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The Quasi-Steady State Cosmology: Some Recent Developments

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Abstract. This paper summarises the recent work on the quasi-steady state cosmology. This includes, the theoretical formulation and simple exact solutions of the basic equations, their relationship to observations, the stability of solutions and the toy model for understanding the growth of structures in the universe.

Key words. Cosmology—creation of matter—structure formation.

1. Introduction

The quasi-steady state cosmology (QSSC hereafter) was proposed in 1993 by Fred Hoyle, Geoffrey Burbidge and myself (Hoyle *et al.* 1993). The observational and cosmogenic issues were discussed by us in two following papers (Hoyle *et al.* 1994a, b). The basic theoretical framework was laid down the following year (Hoyle *et al.* 1995a). Sachs *et al.* (1996) studied the exact solutions of the basic equations that give simple homogeneous and isotropic models.

Here we will briefly review the progress of this model towards offering a viable alternative to the standard hot big bang cosmology. But before proceeding towards this task it is perhaps necessary to say why an alternative is being considered when, it is commonly believed that the standard cosmology offers a good approximation to the actual universe.

I shall begin by questioning this premise. Recent observational checks on the Standard model do not leave any reason for such a complacency. As was discussed by Bagla *et al.* (1996), the constraints of the Hubble constant, the ages of globular clusters, the existence of high redshift objects, the abundance of rich clusters and the deuterium abundance make it impossible for the hot big bang model with inflation and no cosmological constant to survive. Even granting the existence of a nonzero λ, the window of permissible values for H_0 and Ω_0 (the matter density parameter) is very small and may altogether disappear if one takes into consideration the observations of the deceleration parameter and the constraints from gravitational lensing.

Hence the standard model with or without λ is in trouble and it is therefore not premature to give some consideration to the alternative cosmologies. Even so, any alternative proposed must do at least as well as the standard model, if it is to be taken seriously. In particular it must satisfy the following conditions:

1. It must explain the redshift magnitude relation for galaxies, the observations of counts of radio sources and galaxies, the data on angular size redshift relation and the evidence on the variation of surface brightness of galaxies with redshift.

2. It must give a theory for the origin of the microwave background, including its observed spectrum, isotropy and small scale inhomogeneities.
3. It must account for light nuclear abundances which cannot be otherwise understood within the framework of stellar evolution.

Having done so, the alternative cosmology may seek to explain other aspects of the large scale universe where the big bang has so far proved inadequate. These include the problem of accommodating old stellar populations, an understanding of dark matter, the origin of structures and the elimination of a singular beginning.

Finally, the new cosmology should offer predictions that distinguish it from Standard cosmology so that observational tests may be designed to find out which cosmology is right, or closer to reality.

In this paper we will show that the QSSC does offer a serious alternative when judged by the above criteria.

2. The basic theory

The basic theory for the QSSC is the Machian theory of gravity first proposed by Hoyle & Narlikar (1964, 1966) in which the origin of inertia is linked with a long range scalar interaction between matter and matter. Specifically, the theory is derivable from an action principle with the simple action:

$$\mathcal{A} = -\sum_a \int m_a ds_a, \tag{1}$$

where the summation is over all particles in the universe, labelled by a, the mass of the ath particle being m_a. The integral is over the world line of the particle, ds_a representing the element of proper time of the ath particle.

The mass itself arises from interaction with other particles. Thus the mass of particle a arises from all other particles b in the universe:

$$m_a = \sum_{b \neq a} m^{(b)}(X), \tag{2}$$

where $m^{(b)}$ (X) is the contribution of inertial mass from particle b to any particle situated at a general spacetime point X. The long range effect is Machian in nature and is communicated by the scalar mass function $m^{(b)}$ (X) which satisfies the wave equation

$$m^{(b)} + \frac{1}{6} R m^{(b)} + [m^{(b)}]^3 = N^{(b)}. \tag{3}$$

Here the wave operator is with respect to the general spacetime point X. R is the scalar curvature of spacetime and the right hand side gives the number density of particle b. The field equations are obtained by varying the action with respect to the spacetime metric g_{ik}. The important point to note is that the above formalism is conformally invariant. In particular, one can choose a conformal frame in which the particle masses are constant. If the constant mass is denoted by m_p, the field equations reduce to

$$R^{ik} - \frac{1}{2} g^{ik} R + \lambda g^{ik} = -\frac{8\pi G}{c^4}\left[T^{ik} - \frac{2}{3}\left(c^i c^k - \frac{1}{4} g^{ik} c^l c_l\right)\right], \tag{4}$$

where c is a scalar field which arises explicitly from the ends of broken world lines, that is when there is creation (or, annihilation) of particles in the universe. Thus the divergence of the matter tensor T^{ik} need not always be zero, as the creation or annihilation of particles is compensated by the non-zero divergence of the c-field tensor in Eq. (4). The quantities G (the gravitational constant) and λ (the cosmological constant) are related to the large scale distribution of particles in the universe. Thus,

$$G = \frac{3\hbar c}{4\pi m_p^2}, \quad \lambda = \frac{3}{N^2 m_p^2}, \tag{5}$$

N being the number of particles within the cosmic horizon.

Note that the signs of the various constants are determined by the theory and not put in by hand. For example, the constant of gravitation is positive, the cosmological constant negative and the coupling of the c-field energy tensor to spacetime is negative.

3. Matter creation

The action principle tells us that matter creation is possible at a given spacetime point provided the ambient c-field satisfies the equality $c = m_p$ at that point. In normal circumstances, the background level of the c-field will be *below* this level. However, in the strong gravity obtaining in the neighbourhood of compact massive objects the value of the field can be locally raised. This leads to creation of matter along with the creation of negative c-field energy. The latter also has negative stresses which have the effect of blowing the spacetime outwards (as in an inflationary model) with the result that the created matter is thrown out in an explosion.

We shall refer to such pockets of creation as *minibangs* or *mini-creation events.* A spherical (Schwarzschild type) compact matter distribution will lead to a spherically symmetric explosion whereas an axi-symmetric (Kerr type) distribution would lead to jet like ejection along the symmetric axis.

4. The cosmological solution

The feedback of such minibangs on the spacetime as a whole is to make it expand. In a completely steady situation, the spacetime will be that given by the deSitter metric. However, the creation activity passes through epochs of ups and downs with the result that the spacetime also shows an oscillation about the long term steady state. Sachs *et al.* (1996) have computed the simplest such solution with the line element given by

$$ds^2 = c^2 dt^2 - S^2(t)[dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)], \tag{6}$$

where c stands for the speed of light and the scale factor is given by

$$S(t) = e^{t/P}\left[1 + \eta\cos\frac{2\pi\tau(t)}{Q}\right]. \tag{7}$$

The constants P and Q are related to the constants in the field equations, while τ(t) is a function ~ t which is also determined by the field equations. For details see

Sachs *et al.* (*op. cit*). The parameter η may be taken positive and is less than unity. Thus the scale factor never becomes zero: the solution is without a spacetime singularity.

5. Observational checks

(A) The *observations of discrete source populations* provide a direct contact between theory and observations. Hoyle *et al.* (1994a, b) have shown that the above cosmology gives a reasonably good fit to the observations of discrete source populations, such as the redshift-magnitude relation, radio source count, angular diameter-redshift relation and the maximum redshifts so far observed, with the choice of the following set of parameters:

$$P \approx 20Q, \quad Q \approx 4.4 \times 10^{10}\,\text{yrs}, \quad \eta = 0.8,$$
$$\lambda = -0.3 \times 10^{-56}\,\text{cm}^{-2}, \quad t_0 = 0.7Q.$$

Of these, the last is the present epoch of observation. It is not essential that the model has only these parameters. Indeed, the parameter space is wide enough to make the model robust. Moreover, the fitting of observations to theory does not require postulating ad hoc evolution which is commonly necessary in the case of standard cosmology.

What about the microwave background and the origin of the light nuclei? Let us discuss the former first.

(B) A *microwave background* is the thermalized relic starlight left by stars which have burnt during the previous cycles. The present day stellar activity allows us to estimate the total star-burning activity during a typical cycle of duration Q. We can use it to work out the background energy that can be maintained at the same level from cycle to cycle. Thus if the energy density of radiation at a typical minimum-S state of a cycle is u, then the energy density at the end of the cycle to the next minimum state would be $u \exp(-4Q/P)$. For $P \gg Q$, the depletion is by an amount $\approx -4uQ/P$, and this has to be made up by the starlight energy produced during the cycle. Equating the two we can estimate the value of u at the minimum-S phase, and hence at the present epoch. It is very reassuring to find the present day temperature of the microwave background is close to 2.7 K. I may mention that the big bang cosmology does not predict the value of the present temperature: it is assumed as a given quantity.

But what about spectrum and isotropy? Although Hoyle *et al.* (1994a) had discussed these issues, the case of spectrum has recently been discussed by Narlikar *et al.* (1997) who have shown that iron whiskers of around 0.5–1 mm length and about 10^{-5}mm cross sectional diameter can act as efficient thermalisers of starlight without blacking out the extragalactic radio and optical universe. The extinction properties are wavelength–dependent and the outcome is a spectrum of radiation that is Planckian out to wavelengths shorter than ~ 20 cm. Thus there is no conflict with the present observations. Whether the differences from the Planckian spectrum at long wavelengths are present cannot be decided at present as there is considerable contamination of data at these wavelengths from galactic radiation.

The prediction of large scale isotropy, subject to the dipole anisotropy due to the Earth's motion is consistent with observations. The COBE data on small scale inhomogeneities can also be understood as arising from local contributions and also from the inhomogeneities of distribution of grains. The latter effect arises in this way. For a large enough temperature gradient between adjacent region there will be a tendency towards equality by pushing the grains in the direction of lower temperature. However, this effect stops when the ΔT is so small that the grains can no longer be pushed. This is of the right order of magnitude.

(C) The *origin of light nuclei* in this cosmology arises from the decay products of the basic particle created. As seen from Eq. (5), the basic particle has the Planck mass which is ~ 10^{-5} g, i.e., an energy equivalent of ~ 10^{19} Gev. This particle is short-lived, with a time scale of ~ 10^{-43}s. What happens to its decay products? This is a problem for the high energy physicists to solve. It is worth pointing out that the energy regime of these developments is the same as that in the very early universe in standard cosmology. The difference is that in the QSSC, such events are of recurring nature, happening every time that there is a minibang; whereas in the Standard cosmology this happened only once and that too at an epoch that cannot be directly observed. Thus on counts of both repeatability and observability the QSSC provides a physically more realistic scenario for the so-called astroparticle physics.

As is well known, the subject of high energy physics is currently passing through a state of flux, with several ideas ranging from quantum gravity, superstring theories, GUTs, phase transitions and cosmic strings, etc. There is no final TOE (Theory Of Everything) in the offing yet. However, if one follows the standard model of particle physics, which so far is holding out well, then the generally accepted view leads to the group theoretic break-up at lower energies after the GUTs era, of $SU(3)\times SU(2)_L\times U$ (l).At this stage the final products will include the baryon octet, pions, photons and leptons.

Why not antibaryons? The answer is that the universe is already in a broken symmetric state dominated by matter. Given this situation in a particular cycle, the subsequent creation and decay will propagate this broken symmetry to the next cycle. Thus, unlike the big bang cosmology where elaborate departures from symmetry (e.g. CP-violation) are needed to justify why the universe, after a symmetric beginning, is matter dominated today, here the requirement is to understand how the broken symmetry propagates from one cycle to next. Inputs from particle physics are needed to understand this effect.

However, in the neighbourhood of a typical minicreation event the release of decay particles at high energy will establish a Fireball with thermodynamic equilibrium. At temperatures very high compared to the rest mass energy of the baryons the eight members of the octet will be in equal numbers. Of these, all (six) except the neutron and the proton are very short lived and decay to protons whereas the neutron and the proton combine to form the helium nuclei. Thus the fraction by mass of helium will be close to 2/8, i.e., 0.25. More exact calculation considering the details of photons and other decay products will bring down the fraction to between 0.22 and 0.23. In addition the light nuclei like deuterion, lithium, etc., are also produced. The overall abundance distribution does agree very well with observations. For details see Hoyle, *et al.* (1995b).

The density and temperature regime for this nucleosynthesis is very different (higher by several orders of magnitudes) compared to that in the standard hot big bang nucleosynthesis, while the time scales are much shorter. The outcome is that a small quantity of metals is produced as well and the deuterium abundance is not so sensitively linked to the baryon density as in the standard hot big bang.

The abundance of metals in the early stages resolves one difficulty faced by workers in the field of stellar evolution, namely the evolution of massive stars. For such stars the C-N-O cycle cannot operate in a big bang cosmology since these elements are produced in stars later. To get round this difficulty in standard cosmology, massive Population III stars are postulated, which burn slowly on the p-p chain but do manage to produce some metals later. In the QSSC this problem does not arise.

(D) The *dark matter problem* takes on a different complexion in this cosmology. First, there is no restriction like $\Omega = 1$ in this cosmology and so the dark matter component need not be very high. The extent of dark matter has to be estimated from improved observations. In the big bang cosmology a restriction arises from the deuterium abundance which restricts the baryon density to $\sim\Omega_{\text{baryon}} < 0.02$. In the big bang cosmology nonbaryonic matter is needed for another reason: to lower the temperature fluctuations of the microwave background to the low values observed. Neither of these reasons operate in the QSSC where the need for nonbaryonic matter is, therefore, not so compelling. Instead it is possible to argue that dark matter in galaxies arises from the relics of stars of previous generations or in the form of small planetary mass objects. In this sense the MACHO or EROS type observations carry a great significance.

(E) The *age problem* which has assumed significance in the big bang cosmology does not cause any problem for the QSSC. Since the minima of the scale factors do not represent epochs of very high density, stars and galaxies of previous cycles are able to survive into the present cycle. Thus very old stars (age larger than the value H_0^{-1}, H_0 the present value of Hubble's constant) may exist. In fact, stars born during the previous cycles with masses around half a solar mass may just now be evolving off the main sequence. If such stars (with estimated ages in the range 40–50 Gyr) are found, it will be hard to maintain the standard cosmology.

6. Structure formation

I will conclude with a few remarks on structure formation in the QSSC. Unlike the big bang cosmology, where structures have to evolve out of primordial inhomogeneities which are put in by hand, here the problem is to reproduce the structure in the present cycle from what existed in the previous ones. Since the mini-creation events play a pivotal role in this cosmology, it is expected that new nuclei of creation would grow out of matter ejected from them.

Nevertheless, it is worth seeing first, as to how the gravitational instability grows in this cosmology. In a recent work by Banerjee and Narlikar (1997) the following approach was taken. The metric, the density and the *c*-field were perturbed, and by restricting to only first order quantities, the changes in these perturbations were calculated in the background spacetime. Predictably, the density inhomogeneities grew during the contracting phase of an oscillation, and were damped during the expanding phase. Thus there was no significant instability in the solution. While this generates confidence in the basic solution, it also forces one to look for non-gravitational effects to produce structure. The creation process provides a possibility.

In a recent attempt to understand how structures may grow and distribute in space the following numerical experiment suggested by Fred Hoyle was tried by A. Nayeri and the author.

A large number of points ($N \sim 10^5$–10^6) were distributed over a square area at random. Each point was made to produce a random neighbour within a specified fraction of the average interparticle distance of the original set. The area was then scaled to twice the original size, so that the particle density remained the same. Then from the expanded area a central portion corresponding to the original area was retained, the rest being thrown away. With this new square the experiment was repeated.

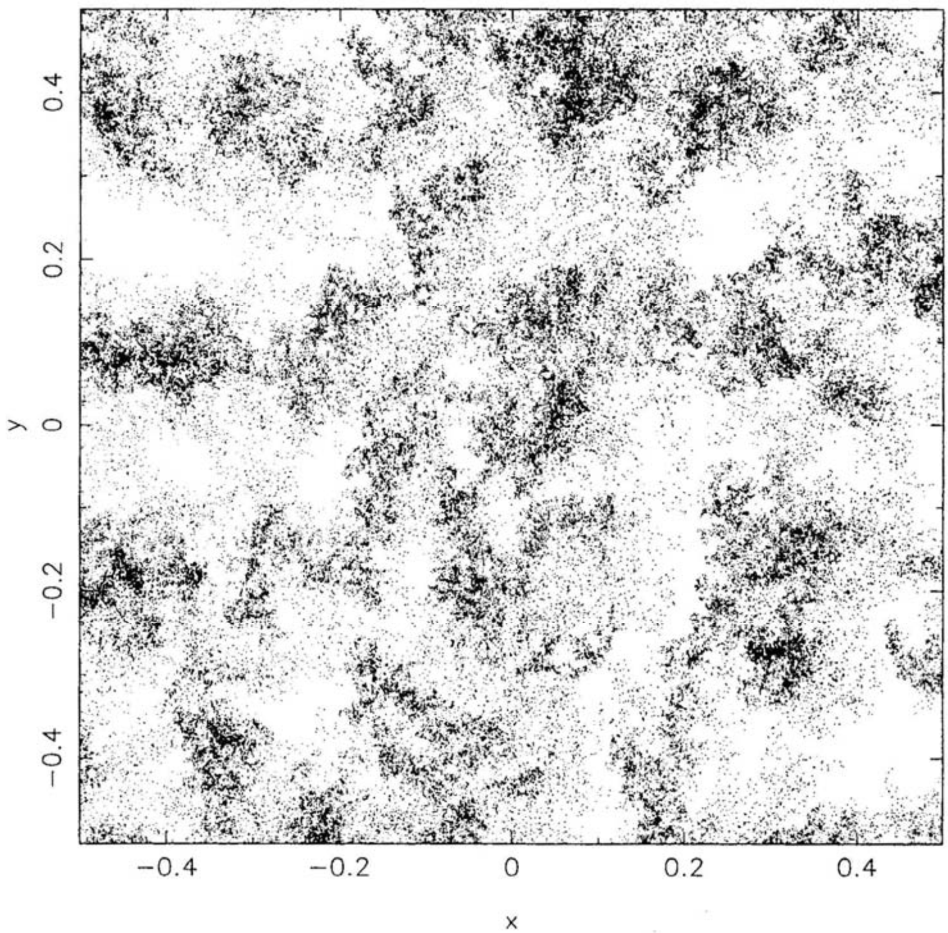

Figure 1. A sample of point set distribution for ~ 100,000 points after 10 iterations wherein the new generation of points created takes note of directionality of earlier ejection. Thus the new point is created in a forward cone of $\pi/2$ vertex angle with respect to the axis of previous ejection. (Computer simulation by Ali Nayeri).

Very soon, i.e., after three or four iterations, clusters and voids began to appear in the picture and voids grew in size while the clustering became denser as the experiment was repeated. If the creation of the new neighbour Q around a typical point P was not entirely random, but linked to previous history of creation of P, so that the direction PQ was broadly aligned with the direction in which P had been ejected, then the filamentary strucure grows along with voids. This latter alignment may be related to the spinning supermassive creation centre discussed in" section 3. Fig. 1 shows a picture generated this way.

These are preliminary attempts to come to grips with what is admittedly a formidable problem. Yet, the similarity of the pictures generated with relatively simple assumptions, with the actual large scale structure suggests that the approach is worth following up further.

7. Future tests

This concludes a brief review of the recent work on the QSSC. It is clear that it does offer a prima facie alternative to the standard cosmology. More work is needed to study its implications in depth. However, progress on that front will necessarily depend on the human power available to tackle the problems.

I may conclude with a few tests which will set this cosmology apart from the hot big bang cosmology. These are:

(A) The discovery of a few objects (galaxies) with blueshifts. These belong to the previous cycle and will necessarily be faint.
(B) The discovery of a class of very old stars, e.g., faint white dwarfs, low mass giants, low mass horizontal branch stars, etc. which are far too old compared to the age of the big bang universe.
(C) The finding of baryonic dark matter well above the limit tolerated by the big bang cosmology.
(D) The detection of gravitational waves by mini-creation events.

8. Discussion

Amitabha Ghosh

Q: Is the oscillating universe of finite dimension? If it is infinite, what does the amplitude of oscillation mean? Can the distance between two very distinct objects vary (at times) at larger than light speed (because the whole infinite universe is oscillating with a finite frequency)?

A: Oscillation coupled with exponential expansion applies to the distance between any two galaxies. The universe itself need not be compact or finite; in fact we use $k = 0$ Robertson-Walker model. As you look farther out you may begin to see some galaxies coming towards you. Thus an observer looking at the universe will see galaxies in different oscillatory phases.

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T.P. Singh

Q: What exactly were the reasons for preparing the new quasi-steady state model, in place of the original steady-state model?

A: The main motivation was to have a universe without a singularity in which matter is created in explosive process but is a physically understood fashion. Any alternative model must do at least as well as the big bang and must be more successful in explaining observation. I believe the QSSC does that.

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Sivaram

Q: (i) You had a negative cosmological constant related to total number of particles. Depending on its magnitude you could get a closed or oscillating universe. Is that right?

(ii) How many cycles do you need to get a $T \simeq 2.7$ K?

(iii) Do the particles created have Planck mass. They perhaps have to be if $G \approx \bar{h}c/m_{pl}^2$ is to be preserved. In G.R. maximum rate of creation $\approx c^3/G \sim MN_{\max} \approx c^3/G_{pl}^M$.

A: (i) With negative λ you always get an oscillating universe, whatever the curvature parameter.

(ii) The T_{MBR} is calculated from all the previous cycles, going back to $t = -\infty$.

(iii) The particles created is a Planck particle. A properly quantized field theory will ultimately determine the creation rate. We do not know such a theory yet.

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Naresh Dadhich

Q: What are the analogues of black hole solutions, like the Schwarzschild and the Kerr solutions in your theory?

A: Exact solutions are not worked out. But one can show that no object can shrink and go within a horizon: the c-field prevents that. So such objects may come to an equilibrium just outside the horizon.

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Tarun Souradeep

Q: What is the role of gravitational clustering instability in the QSSC model? Is there something akin to Jeans length in the context of mass scale below which collapse can occur.

A: Gravity plays a role in compactifying massive object individuality. Clustering, however, develops through one such object producing more in its neighbourhood, as was indicated by the numerical experiment.

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