Riding Gravity Away from Doomsday

Ashoke Sen

Harish-Chandra Research Institute
Chhatnag Road, Jhusi, Allahabad 211019, India
E-mail: sen@mri.ernet.in

Abstract

The discovery that most of the energy density in the universe is stored in the form of dark energy has profound consequences for our future. In particular our current limited understanding of quantum theory of gravity indicates that some time in the future our universe will undergo a phase transition that will destroy us and everything else around us instantaneously. However the laws of gravity also suggest a way out – some of our descendants could survive this catastrophe by riding gravity away from the danger. In this essay I describe the tale of this escape from doomsday.

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1 Doomsday

The discovery of the accelerated rate of expansion of the present universe has had profound influence on our current understanding of the universe [1,2]. The best explanation of this to date is the presence of a small positive cosmological constant in Einstein’s equations. According to our current knowledge, about 70% of the energy density in the universe today comes from the cosmological constant and the rest comes from ordinary matter and dark matter.

A plausible explanation of the origin of the cosmological constant in string theory was provided in [3–5]. From the analysis of these papers and many subsequent papers the picture that has emerged is as follows. The situation in string theory is analogous to (but far more complicated than) a field theory of multiple scalar fields coupled to gravity, with the potential energy density being a complicated function of the fields with many local maxima, minima and saddle points. A one dimensional version of this has been shown in Fig. [1]. Each of the local minima of the potential describes a phase of string theory, with the value of the potential energy density at the minimum giving the value of the cosmological constant. The different phases have very different properties – even the list of ‘elementary particles’ and the forces operating between them are very different. The hope is that someday we shall find a minimum that describes exactly the kind of elementary particles and forces we see in nature, but we are quite far from realizing this goal.

The description of different phases given above is classical. In quantum theory there are fluctuations that keep driving the fields away from the local minimum. Occasionally the fields inside a small region – which we shall call the bubble – would fluctuate to another minimum of the potential. If the latter has lower potential energy density than the original minimum then the potential energy inside this bubble will be lowered if the bubble grows. However the surface tension of the bubble costs energy. Thus the net excess potential energy associated with a bubble of radius \( r \) can be written as

\[
- A r^3 + B r^2
\]

where \( A \) and \( B \) are positive constants. If \( r > B/A \) this is negative. Such a bubble will begin to expand, with the excess potential energy getting transferred to the wall as kinetic energy [6,11]. The wall will begin to accelerate, with its speed eventually approaching the speed of light. During this expansion it will destroy everything that existed in the original phase since even the elementary particles of the original phase do not exist in the new phase.
in the interior of the bubble\footnote{Gravity can make the situation inside much worse \cite{11}.}

As I have already mentioned, we do not yet know our place in the vast landscape of phases of string theory. But we do know that the minimum that describes us has a small but positive value of the potential energy density. We also know that there are other minima of lower energy density since there are many known phases of string theory with zero and negative energy density. This has a sinister consequence: it shows that we cannot exist forever. Sooner or later in some part of the universe a bubble of another phase of lower energy density will form which will subsequently expand and destroy us. Since the bubble wall expands at the speed of light our death will be painless; we shall not even know of the existence of the bubble before it hits us. However this will definitely be the end of our species and the universe around us.

Even though we have used string theory to argue for the metastability of our universe, there are various other independent arguments which indicate that a space-time with positive cosmological constant cannot exist forever \cite{14,24}. String theory provides a concrete realization of this phenomenon, but any other consistent quantum theory of gravity will probably also lead to a similar conclusion.

How long do we have before such a calamity strikes us? Given that our universe has survived for $1.38 \times 10^{10}$ years – which is its current age – it seems likely that our half-life is not much smaller than $10^{10}$ years\footnote{There are different points of view on this issue, see e.g. \cite{12,13}.} This means in particular that the probability that such a calamity will hit us during the next one year is less that 1 part in $10^{10}$. The actual probability may be much smaller. Nevertheless if we wait long enough we are bound to encounter the doomsday some time in the future unless other calamities have destroyed us by then.
Figure 2: This figure illustrates the formation and evolution of bubbles of destruction in our universe. These bubbles are produced at random at some constant rate, and once produced, expand at the speed of light. At the same time, our universe expands exponentially, with the distance between any two points roughly doubling every $10^{10}$ years. Unless the bubble nucleation rate is too high the expansion of the universe wins, leaving us with plenty of safe regions in between the bubbles. However since we do not know when and where a bubble might form, the only way to utilize these safe regions is to spread out so that even when some of us are consumed by a bubble, others may survive.

2 The Escape

The situation looks pretty bleak, particularly since we have no control on when and where such a doomsday bubble may form! Nevertheless there is a course of action that could save some of our descendants from this catastrophe. The essential idea is simple; we must spread out as fast as possible, establishing civilizations on different worlds in different parts of the universe, so that even if some of us are hit by the catastrophe, the others may survive.

Since the bubble expands at the speed of light, it is not obvious that this strategy will work. In fact, in Minkowski space-time this would require accelerating for ever. But in a space-time like ours, the accelerated expansion of the universe helps by separating these different worlds so that eventually even light sent from one of these civilizations cannot reach the other worlds. After this any further communication between these worlds would be impossible – they would have ‘gone outside each other’s horizon’. In this situation a doomsday bubble hitting one of these worlds will typically be unable to reach the other worlds and destroy them \[25\]. Of course there may be other bubbles hitting the other worlds at other times, but as long as we have sufficient number of them, some of the worlds may survive. This has been illustrated in Figs. 2, 3.

In our universe the horizon size is of the order of $10^{10}$ light years. This means that by sending out space-ships we can reach and establish civilizations on different worlds situated within a radius of about $10^{10}$ light years from us today\[6\]. As the universe expands these different worlds will get pulled apart from each other. If they sit idle then eventually each of them will

\[3\]A person travelling at constant acceleration equal to the acceleration due to gravity on earth can achieve this in her own life-time \[27\].
Figure 3: This figure illustrates the multiplication of civilizations. Here cosmic time – measured by the logarithm of the inverse temperature of the microwave background radiation – runs from left to right and the bifurcations denote establishment of new civilizations. Each civilization has a fixed probability per year of meeting its doomsday; these doomsday events are marked by the vertical bars. While some of the civilizations meet their doomsday, the others live on. If they multiply too slowly then it is likely that all the civilizations will eventually meet their doomsday. On the other hand multiplying too fast does not help since several civilizations within each other’s horizon are likely to be annihilated by the same bubble. This figure has been inspired by a similar figure in [26] where it was used in a somewhat different context.

meet its doomsday. To ensure the survival of our species, each of these civilizations must, in turn, spread out and establish new civilizations. In order to optimize the survival probability we have to ensure that at any given time, there is at least one civilization inside a horizon size sphere – a sphere of radius $10^{10}$ light years. Since the size of our universe doubles approximately in every $10^{10}$ years, this would mean that the number of civilizations must grow by a factor of eight in the same time.

Unfortunately this process cannot continue for ever. Our resources are limited, determined by the fact that the total amount of matter at our disposal is what is contained inside the present horizon radius of $10^{10}$ light years. This is a large amount of matter, but having to divide this into the exponentially growing number of worlds will eventually reduce the total amount of matter available to a given world to less than the critical value needed for establishing a civilization [28]. Put another way, we would eventually run out of the worlds on which we can establish new civilizations even if we manage to achieve a technological breakthrough and create new worlds by redistributing the available matter within our horizon. Beyond this point we shall no longer be able to establish new civilizations. Since each of the worlds has a finite half-life, eventually each of them will encounter a doomsday bubble. Nevertheless we would have managed to prolong the life of our species beyond what we would normally have by staying put in one place.
3 Role of Fundamental Theory

The cost of this endeavour is clearly going to be high. So it would make sense to follow this strategy only if the probability of the doomsday event is sufficiently high. Precise information on this probability requires knowledge of the fundamental quantum theory describing gravity and everything else. In the context of string theory this means that we need to identify the correct minimum of the potential that describes the phase in which we live and then compute the probability of decay of this phase by standard techniques. In searching for this minimum we can be guided by our knowledge of low energy physics which is well described by the standard model. Another strong constraint arises by demanding that the value of the quantum corrected potential energy density at the minimum agrees with the observed value of the cosmological constant. Finding a minimum satisfying all these requirements is going to be a herculean task, but given its bearing on the survival of our species, its perusal is worth the effort.

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