Resource Letter: Dark Energy and the Accelerating Universe

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This Resource Letter provides a guide to the literature on dark energy and the accelerating universe. It is intended to be of use to researchers, teachers, and students at several levels. Journal articles, books, and websites are cited for the following topics: Einstein's cosmological constant, quintessence or dynamical scalar fields, modified cosmic gravity, relations to high energy physics, cosmological probes and observations, terrestrial probes, calculational tools and parameter estimation, teaching strategies and educational resources, and the fate of the universe.

I. INTRODUCTION

Acceleration of the expansion of the universe is one of the most exciting and significant discoveries in physics, with implications that could revolutionize theories of quantum physics, gravitation, and cosmology. With its revelation that close to the three-quarters of the energy density of the universe, given the name dark energy, is of a new, unknown origin and that its exotic gravitational "repulsion" will govern the fate of the universe, dark energy and the accelerating universe becomes a topic not just of great interest to research physicists but to science students at all levels.

This Resource Letter endeavors to guide teachers and interested scientists through the yet-inchoate field of dark energy. This subject is continuously developing and is somewhat amorphous, not well bounded due to our ignorance of from what part of physics the explanation of cosmic acceleration will stem. While this raises challenges for pedagogy, it also offers opportunities for giving a broad overview of the interplay of fundamental physics, cosmology, and astrophysics and a living example of how physics is a dynamic field with ongoing discoveries.

The emphasis here is on a broad review along the lines of important concepts rather than specific theories, which rise and fall in popularity, and on the interaction of concepts with observational data. Likewise, the focus for the resources listed is on the widest pedagogical usefulness rather than necessarily the original or latest literature; arXiv.org (Ref. 1), the NASA Astrophysical Data System Abstract Service (Ref. 2), and SPIRES high energy physics (Ref. 3) online servers have efficient searches for the specific literature. The references given to major conferences and to websites supplement these with overviews of the latest results and trends in thought.

Historically, several issues led to dissatisfaction with the idea of a universe presently dominated by matter. These included the age problem of old objects in what dynamics would predict to be a young universe, the pattern of the large scale clustering of galaxies and clusters of galaxies, and the stability problem of a universe with density different from the critical density (or nonzero spatial curvature). While there was a puzzle on the fundamental physics side – why did Einstein's cosmological constant vanish – this was predominantly happily swept out of sight by an assumption that some symmetry would eventually explain it.

Observational evidence for a new component of the universe that brought relief to the astrophysical issues swept the scientific community in 1998, from two independent groups measuring the cosmological distance-redshift relation of Type Ia supernovae, with quick support in the following years from cosmic microwave background data consistent with a critical density universe and more detailed large scale structure observations limiting the matter component contribution. However, the consistent picture on the cosmological side brought to the forefront the puzzle on the quantum side: from where did a cosmological constant of the precise magnitude needed arise, and was it in fact a true, constant vacuum energy?

The new picture of the universe was a dramatic Copernican revolution. From abandonment of humans possessing a special spatial location in the universe, to abandonment of baryon chauvinism – that we are made of the typical stuff of the universe – due to dark matter, we now must abandon "rest mass chauvinism" – the large majority of the universe is not made of components dominated by their rest mass, like most of what we know, but rather is energy-like. Moreover, this dark energy violates the strong energy condition, having effectively negative gravitating mass, so that we are forced to abandon Newton and ask what happens when the force of gravity is no longer attractive.

These are extraordinary, dramatic questions to face. The answers, which we in no wise know yet, will rewrite textbooks. In §II we present resources giving a big picture overview of the impact that the discovery of the accelerating universe has had on cosmology research. Non-cosmological approaches to dark energy are briefly discussed in §III. Classes of possible solutions to the dark energy puzzle are given thumbnail descriptions in §IV, and observational approaches to detecting and characterizing dark energy in §V. In §VI we list resources for some standard calculational methods and tools. §VII discusses approaches to teaching dark energy at various levels, and §VIII goes into more detail concerning the fascinating and complex topic of life in an accelerating cosmos and the fate of the universe. §IX presents a compilation of review articles suitable for broad exploration of the field or aspects of the field. References denoted (E) are at a popular science level, while those listed as (I) are for readers with some familiarity with the basics of cosmology or particle physics, and advanced (A) material requires a technical background in general relativity, field theory, or detailed cosmology. Further references in the form of books, conferences, and research and education websites appear in §X.

II. DARK ENERGY IN COSMOLOGY

With the discovery of the accelerated expansion of the universe in 1998, and its corroboration and more detailed measurement soon thereafter, cosmology and particle physics research took stock of the implications of these extraordinary results and shifted into high gear for exploration of the dark universe. For a comprehensive view of astrophysics in general just before this explosion of effort, see Ref. 4, with a partial update in Ref. 7. A study by a National Academy of Sciences panel tying together the possible revolutions in cosmology and quantum physics led to Refs. 5-6. A recent European overview, from a more astrophysical perspective, is Ref. 9, while Ref. 8 from a DOE-NASA-NSF committee presents a more technically focused report on dark energy.

Research Literature Searches

1. arXiv.org preprint server `http://arXiv.org`. Up to the minute collection of research articles, together with a good search facility. Dark energy related work appears most frequently in astro-ph, gr-qc, hep-th, and hep-ph categories.

2. Harvard-Smithsonian Center for Astrophysics/NASA Astrophysics Data System abstract service `http://adsabs.harvard.edu/ads_abstracts.html`. Comprehensive collection of research article titles and abstracts, with links to published versions, or unpublished versions on Ref. 1. Good search facility.

3. SPIRES high energy physics literature database `http://www.slac.stanford.edu/spires`. Database of research articles, with search facility and citation statistics. Oriented toward high energy physics but includes most cosmology journals.

Committee Overviews

4. **Astronomy and Astrophysics in the New Millennium** (2001) `http://www7.nationalacademies.org/bpa/aanm.html`. Latest in series of decadal surveys of the state of astronomy and astrophysics. Because of the timing (produced by 1999), contains little on dark energy but provides a very broad overview of astrophysics at that time. (I)

5. **Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century** (2003) `http://www.nap.edu/catalog.php?record_id=10079`. Influential assessment of key physics questions unifying particle physics and cosmology. Dark energy is one of the eleven questions, plus several of the others may be related to the accelerating universe. Gives both scientific background as well as programmatic views. (I)

6. **A 21st Century Frontier of Discovery: The Physics of the Universe** (2004) `http://www.ostp.gov/html/physicsoftheuniverse2.pdf`. Report from the National Science and Technology Council discussing strategic implementation of the recommendations of Ref. 5, including dark energy experiments. (I)

7. **Review of Progress in Astronomy and Astrophysics Toward the Decadal Vision** (2005) `http://www7.nationalacademies.org/bpa/Mid_Course_Review_Home.html`. Prompted by increased interaction between particle physics and cosmology, in particular Ref. 5, this reviewed progress since Ref. 4. Contains some mention of dark energy, mostly from the programmatic point of view. (I)

8. **Report of the Dark Energy Task Force** (2006) `http://arxiv.org/abs/astro-ph/0609591`. From an advisory subcommittee for DOE, NASA, and NSF. More technical assessment of experimental methods for probing dark energy, with particular attention to practical issues, ground vs. space observations, and a series of experimental stages. Contains some background material and a long technical appendix. (A)

9. **Report by the ESA-ESO Working Group on Fundamental Cosmology** (2006) `http://arxiv.org/abs/astro-ph/0610906`. European assessment of cosmology issues, similar to Refs. 5, 6, but with less emphasis on particle physics and more on astrophysics. Good overview sections with several discussions of dark energy and the accelerating universe. (I)

III. DARK ENERGY IN THE LAB

Before investigating the main, cosmological aspects of the accelerating universe, we briefly mention the more speculative approaches to exploring a modified gravity origin of cosmic acceleration through laboratory and solar system tests. If gravity is altered due to extra dimensional effects, the excitation (Kaluza-Klein) modes of the extra dimensions might be detectable as particles in high energy accelerators; Ref. 10 considers the possibility of next generation particle accelerators for probing dark energy. The effects of cosmic acceleration could arise from weakening the force of gravity relative to the inverse square law at long distances; the modification of the structure of gravity could also show up at micron scales (e.g. again due to extra dimensional effects) or scales related to the spacetime curvature (solar system scales for orbits bound by the mass of the Sun). Recent results from laboratory tests of the gravitational inverse square law appear in Ref. 11, while Refs. 12-13 present lunar laser ranging constraints, and Ref. 14 discusses the use of planetary orbits. The great preponderance of possible origins for dark energy, including many modifications of gravity, are only detectable through cosmological signatures, however. Ref. 15 gives a simple discussion of why some "direct" detection techniques are not generally expected to be fruitful approaches.

10. Linear Collider Connections to Astrophysics and Cosmology `http://www.physics.syr.edu/~trodden/lc-cosmology`. Working group of the American Linear Collider Physics Group for the International Linear Collider (ILC); no report issued yet, check website for future documents.

11. "Tests of the Gravitational Inverse-Square Law below the Dark-Energy Length Scale," D.J. Kapner, T.S. Cook, E.G. Adelberger, J.H. Grundlach, B.R. Heckel, C.D. Hoyle, and H.E. Swanson, Phys. Rev. Lett. **98**, 021101 (2007). Latest results from laboratory experiments probing submillimeter gravity. (A)

12. "Testing Gravity via Next-Generation Lunar Laser-Ranging," T.W. Murphy, Jr., E.G. Adelberger, J.D. Strasburg, C.W. Stubbs, and K. Nordtvedt, Nucl. Phys. B (Proc. Suppl.) **134**, 155-162 (2004). Motivation and next generation techniques for using lunar laser ranging to probe gravity. (I)

13. APOLLO Project: `http://physics.ucsd.edu/~tmurphy/apollo`. Ongoing experiment to improve limits on the Equivalence Principle and gravitational properties through lunar laser ranging. Contains physics background materials and technical description. (I)

14. "The Accelerated Universe and the Moon," G. Dvali, A. Gruzinov, and M. Zaldarriaga, Phys. Rev. D **68**, 024012 (2003). Theoretical discussion of how modifying the structure of gravity to lead to cosmic acceleration could influence orbits, such as in the solar system. (A)

15. "Dark energy the easy way?," `http://supernova.lbl.gov/~evlinder/easyde.html`. Brief discussion of various direct methods for seeing dark energy and why they are not so easy. (E)

IV. THEORETICAL APPROACHES TO DARK ENERGY

This section aims to give a flavor of classes of models proposed for dark energy, without going into any detail on specific models or attempting to be comprehensive.

Einstein proposed a *cosmological constant* to counterbalance gravitational attraction; its Lorentz invariant form leads to another interpretation in terms of ground state, or zeropoint, vacuum energy of quantum fields. The energy density of a cosmological constant is unchanging with the cosmic expansion, and its pressure to energy density, or equation of state, ratio is fixed at $w \equiv p/\rho = -1$. Scalar fields that do not sit at the minimum of their potential are dynamical, called *quintessence* when they have canonical kinetic terms and minimal coupling to gravity; they possess a time varying energy density and generally a time varying equation of state. *Coupled dark energy* usually involves a scalar field with coupling to dark matter; *k-essence* involves a scalar field with a noncanonical kinetic term.

Other models include *unified dark energy* models, also called Chaplygin gas, quartessence, or mocker models, attempting to explain dark energy and dark matter from a single physical origin. *Holographic dark energy* tries to explain vacuum energy through a summation over modes of zeropoint energy limited by a holographic conception of number of degrees of freedom. *Backreaction models* attempt to obtain merely the perception of acceleration through effects of nonlinear matter structures on the cosmic expansion, or specialized distributions of matter such as Lemaître-Tolman-Bondi models. Modified gravity origins for cosmic acceleration include *scalar-tensor theories* of a scalar field nonminimally coupled to spacetime curvature and $f(R)$ *theories* with more complicated functions of the Ricci spacetime curvature than the Einstein-Hilbert action, and there exist more complicated functions of the full curvature tensor as well, plus extradimensional theories such as *braneworld cosmology*. As stated, this is a partial sampling of the many ideas attempting to explain the origin of cosmic acceleration. See the review articles cited in §IX for further discussion and use Ref. 1 to search on the terms in detail.

V. OBSERVATIONAL APPROACHES TO DARK ENERGY

Here we summarize observational methods for probing dark energy and the accelerating universe, again without going into detail on technical specifics or proposed programs. While direct detection of acceleration is unlikely (see Ref. 15), measurement of the cosmic expansion through geometric quantities such as distances depending only on the cosmic scale factor and spatial curvature is feasible. The slowing and acceleration of scales with time, $a(t)$, map out the cosmic environment history like the lesser and greater growth of tree rings map out the Earth's climate history. The technique that discovered the acceleration, the Type Ia supernova magnitude-redshift test, is such a geometric test. Once the supernovae are calibrated through measuring their properties, the magnitude, or received flux, measures the distance through the cosmological inverse square law, giving the lookback time to the explosion, while the measured redshift gives the scale factor; hence we obtain $a(t)$.

Similar geometric probes can be gotten from distance ratios arising from gravitational lensing observations (both weak lensing where one statistically measures subtle shape distortions in distant galaxies by foreground mass, and strong lensing where multiple images occur) baryon acoustic oscillations (statistically measuring the scale of preferred spatial clustering of galaxies or other baryon-rich objects relative to the primordial sound horizon scale from the cosmic microwave background recombination epoch), and possibly other techniques.

As a further consequence of the accelerated expansion, the growth of large scale structure such as galaxies and clusters of galaxies is suppressed. Structure grows through gravitational instability, but the stretching of space works against aggregation of mass just as a person finds it hard to join a large group of friends if they are at the end of an escalator running the wrong way. Observations of the growth of massive structures through weak lensing, or the formation and evolution of galaxies and clusters, e.g. cluster counts (the abundance of clusters in a certain mass range), employing large surveys in the optical, submillimeter (Sunyaev-Zel'dovich effect), or X-ray bands, or again using weak gravitational lensing to detect mass, can thus give more indirect evidence of acceleration. Other than for weak lensing, which directly measures mass, these techniques also need to translate the observed light to the true mass. Methods that incorporate mass or mass and gas measurements in addition to simple geometry must separate out the astrophysics of galaxy and cluster formation and evolution to extract the cosmological dark energy characteristics.

The cosmic microwave background (CMB) radiation is a precise probe of many cosmological quantities, but is not particularly directly incisive on dark energy, at least in present usage. Basically the CMB gives a snapshot of the early universe, at 0.003% of its present age, and so does not reveal detailed characteristics of the late time acceleration of the universe.

These observational approaches to dark energy are discussed from both scientific and proposed experimental program points of view in the Committee Overviews cited in §II and in the review articles in §IX.

VI. TOOLS FOR DARK ENERGY COSMOLOGY

Analysis tools to compare cosmological models with observations or simulations, while not specific to dark energy, are an important ingredient of understanding the accelerating universe and the physics behind it. These tools range from calculators of distances or other cosmological relations to solvers of coupled perturbation growth equations to fitters of cosmological parameters to various data sets. Cosmology fitters use various techniques to calculate the likelihoods of models, from chi-square minimization to the Fisher information matrix (Gaussian approximation of the likelihood surface near the maximum) to Monte Carlo techniques. We present here a selection of general discussions and publicly available codes to carry out these tasks.

16. "Karhunen-Loève Eigenvalue Problems in Cosmology: How Should We Tackle Large Data Sets?," M. Tegmark, A.N. Taylor, A.F. Heavens, Ap. J. **480**, 22-35 (1997). Technical and mathematical basis for Fisher information matrix analysis. (A)

17. "Cosmic Complementarity: Probing the Acceleration of the Universe," M. Tegmark, D.J. Eisenstein, W. Hu, & R.G. Kron, arXiv:astro-ph/9805117. More accessible guide to Fisher information matrix analysis than Ref. 16, with practical examples. (A)

18. "Observational Bounds on Cosmic Doomsday," R. Kallosh, J. Kratochvil, A. Linde, E.V. Linder, M. Shmakova, JCAP **0310**, 015 (2003). The appendix gives a simplified, step by step guide to applying the Fisher information matrix. (I)

19. "Design a Dark Energy Experiment," E.V. Linder, `http://supernova.lbl.gov/~evlinder/design.pdf`. Summer school lecture on relating data to theory, with emphasis on systematic uncertainties. (I)

20. Minuit `http://wwwasdoc.web.cern.ch/wwwasdoc/minuit/minmain.html`. CERN library program for function minimization (e.g. chi-squared) and error analysis.

21. CosmoMC `http://cosmologist.info/cosmomc`. Markov chain Monte Carlo program for cosmological parameter estimation.

22. CosmoNest `http://www.cosmonest.org`. Implements nested sampling for calculation of Bayesian evidence, or cosmological model likelihoods.

23. CMBfast `http://cfa-www.harvard.edu/~mzaldarr/CMBFAST/cmbfast.html`. Program for calculating cosmic microwave background temperature and polarization anisotropies and matter power spectrum. Standard version has constant equation of state for dark energy (or table of values).

24. CAMB (Code for Anisotropies in the Microwave Background) `http://camb.info`. Extension of CMBfast with high accuracy matter power spectra and Monte Carlo interface. Standard version has constant equation of state for dark energy.

25. CMBeasy `http://www.cmbeasy.org`. Extension of CMBfast with numerous dark energy parameterizations and Markov Chain Monte Carlo generation. Has extensive documentation and graphical user interface.

26. Cross_CMBfast `http://www.astro.columbia.edu/~pierste/ISWcode.html`. Extension of CMBfast for computing integrated Sachs-Wolfe correlations. Includes w_0-w_a dark energy model and constant sound speed.

27. Cosmology Calculator `http://www.astro.ucla.edu/~wright/ACC.html`. Javascript to compute cosmological distances and ages.

28. Kosmoshow `http://marwww.in2p3.fr/renoir/Kosmoshow.html`. Cosmology fitter to supernova data using chi-squared minimization. Allows extensive control of data and error properties, and includes plotting routines. Graphical user interface.

29. Simple Cosfitter `http://qold.astro.utoronto.ca/conley/simple_cosfitter`. Cosmology fitter concentrating on supernovae magnitude-redshift data. Includes terms for supernova color and stretch parameters.

30. Supernovae chi-squared evaluator `http://www.ifa.hawaii.edu/~jt/SOFT/snchi.html`. Calculates chi-squared based on the distance-redshift relation.

31. SNOC (Supernova Observation Calculator) `http://www.physto.se/~ariel/snoc`. Monte Carlo simulator of supernovae data and cosmology parameter fitter. Contains numerous astrophysical effects such as gravitational lensing and dust extinction and is useful for systematic uncertainty studies.

32. DETFast `http://www.physics.ucdavis.edu/DETFast`. Java applet producing cosmological parameter Fisher matrix likelihood contours for various simulated data sets used by the Dark Energy Task Force (see Ref. 8).

VII. APPROACHES TO TEACHING DARK ENERGY

Teaching and communication of aspects of dark energy and the accelerating universe can take place at many levels, as seen for example in the Review Articles of §IX and Education Websites of §X D. On a formal level, students should certainly be familiar with the expansion of the universe and the behavior of matter and radiation equation of states before being introduced to the acceleration of the expansion. Students with exposure to classical mechanics can appreciate the simple scale field Lagrangian, equation of state ratio, and Klein-Gordon equation. A phenomenological approach to modifying the Friedmann expansion equation can create understanding of the effects of a five dimensional braneworld "leaking gravity" model or string theory inspired barotropic terms (additional terms nonlinear in the matter density), especially when considering asymptotic future behavior.

To visualize the geometric effects of the accelerating expansion, and to understand how the differences in dark energy models show up in cosmological observations, it is convenient to look at a conformal horizon diagram. This allows students to see by eye concepts that are more difficult to pick out on a standard scale factor vs. time, $a(t)$, or distance-redshift $d(z)$ Hubble diagram. In Figure 1 comoving length scales would simply be horizontal lines and positive slopes for the expansion history curves correspond to decelerating epochs, and negative slopes are the sign of acceleration. The slope of a curve at present is precisely the deceleration parameter today, q_0. The area under a curve is simply the conformal distance $\eta = \int d\ln a (aH)^{-1}$, precisely the quantity that enters in luminosity distances and angular distances. Thus one can immediately see that distances in an accelerating universe are greater than they would be in a decelerating universe (with the same Hubble constant), or a less accelerating universe. One can even obtain the total equation of state of the universe $w_{\rm tot}$ and its running $w' = dw/d\ln a$ from the slope and curvature of the curves. These relations, and the clear application to inflation as well, make such a figure a useful and visual pedagogical tool.

For more advanced courses, scaling and tracking behavior, numerical solutions of the Klein-Gordon equation (or continuity equation with coupling between dark energy and matter), linear perturbation growth, effects on the distance-redshift Hubble diagram or cosmic microwave background temperature power spectrum are all accessible exercises to give insight into dark energy cosmology.

Introductory level courses can go a considerable way into the main concepts with very modest amounts of math. One key approach is emphasizing that Einstein's Equivalence Principle and the equivalence of energy and mass ("$E = mc^2$") yield a picture of dark energy opposed to attractive gravity. Einstein lessoned us that when determining an object's gravitational mass we must add up all the forms of equivalent energy, including pressure. Hence students can be guided to the idea that an object with positive energy density, but sufficiently negative pressure, can effectively have a negative gravitational mass, and hence acts in repulsion not attraction. Using the rubber sheet image of spacetime, while a ball of matter would cause a depression, experienced by other particles as gravitational attraction, a ball of dark energy causes a hill, perceived by other particles as gravitational repulsion (if not quite in a formal sense). So the cosmic expansion, slowed down by gravitational attraction from the matter contents, can instead be accelerated if there is

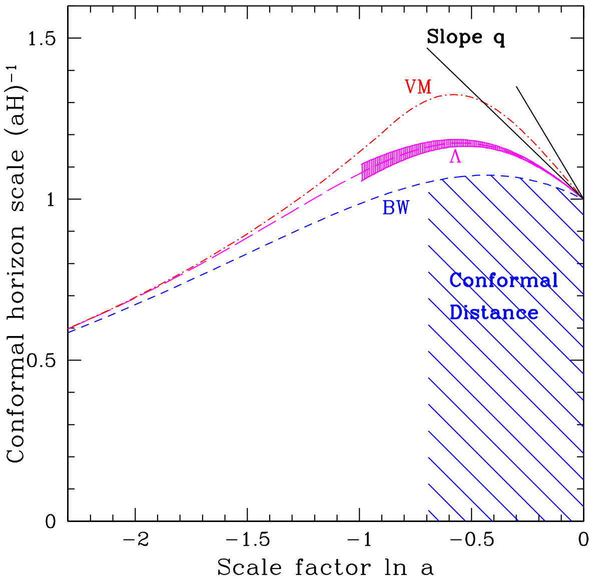

FIG. 1: Plotting the conformal Hubble scale vs. the logarithmic scale factor one can readily visualize acceleration of the cosmic expansion through the slope of a cosmological model curve and distances through the area under the curve. The dense shading around the cosmological constant Λ curve represents a goal for 95% confidence level constraints from next generation measurements, mapping both accelerating and decelerating phases and distinguishing between dark energy physics models.

sufficient negative pressure material – dark energy. One can even motivate the Friedmann acceleration equation from Newton's second law, including Einstein's admonition that we must account for pressure as a form of energy, and hence mass, as well.

Negative pressure can be made more palatable by pointing out that springs and rubber bands essentially have negative pressure. From the first law of thermodynamics we see that the (adiabatic) change in energy of a system when the volume changes is given by the negative of the pressure. The hot air inside your body cools when it expands out through pursed lips, as a student can easily demonstrate for themselves by blowing on their fingers (working as temperature sensors) with lips pursed or with mouth open. Hence the pressure here is a positive quantity. However, when a spring or rubber band is expanded, the energy goes up, implying the pressure is a negative quantity. (Again, students can demonstrate this by touching a rapidly stretched rubber band to their temperature-sensitive lips.)

Now perhaps the students have heard that quantum physics predicts that energy fields, even the zeropoint energy of the vacuum, should act as springs (harmonic oscillators). Lest their eyes glaze over at the mention of field theory, simply explain that a field in physics is not so different than a field of grass. On a lawn or in a meadow, each point has a stalk of grass of some height, like an array of springs of some length. A single number at every point is simply a scalar field $\phi(x)$ (and a trampled field of grass, or crop circles, where each stalk has a length and direction is like a vector field). Quantum physics forbids the springs to be absolutely still, they must have some fluctuations, stretching and compressing. But as we saw with the rubber band, this leads to a negative pressure, so the vacuum itself can have negative pressure.

Putting it all together,

- Newton: gravitational force depends on acting gravitational mass
- Einstein: gravitational mass is equivalent to energy, including the pressure
- ⇒ Gravitational "repulsion" or acceleration of the expanding universe can occur if there is sufficient negative pressure substance.
- Thermodynamics: negative pressure material is allowable, e.g. springs
- Quantum physics: fields have zeropoint energy and this very vacuum acts like springs
- ⇒ Space itself has a vacuum energy with negative pressure that could accelerate the expansion of the universe.

A question than then naturally arises, of considerable pedagogical and scientific interest, is what is the fate of our universe.

VIII. FATE OF THE UNIVERSE

For many years in cosmology, it was declared that geometry equals fate. Models were characterized into open, closed, and critical universes (eternally expanding, eventually contracting, and asymptotically static), taken to be equivalent to negative, positive, and zero spatial curvature models. For accelerating universes, this identification breaks down and one can have open universes with positive curvature, for example. Both the amount and the nature of components enter into determining the fate of the universe. Thus the Newtonian picture of throwing a ball into the air and based on the initial velocity it will either return to earth, orbit, or escape no longer holds; with sufficiently negative equation of state (pressure to energy density ratio) the gravitating mass of the ball can be negative and a softly thrown ball can accelerate away.

In an accelerating universe, the particle horizon (the region within the causally reachable universe) grows rapidly, more rapidly than the speed of light, so as time goes on we see an increasingly small fraction of the universe; effectively, the limits to our astronomy close in as galaxies that used to be visible get pulled away and fade out of sight. (See Ref. 33, 34 for more on horizons.) Matter and radiation get increasingly dilute and the temperature of the background radiation tends toward absolute zero. Whether life can survive as the universe ages is a matter of debate (see Refs. 35-37).

If the equation of state is even more negative, beyond the cosmological constant value of pressure equal and opposite of the energy density, the dark energy becomes "phantom" (see Ref. 38). This leads to the energy density of the substance *increasing* as the expansion dilutes it, and the expansion superaccelerating, in a runaway process called the Big Rip. Naively this would lead to the rapid expansion eventually tearing apart galaxies, stars, and even atoms (see Ref. 39) but quantum particle creation might intervene, ending the runaway.

Other scenarios include dark energy fields that roll down their potential energy to negative values – these can lead to a collapsing universe as the negative density has a negative gravitational repulsion, i.e. an attraction again (see Ref. 40), related models with "sudden singularities" (e.g. Refs. 41, 42), and dark energy that waxes and wanes so cosmic acceleration is merely episodic (e.g. the stochastic model of Ref. 43). Until we understand the physical nature of dark energy we will not know the fate of our universe.

33. "Misconceptions about the Big Bang," C.H. Lineweaver & T.M. Davis, Sci. Am. **292**, 36-45 (Mar. 2005). Leads the reader by the hand through some of the conundra and properties of cosmic expansion and horizons. (E)

34. "Lost horizons," G.F.R. Ellis & T. Rothman, Am. J. Phys. **61**, 883-893 (Oct. 1993). Mathematical discussion of various types of horizons and related phenomena, and their implications, with abundant diagrams. (I)

35. "Time Without End: Physics and Biology in an Open Universe," F.J. Dyson, Rev. Mod. Phys. **51**, 447-60 (1979). Thoughtful and quantitative discussion of physical processes and life in an eternally expanding universe from a thermodynamic perspective. (I)

36. "Life, the Universe, and Nothing: Life and Death in an Ever-expanding Universe," L.M. Krauss & G.D. Starkmann, ApJ **531**, 22-30 (2000). Consideration of astronomical observations and life in a cosmological constant universe using information theoretic arguments. Some conclusions disagree with Ref. 35 and led to lively debate. (I)

37. "Resource Letter: PEs-1: Physical Eschatology," M.M. Ćirković, Am. J. Phys. **71**, 122-133. Wide ranging and thought provoking philosophical and scientific investigation of the future of the universe and objects and life in it. (I)

38. "A phantom menace? Cosmological consequences of a dark energy component with super-negative equation of state," R.R. Caldwell, Phys. Lett. B **545**, 23-29 (2002). Influential article arguing that motivations exist for considering equations of state more negative than the cosmological constant, and examining effects on cosmological observations. (A)

39. "Phantom Energy: Dark Energy with $w < -1$ Causes a Cosmic Doomsday," R.R. Caldwell, M. Kamionkowski, & N.N. Weinberg, Phys. Rev. Lett. **91**, 071301 (2003). Discussion of the dramatic implications of phantom energy for the fate of the universe and objects therein, known as the Big Rip. (A)

40. "Observational bounds on cosmic doomsday," R. Kallosh, J. Kratochvil, A. Linde, E.V. Linder, M. Shmakova, JCAP **0310**, 015 (2003). Investigation of the lifetime of the universe until the accelerated expansion ends and it in fact collapses, if dark energy has a simple linear potential. Gives quantitative limits on the time left based on current data, and future projections. (A)

41. "Sudden future singularities," J.D. Barrow, Class. Quant. Grav. **21**, L79-L82 (2004). Discussion of conditions under which singularities can occur at a finite time in the future of the universe. (A)

42. "Necessary and sufficient conditions for big bangs, bounces, crunches, rips, sudden singularities and extremality events," C. Cattoën & M. Visser, Class. Quant. Grav. **22**, 4913-4930 (2005). Survey of several categories of singularities and similar phenomena in the properties of the universe. (A)

43. "Solving the Coincidence Problem: Tracking Oscillating Energy," S. Dodelson, M. Kaplinghat, & E. Stewart, Phys. Rev. Lett. **85**, 5276-5279 (2000). Examines the possibility of cosmic acceleration as a periodic or stochastic phenomenon, its amelioration of the cosmic coincidence problem, and its observational implications. (A)

IX. REVIEW ARTICLES

Review articles of dark energy cosmology as a whole or specific topics within the field provide an invaluable resource for people interested in getting exposed to the concepts, results, progress, and prospects of the field. The categories give a general indication of the main focus of the articles and the technical levels provide a rough guide to the intended audience.

Dark Energy Characteristics

44. "Insights into Dark Energy: Interplay between Theory and Observation," R. Bean, S. Carroll, & M. Trodden, arXiv:astro-ph/0510059. (A)

45. "An Introduction to Quintessence," R.R. Caldwell, in **Sources and Detection of Dark Matter and Dark Energy in the Universe**, Fourth International Symposium, edited by D.B. Cline (Springer Verlag, New York, 2001), pp. 74-91. (I)

46. "The Cosmological Constant," S.M. Carroll, Living Rev. Relativity **4**, 1 (2001). (A)

47. "Aspects of Cosmology with Scalar Fields," M. Joyce, habilitation thesis 2000, `http://supernovae.in2p3.fr/~joyce`. (A)

48. "The Dynamics of Quintessence, the Quintessence of Dynamics," E.V. Linder, Gen. Rel. Gravitation in press (2007). (A)

49. "Darker Side of the Universe," T. Padmanabhan, in **Proc. 29th Int. Cosmic Ray Conf. 10**, 47-62 (2005). (A)

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51. "Dark Matter and Dark Energy," V. Sahni, in **The Physics of the Early Universe**, edited by E. Papantonopoulos, Lect. Notes Phys. **653**, 141-180 (Springer, Berlin, 2004). (I)

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X. OTHER RESOURCES

A. Books

Perhaps because dark energy and the accelerating universe is such a rapidly developing subject and a mystery regarding its physical origin and properties, there is as yet no definitive book on the popular or monograph levels. Since the field is such a moving target, those seeking less technical approaches to the subject should look to the general journal articles cited under Review Articles and to the websites listed below. For more advanced presentations, consult the technical journal articles under Review Articles and the conference proceedings and websites listed below.

For piecemeal but still useful discussions of aspects of the accelerating expansion, in particular cosmological probes and components with general equations of state, one can explore sections of Refs. 82-85. A compendium of the state of probing dark energy at the time of the Snowmass 2001 meeting on the "Future of Particle Physics" is given in Ref. 86.

82. **Cosmology and Particle Astrophysics**, L. Bergstrom & A. Goobar (Springer-Verlag, Berlin, 2004 2nd ed.). Contains a brief but informative subsection on dark energy and scalar fields, and otherwise gives a good and wide ranging overview of cosmology, relativity, and particle physics. Written on the beginning to mid graduate level. (A)

83. **Modern Cosmology**, S. Dodelson (Academic Press, San Diego, 2003). Contains a couple of small subsections on dark energy, but is rich in general cosmological concepts and applications. Written on the graduate level and as a professional reference. (A)

84. **First Principles of Cosmology**, E.V. Linder (Addison-Wesley, London, 1997). Contains several discussions about dark energy (before it got the name), and light propagation and cosmological probes in generalized cosmologies. Dated on the observational side but gives care to physical analogies and concepts on the theory side. Written on the upper undergraduate to beginning graduate level. (I)

85. **Introduction to Cosmology**, B. Ryden (Benjamin Cummings, 2002). Contains a couple of brief mentions of dark energy, but provides a clear general overview of cosmology, with background concepts and observations. Written on the upper undergraduate to beginning graduate level. (I)

86. **Resource Book on Dark Energy**, edited by E.V. Linder (Berkeley Lab, Berkeley, 2001). Collection of some 40 articles on dark energy by 100 authors, giving a many angled perspective on the subject at the time of the 2001 Snowmass Symposium on the Future of Particle Physics. Also online at `http://supernova.lbl.gov/~evlinder/sci.html`. (I,A)

B. Conferences

Conference proceedings and talks posted on conference websites provide valuable snapshots of research in progress, as well as sometimes overview talks. Here we list some of the main conference series with sessions concentrating on dark energy.

87. Cosmo 07 `http://www.cosmo07.info`. Annual international conference since 1997, covering inflation, the early universe, dark energy, and other topics. Talks are posted online. (A)

88. Dark 2007 `http://www.physics.usyd.edu.au/dark2007`. Roughly biennial international conference since 1996, also known as Heidelberg International Conference on Dark Matter in Astro and

Particle Physics, covering dark matter, astroparticle physics, large scale structure, and dark energy. Talks are not always posted online but conference proceedings are published, e.g. by Springer. (A)

89. Dark Side of the Universe `http://www.ftpi.umn.edu/dsu07`. Annual international workshop since 2005, treating both theory and experiment related to dark matter and dark energy. Talks are posted online and conference proceedings sometimes published, e.g. in AIP Conf. Proc. (A)

90. Santa Fe Cosmology Summer Workshop `http://t8web.lanl.gov/people/salman/sf07`. Annual meeting since 1999 that combines an interactive summer school for students and postdocs with a workshop for researchers. Very useful for people starting out in the field. Concentrates on large scale structure, CMB, dark matter, and dark energy. Talks are sometimes posted online. (A,I)

91. Sources and Detection of Dark Matter and Dark Energy in the Universe `http://www.physics.ucla.edu/hep/dm06/dm06.htm`. Biennial conference since 1994, also known as the UCLA Symposium, covering dark matter, cosmology, and dark energy. Talks are posted online and conference proceedings published, e.g. in Nucl. Ph. B. (A)

92. Texas Symposium on Relativistic Astrophysics `http://www.texas06.com`. Biennial international conference since 1963, concentrating on relativistic astrophysics, with lesser coverage of cosmology and dark energy. Talks are generally posted online and conference proceedings generally published. (A)

C. Discussion Boards

Online community discussion forums provide a more informal view of questions and developments in scientific research. Two forums run by professional physicists include Refs. 93, 94.

93. CosmoCoffee `http://cosmocoffee.info`. Online interactive discussion forum containing sections for comments on arXiv.org papers, technical issues in cosmology analysis, and general audience cosmology questions. (A,I)

94. Cosmic Variance `http://cosmicvariance.com`. Blog posts from highly regarded physicist contributors (not necessarily on technical physics topics, but there is a general dark energy and particle physics theme). Also open comment forum on the posts. (I)

D. Education Websites

Relatively few websites exist providing broad educational resources in dark energy cosmology. Since websites rapidly come and go, or cease being updated, a focused search on the internet may provide the most useful information. Current sites with a strong concentration on dark energy include Ref. 95, 96; unfortunately, ongoing and next generation observational programs provide few practical, general educational resources about dark energy, but see Ref. 98, 99.

95. Universe Adventure `http://universeadventure.org`. Linked series of webpages teaching aspects of cosmology and the history and fate of the universe, aimed at a high school and general audience. Contains abundant graphics, mini-quizzes, glossary, and teacher resources. Similar to the award-winning ParticleAdventure.org, and extended by "History and Fate of the Universe" charts (see `http://pdg.lbl.gov/fate-history/posters.html`) which Ref. 76 was designed to accompany. (E)

96. Cosmology Resources `http://supernova.lbl.gov/~evlinder/scires.html`. A grab bag of cosmology resources ranging from additions to Ref. 84, summer school lectures, faqs, and basic formulas, to dark energy humor. Levels vary from public audience talks to technical papers. (E,I,A)

97. Hidden Dimensions `http://hiddendimensions.org`. Discusses the role of extra dimensions in various puzzles including particle physics, gravity, and the accelerating universe. Suitable for classroom use or individual exploration, contains several animations. (E)

98. WMAP Cosmology 101 `http://wmap.gsfc.nasa.gov/m_uni.html`. Tutorial from the Wilkinson Microwave Anisotropy Probe mission on cosmology with an emphasis on the cosmic microwave background, but contains some mention of dark energy. Includes glossary and teacher resources. (E)

99. Dark Energy Education Outreach `http://snap.lbl.gov/education`. Linked series of webpages introducing many aspects of dark energy and the accelerating universe, aimed at students and general audience. Contains graphics and glossary. While originated for the Supernova/Acceleration Probe (SNAP) project, much of the material is general, giving good summaries of the puzzles facing scientists trying to understand our universe. (E)

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