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GRAVITATIONAL COLLAPSE AND AFTER

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Gravitation is such a familiar phenomenon that it is rather surprising that the incorrect opinion of Aristotle, that heavier objects fall faster, was not challenged until the end of the 16th Century when GALILEO [1] discovered what is now known as the Principle of Universality or Equivalence: gravity affects the trajectories of all freely moving bodies in the same way. This is the basis for the famous but probably apocryphal story about Galileo dropping weights from the Leaning Tower of Pisa. The Principle of Equivalence was incorporated into a mathematical theory by NEWTON [2] who also discovered another very important property of gravity, that it is long range, i. e. it decreases only as the inverse square of the distance. Galileo formulated the Principle of Equivalence only for material bodies but the discovery early in the 18th Century by ROEMER [3] and BRADLEY [4] that light travels at a

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finite velocity led LAPLACE [5] to suggest in 1798 that light might also be subject to gravitational forces and that a sufficiently massive or concentrated body might produce such a strong gravitational field that all the light from it would be dragged back and would not be able to escape. It is remarkable that this situation, which we would now call a "black hole", should have been predicted so early. It must however be classed as a speculation only since it was not based on a consistent theory of the interaction of light with gravity. This did not come until 1915 when EINSTEIN [6] produced the General Theory of Relativity which predicted among other effects that light would be deflected by gravitational fields. This prediction has been experimentally confirmed with increasing accuracy since 1919. It is a measure of how far Einstein was ahead of his time that with the notable exception of OPPENHEIMER [7] hardly any attention was paid in the next fifty years to the remarkable implications of this theory. There seems to have been three reasons for this. First, the theory was thought to be so mathematically complicated that no useful predictions could be made with it. Second, it was thought that any predictions that could be made would not be testable by observation. Third, and probably most important, most physicists were otherwise occupied by the great advances that were being made in that period in quantum mechanics.

The great extension of astronomical observation brought about by the application of technology lead to a revival of interest in general relativity in the early 1960's because it seemed that the strange new objects that were being discovered such as quasars, pulsars and compact X-ray were radiating more energy than could be supplied by nuclear processes. The only possible source of this energy appears to be gravitational which implies that the objects must be very concentrated and must have very strong gravitational fields, fields which would significantly affect the propagation of light. In 1965 PENROSE [8] published the first theorem which showed on

the basis of general relativity and with certain assumptions about the global properties of space-time, that if one had a sufficient concentration of matter in a region of space, not only would it create such a strong gravitational field that no light could escape but also the whole region would undergo a gravitational collapse and produce a space-time singularity. Subsequent work by myself [9, 10, 11] and joint work by PENROSE and myself [12] led to improved singularity theorems which did not involve any unreasonable global assumptions about space-time. These theorems showed that, if general relativity was correct, space-time singularities were inevitable whenever one had more than a certain critical amount of mass in a given region.

A singularity is somewhere where the classical concept of a space-time continuum or manifold breaks down and the ordinary notions of space and time come to an end. An obsever unlucky enough to run into a singularity would be likely to be torn apart by tremendous gravitational tidal forces. Because all the presently known laws of physics are formulated on a classical space-time continuum background, they will all break down at a singularity. This is a great crisis for physics because it means that one cannot predict what will happen when a singularity occurs. In fact some very recent work of mine which I shall describe in a moment indicated that this inability to predict may be fundamental and may correspond to a new level of uncertainty in physics over and above the uncertainty introduced by quantum mechanics: it seems that what comes out of a singularity is completely random.

There are two classes of situations in which singularities are predicted to occur. The first is in the past at the beginning of the present expansion of the universe. This is thought to be the "big bang" which occurred about ten thousand million years ago and which is generally regarded as the beginning of the universe. The second class are those in which the singularities occur in the future either because of the collapse of the whole universe or through the collapse of isolated regions such as massive stars. In the latter case the classical theory of general relativity predicts that the singularities will occur in a region of space-time, called a black hole, which is not visible to an external observer. The boundary of a black hole is called the event horizon and is, classically at least, a sort of a one-way membrane which lets objects fall in but does not let anything out. There is now strong circumstantial evidence that at least one astronomical system, Cygnus X-1, contains a black hole in orbit around a normal star.

Since 1970 most of my research been concerned with black holes. My work [13, 14], together with that of ISRAEL [15], CARTER [16] and ROBINSON [17, 18] showed that a gravitationally collapsing body would produce a black hole which rapidly settled down to a quasi stationary state which depended on only three parameters, the mass, the angular momentum and the electric charge. This means that there are a very large number of different initial configurations for the collapsing body that will all give rise to black holes with the same mass, angular momentum and charge or, in other words, a lot of information is lost in a gravitational collapse because one cannot observe the internal configuration of a black hole. This led BEKENSTEIN [19] to suggest that one might associate an entropy with a black hole which was a measure of the number of unobservable internal configurations. He tentatively identified this entropy with the surface area of the event horizon or boundary of a black hole which I had shown [13] had the properties that it always increased when matter or radiation fell into the black hole and that when two black holes collided and merged together, the area of the event horizon of the final black hole was greater than the sum of the areas of the event horizons of the original black holes.

A major difficulty with Bekenstein's suggestion was that it led to inconsistencies unless black holes emitted thermal radiation at some finite non-zero temperature. This is impossible according to classical general relativity. However just over a year ago I [20, 21] discovered that quantum effects

would indeed cause black holes to emit thermal radiation with a temperature of about 10^{26} M^{-1} where M is the mass in grams of the black hole. The black hole will radiate away its entire rest mass in a time of the order of 10^{-26} M^3 s and then the black hole, the matter that went into forming it and the singularity inside it will apparently disappear, at least from our universe. The radiation coming off is thermal in all senses including the fact that different modes and different numbers of particles in the same mode are completely uncorrelated. The reason for this is that part of the information about the state of the system has been lost down the black hole. As I mentioned before this introduces a new element of randomness into physics over and above that associated with quantum mechanics because one cannot describe the process of formation and evaporation of a black hole by an S matrix but only by a density matrix.

The final stages of the evaporation of a black hole would probably be very rapid producing a tremendous explosion. Fortunately the chances of such an explosion happening near the earth are very remote.

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