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BIBLIOGRAPHY

BIBLIOGRAPHY ON INHOMOGENEOUS COSMOLOGICAL MODELS†

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1. INTRODUCTION AND ABSTRACT

This bibliography is a list of papers (and a few books, too) in which inhomogeneous cosmological models were discussed. A solution of the Einstein field equations is by definition a cosmological model if the arbitrary functions and/or constants that it contains can be specialized in such a way that in the limit a nontrivial metric of the FRIEDMANN (1922, 1924) — LEMAÎTRE (1927, 1931) — ROBERTSON (1929, 1933) — WALKER (1935) class (abbreviated FLRW) is obtained. It is inhomogeneous when its symmetry group (if any exists) has orbits of dimension at most 2; otherwise the solution would have to be either stationary or spatially homogeneous in the sense of Bianchi or KANTOWSKI — SACHS (1966). A FLRW metric is called nontrivial when it is nonstatic (this excludes the generalizations of the Einstein Universe from our consideration) and has a nonvacuum source (this excludes the generalizations of the de Sitter metrics). The Kantowski — Sachs metrics are included here for completeness. For the Bianchi-type solutions, several extended reviews with bibliographies are already available.

The papers listed are sorted by their subjects. In fact, this bibliography is just a permutation of a large subset of the reference list to the review of inhomogeneous cosmological models, recently published by this author (KRASIŃSKI 1993). The list in this section contains papers to which a reference is made in the bibliography for various pieces of general information, not necessarily connected with the inhomogeneous models. Such references are marked by [G] in the subsequent sections.

FRIEDMANN, A.A. (1922), *Z. Physik* **10**, 377.
FRIEDMANN, A.A. (1924), *Z. Physik* **21**, 326.

†The bibliography is based on a monograph, recently prepared by this author (KRASIŃSKI 1993). That work was partly supported by the Scientific Research Committee Grant no 2 1242 91 01.

KANTOWSKI, R., SACHS, R.K. (1966), *J. Math. Phys.* **7**, 443.
KRASIŃSKI, A. (1993), *Physics in an inhomogeneous Universe.* Preprint, a book in preparation.
LEMAÎTRE, G. (1927), *Ann. Soc. Sci. Bruxelles* **A47**, 19.
LEMAÎTRE, G. (1931), *Mon. Not. R. Astron. Soc.* **91**, 483.
ROBERTSON, H.P. (1929), *Proc. Nat. Acad. Sci. USA* **15**, 822.
ROBERTSON, H.P. (1933), *Rev. Mod. Phys.* **5**, 62.
WALKER, A.G. (1935), *Quart. J. Math. Oxford*, ser. 6, 81.

2. THE SZEKERES — SZAFRON FAMILY OF SOLUTIONS

2.1. The general class

The master solution was found here by SZAFRON (1977). It is a family of perfect fluid solutions with no symmetry (BONNOR, SULAIMAN and TOMIMURA 1977). Invariant definitions of this class were given by Szafron and COLLINS (1979) and by WAINWRIGHT (1977). Properties of the Szafron family of solutions were discussed by COLLINS and SZAFRON (1979a, b). The class of Szafron is a generalization of the dust solution found by SZEKERES (1975a). Properties of the latter were discussed by SZEKERES (1975b and 1980), BONNOR (1976a, b, 1986), BONNOR and TOMIMURA (1976), BERGER, EARDLEY and OLSON (1977), SPERO and SZAFRON (1978), COVARRUBIAS (1980), BARROW and SILK (1981), TOMIMURA (1981), GLEISER (1984), DE SOUZA (1985), BONNOR and PUGH (1987). A particularly extended and illuminating discussion is that by GOODE and WAINWRIGHT (1982b). LAWITZKY (1980) found the Newtonian analog of the Szekeres solution.

The generalization of the $\beta' = 0$ subfamily (see KRASIŃSKI 1993 [G] for a description) to the case of nonzero heat flow was found by GOODE (1986). STEPHANI (1987) found a generalization of a subcase of that subfamily to nonzero rotation. The other papers listed in this section contain derivations of various subcases of the Szafron family and of their generalizations to nonzero heat-flow, viscosity and electrically charged source. Papers on the subcases that can be defined invariantly are listed separately in subsequent sections.

BARNES, A. (1974), *Gen. Rel. Grav.* **5**, 147.
BARNES, A., ROWLINGSON, R.R. (1989), *Class. Q. Grav.* **6**, 949.
BARROW, J.D., SILK, J. (1981), *Astrophys. J.* **250**, 432.
BARROW, J.D., STEIN-SCHABES, J.A. (1984), *Phys. Lett.* **A103**, 315.
BAYSAL, H. (1992), *Astrophys. Space Sci.* **196**, 345.
BERGER, B.K., EARDLEY, D.M., OLSON, D.W. (1977), *Phys. Rev.* **D16**, 3086.
BONA, C., STELA, J. (1987), *Phys. Rev.* **D36**, 2915.
BONA, C., STELA, J., PALOU, P. (1987a), *Gen. Rel. Grav.* **19**, 179.
BONA, C., STELA, J., PALOU, P. (1987b), *J. Math. Phys.* **28**, 654.
BONNOR, W.B. (1976a), *Commun. Math. Phys.* **51**, 191.
BONNOR, W.B. (1976b), *Nature* **263**, 301.
BONNOR, W.B. (1986), *Class. Q. Grav.* **3**, 495.
BONNOR, W.B., PUGH, D.J.R. (1987), *South Afr. J. Phys.* **10**, 169.

BONNOR, W.B., SULAIMAN, A.H., TOMIMURA, N. (1977), *Gen. Rel. Grav.* **8**, 549.
BONNOR, W. B., TOMIMURA, N. (1976), *Mon. Not. R. Astron. Soc.* **175**, 85.
BRAY, M. (1986), *Rendiconti di Matematica e delle sue Applicazioni*, ser. VII, **6**, 171.
COLLINS, C.B., SZAFRON, D.A. (1979a), *J. Math. Phys.* **20**, 2347.
COLLINS, C.B., SZAFRON, D.A. (1979b), *J. Math. Phys.* **20**, 2362.
COVARRUBIAS, M. (1980), *J. Phys.* **A13**, 3023.
COVARRUBIAS, G.M. (1983), in: *Relativity, cosmology, topological mass and supergravity.* Proceedings of the 4th SILARG symposium on gravity, gauge theories and supergravity, Caracas 1982. World Scientific, Singapore, p. 251.
COVARRUBIAS, G.M. (1984), *Astrophys. Space Sci.* **103**, 401.
DAS, K.C. (1981), *J. Math. Phys. Sci.* (India) **15**, 151.
DENG, Y., MANNHEIM, P. (1991), *Phys. Rev.* **D44**, 1722.
DE SOUZA, M.M. (1985), *Rev. Bras. Fis.* **15**, 379.
DODSON, C.T.J. (1972), *Astrophys. J.* **172**, 1.
GLEISER, R.J. (1984), *Gen. Rel. Grav.* **16**, 1039.
GOODE, S.W. (1986), *Class. Q. Grav.* **3**, 1247.
GOODE, S.W., WAINWRIGHT, J. (1982a), *Mon. Not. R. Astron. Soc.* **198**, 83.
GOODE, S.W., WAINWRIGHT, J. (1982b), *Phys. Rev.* **D26**, 3315.
LAWITZKY, G. (1980), *Gen. Rel. Grav.* **12**, 903.
LEIBOVITZ, C. (1971), *Phys. Rev.* **D4**, 2949.
LEMAÎTRE, G. (1933b), *C. R. Acad. Sci.* Paris **196**, 903.
LIMA, J.A.S. (1986), *Phys. Lett.* **A116**, 210.
LIMA, J.A.S., GARCIA MAIA, M.R. (1985), *Phys. Lett.* **A110**, 366.
LIMA, J.A.S., NOBRE, M.A.S. (1990), CLASS. Q. GRAV. **7**, 399.
LIMA, J.A.S., TIOMNO, J. (1988), *Gen. Rel. Grav.* **20**, 1019.
LIMA, J.A.S., TIOMNO, J. (1989), *Class. Q. Grav.* **6**, L93.
MITSKEVIČ, N.V., SENIN, Y.E. (1981), *Acta Phys. Polon.* **B12**, 541.
MODAK, B. (1984b), *Pramana* **23**, 809.
MOTTA, D.C., TOMIMURA, N. (1990b), *Astrophys. Space Sci.* **165**, 237.
POLLOCK, M.D., CADERNI, N. (1980), *Mon. Not. R. Astron. Soc.* **190**, 509.
PONCE DE LEON, J. (1988), *J. Math. Phys.* **29**, 2479.
ROY, S.R., SINGH, J.P. (1982), *Indian J. Pure Appl. Math.* **13**, 1285.
ROY, S.R., TIWARI, O.P. (1983), *Indian J. Pure Appl. Math.* **14**, 233.
SCHMIDT, H.J. (1982), *Astron. Nachr.* **303**, 283.
SENIN, YU.E. (1982), in: *Problemy teorii gravitatsii i elementarnykh chastits* [*Problems of gravitation theory and elementary particle theory*], 13th issue. Edited by K.P. Stanyukovich. Energoizdat, Moskva, p. 107.
SOM, M.M., BEDRAN, M.L., VASCONCELLOS-VAIDYA, E.P. (1988), *Nuovo Cimento* **B102**, 573.
SPERO, A., SZAFRON, D.A. (1978), *J. Math. Phys.* **19**, 1536.
STEPHANI, H. (1968), *Commun. Math. Phys.* **9**, 53.
STEPHANI, H. (1987), *Class. Q. Grav.* **4**, 125.
SUSSMAN, R.A. (1992), *Class. Q. Grav.* **9**, 1891.
SZAFRON, D.A. (1977), *J. Math. Phys.* **18**, 1673.

SZAFRON, D.A., COLLINS, C.B. (1979), *J. Math. Phys.* **20**, 2354.
SZAFRON, D.A, WAINWRIGHT, J. (1977), *J. Math. Phys.* **18**, 1668.
SZEKERES, P. (1975a), *Commun. Math. Phys.* **41**, 55.
SZEKERES, P. (1975b), *Phys. Rev.* **D12**, 2941.
SZEKERES, P. (1980), in: *Gravitational radiation, collapsed objects and exact solutions.* Edited by C. Edwards. Springer (Lecture notes in physics, vol. 124), New York, p. 477.
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TOMIMURA, N. (1981), *Astrophys. J.* **249**, 23.
TOMIMURA, N., MOTTA, D.C. (1990a), *Astrophys. Space Sci.* **165**, 231.
TOMIMURA, N., WAGA, I. (1987), *Astrophys. J.* **317**, 52.
VAN DEN BERGH, N., WILS, P. (1985), *Gen. Rel. Grav.* **17**, 223.
WAINWRIGHT, J. (1977), *J. Math. Phys.* **18**, 672.

2.2. The plane- and spherically symmetric solutions of the $\beta' = 0$ subfamily of Szafron

The plane symmetric dust solution of this subfamily was found by ELLIS (1967), and then rediscovered by TOMIMURA (1978) and SCHMIDT (1982, see bibliography in the previous section). LAKE (1992) discussed its properties. It generalizes only the flat FLRW dust solution. The spherically symmetric solutions of this family generalize the Kantowski-Sachs model. The master solution among them was found by KORKINA and MARTINENKO (1975a), and then rediscovered by RUBAN (1983) and WESSON (1989), it is a perfect fluid metric. The dust subcase, with nonzero cosmological constant, was found by RUBAN (1969), and generalized by himself (RUBAN 1972 and 1983) to the case of charged dust with cosmological constant. The dust subcase with zero cosmological constant was found by DATT (1938) and rediscovered by RUBAN (1968). The other papers listed below discussed the Kantowski-Sachs metric with various kinds of sources (perfect fluid with different equations of state, dust with a cosmological constant and/or magnetic field). In the original KANTOWSKI-SACHS paper (1966, [G]) only dust source was considered.

COLLINS, C.B. (1977), *J. Math. Phys.* **18**, 2116.
DATT, B. (1938), *Z. Physik* **108**, 314.
ELLIS, G.F.R. (1967), *J. Math. Phys.* **8**, 1171.
KOMPANEETS, A.S., CHERNOV, A.S. (1964), *ZhETF* **47**, 1939 [*Sov. Phys. JETP* **20**, 1303 (1965)].
KORKINA, M.P., MARTINENKO, V.G. (1975a), *Ukr. Fiz. Zh.* **20**, 626.
KORKINA, M.P., MARTINENKO, V.G. (1975b), *Ukr. Fiz. Zh.* **20**, 2044.
LAKE, K. (1992), *Astrophys. J. Lett.* **401**, L1.
LORENZ, D. (1982), *J. Phys.* **A15**, 2997.
LORENZ, D. (1983), *J. Phys.* **A16**, 575.
MCVITTIE, G.C., WILTSHIRE, R.J. (1975), *Int. J. Theor. Phys.* **14**, 145.
PONCE DE LEON, J. (1988), *J. Math. Phys.* **29**, 2479.
RUBAN, V.A. (1968), *Pisma v Red. ZhETF* **8**, 669 [*Sov. Phys. JETP Lett.* **8**, 414 (1968)].

RUBAN, V.A. (1969), *ZhETF* **56**, 1914 [*Sov. Phys. JETP* **29**, 1027 (1969)].
RUBAN, V.A. (1972), in: *Tezisy dokladov 3y Sovetskoy Gravitatsyonnoy Konferentsii* [*Theses of lectures of the 3rd Soviet Conference on Gravitation*]. Izdatelstvo Erevanskogo Universiteta, Erevan, p. 348.
RUBAN, V.A. (1983), *ZhETF* **85**, 801 [*Sov. Phys. JETP* **58**, 463 (1983)].
SHIKIN, I.S. (1966), *Doklady ANSSSR* **171**, 73 [*Sov. Phys. Doklady* **11**, 944 (1967)].
SHIKIN, I.S. (1967), *Doklady ANSSSR* **176**, 1048 [*Sov. Phys. Doklady* **12**, 950 (1968)].
THORNE, K.S. (1967), *Astrophys. J.* **148**, 51.
TOMIMURA, N. (1978), *Nuovo Cimento* **B44**, 372.
VAN DEN BERGH, N., WILS, P. (1985), *Gen. Rel. Grav.* **17**, 223.
WEBER, E. (1984), *J. Math. Phys.* **25**, 3279.
WEBER, E. (1985), *J. Math. Phys.* **26**, 1308.
WEBER, E. (1986), *J. Math. Phys.* **27**, 1578.
WESSON, P.S. (1989), *Astrophys. J.* **336**, 58.
XANTHOPOULOS, B.C., ZANNIAS, T. (1992a), *J. Math. Phys.* **33**, 1415.
ZAKHAROV, A.V. (1987), *Izv. VUZ Fiz.* **30** no 12, 20 [*Sov. Phys. J.* **30**, 1015 (1987)].

2.3. The plane- and spherically symmetric solutions of the $\beta' \neq 0$ subfamily of Szafron

The master solution in this class was found by ELLIS (1967). It is a dust solution with cosmological constant, and with an arbitrary 3-dimensional symmetry group acting on 2-dimensional orbits. This was generalized by BRONNIKOV and PAVLOV (1979, see also BRONNIKOV 1983) to a source being dust with electric and magnetic (monopole) charge. The plane symmetric subcase of the Ellis solutions, with zero cosmological constant, was rediscovered by EARDLEY, LIANG and SACHS (1972), TOMITA (1975), HORSKY, LORENC and NOVOTNY (1977), TOMIMURA (1978) and NOVOTNY and HORSKY (1979). A generalization of the latter case to plane symmetric dust moving in a vacuum electric field was found by CHATTERJEE and BANERJI (1980), the further generalization to plane symmetric charged dust — by DE and RAY (1983). The spherically symmetric subcase of the Ellis solutions was found by LEMAÎTRE (1933a), then discussed by TOLMAN (1934) and BONDI (1947), and rediscovered by PONCE DE LEON (1991a) and ZECCA (1991). This is a very important subcase that was used in many papers to discuss various physical processes in an inhomogeneous Universe, see section 3 below. GAUTREAU (1984) rederived the subcase corresponding to zero spatial curvature and used it to discuss the influence of cosmic expansion on planetary orbits.

The subcase of the LEMAÎTRE (1933a) solution (which will be called the Lemaître-Tolman model, abbreviated L-T) corresponding to zero cosmological constant was rediscovered more than 20 times, the list of papers (and books) with rediscoveries is given separately after the main list in this section. The further subcase when the dust is self-similar was rediscovered in 11 papers, listed in a third separate list below. The $\Lambda = 0$ subcase of the L-T model was generalized to dust moving in a spherically symmetric electric field by HAMOUI (1969), this generalization was then rediscovered by KORKINA and CHERNYI (1976). The generalization

of this case to arbitrary 3-dimensional symmetry with 2-dimensional orbits was found by SHIKIN (1972) (which thus generalizes the CHATTERJEE-BANERJI 1980 solution). The generalization of the HAMOUI (1969) solution to charged dust was found by MARKOV and FROLOV (1970), and then rediscovered by BAILYN (1973), IVANENKO, KRECHET and LAPCHINSKII (1973), MISRA and SRIVASTAVA (1974) and DATTA (1976). This was further generalized by SHIKIN (1974) to include an arbitrary 3-dimensional symmetry with 2-dimensional orbits and a magnetic charge, the SHIKIN (1974) solution thus generalizes also the SHIKIN (1972) and DE-RAY (1983) results. Another generalization of the MARKOV-FROLOV (1970) class was found by KRECHET, PONOMAREV AND BARVINSKII (1977), this corresponds to the electric field carrier having nonzero mass. Still another generalization, to nonzero cosmological constant, was found by VICKERS (1973) and rediscovered by KHLESTKOV (1975) and ORI (1990, in a coordinate system in which all equations can be integrated explicitly). Ori's result was nearly found, but with errors, by BURLANKOV (1987). The paper by ZECCA (1993b) is apparently in error, too. A generalization of the L-T model to arbitrary anisotropic pressure was worked out by LEMAÎTRE (1933b). The other papers in the list below contain derivations of various subcases of the L-T model or discussions of their properties.

BAILYN, M. (1973), *Phys. Rev.* **D8**, 1036.
BONDI, H. (1947), *Mon. Not. R. Astron. Soc.* **107**, 410.
BRONNIKOV, K.A. (1983), *Gen. Rel. Grav.* **15**, 823.
BRONNIKOV, K.A., PAVLOV, N.V. (1979), in: *Diskusyonnye voprosy teorii otnositelnosti i gravitatsii* [*Controversial questions of the theory of relativity and gravitation*]. Nauka, Moskva, p. 59.
BURLANKOV, D.E. (1987), *ZhETF* **93**, 1921 [*Sov. Phys. JETP* **66**, 1095 (1987)].
CHATTERJEE, S., BANERJI, S. (1980), *Int. J. Theor. Phys.* **19**, 599.
COLLINS, C.B. (1990), *Class. Q. Grav.* **7**, 1983.
DATTA, A.K. (1976), *Indian J. Phys.* **50**, 590.
DE, U.K. (1968), *J. Phys.* **A1**, 645.
EARDLEY, D., LIANG, E., SACHS, R. (1972), *J. Math. Phys.* **13**, 99.
DE, U.K., RAY, D. (1983), *J. Math. Phys.* **24**, 610.
ELLIS, G.F.R. (1967), *J. Math. Phys.* **8**, 1171.
GAUTREAU, R. (1984), *Phys. Rev.* **D29**, 198.
HAMOUI, A. (1969), *Ann. Inst. Poincare* **A10**, 195.
HENRIKSEN, R.N., WESSON, P.S. (1978b), *Astrophys. Space Sci.* **53**, 445.
HORSKY, J., LORENC, P., NOVOTNY, J. (1977), *Phys. Lett.* **A63**, 79.
IVANENKO, D.D., KRECHET, V.G., LAPCHINSKII, V.G. (1973), *Izv. VUZ Fiz.* **16** no 12, 63 [*Sov. Phys. J.* **16**, 1675 (1973)].
JUST, K. (1956), *Z. Physik* **145**, 235.
KHLESTKOV, YU.A. (1975), *ZhETF* **68**, 387 [*Sov. Phys. JETP* **41**, 188 (1975)].
KORKINA, M.P., CHERNYI, L.M. (1976), *Ukr. Fiz. Zh.* **21**, 916.
KRECHET, V.G., PONOMAREV, V.N., BARVINSKII, A.O. (1977), *Izv. VUZ Fiz.* **20** no 9, 7 [*Sov. Phys. J.* **20**, 1123 (1977)].
LEMAÎTRE, G. (1933a), *Ann. Soc. Sci.* Bruxelles **A53**, 51.
LEMAÎTRE, G. (1933b), *C. R. Acad. Sci.* Paris **196**, 903.

MARKOV, M.A., FROLOV, V.P. (1970), *Teor. Mat. Fiz.* **3**, 3 [*Theor. Math. Phys.* **3**, 301 (1970)].
MISRA, R.M., SRIVASTAVA, D.C. (1974), *Phys. Rev.* **D9**, 844.
MITSKEVIČ, N.V., SENIN, Y.E. (1981), *Acta Phys. Polon.* **B12**, 541.
MØLLER, C. (1975), *Det Kongelige Danske Videnskarbens Selskab Matematisk — fysiske Meddelelser* **39** no 7.
NOVOTNY, J., HORSKY, J. (1979), *Scripta Fac. Sci. Nat. Univ. J. E. Purkynianae Brunensis*, Physica 2 **9**, 69.
OPPENHEIMER, J.R., SNYDER, H. (1939), *Phys. Rev.* **56**, 455.
ORI, A. (1990), *Class. Q. Grav.* **7**, 985.
PONCE DE LEON, J. (1991b), *Mon. Not. R. Astron. Soc.* **250**, 69.
RAYCHAUDHURI, A.K. (1975), *Ann. Inst. Poincare* **A22**, 229.
SAKOTO, M. (1977), *C. R. Acad. Sci.* Paris **A284**, 633.
SHIKIN, I.S. (1972a), *Commun. Math. Phys.* **26**, 24.
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SHIKIN, I.S. (1974), *ZhETF* **67**, 433 [*Sov. Phys. JETP* **40**, 215 (1975)].
SIEMIENIEC-OZIĘBŁO, G., KLIMEK, Z. (1978), *Acta Phys. Polon.* **B9**, 79.
SYNGE, J.L. (1934), *Proc. Nat. Acad. Sci.* USA **20**, 635.
TOLMAN, R.C. (1934), *Proc. Nat. Acad. Sci.* USA **20**, 169.
TOMIMURA, N. (1978), *Nuovo Cimento* **B44**, 372.
TOMITA, K. (1975), *Progr. Theor. Phys.* **54**, 730.
VICKERS, P.A. (1973), *Ann. Inst. Poincare* **A18**, 137.
WESSON, P.S. (1978a), *Astrophys. Lett.* **19**, 121.
WESSON, P.S. (1978b), *Astrophys. Space Sci.* **54**, 489.
WESSON, P.S. (1978c), *Cosmology and geophysics.* Adam Hilger Ltd, Techno House, Bristol, p. 199.
WESSON, P.S. (1979), *Astrophys. J.* **228**, 647.
WESSON, P.S. (1984), *J. Math. Phys.* **25**, 3297.
YODZIS, P., SEIFERT, H.J., MÜLLER ZUM HAGEN, H. (1973), *Commun. Math. Phys.* **34**, 135.
ZECCA, A. (1991), *Nuovo Cimento* **B106**, 413.
ZECCA, A. (1993b), *Nuovo Cimento* **B108**, 403.

This is the list of rediscoveries of the L-T model with $\Lambda = 0$ (the criterion for a rediscovery was a published derivation without reference to any previous derivation, some of the authors listed below actually knew that the model was known before):

BANERJEE, A. (1967), *Proc. Phys. Soc.* **91**, 794.
BARNES, A., WHITROW, G.J. (1970), *Mon. Not. R. Astron. Soc.* **148**, 193.
CARR, B.J., HAWKING, S.W. (1974), *Mon. Not. R. Astron. Soc.* **168**, 399.
DATT, B. (1938), *Z. Physik* **108**, 314.
FENG, L.L., MO, H.J., RUFFINI, R. (1991), *Astron. Astrophys.* **243**, 283.
HENRIKSEN, R.N., DE ROBERTIS, M. (1980), *Astrophys. J.* **241**, 54.
KRISHNA RAO, J. (1990), *Pramana* **34**, 423.

KRISHNA RAO, J., ANNAPURNA, M. (1986), *Pramana* **27**, 637.
LANDAU, L.D., LIFSHITZ, E.M. (1948), *Teoria pola.* Second, revised edition. OGIZ, Moskva, exercise 5 to sec. 96.
LANDAU, L.D., LIFSHITZ, E.M. (1962), *Teoria pola*, 4th edition. Gosudarstvennoye Izdatelstvo Fiziko-Matematicheskoy Literatury, Moskva, p. 345.
Lightman, A., Press, W.H., Price, R.H., Teukolsky, S.A. (1975), *Problem book in relativity and gravitation.* Princeton University Press, Princeton, pp. 98 and 460–461.
LIU, H. (1991), *J. Math. Phys.* **32**, 2279.
LYNDEN-BELL, D. (1987), in: *Gravitation and astrophysics* (Cargese lectures 1986). Edited by B. Carter and J. Hartle. Plenum, New York and London, p. 155.
MAEDA, K., SASAKI, M., SATO, H. (1983), *Progr. Theor. Phys.* **69**, 89.
MESZAROS, A., VANYSEK, V. (1988), *Bull. Astron. Inst. Czech.* **39**, 185.
NOVIKOV, I.D. (1963), *Astron. Zh.* **40**, 772 [*Sov. Astr. A. J.* **7**, 587 (1964)].
PAPAPETROU, A. (1974), *Lectures on general relativity.* D. Reidel, Dordrecht, pp. 99–103.
PEEBLES, P.J.E. (1967), *Astrophys. J.* **147**, 859.
SATO, H., MAEDA, K. (1983), *Progr. Theor. Phys.* **70**, 119.
SATO, H. (1984), in: *General relativity and gravitation.* Edited by B. Bertotti, F. de Felice, A. Pascolini. D. Reidel, Dordrecht, p. 289.
ZAKHAROV, A.V. (1987), *Izv. VUZ Fiz.* **30** no 12, 20 [*Sov. Phys. J.* **30**, 1015 (1987)].

This is the list of rediscoveries of the "self-similar" subcase of the L-T model:

CAHILL, M.E., TAUB, A.H. (1971), *Commun. Math. Phys.* **21**, 1.
CARR, B.J. (1990), in: *Proceedings of the Relativity Meeting 89: Recent developments in gravitation*, Barcelona 1989. Edited by E. Verdaguer, J. Garriga, J. Cespedes. World Scientific, Singapore, p. 121.
CARR, B.J., HAWKING, S.W. (1974), *Mon. Not. R. Astron. Soc.* **168**, 399.
CARR, B.J., YAHIL, A. (1990), *Astrophys. J.* **360**, 330.
CHI, L.K. (1987), *J. Math. Phys.* **28**, 1539.
DYER, C.C. (1979), *Mon. Not. R. Astron. Soc.* **189**, 189.
GUROVICH, V.T. (1966), *Doklady ANSSSR* **169**, 62 [*Sov. Phys. Doklady* **11**, 569 (1967)].
HENRIKSEN, R.N., PATEL, K. (1991), *Gen. Rel. Grav.* **23**, 527.
HENRIKSEN, R.N., WESSON, P.S. (1978a), *Astrophys. Space Sci.* **53**, 429.
MAHARAJ, S.D. (1988), *J. Math. Phys.* **29**, 1443.
ORI, A., PIRAN, T. (1990), *Phys. Rev.* **D42**, 1068.
WU, Z.C. [also quoted as Chao] (1981), *Gen. Rel. Grav.* **13**, 625.

3. PHYSICS AND COSMOLOGY BASED ON THE L-T MODEL

A very large body of literature exists in which the L-T model was used to describe various physical processes that might occur in an inhomogeneous Universe. The papers dealing with this subject are listed in this chapter, sorted by the subjects they discuss. Some of the references are repeated from the previous sections. The paper by ZHU (1983), listed for completeness, is actually in error (see KRASIŃSKI 1993 [G]).

3.1. Formation of voids in the Universe

BONDI, H. (1947), *Mon. Not. R. Astron. Soc.* **107**, 410.

BONNOR, W.B., CHAMORRO, A. (1990), *Astrophys. J.* **361**, 21.

BONNOR, W.B., CHAMORRO, A. (1991), *Astrophys. J.* **378**, 461.

CHAMORRO, A. (1991), *Astrophys. J.* **383**, 51.

HENRIKSEN, R.N., DE ROBERTIS, M. (1980), *Astrophys. J.* **241**, 54.

HOFFMAN, G.L., SALPETER, E.E., WASSERMAN, I. (1983), *Astrophys. J.* **268**, 527.

LAKE, K., PIM, R. (1985), *Astrophys. J.* **298**, 439.

MAEDA, K., SASAKI, M., SATO, H. (1983), *Progr. Theor. Phys.* **69**, 89.

MAEDA, K., SATO, H. (1983a), *Progr. Theor. Phys.* **70**, 772.

MAEDA, K., SATO, H. (1983b), *Progr. Theor. Phys.* **70**, 1276.

MESZAROS, A. (1991), *Mon. Not. R. Astron. Soc.* **253**, 619.

OCCHIONERO, F., SANTANGELO, P., VITTORIO, N. (1982), in: *Clustering in the Universe.* Edited by D. Gerbal and A. Mazure. Editions Frontieres, Gif sur Yvette, p. 103.

OCCHIONERO, F., SANTANGELO, P., VITTORIO, N. (1983), *Astron. Astrophys.* **117**, 365.

OCCHIONERO, F., VECCHIA-SCAVALLI, L., VITTORIO, N. (1981a), *Astron. Astrophys.* **97**, 169.

OCCHIONERO, F., VECCHIA-SCAVALLI, L., VITTORIO, N. (1981b), *Astron. Astrophys.* **99**, L12.

OCCHIONERO, F., VIGNATO, A., VITTORIO, N. (1978), *Astron. Astrophys.* **70**, 265.

OLSON, D.W., SILK, J. (1979), *Astrophys. J.* **233**, 395.

PIM, R., LAKE, K. (1986), *Astrophys. J.* **304**, 75.

PIM, R., LAKE, K. (1988), *Astrophys. J.* **330**, 625.

SATO, H. (1982), *Progr. Theor. Phys.* **68**, 236.

SATO, H. (1984), in: *General relativity and gravitation.* Edited by B. Bertotti, F. de Felice, A. Pascolini. D. Reidel, Dordrecht, p. 289.

SATO, H., MAEDA, K. (1983), *Progr. Theor. Phys.* **70**, 119.

SEN, N.R. (1934), *Z. Astrophysik* **9**, 215.

SEN, N.R. (1935), *Z. Astrophysik* **10**, 291.

SUTO, Y., SATO, K., SATO, H. (1984a), *Progr. Theor. Phys.* **71**, 938.

SUTO, Y., SATO, K., SATO, H. (1984b), *Progr. Theor. Phys.* **72**, 1137.

TOLMAN, R.C. (1934), *Proc. Nat. Acad. Sci.* USA **20**, 169.

ZHU, S. (1983), in: *Proceedings of the 3rd Marcel Grossman Meeting on General Relativity.* Edited by Hu Ning. Science Press and North Holland Publishing Company, Amsterdam, p. 1391.

3.2. Formation of other structures in the Universe

BONNOR, W.B. (1956), *Z. Astrophysik* **39**, 143.
KANTOWSKI, R. (1969), *Astrophys. J.* **155**, 1023.
KURKI-SUONIO, H., LIANG, E. (1992), *Astrophys. J.* **390**, 5.
LEMAÎTRE, G. (1933c), *C. R. Acad. Sci.* Paris **196**, 1085.
LEMAÎTRE, G. (1934), *Proc. Nat. Acad. Sci.* USA **20**, 12.
MOFFAT, J.W., TATARSKI, D.C. (1992), *Phys. Rev.* **D45**, 3512.
NEEMAN, Y., TAUBER, G. (1967), *Astrophys. J.* **150**, 755.
NOVIKOV, I.D. (1964a), *Astron. Zh.* **41**, 1075 [*Sov. Astr. A. J.* **8**, 857 (1965)].
SEN, N.R. (1934), *Z. Astrophysik* **9**, 215.
TOLMAN, R.C. (1934), *Proc. Nat. Acad. Sci.* USA **20**, 169.
TOMITA, K. (1969a), *Progr. Theor. Phys.* **42**, 9.
TOMITA, K. (1969b), *Progr. Theor. Phys.* **42**, 978.
TREVESE, D., VIGNATO, A. (1977), *Astrophys. Space Sci.* **49**, 229.

3.3. Influence of the cosmic expansion on planetary orbits

This effect was discussed in a few papers basing on the McVittie solution. Those papers will be mentioned in sec. 4.1. Below, only those papers are listed in which the L-T model was used (this includes the papers by Einstein and Straus, although the authors were unaware that their configuration is a subcase of the L-T model).

EINSTEIN, A. and STRAUS, E.G. (1945), *Rev. Mod. Phys.* **17**, 120.
EINSTEIN, A., STRAUS, E.G. (1946), *Rev. Mod. Phys.* **18**, 148.
GAUTREAU, R. (1984), *Phys. Rev.* **D29**, 198.

3.4. Formation of black holes in the evolving Universe

Note: the result of RAYCHAUDHURI (1966) is incorrect, as shown by BARNES (1970).

BARNES, A. (1970), *J. Phys.* **A3**, 653.
BONDI, H. (1947), *Mon. Not. R. Astron. Soc.* **107**, 410.
DEMIAŃSKI, M., LASOTA, J.P. (1973), *Nature Phys. Sci.* **241**, 53.
LIANG, E.P.T. (1974), *Phys. Rev.* **D10**, 447.
OPPENHEIMER, J.R., SNYDER, H. (1939), *Phys. Rev.* **56**, 455.
PAPAPETROU, A. (1978), *Ann. Inst. Poincare* **A29**, 207.
POLNAREV, A.G. (1977), *Astrofizika* **13**, 375 [*Astrophysics* **13**, 203 (1977)].
RAYCHAUDHURI, A.K. (1966), *Proc. Phys. Soc.* **88**, 545.
SZEKERES, P. (1972), *Proc. Astron. Soc.* Australia **2**, 110.

3.5. Gravitational collapse in electromagnetic field

The list below includes papers discussing the collapse of neutral matter in an exterior electric field, and also the collapse of charged matter. In some of the papers

the process was considered without invoking any specific solution for the interior of the matter sphere. The paper by GERTSENSHTEIN and STANYUKOVICH (1974) is in error (see KRASIŃSKI 1993 [G]) and is included for completeness only.

BEKENSTEIN, J.D. (1971), *Phys. Rev.* **D4**, 2185.
BRONNIKOV, K.A. (1983), *Gen. Rel. Grav.* **15**, 823.
BRONNIKOV, K.A., PAVLOV, N.V. (1979), in: *Diskusyonnye voprosy teorii otnositelnosti i gravitatsii* [*Controversial questions of the theory of relativity and gravitation*]. Nauka, Moskva, p. 59.
GERTSENSHTEIN, M.E., STANYUKOVICH, K.P. (1974), in: *Problemy teorii gravitatsii i elementarnykh chastits* [*Problems of gravitation theory and elementary particle theory*], 5th issue. Edited by K.P. Stanyukovich. Atomizdat, Moskva, p. 162.
LAKE, K., NELSON, L.A. (1980), *Phys. Rev.* **D22**, 1266.
MARKOV, M.A., FROLOV, V.P. (1970), *Teor. Mat. Fiz.* **3**, 3 [*Theor. Math. Phys.* **3**, 301 (1970)].
NOVIKOV, I.D. (1966), *Astron. Zh.* **43**, 911 [*Sov. Astr. A. J.* **10**, 731 (1967)].
NOVIKOV, I.D. (1970), *ZhETF* **59**, 262 [*Sov. Phys. JETP* **32**, 142 (1971)].
ORI, A. (1991), *Phys. Rev.* **D44**, 2278.
PAVLOV, N.V. (1976), *Izv. VUZ Fiz.* **19** no 4, 107 [*Sov. Phys. J.* **19**, 489 (1976)].
PAVLOV, N.V., BRONNIKOV, K.A. (1976), *Izv. VUZ Fiz.* **19** no 7, 106 [*Sov. Phys. J.* **19**, 916 (1976)].
RAYCHAUDHURI, A.K., DE, U.K. (1970), *J. Phys.* **A3**, 263.
SHIKIN, I.S. (1972a), *Commun. Math. Phys.* **26**, 24.
SHIKIN, I.S. (1974), *ZhETF* **67**, 433 [*Sov. Phys. JETP* **40**, 215 (1975)].
SINGH, K.P., Abdussattar (1983), *Proc. Indian Nat. Sci. Acad.* **A49**, 448.
STEIN-SCHABES, J.A. (1985), *Phys. Rev.* **D31**, 1838.
VICKERS, P.A. (1973), *Ann. Inst. Poincare* **A18**, 137.

3.6. Singularities and cosmic censorship

Note: this is not a bibliography on the cosmic censorship hypothesis, but on the exact inhomogeneous cosmological models as a testing ground for the hypothesis. It includes also papers dealing with other aspects of singularities. In all of them the L-T model was used.

BANERJEE, A. (1975), *J. Phys.* **A8**, 281.
CHRISTODOULOU, D. (1984a), *Commun. Math. Phys.* **93**, 171.
CHRISTODOULOU, D. (1984b), in: *General relativity and gravitation.* Edited by B. Bertotti, F. de Felice and A. Pascolini. D. Reidel, Dordrecht, p. 27.
DWIVEDI, I.H., JOSHI, P.S. (1992), *Class. Q. Grav.* **9**, L69.
EARDLEY, D.M. (1979), *Gen. Rel. Grav.* **10**, 1033.
EARDLEY, D.M. (1987), in: *Gravitation and astrophysics* (Cargese Lectures 1986). Edited by B. Carter and J. Hartle. Plenum, New York and London, p. 229.
EARDLEY, D., LIANG, E., SACHS, R. (1972), *J. Math. Phys.* **13**, 99.
EARDLEY, D.M., SMARR, L. (1979), *Phys. Rev.* **D19**, 2239.
ELLIS, G.F.R., MAARTENS, R., NEL, S.D. (1978), *Mon. Not. R. Astron. Soc.* **184**, 439.

GORINI, V., GRILLO, G., PELIZZA, M. (1989), *Phys. Lett.* **A135**, 154.
GRILLO, G. (1991), *Class. Q. Grav.* **8**, 739.
HELLABY, C., LAKE, K. (1984), *Astrophys. J.* **282**, 1.
HELLABY, C., LAKE, K. (1985b), *Astrophys. J.* **294**, 702.
JOSHI, P.S., DWIVEDI, I.H. (1993), *Phys. Rev.* **D47**, 5357.
LEMOS, J.P.S. (1991a), *Phys. Lett.* **A158**, 279.
LEMOS, J.P.S. (1991b), in: *Proceedings of the 7th Latin American Symposium on Relativity and Gravitation* (SILARG 7). Edited by J.C. Olivo, E. Nahmad-Achar, M. Rosenbaum, M.P. Ryan Jr., J.F. Urrutia, F. Zertuche. World Scientific, Singapore, p. 241.
NEWMAN, R.P.A.C. (1986a), *Class. Q. Grav.* **3**, 527.
NEWMAN, R.P.A.C. (1986b), in: *Topological properties and global structure of spacetime.* Edited by P.G. Bergmann and V. de Sabbata. Plenum, New York, p. 153.
SEIFERT, H.J. (1979), *Gen. Rel. Grav.* **10**, 1065.
SZEKERES, P. (1980), in: *Gravitational radiation, collapsed objects and exact solutions.* Edited by C. Edwards. Springer (Lecture notes in physics, vol. 124), New York, p. 477.
SZEKERES, P., IYER, V. (1993), *Phys. Rev.* **D47**, 4362.
WAUGH, B., LAKE, K. (1988), *Phys. Rev.* **D38**, 1315.
YODZIS, P., SEIFERT, H.J., MÜLLER ZUM HAGEN, H. (1973), *Commun. Math. Phys.* **34**, 135.

3.7. Influence of inhomogeneities in matter distribution on the cosmic microwave background radiation

Note: Just as in the previous section, this is not meant to be a bibliography on the subject as a whole, but only on the applications of the exact inhomogeneous cosmological models to this subject.

ARNAU, J.V., FULLANA, M., MONREAL, L., SAEZ, D. (1993), *Astrophys. J.* **402**, 359.
PACZYŃSKI, B., PIRAN, T. (1990), *Astrophys. J.* **364**, 341.
PANEK, M. (1992), *Astrophys. J.* **388**, 225.
RAINE, D.J., THOMAS, E.G. (1981), *Mon. Not. R. Astron. Soc.* **195**, 649.
SAEZ, D., ARNAU, J.V. (1990), in: *Proceedings of the Relativity Meeting 89: Recent developments in gravitation*, Barcelona 1989. Edited by E. Verdaguer, J. Garriga, J. Cespedes. World Scientific, Singapore, p. 145.

3.8. Other papers discussing the L-T model

The papers listed in this section contain results that could not be classified under any of the preceding headings. Some of them present important and illuminating descriptions of the L-T model (notably MILLER 1976, ZELDOVICH and GRISHCHUK 1984, BONNOR 1985b, HELLABY and LAKE 1985a and HELLABY 1987), others are included here just for completeness.

BARTNIK, R. (1988), *Commun. Math. Phys.* **117**, 615.
BONA, C. (1988), *J. Math. Phys.* **29**, 2462.
BONNOR, W.B. (1972), *Mon. Not. R. Astron. Soc.* **159**, 261.
BONNOR, W.B. (1974), *Mon. Not. R. Astron. Soc.* **167**, 55.
BONNOR, W.B. (1985a), *Class. Q. Grav.* **2**, 781.
BONNOR, W.B. (1985b), *Mon. Not. R. Astron. Soc.* **217**, 597.
BONNOR, W.B. (1985c), *Phys. Lett.* **A112**, 26.
BONNOR, W.B., ELLIS, G.F.R. (1986), *Mon. Not. R. Astron. Soc.* **218**, 605.
EARDLEY, D.M. (1974), *Phys. Rev.* Lett. **33**, 442.
FENNELLY, A.J. (1977), *Mon. Not. R. Astron. Soc.* **181**, 121.
GERTSENSHTEIN, M.E. (1966), *ZhETF* **51**, 129 [*Sov. Phys. JETP* **24**, 87 (1967)].
GERTSENSHTEIN, M.E. (1977), *Izv. VUZ Fiz.* **20** no 7, 90 [*Sov. Phys. J.* **20**, 912 (1977)].
GINZBURG, V.L., OZERNOI, L.M. (1964), *ZhETF* **47**, 1030 [*Sov. Phys. JETP* **20**, 689 (1965)].
GOICOECHEA, L.J., MARTIN-MIRONES, J.M. (1987), *Astron. Astrophys.* **186**, 22.
GORINI, V., GRILLO, G., PELIZZA, M. (1990), *Mod. Phys. Lett.* **A5**, 719.
GRIBKOV, I.V., SOLOVIEV, L.S. (1987), *Doklady ANSSSR* **296**, 566 [*Sov. Phys. Doklady* **32**, 723 (1987)].
HELLABY, C. (1987), *Class. Q. Grav.* **4**, 635.
HELLABY, C. (1988), *Gen. Rel. Grav.* **20**, 1203.
HELLABY, C., LAKE, K. (1985a), *Astrophys. J.* **290**, 381.
HELLABY, C., LAKE, K. (1985c), *Astrophys. J.* **300**, 461.
HENRIKSEN, R.N. (1989), *Mon. Not. R. Astron. Soc.* **240**, 917.
JUST, K. (1960), *Z. Astrophysik* **49**, 19.
JUST, K., KRAUS, K. (1962), *Z. Astrophysik* **55**, 127.
KOLESNIKOV, S.M., STANYUKOVICH, K.P. (1965), *Priklad. Mat. Mekh.* **29**, 716 [*Appl. Math. Mech.* **29**, 848 (1965)].
KOLESNIKOV, S.M., STANYUKOVICH, K.P. (1966), in: *Problemy teorii gravitatsii i elementarnykh chastits* [*Problems of gravitation theory and elementary particle theory*], 1st issue. Edited by K.P. Stanyukovich and G.A. Sokolnik. Atomizdat, Moskva, p. 135.
KORKINA, M.P. (1991), *Ukr. Fiz. Zh.* **36**, 647.
KORKINA, M.P., CHERNYI, L.M. (1975), *Izv. VUZ Fiz.* **18** no 1, 23 [*Sov. Phys. J.* **18**, 17 (1975)].
LAKE, K. (1984), *Phys. Rev.* **D29**, 771.
LAKE, K., ROEDER, R.C. (1978), *Phys. Rev.* **D17**, 1935.
LASERRA, E. (1985), *Meccanica* **20**, 267.
LEMOS, J.P.S. (1992a), *Phys. Rev. Lett.* **68**, 1447.
LEMOS, J.P.S. (1992b), in: *Proceedings of the 6th Marcel Grosmman Meeting.* Edited by H. Sato and T. Nakamura. World Scientific, Singapore, p. 1346.
LEMOS, J.P.S., LYNDEN-BELL, D. (1989), *Mon. Not. R. Astron. Soc.* **240**, 317.
LIU, H. (1990), *J. Math. Phys.* **31**, 2459.
LUND, F. (1973a), *Phys. Rev.* **D8**, 3253.
LUND, F. (1973b), *Phys. Rev.* **D8**, 4229.
LYNDEN-BELL, D., LEMOS, J.P.S. (1988), *Mon. Not. R. Astron. Soc.* **233**, 197.

MARKOV, M.A., FROLOV, V.P. (1972), *Teor. Mat. Fiz.* **13**, 41 [*Theor. Math. Phys.* **13**, 965 (1972)].
MAVRIDES, S. (1976a), *C.R. Acad. Sci.* Paris **A282**, 451.
MAVRIDES, S. (1976b), *Mon. Not. R. Astron. Soc.* **177**, 709.
MAVRIDES, S., TARANTOLA, A. (1977), *Gen. Rel. Grav.* **8**, 665.
MESZAROS, A. (1986), *Acta Phys. Hung.* **60**, 75.
MILLER, B.D. (1976), *Astrophys. J.* **208**, 275.
MISNER, C.W., THORNE, K.S., WHEELER, J.A. (1973), *Gravitation.* W.H. Freeman and Co, San Francisco, p. 859.
NARIAI, H., TOMITA, K. (1971), Suppl. *Progr. Theor. Phys.* **49**, 83.
NOVIKOV, I.D. (1962a), *Vestn. Mosk. Univ.* no 5, 90.
NOVIKOV, I.D. (1962b), *Vestn. Mosk. Univ.* no 6, 66.
OLSON, D.W. (1980), *Astrophys. J.* **236**, 335.
OMER, G.C. (1949), *Astrophys. J.* **109**, 164.
OMER, G.C. (1965), *Proc. Nat. Acad. Sci.* USA **53**, 1.
PACHNER, J. (1966a), *Bull. Astron. Inst. Czech.* **17**, 105 and 108.
PACHNER, J. (1966b), *Phys. Rev.* **147**, 910.
PACHNER, J. (1967a), *Bull. Astron. Inst. Czech.* **18**, 219.
PACHNER, J. (1967b), *Mem. Soc. Roy. Sci.* Liege **15**, 45.
PAPAPETROU, A. (1976a), *Ann. Inst. Poincare* **A24**, 165.
PAPAPETROU, A. (1976b), *Ann. Inst. Poincare* **A24**, 171.
PAPAPETROU, A., HAMOUI, A. (1967), *Ann. Inst. Poincare* **A6**, 343.
PEEBLES, P.J.E. (1980), *The large scale structure of the Universe.* Princeton University Press, Princeton, sec. 87.
RIBEIRO, M.B. (1992a), *Astrophys. J.* **388**, 1.
RIBEIRO, M.B. (1992b), *Astrophys. J.* **395**, 29.
RINDLER, W., SUSON, D. (1989), *Aston. Astrophys.* **218**, 15.
SAMOILOV, S.N. (1981), *Ukr. Fiz. Zh.* **26**, 672.
SANNAN, S. (1986), *J. Math. Phys.* **27**, 2592.
SILK, J. (1977), *Astron. Astrophys.* **59**, 53.
STANYUKOVICH, K.P. (1969), *Doklady ANSSSR* **186**, 809 [*Sov. Phys. Doklady* **14**, 547 (1969)].
STANYUKOVICH, K.P., SHARSHEKEEV, O.S. (1973), *Prikl. Math. Mekh.* **37**, 739 [*Appl. Math. Mech.* **37**, 697 (1973)].
STOEGER, W.R., ELLIS, G.F.R., NEL, S.D. (1992), *Class. Q. Grav.* **9**, 509.
TOMITA, K. (1992), *Astrophys. J.* **394**, 401.
ZECCA, A. (1993a), *Int. J. Theor. Phys.* **32**, 615.
ZELDOVICH, YA.B., GRISHCHUK, L.P. (1984), *Mon. Not. R. Astron. Soc.* **207**, 23p.

3.9. General theorems and considerations

This section contains a bibliography of papers in which general results were presented (not necessarily in connection with any explicit solution) that may be of relevance for inhomogeneous cosmological models.

ADAMS, P.J., HELLINGS, R.W., ZIMMERMAN, R.L. (1985), *Astrophys. J.* **288**, 14.
ADAMS, P.J., HELLINGS, R.W., ZIMMERMAN, R.L. (1987), *Astrophys. J.* **318**, 1.
ADAMS, P.J., HELLINGS, R.W., ZIMMERMAN, R.L., FARHOOSH, H., LEVINE, D. I., ZELDICH, S. (1982), *Astrophys. J.* **253**, 1.
BRAUER, U. (1991), *Class. Q. Grav.* **8**, 1283.
BRAUER, U., MALEC, E. (1992a), *Class. Q. Grav.* **9**, 905.
BRAUER, U., MALEC, E. (1992b), *Phys. Rev.* **D45**, 1836.
BURNETT, G.A. (1991), *Phys. Rev.* **D43**, 1143.
DAUTCOURT, G. (1980), in: *9th International Conference on General Relativity and Gravitation*, Jena, p. 315.
DAUTCOURT, G. (1983a), *Astron. Nachr.* **304**, 153.
DAUTCOURT, G. (1983b), *J. Phys.* **A16**, 3507.
DAUTCOURT, G. (1985), *Astron. Nachr.* **306**, 1.
GOLD, T. (1973), *Nature* **242**, 24.
MALEC, E., O'MURCHADHA, N. (1993), *Phys. Rev.* **D47**, 1454.
NOVIKOV, I.D. (1962b), *Vestn. Mosk. Univ.* no 6, 66.
NOVIKOV, I.D. (1964b), *Soobshcheniya GAISH* [*Communications of the State Sternberg Astronomical Institute*] **132**, 3.
NOVIKOV, I.D. (1964c), *Soobshcheniya GAISH* [*Communications of the State Sternberg Astronomical Institute*] **132**, 43.
PARTOVI, M.H., MASHHOON, B. (1984), *Astrophys. J.* **276**, 4.
RYAN, M.P. (1972), *Ann. Phys.* **72**, 584.
WU, Z.C. (1982), *Sci. Sinica* **A25**, 737.

4. THE STEPHANI — BARNES FAMILY OF SOLUTIONS

This family is the collection of those nonstatic solutions whose sources contain a perfect fluid component with shear and rotation being zero.

4.1. The conformally nonflat perfect fluid solutions

This subfamily consists of three classes, all found by BARNES (1973) separately, and then represented by this author (KRASIŃSKI 1989) in a coordinate system covering all of them at the same time. The 3 classes are: the plane symmetric class (rediscovered by BANERJEE and CHAKRAVARTY, 1979, and by KRASIŃSKI 1985), the hyperbolically symmetric class (rediscovered by KRASIŃSKI 1986), and the spherically symmetric class (first found in the now standard form by KUSTAANHEIMO and QVIST, 1948, but rediscovered more than 20 times, see a separate list after the main one). The most general cases are not actually solutions — the Einstein equations were reduced in them to a single differential equation for one function. The cases when the equation can be integrated in terms of elementary functions were investigated by STEPHANI (1983). The case when the matter density is spatially homogeneous was found and investigated by KUSTAANHEIMO (1947), discussed by QVIST (1947), and then rediscovered by TAUB (1968b), BARNES (1973), EISENSTAEDT (1975 and 1976) and GLASS (1979). WYMAN (1976) made a serious effort at integrating the Kustaanheimo — Qvist equation in the highest generality possible, and SUSSMAN (1987, 1988 a, b) presented a systematic classification of the

known explicit solutions in this class (see also KRASIŃSKI 1993 [G] for a detailed classification and description). The other papers contain presentations of various special solutions and their properties. The paper by MCVITTIE (1933) contains the interesting superposition of the Schwarzschild and FLRW metrics. Papers discussing properties of this solution are listed separately at the end of this section. The solution of BAYIN (1986) has an anisotropic fluid as a source and is listed for completeness. The paper by OBOZOV (1979) is in error (see KRASIŃSKI 1993 [G]).

ALEXANDER, D., GREEN, R.M., EMSLIE, A.G. (1989), *Mon. Not. R. Astron. Soc.* **237**, 93.

BANERJEE, A. (1971), *Progr. Theor. Phys.* **46**, 1625.

BANERJEE, A., BANERJI, S. (1976), *Acta Phys. Polon.* **B7**, 389.

BANERJEE, A., CHAKRAVARTY, N. (1979), *Acta Phys. Polon.* **B10**, 3.

BARNES, A. (1973), *Gen. Rel. Grav.* **4**, 105.

BARNES, A. (1984), in: *Classical general relativity.* Edited by W.B. Bonnor, J.N. Islam and M.A.H. MacCallum. Cambridge University Press, Cambridge, p. 15.

BAYIN, S.S. (1986), *Astrophys. J.* **303**, 101.

BREZHNEV, V.S. (1966b), in: *Problemy teorii gravitatsii i elementarnykh chastits* [*Problems of gravitation theory and elementary particle theory*], 1st edition. Edited by K.P. Stanyukovich and G.A. Sokolnik. Atomizdat, Moskva, p. 158.

BREZHNEV, V.S., IVANENKO, D.D., FROLOV, V.N. (1966), *Izv. VUZ Fiz.* **9** no 6, 119.

CHAKRAVARTY, N., DUTTA CHOUDHURY, S.B., BANERJEE, A. (1976), *Austral. J. Phys.* **29**, 113.

COLLINS, C.B. (1985), *J. Math. Phys.* **26**, 2009.

COLLINS, C.B. (1986), *Can. J. Phys.* **64**, 191.

COLLINS, C.B., WAINWRIGHT, J. (1983), *Phys. Rev.* **D27**, 1209.

DIRAC, P.A.M. (1979a), in: *On the path of A. Einstein.* Edited by B. Kursunoglu, A. Perlmutter, L.F. Scott. Plenum, New York, p. 1.

DIRAC, P.A.M. (1979b), *Proc. Roy. Soc.* London **A365**, 19.

DIRAC, P.A.M. (1981), in: *Gauge theories, massive neutrinos and proton decay. Proceedings of Orbis Scientiae 1981.* Edited by B. Kursunoglu and A. Perlmutter. Plenum, New York and London, p. 1.

EISENSTAEDT, J. (1975a), *Phys. Rev.* **D11**, 2021.

EISENSTAEDT, J. (1975b), *Phys. Rev.* **D12**, 1573.

EISENSTAEDT, J. (1976), *Ann. Inst. Poincare* **A24**, 179.

EISENSTAEDT, J. (1977), *Astrophys. J.* **211**, 16.

FAULKES, M.C. (1969b), *Progr. Theor. Phys.* **42**, 1139.

GLASS, E.N., MASHHOON, B. (1976), *Astrophys. J.* **205**, 570.

HENRIKSEN, R.N., EMSLIE, A.G., WESSON, P.S. (1983), *Phys. Rev.* **D27**, 1219.

ISRAELIT, M., ROSEN, N. (1992), *Astrophys. J.* **400**, 21.

KNUTSEN, H. (1982), *Phys. Scripta* **26**, 365.

KNUTSEN, H. (1983a), *Ann. Inst. Poincare* **A39**, 101.

KNUTSEN, H. (1983b), *J. Math. Phys.* **24**, 2188.

KNUTSEN, H. (1984), *Gen. Rel. Grav.* **16**, 777.

KNUTSEN, H. (1985a), *Gen. Rel. Grav.* **17**, 1121.
KNUTSEN, H. (1985b), *Phys. Scripta* **31**, 305.
KNUTSEN, H. (1985c), *Phys. Scripta* **32**, 568.
KNUTSEN, H. (1987a), *Int. J. Theor. Phys.* **26**, 895.
KNUTSEN, H. (1987b), *Phys. Scripta* **35**, 238.
KNUTSEN, H., STABELL, R. (1979), *Ann. Inst. Poincare* **A31**, 339.
KRASIŃSKI, A. (1985), in: *Proceedings of the 4th Marcel Grossman Meeting on General Relativity.* Edited by R. Ruffini. Elsevier, Amsterdam, p. 989.
KRASIŃSKI, A. (1986), in: *Gravitational collapse and relativity.* Proceedings of Yamada Conference XIV. Edited by H. Sato and T. Nakamura. World Scientific, Singapore, p. 500.
KRASIŃSKI, A. (1989), *J. Math. Phys.* **30**, 433.
KRASIŃSKI, A. (1991), *Rep. Math. Phys.* **29**, 337.
KUSTAANHEIMO, P. (1947), *Societas Scientiarum Fennicae Commentationes Physico-Mathematicae* **XIII** no 12, 1.
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LAMBAS, D.G., LAMBERTI, W., HAMITY, V.H. (1987), in: *Relativity, supersymmetry and cosmology.* Proceedings of the 5th Simposio Latino-Americano de Relatividad y Gravitacion (SILARG 5) held at Bariloche, Argentina 1985. Edited by O. Bressan, M. Castagnino and V. Hamity. World Scientific, Singapore, p. 271.
MAITI, S.R. (1984), *Gen. Rel. Grav.* **16**, 297.
MCVITTIE, G.C. (1933), *Mon. Not. R. Astron. Soc.* **93**, 325.
MCVITTIE, G.C. (1967a), *Ann. Inst. Poincare* **A6**, 1.
MCVITTIE, G.C. (1967b), *Mem. Soc. Roy. Sci.* Liege **15**, 41.
MCVITTIE, G.C. (1984), *Ann. Inst. Poincare* **A40**, 235.
MCVITTIE, G.C., STABELL, R. (1968), *Ann. Inst. Poincare* **A9**, 371.
MESZAROS, A. (1985), *Astrophys. Space Sci.* **108**, 415.
MÜLLER, J. (1969), *Wiss. Z. Friedrich Schiller Univ. Jena, Math. Naturw. Reihe* **18**, 169.
NARIAI, H. (1967a), *Progr. Theor. Phys.* **38**, 92.
NARIAI, H. (1967b), *Progr. Theor. Phys.* **38**, 740.
NARIAI, H., TOMITA, K., HAYAKAWA, M. (1968), *Progr. Theor. Phys.* **39**, 601.
OBOZOV, V.I. (1979), *Izv. VUZ Fiz.* **22** no 8, 71 [*Sov. Phys. J.* **22**, 869 (1979)].
QVIST, B. (1947), *Soc. Sci. Fenn. Comment. Phys. Math.* **XIII** no 11.
RAYCHAUDHURI, A.K. (1952), *Phys. Rev.* **86**, 90.
SRIVASTAVA, D.C. (1987), *Class. Q. Grav.* **4**, 1093.
SRIVASTAVA, D.C., PRASAD, S.S. (1983), *Gen. Rel. Grav.* **15**, 65.
SRIVASTAVA, D.C., PRASAD, S.S. (1991), *Class. Q. Grav.* **8**, 1001.
STEPHANI, H. (1983), *J. Phys.* **A16**, 3529.
SUSSMAN, R. (1986), in: *Proceedings of the 4th Marcel Grossman Meeting on General Relativity.* Edited by R. Ruffini. Elsevier, Amsterdam, p. 867.
SUSSMAN, R. (1987), *J. Math. Phys.* **28**, 1118.
SUSSMAN, R. (1988a), *J. Math. Phys.* **29**, 945.
SUSSMAN, R. (1988b), *J. Math. Phys.* **29**, 1177.

TAUB, A.H. (1968a), in: *Abstracts, 5th International Conference on Gravitation and the Theory of Relativity.* Publishing House of the Tbilisi University, Tbilisi, p. 145.
TAUB, A.H. (1968b), *Ann. Inst. Poincare* **A9**, 153.
TAUB, A.H. (1972), in: *General relativity* (papers in honour of J.L. Synge). Edited by O'Raiffertaigh. Clarendon Press, Oxford, p. 133.
WAGH, R.V. (1955a), *J. Univ. Bombay* **24**, 1.
WAGH, R.V. (1955b), *J. Univ. Bombay* **24**, 5.
WYMAN, M. (1946), *Phys. Rev.* **70**, 396.
WYMAN, M. (1976), *Canad. Math. Bull.* **19**, 343.
WYMAN, M. (1978), *Austral. J. Phys.* **31**, 111.

This is the list of rediscoveries of the Kustaanheimo-Qvist class of metrics. The papers by DINGLE (1933) and NARLIKAR (1947) are almost-discoveries (the authors stopped just short of deriving the equation, but were well on the way to doing so), in the paper by WYMAN (1946) the solution flashed through the paper, but was ignored by the author.

BANERJEE, A., CHAKRAVARTY, N. (1979), *Acta Phys. Polon.* **B10**, 3.
BARNES, A. (1973), *Gen. Rel. Grav.* **4**, 105.
CAHILL, M.E., MCVITTIE, G.C. (1970a), *J. Math. Phys.* **11**, 1382.
CAHILL, M.E., MCVITTIE, G.C. (1970b), *J. Math. Phys.* **11**, 1392.
DINGLE, H. (1933), *Mon. Not. R. Astron. Soc.* **94**, 134.
DYER, C.C., MCVITTIE, G.C., OATTES, L.M. (1987), *Gen. Rel. Grav.* **19**, 887.
GLASS, E.N. (1979), *J. Math. Phys.* **20**, 1508.
HOGAN, P.A. (1990), *Astrophys. J.* **360**, 315.
KRASIŃSKI, A. (1984b), in: *Proceedings of the Sir Arthur Eddington Centenary Symposium.* Vol. I: Relativistic astrophysics and cosmology. Edited by V. de Sabbata and T.M. Karade. World Scientific, Singapore, p. 45.
KRISHNA RAO, J. (1973), *Gen. Rel. Grav.* **4**, 351.
KUSTAANHEIMO, P., QVIST, B. (1948), *Societas Scientiarum Fennicae Commentationes Physico-Mathematicae* **XIII** no 16, 1.
MANSOURI, R. (1977), *Ann. Inst. Poincare* **A27**, 175.
MANSOURI, R. (1980), *Acta Phys. Polon.* **B11**, 193.
NARIAI, H. (1968), *Progr. Theor. Phys.* **40**, 1013.
NARLIKAR, V.V. (1947), *Curr. Sci.* **16**, 113.
NOLAN, B. (1993), *J. Math. Phys.* **34**, 178.
SUSSMAN, R. (1989a), *Gen. Rel. Grav.* **21**, 1281.
TAUB, A.H. (1968a), in: *Abstracts, 5th International Conference on Gravitation and the Theory of Relativity.* Publishing House of the Tbilisi University, Tbilisi, p. 145.
TAUB, A.H. (1968b), *Ann. Inst. Poincare* **A9**, 153.
WAGH, R.V. (1955a), *J. Univ. Bombay* **24**, 1.
WAGH, R.V. (1958), *J. Univ. Bombay* **26** no 5, 16.
WYMAN, M. (1946), *Phys. Rev.* **70**, 396.
WYMAN, M. (1976), *Canad. Math. Bull.* **19**, 343.

This is the list of papers in which properties of the McVittie (1933, see first list in this section) solution were discussed:

Hogan, P.A. (1990), *Astrophys. J.* **360**, 315.
Järnefelt, G. (1940), *Ann. Acad. Soc. Sci. Fennicae* **A55** no 3, 3.
Järnefelt, G. (1942), *Ann. Acad. Sci. Fennicae* **A** no 12.
McVittie, G.C. (1966), *Astrophys. J.* **143**, 682.
Noerdlinger, P.D., Petrosian, V. (1971), *Astrophys. J.* **168**, 1.
Nolan, B. (1993), *J. Math. Phys.* **34**, 178.
Sussman, R. (1988b), *J. Math. Phys.* **29**, 1177.

4.2. Generalizations of the conformally nonflat solutions to charged fluid source

The generalization of the whole class of Kustaanheimo and Qvist to charged fluid source was found by Shah and Vaidya (1968), and then rediscovered by Faulkes (1969a), Mashhoon and Partovi (1979) and Nduka (1979 and 1981). Sussman (1987 and 1988) and Srivastava (1992) presented overviews of the known solutions. De (1971) found a cylindrically symmetric an a plane symmetric solution with a charged fluid source, Banerjee and De (1975) rediscovered the first one. The other papers presented various particular solutions, all of them spherically symmetric (see Krasiński 1993 [G] for a detailed classification and description).

Banerjee, A., Chakravarty, N., Dutta Choudhury, S.B. (1975), *Nuovo Cimento* **B29**, 357.
Banerjee, A., Chakravarty, N., Dutta Choudhury, S.B. (1976), *Acta Phys. Polon.* **B7**, 675.
Banerjee, A., Dutta Choudhury, S.B. (1977), *Progr. Theor. Phys.* **57**, 1070.
Banerjee, A., De, U.K. (1975), *Acta Phys. Polon.* **B6**, 335.
Chakravarty, N., Chatterjee, S. (1978), *Acta Phys. Polon.* **B9**, 777.
Chatterjee, S. (1984), *Gen. Rel. Grav.* **16**, 381.
Date, T. H. (1973), *Indian J. Pure Appl. Math.* **4**, 612.
De, U.K. (1971), *Indian J. Phys.* **45**, 487.
Faulkes, M.C. (1969a), *Can. J. Phys.* **47**, 1989.
Mashhoon, B., Partovi, M.H. (1979), *Phys. Rev.* **D20**, 2455.
Mashhoon, B., Partovi, M.H. (1980), *Ann. Phys.* **130**, 99.
Mashhoon, B., Partovi, M.H. (1984), *Phys. Rev.* **D30**, 1839.
Nduka, A. (1979), *Acta Phys. Polon.* **B10**, 479.
Nduka, A. (1981), *Acta Phys. Polon.* **B12**, 833.
Nuñez, L., Rago, H., Aulestia, L. (1983), *Rev. Mex. Fis.* **30**, 83.
Shah, Y.P., Vaidya, P.C. (1967), *Ann. Inst. Poincare* **A6**, 219.
Shah, Y.P., Vaidya, P.C. (1968), *Tensor N. S.* **19**, 191.
Srivastava, D.C. (1986), *Gen. Rel. Grav.* **18**, 1159.
Srivastava, D.C. (1989), *Pramana* **32**, 741.
Srivastava, D.C. (1992), *Fortschr. Physik* **40**, 31.
Sussman, R. (1986), in: *Proceedings of the 4th Marcel Grossman Meeting on General Relativity.* Edited by R. Ruffini. Elsevier, Amsterdam, p. 867.
Sussman, R. (1987), *J. Math. Phys.* **28**, 1118.

SUSSMAN, R. (1988a), *J. Math. Phys.* **29**, 945.
SUSSMAN, R. (1988b), *J. Math. Phys.* **29**, 1177.
VAIDYA, P.C., SHAH, Y.P. (1967), *Curr. Sci.* **36**, 120.

4.3. Generalizations of the conformally nonflat solutions to nonzero heat flow

The generalization of the whole Kustaanheimo-Qvist class to nonzero heat flow was found by STROBEL (1968), and then rediscovered by SANYAL and RAY (1984), DENG (1989) and BANERJEE, DUTTA CHOUDHURY and BHUI (1990). The other papers listed below contain conformally nonflat subcases thereof. The result by BOKHARI (1992) is in error (see KRASIŃSKI 1993 [G]).

BANERJEE, A., DUTTA CHOUDHURY, S.B., BHUI, B.K. (1990), *Pramana* **34**, 397.
BOKHARI, A.H. (1992), *Int. J. Theor. Phys.* **31**, 2087.
BONNOR, W.B. (1987), *Phys. Lett.* **A122**, 305.
DENG, Y. (1989), *Gen. Rel. Grav.* **21**, 503.
DE OLIVEIRA, A.K.G., KOLASSIS, C.A., SANTOS, N.O. (1988), *Mon. Not. R. Astron. Soc.* **231**, 1011.
DE OLIVEIRA, A.K.G., SANTOS, N.O., KOLASSIS, C.A. (1985), *Mon. Not. R. Astron. Soc.* **216**, 1001.
GLASS, E.N. (1981), *Phys. Lett.* **A86**, 351.
MODAK, B. (1984a), *J. Astrophys. Astron.* (India) **5**, 317.
SANTOS, N.O. (1985), *Mon. Not. R. Astron. Soc.* **216**, 403.
SANYAL, A.K., RAY, D. (1984a), *J. Math. Phys.* **25**, 1975.
STROBEL, H. (1968), *Wiss. Z. Friedrich Schiller Univ. Jena, Math. Naturw. Reihe* **17**, 195.
STROBEL, H. (1972), *Wiss. Z. Friedrich Schiller Univ. Jena, Math. Naturw. Reihe* **21**, 111.

4.4. The conformally flat perfect fluid solutions

The most general conformally flat perfect fluid solution was found by STEPHANI (1967a), and then rediscovered by BARNES (1973), BANERJEE and CHAKRAVARTY (1979) and IVANOV (1980). The spherically symmetric subcase of it (which belongs to the Kustaanheimo-Qvist class) was rediscovered more than 20 times, the papers with rediscoveries are listed separately after the main list below. The paper by ROY and BALI (1978a) contains several basic errors (see KRASIŃSKI 1993 [G]). The other solutions are various special subcases of the Stephani solution; the papers in which their properties were discussed are also listed below. Properties of the Stephani solution were discussed by COOK (1975), KRASIŃSKI (1981, 1983 and 1984a) and DĄBROWSKI (1993); also by LORENZ-PETZOLD (1986), but this last paper is totally in error, see KRASIŃSKI (1993 [G]). Generalizations to charged fluid are necessarily conformally nonflat, only those listed in sec. 4.2 are known.

ALEXANDER, D., GREEN, R.M., EMSLIE, A.G. (1989), *Mon. Not. R. Astron. Soc.* **237**, 93.

BANERJEE, A., CHAKRAVARTY, N. (1979), *Acta Phys. Polon.* **B10**, 3.

BARNES, A. (1973), *Gen. Rel. Grav.* **4**, 105.

BONA, C. (1985), in: *Proceedings of the Relativity Meeting 1984*, Universidad de Valencia. Edited by M. Portilla, J.L. Sanz, R. Lapiedra. Universidad de Valencia, Santander, p. 11.

BONA, C., COLL, B. (1985), *C. R. Acad. Sci.* Paris I **301**, 613.

BONA, C., COLL, B. (1988), *Gen. Rel. Grav.* **20**, 297.

BONDARENKO, N.P., KOBUSHKIN, P.K. (1972), *Doklady ANSSSR* **202**, 558 [*Sov. Phys. Doklady* **17**, 48 (1972)].

BONNOR, W.B., FAULKES, M.C. (1967), *Mon. Not. R. Astron. Soc.* **137**, 239.

COLEY, A.A., CZAPOR, S.R. (1992), *Class. Q. Grav.* **9**, 1787.

COLEY, A.A., TUPPER, B.O.J. (1990a), *Class. Q. Grav.* **7**, 1961.

COLEY, A.A., TUPPER, B.O.J. (1990b), *Class. Q. Grav.* **7**, 2195.

COOK, M.W. (1975), *Austral. J. Phys.* **28**, 413.

DĄBROWSKI, M. (1993), *J. Math. Phys.* **34**, 1447.

HENRIKSEN, R.N., EMSLIE, A.G., WESSON, P.S. (1983), *Phys. Rev.* **D27**, 1219.

IVANENKO, D.D., BREZHNEV, V.S., FROLOV, B.N. (1967), in: *Sovremennye Problemy Gravitatsii. Sbornik Trudov II Sovetskoy Gravitatsyonnoy Konferentsii* [*Contemporary problems of gravitation. The collection of proceedings of the 2nd Soviet Conference on Gravitation*], Tbilisi 1965. Edited by D.D. Ivanenko, M.M. Miriyanashvili, V.S. Kiriya, A.B. Kereselidze. Izdatelstvo Tbilisskogo Universiteta, Tbilisi, p. 186.

IVANOV, G.G. (1980), *Izv. VUZ Fiz.* **23** no 12, 22 [*Sov. Phys. J.* **23**, 1002 (1980)].

KRASIŃSKI, A. (1981), *Gen. Rel. Grav.* **13**, 1021 (1981).

KRASIŃSKI, A. (1983), *Gen. Rel. Grav.* **15**, 673 (1983).

KRASIŃSKI, A. (1984a), in: *The Big Bang and Georges Lemaître.* Edited by A. Berger. D. Reidel, Dordrecht, p. 63.

KUMAR, M.M. (1969), *Nuovo Cimento* **A63**, 559.

LORENZ-PETZOLD, D. (1986), *J. Astrophys. Astron.* (India) **7**, 155.

LUKACS, B., MESZAROS, A. (1985), *Astrophys. Space Sci.* **114**, 211.

MAHARAJ, S.D., LEACH, P.G.L., MAARTENS, R. (1991), *Gen. Rel. Grav.* **23**, 261.

MCVITTIE, G.C., STABELL, R. (1967), *Ann. Inst. Poincare* **A7**, 103.

MCVITTIE, G.C., STABELL, R. (1968), *Ann. Inst. Poincare* **A9**, 371.

PAPINI, G., WEISS, M. (1986), *Nuovo Cimento* **B91**, 31.

PONCE DE LEON, J. (1991a), *J. Math. Phys.* **32**, 3546.

RAY, D. (1978), *Int. J. Theor. Phys.* **17**, 153.

ROY, S.R., BALI, R. (1978a), *Indian J. Pure Appl. Math.* **9**, 871.

ROY, S.R., BALI, R. (1978b), *Indian J. Pure Appl. Math.* **9**, 1236.

SHVETSOVA, N.A., SHVETSOV, V.A. (1976), *Izv. VUZ Fiz.* **19** no 7, 138 [*Sov. Phys. J.* **19**, 949 (1976)].

STEPHANI, H. (1967a), *Commun. Math. Phys.* **4**, 137.

STEPHANI, H. (1967b), *Commun. Math. Phys.* **5**, 337.

SUSSMAN, R. (1989a), *Gen. Rel. Grav.* **21**, 1281.

SUSSMAN, R. (1989b), *Phys. Rev.* **D40**, 1364.

SUSSMAN, R. (1990), in: *Proceedings of the 3rd Canadian Conference on General Relativity and Relativistic Astrophysics.* Edited by A. Coley, F. Cooperstock and B. Tupper. World Scientific, Singapore, p. 40.

SUSSMAN, R. (1991), in: *Proceedings of the 7th Latin American Symposium on Relativity and Gravitation* (SILARG 7). Edited by J.C. Olivo, E. Nahmad-Achar, M. Rosenbaum, M.P. Ryan Jr., J.F. Urrutia, F. Zertuche. World Scientific, Singapore, p. 248.

THOMPSON, I.H., WHITROW, G.J. (1968), *Mon. Not. R. Astron. Soc.* **139**, 499.

TOMITA, K., NARIAI, H. (1968), *Progr. Theor. Phys.* **40**, 1184.

VERMA, D.N., ROY, S.N. (1956), *Bull. Calcutta Math. Soc.* **48**, 129.

WESSON, P.S. (1990), *Can. J. Phys.* **68**, 824.

WESSON, P.S., PONCE DE LEON, J. (1989), *Phys. Rev.* **D39**, 420.

WOLF, T. (1986), *J. Math. Phys.* **27**, 2340.

This is the list of rediscoveries of the spherically symmetric subcase of the STEPHANI (1967a) solution. The solution flashed through the paper by WYMAN (1946), but was ignored by the author.

BANERJEE, A. (1972), *J. Phys.* **A5**, 1305.

BONDI, H. (1967), *Nature* **215**, 838.

BREZHNEV, V.S. (1966a), in: *Problemy teorii gravitatsii i elementarnykh chastits* [*Problems of gravitation theory and elementary particle theory*], 1st edition. Edited by K.P. Stanyukovich and G.A. Sokolnik. Atomizdat, Moskva, p. 152.

CAHILL, M.E., MCVITTIE, G.C. (1970a), *J. Math. Phys.* **11**, 1382.

COOK, M.W. (1975), *Austral. J. Phys.* **28**, 413.

EISENSTAEDT, J. (1975a), *Phys. Rev.* **D11**, 2021.

GLASS, E.N. (1979), *J. Math. Phys.* **20**, 1508.

GUPTA, P.S. (1959), *Ann. Physik* **2**, 421.

KUSTAANHEIMO, P., QVIST, B. (1948), *Societas Scientiarum Fennicae Commentationes Physico-Mathematicae* **XIII** no 16, 1.

MISRA, R.M., SRIVASTAVA, D.C. (1973), *Phys. Rev.* **D8**, 1653.

NARIAI, H., TOMITA, K. (1968), *Progr. Theor. Phys.* **40**, 679.

NDUKA, A. (1981), *Acta Phys. Polon.* **B12**, 833.

NOLAN, B. (1993), *J. Math. Phys.* **34**, 178.

PANDEY, S.N., GUPTA, Y.K., SHARMA, S.P. (1983), *Indian J. Pure Appl. Math.* **14**, 79.

PONCE DE LEON, J. (1986), *J. Math. Phys.* **27**, 271.

RAYCHAUDHURI, A.K. (1955), *Z. Astrophysik* **37**, 103.

SRIVASTAVA, D.C. (1992), *Fortschr. Physik* **40**, 31.

STROBEL, H. (1968), *Wiss. Z. Friedrich Schiller Univ. Jena, Math. Naturw. Reihe* **17**, 195.

SUSSMAN, R. (1989a), *Gen. Rel. Grav.* **21**, 1281.

TAUB, A.H. (1968b), *Ann. Inst. Poincare* **A9**, 153.

THOMPSON, I.H., WHITROW, G.J. (1967), *Mon. Not. R. Astron. Soc.* **136**, 207.

VAIDYA, P.C. (1968a), in: *Abstracts, 5th International Conference on Gravitation and the Theory of Relativity.* Publishing House of the Tbilisi University, Tbilisi, p. 10.

VAIDYA, P.C. (1968b), *Phys. Rev.* **174**, 1615.
WYMAN, M. (1946), *Phys. Rev.* **70**, 396.

The following other papers are relevant for the spherically symmetric subcase of the Stephani solution. KARMARKAR (1948), NARLIKAR and SINGH (1950) and KUCHOWICZ (1973) were on the way to deriving it, but stopped short of the goal; the other authors discussed its properties.

BONDI, H. (1969), *Mon. Not. R. Astron. Soc.* **142**, 333.
GUPTA, P.S. (1962), *Nuovo Cimento* **26**, 379.
KARMARKAR, K.R. (1948), *Proc. Indian Acad. Sci.* **27**, 56.
KNUTSEN, H. (1983c), *Phys. Scripta* **28**, 357.
KUCHOWICZ, B. (1973), *Int. J. Theor. Phys.* **7**, 259.
NARLIKAR, V.V., SINGH, K.P. (1950), *Phil. Mag.* **41**, 152.

4.5. Conformally flat solutions with heat flow

A generalization of the STEPHANI (1967a) solution in its full generality to the case of nonzero heat flow was found by BANERJEE, DUTTA CHOUDHURY and BHUI (1989), and rediscovered by JIANG (1992). The other solutions are various special cases. Some of the references are repeated from sec. 4.3 because the papers presented more than one solution each.

BANERJEE, A., DUTTA CHOUDHURY, S.B., BHUI, B.K. (1989), *Phys. Rev.* **D40**, 670.
BERGMANN, O. (1981), *Phys. Lett.* **A82**, 383.
BONNOR, W.B., DE OLIVEIRA, A.K.G., SANTOS, N.O. (1989), *Phys. Rep.* **181** no 5, 269.
CHAN, R., LEMOS, J.P.S., SANTOS, N.O., PACHECO, J.A. DE F. (1989), *Astrophys. J.* **342**, 976.
DENG, Y. (1989), *Gen. Rel. Grav.* **21**, 503.
DENG, Y., MANNHEIM, P. (1990), *Phys. Rev.* **D42**, 371.
GRAMMENOS, T., KOLASSIS, C. (1992), *Phys. Lett.* **A169**, 5.
JIANG, S. (1992), *J. Math. Phys.* **33**, 3503.
KOLASSIS, C.A., SANTOS, N.O., TSOUBELIS, D. (1988), *Astrophys. J.* **327**, 755.
MAITI, S.R. (1982), *Phys. Rev.* **D25**, 2518.
MODAK, B. (1984a), *J. Astrophys. Astron.* (India) **5**, 317.
PATEL, L.K., KOPPAR, S.S. (1987b), *Phys. Lett.* **A121**, 267.
SANYAL, A.K., RAY, D. (1984a), *J. Math. Phys.* **25**, 1975.
SOM, M.M., SANTOS, N.O. (1981), *Phys. Lett.* **A87**, 89.
STROBEL, H. (1968), *Wiss. Z. Friedrich Schiller Univ. Jena, Math. Naturw. Reihe* **17**, 195.
SUSSMAN, R.A. (1993), *Class. Q. Grav.* **10**, 2675.

5. SOLUTIONS WITH NULL RADIATION

The papers listed in this section presented superpositions of the FLRW models with various important vacuum solutions, such as Schwarzschild or Kerr. All the

solutions have null radiation as a component in their sources, and the radiation is coupled to the other components, so that setting the radiation part to zero results in trivializing the solution in other ways. In particular, the superposition of the Schwarzschild solution with the FLRW models (contained as a subcase in the VAIDYA 1977 solution) is not equivalent to the MCVITTIE (1933) solution from sec. 4.1.

BAYIN, S.S. (1979), *Phys. Rev.* **D19**, 2838.
KOPPAR, S.S., PATEL, L.K. (1988), *J. Math. Phys.* **29**, 182.
PATEL, L.K., KOPPAR, S.S. (1987a), *Indian J. Pure Appl. Math.* **18**, 260.
PATEL, L.K., KOPPAR, S.S. (1988), *Acta Phys. Hung.* **64**, 353.
PATEL, L.K., KOPPAR, S.S., PANDYA, N.R. (1990), *Acta Phys. Hung.* **67**, 135.
PATEL, L.K., KOPPAR, S.S., YADAV, S.R. (1989), *J. Math. Phys. Sci.* (India) **23**, 261.
PATEL, L.K., TRIVEDI, H.B. (1982), *J. Astrophys. Astron.* (India) **3**, 63.
PATEL, L.K., YADAV, S.R. (1987), *J. Math. Phys.* Sci. (India) **21**, 167.
PATEL, L.K., YADAVA, S.R. (1987), *Indian J. Pure Appl. Math.* **18**, 840.
SIEMENIEC-OZIĘBŁO, G. (1983), *Acta Phys. Polon.* **B14**, 465.
SINGH, K.M., BHAMRA, K.S. (1990), *Int. J. Theor. Phys.* **29**, 1015.
VAIDYA, P.C. (1966), *Astrophys. J.* **144**, 943.
VAIDYA, P.C. (1977), *Pramana* **8** 512.
VAIDYA, P.C., PATEL, L.K. (1985), *Math. Today* **3**, 41.
VAIDYA, P.C., SHAH, K.B. (1960), *Progr. Theor. Phys.* **24**, 111.

6. SOLUTIONS WITH A STIFF FLUID SOURCE

There are two groups of papers in this section, listed separately. In the papers of the first group, methods of solving the Einstein equations with such a source were discussed. In the second group, explicit solutions were derived and discussed. In some of the papers, the stiff fluid was allowed to be charged, in some others, the source was a mixture of two or more stiff fluids. The detailed classification and description was presented by KRASIŃSKI (1993 [G]).

6.1. Algorithms to solve the Einstein equations

Note: the paper by LI (1992) is in error, see KRASIŃSKI (1993 [G]).

ALENCAR, P.S.C., LETELIER, P.S. (1986), in: *Proceedings of the 4th Marcel Grossman Meeting on General Relativity.* Edited by R. Ruffini. Elsevier, Amsterdam, p. 885.
BRONNIKOV, K.A. (1980), *J. Phys.* **A13**, 3455.
CHANDRASEKHAR, S., XANTHOPOULOS, B.C. (1985), *Proc. Roy. Soc.* London **A402**, 37.
CHARACH, C., MALIN, S. (1979), *Phys. Rev.* **D19**, 1058.
CHARACH, C., MALIN, S. (1980), *Phys. Rev.* **D21**, 3284.
LAL, K.B., SINGH, T. (1973), *Tensor N. S.* **27**, 211.
LAPEDES, A.S. (1977), *Phys. Rev.* **D15**, 946.

LETELIER, P.S. (1975), *J. Math. Phys.* **16**, 1488.
LETELIER, P.S. (1979), *J. Math. Phys.* **20**, 2078.
LETELIER, P.S. (1982), *Nuovo Cimento* **B69**, 145.
LETELIER, P.S., ALENCAR, P.S.C. (1986), *Phys. Rev.* **D34**, 343.
LETELIER, P.S., MACHADO, R. (1981), *J. Math. Phys.* **22**, 827.
LETELIER, P.S., TABENSKY, R.R. (1975a), *J. Math. Phys.* **16**, 8.
LETELIER, P.S., TABENSKY, R.R. (1975b), *Nuovo Cimento* **B28**, 407.
LI, J. (1992), *J. Math. Phys.* **33**, 3506.
MATZNER, R.A., ROSENBAUM, M., RYAN, M.P. (1982), *J. Math. Phys.* **23**, 1984.
RAY, D. (1976), *J. Math. Phys.* **17**, 1171.
RAY, D. (1982), *Phys. Rev.* **D26**, 3752.
SINGH, T. (1978), *Progr. Math.* [this journal is sometimes referred to as *Acad. Prog. Math.*] **12**, 27.
SINGH, T., RAI, L.N., YADAV, R.B.S. (1979), *J. Sci. Res. Banaras Hindu Univ.* **30** no 2, 9 (1979–80).
SINGH, T., YADAV, R.B.S. (1978a), *Indian J. Pure Appl. Math.* **9**, 900.
SINGH, T., YADAV, R.B.S. (1978b), *Acta Phys. Acad. Sci. Hung.* **45**, 107.
STEPHANI, H. (1988), *J. Math. Phys.* **29**, 1650.
TABENSKY, R., TAUB, A.H. (1973), *Commun. Math. Phys.* **29**, 61.
TABENSKY, R., ZAMORANO, N. (1975), *Int. J. Theor. Phys.* **13**, 1.
TOMITA, K. (1978), *Progr. Theor. Phys.* **59**, 1150.

6.2. Explicit solutions

BELINSKII, V.A. (1979), *ZhETF* **77**, 1239 [*Sov. Phys. JETP* **50**, 623 (1979)].
CARMELI, M., CHARACH, C. (1984), *Found. Phys.* **14**, 963.
CARMELI, M., CHARACH, C., FEINSTEIN, A. (1983a), *Ann. Phys.* **150**, 392.
CARMELI, M., CHARACH, C., FEINSTEIN, A. (1983b), *Phys. Lett.* **A96**, 1.
CARMELI, M., CHARACH, C., MALIN, S. (1981), *Phys. Rep.* **76** no 2, 79.
CAROT, J., IBANEZ, J. (1985), *J. Math. Phys.* **26**, 2282.
COLLINS, C.B., LANG, J.M. (1987), *Class. Q. Grav.* **4**, 61.
DIAZ, M., GLEISER, R.J., GONZALEZ, G.I., PULLIN, J.A. (1989), *Phys. Rev.* **D40**, 1033.
GLEISER, R.J., DIAZ, M.C., GROSSO, R.D. (1988a), *Astron. Nachr.* **309**, 239.
GLEISER, R.J., DIAZ, M.C., GROSSO, R.D. (1988b), *Class. Q. Grav.* **5**, 989.
GRIFFITHS, J.B. (1993a), *Class. Q. Grav.* **10**, 975.
GRIFFITHS, J.B. (1993b), *J. Math. Phys.* **34**, 4064 (1993).
IBANEZ, J., VERDAGUER, E. (1986), *Astrophys. J.* **306**, 401.
JANTZEN, R.T. (1980), *Nuovo Cimento* **B59**, 287.
KITCHINGHAM, D.W. (1984), *Class. Q. Grav.* **1**, 677.
KITCHINGHAM, D.W. (1986), *Class. Q. Grav.* **3**, 133.
KRORI, K.D., NANDY, D. (1984), *J. Math. Phys.* **25**, 2515.
LETELIER, P.S., VERDAGUER, E. (1987), *J. Math. Phys.* **28**, 2431.
MACCALLUM, M.A.H. (1984), in: *Exact solutions of Einstein's equations, techniques and results.* Edited by C. Hoenselaers and W. Dietz. Springer, Berlin, p. 334.
MCINTOSH, C.B.G. (1978), *Phys. Lett.* **A69**, 1.

OLIVER, G., VERDAGUER, E. (1989), *J. Math. Phys.* **30**, 442.
RAO, J.R., TIWARI, R.N., BHAMRA, K.S. (1974), *Ann. Phys.* **87**, 470.
TABENSKY, R., TAUB, A.H. (1973), *Commun. Math. Phys.* **29**, 61.
VERDAGUER, E. (1985), in: *Observational and theoretical aspects of relativistic astrophysics and cosmology.* Edited by J.L. Sanz and L.J. Goicoechea. World Scientific, Singapore p. 311.
VERDAGUER, E. (1993), *Phys. Rep.* **229** no 1, 1.
WAINWRIGHT, J., INCE, W.C.W., MARSHMAN, B.J. (1979), *Gen. Rel. Grav.* **10**, 259.

7. OTHER CYLINDRICALLY SYMMETRIC SOLUTIONS

All the solutions from sec. 6 were cylindrically symmetric. There are other cylindrically symmetric solutions with sources more general than the stiff fluid. They are listed in this section.

7.1. Perfect fluid solutions

Note: the paper by GRØN (1985) is in error, see KRASIŃSKI (1993 [G]).

BARROW, J.D., GRØN (1986), *Phys. Lett.* **B182**, 25.
COLLINS, C.B., LANG, J.M. (1987), *Class. Q. Grav.* **4**, 61.
DAVIDSON, W. (1988), *Class. Q. Grav.* **5**, 147.
DAVIDSON, W. (1992), *Gen. Rel. Grav.* **24**, 179.
GÖTZ, G. (1988), *Gen. Rel. Grav.* **20**, 23.
GRØN, Ø. (1985), *Phys. Rev.* **D32**, 1586.
ROY, S.R., PRASAD, A. (1989), *Progr. Math.* **23**, 153.
ROY, S.R., PRASAD, A. (1991), *Astrophys. Space Sci.* **181**, 61.
RUIZ, E., SENOVILLA, J.M.M. (1992), *Phys. Rev.* **D45**, 1995.
SHIKIN, I.S. (1981), *ZhETF* **81**, 801 [*Sov. Phys. JETP* **54**, 427 (1981)].
UGGLA, C. (1992), *Class. Q. Grav.* **9**, 2287.
WAINWRIGHT, J., GOODE, S.W. (1980), *Phys. Rev.* **D22**, 1906.
WILS, P. (1990), *Class. Q. Grav.* **7**, L43.

7.2. Nonperfect fluid solutions

The solutions by ROY and BANERJEE (1988) have viscosity and anisotropic pressure, those by MITSKEVICH and SENIN (1981) have anisotropic pressure, the one by BALI, SINGH and TYAGI (1987) has electromagnetic field.

BALI, R., SINGH, G., TYAGI, A. (1987), *Astrophys. Space Sci.* **139**, 365.
MITSKEVIČ, N.V., SENIN, Y.E. (1981), *Acta Phys. Polon.* **B12**, 541.
ROY, S.R., BANERJEE, S.K. (1988), *Astrophys. Space Sci.* **150**, 213.

8. MISCELLANEOUS SOLUTIONS

8.1. Petrov type N solutions

OLESON, M. (1971), *J. Math. Phys.* **12**, 666.

8.2. Solutions with special properties of the principal null directions of the Weyl tensor

Note: The metrics of WAINWRIGHT (1974) are actually large classes defined by partial differential equations. The other solutions are members of those classes.

MARTIN, J., SENOVILLA, J.M.M. (1986a), *J. Math. Phys.* **27**, 265.
MARTIN, J., SENOVILLA, J.M.M. (1986b), *J. Math. Phys.* **27**, 2209.
MARTIN-PASCUAL, F., SENOVILLA, J.M.M. (1988) *J. Math. Phys.* **29**, 937.
WAINWRIGHT, J. (1974), *Int. J. Theor. Phys.* **10**, 39.

8.3. Spherically symmetric solutions with expansion, shear and acceleration

MCVITTIE, G.C., WILTSHIRE, R.J. (1977), *Int. J. Theor. Phys.* **16**, 121.
NARLIKAR, V.V. (1936), *Phil. Mag.* **22**, 767.
NARLIKAR, V.V., MOGHE, D.N. (1935), *Phil. Mag.* **20**, 1104.
STEPHANI, H., WOLF, T. (1985), in: *Galaxies, axisymmetric systems and relativity.* Essays presented to W.B. Bonnor on his 65th birthday. Edited by M.A.H. MacCallum. Cambridge University Press, p. 275.

8.4. Solutions with an anisotropic fluid source, generated by soliton techniques

CRUZATE, J., DIAZ, M., GLEISER, R., PULLIN, J. (1988), *Class. Q. Grav.* **5**, 883.
DIAZ, M.C., GLEISER, R.J., PULLIN, J.A. (1987), *Class. Q. Grav.* **4**, L23.
DIAZ, M.C., GLEISER, R.J., PULLIN, J.A. (1988a), *Class. Q. Grav.* **5**, 641.
DIAZ, M.C., GLEISER, R.J., PULLIN, J.A. (1988b), *J. Math. Phys.* **29**, 169.
DIAZ, M.C., GLEISER, R.J., PULLIN, J.A. (1989), *Astrophys. J.* **339**, 1.
IBANEZ, J., VERDAGUER, E. (1986), *Astrophys. J.* **306**, 401.
PULLIN, J. (1990), *Astrophys. Space Sci.* **164**, 309.

9. AVERAGING OUT SMALL SCALE INHOMOGENEITIES

The papers listed in this section do not discuss explicit solutions, but consider various proposals to include the procedure of averaging into the Einstein equations. See KRASIŃSKI (1993 [G]) for a description.

BIALKO, A.V. (1973), *ZhETF* **65**, 849 [*Sov. Phys. JETP* **38**, 421 (1974)].
BILDHAUER, S., FUTAMASE, T. (1992), *Gen. Rel. Grav.* **23**, 1251.
CARFORA, M., MARZUOLI, A. (1984a), in: *Atti del VI Convegno Nazionale di Relativita Generale e Fisica della Gravitazione* (FIRENZE 1984).
CARFORA, M., MARZUOLI, A. (1984b), *Phys. Rev. Lett.* **53**, 2445.
ELLIS, G.F.R. (1984), in: *General relativity and gravitation.* Edited by B. Bertotii, F. de Felice, A. Pascolini. D. Reidel, Dordrecht, p. 215.
ELLIS, G.F.R. (1988), in: *Proceedings of the Second Canadian Conference on General Relativity and Relativistic Astrophysics.* Edited by A.A. Coley and B.O.J. Tupper. World Scientific, Singapore, p. 1.
FUTAMASE, T. (1993), *Progr. Theor. Phys.* **89**, 581.

HEMMERICH, A. (1987), *Astron. Astrophys.* **185**, 1.
ISAACSON, R.A. (1968a), *Phys. Rev.* **166**, 1263.
ISAACSON, R.A. (1968b), *Phys. Rev.* **166**, 1272.
KRYMSKY, A.M., MAROCHNIK, L.S., NASELSKY, P.D., PELIKHOV, N.V. (1978), *Astrophys. Space Sci.* **55**, 325.
MAROCHNIK, L.S. (1980a), *Astron. Zh.* **57**, 903 [*Sov. Astr. A. J.* **24**, 518 (1981)].
MAROCHNIK, L.S. (1980b), *Astron. Zh.* **57**, 1129 [*Sov. Astr. A. J.* **24**, 651 (1980)].
MAROCHNIK, L.S. (1980c), *Astrophys. Space Sci.* **69**, 3.
MAROCHNIK, L.S. (1980d), *Astrophys. Space Sci.* **69**, 31.
MAROCHNIK, L.S. (1981), *Astron. Zh.* **58**, 15 [*Sov. Astr. A. J.* **25**, 8 (1981)].
MAROCHNIK, L.S., NASELSKY, P.D., PELIKHOV, N.V. (1980), *Astrophys. Space Sci.* **67**, 261.
MAROCHNIK, L.S., PELIKHOV, N.V., VERESHKOV, G.M. (1975a), *Astrophys. Space Sci.* **34**, 249.
MAROCHNIK, L.S., PELIKHOV, N.V., VERESHKOV, G.M. (1975b), *Astrophys. Space Sci.* **34**, 281.
MATZNER, R.A. (1968a), *J. Math. Phys.* **9**, 1063.
MATZNER, R.A. (1968b), *J. Math. Phys.* **9**, 1657.
NELSON, A.H. (1972), *Mon. Not. R. Astron. Soc.* **158**, 159.
NOONAN, T.W. (1984), *Gen. Rel. Grav.* **16**, 1103.
NOONAN, T.W. (1985), *Gen. Rel. Grav.* **17**, 535.
ROSEN, G. (1980), *Nuovo Cimento* **B57**, 125.
SAAR, E. (1971a), *Eesti NSV Akadeemia Toimetised* [*Izv. Akad. Nauk Eston. SSR*] **20**, 420.
SAAR, E. (1971b), *Tartu Aston. Obs. Publ.* **39**, 206.
SAAR, E. (1971c), *Tartu Aston. Obs. Publ.* **39**, 234.
SAAR, E. (1971d), *Tartu Aston. Obs. Publ.* **39**, 249.
SHIROKOV, M.F. (1967), in: *Sovremennye problemy gravitatsii. Sbornik trudov II Sovetskoy Gravitatsyonnoy Konferentsii* [*Contemporary problems of gravitation. The collection of proceedings of the 2nd Soviet Conference on Gravitation*]. Tbilisi University Publishing House p. 376.
SHIROKOV, M.F., FISHER, I.Z. (1962), *Astron. Zh.* **39**, 899 [*Sov. Astr. A. J.* **6**, 699 (1963)].
SIBGATULLIN, N.R. (1971), *Doklady ANSSSR* **200**, 308 [*Sov. Phys. Doklady* **16**, 697 (1972)].
STOEGER, W.R., ELLIS, G.F.R., HELLABY, C. (1987), *Mon. Not. R. Astron. Soc.* **226**, 373.
SZEKERES, P. (1971), *Ann. Phys.* **64**, 599.
ZALALETDINOV, R.M. (1992), *Gen. Rel. Grav.* **24**, 1015.
ZALALETDINOV, R.M. (1993), *Gen. Rel. Grav.* **25**, 673.
ZOTOV, N.V., STOEGER, W.R. (1992), *Class. Q. Grav.* **9**, 1023.

10. QUESTIONING THE COSMOLOGICAL PRINCIPLE

The papers listed below contain remarks or considerations that are relevant for the inhomogeneous cosmological models, even though they do not discuss solutions of this class. Mainly, the authors emphasized that the cosmological principle has no empirical basis.

ARP, H.C., VAN FLANDERN, T. (1992), *Phys. Lett.* **A164**, 263.
COLLINS, C.B. (1979), *Gen. Rel. Grav.* **10**, 925.
DINGLE, H. (1933), *Mon. Not. R. Astron. Soc.* **94**, 134.
EARDLEY, D., LIANG, E., SACHS, R. (1972), *J. Math. Phys.* **13**, 99.
ELLIS, G.F.R. (1980), *Ann. N. Y. Acad. Sci.* **336**, 130.
ELLIS, G.F.R. (1984), in: *General relativity and gravitation.* Edited by B. Bertotii, F. de Felice, A. Pascolini. D. Reidel, Dordrecht, p. 215.
FABBRI, R., MELCHIORRI, F. (1981), *Gen. Rel. Grav.* **13**, 201.
KERMACK, W. O., MCCREA, W.H., WHITTAKER, E.T. (1933), *Proc. Roy. Soc.* Edinburgh **53**, 31.
KRISTIAN, J. (1967), *Astrophys. J.* **147**, 864.
KRISTIAN, J., SACHS, R.K. (1966), *Astrophys. J.* **143**, 379.
KURKI-SUONIO, H., LIANG, E. (1992), *Astrophys. J.* **390**, 5.
MACCALLUM, M.A.H. (1979), in: *General relativity, an Einstein centenary survey.* Edited by S.W. Hawking and W. Israel. Cambridge University Press, Cambridge, p. 533.
MACCALLUM, M.A.H. (1985), in: *Obsevational and theoretical aspects of relativistic astrophysics and cosmology.* Edited by J.L. Sanz and L.J. Goicoechea. World Scientific, Singapore, p. 183.
MCCREA, W.H. (1939), *Z. Astrophysik* **18**, 98.
MESZAROS, A., VANYSEK, V. (1988), *Bull. Astron. Inst. Czech.* **39**, 185.
TAVAKOL, R.K., ELLIS, G.F.R. (1988), *Phys. Lett.* **A130**, 217.
TOLMAN, R.C. (1934), *Proc. Nat. Acad. Sci.* USA **20**, 169.
VAN DEN BERGH, S. (1990), *J. R. Astron. Soc. Can.* **84**, 275.
WESSON, P.S. (1980), *Gravity, particles and astrophysics.* D. Reidel, Dordrecht, pp. 147–161.

11. HISTORICAL MILESTONES

This section contains a list of papers which, in the opinion of this author, played a crucial role in the development of inhomogeneous cosmological models. It must be stressed that, except for but a few, the papers listed below were never properly appreciated, and many of them are virtually unknown until today. The list is thus a call for historical justice (based on a personal assessment by this author) rather than a presentation of development of the field. Most of the references below are repeated from the previous sections.

LEMAÎTRE (1933a) — the pioneering paper, and probably the most underappreciated one. The author introduced the Lemaître-Tolman model, and in addition presented or solved a few problems commonly associated now with names and

papers younger by a whole generation. Examples: the definition of conserved mass for a spherically symmetric perfect fluid, a proof that the Schwarzschild horizon is not a singularity (by a coordinate transformation to a system of freely falling observers), a preliminary statement of a singularity theorem illustrated with a Bianchi I model.

McVittie (1933) — presented a superposition of the Schwarzschild and FLRW metrics which is a perfect fluid solution. A remarkably bold and early entry, but the solution is still not satisfactorily interpreted.

Dingle (1933) — a preliminary investigation of spherically symmetric shearfree perfect fluid solutions, later completed by Kustaanheimo and Qvist (1948). The paper is remarkable for the author's strong criticism of the cosmological principle and an explicit call for inhomogeneous models.

Tolman (1934) — the first extended investigation of the Lemaître (1933a) solution. The author showed that the solution implies the instability of the Einstein and FLRW models against the formation of condensations and rarefactions (which today would be called voids). Tolman cited Lemaître. All the contemporary authors who call this solution "the Tolman model" evidently did not read Tolman's paper.

Sen (1934) — the first explicit statement that voids should form in an inhomogeneous Universe: "the [Einstein and FLRW] models are unstable for initial rarefaction".

McCrea (1939) — the first elaborate call for inhomogeneous models and the first draft of a theoretical formalism to describe such models and compare them with observations.

Einstein and Straus (1945) — the first formally correct investigation of the influence of expansion of the Universe on planetary orbits. Though formally correct, the investigation unfortunately produced an incorrect result because the model it used was rather peculiar and unstable (see Krasiński 1993 [G]).

Bondi (1947) — a thorough in-depth investigation of geometrical and physical properties of the Lemaître-Tolman model. The author was the first to observe several physically interesting possibilities offered by the model, but the paper was for a long time ignored. Several of Bondi's observations were independently rediscovered and picked up much later by other authors (see Krasiński 1993 [G]).

Kustaanheimo and Qvist (1948) — reduced the Einstein equations for a spherically symmetric metric with a shearfree expanding perfect fluid source to a single ordinary differential equation.

Bonnor (1956) — showed, using the L-T model, that galaxies could not have originated as statistical fluctuations in an initially homogeneous matter distribution (because, according to the view that is still considered valid now, the Universe is much too young to have allowed enough time for the process to succeed).

Ehlers (1961) — a self-contained exposition of relativistic hydrodynamics and thermodynamics in curved space, with several ideas of McCrea (1939, see above) incorporated. An English translation of that paper was published just recently (Ehlers 1993).

SHIROKOV and FISHER (1962) — first pointed out that an "averaged" cosmological model should obey modified field equations, with a "polarization term" arising from averaging out small-scale inhomogeneities.

KRISTIAN and SACHS (1966) — a self-contained theory of observations in an inhomogeneous Universe.

STEPHANI (1967a) — the most general conformally flat solution of the Einstein equations with a perfect fluid source; an important link in the chain of generalizations of the FLRW models.

ELLIS (1971) — foundations of relativistic cosmology with arbitrary geometry, based on the exposition of EHLERS (1961, see above).

BARNES (1973) — a complete set of solutions of the Einstein equations with a shearfree, nonrotating and expanding perfect fluid source; the set includes the solutions of KUSTAANHEIMO and QVIST (1948) and STEPHANI (1967a).

SZEKERES (1975a) — still the most sophisticated dust solutions generalizing the FLRW models.

SZAFRON (1977) — generalization of the Szekeres solutions to nonzero pressure.

GOODE and WAINWRIGHT (1982b) — a reformulation of the SZEKERES (1975a) solutions showing the interconnection between increasing and decreasing modes of perturbation of the FLRW background on the one hand, and the initial conditions (nonsimultaneous Big Bang + initial inhomogeneities in density) on the other. The authors established a link between the Szekeres models and the perturbative methods.

ELLIS (1984) — the first apparently successful call for approaching the relativistic cosmology on a broader basis than the FLRW models.

GAUTREAU (1984) — the first quantitative estimate of the influence of cosmic expansion on planetary orbits.

SATO (1984) — an elaborate theory of evolution of voids in the Universe, based on the L-T model.

PANEK (1992) — a thorough investigation of the influence of inhomogeneities in matter distribution on the anisotropies in the cosmic microwave background radiation, based on the L-T model. Several authors argued that the isotropy of the radiation actually proves the homogeneity of the Universe. However, no quantitative estimates existed of the amount of anisotropy that inhomogeneities in matter distribution would induce in the background radiation. Panek's paper provided the first such estimate which in fact proves the earlier arguments to be void.

ZALALETDINOV (1992) — the first covariant (but only axiomatic) theory of averaging out small-scale inhomogeneities in the metric.

BARNES, A. (1973), *Gen. Rel. Grav.* 4, 105.

BONDI, H. (1947), *Mon. Not. R. Astron. Soc.* **107**, 410.

BONNOR, W.B. (1956), *Z. Astrophysik* **39**, 143.

DINGLE, H. (1933), *Mon. Not. R. Astron. Soc.* **94**, 134.

EHLERS, J. (1961), *Akad. Wiss. Lit. Mainz, Abhandl. Math. Naturw. Kl.*, Nr 11, 791.

EHLERS, J. (1993), *Gen. Rel. Grav.* **25**, 1225.

EINSTEIN, A., STRAUS, E.G. (1945), *Rev. Mod. Phys.* **17**, 120.

ELLIS, G.F.R. (1971), in: *Proceedings of the International School of Physics* "Enrico Fermi", Course 47: General relativity and cosmology. Edited by R.K. Sachs. Academic Press, New York and London, p. 104.

ELLIS, G.F.R. (1984), in: *General relativity and gravitation.* Edited by B. Bertotii, F. de Felice, A. Pascolini. D. Reidel, Dordrecht, p. 215.

GAUTREAU, R. (1984), *Phys. Rev.* **D29**, 198.

GOODE, S.W., WAINWRIGHT, J. (1982b), *Phys. Rev.* **D26**, 3315.

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