RESEARCH PAPER | Physics | Volume : 3 | Issue : 1 | January 2013 | ISSN - 2249-555X

Seven Puzzles for LCDM Cosmology

KEYWORDS

Mohammed Sajid Iqbal

RESEARCH SCHOLAR, CMJ UNIVERSITY, SHILLONG

ABSTRACT *the ΛCDM cosmological model is a well defined, simple and predictive model whichis consistent with the majority of current cosmological observations. despite of these successes there are specific cosmological observations which differ from the predictions of ΛCDM at a level of 2Λ or higher. these observations include the following: 1. large scale velocity flows (ΛCDM predicts significantly smaller amplitude and scale of flows than what observations indicate),2. brightness of type Ia supernovae (SnIa) at high redshift z (ΛCDM predicts fainter SnIa at high z), 3. emptiness of voids (ΛCDM predicts more dwarf or irregular galaxies in voids than observed), 4. profiles of cluster haloes (ΛCDM predicts shallow low concentration and density profiles in contrast to observations which indicate denser high concentration cluster haloes) 5. profiles of galaxy haloes (ΛCDM predicts halo mass profiles with cuspy cores and low outer density while lensing and dynamical observations indicate a central core of constant density and a flattish high dark mass density outer profile), 6. sizable population of disk galaxies (ΛCDM predicts a smaller fraction of disk galaxies due to recent mergers expected to disrupt cold rotationally supported disks). 7. The dark energy may be almost impossible to detect in laboratory and its value is un naturally small Compare to naïve theoretical prediction even though the origin of some of the above challenges may be astrophysical or related to dark matter properties, it should be stressed that even on galactic and cluster scales, the effects of dark energy on the equilibrium and stability of astrophysical systems are not negligible and they may play a key role in the resolution of the above puzzles. here, briefly review these six challenges of and discuss the possible dark energy properties required for their resolution.*

INTRODUCTION

Accumulating diverse observational evidence have indicated that the universe has entered a phase of accelerating expansion. such observations include direct geometrical probes (standard candles like SnIa gamma ray bursts and standard rulers like the cmb sound horizon and dynamical probes (growth rate of cosmological perturbations probed by the redshift distortion factor or by weak lensing . all these observational probes are converging towards confirming the accelerating expansion of the universe assuming the homogeneity of the universe. they have ruled out at several a flat matter dominated universe and they have produced excellent fits for the simplest cosmological model predicting accelerating cosmic expansion. this model is based on the assumptions of flatness, validity of general relativity, the presence of the cosmological constant λ and cold dark matter (ΛCDM from the theoretical viewpoint the main weak points of ΛCDM include

The fine tuning problem:
What is the physical mechanism that sets the value of λ to its observed value which is 120 orders of magnitude smaller than the physically anticipated value?

The coincidence problem:
Why is the energy density corresponding to the cosmological constant just starting to dominate the universe at the present cosmological time? despite of efforts to increase the complexity ofΛCDM (using eg quintessence or modified gravity in order to address the above weak points there has been no successful alternative that addresses the above problems without replacing them with other similar ones involving new tuned parameters. since the theoretical weaknesses of the model have lead to no successful alternative it may be useful to identify the observational weak points of ΛCDM and use these as a guide to building alternative models. in view of the fact that ΛCDM is a simple, well defined and predictive model, it is important and straightforward to test its validity using a wide range of observational probes. if some of these observational probes indicate inconsistency of ΛCDM with observations then it is interesting to consider the modifications of the model required to establish consistency with observations. most approaches in testing the consistency of ΛCDM with observations have focused on comparing ΛCDM with alternative models or parameterizations on the basis of a bayesIan analysis using thegeometrical and dynamical probes mentioned above due to its simplicity and acceptable quality of x2 fit, ΛCDM usually comes out as a winner in such a comparison. despite of the simplicity and apparent consistency of ΛCDM with most cosmological observations there are specific observational challenges for the model which have developed and persisted during the past few years. some of these challenges involve galactic scale phenomena and it has been common wisdom that they will be resolved once astrophysical effects on these scales are better understood.

Other challenges however, involve phenomena on scales larger than ~ 10h`m pc and these mayrequire more drastic modifications of the model in order to be resolved. such large scale challengesof ΛCDM include the observed high amplitude of large scale velocity flows on scales > ~ 100h ~1m pc the unexpected brightness of high redshift type Ia supernovae (SnIa) the halos of massive clusters of galaxies which are more concentrated and denser than predicted by ΛCDM and the emptiness of voids which is unexpected in the context of ΛCDM. on smaller (galactic) scales ΛCDM is challenged by observations of constant density galactic halo cores instead of the ΛCDM predicted cuspy central cores , the higher than expected density of outer galactic haloes and the sizable population of cold rotationally supported disk galaxies.

Since the above effects are statistically significant at 2 level or more it is unlikely that they are all statistical flfluctuations. in fact, it is possible that the resolution of the above puzzles will require more than a better understanding of astrophysical effects present on galactic scales. it may require a significant modification of the cosmological scale properties of the standard ΛCDM model such as the properties of gravity, dark energy or dark matter.

The goal of the present paper is to review the above phenomena challenging the foundations of the standard ΛCDM cosmological model. i will also discuss possible features of the model that may require modification in order to improve consistency with the above observations.

it should be stressed that this is not a complete list of cosmological puzzles related to the standard ΛCDM cosmological model. there are other challenges related to the statistical isotropy of the cmb and the axis of evil (anomalous alignment of cmb multipoles in the direction l ' ¡100, b = 60) which may be less related to the properties of dark matter or dark energy. such challenges are not discussed in the present brief review even though they may be related to the high amplitude and coherence bulk flows discussed in the next section confidence contours obtained from the observed velocity flows (dashed lines) [14] are superposed with the corresponding contours obtained from wmap5 data (blue solid lines) and from wmap5+bao+sn (red dashed line) (from ref. [14]). (Ω0m; 8) = (0:258; 0:796) on scales larger than 50h ¡1m pc is approximately 110km=sec while the probability that a flow magnitude larger than 400km=sec is realized in the context of the above ΛCDM normalization on scales larger than 50h ¡1m pc is less than 1% this is also demonstrated where the (Ω0m; 8) â 2 confidence contours obtained from the observed velocity flows (dashed lines) are superposed with the corresponding contours obtained from wmap5 data (blue solid lines) and from wmap5+baryon acoustic oscillations+SnIa (wmap5+bao+sn: red dashed line).the probability of consistency of bulk flow data with ΛCDM would be even lower if the data were considered where a flow of more than 600km=sec was observed on scales of ~ 600h -1m pc. a potentIal resolution of the above described conflict between the high z wmap5 normalization of ΛCDM and the low z normalization implied by the observed bulk flows could involve the existence of superhorizon sized non-gaussIan and non-inflationary inhomogeneities [27], a large void at distances of order gigaparsecs [28], or a redshift dependent 8 which changes by a factor of 2 between high z and low z due to an unknown physical reason. other possibilities include a very large statistical fluctuation, a redshift dependence of newton's constant or a redshift dependence of the dark energy equation of state parameter w = w(z) leading to amplified gravity and dark energy clustering at early times (w(z) > ¡1 at z > 0:2).

2.2 bright high z SnIa

As discussed in the introduction, geometrical tests of ΛCDM usually involve a bayesIan comparison of ΛCDM with other dark energy parametrizations. this approach has not revealed so far any statistically significant weak points of the model with respect to the geometrical and dynamical probes considered.

Apart from the bayesIan analysis approach, the ΛCDM model can be tested by comparing the real SnIa data with monte carlo simulations consisting of fictitious cosmological data that would have been obtained in the context of a ΛCDM cosmology. this comparison can be made on the basis of various statistics which attempt to pick up features of the data that can be reproduced with difficulty by a ΛCDM cosmology[16]. the existence of such features is hinted by the form of the likelihood contours in various parameter planes containing parameter values corresponding to flat ΛCDM . for example, most SnIa datasets producing likelihood contours in the $\Omega\lambda$ ¡ Ωm parameter plane have the 1 contour barely intersect the line of flatness $\Omega\lambda$ + Ωm = 1 at the lower left side of the contour [3, 4]. similarly, likelihood contours based on either SnIa standard candles or standard

2.1 large scale velocity flows

The bulk flow corresponding to the cmb dipole is closely related to the amplitude of fluctuations on large scales, and can be used to test cosmological models. a number of large scale velocity surveys have been undertaken in the past two decades and a significant amount of pecullar velocity data on a wide range of scales is currently available. the issue of comparing such sparse surveys with expectations from cosmological models has also been investigated by several studies a combined sample of pecullar velocity data has been recently used to investigate the amplitude and coherence scale of the dipole bulk flow. it was found that the dipole moment (bulk flow) of the combined sample extends [14] on scales up to 100h ~1m pc (z · 0:03) and perhaps up to 600h ~1m pc (z < 0:2 [15]) with amplitude larger than 400km=sec [14] (perhaps up to 1000km=sec

The direction of the flow has been found consistently to be approximately in the directionl ' 285 θ, b ' 10θ the expected rms bulk flow in the context of ΛCDM normalized with wmap52. challenging ΛCDM 247 figure 1: the (Ω0m; 8) â2 confidence contours obtained from the observed velocity flows (dashed lines) [14] are superposed with the corresponding contours obtained from wmap5 data (blue solid lines) and from wmap5+bao+sn (red dashed line) (from ref. [14]). (Ω0m; 8) = (0:258; 0:796) on scales larger than 50h ¡1m pc is approximately 110km=sec while the probability that a flow magnitude larger than 400km=sec is realized in the context of the above ΛCDM normalization on scales larger than 50h ¡1m pc is less than 1%.

This is also demonstrated in where the (Ω0m; 8) â2 confidence contours obtained from the observed velocity flows (dashed lines) are superposed with the corresponding contours obtained from wmap5 data (blue solid lines) and from wmap5+baryon acoustic oscillations+SnIa (wmap5+bao+sn: red dashed line).the probability of consistency of bulk flow data with ΛCDM would be even lower if the data of ref were considered where a flow of more than 600km=sec was observed on scales of ~ 600h -1m pc.

A potentIal resolution of the above described conflict between the high z wmap5 normalization of ΛCDM and the low z normalization implied by the observed bulk flows could involve the existence of superhorizon sized non-gaussIan and non-inflationary inhomogeneities [27], a large void at distances of order gigaparsecs [28], or a redshift dependent 8 which changes by a factor of 2 between high z and low z due to an unknown physical reason. other possibilities include a very large statistical fluctuation, a redshift dependence of newton's constant or a redshift dependence of the dark energy equation of state parameter w = w(z) leading to amplified gravity and dark energy clustering at early times (w(z) > ¡1 at z > 0:2).

2.2 bright high z SnIa

As discussed in the introduction, geometrical tests of ΛCDM usually involve a bayesIan comparison of ΛCDM with other dark energy parametrizations. this approach has not revealed so far any statistically significant weak points of the model with respect to the geometrical and dynamical probes considered. apart from the bayesIan analysis approach, the ΛCDM model can be tested by comparing the real SnIa data with monte carlo simulations consisting of fictitious cosmological data that would have been obtained in the context of a ΛCDM cosmology. this comparison can be made on the basis of various statistics which attempt to pick up features of the data that can be reproduced with difficulty by a ΛCDM cosmology[16]. the existence of such features is hinted by the form of the likelihood contours in various parameter planes containing parameter values corresponding to flat ΛCDM . for example, most SnIa datasets producing likelihood contours in the $\Omega\lambda$ ¡ Ωm parameter plane have the 1 contour barely intersect the line of flatness $\Omega\lambda$ + Ωm = 1 at the lower left side of the contour [3, 4]. similarly, likelihood contours based on either SnIa standard candles or standard.

Figure 3: a: a histogram of the probability distribution of nmc obtained using monte carloΛCDM data (Ω0m = 0:34) in the context of the gold06[3] dataset. the thick green dashed line corresponds to the crossing redshift zc of the real gold06 data. b: similar histogram for the pdl crossing model (w0; w1) = (¡1:4; 2) (best fit Ω0m = 0:34) instead of ΛCDM . notice that the crossing redshift zc corresponding to the real gold06 data is a much more probable event in the context of this cosmological model (from ref.[16]). one such difference in the context of SnIa data has been recently pointed out by kowalsky et.

Al. where it was stated that there is `an unexpected brightness of SnIa data at z > 1'. thisfeature is even directly visible by observing the SnIa distance moduli superposed with the best fit ΛCDM model where most high z moduli are below the best fit ΛCDM curve where rs and ½s are the characteristic radius and density of the distribution. a useful parameter characterizing the profile is the concentration parameter c defined as is c = rvir=rs where rvir is the virlal radius of the system. rs and ½s are related to each other (e.g. [41]), so eq. (2.2) is rather a one-parameter family of profiles.

A quite remarkable number of observations show that nfw profiles, displaying an inner cusp, are inconsistent with data. in fact, the latter indicate profiles with a different characteristic, acentral density core, i.e. a region where the dark matter density remains approximately constant.

In addition to the above well-known evidence for which in the inner regions of galaxies (r < 2rd where rd is the stellar disk radius) the dark matter haloes show a flattish density profile, with amplitudes up to one order of magnitude lower than the ΛCDM predictions, at outer radii (r > 4rd) the measured dark matter halo densities are found higher than the corresponding ΛCDM ones.

Thedark matter halo density, known to have a core in the internal regions, does not seem to converge to the nfw profile at 4 ¡ 6rd . this implies an issue for ΛCDM that should be investigated in the future, when, due to improved observational techniques, the kinematic information will be extended to the 100kpc scale.

A possible resolution of the puzzle of higher than expected dark matter halo density in the galactic haloes is that massive halos themselves were assembled at high redshift[19]. if this is the case, modifying the properties of dark energy could play a role in shifting the epoch of galaxy formation towards earlier times. alternatively, modified gravity theories or clustering of dark energy may also be considered as a potentIal resolution of this puzzle.

2.5 cluster halo profiles

In the ΛCDM context, detailed n-body simulations have established a clear prediction that cdm dominated cluster halos should have relatively shallow, low-concentration mass profiles, where the logarithmic gradient flattens continuously toward the center with a central slope tending towards r-1, interior to a characteristic radius, rs » 100 ¡ 200kpc ¢ h -1 multiply-lensed images of various clusters [17] have been used to derive the inner mass profile [48], with the outer profile determined from weak lensing [49]. together, the full profile has the predicted nfw form [40], but with a surprisingly high concentration c = rvir rs and high density when compared to the shallow profiles of the standard ΛCDM model [49, 50]. this result is verified by using not only the lensing based mass profile but also the x-ray and dynamical structure in model independent analyses [51]. a potentIal resolution of the above discrepancy between observed cluster profiles and ΛCDM predictions is that the central region of clusters collapsed, as in the case of galaxies, earlier than expected ie at z > 1, significantly earlier than in the standard ΛCDM , for which clusters form at z < 0:5. the presence of massive clusters at high redshift (z » 2), and the old ages of their member galaxies may also imply clusters collapsed at relatively early times [54], for which accelerated growth factors have been proposed, adopting a generalized equation of state for dark energy [55]. such an equation of state would allow for a non-negligible dark energy density at early times. thus, as in the case of galaxy formation, the properties of dark matter and/or dark energy could also play a significant role in the resolution of this puzzle.

2.6 overpopulation of disk galaxies

Roughly 70% of milky-way size dark matter halos are believed to host late-type, disk dominated galaxies . conventional wisdom dictates that disk galaxies result from fairly quiescent formation histories, and this has raised concerns about disk formation within the hierarchical ΛCDM cosmology. recent evidence for the existence of a sizeable population of cold, rotationally supported disk galaxies at z » 1:6 is particularly striking, given that the fraction of galaxies with recent ergers is expected to be significantly higher at that time . high-resolution, dissipationless nbody simulations studying the response of stellar milky-way type disks to such common mergersshow that thin disks do not survive the bombardment.

The remnant galaxies are roughly three times as thick and twice as kinematically hot as the observed thin disk of the milky way. however, despite of such indications a real evaluation of the severity of the problem is limited by both theoretical and observational concerns.

The role of dark energy in the resolution of this and other astrophysical scale puzzles should not be underestimated. for example, it has been demonstrated that the effects of dark energy on the equilibrium and stability of astrophysical structures is not negligible, and can be of relevance to describe features of astrophysical systems such as globular clusters, galaxy clusters or even galaxies.

It has recently been demonstrated that the dark energy fluid changes certain aspects of astrophysical hydrostatic equilibrium. For example, the instability of previously viable astrophysical systems when dark energy is included has been demonstrated as due to the repulsive non local dark energy force acting on the matter distribution [66]. With the proper evolution of the dark energy equation of state, this repulsive force may also lead to a modification of the profile of the virialized structures thus addressing some of the above discussed puzzles on galactic and cluster scales.n galaxies

2.7 IMPRACTICAL ASSUMPTIONS

Extensive searches for dark matter particles have so far shown no well-agreed detection; the dark energy may be almost impossible to detect in a laboratory, and its value is un-naturally small compared to naive theoretical predictions.

Comparison of the model with observations is very successful on large scales (larger than galaxies, up to the observable horizon), but may have some problems on sub-galaxy scales, possibly predicting too many dwarf galaxies and too much dark matter in the innermost regions of galaxies. These small scales are harder to resolve in computer simulations, so it is not yet clear whether the problem is the simulations, non-standard properties of dark matter, or a more radical error in the model.

Conclusion

I have reviewed some of the potentIal challenges of the ΛCDM cosmological model pointing outthat there are such challenges on both large and small cosmological scales. even though some of the puzzles discussed here may be resolved by more complete observations or astrophysical eFFects, thepossible requirement of more fundamental modifications of the ΛCDM model remains valid.

It is interesting to attempt to identify universal features which connect these puzzles and could therefore provide a guide for their simultaneous resolution. the large scale coherent velocity flows along with the high density dark matter haloes for both galaxies and clusters seem to hint towards a more effective mechanism for structure formation at early times (z > 1) than implied by ΛCDM.

This improved effectiveness could possibly be provided by a mild evolution of newton's constant g (higher g at z > 0:5) or by an evolution of the dark energy equation of state w such that w(z) > ¡1 at z > ~ 0:5 [55]. both of these effects are expected to amplify structure formation at early times and it would be interesting to analyze quantitatively the predictions implied by the evolution of g or w with respect to the velocity flow and high dark matter density puzzles. the bright high z SnIa puzzle would also benefit significantly by a mild evolution of w or g which would imply stronger deceleration at z > 1 than implied by ΛCDM .the improved efficiency of gravity at early times could also help emptying the voids from dark matter haloes and their corresponding galaxies thus making theoretical predictions more consistent with observations. on the other hand, the increased gravitational acceleration would also produce higher pecullar velocities that could lead to more mass inside the voids. therefore, the predicted emptiness of voids in models with an evolving g or w requires a detailed study. in conclusion, the six puzzles for ΛCDM discussed in the present study provide a fertile ground for the development of both new theoretical model predictions on the corresponding observables and new observational data that would either establish or disprove these challenges for ΛCDM.

The ΛCDM model is based on six parameters: physical baryon density, physical dark matter density, dark energy density, scalar spectral index, curvature fluctuation amplitude and reionization optical depth. In accordance with Occam's razor, six is the smallest number of parameters needed to give an acceptable fit to current observations; other possible parameters are fixed at "natural" values e.g. total density = 1.00, dark energy equation of state = -1, neutrino masses are small enough to be negligible. (See below for extended models which allow these to vary). The values of these six parameters are mostly not predicted by current theory (though, ideally, they may be related by a future "Theory of Everything"); except that most versions of cosmic inflation predict the scalar spectral index should be slightly smaller than 1, consistentwith the estimated value 0.96. The parameter values, and uncertainties, are estimated using large computer searches to locate the region of parameter space providing an acceptable match to cosmological observations. From these six parameters the other model values, including theHubble constant and age of the universe, can be readily calculated.

Acknowledgementsthis work was supported by the european research and training network mrtpn-ct-2006035863-1 (universenet).

REFERENCE [1] s. perlmutter et al., astrophys. j. 517, 565 (1999); a. g. riess et al., astron. j. 116, 1009 | (1998); | [2] p. astier et al. [the snls collaboration], astron. astrophys. 447, 31 (2006) [arxiv:astroph/0510447]; t. m. davis et al., astrophys. j. 666, 716 (2007) [arxiv:astro-ph/0701510]; | w. m. wood-vasey et al. [essence collaboration], astrophys. j. 666, 694 (2007) [arxiv:astroph/0701041]; j. l. tonry et al. [supernova search team collaboration], astrophys. j. 594, 1 | (2003) [arxiv:astro-ph/0305008]. | [3] . g. riess et al. [supernova search team collaboration], astrophys. j. 607, 665 (2004), | [arxiv:astro-ph/0402512]. | [4] m. kowalski et al., arxiv:0804.4142 [astro-ph]. |