Jakob Ackeret (1898–1981) at the age of 60. Taken from the anniversary volume of the *Zeitschrift für angewandte Mathematik und Physik*, Vol. 9b (1958).

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JAKOB ACKERET AND THE HISTORY OF THE MACH NUMBER[1]

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I

When Jakob Ackeret was appointed privatdocent at the Federal Institute of Technology (ETH) in Zürich at the age of 30 in 1928, he already had a formidable list of credentials. After his graduation in mechanical engineering at the ETH in 1920, he was assistant to Aurel Stodola (1859–1942) for a year and then moved to Göttingen to work with Ludwig Prandtl (1875–1953). There he made essential contributions to the development of the aerodynamics institute. In 1925, he published the famous Ackeret formulas for the lift and drag of thin supersonic airfoils. A monograph on gasdynamics that he wrote for the *Handbuch der Physik* series appeared in 1927. In that year he also moved back to Zürich to become chief engineer for Escher Wyss, where he initiated the modern aerodynamic treatment of turbines and axial compressors.

His inaugural lecture at the ETH on 4 May 1929 was on drag at very high speeds. When defining the similarity properties of viscous compressible flow, he noted that it would be very convenient to have a special name for the important ratio of flow speed (or flight speed) v to sound speed a. He proposed the designation "Mach number." This was an immediate success, and the name is now known not only to people in the field (like "Reynolds number," a name proposed by Prandtl) but also to the general public.

Ackeret's inaugural lecture was later published (*Schweiz. Bauztg.*, 12

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October 1929); in it, he wrote (translated freely from German), "The well-known physicist Ernst Mach has recognized the sigificance of this ratio with particular clarity and has proved its importance with ingenious experiments; thus it appears to be very justifiable to call v/a the Mach number."

The work of Mach (1838–1916) to which Ackeret was referring is the well-known paper published in 1887 (with P. Salcher; *Sitzungsber. Akad. Wiss Wien* 95:41–50), where the head wave of a supersonic projectile was made visible and photographed for the first time. The experiment, based on the schlieren method invented in 1864 by August Toepler (1836–1912), was a breakthrough in its time; the pictures taken by Mach and Salcher were reproduced in the paper as woodcuts!

In addition to this experiment, Mach also gave a theoretical explanation of the head-wave phenomenon and showed the now standard figure of the Mach cone as the envelope of a series of spherical pulses emitted along the path of the supersonic projectile, each growing with the speed of sound. In Volume 15 (1983) of this series, an excellent and very detailed account of the contributions of Ernst Mach is given by H. Reichenbach, director of the Ernst-Mach-Institut in Freiburg, West Germany. However, it is not mentioned there—and it seems that this fact is headed for oblivion—that Mach's theoretical explanation of the "Mach cone" had already been given forty years earlier (1847) by Christian Doppler! Ackeret himself, however, was well aware of this fact and liked to comment on it when discussing the history of the Mach number. He used to say that the use of Doppler's name (instead of Mach's) could have caused confusion with the Doppler effect or with Doppler's principle. Also, Ackeret wanted to honor the experimentalist. Thus, Doppler was left with his effect, and Mach got his number.

It seems that an article devoted to the memory of Jakob Ackeret is also a suitable place to add a few remarks on the historical role of Doppler. In the next section, the contributions of Ackeret and of his Institute to high-speed aerodynamics are reviewed, including a few brief remarks on his many important contributions in other fields. In the final section, it is shown how the train of thought that initially led Doppler to the discovery of his principle also led him, systematically pursued, to the discovery of the Doppler-Mach cone. The material in this article was gathered by the author while working as a graduate student under the direction of Ackeret.

II

Ackeret was appointed professor at the ETH in 1931. He immediately started work on the construction of the Institut für Aerodynamik. The main facilities were two big wind tunnels, constructed by Ackeret (together with his trusted designer, J. Egli). Ackeret was probably the most successful practical engineer among the scientific pioneers of modern fluid dynamics. He maintained lifelong close connections with Escher Wyss and actively participated in actual designs (e.g. the construction of variable pitch propellers for ships and airplanes). His most important invention (together with C. Keller) is the gas turbine with a closed circuit, a machine that has not yet reached the practical significance that it potentially has.

Of the two wind tunnels constructed by Ackeret, one was a low-speed tunnel of conventional design but of unusual efficiency, a workhorse with many years of use still ahead. The second was the first supersonic wind tunnel built with a closed circuit. Ackeret had two main purposes in mind with his design. First, with the lower pressure level in the tunnel, high-speed runs could be realized with less power. Second, the changing of the pressure level allowed independent variation of the Reynolds number at a constant Mach number.

The construction of this tunnel was connected with important progress in the design of multistage axial compressors. The compressor used in the tunnel was built by Brown Boveri & Co. (BBC) in Baden. It absorbed 900 HP and provided 40 $m^3 s^{-1}$ with a pressure ratio of 2.4; the efficiency of this 13-stage compressor was about 70%. The basic theory of the 1-stage axial compressor was enriched at that time by the thesis work of C. Keller, prepared under the direction of Ackeret. (It appeared in print in 1934.) As related by C. Seippel, who was head of the axial-compressor section of BBC at that time, only a 4-stage experimental engine existed when Ackeret decided to order the practically unproved multistage application of the advanced theory. Its immediate success profoundly influenced the spread of this engine type.

The first important application of the supersonic tunnel made full use of the independent variability of the Mach number and the Reynolds number. Ackeret had the idea to investigate the interaction of shock waves with boundary layers. The results were published in the series *Mitteilungen aus dem Institut für Aerodynamik* (No. 10, by J. Ackeret, F. Feldmann & N. Rott, 1946), as were the results of several other basic experiments using the wind tunnel. These included an examination of the problem of tunnel corrections for models investigated at high subsonic Mach numbers (No. 14, F. Feldmann, 1948); an experimental investigation of bodies of revolution, for which the theory at high subsonic Mach numbers was a matter of controversy before the appearance of the Göthert rule (No. 16, E. R. Van Driest, 1949); a study of the thermal effects in the wake of bluff bodies (No. 18, L. F. Ryan, 1951; No. 21, J. Ackeret, 1954); and experiments on grids in supersonic flow (No. 19, R. M. El Badrawy, 1952) and bodies of revolution at low supersonic Mach numbers (No. 24, H. R. Voellmy, 1958). A few papers on high-speed flow did not appear in the Mitteilungen series—in particular, an experimental verification of the transonic similarity (*Z. Angew. Math. Phys.*, 1950) and measurements on inclined bodies of revolution at high subsonic Mach numbers (*L'Aerotecnica*, 1951), both by J. Ackeret, M. Degen & N. Rott.

By 1967, when Ackeret retired, 32 *Mitteilungen* volumes had appeared; only those were mentioned above in which the Mach number played a role. This is not the place to give a complete survey of this series, but No. 4/5 (H. L. Studer & P. de Haller, 1934) should be mentioned because it included the discovery of the stall flutter of single profiles and a treatment of ground effects on wings. In addition, No. 13 (W. Pfenninger, 1946) should also be noted for its report on important new experiments on boundary-layer suction.

After his retirement, Ackeret remained active in many fields (e.g. wind forces on buildings, ventilation of long tunnels). He also maintained his lifelong interest in the history of science and technology. His most important contribution in this field was the editing of the volume of Euler's works on hydrodynamics. (In 1944, a turbine was built and tested at the Institut according to ideas and sketches published by Euler in 1754.)

In 1973, Ackeret underwent a serious operation, after which he curtailed many of his activities. His main interest remained the solution of the world energy problem. He died on 26 March 1981, nine days after his eighty-third birthday. His life work is an integral part of modern aerodynamics.

III

When Christian Doppler (1803–53) announced in 1842 the principle now bearing his name, he was fully aware that he had to take into account the relative motion of three things: the source, the observer, and the medium (air, ether, etc.). This he did by examining two cases. In case 1, he considered an observer moving toward a source at rest (relative to the medium at rest), with the source emitting signals with its proper frequency ω_0. The frequently measured by the observer is $\omega_{\mathrm{I}} = \omega_0(1+M)$, where M is the Mach number of the approach velocity. In case 2, the observer is at rest relative to the medium and is approached by a source, and thus $\omega_{\mathrm{II}} = \omega_0(1-M)^{-1}$. Only to first order in M are the two results the same. It is also clear that the two cases are vastly different in the level of difficulty needed for their comprehension. Case 1 is almost trivial, while case 2 involves an understanding of the whole field generated by a moving source. In 1842, Doppler restricted his attention to the part of the field lying in the line of the source motion. In due course, however, he considered the whole field, and his results were published (as in 1842) in the *Abhandlungen der*

Böhmischen Gesellschaft der Wissenschaften (Vol. 5, 1847). Doppler's own figures from this paper are reproduced here (Figures 1–6). First, Doppler constructed a subsonic (Figure 1) and a supersonic (Figure 2) field pattern; the latter figure is the first drawing showing a "Mach cone." He then proceeded to discuss the special case of sonic speed (Figure 3). Finally, he applied his construction to curved paths, again for subsonic, supersonic, and sonic speeds (Figures 4–6); these figures show how deeply Doppler explored the problem of a moving sound source. He even considered moving sources in dispersive media, albeit without conclusive results.

The involvement of Mach with Doppler's earlier work from 1842, when the "principle" was laid down, is presented in great detail in Reichenbach's article (mentioned above). Here only a brief outline of the main issues is given.

Mach's contribution to the understanding of the Doppler effect was both experimental and theoretical; his first paper on this subject was published in 1860, when he was a 22-year-old student, in the *Sitzungsberichte der Akademie der Wissenschaften in Wien* (1860; Reichenbach, loc. cit., p. 5). The work of Mach was a defense of Doppler's theories against (unjustified) criticism by Jozsef Petzval (1807–91), also of Vienna. Petzval was already well known for his contributions to geometrical optics; his lens design of 1840 revolutionized the early development of photography. In three papers presented to the Academy in Vienna in 1852, he proposed a theory that he tried to interpret as a refutation of Doppler's results. Basically, Petzval could not accept that a field of a moving source can be found without considering the interaction between source and medium. Doppler, however, came by sheer intuition to the (implicit) conclusion that this interaction only affects a near-field of negligible extension, and he found his results without resorting to any kind of calculations. Actually, Petzval was the first to propose that the field of a moving source could be determined by superposition of pulses distributed along its path, a method that can serve (as was pointed out by Mach) for a mathematical proof of Doppler's results. This method was used again much later by Prandtl (1938, *Schriften der deutschen Akademie für Luftfahrtforschung*).

Petzval remarked correctly that when source and observer are relatively at rest, then there is no frequency shift when the wind blows. From this he tried to construct a contradiction with Doppler's results; naturally, there is none. Mach made in 1862 (in *Annalen der Physik und Chemie*) the acrimonious remark, that in case that Professor Petzval would be serenaded (maybe for his contributions to this controversy), he obviously will hear the music in the correct tune, whether the wind blows or not.

The heated controversy had apparently cooled down considerably by 1887, when Mach made his famous experiments showing pictures of the

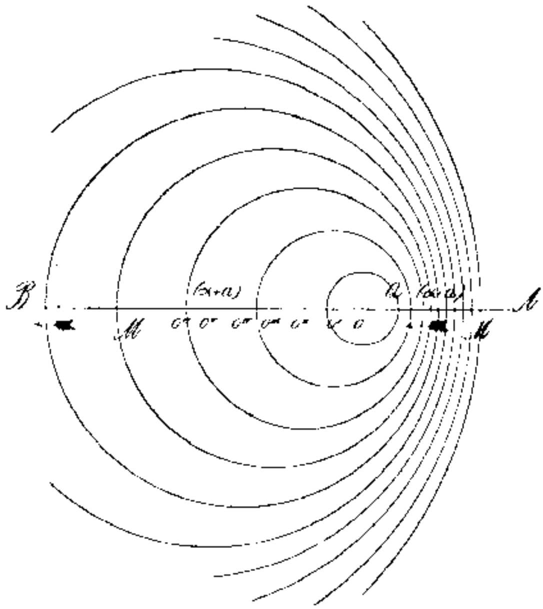

Figure 1

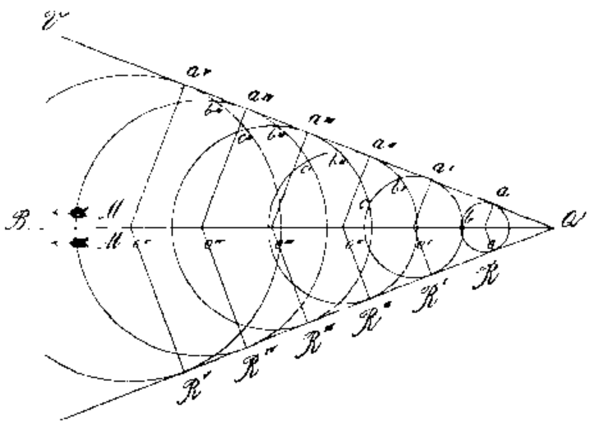

Figure 2

Figures 1–6 Original figures from Doppler's paper entitled "Ueber den Einfluss der Bewegung des Fortpflanzungsmittels auf die Erscheinungen der Aether-, Luft- und Wasserwellen." Figures 1–3: straight path. Figure 1: $M < 1$; Figure 2: $M > 1$; Figure 3: $M = 1$. Figures 4–6: curved paths. Figure 4: $M < 1$; Figure 5: $M > 1$; Figure 6: $M = 1$.

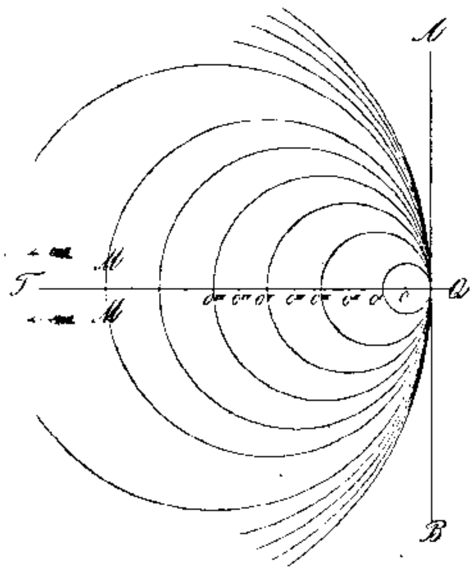

Figure 3

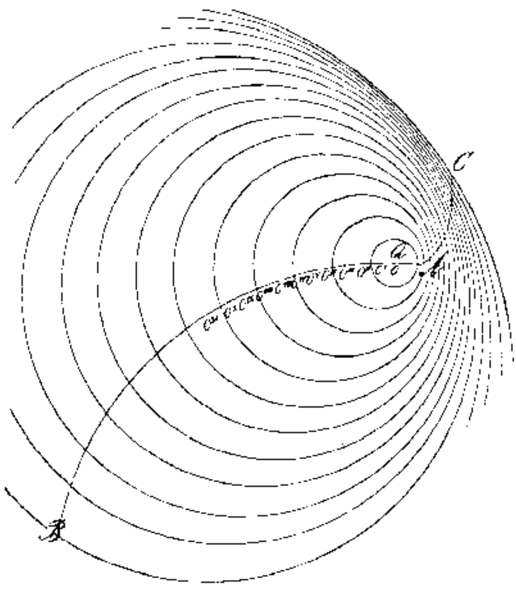

Figure 4

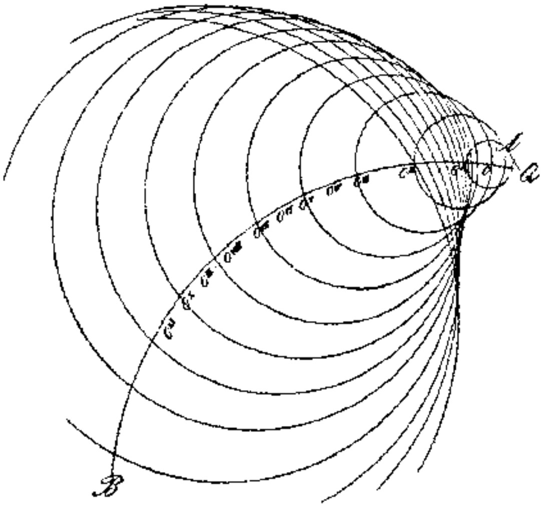

Figure 5

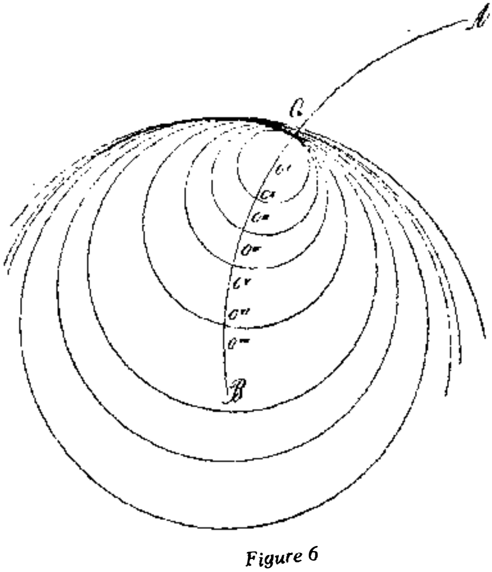

Figure 6

wave system of a supersonic bullet. A full account of these experiments is given by Reichenbach (loc. cit., p. 18); in Reichenbach's article, there is also (p. 25) a remarkable copy of a photograph taken by Mach, made from the original negative. Such pictures marked the beginning of a new era in the understanding of supersonic flow. In the theoretical explanations given by Mach, the legacy of Doppler is preeminently apparent. Mach, however, took the step of extending the ideas of Doppler from the sound field to the flow field.

The reader might ask why we should gloat over these old stories about the great men of the past. I think, however, that the Doppler-Petzval controversy is of interest as an elementary prelude to the difficult acceptance that the special theory of relativity received several decades later. Indeed, if two spaceships approached each other, carrying identical light sources, they could not distinguish the Doppler shifts that they observe. According to Einstein's theory, they would measure the geometric mean of Doppler's ω_{I} and ω_{II}.

The classical part of the history of the Doppler effect was brought to completion by a paper of Waldemar Voigt (1850–1919), best known for his fundamental contributions to the mechanics and optics of crystals. In 1887 he published a paper in the *Göttinger Nachrichten*, in which he showed that by a simple change of variables, the field of a moving source can be obtained from the field of a source at rest as a solution of the wave equation, and that this solution is in agreement with Doppler's predictions. Aerodynamicists know that such a change of variables is (almost) identical with a Lorentz transformation, except for a normalization factor that is trivial in the classical sense but essential for the explanation of the relativistic Doppler effect.

Today, Voigt's paper is largely forgotten and, in particular, not quoted by aerodynamicists. However, as was pointed out to me by Ackeret, the significance of this paper was known to Wolfgang Pauli (1900–58), whose monumental work on relativity appeared in the *Encyclopädie der mathematischen Wissenschaften* in 1921. Here, Voigt's work is the first reference. It represents the end of the classical era and gives a convenient point to establish a bridgehead in a new territory.