

in 1930, who successfully promoted Georges Lemaître's 1927 article for the Scientific Society of Brussels, effected a paradigm shift in interpretation of extragalactic redshifts in 1930. Before then, the astronomical community was generally unaware of the existence of nonstatic cosmological solutions and did not broadly appreciate that redshifts could be thought of locally as Doppler shifts in an expanding matter distribution. Certainly, in 1929 Edwin Hubble referred only to the de Sitter solution of 1917. At the time, the relation between distance and redshift predicted in that model was generally seen purely as a manifestation of static spacetime curvature.

De Sitter's model motivated nearly all studies of the 1920s. Livio and Riess state that Knut Lundmark¹ "provided tentative, qualitative evidence for the expansion." But Lundmark's work was quantitative, and by 1925 he could state that "a rather definite correlation is shown between apparent dimensions and radial velocity, in the sense that the smaller and presumably more distant spirals have the higher velocity." That claim, however, cannot be evidence for "expansion," since neither the concept nor its theoretical justification were known to Lundmark, who was unaware of Alexander Friedmann's early 1920s papers.²

Livio and Riess also state that Lundmark's results "relied on the implausible assumption that all galaxies have the same diameter." But such empirical methods were common at the time. Hubble himself subsequently used galaxies as standard candles.³ Despite considerable scatter, it is certainly plausible that fainter galaxies are more distant on average, and Lundmark was thus correct in concluding that radial velocity increased with distance.

We reiterate that Lundmark's pioneering efforts lacked any interpretation of a relation between distance and redshift in terms of expansion. As Livio and Riess indicate, the first person to treat data in that way was Lemaître in 1927. But the article should have emphasized the significance of Lemaître's work—that he had derived the predicted relation theoretically, based explicitly on the concept of an expanding universe. The details of Lemaître's derivation are given in reference 4.

At the time, Lemaître was thus in the company of a very small number of theorists who understood that cosmological models were generically nonstatic. As far as we are aware, the only workers

who postulated or even knew of nonstatic solutions before Eddington's and de Sitter's public announcements were Friedmann, Yuri Krutkov, Paul Ehrenfest, Lemaître, and Albert Einstein (see the article by Ari Belenkiy, *PHYSICS TODAY*, October 2012, page 38). That small group of scientists hardly supports Livio and Riess's claim that "ever since the 1920s, physicists have known that we live in an expanding universe."

It is a pity that in addition to seriously undervaluing Lemaître's crucial role in establishing the concept of an expanding universe, Livio and Riess did not give greater emphasis to Slipher's achievements. Essentially the world's sole observer able to measure galaxy redshifts over 10 years, he single-handedly established that galaxies tended to be redshifted, which is the revolutionary discovery from which all else flowed. The centenary of his first radial velocity measurement was celebrated in a 2012 conference, and we encourage all those interested in the history of the subject to consult the proceedings.⁵

References

1. K. Lundmark, *Mon. Not. R. Astron. Soc.* **84**, 747 (1924); **85**, 865 (1925).
2. A. Friedmann, *Z. Phys.* **10**, 377 (1922); *Z. Phys.* **21**, 326 (1924).
3. See, for example, E. Hubble, M. L. Humason, *Astrophys. J.* **74**, 43 (1931).
4. H. Nussbaumer, L. Bieri, *Discovering the Expanding Universe*, Cambridge U. Press, New York (2009), chaps. 9 and 10.
5. M. J. Way, D. Hunter, eds., *Origins of the Expanding Universe: 1912–1932*, ASP Conference Proceedings 471, Astronomical Society of the Pacific, San Francisco (2013).

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■ **Livio and Riess reply:** The letter by Michael Way, Ari Belenkiy, Harry Nussbaumer, and John Peacock describes our article as if its intention was to review "studies of the expanding universe from the 1920s to the present." In fact, the intent was to describe current and future methods that are likely to yield values of

the Hubble constant with errors not exceeding a few percent. We only provided a brief historical background to offer a context for the present work and for the recently discovered Lemaître letter. Accordingly, not only were many historical facts described very briefly or omitted altogether, but many past methods—planetary nebulae, novae, mass-loss rates from massive stars, and so on—that were not thought to have the potential to deliver the desired accuracy were not mentioned at all.

We are fully aware of the fascinating history of the subject. In fact, one of us reviewed the proceedings *Origins of the Expanding Universe*, Way and coauthors' reference 5, for the *Journal for the History of Astronomy*. There are a few excellent reviews of the history of the discovery of cosmic expansion, including Way and company's reference 4 by Nussbaumer and Lydia Bieri, which we encourage readers to seek out.

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Corrections

February 2014, page 58—In the second paragraph, the two occurrences of $\sin \alpha$ should be $\cos \alpha$.

April 2014, page 30—The equation-of-state parameter given in the first paragraph "Windows onto dark energy" should be $w_{DE} = -1.027 \pm 0.055$.

May 2014, page 17—The formula for thallium trifluoroacetate should be $\text{Ti}(\text{CF}_3\text{COO})_3$. ■

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