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(*b*. Sneek, Netherlands, 6 May 1872; *d*. Leiden, Netherlands, 20 November 1934), *astronomy, cosmology*. For the original article on de Sitter see *DSB*, vol. 12.

This supplement to Adriaan Blaauw's article in the *Dictionary of Scientific Biography* focuses on de Sitter's important contributions to relativistic cosmology and also calls attention to his views on the methods and nature of science. The bibliography includes only works not mentioned in Blaauw's article.

Theories of Gravitation About 1910, after he had become professor of astronomy in Leiden, de Sitter's main occupation was with celestial mechanics, but this was only one of his research fields. He had an interest in alternatives to Newton's theory of gravitation even before Einstein's theory of general relativity. In 1905 Henri Poincaré had suggested a special-relativistic (and non-Einsteinian) theory of gravitation that five years later was formulated in a different way by H. A. Lorentz. In a paper of 1911 de Sitter examined in detail this kind of theory and its astronomical consequences, concluding that Poincaré's theory predicted an additional perihelion advance, which in the case of Mercury amounted to 7'15" per century. He showed that although the special-relativistic force law could be brought to agree with observations, because of its flexibility (it contained several free parameters) it could not be refuted. At any rate, with the advent of general relativity the Mercury anomaly was fully explained without special hypotheses, and de Sitter immediately turned his interest to the new theory.

As a foreign member of the Royal Astronomical Society, he was invited by Arthur Stanley Eddington (who then served as the society's secretary) to produce an account of the new theory, which he did in three articles in the *Monthly Notices*. These articles introduced Einstein's theory to the English-speaking world, and it was on the basis of them that Eddington wrote his important *Report on the Relativity Theory of Gravitation* in 1918. In the fall of 1916 de Sitter discussed the theory with Einstein, and the discussions led Einstein to attempt to apply his theory to the universe at large. The result was Einstein's closed or spherical model of 1917, incorporating the cosmological constant (Λ). Einstein originally believed that his static, matter-filled model was the only solution to the cosmological field equations. However, in his third report to the Royal Astronomical Society of 1917, de Sitter showed that there exists another solution, corresponding to an empty universe with $\Lambda = 3/R^2$ and spatially closed in spite of its lack of matter (R denotes the radius of curvature). De Sitter termed his new model solution B, to distinguish it from Einstein's solution A. Compared with Einstein's model, de Sitter's was complex and difficult to conceptualize, in particular because it was unclear how to distinguish the properties of the model itself from those properties that merely reflected a particular coordinate representation of it. Although the de Sitter model would eventually be seen as representing an expanding universe, to de Sitter and his contemporaries it represented a static space-time.

When Einstein was confronted with de Sitter's alternative, he was forced to accept it as a mathematical solution to the field equations, but he considered it a toy model with no physical significance. In his third paper to the *Monthly Notices*, de Sitter showed that if a particle was introduced at some distance from the origin of a system of coordinates, it would appear as moving away from the observer. Moreover, he showed that clocks would appear to run more slowly the farther away they were from the observer. Because frequencies are inverse time-intervals, light would therefore be more redshifted the larger the distance between source and observer. De Sitter was careful to point out that although the redshift corresponded to a Doppler shift, it was not caused by a recession but by the particular space-time metric he used. In spite of the red-shift built into de Sitter's model, it was thought of as static.

Keeping abreast of recent astronomical observations in spite of the war, de Sitter suggested that the predicted effect might be related to the measurements of (apparent) radial nebular velocities reported by Vesto Slipher at the Lowell Observatory. This was the first suggestion that Einstein's theory might have connections to the observations of nebular redshifts. With a mean radial velocity of 600 km/s and an average distance of 10 parsecs, he found $R = 3\times10^{11}$ astronomical units. At the end of his 1917 paper de Sitter compared the two rival world models with available astronomical data. Adopting Jacobus Kapteyn's estimate of a density of about 80 stars per 1000 cubic parsecs, he found that on Einstein's model the radius R would be about 10^{12} astronomical units and the total mass of the universe about 10^{12} sun masses.

Although de Sitter's model, being devoid of matter, may seem a very artificial candidate for the real world, it soon became a foundation for further theoretical work, both among astronomers and mathematicians. It was seen as particularly interesting because of its connection with the redshift observations of spiral nebulae, which by the early 1920s left little doubt that there was a systematic recession. In an examination in 1925 of de Sitter's line element, Georges Lemaître transformed it in such a way that the space part increased with time, yet without concluding that the model described an expanding universe. When, in spring 1929, Edwin Hubble published the celebrated paper in which he demonstrated the linear red-shift-distance relationship, he suggested that the relation might represent "the de Sitter effect." However, at that time Hubble did not interpret the redshifts as Doppler shifts caused by the recession of the galaxies.

***Willem de Sitter*. AP IMAGES** .

The Expanding Universe At a meeting of the Royal Astronomical Society on 10 January 1930, Eddington and de Sitter reached the conclusion that because neither of the solutions A and B had proved adequate, interest should focus on nonstatic solutions. Shortly thereafter the two astronomers "rediscovered" a paper Lemaître had published in 1927 and in which he had derived a model for an expanding universe. In the light of Hubble's new measurements, Lemaître's theory appeared as convincing evidence that the universe is indeed in a state of expansion. De Sitter now abandoned his solution B and immediately began to develop expanding models of the type suggested by Lemaître. In June 1930 he presented his own version of the expanding universe, including a derivation of the Hubble law ($v = Hr$) and a recession constant of $H = 490$ km/s/Mpc, not far from Hubble's value. One month later he presented a full investigation of Lemaître's theory which he extended to cover also dynamical solutions that had not been considered by Lemaître. Interestingly, he included among his models big-bang solutions corresponding to $R(t = 0) = 0$, the same kind of model that Lemaître would propose in 1931. However, whereas Lemaître considered it a model of the real universe, to de Sitter it was just a mathematical solution of no particular physical importance.

In his work on Lemaître-like expanding models, de Sitter kept to the cosmological constant, which he found to be a useful quantity, although one whose physical meaning was admittedly unclear. Back in 1917 he had shared Einstein's opinion that it was "somewhat artificial," but he had no strong feelings about the constant and tended to consider it as no stranger than other constants of nature. It is also worth recalling that de Sitter was the first to estimate the value of the cosmological constant: In a letter to Einstein of 18 April 1917 he stated that the constant was certainly smaller than 10^{-45} cm^{-2} and probably smaller than 10^{-50} cm^{-2}.

Although de Sitter was an enthusiastic advocate of the expanding universe, his advocacy did not extend to cosmological models of a finite age. Given his doubts with respect to such models it is noteworthy that he contributed significantly to the early history of big-bang theory, namely in a brief paper of 1932 written jointly with Einstein. The Einstein–de Sitter model made no use of the cosmological constant and assumed space curvature to be zero. It follows that the matter density is given by $\varrho_c = 3H^2/8\pi G$, what in later literature became known as the critical density (corresponding to $\Omega \equiv p/p_c = 1$. The expansion of the Einstein–de Sitter universe follows $R(t) \sim t^{2/3}$, which means that the age is finite and given by $2/3H$. However, Einstein and de Sitter did not write down the variation of $R(t)$, and neither did they note that it implies an abrupt beginning of the world. The Einstein–de Sitter model came to be seen as a typical big-bang model, but in 1932 neither Einstein nor de Sitter seems to have considered it important. With the value of the Hubble constant accepted at the time, the age of their model universe would be 1.2 billion years, which was much less than the age of the stars (and even less than the age of the Earth).

Worried about the age paradox, de Sitter never felt at home with the big-bang theory. He briefly considered the idea in a 1931 paper in the Italian journal *Scientia*, but only to conclude that it was implausible. At a meeting of the British Association for the Advancement of Science in the fall of 1931 he emphasized that the age paradox was a genuine dilemma that somehow might mean that the expansion of the universe and the evolutionary changes of stars were unconnected processes, to be understood in different ways. He apparently preferred two kinds of models at the time, neither of them being the Einstein–de Sitter model. As one possibility he considered a universe of the Lemaître-Eddington type, that is, a model slowly starting its expansion from a stationary state. The other possibility was a model in which the universe had contracted during an infinite time and then, after having passed a minimum, started to expand and would continue to do so indefinitely. In a paper of 1933 he discussed the contraction-expansion scenario, which, he argued, might provide a solution to the paradox of stars being much older than the universe.

An Empiricist Astronomer De Sitter's mind was not of the philosophical kind, but on several occasions, especially in connection with cosmology, he nevertheless expressed his views about the methods and philosophical foundation of science. These views were decidedly empiricist and inductivist in the sense that he stressed that physical theory must begin and end in observation. If a theory was based on a priori principles or went outside the observational realm it was metaphysical, and de Sitter strongly disliked metaphysics. Now cosmology is concerned with the universe as a whole, something which is not observable, and it relies on tremendous extrapolations. De Sitter realized that this was a problem, but of course without drawing the conclusion that cosmology is therefore non-scientific or metaphysical. He always emphasized the danger of extrapolating beyond the observable part of the universe, yet he found it to be acceptable so long as it was understood that models of the entire universe inevitably depend on "our philosophical taste." In *Kosmos*, a book published 1932, he stated that the concept of the universe was after all a hypothesis, and he suggested that it might have properties that would be contradictory and impossible for a finite material structure.

In agreement with his preference for the inductive-empirical method, de Sitter tended to reject theories based on hypotheses and deductions. He believed Einstein's general theory of relativity belonged to the first class, that it was essentially an empirical theory, uncontaminated by metaphysics. At the same time, he found Eddington's ambitious attempt to connect cosmology with micro-physics to be objectionable because it rested on speculations and unverifiable hypotheses. It was also for philosophical reasons that he rejected Edward Arthur Milne's alternative world model without examining it closely. Not only was this model deduced from a priori assumption, it also had no observable consequences— hence from de Sitter's point of view it was hardly a scientific theory. Willem de Sitter died in the fall of 1934 and was thus spared the experience of seeing how popular (and controversial) Milne's system of kinematic relativity became in British cosmological circles.

De Sitter's greatest contribution to cosmology was probably his theory of 1917 which in modernized versions continued to play a role many years after his death, understood in the early twenty-first century as a model of an exponentially expanding universe. For example, the steady-state universe of the 1950s was geometrically described by de Sitter's metric, which was also used in the inflation theories of the very early universe that were developed in the 1980s. In the inflationary model, de Sitter's solution relates to a universe dominated by vacuum energy or, equivalently, the cosmological constant.

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Helge Kragh