

Gravity is the ultimate capitalist principle. In astronomy, a “rich” region of the universe is one that has more matter, a “poor” region less matter, than average. Gravity magnifies differences that already exist. Denser regions expand more slowly, and less dense regions more rapidly, than average. The inevitable result is that the rich get richer and the poor get poorer.

This economic analogy may be illuminating for understanding not only cosmology but also the challenges currently confronting humanity. It can serve as a powerful metaphor for thinking about human-scale problems. This is a perhaps surprising claim, since for most educated people, “the universe” is an intriguing but ultimately formless concept—interesting only as the source of newsworthy discoveries or as a fantasy outlet, but irrelevant to everyday life. One reason for such indifference is that science has refuted all traditional pictures of the universe—pictures in which humans played a role—yet until recently science could not itself present a picture with any reasonable claim to validity. But at the beginning of the new millennium, scientific cosmology is experiencing a golden age of discovery. With breakthroughs based on data from extraordinary new telescopes in space and on the ground, cosmologists are now piecing together humanity’s first picture of the universe as a whole that might actually be true.

According to the emerging story, a process called Cosmic Inflation initiated the Big Bang by causing space to expand extremely rapidly. During this process, slight differences in the amount of matter and energy were created in different places throughout the universe by minuscule quantum fluctuations, which were subsequently vastly expanded in size. After a tiny fraction of a second, the universe stopped inflating and began expanding much more slowly, and gravity began the process that led to the formation of galaxies—including our own galaxy, the Milky Way.

Our modern concept of gravity is not just the simple mutual attraction first proposed by Isaac Newton. Newton’s theory was a good description of gravity on the scale of the solar system, but when he tried to extrapolate his thinking to the universe, he could never explain why everything did not simply fall together. He hypothesized that the universe must be infinite and without a center—although this created a paradox since, if the universe were infinite and filled with stars, the night sky would be white. For two centuries, this paradox went unresolved. Cosmology—the science that attempts to describe the origin, evolution, and structure of the entire universe—was not taken seriously, since the ratio of theory to data was nearly infinite.

Two achievements early in the twentieth century began the development of scientific cosmology. One was Albert Einstein’s creation of the modern theory of

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gravity, called general relativity, and his application of it to cosmology in 1916. This provided the essential intellectual framework. The other was Edwin Hubble's discovery in 1929 that distant galaxies are traveling away from us with a speed proportional to their distance. In other words, the universe is expanding. Billions of years ago it must have been much smaller and hotter than it is today. Einstein's equations of general relativity predicted that the universe had to be either expanding or contracting, but Einstein's instincts told him that this was not the sort of solution nature would choose. So he altered his equations by inserting a new term called the "cosmological constant" to try to keep the universe static. Expansion, though, was predicted by two cosmologists, Alexander Friedmann in 1922, and, in a more general way, by the Belgian priest George Lemaitre in 1927, who were bolder with Einstein's theory than Einstein himself. However, a mistake in the way astronomers had been estimating distances to galaxies led Hubble to calculate the age of the expanding universe to be only about 2 billion years—a big problem for the Big Bang, since the earth was already known to be older than that. So it was still unclear whether the Big Bang theory was right and the universe had cooled off and in other ways evolved since its birth a few billion years ago, or alternatively whether the universe had been essentially unchanged and was probably eternal, as the rival Steady State theory asserted. The crucial evidence favoring the Big Bang was the discovery by Arno Penzias and Robert Wilson in 1965 that "cosmic background radiation" is coming toward us from all directions. The radiation was immediately interpreted as the heat radiation of the Big Bang. Since then telescopes on the ground and in space have confirmed this and also provided many other forms of evidence that favor the Big Bang.

Big Bang theory paints the early universe as expanding uniformly. But we see galaxies in some regions and not others, so there must have been small differences in the density of matter from place to place right from the beginning, and gravity simply magnified them. In 1982 random differences in density were theorized to be caused by quantum fluctuations during the process of Cosmic Inflation. The theory of "cold dark matter" (developed in part by one of the authors of this article) showed how these fluctuations could produce the sort of cosmic structures we actually observe—if they were the right magnitude. In 1992, the COBE satellite discovered differences of just the right magnitude. COBE was the first instrument with adequate sensitivity to detect such extremely small differences (only about one part in 100,000) in the temperature of the cosmic background radiation coming from different directions in the sky. When you look at a star that is ten light years away, you are seeing light that left that star ten years ago, and thus you see the star as it was then. Similarly, the cosmic background radiation shows us what the universe was like some 14 billion years ago. The small temperature differences that we detect correspond to the slightly different densities that existed when the universe first became transparent, about 300,000 years after the Big Bang.

Most of the matter in the universe appears to be some sort of "dark" (that is, invisible) matter that is unlike the ordinary matter of which planets, stars, and dust are made. Dark matter is not made of atoms, nor even of the building blocks that atoms are made of—protons, neutrons, and electrons. Dark matter engulfs every visible galaxy, in an invisible halo extending outward many times the radius of the visible galaxy, and its gravity holds the visible galaxy together. We do not yet know what the dark

matter is, although many experiments are now in progress to try to detect it directly or indirectly.

One way to think of gravity is as a warping of space that tells matter how to move while matter simultaneously tells space how to warp. Gravity never sleeps. For 14 billion years it has been amplifying the minuscule original variations in density. When any region reaches about twice the density of typical regions its size, gravity wins out over expansion. The region reaches a maximum radius, stops expanding, and starts falling together. Through a process wryly called "violent relaxation" by its discoverer, English astrophysicist Donald Lynden-Bell, the collapsing dark matter quickly reaches a stable configuration that is about half the maximum radius reached during the expansion phase, but denser in the center and less dense farther away. It is apparently this process that creates the galaxies and clusters of galaxies that we observe. According to the cold dark matter theory, this falling together happens earlier for smaller regions—i.e., smaller masses—because (traveling at the speed of light) gravity crosses smaller regions earlier. Thus small galaxies form first, and then grow by merging with other small galaxies. Clusters of galaxies, and larger-scale structures including superclusters, form later. The observational evidence favors this picture, but it is still being tested.

It might appear that gravity is inexorable and can never be stopped. But for everything in the universe except black holes, at a certain point gravity gets counterbalanced. Here is how it happens as galaxies form. While dark matter is collapsing on the galactic scale, on smaller scales gravitational forces between small clumps of dark matter generate velocities, and the resulting movement of the dark matter particles in all directions prevents them from falling all the way into the center.

Dark matter particles that collide can go right through each other. Ordinary matter is different. When ordinary matter (mostly gaseous hydrogen and helium) collides, it radiates away energy by emitting photons, so it does fall toward the center. If the infall of the ordinary matter were not stopped, there would be no visible galaxies, only black holes surrounded by dark matter. What stops ordinary matter from falling all the way to the center? The answer is conservation of angular momentum, the same phenomenon that causes an ice skater to spin faster when she brings her arms closer to her body, and which keeps the earth and other heavenly bodies spinning. As ordinary matter falls toward the center it likewise rotates faster about the center until its angular momentum shapes it into a disk and prevents it from falling further. Gravity is now counterbalanced by circular motion, and further collisions are infrequent. Stars form in the disk, and the result is a spiral galaxy. Collisions between these disk galaxies very likely result in the formation of both elliptical galaxies and the bulges in the centers of spiral galaxies. There is evidence that many galaxies may have had the sort of violent youth and turbulent adolescence just described, and one of the major goals of current research in cosmology is to clarify these processes. Much of this activity must have occurred many billions of years ago, since most of the large galaxies like our own Milky Way appear to have assumed something close to their present forms when the universe was less than half its present age. By the time our own sun and solar system formed, about 4.6 billion years

Worldwide, the inequalities are stark and increasing. The incomes of the richest 20 percent grew three times faster than those of the poorest 20 percent from 1960 to 1990. The fifth of the population living in the richest countries account for 86 percent of

the largest fraction incarcerated. Although the United States has the highest average income of any industrial country, it also has the worst income inequality, the largest fraction of its population in poverty, and 40 percent, while the average income of the lowest 90 percent increased only 5 percent. Inflation-adjusted average after-tax income of the top one percent of Americans increased 199 percent of families. From 1989—the peak of the last economic recovery—to 1998, the 1998 as in 1973. Most of the past decade's economic growth has gone to the upper 5 percent of families. Income disparities have increased as salaries of top executives skyrocketed during the past decade, while the average inflation-adjusted hourly wage was about the same in all stock and the top one percent own 42 percent, according to the U. S. Census Bureau. Within the United States, the wealthiest ten percent own more than 75 percent of

inequalities of wealth and power. to achieve. Equity issues arise at all levels, and they are exacerbated by growing restraint and international cooperation will certainly be needed—and neither will be easy quickly. However, as the debate over global warming demonstrates, both national self-continue to expand at the rate of the past century. We will need to slow down, and do so earth can support, but no one contends that our population or our resource use can factor of 100 just in the past century! There is disagreement about how many people the those two trends together produces an increase in global energy consumption by nearly a grown by a factor of nearly twenty-five worldwide during the same period. Multiplying a factor of four during the past century, but our consumption of energy per person has will determine the long-term future of our planet. Human population has grown by about Humanity is confronted today by unprecedented challenges. How we respond

see our problems in a new light. process of structure formation in the universe can provide a metaphor to help us humans appears to work like gravity: the rich get richer and the poor get poorer. Perhaps the Einstein famously said, "at the same level of awareness that created them." Wealth, "What is the relevance of all this to human affairs?" "Problems cannot be solved,"

between atoms in smaller planets like our earth. atoms that make up stars and large gaseous planets like Jupiter, and by chemical forces collapsing to black holes because gravity is opposed by random motions (pressure) of the galaxy bulges. And on a much smaller size scale, stars and planets are saved from stars and gas in spiral galaxies, and the random motion of stars in elliptical galaxies and the random motion of dark matter particles in galaxies and clusters, the circular motion of ultimately us—occurs when gravity is counterbalanced by motion. Such motion includes A key lesson: stability for long term development—stars, planets, life, and

ago, the Milky Way was already a mature galaxy. Once the balance was achieved between gravity and motion, our galaxy could remain stable for billions of years.

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consumption, the poorest fifth a mere 1.3 percent, according to the UN Human Development Report 1999. Although income levels are rising in some developing countries, especially in East Asia, in seventy countries with nearly a billion people consumption per person is lower today than it was twenty years ago. According to the World Bank, 2.8 billion people currently live on less than \$2 per day (in 1993 purchasing parity terms), compared to 2.5 billion people in 1987. Meanwhile, the world's richest 200 people doubled their net worth from 1994 to 1998, to more than a trillion dollars.

If income and wealth inequality continue to increase either domestically or internationally, it is difficult to see how it will be possible to persuade most people to cooperate in solving the problems of population, resource use, and pollution in order to achieve a sustainable relationship with our fragile planet.

What could play the role with regard to wealth that random and organized motion have played in balancing the attraction of gravity? This is not an easy question to answer, as Einstein said, "Politics is harder than physics." The ideal of democratic societies is to give rights and some material security to all, and this requires mechanisms for redistribution. One is the estate tax, which currently affects fewer than 2 percent of Americans. That such a tiny fraction of the population has power far out of proportion to their numbers is demonstrated by the recent decision by Congress to phase out the estate tax. Other forms of progressive taxation, such as a tax on wealth, are common in other rich nations. The only form of wealth tax in America today is property taxes to support local education, but this actually promotes inequality of educational opportunity by unfairly benefiting communities where the rich live.

One of the chief functions of nation states is the implementation of policies that promote the common good. This is much more difficult at the international level. The best solution found so far is the creation of new international regimes which reward behavior that protects the global commons of atmosphere and oceans. The negotiations that will be required to achieve this will clearly have a greater chance of success if, at least on average, the rich stop growing richer and the poor poorer. Something must play the role of motion opposing gravity to keep wealth and power from accumulating without limit and dragging us all into an economic and political black hole. The fact that the cosmos accomplished this may be an inspiration for us all.