Recent WMAP data [35, 36] finds no deviation from the standard ΛCDM model. But ΛCDM model has its own problem. However, ΛCDM model requires 26% of matter in the form of pressureless dust, out of which only 4% are baryons and the rest, about 22% are cold dark matter (CDM). Since dark matter interacts only with the gravitational field, it plays a key role in the structure formation. Thus, the amount of CDM (22%) must have been created in the very early universe, prior to the radiation dominated era, together with the baryons, by some sort of mechanism, viz., supersymmetry breaking, cosmic string decay or particle creation phenomena at the expense of gravitational field. Now, if phenomenologically one considers that CDM may also be produced by gravitational particle creation mechanism, even at a very slow rate, during the late time evolution of the universe, viz., during the matter dominated era, then it may be possible to explain the presently observable acceleration of the universe, without taking dark energy into account. The very advantage of the creation of cold dark matter over dark energy is that it avoids coincidence problem and may be detectable in future experiments. Now, our focus is on the cosmological consequences of particle production on the evolution of late stage of the universe which was initiated by Alcaniz and Lima [158] and Lima, Silva and Santos (lss) [159].

Particle creation phenomena was explored largely during the last century to explain the early universe. Matter constituents may be produced quantum mechanically [160] - [162] in the framework of Einstein’s equations. Cosmological consequence of particle creation mechanism is studied taking into account an explicit phenomenological balance law for the particle number [163] - [165] in addition to the familiar Einstein’s equations. In view of such a balance law, Prigogine et-al [163] successfully explained the cosmological evolution of the early universe.

Recently, Lima et-al [159] have developed a late time model universe, taking into account the creation phenomena in the matter dominated era. The model admits early deceleration followed by a recent acceleration of the universe as suggested by present observations and fits SNe Ia data to some extent. However, they [159] have shown that in their model the creation phenomena is never ending, as a result cosmic evolution does not ever include standard radiation dominated or matter dominated Friedmann era. This definitely creates problem in explaining the structure formation of the universe and the CMBR. Later, Steigman et-al [166] analyzed the model in the two limits of high and low redshifts. They have observed a clear conflict between the WMAP constraint on matter-radiation equality $z_{eq}$ at high redshift and SNe Ia data at low redshift. The main criticisms of the $\beta - \gamma$ model proposed by Lima et-al [159] are that they have not taken into account the amount of CDM created in the very early universe at one end, and that their creation rate $\Gamma = 3\beta H + 3\gamma H_0$ depends on the present Hubble parameter, on the other. If these problems are alleviated, then phenomenologically particle creation process obviously unifies early inflation with late stage of cosmic acceleration in an elegant fashion.

In the present work, we propose a model where, instead of choosing the creation parameter $\Gamma$ arbitrarily, we have considered the experimentally verified fact that the universe has recently entered an accelerated phase of expansion. As a result we have chosen the scale factor judiciously, such that particle creation could start again in the matter dominated era. This naturally alleviates the said problems and unifies the early and the late stages of cosmic evolution, in an elegant fashion. Additionally, the model fits perfectly with the WMAP constraint on matter-radiation equality $z_{eq}$ only if one considers the presence of nearly 26% of primeval matter in the form of baryons and CDM. In view of such a model, particle creation phenomena is now able to explain the history of cosmic evolution from the very early universe till date, without requiring dark energy at any stage and thus avoiding coincidence problem.
3.1 Balance law and the Field equations

Cosmological consequence taking into account particle creation phenomena is studied by using an explicit phenomenological balance law for the particle number [163, 164]. Such a balance law in the process of particle production is modeled by \( \dot{N} + \frac{\dot{n}}{n} = \Psi \), where \( \Psi \) is a source term. For a vanishing \( \Psi \) the particle number is conserved. In the RW metric, above balance law reduces to,

\[
\dot{N} + \frac{\dot{n}}{n} = \Gamma = \Psi.
\]

where, \( u^\alpha \), \( N \), \( n \) and \( H \) are the fluid four velocity vector, the total number of particles, particle number density and the Hubble parameter respectively, while, \( \Theta = u^\alpha \cdot \alpha = 3H \) is the expansion scalar. Thus, the field equations in the spatially flat \( k = 0 \) RW metric associated with particle creation phenomena are,

\[
\begin{align*}
2\dot{H} + 3H^2 &= -8\pi G(p_m + p_{cm}), \\
3H^2 &= 8\pi G(p_m + p_{cm}) = 8\pi G\rho, \\
3H + \frac{\dot{n}}{n} &= \Gamma = \frac{\Psi}{n}, \quad (3.1.3) \\
p_{cm} &= -\frac{\rho + p_m}{3H} \Gamma.
\end{align*}
\]

In the above set of equations, \( H = \frac{\dot{a}}{a} \) is the Hubble parameter, \( p_m \) and \( \rho_m \) are the pressure and the energy density of the matter existing in the universe in the form of a barotropic fluid containing baryons and cold dark matter, created in the very early universe. \( p_{cm} \) and \( \rho_{cm} \) are the pressure and the energy density of the cold dark matter created at the late stage of cosmic evolution, i.e., during matter dominated era. \( \Gamma \) is the creation parameter, and \( n \) is the particle number density.

Now, formulation of equation (3.1.4) in connection with particle creation phenomena has been done in [159, 163]. However, in slightly different approach, here we produce a straightforward calculation. Adiabatic cosmological evolution in the presence of particle creation can be treated in the open system, and so the first law of thermodynamics is modified as,

\[
\begin{align*}
\frac{d(\rho V)}{n} + p_m dV - \frac{h}{n} d(nV) &= 0, \\
TdS &= d(\rho V) + p_m dV - \mu d(nV),
\end{align*}
\]

Combination of the two laws \((3.1.5)\) and \((3.1.6)\) gives,

\[
TdS = \frac{h}{n} d(nV) - \mu d(nV) = T \sigma dN,
\]

where, we have used the usual expression for the chemical potential as \( \mu n = h - Ts \) and define \( s = \frac{S}{V} \) to be the entropy per unit volume and \( \sigma = \frac{S}{N} \) as the specific entropy. Thus we observe that the second law of thermodynamics viz., \( dS \geq 0 \) implies \( dN \geq 0 \), and the reverse process is thermodynamically impossible, i.e., particle can only be created and can not be destroyed. Further, expressing \( S \) in terms of \( \sigma \), the above equation can also be expressed as,

\[
T N d\sigma = 0 \Rightarrow \dot{\sigma} = 0,
\]

Hence, in the adiabatic particle creation phenomena, entropy increases, while the specific entropy remains constant. First law given by equation \((3.1.5)\) can also be expressed as,

\[
V dp + \rho dV + p_m dV - \frac{hV}{n} dn = 0 \Rightarrow V dp - \frac{hV}{n} dn = 0 \Rightarrow \dot{\rho} = \frac{\dot{n}}{n},
\]

3.2. A BRIEF REVIEW OF THE LSS MODEL

Now, the energy-momentum tensor $T^\mu_\nu$ along with the conservation law when creation phenomena is incorporated are,

$$T^\mu_\nu = (\rho + p_m + p_{cm})u^\mu u_\nu - (p_m + p_{cm})g^\mu_\nu, \quad T^\mu_\nu = 0,$$

(3.1.10)

where, $\rho = \rho_m + \rho_{cm}$ is the total energy density and $p_m$ is the thermodynamic pressure, while, $p_{cm}$ is the creation pressure and $u^\mu$ is the component of four velocity vector. The energy conservation law (3.1.10) in homogeneous cosmological models reads,

$$\dot{\rho} + \Theta (\rho + p_m + p_{cm}) = 0,$$

(3.1.11)

where, $\Theta = 3H$ is the expansion scalar, $H$ being the Hubble parameter. If we now plug in $\dot{\rho}$ from equation (3.1.9) in the above equation (3.1.10), we get,

$$p_{cm} = -\frac{\rho + p_m}{\Theta} \left( \Theta + \frac{\dot{n}}{n} \right) = -\frac{\rho + p_m}{\Theta} \Gamma,$$

(3.1.12)

where, $\Gamma = \Theta + \frac{\dot{n}}{n}$ is the creation rate.

Now, the second law of thermodynamics allows the creation of particle from the gravitational field and the process is irreversible. Thus the creation parameter $\Gamma > 0$, and so it is clear from equation (3.1.4) that the particle creation phenomena is always associated with a negative pressure $p_{cm}$, which may be responsible for acceleration at the late stage of cosmic evolution. Further, note that the creation of baryons and CDM in the early universe was also associated with a large negative pressure. However, the creation phenomena weakened and finally stopped, when universe expanded sufficiently, thereby giving way to the hot big bang followed by the radiation dominated era of Friedmann type ($a \propto t^{\frac{1}{2}}$) [163]. There after, the baryons and the CDM created in the very early universe obviously start acting as pressureless dust, so that we can take $p_m = 0$ and hence $\rho_m = \rho_0 a^{-3}$, $\rho_0$ being a constant. Thus we can simplify the above equations to get,

$$\Gamma = 3H + 2\frac{\dot{H}}{H} = 3H \left( \frac{2\dot{H} + 3H^2}{3H^2} \right) = -3H w_e,$$

(3.1.13)

$$p_{cm} = \frac{3H^2}{8\pi G} - \rho_0 a^{-3},$$

(3.1.14)

$$p_{cm} = -\frac{1}{8\pi G} H\Gamma,$$

(3.1.15)

$w_e$ being the effective state parameter. In view of the above set of three equations, we need to find the scale factor ($a$) (and consequently ($H$), the Hubble parameter), the creation rate $\Gamma$, the creation pressure $p_{cm}$ and the creation matter density $\rho_{cm}$. Obviously, we need yet another suitable condition to solve the system of equations.

3.2 A brief review of the lss model

The Friedmann equation, taking into account the created matter, baryonic matter and radiation reads,

$$\left( \frac{H}{H_0} \right)^2 = \Omega_r (1 + z)^4 + \Omega_B (1 + z)^3 + \frac{\rho_{cm}}{\rho_c},$$

(3.2.1)

where, $\rho_c$ is the present value of critical density. To calculate the last term let us take the total number of created particles at an instant to be $N = nV$, where $V = V_0(1 + z)^{-3}$ is the comoving volume at that instant. Thus the creation rate is given as,

$$\frac{1}{N} \frac{dN}{dt} = \frac{d[\ln (\rho_{cm} V)]}{dt} = \Gamma,$$

(3.2.2)
which yields,
\[ \rho_{cm} = \rho_{cm0}(1 + z)^3 \exp \left( - \int_{1}^{t_0} \Gamma dt' \right), \]  
(3.2.3)

where, \( \rho_{cm0} \) is the present value of the created matter density. Thus,
\[ \frac{\rho_{cm}}{\rho_c} = \Omega_{cm}(1 + z)^3 \exp \left( - \int_{1}^{t_0} \Gamma dt' \right), \]  
(3.2.4)

where, \( \Omega_{cm} \) is the density parameter corresponding to the created matter. So, the Friedmann equation (3.2.1) finally reads,
\[ \left( \frac{H}{H_0} \right)^2 = \Omega_r(1 + z)^4 + \Omega_B(1 + z)^3 + \Omega_{cm}(1 + z)^3 \exp \left( - \int_{1}^{t_0} \Gamma dt' \right), \]  
(3.2.5)

Now, under the assumption \( \Gamma = 3\beta H + 3\gamma H_0 \), where, \( \beta \) and \( \gamma \) are constants and \( H_0 \) is the present Hubble parameter, (lss) [159] obtained a solution of the scale factor in the form,
\[ a(t) = a_0 \left[ 1 - \frac{\beta}{2} \left( e^{\frac{\gamma H_0 t}{2}} - 1 \right) \right]^{\frac{1}{3(\beta\gamma)}}, \]  
(3.2.6)

which admits the observed transition from early deceleration to late time acceleration. In a later investigation [166], this model was found to produce a conflict between SNe Ia data at low redshift and WMAP - 7 year data constraint [35] on matter-radiation equality \( z_{eq} = 3141 \pm 157 \), occurred at the high redshift limit of observed ISW (Integrated Sachs-Wolfe) effect. Let us review the situation to find the real problem associated with the conflict. The Friedmann equation (3.2.5) in the model under consideration reads,
\[ \left( \frac{H}{H_0} \right)^2 = \Omega_r(1 + z)^4 + \Omega_B(1 + z)^3 + \Omega_{cm}(1 + z)^3 \exp 3\gamma(\tau - t_0), \]  
(3.2.7)

where, \( \tau = H_0 t_0 \) and \( t_0 = H_0 t_0 \) are the age at any instant and the present age of the universe respectively, in the units of Hubble’s age \( (H_0^{-1}) \). Setting, \( \Omega_{cm} = 1 - \Omega_B \), the \( \gamma - \beta \) relation is obtained (see equation (34) in [166]) as,
\[ \gamma = (1 - \beta) \left[ (1 - \Omega_B)^{\frac{1}{2}} - \{\Omega_r(1 + z_{eq}) - \Omega_B\}^{\frac{1}{2}}(1 + z_{eq})^{\frac{3\beta}{2}} \right]. \]  
(3.2.8)

This model fits SNe Ia data for \( \beta = 0 \) and \( \gamma = 0.66 \pm 0.04 \), while \( 1 + z_{eq} = 1798^{+536}_{-552} \), taking \( \Omega_B = 0.042 \). Clearly, the model does not fit with the WMAP - 7 year data constraint [35] on matter-radiation equality \( z_{eq} = 3141 \pm 157 \), occurred at the high redshift limit of observed ISW effect. This contradiction may be alleviated easily, if we consider existence of cold dark matter that was created in the early universe and which was responsible for inflation. As, already mentioned, this amount of CDM created in the very early universe behaves now as pressureless dust and has been redshifted like baryons. If we now add corresponding density parameter \( \Omega_{CDM} \), associated with the cold dark matter created in the very early universe in equation (3.2.5), it reads
\[ \left( \frac{H}{H_0} \right)^2 = \Omega_r(1 + z)^4 + \Omega_m(1 + z)^3 + \Omega_{cm}(1 + z)^3 \exp \left( - \int_{1}^{t_0} \Gamma dt' \right), \]  
(3.2.9)

where, \( \Omega_m = \Omega_B + \Omega_{CDM} \) and, \( \Omega_{cm} = 1 - \Omega_m \). In the absence of matter creation phenomena in the late universe, \( \beta \), \( \gamma \) vanish, and hence \( \Gamma = 0 \). Thus there is no creation pressure \( p_m \) as well as creation matter density \( \rho_{cm} \). Hence, \( \Omega_{cm} = 0 \). Thus at the matter-radiation equality \( (z_{eq} = \frac{t_0}{H_0} - 1) \) taking, \( \Omega_m = \Omega_B + \Omega_{CDM} = 0.26 \) and \( \Omega_r = 8 \times 10^{-5} \), one recovers \( z_{eq} = 3249 \), which is at par with WMAP data. Equation (3.2.8) now takes the form,
\[ \gamma = (1 - \beta) \left[ (1 - \Omega_m)^{\frac{1}{2}} - \{\Omega_r(1 + z_{eq}) - \Omega_m\}^{\frac{1}{2}}(1 + z_{eq})^{\frac{3\beta}{2}} \right]. \]  
(3.2.10)
3.3. THE MODEL THAT WE PROPOSED

If we now consider that 16% of CDM (say) were produced in the very early universe, then \( \Omega_m = \Omega_B + \Omega_{\text{CDM}} = 0.2 \) and thus for \( \beta = 0 \) and \( \gamma = 0.66 \pm 0.04 \), \( z_{eq} = 3186^{+254}_{-214} \), which is very much at par with WMAP data [34] - [36]. This clearly indicates that one should include the contribution of CDM created at the very early universe. The creation of CDM in the very early universe was halted and the universe entered usual Friedmann radiation dominated era. Thereafter, this amount of CDM is being redshifted like baryons.

In the above analysis, while we have showed how the conflict encountered between low and high redshift data [166] may be reduced, nevertheless, it does not support the model [159]. Firstly, in their \( \beta - \gamma \) model, \( \beta = 0 \), somehow fits SNe Ia data, which is not a very good fit at all (see fig. 1 of [166]). Further, \( \beta = 0 \) turns out to give a constant creation rate throughout the evolution of the universe, which is highly objectionable. Also, the choice of the creation parameter (\( \Gamma \)) as a function of present Hubble parameter (\( H_0 \)) implies that the model is plagued by the coincidence problem. Finally, we could accommodate only 16% of CDM out of 22% to alleviate the conflict [166]. Addition of another 6% of CDM shifts \( z_{eq} \) to a much higher value. In view of the above criticism we pose to present a more realistic model.

3.3 The model that we proposed

In this work, we propose a model where, instead of choosing the creation parameter \( \Gamma \) arbitrarily, we have chosen the scale factor judiciously, such that particle creation could start again in the matter-dominated era, which may be responsible for the accelerated phase of expansion of the universe. So, let us try with a scale factor associated with the so called intermediate inflationary solution [167], viz.,

\[
a = a_0 \exp \left[A t_f\right],
\]

(3.3.1)
a_0 being a constant. Such a solution for \( A > 0 \) and \( 0 < f < 1 \), was presented by Barrow [167], and was shown to lead to late time acceleration [168] in different models. To appreciate the underlying beauty of the ansatz (3.3.1), let us expand it as,

\[
a = a_0 \left[1 + \frac{A t_f}{2!} A^2 t_{f}^2 + \ldots\right],
\]

(3.3.2)
and observe that for \( f = \frac{2}{3} \), the standard matter dominated era of Friedmann model is recovered in the early universe when second term dominates, and the third term becomes responsible for accelerated expansion in the late stage of cosmological evolution. For \( f = \frac{1}{3} \), the third term leads to the standard Friedmann model and acceleration starts a little late. For even smaller values of \( f \), the model tracks decelerated expansion for a longer time recovering the standard Friedmann model at some intermediate stage of evolution and leads to accelerated expansion at much later stage of cosmic evolution. The redshift parameter \( 1 + z = \frac{a(t_0)}{a(t)} \), where, \( t_0 \) is the present time, is found as

\[
1 + z = \exp \left[A \left(t'_0 - t'\right)\right].
\]

(3.3.3)

Hence, the Hubble parameter takes the following form,

\[
H = \frac{Af}{(1-f)} = \frac{Af}{\left[t'_0 - \ln(1+z)\right]^{\frac{1}{1-f}}},
\]

(3.3.4)
where, we have used equation (3.3.3) to get the second equality in the expression of \( H \). In view of equation (3.1.13), we can now find a form of \( \Gamma \) as,

\[
\Gamma = 3H - 2(1-f) \left(\frac{H}{Af}\right)^{\frac{1}{1-f}}.
\]

(3.3.5)
This form of \( \Gamma \) is clearly different from the \( \beta - \gamma \) model [159]. The most important difference is that the creation rate \( \Gamma \) here, starts developing only when the Hubble parameter, 

\[
H \geq \left( \frac{3}{2(1-f)} \right)^{(1-f)} A f^{\frac{1}{2}},
\]

(3.3.6)
since, \( \Gamma < 0 \) is not allowed by the second law of thermodynamics. The creation pressure and the creation matter density are now found as,

\[
8\pi G \rho_{cm} = -\Gamma H = H \left[ 3H - 2(1-f) \left( \frac{H}{Af} \right)^{\frac{1}{2}} \right],
\]

(3.3.7)

\[
8\pi G \rho_m = 3H^2 - 8\pi G \rho_m,
\]

(3.3.8)

where,

\[
8\pi G \rho_m = 8\pi G \rho_{m0}(1+z)^3 = \frac{\rho_{m0}}{\rho_c} 3H_0^2(1+z)^3 = 3H_0^2 \Omega_m (1+z)^3,
\]

(3.3.9)
in which, \( \rho_c, \rho_{m0} \) and \( \Omega_m \) are the present values of critical density, matter density and the matter density parameter respectively. We can find the effective state parameter and also the state parameter of the created matter as,

\[
w_e = - \frac{2H + 3H^2}{3H^2} = -1 + \frac{2}{3} \left( \frac{1-f}{AfH} \right).
\]

(3.3.10)

\[
w_{cm} = - \frac{2H + 3H^2}{3H^2 - 8\pi G \rho_m} = - \frac{3A^2 f^2 - 2Af(1-f)}{3A^2 f^2 - 3 \Omega_m H_0^2(1+z)^3} \left( \frac{t_0}{t} - \frac{\ln(1+z)}{A} \right)^{-1},
\]

(3.3.11)

Now let us see how far this model parametrized by the two parameters \( A \) and \( f \) fits with the observed data. We have kept \( 0.67 \leq H_0 t_0 \leq 1 \) and \( 0.67 \leq h = \frac{978}{H_0} \text{ Gyr}^{-1} \leq 0.7 \), as par with HST project [169]. As already mentioned, the restriction on the parameters are, \( A > 0 \) and \( 0 < f < 1 \). We have tested the model by choosing \( A \) and \( f \) which fit SNe Ia data, from a wide range of values between \( 0.08 \leq A \leq 25 \) and \( 0.03 \leq f \leq 0.99 \). The fit requires large \( A \) for small \( f \) and vice-versa. We have presented our results briefly in the following table-2, taking only some integral values of \( A \) starting from \( A = 15 \), since for lower values this model does not probe to large redshift \( z \). We have taken \( z_{eq} = 3300 \), which is very much at par with recently released WMAP data [35, 36] and \( \Omega_B = 0.042 \), to find the amount of matter produced in the late stage of cosmic evolution restricting the amount CDM produced in the very early universe.

<table>
<thead>
<tr>
<th>( A )</th>
<th>( f )</th>
<th>( z_{\Gamma=0} )</th>
<th>( z_a )</th>
<th>( w_{e0} )</th>
<th>( \Omega_m )</th>
<th>( \Omega_{cm} )</th>
<th>( \Omega_{CDM} )</th>
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<tr>
<td>15</td>
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<td>0.745</td>
<td>0.213</td>
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<td>0.82</td>
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<td>0.255</td>
<td>0.745</td>
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</tr>
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<td>-0.33</td>
<td>0.256</td>
<td>0.744</td>
<td>0.214</td>
</tr>
</tbody>
</table>
3.3. THE MODEL THAT WE PROPOSED

In table-2, $z_{\Gamma=0}$ and $z_a$ symbolize the redshift values at which the creation of matter and the acceleration start respectively, while $w_{e0}$ is the present value of effective state parameter. Let us list our observation point by point.

1. The distance modulus versus redshift curve fits between the present and the $\Lambda$CDM model (taking $\Omega_\Lambda = 0.74$ and $\Omega_m = 0.26$) almost perfectly for a wide range of values of the parameters $A$ and $f$. Figure 3.1 shows one of these plots.

2. It is observed that for the combinations of $A$ and $f$, which can probe to a distant redshift, the present value of the state parameter is nowhere near $-1$, yet, the model fits both the experimental data, viz., SNe Ia and WMAP. Particularly, for $A \geq 22$, the acceleration is yet to start.

3. The most important point is to note that for $A > 10$, $z_{eq}$ is at par with the recent WMAP data [35, 36], only if $24\% - 26\%$ of matter (baryons and CDM) is assumed to have formed in the very early universe. Table-2 shows that the density parameter $0.74 \leq \Omega_{cm} \leq 0.76$, which corresponds to $74\% - 76\%$ of matter created in the matter dominated era. Thus, instead of taking into account $74\%$ of dark energy, creation of dark matter by the same amount in the matter dominated era, solves the cosmic puzzle.

4. The behaviour of the creation parameter $\Gamma$ given in equation (3.3.5) has been plotted in figure 3.2 for a particular pair of the parameters $A = 19$ and $f = 0.046$. It shows that the creation started at $z = 2050$, reaches a maxima and presently it is insignificantly small. The behaviour is the same for all other pairs of $A$ and $f$, only the redshift values at which creation starts ($z_{\Gamma} = 0$) and its maxima changes.

5. We have also presented a suitable contour plot in figure 3.3, to explore the data presented in table-2 at a glance. The plot presents all the successful combinations of the parameters $A$ and $f$, which fit SNe Ia data, and satisfy WMAP constraint on $z_{eq} = 3300$, keeping $H_0t_0 \approx 1$, and $24\% \leq \Omega_m \leq 26\%$. Calculation shows that WMAP constraint on $z_{eq}$ is not satisfied for lower or higher values of $\Omega_m$, with the same parametric combination of $A$ and $f$. Particularly, for $\Omega_m = 0.2$, $2400 \leq z_{eq} \leq 2500$, while for $\Omega_m = 0.3$, $3800 \leq z_{eq} \leq 3900$. Thus, nearly $26\%$ of primeval matter in the form of baryons and CDM, is required to fit presently observable data, in view of particle creation phenomena.
CHAPTER 3. PARTICLE CREATION PHENOMENA

Figure 3.2: The behaviour of $\Gamma$ versus $z$ has been depicted for $A = 19$ and $f = 0.046$. Creation starts in the matter dominated era around $z = 2050$ and its rate has a maxima around $z\Gamma_{\text{max}} = 1100(= z_{\text{recombination}})$. Presently the creation rate is insignificantly small. The behavior is the same for all other combinations of $A$ and $f$, only $z\Gamma=0$ and $z\Gamma_{\text{max}}$ are different.

Figure 3.3: The contour plots of $H_0 t_0 = 1$ (dashed line) and $\Omega_m$ for different parametric values of $A$ and $f$ which fit SNe Ia data, have been combined together. The plot shows that $H_0 t_0 = 1$ line lies within the two lines $\Omega_m = 0.24$ and $\Omega_m = 0.26$, which are calculated taking $z_{eq} = 3300$. Thus, the present model fits SNe Ia data, satisfies WMAP constraint on $z_{eq}$, demanding the correct amount of $\Omega_m$ required for structure formation and agrees with experimental constraint on $H_0 t_0 = 1$. 
6. The last data in table-2 shows that for $A = 22$ and $f = 0.0392$, the acceleration of the universe is yet to start. So, one can find other larger values of $A$, which fit SNe Ia data and also consistent with all presently available observational data without a late-time accelerated phase of the universe at all.

Thus, the cosmological evolution of the universe may be explained successfully in view of particle-creation phenomena from early time till date, single handedly, without taking into account dark energy at all, which may be resolved in future experiments. The work discussed in this chapter has been explored in paper-1.