Baryogenesis and the New Cosmology

Mark Trodden
Syracuse University

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What's it All About?

Matter Vs Antimatter
A Classic Particle Cosmology Problem

- Wherever you look you see matter and not antimatter.
- Particle physics teaches us matter and antimatter are the same.
- Cosmology teaches us they must exist in equal abundances in the early universe.
- What happened between then and now?
- Baryogenesis!
Quantifying the Asymmetry

- Remarkable region of concordance.
- Possible for a single value of $\eta \sim 10^{-10}$.
- A major test of the Big Bang theory ...
- ... and our earliest direct cosmological data.
Outline

- A reminder to get us all on the same page.
- A quick status summary of a popular mechanism - electroweak baryogenesis.
- A plea for cosmological economy.
- Quintessential Baryogenesis.
- I'll just sketch the main ideas here - please come to discuss the details with me later.

"Quintessential Baryogenesis", Antonio De Felice, Salah Nasri & M.T.
hep-ph/0207211

(See also parallel session talk by Xinmin Zhang)
What’s a Particle Theory to do?

- Sakharov (1968):
  - Violate Baryon number (B) symmetry
  - Violate the Charge conjugation and Charge-Parity symmetries (C & CP)
  - Depart from thermal equilibrium (because of the CPT theorem!!! More about this later.)
  - There are LOTS of ways to do this!
Also an Important Clue for Particle Physics

• The Standard Model of particle physics, even though in principle it satisfies all 3 Sakharov criteria, (anomaly, CKM matrix, finite-temperature phase transition) cannot be sufficient to explain the baryon asymmetry!

• This is a clear indication, from observations of the universe, of physics beyond the standard model!
So What’s Viable?

- Electroweak-like baryogenesis models using 2-higgs, SUSY, ...
- Affleck-Dine models - inflation driven
- GUT baryogenesis
- Baryogenesis through preheating after inflation (high and low scale)
- Baryogenesis through leptogenesis
- And many more ...
Electroweak Baryogenesis I

\[ V[A,\phi] \]

Sphaleron

\[ V_{\text{eff}}[\phi] \]

T>T_c

T=T_c

T=0

False Vacuum: Unbroken Phase
\( \Gamma > 0 \)

True Vacuum: Broken Phase
\( \Gamma = 0 \)

- 1_o

- 1_o

\[ \delta \]
Electroweak Baryogenesis II

• Requires more CP violation than in SM
• (Usually) requires a (sufficiently strong) 1st order thermal EW phase transition in the early universe.
• Our most popular model of recent years

• Popularity of this idea is tightly bound to its testability.
• Physics involved is all testable in principle at realistic colliders.
• Small extensions needed can all be found in SUSY, which is an independently attractive
• However, the testability of electroweak scenarios also leads to tight constraints.
Bounds and Tests

- Exists only a small window of parameter space in extensions of the electroweak theory in which baryogenesis is viable.
- Because electroweak baryogenesis requires a strong enough first order phase transition.
- Severe upper bound on lightest Higgs boson mass, $m_h < 120$ GeV (in the MSSM).
- Stop mass may be close to experimental bound and must be < top quark mass.

(See Carena, Quiros, Seco and Wagner, hep-ph/0208043)
Direct Tests

- Search for the lightest Higgs at Tevatron or LHC.
- Search for the lightest stop at the Tevatron or LHC.
- Crucial test may come from B-physics - CP-violating effects (but not guaranteed at B factories)
- Essential to have new measurements of CP-violation, particularly in the B-sector
Testable Alternatives

• Might hope that Affleck-Dine occurs at low enough energies - new particles
  (Dine, Randall & Thomas)

• BUT low scale inflation is very hard to make work

• Leptogenesis hard to test if have heavy right-handed neutrinos (Low-scale versions might help)
What Might We Hope For?

- EWBG is so great because it is testable and uses physics that is already there for a good particle physics reason.
- If EWBG is successful, it is a triumph of the particle physics/cosmology union.
- If EWBG is unsuccessful, our primary attention should be focused on models with the same properties.
A Plea for Cosmological Economy

- Despite indicators to the contrary (none discovered in nature to date)
- Cosmology continues to experience a robust period of growth in the scalar field sector

- Possible that this scalar field bubble may burst
- At the very least we may consider limiting our exposure in this sector.
- ...and do our best to avoid accounting scandals.
There is a considerable amount of data in agreement with predictions of a wide class of inflationary models.

Data also seems to point to a dominant dark energy component in the universe.

Maybe they are due to the same field!
Quintessential Inflation II

- One field drives inflation
- Much later, it then drives quintessence

- In interim, universe is kinetic energy dominated
  → radiation-dominated → matter-dominated
- Matter creation not through reheating but through particle creation during transition from inflation to “kination”.

\[ V(\phi) \]

\[ \phi \]
Quintessential Baryogenesis

(De Felice, Nasri & MT; see also Li, Wang, Feng & Zhang)

- When I told you about the departure from equilibrium I omitted a loophole. (Nice review in Dolgov)
- If CPT is broken - asymmetry can be generated in equilibrium!
  - Can't break CPT explicitly
  - But if broken *spontaneously*, can generate a baryon asymmetry.

Might the Quintessential Inflation field play this role?
What is Required?

Terms in effective Lagrangian of form

\[
L_{\text{eff}} = \frac{\lambda'}{M^2} \partial_\mu \phi J^\mu
\]

\(J^\mu: \text{current} \leftrightarrow \text{some global symmetry (e.g. B or B-L)}\)

Since \(\phi\) homogeneous can write

\[
L_{\text{eff}} = \frac{\lambda'}{M^2} \dot{\phi} \Delta n \equiv \mu(t) \Delta n
\]

A time-dependent “chemical potential” for (e.g.) baryon number

What net baryon number does this yield?
Calculating the Asymmetry

\[
\Delta n(T;\mu) = \int \frac{d^3\vec{p}}{(2\pi)^3} \left[ f(E,\mu) - f(E,-\mu) \right]
\]

\[
\Delta n(T) \sim \frac{\lambda' g}{6M} T^2 \dot{\phi}
\]

Number density at nonzero chemical potl.

So

- Divide by entropy density
- Note that baryon number violating processes “freeze out” at temperature \( T_F \)
- Resulting baryon to entropy ratio is

\[
\eta_F \equiv \eta(T_F) \equiv \frac{\Delta n}{s}(T_F) \sim 0.38 \lambda' \left( \frac{g}{g^*} \right) \frac{\dot{\phi}(T_F)}{M T_f}
\]

(This is all standard spontaneous baryogenesis)
Calculating $T_F$

This is where the details of quintessential inflation are crucial. Answer depends on:

- The potential $V(\phi)$ (but not really a free parameter - constrained through cosmology)
- The source of baryon number violation
- The evolution of the universe before and at $T_F$

- Important to take into account that universe could be kinetic-energy dominated down to below $T_F$ (Joyce; Joyce & Prokopec)
- Affects not only the asymmetry produced, but how much it may be diluted by anomalous electroweak processes.
Constraints and Tests

• If our current is that for baryon number, then

\[
L_{\text{eff}} = -\frac{\lambda'}{M} \phi n_f \left( \frac{g^2}{32\pi^2} \tilde{W}_{a\mu\nu} \tilde{W}^{a\mu\nu} - \frac{g'^2}{32\pi^2} B_{\mu\nu} \tilde{B}^{\mu\nu} \right)
\]

• Electromagnetic part → rotation of polarized light from radio sources

⇒ \[ \lambda' \frac{M_P}{M} < 8 \]

In Peebles-Vilenkin model

Consistent with quintessential baryogenesis!

(See Carroll, PRL 81, 3067 (1998), astro-ph/9806099)
Conclusions I

- There are many models out there that have a chance to explain the asymmetry.
- *We should focus on those that are consequences of other physics.*
- Upcoming collider experiments will test some of our favorite models.
Conclusions II

- Have demonstrated how a single scalar field can be responsible for:
  - Inflation
  - Baryogenesis
  - Dark energy

- Model may be testable if the scales and couplings are of the right size
- An attempt to understand how independently-motivated models may explain other cosmological phenomena

-Thank You -