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Preface

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I. BACKGROUND OF THE SYMPOSIUM

DURING the postwar years, there has been a remarkable growth in the research areas common to aerodynamics and astronomy. In part this growth reflects the expanding frontiers of aerodynamics. In part it results from a finally developing awareness among astronomers that the velocity fields they infer in stellar phenomena must be investigated from a self-consistent gas-dynamical approach.

The problems of exploiting such a common research area are essentially of two kinds. One wishes to ascertain whether a particular body of astronomical data falls within the conceptual framework which the astronomer rushes enthusiastically to borrow from the aerodynamicist. Also, one wishes to extend the conceptual framework of aerodynamics to include the wider phenomenological range covered by astronomical conditions. A major uncertainty lies in ascertaining whether the empirical parameters the astronomer thinks he has established actually reflect a physical situation or a misinterpretation of observations.

A concern with gas-dynamical phenomena in astronomy promises to expand the scope of aerodynamics in three directions. For one, the ambient conditions in much of the astronomical environment are such that the gas is in a highly excited state relative to the ambient conditions found in terrestrial aerodynamics. In consequence, a relatively smaller disturbance is required to couple the macroscopic velocity field to the radiation field of the gas, thus providing radiative dissipation, the possibility of cyclic thermodynamic processes, and phenomena of nonequilibrium thermodynamics in a quasi-steady state. Second, the ambient medium is often ionized to a significant degree, which leads to the appearance of electric currents and magnetic fields, which react upon the motion of the gas. A third aspect is introduced by the astronomical scale, enormously larger than in the terrestrial laboratory. This factor is most useful in stability studies, and in enhancing magneto-gas dynamic effects.

A comparison of the prewar, immediate postwar, and more recent trends in the application of gas-dynamic concepts to astronomy illustrates the general situation and the background for the Symposia of which the present is the third. The following is schematic rather than exhaustive, particularly with respect to references, attempting merely to sketch the trend of evolution and to provide a few illustrative references from which those interested may go further. Eddington's treatment[1] of stellar pulsation under the assumption that it might be described by a system of standing waves represents the first detailed attempt to interpret the gas-dynamical velocity fields observed in astronomy. Schwarzschild's suggestion[2,3] that a system of progressive waves must arise in the stellar atmospheric regions, to which the observations refer, represents an attempt to investigate the actual gas-dynamical problem rather than assume a solution. This progressive wave solution for the atmospheric motions was treated acoustically, in spite of the observational analysis implying a supersonic velocity for the wave, until the postwar suggestions that shock waves must ultimately develop,[4–7] thus illustrating at once the conceptual incompleteness of the prewar attempts to apply aerodynamics to astronomy and the utility of an exposure of astronomers to aerodynamics. These later discussions of the problem from the standpoint of aerodynamic self-consistency have led to systematic attempts to treat the actual nonlinear problem.[8]

The aerodynamic concept most often applied to astronomical gas dynamics has been that of turbulence. The prewar applications stemmed from the notion that turbulence should exist in the astronomical environment; the postwar, that something definite could be said about the turbulent velocity spectrum under almost any conditions. The concept of "astronomical turbulence" was launched by Rosseland's observation[9] that because of the enormous distance scales entering in astronomy, the Reynolds number is bound to exceed the critical value for onset of turbulence. In consequence, virtually all astronomical velocity fields should be accompanied by turbulence. The important question of what length should enter the stability calculation in the astronomical environment has thus far not been settled; and the phrase "accompanied by turbulence"

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[1] A. S. Eddington, Monthly Notices Roy. Astron. Soc. **79**, 2, 177 (1918). [The first suggestion and treatment of a stellar pulsation theory is that by A. Ritter, Wiedemanns Ann. **8**, 172 (1879).]

[2] M. Schwarzschild, Harvard Circulars, **429**, 431 (1938).

[3] M. Schwarzschild, Z. Astrophys. **15**, 14 (1938).

[4] R. N. Thomas, Astron. J. **52**, 158 (1947).

[5] Schwarzschild, Schwarzschild, and Adams, Astrophys. J. **108**, 207 (1948).

[6] M. Schwarzschild, Transactions of the International Astronomical Union **8**, 811 (1954).

[7] R. N. Thomas and C. A. Whitney, Astron. J. **58**, 235 (1953).

[8] C. A. Whitney, Ann. Astrophys. **19**, 34, 142, et seq. (1956).

[9] S. Rosseland, Monthly Notices Roy. Astron. Soc. **89**, 49 (1929).

has often been transposed in practice into "completely turbulent."

When it was found that the solar chromosphere-corona and the entire atmospheres of some other stars were far more distended than thermal pressure (at the presumed atmospheric temperature) would permit, a "turbulent" pressure was invoked[10,11] as the support mechanism, but energy dissipation was explicitly ignored. Objections to this omission of energy dissipation,[12] and to the whole concept of such a velocity field being treated as turbulence[4,13] essentially rest on the necessity for the relative velocities involved to be highly supersonic, thus requiring presence of shocks and rapid energy dissipation.

Similar arguments for the presence of galactic fields of supersonic turbulence,[14] and against its possibility[15] have been entered, with additional arguments (Pickelner) that the presence of the galactic magnetic field inhibits energy dissipation in collision of turbulent elements.

Although a number of astronomers have urged that "astronomical turbulence" be viewed as quite another phenomenon than "aerodynamic turbulence," the advent of the Kolmogoroff spectrum derived for fully developed, isotropic, homogeneous turbulence found a rush of attempts to apply it to represent astronomical data. Among these may be mentioned the von Weizsäcker,[16] von Hoerner[17] application to the velocity spectrum of the Orion Nebula, Schwarzschild's and Richardson's[18] application to the solar granules, and Minnaert's[19] attempt to apply it to the convection pattern in the solar atmosphere.

In a strong sense, these attempts at applying postwar developments in aerodynamic turbulence theory to astronomical data represented a wishful feeling that these statistical theories, developed for application because a physical theory of turbulence was lacking, were perhaps the proper approach to astronomical velocity fields whose presence astronomers only vaguely understood. Quite another approach was launched by Burgers[20] and Oort,[21] who attempted a detailed aerodynamic study of the expansion of an individual interstellar gas cloud. Attempts were made to discuss the variation in density and temperature of such a cloud, its interaction with the interstellar medium, and phenomena attending collision with another gas cloud, particularly with regards to energy dissipation. Magnetic effects were neglected. A very similar attempt to discuss the aerodynamic behavior of an individual dynamic element in the solar atmosphere was presented by Thomas.[13]

Burgers' and Oort's interest in the possibility that collaboration between the aerodynamicist and astronomer might resolve at least some of these gas-dynamic problems of the interstellar medium, through either the aerodynamic treatment of individual phenomena or the application of "turbulence" theories to ensembles of data on the velocity field, led to the convocation of the First Symposium on Cosmical Gas Dynamics in Paris in 1949. As outlined by Oort in the opening address, two main problems were raised for consideration: (1) Can the formation of interstellar gas clouds be understood from aerodynamic considerations on the stability of the rotating galaxy? (2) How will existing clouds behave in their individual expansion and in possible collision? In addition, the general question was raised of what kind of effects beside gravitation and gas pressures need be considered; for example, magnetic effects, radiation pressure being discounted. Finally, the general problem of the relation between the hot stars and gas clouds was raised, remarked by the close empirical association often found.

In the First Symposium, the question of the production of the interstellar gas clouds was divided into two parts—the kind of turbulent velocity fields that must result from stability consideration in galactic rotation, and whether this turbulence could produce density fluctuations which we would view as clouds.

This question of the possible turbulent instability of a rotating galaxy has carried through the Second and Third Symposia and seems no clearer now than when first posed. Progress seems to have been made in one direction. During the recent Symposium, and in a variety of other places between symposia as already mentioned, attempts were made to describe the observed interstellar velocity fluctuations in terms of the Kolmogoroff spectrum. An apparent initial success during the Second Symposium was shown during the Third Symposium to have been illusory. If the interstellar velocity fields can be represented in terms of some kind of velocity spectrum, it departs considerably from the Kolmogoroff.

During the Second Symposium many avenues of thought expressed the need to consider compressibility effects in formulating a description of the interstellar differential velocity fields. It became apparent that in addition to instability effects, one must consider the possibility that velocity fields are produced by differential pressures resulting from differential ionization of the interstellar medium. Also, dissipation by collision and shock mechanisms are likely to be as important as turbulent dissipation. Thus, the question of the origin and evolution of the interstellar velocity fields has been

[10] W. H. McCrea, Monthly Notices Roy. Astron. Soc. **89**, 49 (1932).
[11] O. Struve and C. T. Elvey, Astrophys. J. **79**, 409 (1934).
[12] S. Chandrasekhar, Monthly Notices Roy. Astron. Soc. **94**, 16 (1934).
[13] R. N. Thomas, Astrophys. J. **108**, 130, et seq. (1948).
[14] S. B. Pickelner and I. S. Shklovsky, Revs. Modern Phys. **30**, 935 (1958), this issue.
[15] L. Spitzer, Astrophys. J. **124**, 20 (1956).
[16] C. F. von Weizsäcker, "Problems of cosmical aerodynamics," CADO, Dayton, Ohio, Chap. 22 (1951).
[17] S. von Hoerner, Z. Astrophys. **30**, 17 (1951).
[18] M. Schwarzschild and R. S. Richardson, Astrophys. J. **111**, 351 (1950).
[19] M. Minnaert, *The Sun*, edited by G. P. Kuiper (University of Chicago Press, Chicago, Illinois, 1953), p. 174.
[20] J. M. Burgers, Proc. Akad. Sci. Amsterdam **49**, 589 (1946).
[21] J. H. Oort, Monthly Notices Roy. Astron. Soc. **106**, 159 (1946).

alternatively phrased in terms of the question of the energy balance of the interstellar medium—what is the source of the nonradiative, mechanical, energy in the interstellar medium? And, how do observed macroscopic velocity fields couple with internal degrees of freedom of the gas to provide energy dissipation, ultimately through radiation?

Finally, the question of magneto-gas dynamic effects keeps recurring, largely through two questions. What is the effect of an exterior magnetic field upon (a) the aerodynamic stability of an ionized gas and (b) upon the energy dissipation processes? This last is often phrased in terms of the degree to which equipartition may set in between velocity and magnetic fields. In view of the widespread tendency to assume complete equipartition, probably one of the most useful results of the Third Symposium was the general frank admission that to neither of the two questions do we have an answer, only speculation.

In summary, the most useful product of these symposia has been to bring home to both astronomers and aerodynamicists a realization that in the astronomical domain a whole new range of aerodynamic phenomena has been opened, to which we cannot blindly apply the concepts of conventional laboratory aerodynamics. Over the period covered by these Symposia the meaning of conventional laboratory aerodynamics has of course changed very considerably, and a good part of aerodynamics has virtually become aerophysics. The partnership of physics and astrophysics in the development of classical spectroscopy and quantum mechanics as applied to gases in the quiescent state seems about to be duplicated in the application to gases in the dynamic state. We have therefore been deeply grateful for Dr. Condon's suggestion that we might publish these Proceedings in the *Reviews of Modern Physics*, with the idea that the Proceedings summarize the evolution of a train of thought on an interfield discipline, not simply a single Symposium. We hope that the reader will note particularly the two summary sessions, Parts III and VIII in this respect.

At the final session of the Symposium, a special discussion held under the chairmanship of Professor M. Minnaert led to the unanimous recommendation that it would be desirable to continue these meetings where astrophysicists and aerodynamicists and physicists could come together to discuss problems of interest to them all; the subject suggested has been *Aerodynamic Phenomena in Stellar Atmospheres*.

As a possible date the years 1960 and 1961 have been considered; as a meeting place the Netherlands (Utrecht or Leiden). A provisional committee was appointed consisting of J. M. Burgers, M. Minnaert, and R. N. Thomas who should bring proposals to the two International Scientific Unions involved, for arranging for a Fourth Symposium.

Because of the rapid growth of interest in these Symposia, as judged by the participation, a broader preparatory base has been suggested, including such proposals as the preparation of a bibliography in this area of work. The provisional committee would welcome suggestions.

II. MECHANICS OF THE SYMPOSIUM

The Third Symposium was held from June 24 to 29, 1957, at the Smithsonian Astrophysical Observatory, Cambridge, Massachusetts.

Like the two preceding Symposia, it was organized by the International Union of Theoretical and Applied Mechanics and the International Astronomical Union. The Organizing Committee consisted of: G. K. Batchelor, J. M. Burgers, S. Chandrasekhar, G. D. Colchagoff, H. L. Dryden, A. R. Kantrowitz, O. Laporte, J. H. Oort, R. J. Seeger, L. Spitzer, G. I. Taylor, R. N. Thomas, G. E. Uhlenbeck, H. C. van de Hulst, Th. von Karman, and F. L. Whipple.

Chairman and secretary of the Symposium were J. M. Burgers and R. N. Thomas, who together with G. D. Colchagoff acted as editorial committee for the publication of the Proceedings. Arrangements at the Astrophysical Observatory were prepared by Thomas and Miss Mary Ann Dexter. We are indebted to the staff of the Observatory, to its Director, Dr. F. L. Whipple, to Dr. G. F. Schilling, and to Dr. L. Carmichael, Secretary of the Smithsonian Institution for their role as hosts to the Conference and a generous financial grant to facilitate publication and distribution of the Proceedings. To Dr. E. U. Condon, editor of the *Reviews of Modern Physics*, we are much indebted for easing and expediting a difficult publication problem.

Major G. D. Colchagoff, through the consideration of the ARDC USAF, has organized the microphonic recording and transcription of the speeches, and with Miss Dexter has compiled the records of the discussions during and immediately after the sessions, so that texts could be corrected at once by all the speakers. Considerable secretarial help was needed for this purpose; for this we are indebted to the Boulder Laboratories of the National Bureau of Standards, to the Smithsonian Astrophysical Observatory and to the AVCO Research Laboratories through its Director Dr. A. G. Kantrowitz.

The two International Unions with the aid of UNESCO made available a sum of money for paying part of the traveling and subsistence expenses of scientists coming from abroad.

The Office of Scientific Research of the U. S. Air Force arranged transportation by the Military Transport Service of seventeen scientists coming from Europe; for this we are indebted to Dr. William J. Otting and General H. F. Gregory.

The National Science Foundation has given a grant of money out of which transportation expenses of a number of American and Canadian scientists could be paid; thanks are due Dr. R. J. Seeger, Acting Program

Director for Physical Sciences, and to Dr. F. Edmondson, Program Director for Astronomy.

We are especially indebted to the National Academy of Sciences, through Dr. A. C. Simonpietri for continued advice, aid, and consultation on the planning of the Conference and for liaison with the U. S. State Department on matters involving foreign visitors. We express our warm thanks to the State Department for their active efforts on, and sympathetic cooperation in, our problems.

The AVCO Research Laboratories offered hospitality at a cocktail party, and detailed help in the mechanics of the Symposium.

The Symposium was attended by somewhat over 80 scientists, 24 of whom came from outside the United States (Australia 1, Canada 1, France 3, Germany 2, Great Britain 10, Netherlands 3, U.S.S.R. 4), while about 60 scientists came from the United States.

PARTICIPANTS FROM OUTSIDE THE UNITED STATES

V. A. Ambartsumian, Erevan, U.S.S.R.
J. Bass, Paris, France
G. K. Batchelor, Cambridge, England
L. Biermann, Göttingen, Germany
E. C. Bullard, Cambridge, England
R. D. Davies, Jodrell Bank, England
G. de Vaucouleurs, Canberra, Australia
F. A. Goldsworthy, Manchester, England
F. D. Kahn, Manchester, England
L. Mestel, Cambridge, England
A. G. Massevitch, Moscow, U.S.S.R.
M. Minnaert, Utrecht, Netherlands
B. E. J. Pagel, Royal Greenwich Observatory, England
J. C. Pecker, Meudon, France
S. B. Pickelner, Simeis, U.S.S.R.
R. O. Redman, Cambridge, England
E. Schatzman, Paris, France
A. Schlüter, Göttingen, Germany
D. W. Sciama, Cambridge, England
M. J. Seaton, London, England
L. I. Sedov, Moscow, U.S.S.R.
R. W. Stewart, University of British Columbia, Canada
H. C. van de Hulst, Leiden, Netherlands
H. Zanstra, Amsterdam, Netherlands

PARTICIPANTS FROM THE UNITED STATES

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J. W. Bond, Convair
W. H. Bostick, Stevens Institute of Technology
R. Brown, NSF (National Science Foundation)
J. M. Burgers, University of Maryland
G. F. Carrier, Harvard University
J. W. Chamberlain, Yerkes Observatory
G. D. Colchagoff, AF ARDC (Air Research and Development Command)
B. Donn, Wayne University
F. D. Drake, Harvard University
H. U. Eckert, Convair
J. A. Fay, MIT (Massachusetts Institute of Technology)
G. B. Field, Princeton University
F. N. Frenkiel, John Hopkins Applied Physics Laboratory
H. D. Greyber, General Electric
W. D. Hayes, Princeton University
D. Heeschen, Harvard University
A. Kantrowitz, AVCO Research Laboratories
J. King, AF CRC GRD (Geophysics Research Directorate)
M. Krook, Harvard University
R. Landshoff, Lockheed
J. Laurmann, University of California, Berkeley
D. R. Layzer, Harvard University
M. Levine, AF CRC GRD
H. W. Liepmann, GALCIT
C. C. Lin, MIT
A. E. Lilley, Yale University
W. V. R. Malkus, Woods Hole
G. C. McVittie, University of Illinois
T. K. Menon, Harvard University
R. Meyerott, Lockheed
N. Milford, St. John's College
R. Minkowski, Mt. Wilson
G. Münch, California Institute of Technology
W. J. Otting, AF OSR (Office of Scientific Research) ARDC
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K. Prendergast, Yerkes Observatory
S. G. Reed, Jr., ONR (Office of Naval Research)
W. H. Reid, Yerkes Observatory
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M. P. Savedoff, Rochester University
G. F. Schilling, Smithsonian Astrophysical Observatory
H. K. Sen, AF CRC GRD
S. Silverman, ONR
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F. L. Whipple, Smithsonian
C. A. Whitney, Smithsonian
O. C. Wilson, Mt. Wilson