cosmology: whether or not the expansion of the universe is accelerating. The article cites the most recent observational data in support of this thesis. The overriding concomitant question is what is the cause for the acceleration, and the search for an answer has become a major area of research. It seems fairly well agreed that inclusion of the cosmological constant Λ in the Einstein equations provides an excellent *description* of the expansion and its acceleration. But, its *interpretation* is open to question.

The majority opinion is that the term $\Lambda g_{\mu\nu}$ is a vacuum energy—the "dark energy." This view was initiated by particle theorists[1] in search of a solution to the problem posed by the absence (apart from the Casimir effect) of any observable zero-point energy. This zero-point energy is computed to be 120 orders of magnitude greater than the observed values for Λ. So the attitude is that the observed value is an *effective* value and must be composed of the zero-point energy and compensating sources; hence, the preoccupation with dark energy and quintessence.

There is, however, a minority opinion that quintessence is inappropriate. The Einstein equations in canonical form are

$$R_{\mu\nu} - {}^1\!/_2 R g_{\mu\nu} + \Lambda g_{\mu\nu} = -\kappa\,[(\rho + p)u_\mu u_\nu + p g_{\mu\nu}].$$

With Λ transferred to the right-hand side to be a species of energy, the equations are

$$R_{\mu\nu} - {}^1\!/_2 R g_{\mu\nu} = -\Lambda g_{\mu\nu} - \kappa\,[(\rho + p)u_\mu u_\nu + p g_{\mu\nu}].$$

There is a profound difference in principle between these two ways of writing the equations. John Wheeler has put it this way: The gravitational field equations are simply geometry = mass-energy. Is $\Lambda g_{\mu\nu}$ geometry or is it energy? There are strong, theoretical, a priori arguments that it is purely geometric.

The Einstein tensor is $G_{\mu\nu} \equiv R_{\mu\nu} - {}^1\!/_2 R g_{\mu\nu}$, and it serves exceedingly well in all noncosmological situations. Its importance motivated close scrutiny of its structure by Albert Einstein's colleagues. The Einstein tensor is a second-rank tensor constructed solely from the metric tensor and its first and second derivatives. It is linear in terms of the second differential order and has a vanishing covariant divergence.

Study of the Einstein tensor's structure was begun as early as 1917 by H. Vermeil. The most recent result in this area of study is a theorem constructed by David Lovelock,[2] which severely delimits its form. He has shown that, if the field equations are to be derived from a variational principle, then in a four-dimensional space, the only type (2,0) tensor density whose components satisfy $A^{ij} = A^{ij}(g_{ab}, g_{ab,c}, g_{ab,cd})$ with $A^{ij}{}_{;j} = 0$ is given by $A^{ij} = \sqrt{g}\,[R^{ij} - {}^1\!/_2 g^{ij} R] + \Lambda\sqrt{g}g^{ij}$.

Although accumulating evidence for an accelerating expansion is leading to a general acceptance of $\Lambda g_{\mu\nu}$ as a proper term in the Einstein equations, this evidence has not erased the original stigma due to Einstein's characterization of it as "the biggest mistake of my life." It is not generally accepted that Λ is part of the geometry. However, to burden Λ as the vehicle for solving the zero-point energy problem is questionable. The introduction of quintessence is uncomfortably reminiscent of the introduction of ether in the 19th century. Zero-point energy is a purely quantum phenomenon and its "problem" will be solved in the context of a quantized theory of gravitation.

The behavior of the cosmos seems to be that of a de Sitter space. Recall that the simplest vacuum solution of the Einstein equations without Λ is a Minkowski spacetime; if Λ is included, it is a de Sitter spacetime. Recall further that, in a vacuum de Sitter spacetime, a particle at a distance $\vec{x}$ from the origin is subject to a force $\vec{F} = mc^2\Lambda/3\ \vec{x}$. Any attempt at solving astrophysical–cosmological problems must accept from the beginning that $\Lambda g_{\mu\nu}$ is "geometry."

References

1. For a comprehensive exposition of this view and its implications, see S. M. Carroll, http://arxiv.org/abs/astro-ph/0004075.
2. D. Lovelock, *J. Math. Phys.* **13**, 874 (1972); D. Lovelock, H. Rund, *Tensors, Differential Forms, and Variational Principles*, Dover, New York (1989), p. 314.

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A Moment of Gravity

In a note entitled "An Optical Stretcher" in Physics Update (Physics Today, November 2001, page 9), the term "center of gravity" is incorrect. The correct term is "center of mass." Gravity has nothing to do with conservation of momentum.

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