Cosmologists in the dark

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Abstract.
We review the present status of cosmological discoveries and how these confirm our modern cosmological model, but at the same time we try to focus on its weaknesses and inconsistencies with an historical perspective, and foresee how the on-going big cosmological projects may change in the future our view of the universe.

Motto: "O dark dark dark. They all go into the dark, The vacant interstellar space, the vacant into the vacant" (T. S. Elliot, in "East Coker", No. 2 of The Four Quartets)

1. Introduction

Cosmology is the study of the universe as a whole, it is the science of the large-scale structure of the universe, its origin, and its evolution from the early times into the future. In this context universe means all that exists in a physical sense, not only the part of the universe that we can observe (Ellis 2007) using our telescopes and detectors on the ground and in space. The observable universe could certainly be a tiny fraction of the whole universe, even an infinitesimal fraction if the universe were infinite.

Cosmology today can be considered a branch of physics with a slight difference: we cannot experiment with the subject of our discussion, the universe, we can only observe it and model it.

The statement that "we are living in the era of precision cosmology" is certainly one of the most heard ones in the last 10 years in conferences, seminars and talks about the field. There is no doubt that within this period, modern cosmology has expanded from what Allan Sandage (1970) once described as "the search for two numbers", meaning the Hubble and the deceleration parameters. These and a few more numbers are conforming now a self-consistent set, derived from several different cosmological observations: high-redshift supernovae, fluctuations of the Cosmic Microwave Background (CMB) radiation, the large-scale structure of the universe, gravitational lensing, etc., but the emergent concordance cosmology provided by all these probes (sharing all beautiful hard-to-get cosmological data) is in a sense disappointing. We need to claim for the existence

of gravitating non-baryonic dark matter of unknown nature, and furthermore, the universe today has to be dominated by an exotic dark energy, acting as a repulsive gravity. Some cosmologists take those theories as seriously as Ptolemy and colleagues took epicycles and deferents to reconcile the geocentric model with the early observations of planetary motion, or how physicists prior to the Michelson-Morley experiment considered the aether of undoubted certain existence. Since cosmology is not an experimental science, but an observational one, we must take this into account when we try to falsify our theories in the sense advocated by Karl Popper (1959): our requirement is just that our theories should be consistent with present and future observations. In contrast to what happens in experimental physics, astronomers cannot modify the object under study. They cannot control it in any way; they only can observe it many times, with different exposure times or at different frequencies or observe many objects of the same type (Kolb 2007a). This fact inevitably conditions the way we do our research and plan our observations.

2. The establishment of the present cosmological paradigm

Research done during the previous century established our Standard Cosmological Model. Cosmology started to be considered a scientific discipline with the introduction in 1917 of the General Theory of the Relativity by Albert Einstein, which acts as theoretical framework for the development of the cosmological models. In the decade of 1920 Alexander Friedmann and Georges Lemaître suggested solutions to the equations of Einstein that provided dynamic universes, in expansion or in contraction. The discovery of the expansion of the universe carried out by Edwin Hubble in 1929 allowed for non-static models of universe that accounted for the observed expansion (the models of Friedmann-Lemaître that make use of the Robertson-Walker metric).

The idea that the universe might experience constant change locally and yet be on average invariable for very long times or eternity can probably be found among the ancient Greeks (Democritus). But the modern version dates firmly to 1948 and a pair of papers by Bondi & Gold (1948) and by Hoyle (1948), suggesting that the expansion of the universe, as implied by Hubble's and later work (Hubble 1929), is perfectly real but that additional matter is created at just the rate needed (about one atom per 10^6 cm^3 per Hubble time) to keep the mean density constant, new galaxies being constantly formed from that new matter. A few of the observational objections to this picture would disappear if the new material consisted of about 1 helium atom for every 10 hydrogens, and perhaps 5 times as much in some form of dark matter capable of gravitational (and perhaps weak) interactions only, though DM was not, of course, part of the Bondi-Gold-Hoyle picture. Their intentions were at least partially philosophical, for instance to bring the process of creation within the observable universe.

The rate of creation required is very far below observability. But a pure steady state universe requires that the average mass and luminosities of galaxies, their clustering properties, and their propensity to emit strong radio fluxes must not change with redshift (time or place). The average age should be 1/3 of the Hubble time, making our Milky Way unusually old (though critics who had not thought through the issues tended to claim that the absence of young galaxies

was the greater objection). But it was the requirement for a constant percent of galaxies to be strong radio sources that already cast serious doubt on the steady state model before 1960. Counting radio sources (Scheuer 1957; Ryle & Clarke 1961) was a disputed issue, but after the discovery of the redshifts for quasars (Schmidt 1963), there was no doubt that strong radio sources had been stronger and more common in the past (Schmidt 1968), providing evidence against the steady state model.

It was also not easy to reconcile the apparent brightness and angular diameters of distant galaxies with steady state requirements (since average properties must not change with time), and if creation was of pure hydrogen, then turning one-quarter of the material to helium in stars implied galaxies 5-10 times brighter than the ones we see.

In addition, clearly, there must not be anything found in the universe that could only have arisen under conditions very different from the present ones. Thus the 1965 discovery of the cosmic microwave radiation (Penzias & Wilson 1965) was the death of the steady state model for most astronomers who had not paid much attention to the earlier problems. There remains a small group of supporters of a short quasi-steady-state model, with much less of the simplicity enjoyed by the original one and the need still to doubt the cosmological nature of QSO redshifts as well as a need for intergalactic iron filings to thermalize the CMB and colorlessly absorb light from distant supernovae. We can admire their courage without having any desire to follow their ideas.

The discovery of the cosmic background radiation emitted by the hot gas when the universe was at 3000 degrees and had an age of about $380\,000$ years was a definite support for a general acceptance of a universe in expansion, with a finite age and an extremely dense and hot beginning, in what the physicist Fred Hoyle pejoratively called Big Bang. The name settled and the theory of the Hot Big Bang became the basic cosmological model, with some of its predictions ending up with clear observable successes, as the explanation (Alpher, Bethe & Gamow 1948; Peebles 1966) of the relative proportions observed in our local environment of the light elements (helium, deuterium and lithium).

The model itself was not exempt from some paradoxes, as the problem of the extreme homogeneity and isotropy among parts of the universe that had never been in causal contact (due to the finiteness of the light speed) or did not provide a convincing reason to justify that the density of matter and energy was so close to the critic value (flatness problem). With the introduction of the concept of inflation (Guth 1981) that suggests a phase of fast acceleration of the cosmic expansion in the early stages of the universe, some of these problems are solved, from the theoretical point, at the expense of introducing an additional hypothesis, which certainly is still not completely proved by observations.

3.   The dark side

3.1.   Dark matter

In the 1970s the need to advocate for the existence of a considerable quantity of dark matter (DM) in the universe was clearly established. The measurement of the Doppler shifts of star light in the external parts of the spiral galaxies shows an unexpected behaviour: The velocities of stars (or HII regions) orbiting

around the galactic center did not decrease following the foreseeable Keplerian dynamical behaviour (Rubin & Ford 1970), but instead remained roughly constant to great distances from the galactic center. The presence of dark matter in the galactic dynamics was used for rescuing the works of Fritz Zwicky of the decade of 1930 from the oversight. Zwicky had to advocate the existence of this type of matter (*dunkle Materie*) to maintain the stability of the galaxy clusters (Zwicky 1933)[1]. The measurements of the average peculiar velocity dispersion in the radial direction with values of the order of 1000 km/sec in the Coma cluster led Zwicky to this conclusion. The velocities of galaxies within the cluster are a consequence of the gravitational potential associated to the total cluster mass. In this kind of virialized systems, the potential energy is related with the kinetic energy, –associated to the distribution of individual galaxy velocities– through the virial theorem ($2K + U = 0$), providing a method to estimate the total cluster mass.

Other observations carried out in the 1980s, as the emission in X-rays produced by the hot gas in clusters of galaxies or the image distortions and magnifications produced by galaxy clusters acting as gravitational lenses, have corroborated the need for dark matter.

It is essential to distinguish two aspects: existence and nature, with the former quite firmly established and the latter much constrained but still unknown. One can, in a sense, regard "dark matter" as a shorthand for a very large number of observations on many scales, indicating that mass to light ratios increase as you look at larger entities. This was pointed out in a pair of important and influential papers by Einasto, Kaasik, and Saar (1974) and Ostriker, Peebles, and Yahil (1974). These and other observations, when collectively plotted on a logarithmic scale of luminosity-to-mass ratio vs. the length scale, show a monotonic rise from unity for 1-parsec diameter young star clusters to something like 200-300 $M_\odot/L_\odot$ for the largest superclusters of galaxies and other very large scale structures explored with weak gravitational lensing. The rise does not continue on larger scales, though many back in the 1980s thought it would. Such a plot could have been made before the Second World War, using Hubble's numbers for the inner parts of galaxies, Babcock's rotation curve for M31 (Babcock 1939), Holmberg's binary galaxies (Holmberg 1940), and the data on the Coma and Virgo clusters from Zwicky (1933) and Smith (1936).

More modern data include a still large range of systems – disks of galaxies from motions of stars and gas perpendicular to them, whole clusters from X-ray and lensing data, and the very largest scale information we have from the CMB, Type Ia supernovae, and weak gravitational lensing. The only possible conclusions are either that gravity becomes monotonically stronger on large scales or that the ratio of non-luminous matter increases with length scale. The latter is by far the majority view in the astronomical community and centers around something like 23% of the closure density being in non-luminous, non-baryonic dark matter.

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[1]Zwicky was not, however, the first either to use the phrase dark matter or the first to report a number for it. James Jeans (1922) and Jacobus Kapteyn (1922) estimate the mass in the disk of the Milky Way (by method refined by Jan Hendrik Oort in 1932), reporting the presence of dark stars.

A number of ideas in modern physics imply dark matter candidates, of which the most often sought is supersymmetric partners of known particles, the lowest-mass supersymmetric particle in 4-d space time or perhaps the lowest-mass Kaluza-Klein particle in 5-d space time. Current observations and experiments are looking for three manifestations: (1) photons or $e^{\pm}$ pairs produced when DM particles annihilate today, (2) scattering of the particles in large laboratory detectors (made of NaI crystals, very pure water, or other substances), and (3) production of DM particles in accelerators like the upcoming LHC. Other viable DM candidates include axions, black holes in a few unprobed mass ranges, topological singularities, and many more exotic entities. Remembering here, as in other places in this chapter, that theories are cheap but telescopes or accelerators are expensive, we encourage our theoretical colleagues to think broadly and to deduce possible detectable consequences of their DM-candidates, particularly consequences that might be found (like gamma ray emissions or positron excesses) in projects that are being carried out for other purposes. Very large investments in programs narrowly aimed at a single candidate are harder to feel positive about (White 2007) .

3.2. Dark energy

Dark energy (DE), like dark matter, is a shorthand for a large number of observations and ideas. But in this case, an idea came first. The differential equations for a homogeneous, isotropic, relativistic universe are second-order, and so admit two integration constants. The first (in suitable units) is the Hubble parameter at some reference time. The second takes the form of a uniform density (always positive) and pressure (which can be positive or negative), with negative pressure tending to oppose ordinary gravity (McVittie 1956). Einstein called it λ and wanted it initially to permit a static universe (which turned out to be unstable). It is now generally written as Λ , and Einstein left it out of his publications after 1930. In 1934, however, R.C. Tolman included the possibility of both positive and negative values of Λ, and one of his model universes, with negative pressure Λ, expanded from a singularity to infinite size, with an empty de-Sitter universe as its limit.

Despite the frequent phrases "Einstein's infamous cosmological constant" and "Einstein's worst blunder," Λ has never entirely disappeared from the literature, serving in at least a few minds as a solution to the problem presented by a universe somewhat younger than its contents, a problem never entirely eliminated by recalibrations of the Hubble constant between 1952 and the present. De Vaucouleurs, for instance, always included Λ in his cosmological discussions, beginning in about 1956. There was another revival around 1970 in connection with the apparent excess of QSOs with redshifts close to 1.95. Eventually regarded as a selection effect, this could, in principle, have been a signature of a coasting phase in an open universe with non-zero Λ. Incidentally, the critical density case (now thought to be very close to reality) has no coasting phase, only an inflection point in the expansion parameter $a(t)$.

Observational cosmology, gradually involving many more kinds of observations than just Sandage's "search for two parameters" proceeded apace, and by the time of the 1997 IAU General Assembly in Kyoto, evidence had accumulated from large scale structure, galaxy formation simulations, ages, and big bang nu-

cleosynthesis for a flat (critical density) universe with something like 70% of the gravitation coming from negative-pressure Λ. Since then, the numbers favoured by several panel members there (4-5% baryons, $23 - 25\%$ dark matter, and the rest Λ) have been reinforced by results of studies of weak gravitational lensing, supernovae, and angular fluctuations of the CMB seen by WMAP.

For many decades cosmologists have been trying to quantify how the expansion of the universe discovered by Hubble (1929) was slowing down due to gravity. However, in 1998, two independent teams (Riess et al. 1998; Perlmutter et al. 1999) presented convincing evidence for just the contrary: an accelerated expansion. They used high-redshift Type Ia supernovae (SNe Ia) as standard candles (Phillips 1993). The behaviour of its calibrated luminosity-distance as a function of the redshift of their host galaxies ruled out the Einstein-de Sitter spatially flat cosmological model, indicating that the cosmic expansion had been speeding up during the last 5 Gyr or so. Λ was then definitively rescued from the wastebasket in 1998 with the interpretation of the luminosity-distance-redshit relation of very distant type Ia supernovae as evidence for acceleration in cosmic expansion. The two mentioned teams analyzed a set of high-z supernovae and found them fainter than expected. After ruling out possible systemic obscuration by dust or evolutionary effects, they interpreted the dimmer luminosity as a consequence of being farther away, and thus implying an acceleration in the expansion.

At this point, physicists step into the picture, asking "what is Λ apart from the integration constant that Einstein called it?[2]" And "why does it have the numerical value we find?" New words, especially dark energy and quintessence, are invented to describe it and to suggest the possibility of variation with time and perhaps space. It acquires an equation of state: $p = w\rho$, where w exactly and always -1 is just Λ back again, therefore the simplest form of dark energy is the stress-energy of empty space –the vacuum energy–, which is mathematically equivalent to the Einstein's cosmological constant, but other values of w and time variability might allow eventually recontraction of the universe or expansion so fast that it tears. These other forms of dark energy that dynamically evolve with time have been considered in the literature (Peebles & Ratra 2003) and are called "quintessence". The astronomical community has embraced very quickly the idea of accelerated expansion. The solid arguments accompanying the observations of the SNe Ia have been confirmed with spectroscopic analyses (Bronder et al. 2008; Sullivan et al. 2009) that test for possible systematic uncertainties. Their results confirm the reliable use of SNe Ia as standardized candles. Moreover, there exists other independent observational evidence supporting the accelerated expansion of the universe. For a review see Frieman et al. (2008). Amongst these probes, one of the most promising techniques is the measurement of the baryon acoustic oscillations (BAOs) in the large-scale distribution of matter in the universe (Eisenstein et al. 2005; Cole et al. 2005; Martínez et al. 2008).

Dark energy in this modern sense has been associated with the last gasp of inflation, new scalar fields, vacuum field energy, and other innovative physics

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[2]In a letter to Besso quoted by Kragh (1996), Einstein explained: "Since the universe is unique, there is no essential difference between considering Λ as a constant which is peculiar to a law of nature or as a constant of integration."

that we do not pretend to fully understand. The catch in most cases is that the natural amount should have a density of one Planck mass (10^{-5} g) per Planck volume (10^{-99} cm^3), something like 10^{120} larger than the 73% of closure density implied by the concordant observations of supernovae, the CMB, large scale structure, etc.

4. Falsifiability, confirmability, evidence and all that

Belief in a scientific theory must always be established on an objective assessment of the evidence. That several lines of evidence give the same numbers is not a perfect guarantee of correctness – Kelvin was sure he knew the age of the sun and solar system because his calculation of the cooling age of the earth gave the same 10-20 Myr as the lifetime of a solar mass star with gravitational contraction as its only energy source.

There are respectable motivations to take the Λ-CDM model seriously as a hypothesis about the universe, but this is not equivalent to declaring its unvarnished truth.

4.1. Falsifiability

For many years, the Einstein-de Sitter model was the most popular hypothesis for a dynamical description of the universe. The high redshift Type Ia supernovae were a strong evidence supporting its inconsistency. Today the evidence against this once favoured hypothesis comes from many different observations.

But the important thing of the present standard model (Λ-CDM) is that it can make predictions that can be tested by observations and therefore the theory is falsifiable (vulnerable to being shown false by observation or experiment). An example from the past in cosmology: steady state was falsified (fairly quickly, in fact, as we had already explained) because it made some definite predictions. An example for hopefully the near future: of the popular ideas out there now, inflation is surely falsifiable

a) via polarization structure of CMB and such, indeed it is looking a little weak in the knees now: polarization-sensitive CMB experiments will come very soon.

b) via detection of a stochastic gravitational wave background.

4.2. Consensus?

The consensus about the existence of dark matter is high. The evidence of its existence is clearly stronger than the evidence of the existence of dark energy. Prospects for the detection of dark matter candidates are ongoing in different experiments. There are interesting, well-motivated DM candidates (and also of course some silly ones), being the neutralino the everyone's favourite candidate for the moment (Kolb 2007b).

One of the first alternatives to dark matter was formulated by Finzi (1963) to guarantee the stability of clusters of galaxies without advocating for dark matter. Finzi's hypothesis was a modification of the gravitational Newton law in such a way that the actual attraction at long distances should be stronger than the value predicted by the Newton's Law, but probably the optimal ver-

sion of this has not yet been put forward. Two decades later, Milgrom (1983) proposed a different alternative to the dark matter based in a modification of Newtonian dynamics (or MOND for short). In this hypothesis, the Newton's second law of dynamics is modified in such a way that when accelerations experienced by objects are smaller than a certain value, the gravity force is inversely proportional to the distance, instead of to the distance squared. This modification explains rather well the flat rotation curves of the spiral galaxies (Sanders & McGaugh 2002) whose dynamics are a consequence of the luminous baryonic matter alone, with no need to claim for dark matter. Although MOND has successfully explained other cosmological observations, it does not reproduce so well the dynamics of clusters of galaxies and the observations of weak and strong lensing and the CMB.

4.3. Success?

Should we regard the "discovery" of the dark energy and the acceleration of the expansion in the universe as a scientific success? Certainly in 1998, Science magazine considered this discovery as the breakthrough of the year and we agree with that decision. This discovery put together many astrophysicists, cosmologists and high-energy physicists in a common effort trying to understand the nature of the dark energy (see for example the Dark Energy Task Force report by Albrecht et al. (2006) and the ESA-ESO Working Group on "Fundamental Cosmology by Peacock et al. (2006)). But is the discovery of the dark energy by itself a scientific success? It is certainly a crucial step, but probably the story should not be considered a success at least until it can be well explained in terms of an existing theory. As Lee Smolin (2006) says: "The discovery of the dark energy cannot be counted as success, for it suggests that there is a major fact that we are all missing." Of course, this statement does not subtract the merit to the Supernova Cosmology Project led by Saul Perlmutter and the High-z Supernova Search Team led by Brian Schmidt and other observations supporting the accelerating world models; what it means is that the presence of a non-zero vacuum energy is a problem that has to be explained in much the same way the existence of the aether was a problem that had to be explained by the physicists prior to the Michelson-Morley experiment. In that case the experiment acted denying the existence of the aether and that was the solution. In Cosmology, future planned and ongoing observations have as a major scope to understand the nature of the dark energy (Albrecht et al. 2009). Some of these projects are based on distant supernovae (Wood-Vasey et al. 2007) and BAOs (Benítez et al. 2009; Glazebrook et al. 2007; Schlegel et al. 2009; Cimatti et al. 2009).

In any case and if what you care about is things like galaxy formation and evolution, then DE was not important when most of the relevant processes were going on. As White (2007) has remarked in a recent essay DE is an interesting problem to plan astronomical observations, but it is just "one of many."

5. Conclusions

It seems clear that many of the pre-Copernican astronomers who made earth-centered models gradually more complex to match better observations thought

– according to historians, anyhow – that they were describing the phenomena, not explaining them. Are cosmologists continuously re-editing an undeclared unsuccessful model of the universe to accommodate it to new and unexpected observations? (Disney 2007). Several authors (Horvath 2008) are already declaring the crisis of the present cosmological model and advocating for the need of a paradigm shift in a Khunian sense (Khun 1962) but, at the same time, the general adherence to the mainstream concordance Λ-CDM model does not leave too much room for thinkers outside the accepted cosmic paradigm.

Does this mean that theorists or observers or both should give up on the universe and go back to studying cataclysmic variables (of which we are secretly very fond)? Certainly not! What it does mean, we think, is

1. Observers should be careful when combining many different sorts of data into a many-parameter model that they have not started off their minimization process from a place in the associated many-dimensional space that will trap them in a false minimum of values that seem to be the best possible fit but are far from the truth.

2. Theorists should put forward as many candidates as they want, but should ask whether their favorites (for instance w a smidge larger or smaller than -1) might have observable/testable consequences that can be extracted from programs and missions that have significant potential for learning other important things about the universe and its contents if the dark energy continues, as it has done so far, to act precisely like a pure, infamous cosmological constant. This, of course, especially true for candidates associated with various multiverse concepts.

As Rocky Kolb (private communication) has emphasised after reading a first draft of this manuscript: "Our goal must not be a cosmological model that just explains the observations, the ingredients of the cosmological model must be deeply rooted in fundamental physics. Dark matter, dark energy, modified gravity, mysterious new forces and particles, etc., unless part of an overarching model of nature, should not be part of a cosmological model. We may propose new ideas, but they must wither unless nourished by fundamental physics."

References

Albrecht, A., et al. 2006, arXiv:astro-ph/0609591
Albrecht, A., et al. 2009, arXiv:0901.0721
Babcock, H. W. 1939, Lick Observatory Bulletin, 19, 41
Benítez, N., et al. 2009, ApJ, 691, 241
Bondi, H., & Gold, T. 1948, MNRAS, 108, 252
Bronder, T. J., et al. 2008, A&A, 477, 717
Cimatti, A., et al. 2009, Experimental Astronomy, 23, 39
Cole, S., et al. 2005, MNRAS, 362, 505
Disney, M. J. 2007, American Scientist, 95(5), 383
Einasto, J., Kaasik, A., & Saar, E. 1974, Nature, 250, 309

Ellis, G. F. R. 2007, in Philosophy of Physics, part B, eds. J. Butterfield, J. Earman,
     North Holland and Elsevier, Amsterdam, p. 1183
Eisenstein, D. J., et al. 2005, ApJ, 633, 560
Finzi, A. 1963, MNRAS, 127, 21
Frieman, J. A., Turner, M. S., & Huterer, D. 2008, ARA&A, 46, 385
Glazebrook, K., et al. 2007, Cosmic Frontiers, 379, 72
Guth, A. H. 1981, Phys.Rev.D, 23, 347
Holmberg, E. 1940, ApJ, 92, 200
Horvath, J. E. 2008, arXiv:0809.2839
Hoyle, F. 1948, MNRAS, 108, 372
Hubble, E. 1929, Proceedings of the National Academy of Science, 15, 168
Jeans, J. H. 1922, MNRAS, 82, 122
Kapteyn, J. C. 1922, ApJ, 55, 302
Khun, T. S. 1962, The structure of scientific revolutions, Chicago University Press,
     Chicago
Kolb, E. W. 2007a, Rep. Prog. Phys., 70, 1583
Kolb, E. W. 2007b, arXiv:0709.3102
Kragh, H. 1996, Cosmology and controversy: the historical development of two theories
     of the universe, Princeton University Press, Princeton
McVittie, G. C. 1956, General Relativity and Cosmology, Chapman and Halll, London
Martínez, V. J., et al. 2009, ApJ (in press) arXiv:0812.2154
Milgrom, M. 1983, ApJ, 270, 365
Oort, J. H. 1932, Bulletin of the Astronomical Institutes of the Netherlands, 6, 249
Ostriker, J. P., Peebles, P. J. E., & Yahil, A. 1974, ApJ, 193, L1
Peacock, J. A., Schneider, P., Efstathiou, G., Ellis, J. R., Leibundgut, B., Lilly, S. J., &
     Mellier, Y. 2006, ESA-ESO Working Group on "Fundamental Cosmology", ESA
Peebles, P. J. E. 1966, ApJ, 146, 542
Peebles, P. J., & Ratra, B. 2003, Reviews of Modern Physics, 75, 559
Penzias, A. A., & Wilson, R. W. 1965, ApJ, 142, 419
Perlmutter, S., et al. 1999, ApJ, 517, 565
Phillips, M. M. 1993, ApJ, 413, L105
Popper, K. 1959, The logic of scientific discovery, Basics Books, New York
Riess, A. G., et al. 1998, AJ, 116, 1009
Rubin, V. C., & Ford, W. K. J. 1970, ApJ, 159, 379
Ryle, M., & Clarke, R. W. 1961, MNRAS, 122, 349
Sandage, A. R. 1970, Physics Today, 23, 34
Sanders, R. H., & McGaugh, S. S. 2002, ARA&A, 40, 263
Scheuer, P. A. G. 1957, Proceedings of the Cambridge Philosophical Society, 53, 764
Schlegel, D., White, M., & Eisenstein, D. 2009, arXiv:0902.4680
Schmidt, M. 1963, Nature, 197, 1040
Schmidt, M. 1968, ApJ, 151, 393
Smith, S. 1936, ApJ, 83, 23
Smolin, L. 2006, The trouble with physics : the rise of string theory, the fall of a science,
     and what comes next, Houghton Mifflin, Boston
Sullivan, M., Ellis, R. S., Howell, D. A., Riess, A., Nugent, P. E., & Gal-Yam, A. 2009,
     ApJ, 693, L76
Tolman, R. C. 1934, Relativity, Thermodynamics, and Cosmology, Clarendon Press,
     Oxford
White, S. D. M. 2007, Rep. Prog. Phys., 70, 883
Wood-Vasey, W. M., et al. 2007, ApJ, 666, 694
Zwicky, F. 1933, Helvetica Physica Acta, 6, 110