PERSPECTIVES: COSMOLOGY

Cosmic Explosions in an Accelerating Universe

Mario Livio

Will our universe expand forever or will the current expansion come to a halt, followed by collapse to a "big crunch"? What is the dominant form of energy in the universe? Modern cosmology may soon be able to answer these fundamental questions. In 1998, two groups of astronomers presented strong evidence that the expansion of the universe is accelerating, despite the inevitable slowing down induced by gravity's pull (*1*). If confirmed, these findings also suggest that the energy density of the universe is dominated not by the density of matter (producing gravity), but by the action of an "antigravity" force at the largest scales of the universe.

These unexpected conclusions were drawn from measurements of the distance to stellar explosions known as type Ia supernovae (SNe Ia). Theoretical models and observations suggest that SNe Ia arise from thermonuclear explosions of compact stars known as white dwarfs (*2*). Toward the end of their lives, stars like the sun shed their outer layers as a result of the pressure of their intense radiation and leave behind a dense core (a white dwarf). An isolated white dwarf cools to obscurity by radiating away its heat energy. In contrast, if the white dwarf has a companion star, this companion can transfer matter to the white dwarf. Once the latter reaches its maximum allowed stable mass of about 1.4 solar masses, nuclear "burning" reactions of carbon lead to a thermonuclear runaway effect (*3*). The resulting explosion disperses the white dwarf's contents into the interstellar medium, from which later generations of stars are formed.

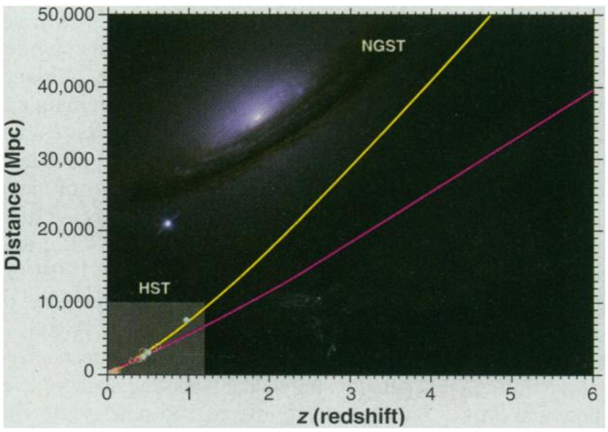
These cosmic nuclear bombs are an indispensable tool for cosmology. Their extreme luminosity (at its peak, a SN Ia can outshine an entire galaxy) allows their detection and identification at distances spanning half the universe's age. Furthermore, SNe Ia are nearly perfect "standard candles": The intrinsic brightness of 80% of all SNe Ia is nearly the same (*4*). Those differences in brightness that do exist are fairly well calibrated through a tight, observationally determined relation between the decrease in brightness 15 days after maximum light and the peak luminosity (*5*). SNe Ia are thus superb distance indicators, in the same way that the distance to a standard 100-watt bulb can be determined from the observed dimming with distance of its light.

Equipped with knowledge of these properties of SNe Ia, two teams, the Supernova Cosmology Project and the High-*z* Supernova Team (*z* denotes the redshift), recently set out to measure the deceleration that was expected in the universal expansion because of gravity. The common wisdom before 1998 was as follows: The light we see from distant objects was emitted a long time ago, when the expansion was faster, and therefore the measured speeds of such objects should be higher than those predicted by Hubble's simple proportionality law between distance and speed (*6*). The deceleration is expected to be larger the higher the mass density in the universe is (because gravity's braking force is stronger then). Determination of the deceleration thus provides a direct measure of the cosmic mass density.

The principle underlying the observational strategy is simple. On average, one SN Ia explodes in a typical galaxy every 300 years or so. A monitoring program that follows 5000 galaxies can therefore expect to find one or two supernovae per month. By taking images of the same part of the sky a few weeks apart, astronomers can detect points of light that appear or disappear, identify SNe Ia, and determine their temporal brightness variations and peak luminosity. The Hubble Space Telescope (HST), with its superior resolution, plays an important role in correctly subtracting the luminosity of the host galaxy from that of the point source, enabling accurate determination of SN Ia luminosities.

The results of the two studies came as a shock. The teams found, independently, that distant SNe Ia appeared to be receding more slowly than expected from the Hubble law (see the figure), consistent with an accelerating (rather than a decelerating) cosmic expansion (*1*). If confirmed, these results suggest the action of some repulsive force on the largest scales of the universe and imply that the universe will expand forever.

Such an "antigravity," although counterintuitive, is precisely the expected effect of the cosmological constant introduced by Einstein in a paper written during World War I (*7*). In his first attempts to apply the equations of general relativity to the entire universe, Einstein realized that without a repulsive force, gravity will collapse any static distribution of galaxies. The expansion of the universe had not yet been discovered, although indications for it existed, unbeknownst to Einstein, in the observations of Vesto Slipher (*8*). Einstein introduced a repulsive force term into the equations to support the (assumed static) universe against its own weight.



The past and the future. Measured distances to SNe Ia (in megaparsecs; 1 parsec ≅ 3.2 light years) as a function of redshift *z* allow cosmologists to distinguish between models of cosmic expansion (*12*). Some existing observations are indicated by circles; blue filled circles denote observations by the Hubble Space Telescope (HST). NGST will be able to distinguish easily between a universe with no contribution to the energy density by a cosmological constant (red line) and one with a dominant contribution (yellow line), under the assumption of a flat universe. In the background, the SN Ia SN1994d can be seen at the outskirts of galaxy NGC 4526.

After it became clear that the universe is not static but expanding, Einstein came to regret the introduction of the cosmological constant (referring to it as his "biggest blunder") and retracted it in 1931. It was another great cosmologist, Yakov Zeldovich, who showed in 1967 that, if one associates an energy density with the repulsive cosmological constant, this energy has the same effects as the energy associated with the quantum vacuum. In quantum mechanics, the vacuum is bubbling with virtual pairs of particles and antiparticles that appear and disappear on time scales of 10^{-21} seconds. The vacuum has a negative pressure (like suction), which in the

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context of general relativity results in a repulsive gravitational force. The measurements of accelerated expansion (*1*) are consistent with the energy density of the vacuum (or the cosmological constant) contributing about 70% of the total cosmic energy density. Current theories cannot explain the value of 70%, but it is consistent with recent measurements of the anisotropy of the cosmic microwave background, which suggest that the matter and vacuum energy together account for an amount close to the critical density that makes the universe geometrically flat (*9*).

One may ask whether the supernovae may somehow fool us into believing that we are observing accelerated expansion. The observed effect is simply that the more distant supernovae are dimmer than expected by about 25%; could this dimming be caused by other effects than accelerated expansion? This is a very relevant question, particularly in view of the fact that the precise progenitor systems of SNe Ia are not known. There is strong evidence that the exploding star is an accreting white dwarf, but the nature of the companion star is not known. The cannibalized star could be another white dwarf that merges with the "hungry" object, or it could be a normal star. Is it conceivable that nearby SNe Ia are formed by one type of system, whereas the more distant supernovae are formed by the other type? This could result in a systematic difference between the nearby and the distant samples, which could provide an alternative interpretation of the data. Recent theoretical work indicates, however, that it is not very likely that the nearby and distant populations of SNe Ia are dominated by different progenitor classes (*10*). Detailed calculations show that dominance by two separate classes would have resulted in a larger diversity in the local sample of SNe Ia than is observed.

Another potential alternative to accelerated expansion could be obscuration by dust. But in that case, one would expect the distant supernovae to appear redder, because dust grains filter blue light more than red, as they do during sunsets on Earth. This is not observed (*1*).

More observations of distant SNe Ia, and more theoretical work on the nature of their progenitors and on other potential evolutionary effects, will be required before one can safely conclude that the cosmic expansion is indeed accelerating (*11*). Observations of SNe Ia at higher redshifts will be particularly important. When the universe was half its present age, gravity in the denser universe must still have had the upper hand over the cosmological constant, and the expansion should have been decelerating at that time. A direct observational confirmation of this transition from slowing down to speeding up would be very difficult to mimic by evolutionary or other systematic effects, and the accelerated expansion would thus be confirmed.

Once the Next Generation Space Telescope (NGST) is launched in 2008, detection and identification of SNe Ia at even higher redshifts will become possible. At these distances, the difference between a universe dominated by matter and one dominated by the cosmological constant will become crystal clear (see the figure).

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PERSPECTIVES: PLANT BIOLOGY

No Stigma Attached to Male Rejection

Hugh Dickinson

Flowering plants are a very successful group thanks to a combination of hermaphrodite flowers and self-incompatibility (SI), that is, the ability to recognize and reject their own pollen (*1*). There are two SI characteristics that are common to all plants: the generation of a male signal by pollen and the growth arrest of self pollen that lands on its own female stigma. However, the mechanisms underlying these characteristics remain unclear. Now, two papers in this issue shed light on SI in members of the *Brassica* (cabbage) family. Schopfer *et al.* on page 1697 (*2*) characterize the male recognition protein produced by pollen (SCR); and Stone and colleagues on page 1729 (*3*) identify one of the earliest components of the self-pollen rejection pathway, ARC1.

When it comes to pollination, plants face a paradox. Individual plants are anchored, relying on wind, insects, and other vectors to deliver pollen to other plants of the same species. Thus, characteristics that maximize the delivery of pollen to the stigmas of other plants have been selected for in evolution. Unfortunately, these same characteristics, combined with hermaphrodite flowers (admittedly an excellent strategy for accelerating gene flow), conspire to promote self-pollination. This in turn leads to restriction of gene flow and inbreeding. Plants have responded to this challenge by developing mechanical devices to prevent self-pollination, by having sex organs arranged far apart or sex organs that mature at different times. Recently, it has become evident that some plants are able to identify and reject their own pollen. This selective pressure on plants to outbreed (that is, not to self-pollinate) is so great that there exist at least five different mechanisms of SI (*4*). Advanced genera, such as the grasses, crucifers, and composites, are able to reject self pollen as soon as it lands on the dry surface of the female stigma; other plant groups allow all pollen to germinate in the stigma's wet secretion, and then identify and reject the self pollen tubes after they have penetrated the tissues of the style.

Many of the SI components in the female part of the flower (the carpel, stigma and style) have been identified, whereas those in the male part (anther) have not. Luckily, the genetics regulating SI are comparatively simple. For example, in the Solanaceae (the family that includes tobacco, potato, and tomato plants), SI is controlled by a single multiallelic (*S*) locus—the haploid pollen carries one allele and the diploid stigma, two. If the pollen and stigma share an allele (of which there are commonly up to 50), the pollen is

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