QUASARS, GALAXIES AND PSEUDO-VACUUM DROPLETS

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It is suggested that quasars and active galactic nuclei are small regions (droplets) of psuedo-vacuum, possibly containing matter, that decay into real vacuum and ordinary matter. In addition, the droplets may play a role in galaxy formation.

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The primary energy source of quasars remains as mysterious today as some thirty years ago when they were discovered [1]. Current opinion is that the energy is gravitational in origin and due to slow matter in-fall towards a supermassive black hole [2]. However, there is no simple and compelling explanation for the expulsive phenomena (*e.g.* jets) associated with some quasars and other active galactic nuclei [3]. In this paper we suggest an alternative explanation for the powerhouse of quasars and active galactic nuclei, which is associated with energy production and outflow rather than matter in-fall. According to the modern particle physics theory of the vacuum the energy densities and potential energies involved are enormous and, in our model, it is some of this energy that the quasars and active galactic nuclei release.

The basic idea is that quasars and active galactic nuclei (AGN) are small regions (droplets) of psuedo-vacuum, possibly containing matter, that decay into real vacuum and ordinary matter. These droplets may have strong electro-magnetic fields on their boundaries that tend to stabilize them, but ultimately they decay and release their huge content (partially in the form of accelerated particles). In other words, we suggest that the basic energy of quasars and AGN comes from inside the objects themselves. The droplet model may also help to solve some other longstanding astrophysical puzzles, such as the origin of cosmic rays and spiral arms in galaxies. It is even possible that the droplets lead to the formation of the galaxies themselves, either directly, by ejecting matter, or indirectly, by acting as seeds of condensation in the surrounding gas. Most likely, these droplets are left over from a phase transition in the early Universe and we find that the required energy density of the droplets is approximately $(100 \text{ eV})^4$. Of course, there are many open problems in this scenario, but this should not obscure the fact that the droplet model may shed new light on some major questions in astrophysics that would be hard to understand from the usual hypothesis of black hole accretion disks. In the following we will first sketch our present (limited) understanding of the structure of the vacuum and then turn to the possible role of psuedo-vacuum droplets in cosmology. We will use natural units with $\hbar = c = k = 1$ and Planck mass $M_P \equiv G^{-1/2} = 1.2\ 10^{19}$ GeV, except when conventional astronomical units are more convenient.

In particle physics, in the last two decades, a new phenomenon has become essential ingredient of the theory. This is spontaneous symmetry breakdown, a mechanism where the physical vacuum contains fields in such a way that the total energy is well below that of the 'bare' vacuum. Very conservatively, at least two such field combinations are generally accepted:

1. the Higgs field of the electro-weak interactions;
2. the σ-field associated with chiral symmetry breakdown.

In the first case the Higgs field present in the vacuum corresponds to a huge energy density. This energy density, relating to a vacuum expectation value of 250 GeV of the Higgs field, depends quadratically on the unknown mass of the Higgs, but given that this mass is known to be at least 45 GeV the energy density exceeds $(63 \text{ GeV})^4$, which corresponds to $3.6\ 10^{24}\text{g cm}^{-3}$. This kind of energy density completely dwarfs any other type of energy distribution seen in the Universe.

The σ field is more complicated. The σ particle is not a fundamental particle, but a quark-antiquark state of spin zero. Other than that, the mechanism is supposedly quite analogous to the Higgs mechanism, except scaled down by a large factor: the vacuum expectation value of this field is of the other order of 90 MeV. Most of the details concerning this situation are completely unknown. One simply assumes an effective interaction as needed.

So far few particle theorists would argue with the idea that the vacuum contains these fields. The first is needed to set the scale of weak interactions, *i.e.* the vector boson masses, the second sets the scale for the effective strong interactions, *i.e.* the nucleon mass[1]. It is disturbing that many ideas relating to the content of the vacuum have not met with success (we refer here to things as axions, and strong CP violation), but overall the theory of the standard model is so successful that one must take these ideas seriously. Something on a global scale has to provide the mass scales mentioned.

It should, however, be understood that many other possibilities exist. For example, the interaction between σ particles is not very likely to be the smooth fourth order function customarily assumed. After all, this interaction must be seen as some kind of effective interaction arising from a complex system, not unlike van der Waals forces. It might well be that there is another minimum nearby the usually understood one, differing only very little in energy, and separated by some barrier. Then the decay to the present vacuum state could go in two steps, with the last step possibly involving only a relatively small drop in energy.

Yet other configurations are imaginable. For example, assuming that there is some truth in grand unification theories, such as SU(5) of Georgi and Glashow [4], then the process of spontaneous symmetry breakdown becomes much more involved. In the first place there is the usual Higgs field, providing mass to the known vector bosons of weak interactions. Secondly, the remaining SU(4) symmetry must break down; this process amounts also to selecting the electromagnetic field as the only unconfined long range field allowed to exist. It is possible that in the process a constant electro-magnetic potential comes into existence, which would not normally be observable unless there are some left-over regions that would for some reason not get such a potential, or get a different one. No energy density would be associated with such a constant potential, except in the surface regions. In the surface region there would be exceedingly strong electro-magnetic fields, that could play a role in the relative stability of such regions.

Be that as it may, fact is that present day particle theory contains an area of speculation whose precise details are neither well understood nor experimentally verified. It may very well be that symmetry breakdown occurs in steps, and at any step the breakdown may occur piecewise in complicated patterns. Any amount of energy may be associated with that and the corresponding energy densities, though possibly small from the particle physics point of view, can be enormous for astrophysical applications. To complicate matters further, in regions where the symmetry has not com-

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[1] Actually, the scales derive from dimensionful coupling constants in the Lagrangian, *i.e.* the coefficient of the square of the Higgs field and the anomalous dimension of the QCD coupling constant.

pletely broken down to 'our' vacuum, physics might be subtly, or not so subtly different. For example, the breakdown of chiral symmetry is related to the nucleon mass, in fact it sets the scale for that mass; a slightly different vacuum would give rise to a sightly different nucleon mass, which may influence nuclear physics.

At this point, we do not know of any precise sequence of condensation that might give rise to quasar-like objects. Assuming, however, that there is such a sequence one may try to deduce properties from the astronomical observations, and at least verify that no immediate contradictions arise.

We turn then to the cosmological aspects of pseudo-vacuum droplets. A pseudo-vacuum droplet is a region, where the symmetry has not completely broken down to 'our' vacuum. Such a region could contain matter that is not largely different from that outside of the droplet. For simplicity, we assume that the difference in energy density $\Delta\rho$ between a pseudo-vacuum and our present, real, vacuum is characterized by a single energy scale M_Φ, so that $\Delta\rho \sim M_\Phi^4$. At the epoch when the Universe had a photon temperature $T_\gamma \sim M_\Phi$ the real vacuum condensed, but pockets of pseudo-vacuum could very well be left over, some of which would remain as quasi-stable droplets. If we view the droplets as defects resulting from a phase transition, then, from causality, the typical droplet separation cannot be greater than the particle horizon at that moment ($d_{\rm horizon} = 2t$; $t = 0.3 N_*^{-1/2} M_P/T_\gamma^2$, with N_* the effective number of helicity states). Because the details of the droplet formation and subsequent evolution are completely unknown we estimate the resulting droplet separation as f times the particle horizon at $T_\gamma \sim M_\Phi$, where we assume the factor f to be of order unity. Writing $D_{\rm d}$ for the present ($T_{\gamma 0} = 2.7$ K) droplet separation we find

$$D_{\rm d} \sim 0.6 N_*^{-1/2} f M_{\rm P} T_{\gamma 0}^{-1} M_\Phi^{-1} \sim f\left(\frac{100{\rm eV}}{M_\Phi}\right){\rm Mpc}. \tag{1}$$

Presently, we observe separations of AGN, or for that matter of galaxies in general, not very much less than 1 Mpc. In our model this corresponds to the droplet separation $D_{\rm d}$ and we find from (1) an upper bound on the energy scale M_Φ

$$M_\Phi \lesssim f\left(\frac{1{\rm Mpc}}{D_{\rm d}}\right)100{\rm eV}. \tag{2}$$

After the droplets have formed, the very heavy ones will immediately form black holes and are thus unable to power by their decay the AGN. To estimate this critical mass consider, for simplicity, spherical droplets of radius $R_{\rm d}$ and uniform total energy density $\rho_{\rm d} = M_\Phi^4$. Droplets with size $R_{\rm d}$ less than F times the Schwarzschild radius $2GM_{\rm d}$ will collapse rapidly, where F is a factor of order unity. This gives a maximum radius for quasi--stable droplets of the order of

$$R_{\rm d}^{\rm max} \sim \sqrt{3/8\pi}F^{-1/2}M_{\rm P}M_{\Phi}^{-2}$$
$$\sim F^{-1/2}\left(\frac{0.3{\rm keV}}{M_{\Phi}}\right)^2 {\rm lyr}. \qquad (3)$$

Rapid variations in the output of quasars over the period of a year, or even less, have been observed and they limit, in general, the size of the energy source. Demanding $R_{\rm d}^{\rm max}$ to be less than a light-year, say, give a lower bound from (3) on the energy scale M_{Φ}

$$M_{\Phi} \gtrsim F^{-1/4}\left(\frac{1\ {\rm yr}}{t_{\rm variation}}\right)^{1/2} 0.3{\rm keV}. \qquad (4)$$

Of course, smaller droplets could vary more rapidly than a year.

We emphasize that the numbers on the right-hand sides of (2) and (4) are only indicative, with most uncertainties buried in the factors f and F. Nevertheless, it is remarkable that these independent bounds are close and possibly consistent for

$$M_{\Phi} \sim 100{\rm eV}. \qquad (5)$$

Alternatively, we can say that if the observed quasar phenomenon has something to do with a vacuum structure and droplets left over from a phase transition, it would point to some physics operating at this rater low energy scale, perhaps related to the σ field. Note that the energy scale (5) is such that gravitationally bound defects (droplets) left-over from a phase transition could provide the critical density of our present Universe, but that if M_{Φ} were much larger the energy density of defects would become unacceptably large.

We have argued that pseudo-vacuum droplets, with an energy density M_{Φ}^4 set by (5), could power AGN, but they could no more perhaps. In fact, the maximum droplet mass from (3)

$$M_{\rm d}^{\rm max} \sim F^{-3/2}\left(\frac{100{\rm eV}}{M_{\Phi}}\right)^2 2\ 10^3 M_{\odot} \qquad (6)$$

corresponds, very roughly, to the maximum mass observed in galaxies and one might speculate that galaxies are due to matter ejected from the droplets. The crucial question, however, is wether or not there are enough baryons in the droplets to account for the galaxies as observed[2]. At $T_{\gamma} \sim M_{\Phi}$

[2] Note that nucleosynthesis in the early Universe occurred at $T_{\gamma} \sim 0.1$ MeV, well before the droplet phase transition from psuedo- to real vacuum at $T_{\gamma} \sim M_{\Phi}$. From this it follows that baryons in the pseudo-vacuum cannot be very different from those in the real vacuum, on which the original nucleosynthesis calculations were based.

the energy density in baryons relative to the droplet energy density is

$$\frac{\rho_{\rm B}}{\rho_{\rm d}} \sim \frac{m_{\rm nucleon}(n_{\rm B}/n_\gamma)(0.24 M_\Phi^3)}{M_\Phi^4}$$
$$\sim 2\, 10^{-3} \left(\frac{100{\rm eV}}{M_\Phi}\right)\left(\frac{n_{\rm B}/n_\gamma}{10^{-9}}\right). \qquad (7)$$

Recall that a present ratio of $n_{\rm B}/n_\gamma \sim 10^{-9}$ corresponds to a baryon energy density relative to the critical density of $\Omega_{B0} \sim 0.1$, which is not too far from current estimates. In the absence of a mechanism to concentrate baryons in the droplet or to create them in the decay of the droplet, we then expect that approximately 0.1% of the droplet mass can come out in the form of baryons and this may not be enough to make the largest galaxies. However, the droplets also act as seeds for condensation in the surrounding gas and this could bring in more matter. So we see that droplets could have played a significant role in the formation of galaxies. Note that these massive droplets are extremely small ($\lesssim$ 1 lyr), so that they perturb the 2.7K cosmic background radiation only over small angles ($\lesssim 10^{-4}$ arcmin), for which $\Delta T/T$ is washed out by the finite thickness of the last scattering surface of the photons. As to the structure of galaxies, it is conceivable that the outflow of energy and matter from the droplets gives rise to spiral arms and the resulting star formation. Finally, droplets that were heavier than (6) would immediately collapse into black holes and be unable to power by their decay the AGN or trigger spiral arms and star formation. We do not know the initial mass spectrum of droplets, but we may expect these massive black holes to have lower spatial densities than the largest galaxies or AGN. Possibly, these black holes without surrounding stars could show up as gravitational lenses for more distant luminous objects.

To conclude, it is possible that psuedo-vacuum droplets are responsible for the energetic phenomena observed in quasars and other active galactic nuclei, perhaps even for the existence of the galaxies themselves.

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Note added:

After the present paper was completed, we have become aware of earlier work that overlaps in part with ours. In particular, we should mention the work on "neutrino balls" [5]. However, the scale involved in these neutrino balls is of order 1 TeV, which makes it difficult to explain typical quasar separations.

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