore decrease as time progresses. After some point of time, rates of certain reactions decrease so much that they fail to have any impact on the abundances of particles. The number densities of participating nuclei do not change much thereafter – they 'freeze out'. One therefore has to keep track of all reactions and how their rates evolve due to expansion of the universe.

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Let us look at the production of helium nuclei (2 protons +2 neutrons). When the age of the universe was about 1 second the universe was a hot dense mixture of protons, electrons, neutrons, neutrinos and photons. Neutrinos mediate the interactions that convert protons into neutrons and vice versa. The ratio of protons to neutrons was close to unity then as they were in equilibrium since the rate of these reactions was high enough to keep the participant particles in balance. However, soon (when the age of the universe was around 2 seconds) the neutrino mediated reactions slowed down miserably. The ratio of protons to neutrons (p/n) did not change much after that. (We are neglecting some details here as they are not relevant).

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In the meantime, the protons and neutrons begin to form helium nuclei, just as in the core of the Sun. Calculations show that the ratio p/n is 7 when this happens. So for every 14 protons there are 2 neutrons. This means that for every 14 protons, there would be 1 helium nucleus and 12 protons. Since the mass of the helium nucleus is nearly 4 times that of a proton, the mass fraction of helium in the universe (since in the universe there is mostly hydrogen and helium) is $4/(4+12)=1/4$. The Big Bang model therefore predicts that about 25% of the universe should be in the form of helium, which is also the observed fraction.

The production of 4He is not the end of nucleosynthesis though. Other nuclei like deuterium, 3He (2 protons +1 neutron) and lithium also form. The results of these reactions depend crucially on the ratio of matter density to that of radiation. If this ratio is too small, then radiation is too intense and the fragile deuterium nuclei are destroyed before the other nuclei form out of it. If the ratio is too large then there would not be enough matter (or protons) to create deuterium in the first place. So the observed present day abundance of these light elements can fix this ratio and the amount of (normal) matter in the universe. Here only the normal kind of matter (protons, neutrons etc.) is relevant as the nucleosynthesis uses only the normal particles. Detailed calculations show that this means a density of normal matter of order $\Omega_{\text{normal}} = 0.06 \pm 0.02$ (this also depends on other cosmological parameters that we have not discussed, but this is the most probable value). This is certainly smaller than the total mean density that

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was inferred from the motions of galaxies, $\Omega_{\text{matter}} > 0.2$–$0.3$. We have to therefore conclude that the amount of normal matter in the universe (luminous + non-luminous) is smaller than that of total matter in the universe.

The amount of luminous matter can be estimated by using the density of starlight in the universe and an average mass-to-light ratio (as in Part I). This amounts to $\Omega_{\text{luminous}} \sim 0.005$. The difference between Ω_{luminous} and Ω_{normal} must be made up of normal dark matter (like brown dwarfs, black holes etc.).

This is then the result of taking an inventory of matter in our universe: $\Omega_{\text{luminous}} < \Omega_{\text{normal}} < \Omega_{\text{matter}}$. There must be some normal matter which is dark, and there must be some dark matter which is of exotic type, although the amount of each remains somewhat uncertain.

What could be this exotic dark matter? Clues to this question come from studying the problem of formation of galaxies and clusters in the universe. It is thought that these structures grew out of small fluctuations in the density of the universe. Regions which are slightly overdense compared to the surrounding regions collapsed due to gravity and formed structures like galaxies. What makes the study of galaxy formation interesting is the fact that the growth of structures depends crucially on the type and amount of dark matter. Results from recent studies indicate that the dominant type of dark matter must be fairly massive and only weakly interacting. This has prompted the particle physicists to find out the best candidates for such WIMPs (weakly interacting massive particles) and eventually try to detect them. A confirmed detection would certainly change the way we think of our universe.

Suggested Reading

[1] V Jayant Narlikar, *The Lighter Side of Gravity*, Cambridge University Press, 1996.
[2] V Jayant Narlikar, *The Primeval Universe*, Oxford University Press, 1988.
[3] N Cohen, *Gravity's Lens: views of the new cosmology*, Wiley and Sons, 1988.
[4] Virginia Trimble, Existence and Nature of Dark Matter in the Universe, *Annual Review of Astronomy and Astrophysics*, 25, 425, 1987.

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