The ‘alarming’ phenomenon of particle creation in the early universe

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della Fisica
An early particle cosmologist

In mid-1930s, influenced by Eddington & Lemaitre, Schrödinger turned to cosmological issues.

1938-1939: Graz ➔ Vatican ➔ Gent, Belgium ➔ Dublin
The proper vibrations of the expanding universe

Erwin Schrödinger, *Physica* 6, 899 (1939)

**Introduction:**
“… proper vibrations [positive and negative frequencies] cannot be rigorously separated in the expanding universe. … this is a phenomenon of outstanding importance. With particles it would mean production or annihilation of matter, merely by expansion,… Alarmed by these prospects, I have examined the matter in more detail.”

**Conclusion:**
“… There will be a mutual adulteration of positive and negative frequency terms in the course of time, giving rise to … the ‘alarming phenomenon’…”
The proper vibrations of the expanding universe

Erwin Schrödinger, *Physica* 6, 899 (1939)

Creation of a **single** pair of particles per Hubble volume per Hubble time with “Hubble energy”

\[
H \approx 60 \text{ km s}^{-1}\text{Mpc}^{-1}
\]

\[
V_H \equiv \left( \frac{c}{H} \right)^3 \approx 10^{12} \text{Mpc}^3
\]

\[
t_H \equiv H^{-1} \approx 10^{10} \text{ years}
\]

\[
E_H \equiv \hbar H \approx 10^{-33} \text{ eV}
\]

Alarming?
“When the storms rage around us, and the state is threatened by shipwreck, we can do nothing more noble than to lower the anchor of our peaceful studies in the ground of eternity.” - J. Kepler

1600-1630: Graz ➔ Prague ➔ Linz ➔ Sagan ➔ Ratisbon
“When the storms rage around us, and the state is threatened by shipwreck, we can do nothing more noble than to lower the anchor of our peaceful studies . . .
Disturbing the vacuum

Strong gravitational field → particle production

(Hawking radiation)

Black Hole
The seeds of structure were planted by the Alarming Phenomenon.
Simulation (sīməˈleɪʃən). ME. [a. OF., ad. L. simulationem.] 1. The action or practice of simulating, with intent to deceive; false pretence, deceitful profession ME.
Primordial perturbations

CBR: a snapshot of the universe 380,000 AB correlations on scales \( \gg 380,000 \) light years

Sachs-Wolfe
More than 380,000 light years in less than 380,000 years?

- $v \leq c$ for velocity through space
- no limit on expansion velocity of space
- “acausal” requires “accelerated” expansion

$\text{SPEED LIMIT}$

$\text{v} \leq \text{c}$
Newton Einstein $\ddot{a} \propto -G (\rho + 3p)$

$H \equiv \frac{\dot{a}}{a}$

normal
$\ddot{a} < 0$
$\rho + 3p > 0$

accelerated
$\ddot{a} > 0$
$\rho + 3p < 0$

vacuum energy?
<table>
<thead>
<tr>
<th>expansion tempo</th>
<th>movement</th>
<th>epoch</th>
<th>relic</th>
</tr>
</thead>
<tbody>
<tr>
<td>pizzicato</td>
<td>string dominated $H \approx ???$</td>
<td>$10^{-43}$ sec.?</td>
<td>???</td>
</tr>
<tr>
<td>presto</td>
<td>vacuum dominated (inflation) $H \approx \text{const}$</td>
<td>$10^{-35}$ sec.?</td>
<td>CBR fluctuations, gravitational waves, seeds of structure</td>
</tr>
<tr>
<td>allegro</td>
<td>radiation dominated $H \approx a^{-2}$</td>
<td>earlier than 10,000 yrs.</td>
<td>abundance of the light elements</td>
</tr>
<tr>
<td>andante</td>
<td>matter dominated $H \approx a^{-3/2}$</td>
<td>later than 10,000 yrs.</td>
<td>distant quasars and galaxies</td>
</tr>
<tr>
<td>largo</td>
<td>vacuum dominated (inflation) $H \approx \text{const}$</td>
<td>day before yesterday</td>
<td>acceleration of the universe</td>
</tr>
</tbody>
</table>
Potential energy: energy of infinite-wavelength mode
Particle content: condensate of infinite-wavelength particles

Classical equations of motion

\[ V(\phi) \neq 0 \quad \rightarrow \quad V(\phi) = 0 \]
Particle creation: finite-wavelength modes

$\phi$ not smooth

$V(\phi)$

Quantum fluctuations

$\delta \phi \rightarrow \delta \rho \rightarrow \delta T$
The alarming phenomenon

Einstein gravity \[ S = \int d^4 x \sqrt{-g} \left[ -\frac{M_{Pl}^2}{16\pi} R + \frac{1}{2} (\partial \phi)^2 - V(\phi) \right] \]

Inflaton field

\[ g_{\mu \nu}(\vec{x},t) = g^{FRW}_{\mu \nu}(t) + \delta g_{\mu \nu}(\vec{x},t) \]

\[ \phi(\vec{x},t) = \phi_0(t) + \delta \phi(\vec{x},t) \]

Tensor perturbations (gravitational waves) \[ \nu(\delta g_{ij}) \]

in terms of \[ \nu \propto \text{gravitons} \]

\[ S = \int d^4 x \left( \partial_\mu \nu \partial^\mu \nu - \frac{1}{2} m_\nu^2 \nu^2 \right) \]

Minkowski space (conformal time)

\[ m_\nu^2 \] changes because of expansion
all structures in the universe arise from "Schrödinger’s alarming phenomenon"
A pattern of vacuum quantum fluctuations (the alarming phenomenon)
Origin of structure: a complex natural phenomenon

Perturbations from inflation: a simple, elegant, compelling explanation

“For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation.”

- Tommy Gold
Who is the inflaton?
Top down
(superstring inspired)

Bottom up
(phenomenology perspired)

inspired: as if prompted by or emanating from a supernatural source.

(Oxford English Dictionary)
Inflation phenomenology

Inflaton Potential

seeds of structure
(creation of inflaton quanta)
gravitational waves
(creation of graviton quanta)
Imprint of the Alarming Phenomenon

Big Bang plus 10^{-35} seconds

Inflation

Big Bang plus 380,000 Years

Seeds of Structure + Gravitational Waves

Big Bang plus 14 Billion Years
Angular power spectrum

\[ \delta T(\theta_1, \phi_1) \quad \delta T(\theta_2, \phi_2) \]

\[ \delta T(\theta, \phi) = \sum a_{lm} Y_{lm}(\theta, \phi) \]

\[ C_l \equiv \left\langle |a_{lm}|^2 \right\rangle \]
Angular power spectrum

Angular Scale [Degrees]

- a simple inflation model

\[ [a(a+1)C_\ell / 2\pi]^{1/2} [\mu K] \]

MAP

expected precision

Ned Wright - 6 May 2001
Angular power spectrum

seeds of structure
gravitational waves
CMB polarization

Stebbins, Kosowsky, Kamionkowski

E modes

Seljak & Zaldarriaga

B modes

(gravitational waves)
CMB polarization

DASI makes a start: astro-ph/0209478

Kovac, Leitch, Pryke, Carlstrom, Halverson, Holzapfel
CMB polarization
LIGO → LISA → BBO

4 km arms

4 Mkm arms
Comparison to observation:

1. a (nearly exact) power-law
2. spectrum of gaussian
3. super-Hubble-radius
4. scalar perturbations (seeds of structure) &
5. tensor perturbations (gravitational waves)
6. related by a consistency relation
7. in their growing mode
8. in a spatially flat universe.
Dark matter

another alarming phenomenon?
M33 rotation curve

- observed
- expected from luminous disk

- galaxy & cluster dynamics
- gravitational lensing
- structure formation
- CMB observations
\[ \Omega_i \equiv \frac{\rho_i}{\rho_{\text{CRITICAL}}} \]
\[ \Omega_{\text{TOTAL}} = 1 \]

**Cosmic Pie**

- **Heavy Elements:**
  \[ \Omega = 0.0003 \]

- **Cold Dark Matter:**
  \[ \Omega = 0.25 \]

- **Dark Energy (Λ):**
  \[ \Omega = 0.70 \]

- **Neutrinos (ν):**
  \[ \Omega = 0.0047 \]

- **Stars:**
  \[ \Omega = 0.005 \]

- **Free H & He:**
  \[ \Omega = 0.04 \]

**ACDM**
Cosmo-illogical constant

Mass density of space:

$$\rho \approx 10^{-30} \text{ g cm}^{-3}$$

The unbearable lightness of nothing!
Dark energy depression?

1. Alcohol*
2. Drugs*
3. Anthropic principle*
4. Creative theories
5. Hard experimental work
6. Observational direction

* Therapy, medication, and twelve-step programs available.
We’re almost free, I just felt the first drops of rain
Dark matter candidates

• Modified Newtonian dynamics?
• Planets?
• Mass disadvantaged stars?
  brown  red  white
• Black holes?
• Dark baryons?
• Nonbaryonic particle dark matter?
Cold thermal relics

\[ \Omega_X \propto \sigma_A^{-1} \quad \text{(independent of mass)} \]
“For every complex natural phenomenon
There is a simple, .....
**Alarming phenomenon of particle creation**

(Arnowit, Birrell, Bunch, Davies, Deser, Ford, Fulling, Grib, Hu, Kofman, Mostepanenko, Page, Parker, Starobinski, Unruh, Vilenkin, Wald, Zel’dovich, …)

**first application:**

- density perturbations from inflation
- gravitational waves from inflation

(Guth & Pi; Starobinski; Bardeen, Steinhardt, & Turner; Hawking; Rubakov; Fabbi & Pollack; Allen)

**new application:** dark matter

(Chung, Kolb, & Riotto; Kuzmin & Tkachev)

- require (super)heavy particle “X”
- stable (or at least long lived)
- initial inflationary era followed by radiation/matter
**Superheavy particles**

- Inflaton mass (in principle measurable from gravitational wave background, guess $10^{12}$ GeV) may signal a new mass scale in nature.

- Other particles may exist with mass comparable to the inflaton mass—natural to have $\Omega = 1$.

- Superheavy *DARK MATTER*!

- Abundance independent of interactions
  
  **undetectable?**
  
  **detectable?**
  
  • direct/bulk
  
  • UHE cosmic rays
  
  • annihilation

  -- galactic center, sun

  • other signals?
WIMPZILLAS!

TEXAS-SIZE DARK MATTER

SIZE DOES MATTER
The alarming phenomenon

- The “alarming phenomenon” may produce seeds of structure
  - astrophysical signatures of the quantum vacuum
- The “alarming phenomenon” may produce dark matter.
  - dark matter may be WIMPZILLAS!
  - WIMPZILLAS may be undetectable!
  - but then again, they may be detectable!
Inner space / Outer space

http://home.fnal.gov/~rocky/texas.pdf