IV. THE DISTANT UNIVERSE

Measuring the Cosmological Parameters

We have known since the late 1920s that the universe is expanding. Quantifying the expansion is done conventionally in terms of two numbers. H_0, the Hubble constant, measures the current expansion rate of the universe, and q_0 is the rate at which the expansion is slowing, or decelerating, because of the self-gravitational pull of all the matter in the universe. The standard cosmological solutions of Einstein's equations of general relativity are specified by H_0 and q_0. H_0^{-1}, the inverse of the Hubble constant, is a measure of the current age of the universe, while q_0 is a measure of how long the universe will continue to expand.

Two additional quantities that affect the expansion are the cosmological constant, , the vacuum energy density of the universe, and , the ratio of the total mass/energy density in the universe to the critical density, which is required to just bring the expansion to a halt in the infinite future. Consider first the case where $\Lambda = 0$. If $\Omega < 1$, the self-gravity of the universe is insufficient ever to stop its expansion (an "open" universe). If $\Omega > 1$, the expansion will eventually stop and the universe will collapse (a "closed" universe).

The term represents a strange phenomenon. As noted, it measures the energy density of a vacuum, which remains constant as the universe expands, unlike ordinary matter and radiation whose densities decrease with expansion. A non-zero vacuum energy density would mean that energy is present in an empty universe even in the absence of particles or radiation. Though it seems odd, such a possibility is consistent with Einstein's theory of gravitation. The key point about Λ is that such energy generates gravity even without normal matter or radiation--hence, gravity from a vacuum. Because of this phenomenon, and because Λ remains constant as the universe expands (a vacuum cannot be diluted), the existence of non-zero Λ radically changes the dynamics of the universe. This is the key concept that underlies inflation, which is discussed in section V. If there is currently no vacuum energy density in the universe, then $\Lambda = 0$ and $q_0 = \Omega/2$; most cosmologists believe that Λ is 0, but understanding why it is so small is a profound question of fundamental physics.

The Hubble constant, H_0

The Hubble constant measures how fast the universe is expanding today. In addition, the age of the universe can be expressed as approximately $(2/3)H_0^{-1}$ (the precise value depends on and). The accurate determination of H_0 has occupied astronomers for several decades, and the scientific motivation for finding an accurate value of this critical constant has become ever stronger. Another key use of H_0 is to estimate the physical distance and size of objects that have measurable redshifts. For example, the size of the largest structures in the universe is related to the distance that light could have traveled in the time up to the epoch when matter began to dominate over radiation. The corresponding size scale today is an important relic of the Big Bang, but its value is proportional to H_0^{-2} and therefore suffers from the current uncertainty. An accurate measurement of H_0 is crucial for assessing whether the detailed models of the evolution of structure in the universe can be reconciled with a wide range of observations.

Current estimates of H_0 range between 45 km/s per megaparsec (a megaparsec is about 3 million light-years) and 90 km/s per megaparsec. A value near 45 to 50 is considered low and 80 to 90 is considered high. If $\Lambda = 0$ and $\Omega = 1$ (the theoretically preferred values for these parameters), then $H_0 = 50$ km/s per megaparsec means an age of 13.3 billion years, and $H_0 = 90$ km/s per megaparsec means 7.4 billion years. A fundamental reality check comes from requiring the oldest stars in our galaxy to be younger than the age of the universe. This requirement, a logical necessity, sets an upper limit to H_0. Astronomers' best estimates of the age for such globular cluster stars are near 15 billion years, in conflict with the smaller value of the age of the universe estimated by high values of H_0.

Ground-based facilities and techniques have improved dramatically over the past three decades, yet H_0 still remains uncertain to almost a factor of two. The problem is that different techniques and different research groups get discrepant values for H_0. This is a sure sign that unknown systematic errors exist. Which value is correct? The successful repair of the Hubble Space Telescope (HST) has enabled that instrument to help resolve this long-standing issue. The HST observations employ a well-established astronomical technique that relies principally on using Cepheid variable stars in other galaxies as "standard candles" of known luminosity. The technique provides estimates of the distance to other galaxies. The distances, together with the recession velocities measured by the redshifts of their spectra, permit determination of the value of H_0. Recent results derived from HST observations yield a value of H_0 = 80 17 km/s per megaparsec, consistent with low values of the age-below 10 billion years. The resulting conflict with estimates for globular cluster ages may emerge as one of the most exciting cosmological questions of the next decade. Solving this problem could require major changes to stellar evolution theory, or even non-zero values for Λ.

The planned refurbishment of the HST with a new, advanced camera in 1999 should enable it to make an even more accurate calibration of the cosmic distance scale and a more definitive measurement of the Hubble constant. However, because of the critical conflict between the estimated ages, it is clearly vital to verify the HST value by alternative, independent means. These include methods based on the detailed study of supernova atmospheres, the attenuation of CMBR radiation as it passes through the hot gas within galaxy clusters (the Sunyaev-Zel'dovich effect), and the difference in arrival time between separate components of gravitationally lensed quasars (discussed below). All these approaches offer alternative measurements of H_0.

The deceleration parameter, q_0

Measuring q_0 directly requires measuring the change in the universal expansion rate over a large range of cosmic time. This is done using "global" cosmological tests extending over large enough distances that the travel time of light is an appreciable fraction of the age of the universe. The basic idea is that the size and appearance of a distant patch of the universe, as viewed from our vantage point, depends both on how the universe expands (its global geometry) and on the bending of light by the gravity of intervening matter.

Extensive efforts in the 1960s and 1970s to study the apparent luminosity or size of distant objects, such as very luminous galaxies, were based on the hope that these objects were constant in brightness. These efforts were mostly abandoned after it was learned that the intrinsic luminosity of these standards probably changed significantly with time because of galaxy evolution. Recent studies of the apparent size of features in distant radio galaxies might provide a new way to measure q_0. Direct counts of galaxies as a function of measured redshift can also be a powerful probe of the curvature of space-another name for q_0. This test was attempted in the last decade, but again yielded ambiguous conclusions. With improved modeling of the evolution of galaxies and a major effort to obtain spectra of a large sample of faint galaxies, this test might prove to be an effective way to measure both q_0 and . Cosmological models with different values of q_0 and predict different volumes of space for a given observed redshift, and the number of galaxies is a measure of the size of that volume. This volume evolution affects not only the number of quasars, supernovae, or galaxies at any redshift, but also the number of potential gravitational lenses (discussed below). Preliminary results from a study of quasar images with HST suggest that lensed quasars are relatively rare. Models with large overpredict the number of observed gravitational lenses; therefore, is not large.

The density parameter, Ω

Without going to cosmological distances, it is possible to measure the density parameter , by means of so-called local tests. Many of the local tests "weigh" local structures by applying the virial theorem, which states that the kinetic energy of a self-gravitating system should be approximately equal to its potential energy. Since the motion of luminous galaxies must be observed to estimate the kinetic energy of the system, only the component of the mass density clustered with luminous galaxies can be examined in this fashion. As noted earlier, such measurements tend to give low values of Ω, around 0.1 to 0.2. However, as mentioned in the discussion of cosmic velocity flows in section III, there may be a component of dark matter clumped in sizes larger than clusters of galaxies but smaller than superclusters. Cosmic velocity flows may be detecting structures on this scale, giving values of Ω near 1. If there exists a perfectly smooth background of mass density unclustered with the galaxy distribution on any scale, it can be detected only by its effects on the curvature of space, in the global measurements of q_0.

Deep Imaging of Galaxies

Galaxies have been used as beacons to map the distribution of matter in the universe ever since they were recognized as independent systems of stars. As described above, the "local" distribution of galaxies shows a complicated network of structures. When averaged over the largest distances, many billions of light-years, the distribution of matter is expected to be more homogeneous. Current research programs on very distant galaxies have two distinct goals. The first is to use the number of visible galaxies as a measure of the surveyed volume. If galaxies were stationary and the geometry of space were determined by the rules of euclidean geometry, then the number of galaxies seen would be roughly proportional to the cube of the distance probed (N r^3). When the effects of redshift and non-euclidean geometry are taken into account, the number of galaxies is expected to increase more slowly than r^3 at larger distances, as is indeed observed. (If these effects were not present, the night sky would not be dark! This is known as Olbers's paradox.) Questions about the geometry of the universe-is space positively or negatively curved, infinite or finite?-can be related by general relativity to the dynamics of the expansion (will the universe expand forever, or will it stop expanding and collapse in a Big Crunch?). Thus, measuring the curvature of the universe in the past can be used to predict the expansion of the universe in the future.

The second use of distant galaxies is to probe for signs of evolution of galaxies and of the clustering of galaxies in the universe over the billions of years during which their light has been traveling to us. The notion is that a galaxy seen at an earlier stage in its life should have more gas available out of which to form new stars, and consequently it should appear brighter and bluer (when adjusted for redshift) because of the presence of many massive, hot young stars. A trend to bluer colors in fainter galaxies has been detected, and its detailed interpretation is a subject of active current research.

Evolution of Large- Scale Structure Back in Time

Since density fluctuations tend to grow, the amplitude of the density variations associated with the large-scale structure must have been smaller when the universe was younger. The unique capability of large telescopes to look deep into space corresponds to being able to look back in time-cosmologists can map the distant universe and see the galaxy distribution as it was billions of years ago. By comparing different depths in space, cosmologists can in effect "make a movie" of the developing structure. Successive scenes in the movie are first galaxy formation, then cluster formation, and finally superclustering today. Present optical and x-ray data hint strongly that clustering in the universe continues to grow rapidly, but these observations are still primitive. The evolution of galaxies and large-scale structure is a sensitive probe of alternative models of structure formation, but one that has been little utilized to date. With the completion of giant new optical telescopes (such as the Keck (Figure 5), the Gemini, and other large telescopes under construction), as well as the refurbishment of the HST with a new, advanced camera, progress in this important field should accelerate.

Looking all the way back to a time when the universe was only a quarter of its present age requires maximum light-gathering power since very distant galaxies must be observed. There are several requirements for such studies-the largest possible optical-infrared telescopes with wide fields of view; spectrographs capable of measuring many galaxies simultaneously; the largest possible optical CCDs and infrared array detectors; and deep surveys in other wavelengths, including radio and x-ray regions.

Supernovae, Quasars, and Absorption Line Systems: Probes for Cosmology

In a closed cosmological model (e.g., $q_0 \geq 0.5$, $\Lambda = 0$), space is positively curved and finite. A two-dimensional analog is the curved and finite surface of a sphere. In an open model, space is negatively curved and infinite. A two-dimensional analog is a hyperboloid, which is shaped like a saddle. At a given redshift, sources of the same intrinsic luminosity appear to be larger and brighter in a closed universe than in an open universe, because of the focusing effects of the curvature and the more rapid deceleration. Astronomers endeavor to identify and employ classes of bright sources of known or calculable luminosity as "standard candles." By measuring the apparent luminosity at various redshifts of these sources, cosmologists can determine whether the universe is closed or open. Supernova explosions provide sources of this kind because their intrinsic brightness is governed by the physics of the explosion, of which there is good theoretical understanding.

Figure 5. The first Keck telescope, atop Mauna Kea, Hawaii. This 10-m-diameter optical telescope is the first in a new generation and will be joined by the second Keck telescope.

Quasars are star-like objects with large redshifts and inferred luminosities that are often hundreds of times those of normal galaxies. They are thought to occur in the nuclei of galaxies, but the conditions required for a galaxy to harbor a quasar are not known. Quasars show strong evolution in the sense that they emitted much more energy at earlier cosmic epochs, but why this is so is also unknown. Moreover, the observed rapid variation in brightness of individual quasars is not understood. The task of understanding the nature and origin of quasars is still at the forefront of cosmological research.

Quasars can serve as background lamps against which absorption from intervening material can be detected spectroscopically. The material may be in the form of gas in galaxies (the galaxy itself may or may not be visible) or in the form of intergalactic clouds of gas that have never been processed through stars. The technique has exceptionally high sensitivity to small amounts of material, and so it provides a probe of the universe that is independent and complementary to that provided by visible galaxies. The change in the average number of absorbers as a function of redshift is an important diagnostic for understanding the evolution of these objects. Spectroscopic attributes of the absorbers can tell us about their physical properties as well as the intensity and spectrum of the intergalactic radiation falling on them.

These absorption studies have shown that the absorbing gas occurs in lumps, and that there is little neutral hydrogen in a smoothly distributed intergalactic medium. One explanation of this lack of neutral hydrogen is that, at some point, the entire universe was reionized--heated so hot that hydrogen atoms were broken up into their constituent protons and electrons. But if the universe was reionized, what were the heating agents and when did the reionization occur? On the other hand, if there was no epoch of reionization, what conditions yielded such high efficiency in clearing intergalactic space of neutral hydrogen? This field will be advanced with the further identification of close pairs of quasars to provide nearly coincident lines of sight, as well as the further identification of galaxies likely to be responsible for individual absorption systems. At present these absorption lines provide one of our only probes of nonluminous structure at high redshift. Continued theoretical as well as observational studies provide our best hope for an accurate picture of the intergalactic medium and its evolution.

Gravitational Lenses

What are gravitational lenses, and why are they important?

The gravitational lens is a relatively newly discovered phenomenon that is emerging as an important research tool in cosmology. Lensing can be produced when light propagating through the universe is deflected by the gravitational field of a massive object positioned near its path. Gravitational lensing effects are similar to those produced when a glass lens deflects the path of light rays in a camera, but the deflections are too small to be observed in a terrestrial laboratory. However, in 1979 the discovery of a double quasar, which was actually twin images of the same quasar, provided the first convincing demonstration that gravitational lensing produces observable effects in the cosmos.

Gravitational lensing has been observed in several forms. There are now approximately 20 known cases of strong lenses in which two or more images of a background source are produced by a foreground gravitational lens. This striking phenomenon is the most easily recognized, and early work in gravitational lensing concentrated on the study of strong lensing. Figure 6 shows an Einstein cross, a lens that produces four multiple images of a distant quasar with a central object. Another manifestation is weak lensing, in which background sources, though not multiply imaged, are visibly distorted by the presence of the intervening gravitational field

(Figure 7). Changes in the gravitational field, produced for example by relative motion of the source and the lens, have been observed through the changes in the magnification of the source that produce variations in the source brightness. The multiple images found in strong lenses are associated with different propagation times from source to observer, and the resulting time delay between the arrival times of signals from each image has also been observed. In the best studied case, the measured time delay from one image to the other is approximately 1.5 years. Finally, the presence of a population of massive objects, such as galaxies, screening a population of background sources, such as quasars, produces lensing effects detectable through statistical analysis of the ellipticities of the lensed images.

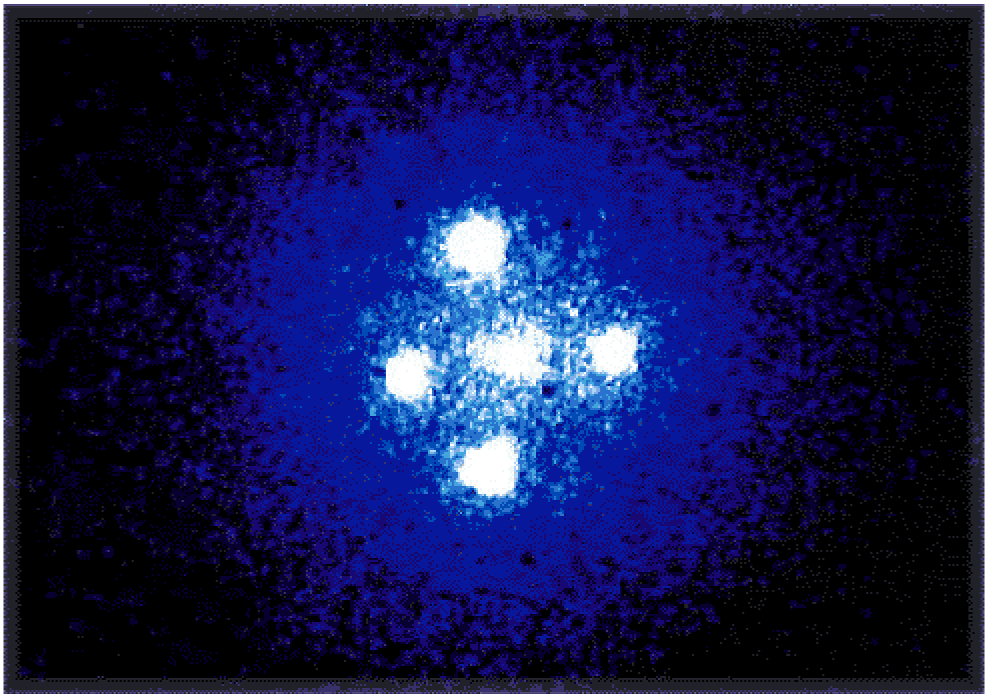

Figure 6. The image of an Einstein cross produced by a gravitational lens 2237+0305. A distant quasar is precisely aligned behind the foreground galaxy whose gravitational field deflects the light from the quasar into four distinct images. (Courtesy of the Space Telescope Science Institute.)

Gravitational lenses provide a unique opportunity to infer the properties of the space-time in which they are embedded, the mass distribution of the lens, and the detailed properties of the background source. These opportunities are being realized as instruments improve in angular resolution and sensitivity, as our data-handling capabilities grow, and as increased computational capacity can be applied to theoretical analyses of lenses.

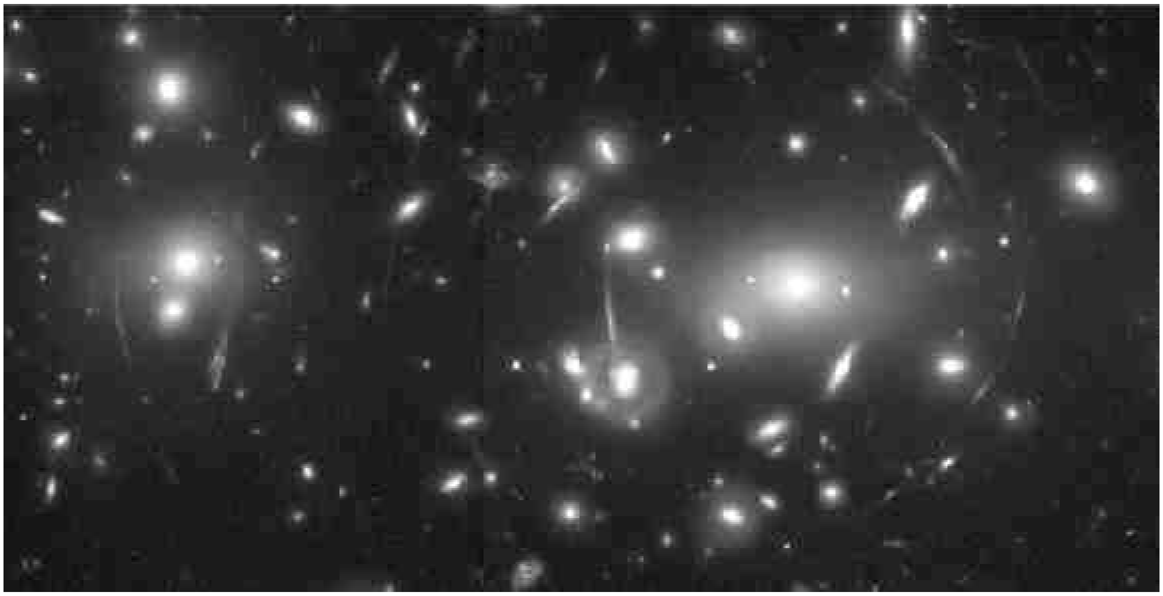

Figure 7. Gravitational lensing of distant background galaxies by the potential well of a foreground cluster of galaxies. The distinctive arcs are a result of strong lensing in which the images formed by the lens encircle the optical axis of the system. (Courtesy of Space Telescope Science Institute.)

Measuring cosmological parameters with gravitational lenses

Because the light rays in a gravitational lens system propagate across large distances, their interpretation is subject to assumptions about the cosmological model. Observations of gravitational lenses therefore provide a way to measure or constrain the cosmological parameters H_0, q_0, Λ and described above. The Hubble constant is most directly inferred through a measurement of the time delay in the arrival of signals from the multiple images of a strong gravitational lens. The success of this technique is predicated on a precise understanding of the distribution of the matter in the lens, which must be reconstructed purely from the properties of the images. The statistics of gravitational lenses provide a powerful technique for the determination of cosmological parameters. For example, the frequency of occurrence of gravitational lenses depends strongly on the geometry of the universe. A high-redshift quasar is twice as likely to be gravitationally lensed in a $q_0 = 0$ universe as in a $q_0 = 0.5$ universe. Similarly, a high-redshift quasar is about 15 times more likely to be strongly lensed in a flat universe if $\Lambda = 1$ than if $\Lambda = 0$. Current limits appear to preclude models in which the term dominates the universe; improved constraints will be possible with improved imaging using the newly completed Very Long Baseline Array (VLBA), the HST, and ground-based optical telescopes equipped with adaptive optics systems.

Gravitational lensing, along with the spectroscopic absorption studies of intergalactic clouds, is one of the few techniques in cosmology in which our ability to detect the presence of matter does not require that the matter be luminous. Lensing can address the important issues of the nature and the distribution of dark matter on a wide range of scales. For example, the measurement of weak lensing, in which faint background galaxies would be expected to have correlated orientations due to the gravitational distortions induced by the foreground mass distribution, can be studied by careful analysis of high-quality images covering large fields of view. Recent theoretical analysis describes how this method can provide a solid measurement of the matter-clustering amplitude of the foreground mass distribution. Elongated images are more likely to occur near large concentrations of matter, such as clusters of galaxies, where several spectacular examples have already been observed (see Figure 7).

On small scales (stellar masses or smaller), the most effective technique is observation of microlensing, the variations in flux detected from a background source due to the focusing of rays caused by the passage of a massive object through the beam. By searching for microlensing events in the direction of nearby concentrations of stars, three separate research groups have found spectacular examples of large flux amplification (up to a factor of 14!). These events might imply that the dark matter comprising the halo of our galaxy is dominated by compact stars that were never sufficiently massive to ignite their nuclear furnaces and become luminous, or that there exist many more remnants of normal stars in an extended disk of our galaxy than had been anticipated. The time behavior of one well-documented microlensing event in the direction of the nearby Large Magellanic Cloud is shown in Figure 8.

The study of gravitational lensing has already provided important results in cosmology. Improved instrumentation and data-handling techniques are allowing astrophysicists to recognize and exploit subtle manifestations of gravitational lensing, as well as the striking examples of strong lensing. With the planned capabilities of future generations of instruments, and the growing interest in gravitational lensing as an observational tool, it is likely that this trend will continue.

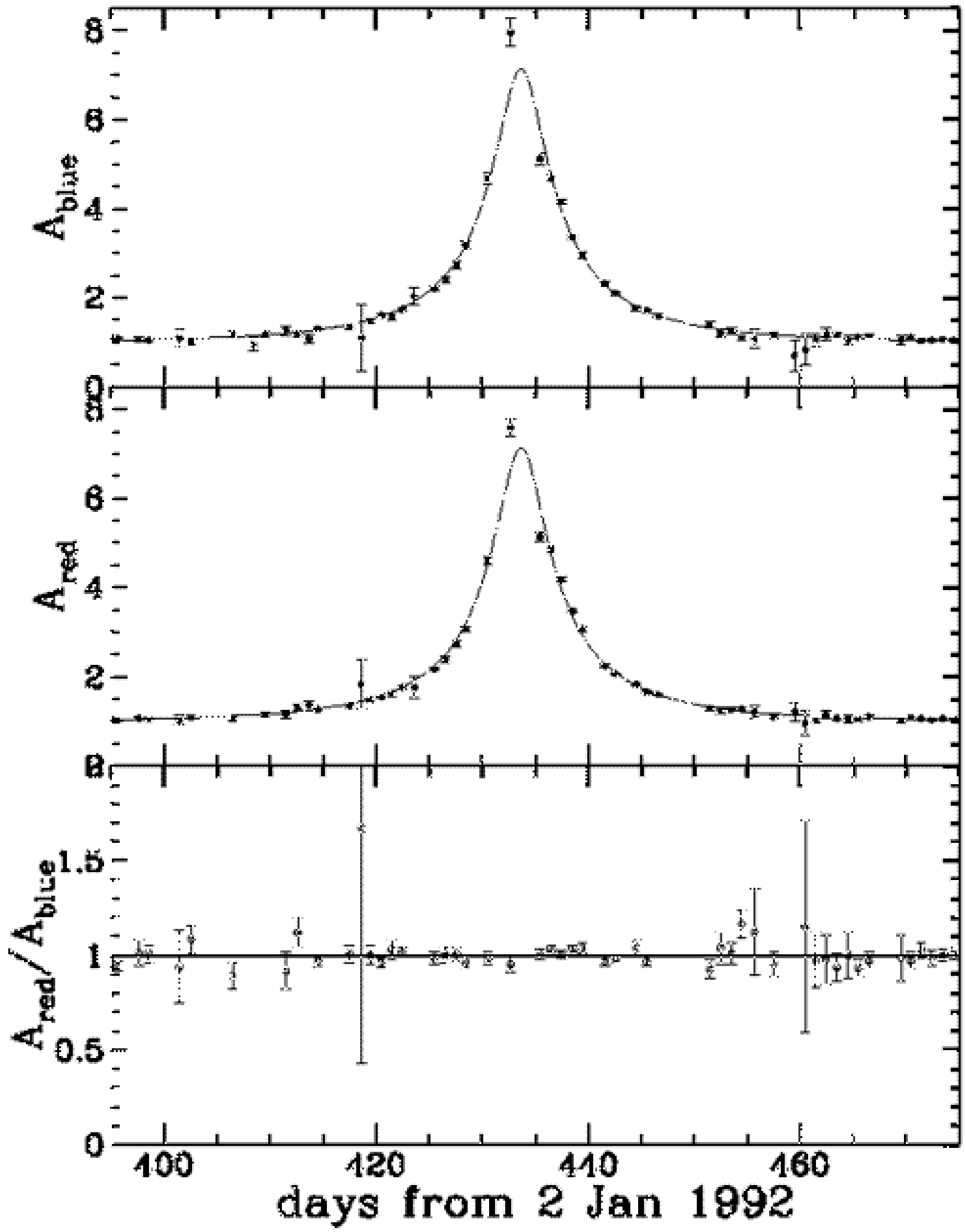

Figure 8. The first well-documented microlensing event, detected when a faint object of approximately 0.1 solar mass crossed very close to the line of sight between Earth and a star in the Large Magellanic Cloud (LMC). The gravitational lensing caused by the object has focused and intensified the light detected from an LMC star in the background, causing the peak in the brightness at both blue (A_{blue}) and red (A_{red}) wavelengths recorded as a function of time. (Courtesy of Charles Alcock for the MACHO Project.)