In a remarkable paper published in Nature in 1975, James Gunn and Beatrice Tinsley argued that the expansion of our universe is not slowing down under the effects of its gravity, but that it is accelerating. They used simple ideas of how galaxies should evolve and interpreted the data on brightnesses of galaxies at different distances (that is, at different epochs in the past) to come to this conclusion. After two decades, their result stands vindicated by new observations which do not suffer from uncertainties of galactic evolution, but which rely on the standard brightnesses of a certain kind of supernovae (explosions that destroy a star). New observations point toward the existence of a cosmological constant which endows space a repulsive force that accelerates the expansion of the universe, just as Tinsley describes below in this article she wrote in 1975.

Biman Nath

From Big Bang to Eternity?

Beatrice Tinsley

From ancient times until only half a century ago, the prevailing cosmological belief was that the universe must be unchanging. Then came the fundamental astronomical discovery that the universe is expanding, followed shortly by theoretical indications that the expansion started billions of years ago from an explosive Big Bang. Recent research sheds new light on the key cosmological question about the distant future: Will the universe expand forever or will it eventually revert to a contraction that ends in an apocalyptic "big crunch?"

Our own galaxy, the Milky Way, has about one hundred billion stars, among them the sun, and beyond our galaxy are uncounted billions of others. When the starlight from a distant galaxy is spread out into a spectrum, it shows features characteristic of stars in the Milky Way, but shifted to the longer wavelengths at the red end of the spectrum. This red shift is interpreted as being an example of the familiar Doppler effect whereby the pitch of a sound drops – that is, its wave-length increases – when the source is moving away from the listener. By analogy, we infer that distant galaxies are moving away from ours. Moreover, the amount of red shift has been found to be greatest for the

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most distant galaxies. A pattern in these observations indicated that the speeds of recession of galaxies are proportional to their distances from us. The more distant a galaxy, the faster it moves. This relationship, discovered by the great American astronomer Edwin Hubble in the 1920s, is known as Hubble's law. The ratio of speed to distance is currently estimated to be 10,000 miles per second per billion light-years.

Hubble's law at first suggests the anti-Copernican notion that our galaxy is at the center of the universe, but a more acceptable interpretation is that the whole universe is expanding uniformly, that it has no "center", and astronomers in any galaxy would see the others moving away at speeds proportional to their distances. The situation can be pictured with the popular analogy in which galaxies are represented as dots on a balloon that is being blown up: as the balloon expands, each dot moves relative to all the others in obeyance with Hubble's law.

A dramatic conclusion follows from Hubble's discovery. At some time in the past, all the galaxies must have been twice as close together as they are now; at some even more remote time, they must have been 100 times closer – at which point they would have been intermingling so that separate galaxies could not have existed. Earlier still, the material of galaxies would have been still more condensed, and so forth. There is no limit to this increase of density until we get back to a time, ten to twenty billion years ago, when every particle in the universe was infinitesimally close to every other. That was the moment of the beginning, when according to most theorists, a gigantic explosion – The Big Bang – took place. It is not clear what it means to talk about conditions before that beginning, but the universe in its first few minutes after the Big Bang is believed to have been an enormously dense mixture of subatomic particles, atomic nuclei, and hot radiation. From this primordial fireball, the universe has been expanding ever since, to lower and lower densities and cooler and cooler temperatures. (Of course, while the average density has been steadily decreasing due to the expansion, there are regions of the universe where matter has collected again into galaxies and stars.)

What of the future? Will the expansion go on forever? To answer this question, we must consider the forces that act over very great distances and so affect the rate of expansion. Physics tells us that the most effective force on such a scale is gravity. Since gravitation acts as an attraction between all the pieces of matter in the universe, it will inevitably cause expansion to slow down. According to Einstein's general theory of relativity, this eventuality leads to two possible alternatives for the future.

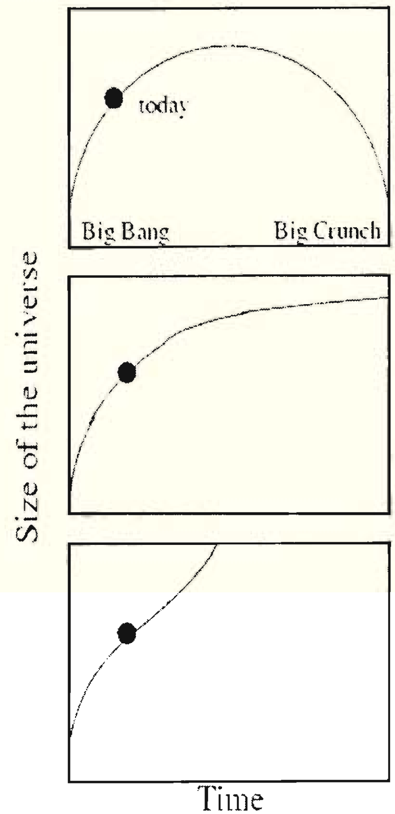
In one projection, if the average density of matter in the universe is great enough, the mutual gravitational attraction between bodies will eventually slow the expansion to a halt. The universe will then contract and finally collapse into a hot fireball like the globule of matter from which it emerged. It has also been suggested that the universe might "bounce" and begin a new era of expansion with a new Big Bang of the compressed matter. In that manner the universe could go on cyclically forever, oscillating between expansion and contraction. However, despite widespread acceptance of the original Big Bang, there is no known physical mechanism that explains it and that could reverse a catastrophic big crunch. Apparently, if the universe becomes dense enough, it is in for a hot death.

But if the universe has a low density, its death will be cold. It will expand forever, at a slower and slower rate. Galaxies, in time, will turn all of their residual gas into stars, and the stars will burn out. Our own sun will become a cold, dead remnant, floating among the corpses of other stars in an increasingly isolated Milky Way.

To decide what kind of future is in store, we should first measure the density of the universe and compare the result with the so-called critical value, above which gravity will eventually reverse the expansion. The most direct approach is to add up the masses of all the galaxies in a large volume of space and see what average density they give. This is not completely accurate because one has to assess how much "hidden" matter galaxies contain in addition to their visible stars. Densities of between 2 percent and 30 percent of the critical value are derived by different workers, with a typical "best guess" at 5 percent to 10 percent. Although lingering uncertainties mean that the answer is not conclusive, this approach indicates that there probably is not enough matter in the universe to reverse the expansion.

The density can also be estimated indirectly from the abundance of some chemical elements believed to have been made by nuclear reactions in the minutes following the Big Bang. The abundances disclose the density of interacting particles when the universe began, which can be scaled down in a known way to give the present average density of the universe. This approach also shows that the density is probably only 5 percent to 10 percent of the critical value.

A different way of calculating the future of the universe is to try to determine its rate of deceleration, or slowing down, which can then be compared with a "critical" minimum rate needed if the expansion is headed for reversal. One method of measuring decelera-



The density of matter in the universe is a crucial factor in predicting the future of the cosmos. Assuming the universe began with a Big Bang (which also marked the beginning of time) and has been expanding ever since, there are three possibilities. According to the first (top figure), the density of the universe is greater than the critical value required to halt expansion. Gravitational attraction therefore reverses expansion and the universe contracts and eventually collapses. In the second case (middle figure), the density is less than critical so the universe expands forever, but at an ever slower rate. In the third case (bottom figure), the universe also expands forever, at a decelerating rate at first because of gravity and then at an accelerating rate because of a force of cosmic repulsion. (Adapted from B. Tinsley, Natural History, October 1975)

tion assumes that if the expansion speeds of the galaxies had always been constant, the ratio of speed to distance in Hubble's law would mean that the Big Bang occurred more recently. The oldest stars are thought to be twelve to sixteen billion years old, which, compared with twenty billion years, limits the amount of deceleration to a value less than the critical minimum. The present rate of expansion and the ages of stars are not known accurately enough for this estimate to be decisive – it is, however, consistent with our conclusions based on density.

Finally, it may be possible to determine the past expansion rate fairly directly. The speeds, or red shifts, of galaxies can be measured out to distances of about eight billion light-years, which means that we are actually observing the rate of expansion of eight billion years ago, when the light left the galaxies. Galaxies far enough away for the difference between present and past expansion rates to be detectable should have greater red shifts than predicted by Hubble's law, and the excess gives a measure of deceleration. The chief problem with this approach lies in determining the distances of the galaxies from the earth. It has been found best to use their apparent luminosities for this purpose, but there are serious practical and theoretical difficulties in measuring the luminosities of far distant galaxies and then effectively converting those brightnesses to distances. For example, we have to calculate by how much the intrinsic luminosities of galaxies have diminished owing to the evolution of their stars over the past eight billion years. The best that might be hoped for is that the attempt to measure the past expansion rate would give results consistent with the other computations – a small deceleration, predictably caused by a density of matter much less than critical. Until recently, that was indeed a credible interpretation of the data.

But the latest and most precise results have surprised us. They seem to show that distant galaxies have red shifts smaller than the Hubble law values, implying that the past expansion was slower than the present rate. In other words, expansion seems to be accelerating. This is very disturbing because it was a fundamental theoretical prediction that the ubiquitous effects of gravity must cause deceleration. One way out of the dilemma might be to go back and look for systematic errors in our interpretation of the data; for instance, if we found that the galaxies are closer to the earth than our current estimates allow, their red shifts might no longer seem too small. A more exciting possibility is to accept the results at face value (while still studying the mundane possibility of errors, or course) and postulate that some force of repulsion is, in fact, predominant over gravitational attraction on the cosmological scale.

It is fascinating to note that Einstein himself once believed that such a force must exist, simply because in the days before cosmic expansion was recognized, he assumed that the universe must be static; a force of repulsion was therefore needed to balance that of gravity. Perhaps we will return to something similar to Einstein's former idea. With a slightly different value for the repulsive effect than that assigned by Einstein, a force of repulsion could account for the universe starting with infinitely rapid expansion following the Big Bang, then slowing down, and eventually, when the density became so small that cosmic repulsion won out over gravitational attraction, starting to accelerate. If this should prove to be the correct interpretation of the data, the pull of gravity will never be preeminent again, and we can be sure that the universe will expand forever.