Flat FRW Cosmologies with Adiabatic Matter Creation: Kinematic tests

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Abstract. Some observational consequences of a cosmological scenario driven by adiabatic matter creation are investigated. Exact expressions for the lookback time, age of the universe, luminosity distance, angular diameter, and galaxy number counts redshift relations are derived and their meaning discussed in detail. The expressions of the conventional FRW models are significantly modified and provide a powerful method to limit the parameters of the models.

Key words: Cosmology, Kinematic Tests, Matter Creation

Nowadays, the increasing difficulties of the standard Friedmann-Robertson-Walker (FRW) cosmologies compel the investigation of alternative big-bang models. One of the main observational motivations is the conflict between the expanding age of the universe, as inferred from recent measurements of the Hubble parameter (Friedmann 1998), and the age of the oldest stars in globular clusters (Bolton and Hogan 1995, Pont et al. 1998). The corresponding uncertainties related with such determinations are now believed to be considerably small, thereby ruling out large regions in the space parameter of the standard cosmology even for open models (Bagla, Padmanabhan and Narlikar 1996). Such restrictions may be even more efficient near future, first, from better data analysis with consequent reduction in uncertainties, and second, due to improved experiments as well as new observational facts. For instance, the recent discovery of a 3.5Gyrs old galaxy at \(z = 1.554\) (Dunlop et al. 1996) has been proved to be incompatible with ages estimates for a flat universe unless the Hubble parameter is less than \(45\text{km s}^{-1}\text{Mpc}^{-1}\). Such a constraint is more stringent than globular cluster age constraints (Krauss 1997). This “age problem” is not an isolated difficulty of the FRW model since it also affect others basic features of the standard cosmology, like the structure formation through gravitational amplification of small primeval density perturbations (Jeans’ Instability). Indeed, with exception of a very low Hubble constant variant this galaxy formation scenario seems to be unconsistent with the estimated age of the universe. For open universes, where the “age problem” is less acute, this happens because the growth of perturbations since recombination is relatively supressed in a low density models (Kofmann, Gnedin and Bahcall 1993, White and Bunn 1995).

On the other hand, recent measurements of the deceleration parameter using Type Ia supernovae (Garnavich et al. 1998, Perlmutter et al. 1998) indicate that the universe may be accelerating today, or equivalently, that the deceleration parameter may be negative. These measurements pose a big problem to the standard model (for any of its variants) since their predictions are \(q_o > 0\), whatever the sign adopted for the curvature of the model. More recently still, improved observations from a sample of 16 supernovae type Ia plus 34 nearby novae were used to place constraints in \(H_o, \Omega_m, \Omega_\Lambda\) and \(q_o\) (Riess et al 1998). These authors concluded that the standard flat model (\(\Omega_m = 1, \Omega_\Lambda = 0, q_o > 0\)) is ruled out and that several effects, among them, extinction, evolution, sample selection bias, local flows are not enough to reconcile the data with the predictions of this model. In such state of affairs, it seems more prudent to follow the tradition in cosmology by thinking about alternative big-bang scenarios. As a matter of fact, the positive evidences to standard model, although not negligible are not at all abundant, and are presently under suspicion.

Some years ago, a thermodynamic description for gravitational creation of matter and radiation has been proposed in the literature (Prigogine et al. 1989; Lima, Calvão and Waga 1991; Calvão, Lima and Waga 1992; Lima and Germano 1992). The crucial ingredient of this formulation is the explicit use of a balance equation for the number density of the created particles in addition to Einstein field equations (EFE). In this framework, the thermodynamic second law leads naturally to a reinterpretation of the en-
ergy momentum tensor (EMT) corresponding to an additional stress term (creation pressure), which in turn depends on the matter creation rate, and may alter considerably several predictions of the standard big-bang cosmology. The issue related to the compatibility between this approach and the kinetic theory of a relativistic gas has also been addressed (Triginer, Zimdahl and Pavón 1996, Zimdahl, Triginer and Pavón 1996). Studies involving matter creation and the early universe physics include the singularity problem (Prigogine et al. 1989; Abramo and Lima 1996), reheating during the inflationary epoch (Zimdahl and Pavón 1994), the age of the universe problem (Lima, Germano and Abramo 1996), the entropy problem (Lima and Abramo 1996; Brevik and Stokkan 1996) and causal formulation (Gariel and Le Denmat 1995). These studies revealed clearly that matter creation cannot consistently be modeled by the bulk viscosity mechanism even considering that both are scalar processes.

An overlook in the literature show, however, that the dynamical properties of cosmological models with “adiabatic” matter creation have been more carefully investigated than their observational consequences in the present matter dominated phase. This is an important point, because the question for viability of big-bang models with matter creation could partially be answered deriving expressions for the classical cosmological tests, thereby analysing the influence of this mechanism on the well known predictions of the standard FRW model.

In order to fill this gap, we focus our attention here on the quantities of astrophysical interest to the present dust like stage. The outline of the paper is as follows. In section 2, we set up the cosmological equations with adiabatic matter creation, reviewing briefly some basic features of such an approach. In section 3, by adopting a creation scenario recently proposed (Lima, Germano and Abramo 1996), we derive new expressions for the observable quantities and analyse some of their properties. The data are then used to limit the unique free quantity (creation parameter) of the model. We conclude with a discussion of the main results.

1. Flat FRW Equations With “Adiabatic” Matter Creation

Let us now consider the flat FRW line element \((c = 1)\)
\[
ds^2 = dt^2 - R^2(t)(dr^2 + r^2d\theta^2 + r^2\sin^2\theta d\phi^2) ,
\]
where \(r, \theta, \) and \(\phi\) are dimensionless comoving coordinates and \(R\) is the scale factor.

In that background, the nontrivial EFE for a fluid endowed with “adiabatic” matter creation and the balance equation for the particle number density can be written as (Prigogine et al. 1989; Calvão, Lima and Waga 1992)
\[
8\pi G p = 3\frac{\dot{R}^2}{R^2} ,
\]
\[
8\pi G(p + p_c) = -2\frac{\ddot{R}}{R} - \frac{\dot{R}^2}{R^2} ,
\]
\[
\frac{n}{n} + 3\frac{\dot{R}}{R} = \frac{\psi}{n} ,
\]
where an overdot means time derivative and \(\rho, p, n\) and \(\psi\) are the energy density, thermostatic pressure, particle number density and matter creation rate, respectively. The creation pressure \(p_c\) depends on the matter creation rate, and for “adiabatic” matter creation, it assumes the following form (Calvão, Lima and Waga 1992; Lima and Germano 1992)
\[
p_c = \frac{\rho + p}{3nH} \psi ,
\]
where \(H = \dot{R}/R\) is the Hubble parameter.

As usual in cosmology, the cosmic fluid obeys the “gamma-law” equation of state
\[
p = (\gamma - 1)\rho ,
\]
where the constant \(\gamma\) lies on the interval \([0,2]\).

Combining Eqs. (2) and (3) with (5) and (6) it is readily seen that the scale factor satisfies the generalized FRW differential equation
\[
R\dot{R} + \left(\frac{3\gamma - 2}{2}\right)\dot{R}^2 = 0 ,
\]
where \(\gamma_s\) is an effective “adiabatic index” given by
\[
\gamma_s = \gamma(1 - \frac{\psi}{3nH}) .
\]
To proceed further it is necessary to assume a physically
reasonable expression to the matter creation rate \( \psi \). As can be seen from (4), the dimensionless parameter \( \frac{\Delta}{nH} \) is the ratio between the two relevant rates involved in the process. When this ratio is very small the creation process can be neglected, and if it is much bigger than unity, we see from (5) that \( p_c \) becomes meaningless, because it will be much greater than the energy density. A reasonable upper limit of this ratio should be the unity (\( \psi = 3nH \)), since in this case \( \psi \) has exactly the value that compensates for the dilution of particles due to expansion. In this work we confine our attention to the simple phenomenological expression (Lima, Germano and Abramo 1996)

\[
\psi = 3\beta nH ,
\]

where \( \beta \) is smaller than unity, and presumably given by some particular quantum mechanical model for gravitational matter creation. In general, \( \beta \) must be a function of the cosmic era, or equivalently, of the \( \gamma \) parameter, which specifies if the universe is vacuum (\( \gamma = 0 \)), radiation (\( \gamma = \frac{4}{3} \)) or dust (\( \gamma = 1 \)) dominated. However, for the sake of brevity we denote all of them generically by \( \beta \), assumed here to be a constant at each phase.

With this choice, the FRW equation for \( R(t) \) given by (7) can be rewritten as

\[
R \ddot{R} + \Delta \dot{R}^2 = 0 ,
\]

the first integral of which is

\[
\dot{R}^2 = \frac{A}{R^2 \Delta} ,
\]

where \( \Delta = \frac{3n(1-\beta) - 2}{2} \), and from (2) \( A \) is a positive constant, which must be determined in terms of the present day quantities. It is worth notice that for \( \beta \geq 1 - \frac{2}{3\gamma} \), or equivalently, \( \Delta \leq 0 \), the above equations imply that \( \dot{R} \geq 0 \), thereby leading to power law inflation. In particular, for \( \Delta = 0 \), these universes expand with constant velocity, and are new examples of coasting cosmologies whose dynamic behavior is driven by matter creation. The observational consequences of “coasting cosmologies” generated by exotic “K-matter”, like cosmic strings, have been studied in detail (Gott and Rees 1987; Kolb 1989). All of them are characterized by the fact the energy density \( \rho \sim R^{-2} \) and the total pressure \( P_t = -\frac{1}{2} \rho \) (see equations (12) and (15)).

Using equation (11), it is straightforward to obtain the energy density, the pressures (\( p \) and \( p_c \)) and the particle number density as functions solely of the scale factor \( R \) and of the \( \beta \) parameter. These quantities are given by:

\[
\rho = \rho_o \left( \frac{R_o}{R} \right)^{3\gamma(1-\beta)} ,
\]

\[
p_c = -\beta \gamma \rho_o \left( \frac{R_o}{R} \right)^{3\gamma(1-\beta)} ,
\]

\[
P_t = (\gamma - 1)\rho = |\gamma(1 - \beta) - 1|\rho_o \left( \frac{R_o}{R} \right)^{3\gamma(1-\beta)} ,
\]

In the above expressions the subscript “o” refers to the present values of the parameters, and the total pressure is \( P_t = p + p_c \). As expected, for \( \beta = 0 \), equations (12)-(15) reduce to those of the standard FRW flat model for all values of the \( \gamma \) parameter (Kolb and Turner 1990).

The solution of (11) for all values of \( \gamma \) and \( \beta \) can be written as

\[
R = R_o \left[ 1 + \frac{3\gamma(1-\beta)}{2} H_o(t-t_o) \right]^{ \frac{2}{3\gamma(1-\beta)}.}
\]

Note also that for \( \gamma > 0 \), we can choose \( t_o = 2H_o^{-1}/3\gamma(1-\beta) \), with the above equation assuming a more familiar form, namely:

\[
R(t) = R_o \left[ \frac{3\gamma(1-\beta)}{2} H_o t \right]^{ \frac{2}{3\gamma(1-\beta)}.}
\]

In particular, for a “coasting cosmology” driven by matter creation one finds \( R \sim t \) as it should be. Note also that in the limit \( \beta = 0 \), equations (16) and (17) reduce to the well known expressions of the FRW flat model.

2. Expressions for the Observational Quantities

In what follows we assume that the present material content of the universe is dominated by a pressureless non-relativistic gas (dust). Following standard lines we also define the physical parameters \( q_o = -\frac{R \ddot{R}}{R^2} |_{t=t_o} \) (deceleration parameter) and \( H_o = \frac{\dot{R}}{R} |_{t=t_o} \) (Hubble parameter). From (10) it is readily seen that

\[
q_o = 1 - \frac{3\beta}{2} .
\]

Therefore, for a given value of \( \beta \), the deceleration parameter \( q_o \) with matter creation is always smaller than the corresponding one of the FRW flat model. The critical case (\( \beta = 1/3, q_o = 0 \)), describes a “coasting cosmology”. Curiously, instead of being supported by “K-matter” (Kolb 1989), this kind of model is obtained in the present context for a dust filled universe. It is also interesting that even negative values of \( q_o \) are allowed for a dust filled universe, since the constraint \( q_o < 0 \) can always be satisfied provided \( \beta > 1/3 \). These results are in line with recent measurements of the deceleration parameter \( q_o \) using Type Ia supernovae (Perlmutter et al. 1998, Garnavich et al 1998, Riess et al 1998). Such observations indicate that the universe may be accelerating today (\( q_o < 0 \)), which corresponds dynamically to a negative pressure term in the EFE. This would also indicate that the universe is
much older than a flat model with the usual deceleration parameter $q_o = 0.5$, and reconcile other recent results (Freedman 1998), pointing to a Hubble parameter $H_o$ larger than 50 km s$^{-1}$ Mpc$^{-1}$ (see discussion below Eq.(21)). To date, only models with a cosmological constant, or the so-called “quintessence” (of which $\Lambda$ is a special case), or still a second dark matter component with repulsive self-interaction have been invoked as being capable of explaining these results (Steinhardt et al. 1997, Cornish and Starkman 1998). In the present context, these prescriptions for alternative cosmologies are replaced by a flat model endowed with an “adiabatic” matter creation process. Before continuing, we need to express the constant A in terms of $R_o$ and $H_o$. From (8) one finds

$$A = H_o^2 R_o^3 (1 - \beta) \quad . \quad (19)$$

The kinematical relation distances must be confronted with the observations in order to put limits on the free parameter of the models.

a) Lookback Time-Redshift

For a given redshift $z$, the scale function $R(t_z)$ is related with $R_o$ by $1 + z = \frac{H_o}{R(t_z)}$. The lookback time is exactly the time interval required by the universe to evolving between these two values of the scale factor. Inserting the value of $A$ given above in the first integral (11), the lookback time-redshift relation can be easily derived and it is given by

$$t_o - t(z) = \frac{2H_o^{-1}}{3(1 - \beta)} \left[ 1 - \frac{1}{(1 + z)^{3(1 - \beta)}} \right] , \quad (20)$$

which generalizes the standard FRW flat result (Sandage 1988). In figure 1 we have plotted the lookback time as a function of the redshift for some selected values of $\beta$.

Taking the limit $z \to \infty$ in (20) the present age of the universe (the extrapolated time back to the bang) is

$$t_o = \frac{2H_o^{-1}}{3(1 - \beta)} \quad , \quad (21)$$

which reduces for $\beta = 0$ to the same expression of the standard dust model (Kolb and Turner, 1990).

Estimates of the Hubble expansion parameter from a variety of methods are now converging to $h \equiv (H_o/100\text{km/sec/Mpc}) = 0.7 \pm 0.1$ (Freedman 1998). Assuming no matter creation ($\beta = 0$), the lower and upper limits of this value imply that the expansion age of a dust-filled flat universe, which is theoretically favored by inflation, would be either $10.8 \times 10^9$ years or $8.2 \times 10^9$ years. These results are in direct contrast to the measured ages of some stars and stellar systems, believed to be at least $(12 - 16) \times 10^9$ years old or even older if one adds a realistic incubation time (Bolte and Hogan 1995, Pont et al. 1998). As can easily be seen from (21), the matter creation process helps because for a given Hubble parameter $H_o$ the expansion age $t_o$ is always larger than $\frac{4}{3}H_o^{-1}$, which is the age of the universe for the FRW flat model. It is exactly $H_o^{-1}$ for a coasting cosmology ($\beta = \frac{1}{3}$), and greater than $H_o^{-1}$ for $\beta > \frac{1}{3}$. In this way, one may conclude that the matter creation ansatz (9) changes the predictions of standard cosmology, thereby alleviating the problem of reconciling observations with the inflationary scenario. It is interesting that matter creation increases the dimensionless parameter $H_o t_o$ while preserving the overall expanding FRW behavior.

b) Luminosity Distance-Redshift

The luminosity distance of a light source is defined as $d_l^2 = \frac{L}{4\pi r^2}$, where $L$ and $l$ are the absolute and apparent luminosities respectively. In the standard FRW metric (1) it takes the form (Sandage 1961; Weinberg 1972)

$$d_l = R_o r(z)(1 + z) \quad , \quad (22)$$

where $r(z)$ is the radial coordinate distance of the object at light emission. Starting from (1), this quantity can be easily derived as follows: since a light signal satisfies the geodesic equation of motion $ds^2 = 0$ and geodesics intersecting $r_o = 0$ are lines of constant $\theta$ and $\phi$, the geodesics equation can be written as

$$\int_o^r dr = \int_{R(t)}^{R_o} \frac{dR(t')}{R(t') R(t')} \quad . \quad (23)$$
Now, substituting \((11)\) with the value of \(A\) given by \((19)\) in the above equation, the radial coordinate distance as function of redshift is given by

\[
r(\beta) = \frac{2}{(1 - 3\beta) R_o H_o} \left[ 1 - (1 + \beta z) \frac{3 + z}{2} \right],
\]

and therefore, the luminosity distance-redshift relation is written as

\[
H_o d_l = \frac{2}{(1 - 3\beta)} \left[ (1 + \beta z) - (1 + z)^{\beta} \right].
\]

As one may check, taking \(\beta = 0\), the above expression reduces to

\[
H_o d_l = 2 \left[ (1 + z) - (1 + z)^{\beta} \right],
\]

which is the usual FRW result \(\text{(Weinberg 1972)}\). On the other hand, expanding \((25)\) for small redshifts after some algebra one finds

\[
H_o d_l = z + \frac{1}{2} (1 - \frac{3\beta}{2}) z^2 + ...,
\]

which depends explicitly on the matter creation \(\beta\) parameter. However, inserting \((18)\) we recover the usual FRW expansion for small redshifts, which depends only on the effective deacceleration parameter \(q_0\) \(\text{(Weinberg 1972; Kolb and Turner 1990)}\). The luminosity distance as a function of the redshift is shown in figure 2. As expected, in these diagrams different models has the same behavior at \(z << 1\) \(\text{(Hubble law)}\), and the possible discrimination among different models comes from observations at large redshifts \((z \geq 1)\). However, it is usually believed that in such scales evolutionary effects can not be neglected. The range of possible data at the limiting \(z\), for which evolutionary effects are not important are indicated by the data point and error bar \(\text{(Kristian, Sandage and Westphal 1978)}\).

c) Angular Diameter-Redshift

The angular size \(\theta\) of an object is an extremely sensitive function of the cosmic dynamics. In particular, the apparent continuity of the \(\theta(z)\) relation for galaxies and quasars is also believed to be a strong support to the cosmological nature of the redshifts \(\text{(Kapahi 1987)}\). Here we are interested in angular diameters of light sources described as rigid rods and not isophotal diameters. These quantities are naturally different, because in an expanding world the surface brightness varies with the distance \(\text{(for more details see Sandage 1988)}\).

Let \(D\) be the intrinsic size of a source located at \(r(z)\), assumed independent of the redshift and perpendicular to the line of sight. If it emits photons at time \(t_1\) that at time \(t_o\) arrive to an observer located at \(r = 0\), its angular size at the moment of reception is defined by \(\text{(Sandage 1961)}\)

\[
\theta = \frac{D(1 + z)}{R_o r(z)}.
\]

Inserting the expression \((24)\) for \(r(z)\) into \((28)\) we find

\[
\theta = \frac{D H_o (1 - 3\beta)(1 + z)^{\frac{3(1 - \beta)}{2}}}{2 \left(1 + z \right)^{\frac{3(1 - \beta)}{2}} - 1}.
\]

A log-log plot of angular size versus redshift is shown in figure 3 for selected values of \(\beta\).

For all models, the angular size initially decreases with increasing \(z\), reaches its minimum value at a given \(z_c\), and eventually begins to increase for fainter magnitudes. This generic behavior for an expanding universe was predicted long ago in the context of the standard model \(\text{(Hoyle 1959)}\). It may qualitatively be understood in terms of an expanding space: the light observed today from a source at high \(z\) was emitted when the object was closer. How this effect depends on the \(\beta\) parameter? As can be seen from \((29)\) the minimal value of which occur at \(z_c(\beta) = \left(\frac{3(1 - \beta)}{2}\right)^{-\frac{2}{3(1 - \beta)} - 1}\). Hence, the minimum persists in the presence of adiabatic matter creation, and is pushed to the right direction, that is, it is displaced to higher redshifts as the \(\beta\) parameter is increased. As expected, for \(\beta = 0\) one finds \(z_c = \frac{3}{2}\), which is the standard result for a dust filled FRW flat universe. It is also convenient to consider the limit of small redshifts in order to clarify the role played by \(\beta\). Expanding \((29)\) we have \(z\)

\[
\theta = \frac{D H_o}{z} \left[ \frac{1}{2} (3 + \frac{1 - 3\beta}{2}) z + ... \right].
\]
Hence, “adiabatic” matter creation as modelled here also requires an angular size decreasing as the inverse of the redshift for small $z$. However, the second order term is a function of the $\beta$ parameter. Its overall effect on the angular size is depart it from the Euclidean behavior ($\theta \approx z^{-1}$) more slowly than in the corresponding FRW model (see fig.3). In terms of $q_o$, inserting (18) into (30) it is readily obtained

$$\theta = \frac{DH_o}{z} \left[ 1 + \frac{1}{2} (3 + q_o) z + \ldots \right], \quad (31)$$

which is formally the same FRW result for small redshifts (Sandage 1988). Note that even at this limit, constraints on the decceleration parameter from the data are equivalent to place limits on the values of $\beta$ (see (18)).

d) Number Counts

Let us now derive the galaxy number per redshift interval in the presence of adiabatic matter creation. We first remark that although modifying the evolution equation driving the amplification of small perturbations, and so the usual adiabatic treatment for galaxy formation, the created matter is smeared out and does not change the total number of sources present in the nonlinear regime. In other words, the number of galaxies already formed scales with $R^{-3}$.

Let $n_g(z,L) dL$ be the proper concentration of sources at redshift $z$ with absolute luminosity between $L$ and $L + dL$. The total number of galaxies $N_g(z)$ is proportional to the the comoving volume

$$dN_g(z) = n_g dL dV_c = 4\pi n_o r^2 dr dL \quad . \quad (32)$$

Now, by using that $\frac{dR}{R(t)} = \frac{dR}{H_R} = -dr$, we find that

$$\frac{dN_g}{4\pi n_o dz dL} = \left( \frac{R_o H_o}{R} \right)^{-1} \frac{r(z)^2}{(1 + z)^{3(1-\beta)/2}} \quad , \quad (33)$$

where $n_g(z,L) = n_o(L)(1 + z)^3$.

On the other hand, since the radial coordinate $r(z)$ is given by eq.(24) it follows that the expression for number-counts can be written as

$$(H_o R_o)^3 dN_g = \frac{\delta^2}{2} \left[ 1 - (1 + z) - \frac{(1+3\beta)}{z} \right] \frac{2}{z^2 (1+z)^{3(1-\beta)}} \quad , \quad (34)$$

where $\delta = \frac{2}{1-3\beta}$. For small redshifts, we have that

$$(H_o R_o)^3 dN_g = 1 - 2 \left[ \frac{(1 - 3\beta)}{2} + 1 \right] z + \ldots \quad . \quad (35)$$

The number count-redshift diagram for a dust-filled model with “adiabatic” matter creation is shown in the figure 4, for the indicated values of $\beta$. Table 1 summarizes the limits to $\beta$ obtained from each kinematical test.
3. Conclusion

The cosmological principle (homogeneity and isotropy of space) defines the shape of the line element up to a spatial scale function, which must be time dependent from the cosmological nature of the redshifts. As discussed here, the expanding “postulate” and its main consequences may also be compatibilized with a cosmic fluid endowed with adiabatic matter creation. The similarities and differences among universe models with matter creation as described in the new thermodynamic approach and the conventional matter conserved FRW model have been analysed both from formal and observational view points. The rather slight changes introduced by the matter creation process, which is quantified by the $\beta$ parameter, provides a reasonable fit of some cosmological data. Kinematic tests like luminosity distance, angular diameter and number-cuts versus redshift relations constrain perceptively the matter creation parameter (see table 1). For flat models with $\beta \neq 0$, the age of the universe is always greater than the corresponding FRW model ($\beta = 0$). More important still, the deceleration parameter $q_0$ may be negative as suggested by recent type Ia supernovae observations. In this concern, the models studied here are alternatives to universes dominated by a cosmological constant or “quintessence”.

The angular size versus redshift curves have the minimum displaced for higher values of $z$, thereby alleviating the problem in reconciling the angular size data from galaxies and quasars at intermediate and large redshifts. It is also interesting that all the theoretical and observational results previously obtained within a scenario driven by $K$-matter (Kolb 1989), are reproduced for a dust-filled universe with $\beta = \frac{1}{3}$.

We also stress that in spite of these important physical consequences, the present day matter creation rate, $\psi = 3n_o H_o \approx 10^{-16}$ nucleons $cm^{-3} yr^{-1}$, is nearly the same rate predicted by the steady-state universe (Hoyle, Burbidge and Narlikar 1993). This matter creation rate is presently far below detectable limits.

The constraints on the $\beta$ parameter should be compared with the corresponding ones using the predictions of light elements abundances from primordial nucleosynthesis. In fact, the important observational quantity for nucleosynthesis is the baryon to entropy ratio. In these models the temperature scale-factor relationship and entropy density are modified, therefore one may expect sensitive implications to the nucleosynthesis scenario.

Finally, we remark that it is not so difficult to widen the scope of the kinematic results derived here to include curvature effects as well as a non-zero cosmological constant. In particular, concerning the “age problem”, even closed universes seems to be compatible with the ages of the oldest globular clusters, when the value of the creation parameter is sufficiently high. Further details about kinematic tests in closed and opened universes with matter creation will be published elsewhere (Alcaniz and Lima 1999).

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Table 1. Limits to $\beta$

| Test                      | $\beta$ |
|---------------------------|---------|
| Luminosity distance-redshift | $\beta \leq 0.48$ |
| Angular size-redshift     | $0.20 \leq \beta \leq 0.84$ |
| Number counts-redshift    | $\beta \leq 0.36$ |

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