Black Hole Cosmology in Gravity with Torsion

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We can see the Universe expanding: galaxies look redder as they speed away (just as sirens sound lower pitched).

The 2-dimensional surface of the balloon is an analog to our 3-dimensional space.

The 3-dimensional space in which the balloon expands is not analogous to any higher dimensional space. Points off the surface of the balloon are not in the Universe in this simple analogy.

The Universe may be finite or infinite.
Explains what happens in black holes: regions of space from where nothing can escape. Black holes form from most massive stars and at centers of galaxies.
Big Bang Theory:
• Is based on Einstein’s general theory of relativity (GR),
• Agrees with the observed amounts of the lightest elements in the Universe,
• Predicts the Cosmic Microwave Background (CMB) radiation.

CMB:
• Coming from all directions in the sky,
• Is a footprint left behind by the very early, hot Universe,
• It looks the same in all directions (horizon problem). Why?
• Universe is nearly flat (flatness problem). Why?

Physicists came up with cosmic inflation:
• The Universe rapidly (exponentially) expanded right after the Big Bang,
• It explains why the CMB temperature is almost constant in all directions,
• It predicts that this temperature slightly changes with the direction on the sky, which is consistent with observations. These variations are seeds for large scale structure of the Universe (galaxy clusters and voids).
Problems of general relativity

GR describes gravity as curvature of spacetime: Matter tells spacetime how to curve, spacetime tells matter how to move.

• Singularities: points with infinite density of matter. Unphysical.

• Incompatible with quantum mechanics (QM). We need quantum gravity. It may resolve the singularity problem.

• Field equations contain the conservation of orbital angular momentum, contradicting Dirac equation which gives the conservation of total angular momentum (orbital + spin) and allows spin-orbit exchange.

Simplest extension of GR to include QM spin: Einstein-Cartan theory (EC).

EC theory also resolves the singularity problem.
Problems of Big Bang cosmology & inflation

• Big Bang singularity.

• What caused the Big Bang? What existed before?

• What caused inflation? Inflation requires hypothetical types of matter that have not been observed and rely on models that must be adjusted to match existing observational data.

• Why did inflation end? (no eternal inflation)

EC replaces the singular Big Bang by a nonsingular Big Bounce, at which the Universe had a finite size. The dynamics immediately after the bounce explains the flatness/horizon problems. NP, PLB 694, 181 (2010).
Einstein-Cartan gravity

It takes into account that elementary particles possess an intrinsic angular momentum (spin) which does not represent rotation. Spin is predicted by relativistic QM.

Spin requires spacetime to have curvature and torsion.

Curvature – “bending” of spacetime by energy and momentum.
Torsion – “twisting” of spacetime by spin.

Twisting a thin rod is less apparent than bending. Effects of torsion are important only at extremely high densities (in black holes and in the very early Universe).

Torsion in Einstein-Cartan theory manifests itself as a repulsive force which opposes gravitational attraction and prevents singularities.
Black holes are wormholes

- Condensed matter in a black hole reaches an extremely high density, it stops, bounces, and rapidly expands into a new region of space.
- After the bounce the black hole becomes a doorway to a new, growing universe.
- Accordingly, our Universe may be the interior of a black hole existing in another universe: Black-Hole Cosmology (BHC).
- **BHC** explains inflation and agrees with the CMB observations.

- A child universe in a black hole is invisible for observers outside the black hole (which exists in a parent universe) because the black hole forms in infinite future for such observers.
- For observers in the child universe, the bridge looks like a white hole (the opposite of a black hole).

The motion of matter through a bridge is one-directional and can define the arrow of time.
Einstein-Cartan gravity

Spacetime has curvature and torsion.

- Cartan equations:
  Torsion is proportional to the spin density of fermions. EC in vacuum reduces to GR and passes all observational tests. It differs from GR at densities around $10^{45}$ kg/m$^3$ and higher.

  \[ S_{jik} - S_i g_{jk} + S_k g_{ji} = -\frac{1}{2} \kappa s_{ijk} \]

- Einstein equations:
  Curvature is proportional to the energy and momentum density.

  \[ G^{ik} = \kappa T^{ik} + \frac{1}{2} \kappa^2 \left( s^{ij} s_{kl} - s^{ij} s_{kl} - s^{jli} s_{kl} + \frac{1}{2} s^{jli} s_{jkl} + \frac{1}{4} g^{ik} (2 s_{jlm} s^{jm} - 2 s_{jlm} s^{jm} + s^{jlm} s_{jlm}) \right) \]
Universe with spin fluid

Dirac particles can be averagedmacroscopically as a spin fluid.

\[ s^{\mu \nu \rho} = s^{\mu \nu} u^\rho \quad s^{\mu \nu} u_\nu = 0 \quad s^2 = s^{\mu \nu} s_{\mu \nu} / 2 \]

Einstein-Cartan equations for a closed, homogeneous, and isotropic Universe become Friedman equations.

\[
\begin{align*}
\dot{a}^2 + 1 &= \frac{1}{3} \kappa \left( \epsilon - \frac{1}{4} \kappa s^2 \right) a^2, \\
\dot{a}^2 + 2a \ddot{a} + 1 &= -\kappa \left( p - \frac{1}{4} \kappa s^2 \right) a^2
\end{align*}
\]

Spin and torsion modify the energy density with a negative term proportional to the square of the fermion number density, which acts like repulsive gravity and prevents the scale factor from reaching zero. The Big Bang singularity is avoided.
Universe with spin fluid

For relativistic matter, Friedman equations can be written in terms of temperature.

\[ \frac{\dot{a}^2}{c^2} + k = \frac{1}{3} \kappa \tilde{e} a^2 = \frac{1}{3} \kappa \left( h \star T^4 - \alpha h_{nf}^2 T^6 \right) a^2, \]

\[ \frac{\dot{a}}{a} + \frac{\dot{T}}{T} = \frac{cK}{3h_{n1} T^3}, \]

2\textsuperscript{nd} Friedman equation is rewritten as 1\textsuperscript{st} law of thermodynamics for constant entropy. Parker-Starobinskii-Zel’dovich particle production rate $K$, proportional to the square of curvature, produces entropy in the Universe. No reheating needed.

Generating inflation with only 1 parameter

Near a bounce:

\[
\frac{\dot{a}}{a} \left[ 1 - \frac{3\beta}{c^3 h_n T^3 \left( \frac{a}{T} \right)^3} \right] = -\frac{\dot{T}}{T}
\]

To avoid eternal inflation:

\[\beta < \beta_{cr} = \frac{\sqrt{6}}{32} \frac{h_n h_{nf}^3 (hc)^3}{h_*^3} \approx \frac{1}{929}\]

During an expansion phase, near critical value of particle production coefficient \(\beta\):

\[
\frac{\dot{a}}{a} \approx \frac{c\beta (\kappa \tilde{\epsilon})^2}{3 h_n T^3} \approx c \left( \frac{1}{3} \kappa \tilde{\epsilon} \right)^{1/2}
\]

\[
\tilde{\epsilon} \approx \frac{h_*^3}{8 \alpha^2 h_{nf}^4}
\]

Exponential expansion lasts about \(\tau\) then \(T\) decreases.

Torsion becomes weak and radiation dominated era begins.
No hypothetical fields needed.
• The temperature at a bounce depends on the number of elementary particles and the Planck temperature.

• Numerical integration of the equations shows that the numbers of bounces and e-folds depend on the particle production coefficient but are not too sensitive to the initial scale factor.
Dynamics of the early Universe

$\beta/\beta_{cr} = 0.9998$
Universe does not have enough energy to expand for forever so it begins collapsing.

Black hole forms and begins collapsing.

This is a bounce where torsion temporarily repels stronger than gravity attracts.

Particle production occurs near this point.
If quantum effects in the gravitational field near a bounce produce enough matter, then the closed Universe can reach a size at which dark energy becomes dominant and expands to infinity.

Otherwise, the Universe contracts to another bounce (with larger scale factor) at which it produces more matter, and expands again.
How to test that every black hole is a doorway to another universe?

To boldly go where no one has gone before.

Torsion predicts that elementary particles are spatially extended \((10^{-27} \text{ m})\) which may be observed one day. *NP, PLB 690, 73 (2010).*

BHC with torsion is consistent with observations of CMB.
It is possible to find a scalar field potential which generates a given time dependence of the scale factor, and calculate the parameters which are being measured in CMB.

Consistent with Planck 2015 data.

S. Desai & NP, PLB 755, 183 (2016)
Black holes (regions of space from where nothing can escape) form from massive stars that collapse because of their gravity.

The Universe is expanding, like the 3-dimensional analogue of the 2-dimensional surface of a growing balloon.

Problem. According to general theory of relativity, the matter in a black hole collapses to a point of infinite density (singularity). The Universe also started from a point (Big Bang). But infinities are unphysical.

Solution: Einstein-Cartan theory. Adding quantum-mechanical angular momentum (spin) of elementary particles generates a repulsive force (torsion) at extremely high densities which opposes gravitational attraction and prevents singularities.

We argue that the matter in a black hole collapses to an extremely high but finite density, bounces, and expands into a new space (it cannot go back).

Every black hole, because of torsion, becomes a wormhole (Einstein-Rosen bridge) to a new universe on the other side of its boundary (event horizon).

If this scenario is correct then we would expect that:

- Such a universe never contracts to a point.
- This universe may undergo multiple bounces between which it expands and contracts.

Our Universe may thus have been formed in a black hole existing in another universe. The last bounce would be the Big Bang (Big Bounce). We would then expect that:

- The scalar spectral index ($n_s$) obtained from mathematical analysis of our hypothesis is consistent with the observed value $n_s = 0.965 \pm 0.006$
- Obtained the Cosmic Microwave Background (CMB) data.

RESULTS

Fig. 1. Sample scale factor $a(t)$. Several bounces, at which $a$ is minimum but always $>0$, may occur.

Fig. 2. The simulated values of $n_s$ in our model are consistent with the observed CMB value $n_s$ for a small range of $\beta$ and a wide range of $a_0(m)$.

METHOD

To evaluate our expectations:

1. We wrote a code in Fortran programming language to solve the equations which describe the dynamics of the closed universe in a black hole (NP, arXiv:1410.3881) and then graph the solutions. These equations give the size (scale factor) $a$ and temperature $T$ of the universe as functions of time $t$ (see Fig. 1).

$$\frac{d^2 a}{dt^2} + 1 = \frac{1}{3} \alpha a^2, \quad \epsilon = \hbar cT^3 - \alpha h_0^2 T^6$$

$$\frac{\dot{a}}{a} \frac{d}{dt} = \frac{\epsilon K}{2a_0^3 T^3} - K = \beta(\infty)^2$$

2. From the obtained graphs we found the values of the scalar spectral index $n_s$ and compared them with the observed CMB value (see Fig. 2).

CONCLUSIONS

- The dynamics of the early universe formed in a black hole depends on the quantum-gravitational particle production rate $\beta$, but is not too sensitive to the initial scale factor $a_0$.
- Inflation (exponential expansion) can be caused by particle production with torsion if $\beta$ is near some critical value $\beta_{cr}$.
- Our results for $n_s$ are consistent with the 2015 CMB data, supporting our assertion that our Universe may have been formed in a black hole.

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