Axions and Gauge Mediation

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Outline

1. Axions: Virtues, Warts, Cosmology
2. PQ Symmetry Broken In String Theory/Higher Dimensions
3. PQ Breaking Within the Effective Field Theory

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Setting: The Strong CP Problem and Proposed Solutions

1. $m_u = 0$ Simple. Could result as an accident of discrete flavor symmetries (Banks, Nir, Seiberg), or a result of “anomalous" discrete symmetries as in string theory.
2. CP exact microscopically, $\theta = 0$; spontaneous breaking leads only to small effective θ (Nelson, Barr). In critical string theories, CP is an exact (gauge) symmetry, spontaneously broken at generic points in typical moduli spaces. A plausible framework.
3. Axions: global, anomalous symmetry. Axion adjusts to yield $\theta \approx 0$. String theory answers question of why one should have an extremely good (but approximate) global symmetry: Peccei-Quinn symmetries which hold to all orders of perturbation theory.

Problems with each of these solutions:

1. $m_u = 0$. Lattice computations seem to rule out.$^{*}*$
2. Spontaneous CP: need to consider fixing of moduli. Flux vacua as a model: 10^{500}, say, arising from turning on many different fluxes. But only half of fluxes, typically, invariant under CP: $10^{500} \rightarrow 10^{250}$. So only a tiny fraction of states. Not clear that these are otherwise singled out in an interesting way (e.g. cosmologically, anthropically).
3. Axions: In string theory, not clear, when moduli are fixed, why axions should survive to low energies.

Focus on axions, in various settings, mainly, today, gauge mediation. But first explore more generally.

1. String Theory (PQ spontaneously broken in higher dimensions and/or by stringy effects)
2. Effective Field Theory

and within these categories:

1. No low energy supersymmetry
2. Supersymmetry, intermediate scale breaking (“gravity mediation")
3. Supersymmetry, low scale breaking (*gauge mediation*)

Two puzzles with axions

1. Astrophysics, cosmology seem to constrain the axion decay constant to a rather narrow range. If axion is to be dark matter, expect $f_a \sim 10^{12}$ GeV. Why this number?
2. PQ symmetry a global symmetry, presumably an accident [Glashow et al; Kamionkowski, March-Russell]. Needs to be a very good symmetry if to solve strong CP.

$$V_{qcd} \approx -m_\pi^2 f_\pi^2 \cos(\frac{a}{f_a}).$$

Requirements of the Global Symmetry

Natural value of axion potential:

$$V_a = f_a^4 \cos(\frac{a}{f_a} - \theta_0)$$

so if axion to solve strong CP problem, need suppression by 62 orders of magnitude! In terms of Planck suppressed ops, $(f_a/M_p)^n$, $n > 10$, for $f_a = 10^{12}$; $n > 16$ for $f_a = 10^{15}$ Why should there be a PQ symmetry at all, and why such a good symmetry?

Accounting for A Very Good Global Symmetry

1. String theory/higher dimensions: PQ symmetry accidental consequence of two form gauge invariance of the theory, or of discrete (presumably gauge) symmetries of string theory (e.g. subgroup of $SL(2,Z)$). A good symmetry of perturbation theory. So breaking could be exponentially small in some parameter, $\epsilon = e^{-8\pi^2/g^2}$. E.g. KKLT scenario: fluxes lead to a small number, but all moduli fixed *at scales well above susy breaking scale*. No light axions. Perhaps axions in a small subset of states, but why are these special?
2. If PQ breaking at low energies, discrete symmetries might explain (e.g. Z_N, with N quite large). Doesn't sound particularly generic (Z_{12}, Z_{24}), unless correlated with other phenomena.

Axion as Dark Matter

Axions have long been considered a plausible dark matter candidate. Produced coherently in the early universe, by misalignment (I'll assume that the reheat temperature after inflation is below f_a). The energy density of axions is proportional to the square of the misalignment angle, θ_0.

$$\Omega_a h^2 \approx 0.15\theta_0^2 \left(\frac{f_a}{10^{12}}\right)^{7/6}.$$

This gives an upper bound on f_a, if $\theta_0 \sim 1$, of order 10^{12}. If the bound is saturated, the dark matter is accounted for. There is a lower bound coming from astrophysics (esp. supernova 1987a, globular clusters) of about 10^9 GeV.

Relaxing the Bound

Three possibilities:

1. Late decays of particles (e.g. moduli in string theory) can allow f_a up to $10^{14} - 10^{15}$ (Dine,Fischler; Turner; Banks, Dine).
2. Small θ_0 relaxes the bound. Note that if the PQ transition occurs after inflation, different regions have different θ_0. So we could just be (un)lucky (Dine, Fischler).
3. As above, but perhaps anthropic considerations select for small θ_0 (Linde; Aguirre, Reiss, Tegmark, Wilczek). No definitive conclusion, but plausible that hospitable universes lie in a narrow range of Ω_a. Note the assumption of inflation means that, *if there is some peaking in the distribution*, some selection is inevitable.

Having introduced in a rather non-controversial way, anthropic selection for θ_0, it is tempting to consider anthropic selection for

1. The existence of axions
2. Other parameters, such as f_a.

The first point requires that, in some theoretical framework, axions be a particularly "generic" type of dark matter. In the second, in an underlying landscape, one might expect that f_a varies. This might be interesting if requiring an axion to be the dark matter simultaneously explains the smallness of the observed θ.

Axion as Accidental Dark Matter

How light does axion have to be? Our basic requirement is that the axion not dominate the energy density for temperatures above about 1 eV. If the Peccei-Quinn symmetry is violated by some higher dimension operator, scaled by M_p, such as

$$\delta = \frac{1}{M_p^n} \phi^{n+4}$$

Then the axion mass is:

$$m_a^2 = f_a^2 \left(\frac{f_a}{M_p} \right)^n$$

On the other hand, the initial axion energy density is of order $f_a^2/M_p^2 = 10^{-12}\left(\frac{f_a}{10^{12}}\right)^2$. So we require:

$$10^{27}\left(\frac{f_a}{M_p}\right)^{\frac{n+10}{4}} < 1$$

For $f_a = 10^{12}$, this indeed requires $n > 8$, but the requirement of small enough θ means $n > 10$.
It is hard to assess the relative likelihood of these two cases; e.g. if due to discrete symmetry, a large discrete symmetry in each case, but one might worry that a larger symmetry is exponentially less likely.

Interestingly, for larger f_a there is a crossover; the requirement of dark matter insures small enough θ for $f_a \sim 10^{14}$. However, the required n's are huge, more than 20!
In string theory, within our present, limited understanding, the problem looks different.

The θ Problem in String Theory

Issues:

1. Mechanism which fixes moduli must leave one Peccei-Quinn symmetry nearly exact. Not clear that this is generic.
   Simplest version of KKLT scenario: all moduli fixed at high scales. Lightest is Kahler modulus: $W = W_0 + e^{-\rho}$, $W_0 > m_{3/2}$. Multiple Kahler moduli? Perhaps some don't appear in superpotential, or appear suppressed by $e^{-n\rho}$. (If, e.g., $e^{-\rho} = m_{3/2}^2/M_p^2$, need $n \geq 3$). Not clear whether such a phenomenon is generic; what might select for it. Perhaps dark matter?.
2. Moduli problem: saxion mass must be 30 TeV or so if to decay before nucleosynthesis (Banks, Kaplan, Nelson).

String Theory: A picture without supersymmetry

E.g. suppose that there is a small parameter, $e^{\frac{-8\pi^2}{g^2}} = \epsilon$.
First, suppose no susy. If ϵ is the strength of PQ breaking, and if $f_a = 10^{15}$, need

$$\epsilon = 10^{-74}$$

to account for θ.
This is *weaker* than the condition to account for dark matter!

String Theory With Supersymmetry

If supersymmetry is broken at low energies, there is another small parameter. Take $\epsilon = m_{3/2}^2/M_p^2$. Need ϵ^3 suppression to account for dark matter. Again, this is enough to explain θ_{qcd}. Alternatively, there might be some other small quantity, $\epsilon' \ll \epsilon$.

Field Theory Models Without Supersymmetry

Before turning to gauge mediation, we consider non-supersymmetric and intermediate supersymmetric cases. Can now pose the following question. As Aguirre et al argue, initial value of θ_0 might be selected so as to account for a large f_a. In a non-supersymmetric theory, we would expect small f_a very fine tuned; $\theta_0 < 10^{-3}$ far less so (e.g. if f_a selected from a landscape of possibilities, small θ_0 would seem far more probable).

Dynamical Breaking of PQ Symmetry

Different if f_a dynamical. E.g. $SU(N)$ theory,
$Q = (N, 5)$ $\overline{Q} = (\overline{N}, \overline{5})$, $q = (N, 1)$, $\overline{q} = (\overline{N}, 1)$.
Then

$$\langle \bar{Q} Q \rangle \approx \Lambda^3 \quad \langle \bar{q} q \rangle \approx \Lambda^3$$

break a PQ symmetry with QCD anomaly; $f_a \approx \Lambda$.
$\Lambda = M_p e^{\frac{-8\pi^2}{b_0 g^2}}$; if g^2 uniformly distributed, small f_a is favored over small θ_0.
A "naturalness" argument that axions might be observable in cavity experiments.

In this dynamical context, a smaller discrete symmetry might account for the quality of the PQ symmetry. If $f_a = 10^{12}$, ops like

$$\delta\mathcal{L} = \frac{(\bar{q}q)^n}{M_p^{3n-2}}$$

explicitly break the PQ symmetry. Need $n > 3$. Dark matter requires only $n = 3$. Perhaps (un) lucky.

Intermediate scale SUSY breaking

Such a structure would seem natural in string theory, but one might expect a large f_a.
One might hope that the axion would emerge from the hidden sector dynamics, tieing f_a to the scale of supersymmetry breaking. In that case, the axion need not lie in an identifiable supermultiplet. E.g. there need be no saxion, axino. The problem, however, is that in this case, there will be fields charged under the standard model (responsible for the PQ anomaly), with masses of order f_{PQ}. As a result, the sparticles of the MSSM fields will be very massive.

Alternative: axion couples only through Planck (or other large scale) suppressed operators to the hidden sector. Then necessarily part of a supermultiplet, $\mathcal{A}$. The scalar field, the saxion, in this multiplet is necessarily a (pseudo) modulus. If it has a TeV scale mass, it is cosmologically problematic (Banks, Kaplan, Nelson). At about 30 Tev, it decades before nucleosynthesis. The situation is somewhat better if the relevant scale is lower (e.g. M_{gut}). It is necessary to produce the baryon asymmetry in these decays.
The problem of higher dimension operators is *slightly* ameliorated by supersymmetry.

Low Scale Supersymmetry Breaking (Gauge Mediation)

Calling f the underlying scale of supersymmetry breaking, roughly $10^5\mathrm{GeV} < f < 10^9\mathrm{GeV}$.
Suppose that the saxion couples to the messengers/susy breaking sector through Planck or Gut suppressed operators.
Even in the latter case, and for $f = 10^9$, $m_s \sim 1GeV$. Its lifetime is of order

$$\Gamma \approx \frac{m_s^3}{M^2} \approx 10^{-32}$$

long after nucleosynthesis. Even if f_a is 10^{12}, lifetime is too long.
Perhaps there is a solution, but seems even more contrived (tuned) than the heavy modulus in the intermediate scale case.
Suggests that $\mathcal{A}$ should couple directly to Messengers.

A simple model with unbroken supersymmetry:

χ neutral under PQ, $S_\pm$ charges ± 1.

$$W = \chi(S_+S_- - \mu^2) + S_+q\bar{q} + S_-\ell\bar{\ell}$$

Write $S_\pm = \mu exp(\pm\mathcal{A}/\mu)$. $\mathcal{A}$ is a modulus; it's real part determines f_a. The imaginary part is the axion.

Adding supersymmetry breaking

SUSY breaking can fix $\mathcal{A}$. E.g. consider adding a field X, with couplings (Shih) which lead to a non-zero $F_x = f^2$, $\langle x \rangle$.
Couple $S_\pm$, X to some fields $a_i, \tilde{a}_i, b_i, \tilde{b}_i$ (neutral under SM for the moment)

$$X(a_1\tilde{a}_1 + a_2\tilde{a}_2 + b_1\tilde{b}_1 + b_2\tilde{b}_2) + hS_+a_1\tilde{a}_2 + yS_-b_1\tilde{b}_2$$

For a range of parameters, one finds a minimum of the saxion potential. (Expect since for large $S_\pm$, the potential grows logarithmically).
Now add messengers (weakly coupled to X, S:

$$X(q_1\bar{q}_1 + \ell_1\bar{\ell}_1) + S_+q_2\bar{q}_2 + S_-\ell_2\bar{\ell}_1$$

Definitely won't win beauty contest

Currently exploring a variety of models. Hope is to find a model where the hierarchy between the susy breaking scale and f_a arises as a result of the slowly varying potential on the pseudomoduli space. E.g.

1. Stabilized in a hierarchical fashion through corrections to the Kahler potential, as in Witten's "inverted hierarchy".
2. Stabilized by higher dimension terms in the potential.

We have several examples of these phenomena, but not particularly simple or pretty.

Cosmology and the scales f and f_a

x represents the scale of R symmetry breaking; in order that one obtains suitable gaugino masses, we require $x \sim f$.
Claim: $f_a \sim x$.
Issue is mass of saxion. Suppose, e.g., $f \sim 10^5$ GeV. Then saxion mass of order

$$m_s^2 = \text{loop factor} \times \frac{f^4}{f_a^2} \sim 10^{-4}\text{GeV}^2$$

Saxion lifetime is

$$\Gamma = \frac{1}{4\pi}\frac{\alpha_s}{4\pi}^2\frac{m_s^3}{f_a^2} \sim 10^{-35} GeV!$$

So need, instead, $f \sim 10^{8.5}$ if to decay before nucleosynthesis.

$$m_s \sim 10^4\text{GeV} \quad \Gamma \sim 10^{-17},$$

well before nucleosythensis.

So need susy breaking scale *high*. Messengers in gauge mediation than at scales comparable to f_a!
Natural that messengers are at f_a ($S_\pm$ couple to messengers).
R breaking scale (x) similar to f_a.
In other words, axions, in gauge mediation, point to a high scale for the underlying supersymmetry breaking!

Conclusions

A few “takeaway" lessons (at least for me):

1. Spontaneous CP not a likely solution of the strong CP problem.
2. Existence of a PQ symmetry, good enough to solve strong CP, *might* be correlated with the problem of dark matter
3. In non-supersymmetric theories, low f_a is natural if PQ breaking dynamical
4. In string theory, existence of axions likely also correlated with existence of a very small parameter (and, with dark matter)
5. If we discover evidence for gauge mediation, and if we are convinced that $m_u \neq 0$, then strong CP suggests rather high scales of susy breaking.

THE END