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The past and the future fate of the universe and the formation of structure in it

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ABSTRACT The history and the ultimate future fate of the universe as a whole depend on how much the expansion of the universe is decelerated by its own mass. In particular, whether the expansion of the universe will ever come to a halt can be determined from the past expansion. However, the mass density in the universe does not only govern the expansion history and the curvature of space, but in parallel also regulates the growth of hierarchical structure, including the collapse of material into the dense, virialized regions that we identify with galaxies. Hence, the formation of galaxies and their clustered distribution in space depend not only on the detailed physics of how stars are formed but also on the overall structure of the universe. Recent observational efforts, fueled by new large, ground-based telescopes and the Hubble Space Telescope, combined with theoretical progress, have brought us to the verge of determining the expansion history of the universe and space curvature from direct observation and to linking this to the formation history of galaxies.

Cosmological Models. Starting from the small size scales of elementary particles, the complexity of the universe seems to increase with the physical size of the system under consideration. However, theoretical considerations predict, and direct observations confirm, that on the largest scales the universe becomes simple again: isotropic and statistically homogeneous. There is no preferred direction, and any sufficiently large subvolume of the universe has the same gross properties as any other.

These two properties, in conjunction with General Relativity, restrict the possible global structure of the universe to a well defined set, the Robertson–Walker metrics. None of these metrics has (stable) static solutions, and therefore the universe must either expand or contract. The universe is expanding now, at a rate that implies that it started from a hot initial state of vanishing extent about 10–15 billion years ago, the so-called Big Bang.

Exactly how the universe expanded to its present state depends on the initial expansion rate and its subsequent deceleration or acceleration. Any mass in the universe will decelerate the initial expansion.

Conversely, a cosmological constant, Λ, which may arise from vacuum energy and would act like a repulsive force accelerating the expansion of space itself, has come in and out of fashion repeatedly (2). Originally, Λ was introduced by Einstein to construct a static model of the universe, an idea dismissed as soon as Hubble found that the universe in expanding. But Λ has recently been revived as a possible way to reconcile the inferred low mass-density of the universe (which by itself would imply a hyperbolic geometry of space) with the prediction of most inflation scenarios that space is flat.

On the experimental side, the task is to decide in which of these possible universes we live. As the set of possible universes differs in its expansion history, its mass content and the overall curvature of space, it leads to differing testable predictions of how bright distant objects, whose light has been traveling to us while the universe expanded, should appear.

The Formation of Structure and of Galaxies. This overall expansion of the universe is paralleled by the hierarchical formation of structure in the universe. Observations of the cosmic microwave background (3) show that the universe was initially exceedingly smooth (fractional density contrasts of $<10^{-5}$) on the observable scales. Yet, stars, or human bodies, are now 10^{28} times denser than the mean over the universe. Gravitational instability, that fact that slightly denser patches exert a net force on the surrounding material and hence increase their density contrast, is widely accepted as the dominant mechanism that creates the structure in the universe from stars, to galaxies, to galaxy clusters and "large-scale structure." Over a vast range of scales up to a few percent of the observable size of the universe, mass is now correlated, i.e., the presence of mass makes the presence of nearby mass more likely. In particular, sufficiently dense regions decouple from the overall "Hubble" expansion, collapsing and forming bound, virialized systems that range in mass from 10^6 to 10^{13} times the mass of the Sun, $M_\odot$, and which we identify with galaxies. These systems may subsequently merge with nearby other ones in inelastic collisions, forming bigger systems. It has become clear over the last 20 years that an unidentified ubiquitous constituent of the universe, called dark matter, dominates the mass density of the universe, and hence this gravitational self-organization process. Yet, to be a galaxy, which is defined as a system of stars, the initially gaseous, baryonic material confined within the collapsed dark matter structures must be turned into stars. The overall morphology, the structural parameters, and the stellar content of the resulting galaxy depends on the relative time-ordering of (*i*) the collapse and merging and (*ii*) the formation of stars. The complex geometry of the situation precludes an analytic treatment of this situation, and numerical simulations face the problem that the mass scales involved range from the galaxy as a whole to stars. Only recently has the state of numerical simulations evolved to the point where larger scales ($\approx10^7$–10^{12} $M_\odot$) are directly simulated and combined with analytic parameterizations for the smaller scales (4). Semi-analytic models are being developed in parallel (5, 6) that replace most numerical calculation steps by approximations and explore—with the gained computation speed—the parameter space of initial density fluctuations, cosmological model, and star-formation efficiency. As Guinevere Kauffmann presented, these efforts (5) are leading to the conclusion that the formation of stars within the collapsing and merging dark matter halos is a delicately self-regulated process, in which the energy output of the young, newly formed stars, determines how the star-formation proceeds subsequently. Indeed, it appears that to understand galaxy formation, we first have to understand the cosmological model and its

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gravitational instabilities independently. In the final section, we describe one of the ongoing and promising efforts to determine exactly that, as presented by Alex Filippenko.

Mapping the Universe's Expansion Rate by Using Supernovae. For very distant objects, red shift is a straightforward measure of distance: radiation from distant sources is observed at longer (redder) wavelengths than it was emitted, simply reflecting the expansion of space while the light was traveling to us. Qualitatively, more distant sources have a larger red shift. However, any quantitative conversion of red shift into a physical distance measure depends on the detailed expansion history of the universe during this time, in particular on whether the expansion accelerated or decelerated. In static, Euclidean space, the flux received from a source decreases inversely proportional to the square of its distance. When light-travel time from a distant object becomes comparable to the time scale over which the universe expands significantly, then the apparent brightness of an object depends on the competition between the light "trying" to reach us and the expansion of space, which makes the path longer.

In principle, measuring the flux of standard candles (objects of known luminosity) at different red shifts and comparing it to predictions of different "cosmologies" allows us to determine in what kind of universe we live. Astrophysical sources for such experiments need not only have a predictable intrinsic luminosity but also must be bright enough to be detectable "all the way across the observable universe" with the available technology. Supernovae of type Ia, which are explosions of white dwarf stars, have luminosities that rise to a maximum and subsequently fade with a characteristic time-dependence, or light-curve. At maximum, Type Ia supernovae (SN Ia) are bright enough to be detected (with the Hubble Space Telescope and the largest ground-based telescopes) to distances from which light has been traveling to us for over half the age of the universe (7). Relatively nearby SN Ia were found not all to have the same maximum luminosity, making them seemingly unsuited as standard candles. A breakthrough occurred when Mark Philips (8) found that the maximum luminosity correlated well with the shape of the light-curve, in the sense that intrinsically dimmer SN Ia faded faster: SN Ia, though not standard candles, had intrinsic peak luminosities that could be predicted to within 10%!

After this discovery, a number of large and coordinated efforts (7, 9, 10) were undertaken to find SN Ia at great distances to compare their observed peak brightnesses to the values predicted for different cosmologies, given their red shift and inferred intrinsic luminosity. These observational programs consist of three steps: first, an imaging survey is carried out over a considerable area, trying to find a number of supernovae before, or near, their maximum; second, within 1 or 2 weeks, a spectrum of the supernova must be taken to determine its red shift and to confirm that it is of the subtype (Ia) with the desired properties; and finally, the light-curve of the supernova must be determined through repeated imaging, to permit the above correction.

The results (11, 12) to date are shown in Fig. 1, along with the expected brightness–luminosity relations for various cosmologies. The lowest curve (*Upper*) shows the expected flux–red shift relation for a universe containing just enough mass to bring its current expansion to a halt at infinity. The required mass-density is denoted as $\Omega_M = 1$), and all recollapsing cosmologies would have lines below it. Clearly, the data do not favor this case. The dotted line represents a low-density universe ($\Omega_M = 0.2$), where the expansion is decelerated only weakly. The top line corresponds to a universe which is accelerating under the repulsive force of the vacuum. Surprisingly, the data seem to favor this scenario, and we may have to face the reality of a cosmological constant.

Clearly, it is too early to base such a fundamental conclusion solely on the available data (shown in detail in Fig. 1 *Lower*). However, current technology will permit an increase in the number of observed distant supernovae (thus improving the statistics) and will permit discovery of even more distant supernovae. Because the flux–red shift relations diverge toward larger red shifts, the discriminating power of each measurement increases with increasing distance.

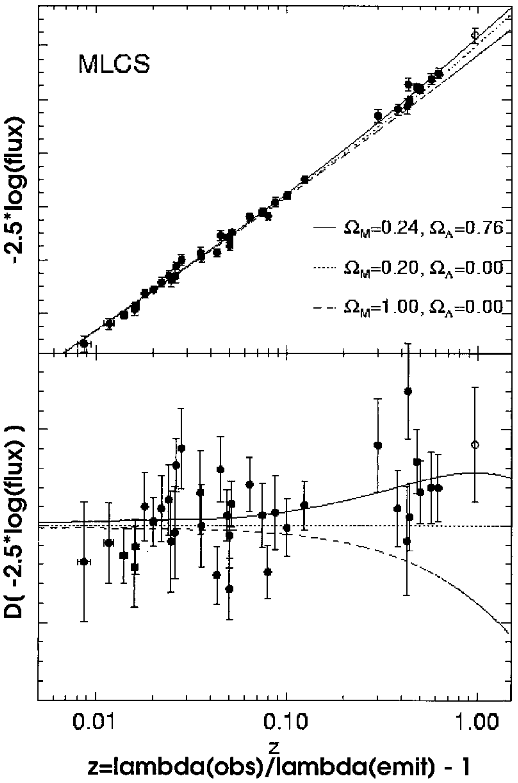

FIG. 1. Observed peak flux from supernovae of type Ia, as a function of red shift (= distance); *Lower* reiterates *Upper*, with the overall gradient removed. Shown are the predictions of different cosmological models (see text). The data favor the *Upper* model, in which the universe's expansion is accelerating, due to a cosmological constant (11, 12).

In a few years, these results can be combined with high-precision measurements of the microwave background fluctuations over small angular scales. Mapping this radiation, which was emitted when the universe was less than 1/1,000 of its present size, can be combined with the SN Ia measurements to provide the definitive answer of how our universe has expanded in the past and what will happen to it in the distant future.

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