Is Dark Matter made up of
Massive Quark Objects?

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Abstract. We suggest that dark matter is made up of massive quark objects that have survived from the Big Bang, representing the ground state of “baryonic” matter. Hence, there was no overall phase transition of the original quark matter, but only a split-up into smaller objects. We speculate that normal hadronic matter comes about through enforced phase transitions when such objects merge or collide, which also gives rise to the cosmic gamma-ray bursts.

1. Introduction

In this talk I will try to convince you that dark matter consists of objects made up of quarks in the form of so-called quark-gluon plasma (QGP), with up to a few solar masses. This model builds on an idea by Witten from 1984 [1], but is more radical in the sense that our quark objects are not just “nuggets”, nor do just “contribute” to dark matter. We also suggest that cosmic gamma-ray bursts (GRBs) result from mergers of quark objects.
which relates dark matter to GRBs in a unique way. A more detailed account of the model can be found in [2].

Witten’s idea was much discussed a decade ago, but seems out of fashion today, which might be due to the current interest in supersymmetry, neutralinos and the like. The notion of “QGP in space” is still popular, but mainly in models for neutron stars, or other high-density objects [3].

We believe that time is ripe for reviving quarks as the source of dark matter. The main motivation is one of simplicity. It is generally acknowledged that all normal matter was once upon a time a quark-gluon plasma. One way or the other, it went through a phase transition, and turned into our world. What would be more natural than to assume that something went “wrong”, so that most of this plasma remained as dark matter? It seems less natural to invent a third form of matter (axions, neutralinos,...), unrelated to our matter, and without experimental support.

Since our dark-matter model requires quark objects to be less energetic than normal hadronic matter, i.e., representing the absolute ground-state of matter, I will start by discussing the stability aspects.

2. The Stability of Quark Matter

It was suggested in 1971 by Bodmer [4] that a QGP might represent the ground state of matter. This idea was strengthened by many analyses [5, 6, 7, 8]. It became clear that such objects could be “dark”, because the best ground-state candidate is a QGP consisting of equal (or almost equal) parts of \( u \), \( d \) and \( s \) quarks, making it (almost) electrically neutral.

These ideas cannot be rigorously proven from first principles, i.e., from QCD. Rather, one has to rely on phenomenological models, and the one most frequently used for analysing quark objects is the so-called MIT bag model [9, 10], where quarks are confined to “bags” due to an external “vacuum” pressure, quantified by the so-called bag constant \( B \) (quoted as \( B^{1/4} \approx 150 \text{ MeV} \)). Many versions of the MIT bag model have been developed, containing various corrections, one of which is for interactions among the quarks, which were assumed to be free inside the bag in the original version. A recent review of strange quark matter is given in [11].

The original MIT bag model results for protons and other low-mass hadrons were achieved through exact solutions of the Dirac equation inside a spherical bag. Various approximations must be applied for systems with many quarks. Typically, systems with more than a few dozen quarks are lighter than the corresponding atomic nuclei [11]. This result is not violated by the apparent stability of heavy nuclei, since it is utterly improbable that they would decay into “strangelets” of equally many \( u \), \( d \) and \( s \) quarks.
For extremely heavy objects gravity plays an important role, and the MIT bag model (or any other microscopic model) must be complemented with general relativity. This is normally done by applying the so-called Tolman-Oppenheimer-Volkoff (TOV) equation [12] from 1939, which describes a static, spherical, ideal-liquid system, where the stability is equivalent to a zero-pressure at the surface of the object. It is derived in many textbooks in general relativity, e.g., [13]. Several such analyses of astrophysical systems can be found in the literature. They are based on different equations of state (with or without quark effects), and other detailed assumptions.

Some recent computations by one of us [14] give results that are typical for analyses in the spirit of the MIT bag model (or other bag models). A QCD-based equation of state for a system of (equally many) \( u \), \( d \) and \( s \) quarks was used. As an example, the quark objects have masses below around \( \sim 1.8M_\odot \) (\( M_\odot \) being the solar mass) and radii below \( \sim 11 \) km when \( B^{1/4} = 150 \) MeV. Similar values can be found in analyses of the stability of neutron stars, in particular those with a sizeable quark-matter core [3].

Here one might ask how one and the same approach can lead to predictions of a quark core inside neutron stars, as well as of the existence of pure quark stars. Should not one of these systems be the absolute ground-state of matter? The answer might be that a neutron star is created by contraction of normal nuclear matter (with \( u \) and \( d \) quarks) in a supernova, while “our” quark stars are created from the primordial quark gluon plasma with equal numbers of the three lightest quarks. Therefore, the final states need not be identical. A decay of a neutron (hybrid) star into a pure quark star could be utterly improbable.

3. A Novel Big Bang Scenario

In Witten’s model [1], the early universal plasma went through a phase transition into hadronic matter. However, thanks to the high pressure of the hadronic gas, a fraction of the QGP managed to survive in the form of quark nuggets. Their high internal pressure was balanced by the outer hadronic pressure until they cooled down and survived on their own (being the ground state of matter).

It is unrealistic to assume that such a scenario could lead to a final state where 90 – 99 per cent would be quark objects. We therefore suggest that there was no overall phase transition at all! The present Universe is instead a result of an early split-up of the plasma into smaller pieces of all possible sizes. We assume that the internal forces inside the original QGP could not withstand the rapid expansion, and the plasma “cracked” along surfaces of lower density, or weakened quark forces. This is, in fact, a normal chain of events for classical explosions.
The further development depends on the scale of this first split-up, i.e., the mass distribution among the first generation of quark objects, which seems impossible to estimate from first principles. It could be due to events during the inflation phase (e.g., quantum fluctuations), or to random occurrence of colour-neutral subregions. Neither is it possible to apply arguments built on the concept of an event horizon \[15\]. We do not know when the split-up took place. It could have been when the plasma was strongly super-cooled, i.e., when it had a density lower than that of nuclear matter. Also, the concept of a horizon loses its meaning inside a high-density, uniform Universe, where it is even impossible to define a length.

We will therefore discuss three possible ways that the QGP could have split up. Each one has its own phenomenological motivation.

The least interesting version is that the plasma split up directly into \(1 - 10\) per cent normal nucleons and \(90 - 99\) per cent quark objects of up to solar masses. Or alternatively, that nucleons quickly “boiled off” the surfaces of quark objects that had not yet stabilised. This would explain the “observed” fraction of normal matter, without introducing any dramatic, subsequent events. One only needs to assume that the further fate of the Universe was dominated by gravity.

However, this scenario does not explain why the normal matter gathered mostly in the centre of galaxies, while dark matter seems to be more peripheral. Neither does it give a clue to the well-known problem of galaxy formation, i.e., how galaxies could form in less than a billion years.

It is therefore tempting to speculate that the mass scale of galaxies played some role during the first split-up of the plasma. Hence, either the original plasma separated immediately into subregions with typical galactic masses, or there was a more or less fractal split-up, where the galactic scale was only one of many mass-scales. The latter alternative fits well the findings of a fractal structure of the present Universe.

Let us start by discussing quark objects of galactic masses, or more generally, of masses in excess of the limit given by the Schwarzschild radius. As an example, the Milky Way, assuming a 90 per cent dark-matter fraction, would have been a quark object with a radius of around 80,000 km (if it was spherical), and containing some \(10^{69}\) quarks.

Obviously, such objects must have been highly unstable, and would seemingly have disappeared quickly into black holes. However, during the very early phase their interiors were still following the general expansion of the Universe, and they most probably also rotated (as they do today). Consequently, it might have happened that only the inner part of a proto-galaxy went into a black hole, while the outer parts continued to expand. This would explain why many galaxies appear to have massive central black holes of masses \((10^5 - 10^{10}) M_\odot\).
This opens up for an interesting history of a galaxy. The black hole would suddenly “empty” the inner part of the quark object, and temporarily turn it into a hollow system. Since there would be no resistance from gravity, nor from a bag pressure, matter would continue to flow into the central cavity, and probably in small-enough pieces to condense into normal hadronic matter, while giving off radiation. The visible galaxy would then be created as an accretion disk (or sphere) around the central black hole. This process ends when the radiation pressure blows the rest of the galaxy apart. If all visible matter in the Milky Way was created in this process, it would have given off some $10^{63} - 10^{64}$ erg of radiation (assuming an energy gain of 10 - 100 MeV per hadron during the condensation). This is enough to break apart the dark-matter galactic shell into smaller quark objects, and send them out in the distant periphery. After this violent phase, gravity took over and formed the Milky Way of today. Interestingly enough, it was noted already in 1958 [17] that some galaxies seem to have been formed by explosions, and this idea cannot easily be dismissed even in the light of more recent observations [18].

Let us now turn to the less dramatic option that the original QGP split up into pieces with masses below the one given by gravitational stability, \textit{i.e.}, from isolated hadrons up to objects of a few solar masses. A hint of the mass distribution is given by the observation of machos in the periphery of the Milky Way. These seem to have a mass range of $(0.01 - 0.8)M_{\odot}$ [19], with a mean macho mass of roughly $0.5M_{\odot}$, and a 50 per cent macho fraction in the Milky Way (dark) halo (assuming a spherical shape). Such estimates naturally depend strongly on the assumed total amount of dark matter. For the sake of our model it can nevertheless be concluded that the mass distribution is biased toward heavy objects - from “planetary” to solar masses.

Still, we assume that some early mechanism, such as a fractal break-up of the original plasma, made these quark objects appear at once in proto-galactic clusters, with a higher density in the centre than in the periphery. If so, the next step in the development of a galaxy should have been mergers, or collisions, of quark objects. This phase started as soon as the interior of a proto-galaxy was shielded from the general expansion of the Universe, so that gravity and/or random motion became the dominant factors. This could have started almost “immediately”, \textit{i.e.}, within a fraction of a second after the first break-up of the QGP.

A merger of a binary system of quark objects should be a dramatic event. In systems corresponding to solutions to the TOV equation, with a vacuum pressure typical for the MIT bag model, the overall density is about the same as inside a free nucleon. However, this density depends very strongly on the pressure, and would drop far below that of normal nuclear matter, would the bag constant drop from the normal $B^{1/4} = 150$ MeV to,
say, 75 MeV \(^{14}\). This effect is strongest at the periphery of the objects. A similar, but weaker depletion of the density is expected if gravity would be “turned off”. Both these phenomena are expected when two massive quark objects merge, while counterbalancing each other’s internal gravity, and screening each other from the vacuum pressure.

All in all, we expect bridges or jets of quark matter to appear between the two objects just before they merge into one. This corresponds to a more or less continuous stream of “boiled-off” quarks, which would hence hadronise into normal matter, while radiating the excess energy in the form of gammas, mesons etc. This zone of newborn hadrons and radiation would, in fact, be a mini-copy of the conventional Big Bang scenario for the whole Universe. The main difference is that the conventional Universe found its true ground state when expanding and cooling, while our quark objects are forced into an “unnatural” hadronisation with the help of the gravitational energy released in the binary system. Such matter-flows occur in many cosmic situations, e.g., between galaxies, between normal stars in a binary system, and from an accretion disc into a black hole. There are rather well-established formalisms for analysing such situations \(^{20}\).

It is worth noting that a most popular class of models for cosmic gamma-ray bursts assume that they originate from neutron-star mergers \(^{21}\). A majority of these models rely on some either unspecified, or very complicated, mechanism for converting the energy-gain into gammas. However, there are also models were the gamma-ray bursts originate from a hadron-quark phase transition inside a neutron star, or in connection to a merger (see, e.g., \(^{22}\)). These transitions are from a hadron phase to a quark phase, and hence quite opposite to our scenario.

So, in this version of our model, the early proto-galaxy will experience a myriad of such mergers, where the most violent ones will be between quark objects of a few solar masses. They will result in miniversions of the conventional overall phase transition from quark to hadron matter, and hence lead to normal matter mainly in the galactic centre, and to gamma-ray bursts.

The expected energy-release in the form of gammas is in line with observations. Supposing that a maximal amount of one solar mass can convert to hadrons in a merger, this energy will be \(10^{53} - 10^{54}\) erg (again assuming an energy-gain of 10 – 100 MeV per produced hadron), which fits well the estimated energies of those bursts that have so far been localised with the help of observed redshifts.

As the radiated gammas cannot penetrate more than around 100 fm inside dense hadron (or quark) matter, we expect the radiation to blow the hadronic zone apart, and partly thermalise, and hence prevent the hadrons from falling into the quark objects again. The quick merging of many
binaries probably led to an overall expansion of the whole proto-galaxy due to the collective radiation pressure.

After this violent phase, the hadrons (mostly baryons) went through a normal development, e.g., nucleosynthesis into light elements, formation of atoms etc. It has been suggested recently \([23]\) that some of the paradoxes with the fraction of light elements might be solved if nucleosynthesis took place in rather small, disjoint systems, of down to kilometre sizes, which at least suggests that the Universe split up into smaller objects before hadronising.

In the present Universe, and in the visible galaxies, gamma-ray bursts are rare, because the original binary systems merged very early, and new ones are created only by accident in the very diluted dark halo. In this respect, our model differs from the ones built on neutron star mergers, because neutron stars are continuously created in all galaxies, while quark matter is not. Hence, we predict that gamma-ray bursts are much more frequent in very distant galaxies than in the nearby ones. This is in line with observations, at least of the “localised” GRBs.

Also, we can only observe the most violent ones. Maybe there are more frequent, but invisible, mergers between quark objects of much smaller masses. It would be interesting to analyse the observed gamma-ray “background” in our own galaxy in the light of this idea, and try to restrict some model parameters. In any case, we expect a full range of gamma-ray energies, contrary to models built on neutron star mergers, because neutron stars are more uniform in size. Hence, gamma ray bursts are not expected to be “standard candles”.

Finally, some of you might want to know if we expect an alarming rate of these objects in our own solar system. Well, they would certainly \textit{not} make up ten times the mass of the sun, because there is a lot of empty space inbetween the stars. So, even if our galaxy has quark objects of a total mass of some 1 trillion solar masses, they would be distributed in a volume much larger than that of the visible Milky Way, and probably more or less evenly in space (perhaps even spherically around the galaxy). In a volume corresponding to a sphere inside the orbit of the earth around the sun we expect no more quark matter than contained in a centimetre-sized object. Nevertheless, it would have the mass of a medium-sized mountain (a few billion tonnes), and it would not be of much help to call for Bruce Willis, because there would be no way to blow it apart, even if we would observe it in space!

\textbf{Acknowledgements}

SF would like to thank the Organisers for arranging an excellent conference in the beautiful city of Heidelberg, and the Max-Planck-Institut für
Kernphysik, and in particular Professors B. Povh and B. Kopeliovich for their hospitality during his two-month stay in Heidelberg. DE would like to thank Professors J. Silk, C. Uggla and E. Witten for inspiring discussions and constructive comments. This project is supported by the European Commission under contract CHRX-CT94-0450, within the network "The Fundamental Structure of Matter".

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