Mem. S.A.It. Vol. 83, 1048
Memorie della

From large scale structure to the Milky Way halo

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Abstract. In the last decade, the accumulation of extremely high quality data from astrophysical observations has heralded the era of ”Precision Cosmology”. A number of surveys have provided a substantially comprehensive picture of the Universe, represented as a spatially flat geometrical manifold, with a matter content well below the critical value needed to close it and an accelerated expansion stage. The model which better agrees with the wealth of astrophysical data is the so-called Lambda Cold Dark Matter (ΛCDM) model, composed up of a cosmological constant (or cosmological fluid with negative pressure) otherwise known as dark energy (DE), cold dark matter (CDM) and baryons each contributing roughly 70%, 26% and 4% respectively to the global energy budget of the universe. Notwithstanding the satisfactory agreement with observations at large scales, the ΛCDM model still faces several theoretical (e.g. cosmological constant problem, coincidence problem) and observational issues at galactic scales (e.g. substructure problem, core vs cuspy density profiles, satellite anisotropy problem, angular momentum problem). Astrometric cosmology promises to play a defining role in differentiating between the ΛCDM model and alternatives at galactic scales.

1. Introduction

A sizeable collection of observations have contributed to establish a comprehensive picture of the Universe. These range from Hubble diagrams derived from the observations of Type Ia supernovae (SNeIa), the optical surveys on the large scale structure, the measures of the microwave background radiation anisotropies, and the cosmic shear measures through gravitational weak lensing surveys. The model which better agrees with such a wealth of astrophysical data is the so-called Λ Cold Dark Matter (ΛCDM) model, with a cosmological constant (or cosmological fluid with negative pressure) contributing ∼70% to the global energy budget of the universe, while the other 30% is constituted by ∼4% baryons and, for the remaining part, by cold dark matter (CDM). This model can be reasonably assumed as a first step towards a new standard cosmological model. Notwithstanding the satisfactory agreement with observations, the ΛCDM model still faces several theoretical issues. If the cosmological constant constitutes the ”vacuum state” of the gravitational field, one should be able to explain the huge difference between the vacuum value predicted by any quantum gravity theory and the one observed at a cosmological level. Furthermore, one should be able to resolve the coincidence problem, for which dark+baryonic matter and the cosmological constant (i.e., dark energy, DE) are today qualitatively of comparable orders of magnitude,

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even if they evolved decoupled over the past history of the Universe.

Moving from cosmological to galactic scales, the ΛCDM model seems unable to fully explain some recent observations. For instance, ΛCDM simulations of the formation of dark haloes show a universal density distribution (independent of the total virial mass) characterized by a steep central cusp: this is consistent with the dynamics of some spiral galaxies, but not with many observations of late-type (LT) galaxies. Furthermore, dynamical studies of some "ordinary" early-type (ET) galaxies have shown a considerably low CDM content. The substructure problem indicates a discrepancy in the number of satellite galaxies seen in N-body simulations as compared to what is observed in our local group alongwith the anisotropic distribution where the satellites occupy a plane nearly perpendicular to that of the Milky Way at odds with simulations. Also, disk simulations of the galaxy demonstrate disks that are too compact due to an issue with the transfer of angular momentum between the dark matter and baryonic components. These problems will be addressed in more detail including possible explanations trying to resolve the discrepancies between the ΛCDM model and observations in the solar neighbourhood.

It remains to be seen whether these issues can be traced to observational problems (e.g. different star formation efficiencies) rather than to oversimplified predictions of the halo properties, or ultimately indicate a necessary revision in the theoretical foundations of the ΛCDM paradigm. Hence, it comes as no surprise that this uncertain context has been fertile ground for alternative approaches to the so-called "missing mass problem". For example, MOND (Modified Newtonian dynamics, Milgrom 1983) is based on phenomenological modifications of Newton dynamics in order to explain the flat rotation curves of spiral galaxies. Instead, motivated from cosmology and quantum field theories on curved spacetimes, a new approach has been proposed to study the gravitational interaction: the Extended Theories of Gravity. In particular, f(R)-theories seem to explain correctly the dynamics of spiral galaxies, the mass profiles of galaxy clusters, and the present observed cosmic acceleration without taking into account exotic ingredients, not yet definitively identified at a fundamental level as CDM and DE (Capozziello et al. 2007). The crucial point of such an approach is that the Einstein theory is tested only up to Solar System scales and then it is extrapolated to extragalactic and cosmological scales.

2. Large scale structure on linear scales

The inflationary phase of the universe gave rise to primordial perturbations in the cosmic soup further acting as the seeds for structure formation. The gravitational interaction of dark matter and amplification of the primordial fluctuations subsequently led to the formation of large scale structures in an ever expanding universe.

The first galaxy surveys clearly demonstrated the distribution of galaxies on large scales. For example, the Center for Astrophysics (CfA) Redshift survey that was started in 1977, led to the 1989 discovery of the 'Great Wall' supercluster of galaxies with an impressive dimension of 600x250x60 million light years (Geller & Huchra 1989). More recent low redshift surveys, such as the Sloan Digital Sky Survey (SDSS), with observations obtained using a 2.5m optical telescope in New Mexico, maps a quarter of the sky and accounts for roughly 1 million galaxies (Abazajian et al. 2009). The SDSS found the largest known structure in our galaxies spanning 1 billion light years across. The 2 degree Field Galaxy redshift survey (2dfGRS) has also mapped close to 250,000 galaxies with the help of a 3.9m Anglo-Australian telescope (Colless 2002). High redshift surveys, e.g. Vimos VLT Deep Survey (VVDS, Le Fèvre et al. 2005), a spectroscopic survey of about 9000 galaxies upto $z \sim 5$ over 0.5 square degrees imaged using the CFHT camera and ESO 2.2m WFI, and the DEEP2 survey of several 10,000 galaxies over a larger area, has led to a better understanding of the evolution of galaxy properties and the underlying dark matter.

These past surveys and ongoing ones show the cosmic web of structure on large scales, with a highly filamentary structure of galaxies, nodes of superclusters and mostly empty voids. It is difficult to test cosmological theories characterizing the primordial fluctuations in deterministic terms due to the lack of direct observational evidence and the long time scale for cosmological evolution. Hence the evolution of structure is done statistically (Bernardeau et al. 2002). For example the distribution and amount of clustering of matter can be quantified with the correlation function and is a much widely used approach. The two point correlation function is the probability, in excess of random, of finding a galaxy at a fixed distance from a random neighbor. Whereas the power spectrum is given by the Fourier transform of the correlation function. However, in order to better study deviations from Gaussianity that arises from the non-linear evolution of structure higher-order statistics are used.

The evolution of the cosmic web on large scales can be described with the help of perturbation theory. However, at highly non-linear scales this description breaks down and no longer provides a rigorous framework for describing how the distribution of galaxies differs from that of dark matter. In this case a halo based approach can provide the explanation by following the assumption that galaxies form due to gas cooling and evolve within virialized bound structures otherwise known as dark matter halos (Cooray & Sheth 2002). The statistics at all scales is then simply described as the sum of the statistics on small scales, known as the 1 halo term, and the statistics on large scales, aka the 2 halo term. The 1 halo term is described in terms of the halo mass function and the halo density profile, whereas the 2 halo term uses the halo mass function and halo-halo correlation function. In this context, the environmental dependence of the clustering of dark matter as seen in simulations and SDSS galaxies is seen to support the hierarchical formation of structure scenario (Abbas & Sheth 2005, 2006).

3. Concordance model on non-linear scales

On smaller scales, i.e. the size of our local group of galaxies, presently the concordance model faces several issues. These scenarios are seen in N-body dark matter simulations which are only recently becoming more adapted to studies of galaxies at small scales, i.e. in terms of mass resolution. The most resolved mass per particle is about $10^3\ M_\odot$ translating into roughly billion particles making up a single galaxy (GHALO simulation, Stadel et al. 2009). Furthermore, as galaxy formation and evolution is a highly complex process, the inclusion of sophisticated and often not-well understood 'gastrophysics' is a dynamical study and several issues can possibly be resolved with further developments in our understanding.

In N-body simulations several orders of magnitude more satellite galaxies are seen at the scales of our local group as compared to observations (only few tens are known) and is known as the 'substructure problem'. However, within the halo model framework, galaxies form within dark matter halos having sufficient mass that provides the potential well within which gas cools and leads to the formation of a galaxy. The existence of so called dark satellites, or low mass halos and those with suppressed star formation, can account for a missing fraction of satellites. Furthermore, reionization at high redshifts would suppress the cooling of gas in halos of low mass thereby leading to thousands of 'unlit' dark matter halos. It should also be noted that the last few years has seen a rapid increase in the discovery of smaller mass Milky Way satellite galaxies, leading to an increasing number of observationally known satellites with the present known number a factor of more than 2 larger as that of 2005. Moreover, the presence of ultrafaint dwarfs can be investigated by precise proper motions to determine their origin and evolution through encounters with the Milky Way. The nature of dark matter strongly affects the minimum mass and count of dark satellites, for instance by invoking dark matter particles as warm (WDM - sterile neutrinos), instead of cold, leads to simulations with less than a hundred satellites truncated at $M < 10^8\ M_\odot$. WDM, characterized by lower phase-space density and higher velocity dispersion, also helps with explaining the cuspy density profiles of dark matter halos that will be addressed below.

Observationally the anisotropic distribution of satellites shows that the Milky Way satellite galaxies lie in a disk like structure nearly perpendicular to the Milky Way plane. In simulations this could be caused by satellites that may have fallen into the local group as part of a few sets of dark matter sub-halos. Larger satellites could break up and the formation of tidal dwarf galaxies can partly explain this anisotropic distribution (Kroupa et al. 2010).

The density profiles of dark matter is shown to follow a universal trend (e.g. NFW, Navarro et al. (1997), Moore et al. (1998) profiles being among the popular ones). The NFW profile is given by $\rho_{NFW}(r) = \rho/(r/r_s)/(1 + r/r_s)^2$. This profile is intrinsically cuspy within small radii following a $\sim 1/r$ behaviour and in contrast to the profiles of Low Surface Brightness (LSB) and Dwarf galaxies that predominanty show a cored density profile. An example of a cored profile is an isothermal profile given by $\rho_{ISO}(r) = \rho_0(1 + [r/r_c]^2)^{-1}$. However, systematic effects caused for e.g. by slit misplacements, slit width, inclination of the galaxy etc. can underestimate the density profiles of such galaxies by 30 – 50% (van den Bosch et al. 2000; Hayashi et al. 2004) leading to what could be mistaken for a cored profile. Furthermore, non-circular motions upto 20 km/s over the disk in simulation is consistent with CDM (de Blok et al. 2003). On the other hand, typically upto a few km/s are observed (Trachternach et al. 2008).

The angular momentum problem arises due to the transfer of too much of angular momentum from the visible to the dark component during infall in numerical simulations of galactic disk formation leading to disks that are too compact. However, this can be resolved by stellar feedback and WDM (Piontek & Steinmetz 2011).

4. Role of Astrometric Cosmology

Astrometry with its more than two millenia history dating back to the time of Hipparchus (~ 130 BC) is based on precise measurements and physical theory. Present day catalogs include measurements at the milliarcsecond (mas) level as provided by the Hipparcos mission with a catalog of over 100,000 stellar positions with half of these with distances known to better than 20% out to roughly 100 parsecs. Many areas of Astronomy and Astrophysics have benefited from the Hipparcos measurements, in particular stellar structure and its evolution and the structure and dynamics of the Milky Way Galaxy. Results of observing the distances and motions of stars perpendicular to the plane of the Milky Way Galaxy have also been used to probe the distribution of dark matter in the universe (Perryman 2000). The kinematics is traced by the stars giving information on the gravitational interactions of the massive material in the galaxy irrespective of the constitution of matter. For instance, the Hipparcos results have shed light on the presence of dark matter distributed in the galactic halo rather than in the disk, which is dominated by stars.

The upcoming ESA cornerstone mission, Gaia, presently stipulated to be launched in June, 2013 will provide the astrometry, photometry and spectroscopic measurements of ~1 billion objects in our solar neighbourhood. This is indeed the golden era for astrometry as Gaia will push us into the realms of high-precision measurements down to the μ-arcsecond level. This map of unprecedented precision will allow us to further probe the nature of dark matter and its role in the formation of galaxies. Our Milky Way galaxy and Local Group will provide the ultimate laboratory in testing and validating the present concordance model of cosmology and alternatives.

The bottom-up scenario for structure formation is well supported by galaxy redshift surveys and N-body simulations of dark matter (and dark energy) and show the classical signatures of walls, filaments and voids. However, in order to resolve the excess of substructure issue in the presence of CDM one will have to resort to 'near-field' cosmology. Information

Table 1. Galactic Dynamics and local DM experiments

Experiment	No. of Stars	Magnitude range, V	PM Accuracy, μas/yr
Tidal Streams	400	11-19	4-20
Milky Way & Extragalactic High-Velocity Stars	20	18-20	10-60
Satellite Orbits	350	14-20	7-40
Angular Momentum Profile	100	16-20	50-75
Dark Matter in Dwarf Galaxies	200	17-19	11
Local Group Galaxy motions	600	17-20	2-10

on the early galactic formation can be obtained from the orbital dynamics of halo stars and globular clusters, whereas infall processes affecting more recent galaxy assembly and the dark matter distribution in the halo can be studied through satellite galaxies (Davidson et al. 2009).

High precision astrometric observations can also constrain the total mass, mass profile and shape of the DM distribution in the Milky Way upto its virial radius. Proper motions of distant halo stars and globular clusters that trace the dark matter distribution in the halo would provide information on the mass profile and allow for direct comparisons to the predictions from the CDM model. Furthermore, the proper motions would allow us to model full three-dimensional orbits and study the angular momenta and eccentricity. According to the CDM paradigm, the halo stars and globular clusters in the inner confines of the halo tend to exhibit isotropic orbits as compared to the radially biased orbits of these objects placed in the outermost regions. Dwarf satellite galaxies that are part of late infall can be an exception to this rule. On the other hand, proper motions of stars in various tidal streams would give clues on the halo shape and its orientation and whether it is triaxial as in CDM models, or closer to being prolate, spherical or oblate. Entire streams will also illuminate the overall shape and smoothness of the galactic potential. Radial velocities and the astrometric motions of stars will help in determining the density core vs cusp profile and requires proper motions to about 7 km/s on roughly 200 stars per galaxy corresponding roughly to 15 μas/yr for 19th magnitude stars (Davidson et al. 2009).

High accuracy proper motions ($<10\,\mu$as/yr) of galaxies within the local group can be used to solve for the trajectories of galaxies and provide predictions on their masses. This is an application of the least-action method by (Peebles 1989) and requires adjusting the masses of individual galaxies and assumes that the orbits are not complex. The accuracy required in proper motions is much higher than that to be obtained with Gaia, but can certainly be addressed with follow-up astrometric missions. Table 1 taken from Davidson et al. (2009) shows the number of stars required within a magnitude range and their proper motion accuracy for various experiments.

5. Conclusions

The gamut of observational data of Type Ia Supernovae, of the large scale structure at high and low redshifts, of the cosmic microwave background, and of cosmic shear due to weak lensing, all point towards what is known today as the concordance model of the universe. This model predicts that the visible, baryonic matter comprises ~4% of the energy budget of the universe, with the remaining ~96% divided up into ~70% dark energy and ~26% dark matter. Numerical N-body simulations conducted within this framework predict structures on large scales in accordance with redshift surveys. The recent accumulation of spectroscopic and photometric data of galaxies to increasing redshifts provides fertile grounds for testing the ΛCDM model, and at looking at the nascent phase and evolution of stars and galaxies. Whereas, upcoming high precision astrometric data will provide the laboratory for validating the concordance model within our Milky Way Galaxy and Local Group. The lack of problems faced by the ΛCDM model at large scales is juxtaposed by enough problems on small scales. This points towards the local scales as providing the critical platform for validating and testing the concordance model and alternatives, thereby providing the means for differentiating between them.

Acknowledgements. I thank the LOC for the wonderful organization and smooth running of the meeting. The choice of location, for my first time visit to Portugal, was nothing short of enjoyable. I thank in particular Mariateresa Crosta and Sonia Anton for inviting me to present and attend the workshop. The social dinner on the boat cruising the Douro river will remain a treasured memory. Finally, I thank all my lovely colleagues, friends and new aquaintances, without whom the meeting would have been a drag!

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