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OBITUARY

Hans A. Buchdahl (7.7.1919–7.1.2010)

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With the death of our esteemed colleague Hans Buchdahl, we have lost a most creative, thoughtful and independent member of the relativity-and-gravitation community. At first, world history both hindered and directed his career. Born in Mainz, Germany, he and his older brother Gerd (later to become a well-known philosopher of science) were sent by his parents to England, in 1933, to receive a higher education and to escape the beginning terror of the German nationalsocialist government. Right after having finished at the London Royal College of Science, in 1939, and having obtained half of an Imperial College Governor's Prize, Buchdahl was detained as a German national, in summer of 1940, and deported to Australia together with his brother and other fellow sufferers. Once his mathematical abilities had been recognized there, he was released on a guarantor program and was transferred to the Physics Department of the University of Tasmania in Hobart. There, he had to assist the overloaded teaching staff, involved in wartime military research in optics. After having gained the trust of both students and staff, Buchdahl could join the optics group and calculated aberration coefficients for spherical systems. After becoming part-time lecturer and research physicist, in 1947, he received his doctorate from the University of Tasmania in 1948. In 1956, he was awarded a D.Sc. from Imperial College, London, and in the same year advanced to the new position of a reader. From 1963 he was professor and head of the Department of Theoretical Physics in the Faculty of Science at the Australian National University in Canberra (A.C.T.). He kept this post until his retirement in 1984; he regularly was a guest at centers of research abroad [1].

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Physicists working in general relativity, gravitation and astrophysics mostly are aware only of his important work in their fields. It reaches from the generation of solutions of Einstein's field equations to the physics of fluid spheres as stellar interiors, to alternative gravitational (and classical unified field-) theories, to wave equations of arbitrary spin in a gravitational background. Before I return to these topics in more detail, some remarks on his other research interests seem in order. Besides the work just mentioned in geometrical optics, Hans Buchdahl contributed to the foundations of phenomenological thermodynamics and to "tensor and spinor analysis" as he termed the field himself.

While his very first paper was concerned with higher-order aberrations, among the following 20 publications just two were in geometrical optics. This is explained by his first book on "Optical Aberration Coefficients" appearing in 1954, and in which he collected his remarkable research results of 6 years concerning the calculation of exact monochromatic and chromatic primary and higher order aberration coefficients. Already here can we recognize the extraordinary ability of Hans Buchdahl to simplify and manipulate involved calculational schemes and for devising new ones with improved effectiveness. His work led to numerous applications in the optical design of all sorts of imaging systems, world wide. During a year as New York State Professor of Optics at the University of Rochester in 1968/1969, he added an *Introduction to Hamiltonian Optics* [2]. His steady work in optics from 1945 to 1996, besides the books, is expressed in around 50 papers. Recent publications on *Mercado–Robb–Buchdahl coefficients* [3], *Buchdahl–Rimmer coefficients*, or *Buchdahl's glass dispersion coefficients* testify to the ongoing importance of his work in geometrical optics.

His interest in thermodynamics at first was focussed on fitting Carathéodory's axiomatic formulation better to a physicist's intuition. In an approach expressed in eight papers, eventually, he aimed at a clarification of the entropy concept and the second law by a reformulation of what he termed Carathéodory's Principle and Carathéodory's Theorem. Nevertheless, Buchdahl's attempt at making more concise the foundations of thermodynamics was far from advertising the use of the axiomatic method; instead it was an endeavour allowing "physical intuition to take precedence over mathematical niceties" ([4], preface). Later work shows that his approach did gain affirmation (cf. [5,6]). On the other hand, in his papers on the Fermi-Dirac gas, he engaged in rather practical work including numerical calculations in order to replace the parametric form of the equation of state by easy-to-handle approximate elementary algebraic equations. Also in the field of thermodynamics, Hans Buchdahl wrote two well received books [7,4]; his articles cover a period of 35 years.

Buchdahl's interest in tensor and spinor analysis certainly was related to his pleasure in dealing with formalisms and calculational procedures, be it spherical and spheroidal harmonics, γ-matrices, or a calculus reflecting $SO(3, 2) \sim Sp(2, R)$. While working with Weyl's theory and quadratic Lagrangians, he decided to present the Euler–Lagrange derivative of the most general Lagrangian built from the metric, the curvature tensor and its derivatives to arbitrary order [8]. This paper in a respected mathematical journal written in German is little known although it covers all later rederivations of field equations with higher order Lagrangian (i.e., of higher order in curvature) by many authors. D. Lovelock, G. W. Horndeski and J. C. Du Plessis elegantly have continued such kind of work in a thick forest of tensors [9–11]. During his study of spinors H. Buchdahl devised a new "rotor" calculus [12] for self-dual bivectors in a complex three-dimensional space. With it he proved that a certain curvature invariant is a divergence. This is when we got into contact after I had shown the same with another method [13,14]. Besides a special interest in Cartesian tensors, investigations of 2- and 4-spinors, and the wave equations to be satisfied by them, were high on his list (see below). However, he did not join those using spinors as an important tool in general relativity, e.g., for the study of gravitational radiation and null infinity [15].

In the realm of gravitational theory, Hans Buchdahl's papers on the generation of exact static solutions from others of Einstein's equations or scalar-tensor theory are almost as well-known as his spherically symmetric solutions describing the interior of stars (cf. [16], §14.1, 30.3, 30.5). In connection with Boson stars (cf. [17]) or superdense stars (cf. [18]) we still find references to his seminal papers on fluid spheres ([19,22]) in which he gave an inequality for central pressure improving a result of Eddington. From his work on higher order Lagrangians he concluded that theories with quadratic Lagrangians or $f(R)$-theories are unphysical (cf. [7]; private communication, 15 July 1977). These warnings were not heeded by some of those suggesting remedies for dark energy 30 years later. Likewise, the results on the application of *Palatini's device*, i.e., an independent variation of metric and affine connection within Riemannian geometry, to quadratic Lagrangians by Hans Buchdahl [21], did not get the needed attention. Here, he showed that in but a few exceptions the method leads to field equations with solutions exhibiting all sorts of under- or un-determinacies. These ambiguities are left undiscussed in some current applications of Palatini's device to cosmological models.

Another topic occupying Hans Buchdahl's mind for two decades was the compatibility of wave equations for particles with higher spin ($\geq$3/2) and non-vanishing mass in a space with curvature. By dropping non-minimal coupling, he was able to write down such consistent wave equations [23]. It was shown later that with a symmetrization of his equations the principle of minimal coupling could still be upheld [24]. Although he took into account Cartan-geometry, torsion and its use in physics (Poincaré gauge theory) did not attract him [25]. Interestingly, in 1968, when Hans Buchdahl first approached the problem, supersymmetry making its solution more urgent had not yet been invented.

A cross-fertilization between optics and gravitation is shown in his papers concerned with the world function of Robertson-Walker-, Schwarzschild-, and Gödel-metrics. This function corresponds to the point characteristic of geometrical optics and contains complete information about all geodesics. For practical use in general relativity, in most cases it must be approximated, though.

When Einstein was still alive, as with many other theorists Hans Buchdahl could not escape the lure of the famous scientist's "unified field theory" of gravitation and electricity. However, as Buchdahl's papers in this field show, he was attracted by the enlarged constructive possibilities of the more general geometries, not by any hoped-for physics behind the theory. As shown in his "17 simple lectures", his understanding of general relativity made him clearly stay away from and criticize the parlance of the main stream following J. A. Wheeler when speaking of "mass-energy curving space", "black hole" (in place of the physically more appealing "occluded star", or "frozen star") and, in the frame of quantum gravity, of "foamlike 3-geometry".

That teaching was dear to his heart is shown by his papers concerning elementary subjects as angular momentum, harmonic oscillator, or Schwarzschild's interior solution in the American Journal of Physics. None the less, to me it seems that research work took first place. Buchdahl's papers with co-authors include doctoral students as Peter J. Sands, or Greg Forbes (both then working in optics) as well as honours- and B.Sc., students.

Hans Buchdahl regularly spent time abroad for scientific exchange with colleagues and for writing up papers and some of his books (Imperial College, London 1950; Institute for Advanced Studies, Princeton (1959/1960); University of Rochester (1968); Weizmann Institute of Science, Rehovot (1975); Churchill College, Cambridge (1979); University of Göttingen (1975, 1986). He was honored by grants, prizes, medals, and memberships, to list some of them: Fellow of the Australian Academy of Science (1968), Thomas Rankin Lyle Medal (1972), Member of the American Optical Society (1974), Overseas Fellow of Churchill College, Cambridge (1979), Walter Burfitt Medal (Roy. Soc. NSW) (1980), C. E. K. Mees Medal (Opt. Soc. Amer.) (1993), A. E. Conrady Award (Int. Soc. Opt. Eng.) (1997).

Hans Buchdahl was one of the few members of a vanishing "species": gifted scientists working without much ado, i.e., without the permanent need for marketing and networking. He shied away from becoming trendy by his work, or an opinion leader, yet poured out a constant flow of results some of which will be lasting when the next fashion has ended. Of course, the price to be paid for this, and for not belonging to a larger set of closely interacting researchers, was his becoming separated from the majority agenda. Yet he was determined to pay this price: he wanted to be able to keep his independent, original way of thinking. Although very much applicable to the real world (optics, thermodynamics), his research in classical gravitation aimed at science pure. This is seen also in his work in optics by the fact that, despite the possibilities at hand, Hans Buchdahl did not care for getting patents in optical design. With the tragic death in 1992 of his youngest daughter, a promising violinist, the stream of Buchdahl's publications ended. He is survived by his caring wife of 60 years Pamela, and their children Tanya Tintner, a writing and editing professional, and Nicholas Buchdahl, a mathematician. For me, Hans Buchdahl, creative and sharp-witted, liberal and compassionate, was a role model in science and beyond.

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Appendix

List of publications by Hans Buchdahl.

Monographs

Optical Aberration Coefficients. London: Oxford University Press 1954; Dover Edition, New York: Dover Publications Inc. 1968.

The Concepts of Classical Thermodynamics. Cambridge: University Press 1970.

An Introduction to Hamiltonian Optics. Cambridge: University Press 1970. Dover Edition, New York: Dover Publications Inc. 1993.

Twenty Lectures on Thermodynamics. Sydney: Pergamon Press 1975.

Seventeen Simple Lectures on General Relativity. New York: Wiley Interscience 1981.

Papers

1946
"The algebraic analysis of the higher order aberrations of optical systems." *Proc. Phys. Soc. London* **58**, 545–575

1948
"On Eddington's higher order equations of the gravitational field." *Proc. Edinburgh Math. Soc.* **8**, 89–94

"Algebraic theory of the primary aberrations of the symmetrical optical system." *J. Opt. Soc. Amer.* **38**, 14–19
"A special class of solutions of the equations of the gravitational field arising from certain gauge-invariant action principles." *Proc. Nat. Acad. Sci. U.S.A* **34**, 66–68
"The hamiltonian derivatives of a class of fundamental invariants." *Quart. J. Math. Oxford* **19**, 150–159

1949
"On the Principle of Carathéodory." *Amer. J. Phys.* **17**, 41–43
"On the Theorem of Carathéodory." *Amer. J. Phys.* **17**, 44–46
"On the unrestricted theorem of Carathéodory and its applications in the treatment of the second law of thermodynamics." *Amer. J. Phys.* **17**, 212–218
"Temperature equilibrium in a stationary gravitational field." (Letter) *Phys. Rev.* **76**, 427–428

1950
"On Tolman's equations describing the thermal equilibrium in a gravitational sphere of fluid." *Phil. Mag.* **41**, 362–363
"Über die Variationsableitung von Fundamentalinvarianten beliebig hoher Ordnung." *Acta Math.* **85**, 63–72

1951
"On the hamiltonian derivatives arising from a class of gauge-invariant action principles in a W_n." *J. London Math. Soc.* **26**, 139–149
"An identity between the hamiltonian derivatives of certain fundamental invariants in a W_4." *J. London Math. Soc.* **26**, 150–152

1953
"On a set of conformal-invariant equations of the gravitational field." *Proc. Edinburgh Math. Soc.* **10**, 16–20

1954
"Integrability conditions and Carathéodory's Theorem." *Amer. J. Phys.* **22**, 182–183
"Reciprocal static solutions of the equations $G_{\mu\nu} = 0$." *Quart. J. Math. Oxford* **5**, 116–119

1955
"Simplification of a proof of Carathéodory's Theorem." *Amer. J. Phys.* **23**, 65–66

1956
"Approximationen der Thomas-Fermi Funktion." *Ann. Physik* (6) **17**, 238–241
"Reciprocal static solutions of the equations of the gravitational field." *Aust. J. Phys.* **9**, 13–18
"Optical aberration coefficients. I. The coefficient of tertiary spherical aberration." *J. Opt. Soc. Amer.* **46**, 941–943
"Variation of integrals and the field equations in the unitary field theory." *Phys. Rev.* **104**, 1142–1145

1957
"Gauge-invariant generalization of field theories with an asymmetric fundamental tensor." *Quart. J. Math. Oxford* **8**, 116–119
"Reciprocal static solutions of field equations involving an asymmetric fundamental tensor." *Nuovo Cimento* **5**, 1083–1093

1958
"Optical aberration coefficients. II. The tertiary intrinsic coefficients." *J. Opt. Soc. Amer.* **48**, 563–567
"On phase-invariant and gauge-invariant spinor analysis." *Quart. J. Math. Oxford* **9**, 109–113
"Optical aberration coefficients. III. The computation of the tertiary coefficients." *J. Opt. Soc. Amer.* **48**, 747–756
"Optical aberration coefficients. IV. The coefficient of quaternary spherical aberration." *J. Opt. Soc. Amer.* **48**, 757–759
"Gauge-invariant generalization of field theories with an asymmetric fundamental tensor. II." *Quart. J. Math. Oxford* **9**, 257–264
"A formal treatment of the consequences of the second law of thermodynamics in Carathéodory's formulation." *Z. Physik* **152**, 425–439
"On the compatibility of relativistic wave equations for particles of higher spin in the presence of a gravitational field." *Nuovo Cimento* **10**, 96–103

1959
"On extended conformal transformations of spinors and spinor equations." *Nuovo Cimento* **11**, 496–506
"Über Approximationen der Zustandsgleichung eines Fermi-Dirac Gases." *Ann. Physik* (7) **3**, 345–351
"On the trace of the energy momentum tensor of fields associated with particles of zero rest mass." *Aust. J. Math.* **1**, 99–105
"Optical aberration coefficients. V. On the quality of predicted displacements." *J. Opt. Soc. Amer.* **49**, 1113–1121
"Optical aberration coefficients. VI. On computations involving coordinates lying partly in the image space." *J. Opt. Soc. Amer.* **50**, 534–539
"Reciprocal static metrics and scalar fields in the general theory of relativity." *Phys. Rev.* **115**, 1325–1328
"General relativistic fluid spheres." *Phys. Rev.* **116**, 1027–1034

1960
"Optical aberration coefficients. VII. The primary, secondary and tertiary deformation and retardation of the wavefront." *J. Opt. Soc. Amer.* **50**, 539–544
"Optical aberration coefficients. VIII. The coefficient of spherical aberration of order eleven." *J. Opt. Soc. Amer.* **50**, 678–683
"Non-linear Lagrangians and Palatini's device." *Proc. Cambridge Philos. Soc.* **56**, 369–400
"The concepts of classical thermodynamics." *Amer. J. Phys.* **28**, 196–201
"On the non-existence of a class of static Einstein spaces asymptotic at infinity to a space of constant curvature." *J. Math. Phys.* **1**, 537–541

1961
"Optical aberration coefficients. IX. The theory of reversible optical systems." *J. Opt. Soc. Amer.* **51**, 608–616

1962
"On certain identities involving basic spinors and curvature spinors." *J. Aust. Math. Soc.* **2**, 369–379
"On the gravitational field equations arising from the square of the Gaussian curvature." *Nuovo Cimento* **23**, 141–157
"Optical aberration coefficients. X. Theory of concentric optical systems." *J. Opt. Soc. Amer.* **52**, 1361–1367
"Optical aberration coefficients. XI. Theory of a concentric corrector." *J. Opt. Soc. Amer.* **52**, 1367–1372
"On the compatibility of relativistic wave equations in Riemann spaces." *Nuovo Cimento* **25**, 486–496
"Heuristic approximations of the equation of state and energy function of a perfect Fermi-gas for arbitrary temperature and degeneracy." *Ann. Physik* (7) **10**, 31–46
"Entropy concept and ordering of states. I." *Z. Physik* **168**, 316–321
(with W. Greve) "Entropy concept and ordering of states." II. *Z. Physik* **168**, 386–391
" Remark concerning the eigenvalues of orbital angular momentum." *Amer. J. Phys.* **30**, 829–831

1963
"Remark on the eigenvectors of angular momentum operators." *Amer. J. Phys.* **31**, 829–834

1964
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(with L. T. Tassie) "Gauge-invariant theory of symmetry. I." *Aust. J. Phys.* **17**, 431–439

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"Optical aberration coefficients. XII. Remarks on aberration of any order." *J. Opt. Soc. Amer.* **55**, 641–649
(with L. T. Tassie) "Gauge-invariant theory of symmetry. II." *Aust. J. Phys.* **18**, 109–117
"Remark on the defining relations of the σ-symbols." *J. Aust. Math. Soc.* **5**, 393–395

1966
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"On rotor calculus. II." *J. Aust. Math. Soc.* **6**, 424 –448
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"Remark on the harmonic radius vector." *Amer. J. Phys.* **38**, 291–294
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"Hamiltonian optics. The point characteristic of a refracting plane." *J. Opt. Soc. Amer.* **59**, 996–1000
"Point characteristics of some static spherically symmetric space times." *Optica Acta* **17**, 707–713
"Non-linear Lagrangians and cosmological theory." *Mon. Not. Roy. Astr. Soc.* **150**, 1–8
"Remark on a result relating to path differences." *Optica Acta* **17**, 943–950

1971
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1972
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"On certain tensors and spinors associated with the Dirac algebra." *Tensor N.S.* **25**, 137–147
"Hamiltonian optics. III. On systems with discrete axial symmetry." *Optik* **35**, 459–467
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"Adjoined solutions of the Brans-Dicke equations." *Int. J. Theor. Phys.* **7**, 287–289

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"Quadratic Lagrangians and static gravitational fields." *Proc. Camb. Phil. Soc.* **74**, 145–148
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"On solutions of Einstein's equations with scalar zero-mass sources." *Gen. Rel. Grav.* **9**, 59–70
"Kepler problem and Maxwell fish-eye." *Amer. J. Phys.* **46**, 840–843
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"The field equations generated by the square of the scalar curvature: solutions of Kasner type." *J. Phys. A* **11**, 871–876
"Remark on the equations $\delta R^2/\delta g_{ij} = 0$." *Int. J. Theor. Phys.* **17**, 149–151

1979

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"Remark on a family of static relativistic stellar models." *Class. Quant. Grav.* **1**, 301–304
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1985
"Power series of geometrical optics. III." *J. Opt. Soc. Amer. A* **2**, 847–851
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"Isotropic Coordinates and Schwarzschild metric." *Int. J. Theor. Phys.* **24**, 731–739

1986
(with G. W. Forbes) "Power series of geometrical optics. IV." *J. Opt. Soc. Amer. A* **3**, 1142–1151
"On the redundancy of the zeroth law of thermodynamics." *J. Phys. A* **19**, L561–L564
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