Freytag, B.; **Steffen, M.**; **Ludwig, H.-G.**; **Wedemeyer-Böhm, S.**; **Schaffenberger, W.**; **Steiner, O.**

Simulations of stellar convection with CO5BOLD. (English) Zbl 1241.85003

J. Comput. Phys. 231, No. 3, 919-959 (2012).

Summary: High-resolution images of the solar surface show a granulation pattern of hot rising and cooler downward-sinking material – the top of the deep-reaching solar convection zone. Convection plays a role for the thermal structure of the solar interior and the dynamo acting there, for the stratification of the photosphere, where most of the visible light is emitted, as well as for the energy budget of the spectacular processes in the chromosphere and corona. Convective stellar atmospheres can be modeled by numerically solving the coupled equations of (magneto)hydrodynamics and non-local radiation transport in the presence of a gravity field. The CO5BOLD code described in this article is designed for so-called "realistic" simulations that take into account the detailed microphysics under the conditions in solar or stellar surface layers (equation-of-state and optical properties of the matter). These simulations indeed deserve the label "realistic" because they reproduce the various observables very well – with only minor differences between different implementations. The agreement with observations has improved over time and the simulations are now well-established and have been performed for a number of stars. Still, severe challenges are encountered when it comes to extending these simulations to include ideally the entire star or substellar object: the strong stratification leads to completely different conditions in the interior, the photosphere, and the corona. Simulations have to cover spatial scales from the sub-granular level to the stellar diameter and time scales from photospheric wave travel times to stellar rotation or dynamo cycle periods. Various non-equilibrium processes have to be taken into account. Last but not least, realistic simulations are based on detailed microphysics and depend on the quality of the input data, which can be the actual accuracy limiter. This article provides an overview of the physical problem and the numerical solution and the capabilities of CO5BOLD, illustrated with a number of applications.

MSC:

85-08 Computational methods for problems pertaining to astronomy and astrophysics
85A15 Galactic and stellar structure
85A30 Hydrodynamic and hydromagnetic problems in astronomy and astrophysics
76E20 Stability and instability of geophysical and astrophysical flows

Keywords:

numerical simulations; radiation (magneto)hydrodynamics; stellar surface convection; CO5BOLD

Software:

HLLE; Linfor3D; ZEUS; ASH; NIRVANA; HE-E1GODF; CO5BOLD; ANTARES; VODE

Full Text: DOI arXiv

References:

[1] Vitense, E., Die wasserstoffkonvektionszone der sonne, Z. astrophys., 32, 135-164, (1953)

[2] Böhm-Vitense, E., Über die wasserstoffkonvektionszone in sternen verschiedener effektivtemperaturen und leuchtkräfte, Z. astrophys., 46, 108-143, (1958)

[3] Mihalas, D., Stellar atmospheres, (1978), W.H. Freeman and Co. San Francisco

[4] R.L. Kurucz, Atlas: a Computer Program for Calculating Model Stellar Atmospheres, SAO Special Report, 309, 1970.

[5] Kurucz, R.L., ATLAS12, SYNTHE, ATLAS9, WIDTH9, et cetera, Mem. soc. astron. italiana suppl., 8, 14-24, (2005)

[6] Gustafsson, B.; Bell, R.A.; Eriksson, K.; Nordlund, Å., A grid of model atmospheres for metal-deficient giant stars. I, A&a, 42, 407-432, (1975)

[7] Gustafsson, B.; Edvardsson, B.; Eriksson, K.; Jørgensen, U.G.; Nordlund, Å.; Plez, B., A grid of MARCS model atmospheres for late-type stars. I. methods and general properties, A&a, 486, 951-970, (2008)

[8] Allard, F.; Hauschildt, P.H., Model atmospheres for \textit{M} (sub)dwarf stars. I. the base model grid, Apj, 445, 433-450,

(1995)

[9] Allard, F.; Hauschildt, P.H.; Alexander, D.R.; Tamanai, A.; Schweitzer, A., The limiting effects of dust in Brown dwarf model atmospheres, Apj, 556, 357-372, (2001)

[10] Steffen, M.; Jordan, S., Numerical simulation of stellar convection: comparison with mixing-length theory, ()

[11] Fuhrmann, K.; Axer, M.; Gehren, T., Balmer lines in cool dwarf stars. I. basic influence of atmospheric models, A&a, 271, 451-462, (1993)

[12] M. Steffen, H. Ludwig, Balmer line formation in convective stellar atmospheres, in: A. Gimenez, E.F. Guinan, B. Montesinos, (Eds.), Stellar Structure: Theory and Test of Convective Energy Transport, Astronomical Society of the Pacific Conference Series, vol. 173, 1999, pp. 217-220.

[13] Christensen-Dalsgaard, J.; Däppen, W.; Ajukov, S.V.; Anderson, E.R.; Antia, H.M.; Basu, S.; Baturin, V.A.; Berthomieu, G.; Chaboyer, B.; Chitre, S.M.; Cox, A.N.; Demarque, P.; Donatowicz, J.; Dziembowski, W.A.; Gabriel, M.; Gough, D.O.; Guenther, D.B.; Guzik, J.A.; Harvey, J.W.; Hill, F.; Houdek, G.; Iglesias, C.A.; Kosovichev, A.G.; Leibacher, J.W.; Morel, P.; Proffitt, C.R.; Provost, J.; Reiter, J.; Rhodes, E.J.; Rogers, F.J.; Roxburgh, I.W.; Thompson, M.J.; Ulrich, R.K., The current state of solar modeling, Science, 272, 1286-1292, (1996)

[14] Bahcall, J.N.; Pinsonneault, M.H.; Basu, S., Solar models: current epoch and time dependences, neutrinos, and helioseismological properties, Apj, 555, 990-1012, (2001)

[15] Latour, J.; Spiegel, E.A.; Toomre, J.; Zahn, J., Stellar convection theory. I. the anelastic modal equations, Apj, 207, 233-243, (1976)

[16] Latour, J.; Toomre, J.; Zahn, J., Stellar convection theory. III. dynamical coupling of the two convection zones in \textit{A}-type stars by penetrative motions, Apj, 248, 1081-1098, (1981)

[17] Toomre, J.; Zahn, J.; Latour, J.; Spiegel, E.A., Stellar convection theory. II. single-mode study of the second convection zone in an \textit{A}-type star, Apj, 207, 545-563, (1976)

[18] Musman, S.; Nelson, G.D., The energy balance of granulation, Apj, 207, 981-988, (1976)

[19] Nelson, G.D., A two-dimensional solar model, Sol. phys., 60, 5-18, (1978)

[20] Chan, K.L.; Wolff, C.L., ADI on staggered mesh – a method for calculation of compressible convection, J. comput. phys., 451, 109-129, (1982) · Zbl 0492.76084

[21] Hurlburt, N.E.; Toomre, J.; Massaguer, J.M., Two-dimensional compressible convection extending over multiple scale heights, Apj, 282, 557-573, (1984)

[22] Steffen, M.; Ludwig, H.-G.; Krüß, A., A numerical simulation study of solar granular convection in cells of different horizontal dimension, A&a, 213, 371-382, (1989)

[23] Nordlund, Å., Numerical simulations of the solar granulation. I. basic equations and methods, A&a, 107, 1-10, (1982) · Zbl 0502.76099

[24] Dravins, D.; Lindegren, L.; Nordlund, Å., Solar granulation – influence of convection on spectral line asymmetries and wavelength shifts, A&a, 96, 345-364, (1981)

[25] Toomre, J.; Brummell, N.; Cattaneo, F.; Hurlburt, N.E., Three-dimensional compressible convection at low Prandtl numbers, Comput. phys. commun., 59, 105-117, (1990) · Zbl 0875.76183

[26] Malagoli, A.; Cattaneo, F.; Brummell, N.H., Turbulent supersonic convection in three dimensions, Apjl, 361, L33-L36, (1990)

[27] Cattaneo, F.; Brummell, N.H.; Toomre, J.; Malagoli, A.; Hurlburt, N.E., Turbulent compressible convection, Apj, 370, 282-294, (1991)

[28] Hossain, M.; Mullan, D.J., Three-dimensional compressible hydrodynamic convection in the Sun and stars, Apj, 380, 631-654, (1991)

[29] Singh, H.P.; Chan, K.L., A study of the three-dimensional turbulent compressible convection in a deep atmosphere at various Prandtl numbers, A&a, 279, 107-118, (1993)

[30] Asplund, M., New light on stellar abundance analyses: departures from LTE and homogeneity, Annu. rev. astron. astrophys., 43, 481-530, (2005)

[31] Asplund, M.; Grevesse, N.; Sauval, A.J.; Scott, P., The chemical composition of the Sun, Annu. rev. astron. astrophys., 47, 481-522, (2009)

[32] Caffau, E.; Ludwig, H.-G.; Steffen, M.; Ayres, T.R.; Bonifacio, P.; Cayrel, R.; Freytag, B.; Plez, B., The photospheric solar oxygen project. I. abundance analysis of atomic lines and influence of atmospheric models, A&a, 488, 1031-1046, (2008)

[33] Caffau, E.; Ludwig, H.-G.; Steffen, M.; Freytag, B.; Bonifacio, P., Solar chemical abundances determined with a CO5BOLD 3D model atmosphere, Sol. phys., 255-269, (2011)

[34] Cayrel, R.; Steffen, M.; Chand, H.; Bonifacio, P.; Spite, M.; Spite, F.; Petitjean, P.; Ludwig, H.-G.; Caffau, E., Line shift, line asymmetry, and the ^{6}Li/7 Li isotopic ratio determination, A&a, 473, L37-L40, (2007)

[35] Ludwig, H.-G.; Freytag, B.; Steffen, M., A calibration of the mixing-length for solar-type stars based on hydrodynamical simulations. I. methodical aspects and results for solar metallicity, A&a, 346, 111-124, (1999)

[36] Freytag, B.; Ludwig, H.-G.; Steffen, M., Hydrodynamical models of stellar convection. the role of overshoot in DA white dwarfs, \textit{A}-type stars, and the Sun, A&a, 313, 497-516, (1996)

[37] Samadi, R.; Nordlund, Å.; Stein, R.F.; Goupil, M.J.; Roxburgh, I., Numerical 3D constraints on convective eddy time-correlations: consequences for stochastic excitation of solar \textit{p} modes, A&a, 404, 1129-1137, (2003)

[38] Samadi, R.; Georgobiani, D.; Trampedach, R.; Goupil, M.J.; Stein, R.F.; Nordlund, Å., Excitation of solar-like oscillations

across the HR diagram, A&a, 463, 297-308, (2007)

[39] Straus, T.; Fleck, B.; Jefferies, S.M.; Cauzzi, G.; McIntosh, S.W.; Reardon, K.; Severino, G.; Steffen, M., The energy flux of internal gravity waves in the lower solar atmosphere, Apjl, 681, L125-L128, (2008)

[40] Grossmann-Doerth, U.; Knölker, M.; Schüssler, M.; Weisshaar, E., Models of magnetic flux sheets, (), 481-492

[41] Steiner, O.; Grossmann-Doerth, U.; Knölker, M.; Schüssler, M., Dynamical interaction of solar magnetic elements and granular convection: results of a numerical simulation, Apj, 495, 468-484, (1998)

[42] Steiner, O.; Knölker, M.; Schüssler, M., Dynamic interaction of convection with magnetic flux sheets: first results of a new MHD code, (), 441-470

[43] Atroshchenko, I.N.; Sheminova, V.A., Numerical simulation of the interaction between solar granules and small-scale magnetic fields, Kinemat. phys. celestial bodies, 12, 21-32, (1996)

[44] Nordlund, Å., 3-D model calculations, (), 83-102

[45] Nordlund, Å.; Stein, R.F.; Asplund, M., Solar surface convection, Living rev. sol. phys., 6, 2, (2009)

[46] Galloway, D.J.; Weiss, N.O., Convection and magnetic fields in stars, Apj, 243, 945-953, (1981)

[47] Deinzer, W.; Hensler, G.; Schüssler, M.; Weisshaar, E., Model calculations of magnetic flux tubes. II. stationary results for solar magnetic elements, A&a, 139, 426-449, (1984)

[48] Hurlburt, N.E.; Toomre, J., Magnetic fields interacting with nonlinear compressible convection, Apj, 327, 920-932, (1988)

[49] Weiss, N.O.; Brownjohn, D.P.; Hurlburt, N.E.; Proctor, M.R.E., Oscillatory convection in sunspot umbrae, Mnras, 245, 434-452, (1990)

[50] Fox, P.A.; Theobald, M.L.; Sofia, S., Compressible magnetic convection – formulation and two-dimensional models, Apj, 383, 860-881, (1991)

[51] V.H. Hansteen, B. Gudiksen, 3D numerical models of quiet Sun coronal heating, in: B. Fleck, T.H. Zurbuchen, H. Lacoste (Eds.), Connecting Sun and Heliosphere, ESA Special Publication, vol. 592, 2005, pp. 483-486.

[52] Gudiksen, B.V.; Carlsson, M.; Hansteen, V.H.; Hayek, W.; Leenaarts, J.; Martínez-Sykora, J., The stellar atmosphere simulation code bifrost. code description and validation, A&a, 531, A154, (2011)

[53] W. Schaffenberger, S. Wedemeyer-Böhm, O. Steiner, B. Freytag, Magnetohydrodynamic simulation from the convection zone to the chromosphere, in: D.E. Innes, A. Lagg, S.A. Solanki, (Eds.), Chromospheric and Coronal Magnetic Fields, ESA Special Publication, vol. 596, 2005, p. 65.

[54] Vögler, A.; Shelyag, S.; Schüssler, M.; Cattaneo, F.; Emonet, T.; Linde, T., Simulations of magneto-convection in the solar photosphere. equations, methods, and results of the muram code, A&a, 429, 335-351, (2005)

[55] Heinemann, T.; Nordlund, Å.; Scharmer, G.B.; Spruit, H.C., MHD simulations of penumbra fine structure, Apj, 669, 1390-1394, (2007)

[56] Jacoutot, L.; Kosovichev, A.G.; Wray, A.; Mansour, N.N., Realistic numerical simulations of solar convection and oscillations in magnetic regions, Apjl, 684, L51-L54, (2008)

[57] Muthsam, H.J.; Kupka, F.; Löw-Baselli, B.; Obertscheider, C.; Langer, M.; Lenz, P., ANTARES - a numerical tool for astrophysical research with applications to solar granulation, New astron., 15, 460-475, (2010)

[58] R.F. Stein, Å. Nordlund, D. Georgoviani, D. Benson, W. Schaffenberger, Supergranulation-scale convection simulations, in: M. Dikpati, T. Arentoft, I. González Hernández, C. Lindsey, F. Hill, (Eds.), Solar-Stellar Dynamos as Revealed by Helio- and Asteroseismology, Astronomical Society of the Pacific Conference Series, vol. 416, 2009, pp. 421-426.

[59] Å. Nordlund, K. Galsgaard, A 3D MHD code for Parallel Computers, Technical Report, Astron. Observ., Copenhagen University, 1995.

[60] Cheung, M.C.M.; Rempel, M.; Title, A.M.; Schüssler, M., Simulation of the formation of a solar active region, Apj, 720, 233-244, (2010)

[61] Rempel, M.; Schüssler, M.; Cameron, R.H.; Knölker, M., Penumbral structure and outflows in simulated sunspots, Science, 325, 171-174, (2009)

[62] V.H. Hansteen, M. Carlsson, B. Gudiksen, 3D numerical models of the chromosphere, transition region, and corona, in: P. Heinzel, I. Dorotovič, R.J. Rutten, (Eds.), The Physics of Chromospheric Plasmas, Astronomical Society of the Pacific Conference Series, vol. 368, 2007, pp. 107-114.

[63] Hansteen, V.H.; Hara, H.; De Pontieu, B.; Carlsson, M., On redshifts and blueshifts in the transition region and corona, Apj, 718, 1070-1078, (2010)

[64] Martínez-Sykora, J.; Hansteen, V.; Carlsson, M., Twisted flux tube emergence from the convection zone to the corona, Apj, 679, 871-888, (2008)

[65] Abbett, W.P., The magnetic connection between the convection zone and corona in the quiet Sun, Apj, 665, 1469-1488, (2007)

[66] Abbett, W.P.; Fisher, G.H., Improving large-scale convection-zone-to-corona models, Mem. soc. astron. italiana, 81, 721-728, (2010)

[67] Isobe, H.; Proctor, M.R.E.; Weiss, N.O., Convection-driven emergence of small-scale magnetic fields and their role in coronal heating and solar wind acceleration, Apjl, 679, L57-L60, (2008)

[68] Weiss, N.O.; Brownjohn, D.P.; Matthews, P.C.; Proctor, M.R.E., Photospheric convection in strong magnetic fields, Mnras, 283, 1153-1164, (1996)

[69] Tobias, S.M.; Brummell, N.H.; Clune, T.L.; Toomre, J., Pumping of magnetic fields by turbulent penetrative convection, Apjl,

502, L177-L180, (1998)

[70] Cattaneo, F., On the origin of magnetic fields in the quiet photosphere, Apjl, 515, L39-L42, (1999)

[71] Ossendrijver, M.; Stix, M.; Brandenburg, A., Magnetoconvection and dynamo coefficients: dependence of the alpha effect on rotation and magnetic field, A&a, 376, 713-726, (2001)

[72] Cattaneo, F.; Emonet, T.; Weiss, N., On the interaction between convection and magnetic fields, Apj, 588, 1183-1198, (2003)

[73] Archontis, V.; Moreno-Insertis, F.; Galsgaard, K.; Hood, A.W., The three-dimensional interaction between emerging magnetic flux and a large-scale coronal field: reconnection, current sheets, and jets, Apj, 635, 1299-1318, (2005)

[74] Cheung, M.C.M.; Moreno-Insertis, F.; Schüssler, M., Moving magnetic tubes: fragmentation, vortex streets and the limit of the approximation of thin flux tubes, A&a, 451, 303-317, (2006) · Zbl 1096.85505

[75] Glatzmaier, G.A., Numerical simulations of stellar convective dynamos. I. the model and method, J. comput. phys., 55, 461-484, (1984)

[76] Browning, M.K.; Miesch, M.S.; Brun, A.S.; Toomre, J., Dynamo action in the solar convection zone and tachocline: pumping and organization of toroidal fields, Apjl, 648, L157-L160, (2006)

[77] Clune, T.C.; Elliott, J.R.; Miesch, M.S.; Toomre, J.; Glatzmaier, G.A., Computational aspects of a code to study rotating turbulent convection in spherical shells, Parallel comput., 588, 361-380, (1999) · Zbl 1047.68514

[78] Dobler, W.; Stix, M.; Brandenburg, A., Magnetic field generation in fully convective rotating spheres, Apj, 638, 336-347, (2006)

[79] Ziegler, U., Self-gravitational adaptive mesh magnetohydrodynamics with the NIRVANA code, A&a, 435, 385-395, (2005)

[80] Å. Nordlund, R.F.Stein, Accurate radiation hydrodynamics and MHD Modeling of 3-D stellar atmospheres, in: I. Hubeny, J.M. Stone, K. MacGregor, K. Werner, (Eds.), Recent Directions in Astrophysical Quantitative Spectroscopy and Radiation Hydrodynamics, American Institute of Physics Conference Series, vol. 1171, 2009, pp. 242-259.

[81] Carlsson, M., Hydrodynamics and radiative transfer of 3D model atmospheres. current status, limitations, and how to make headway, Mem. soc. astron. italiana, 80, 606-613, (2009)

[82] Steiner, O., Magnetic coupling in the quiet solar atmosphere, (), 166-185

[83] Spitzer, L., Physics of fully ionized gases, (1962), Interscience Publishers New York · Zbl 0074.45001

[84] Thomas, L.H., The radiation field in a fluid in motion, Q. J. math., 1, 239-251, (1930) · Zbl 56.1361.02

[85] Nordlund, Å.; Spruit, H.C.; Ludwig, H.-G.; Trampedach, R., Is stellar granulation turbulence?, A&a, 328, 229-234, (1997)

[86] Spiegel, E.A., The smoothing of temperature fluctuations by radiative transfer, Apj, 126, 202-207, (1957)

[87] Unno, W.; Spiegel, E.A., The Eddington approximation in the radiative heat equation, Publ. astron. soc. jpn., 18, 85-95, (1966)

[88] Brun, A.S.; Miesch, M.S.; Toomre, J., Global-scale turbulent convection and magnetic dynamo action in the solar envelope, Apj, 614, 1073-1098, (2004)

[89] Schrijver, C.J., Catastrophic cooling and high-speed downflow in quiescent solar coronal loops observed with TRACE, Sol. phys., 198, 325-345, (2001)

[90] Klimchuk, J.A., On solving the coronal heating problem, Sol. phys., 234, 41-77, (2006)

[91] Strang, G., On the construction and comparison of difference schemes, SIAM J. numer. anal., 5, 506-517, (1968) · Zbl 0184.38503

[92] Wedemeyer, S.; Freytag, B.; Steffen, M.; Ludwig, H.-G.; Holweger, H., Numerical simulation of the three-dimensional structure and dynamics of the non-magnetic solar chromosphere, A&a, 414, 1121-1137, (2004)

[93] Iglesias, C.A.; Rogers, F.J.; Wilson, B.G., Spin-orbit interaction effects on the rosseland Mean opacity, Apj, 397, 717-728, (1992)

[94] Hauschildt, P.H.; Baron, E.; Allard, F., Parallel implementation of the PHOENIX generalized stellar atmosphere program, Apj, 483, 390-398, (1997)

[95] Steffen, M.; Freytag, B., Lyapunov exponents for solar surface convection, Chaos solitons fract., 5, 1965-1973, (1995)

[96] Freytag, B.; Allard, F.; Ludwig, H.-G.; Homeier, D.; Steffen, M., The role of convection, overshoot, and gravity waves for the transport of dust in \textit{M} dwarf and Brown dwarf atmospheres, A&a, 513, A19, (2010)

[97] Roe, P., Characteristic-based schemes for the Euler equations, Annu. rev. fluid mech., 18, 337, (1986) · Zbl 0624.76093

[98] LeVeque, R.J., Numerical methods for conservation laws, (1992), Birkhäuser Verlag Basel · Zbl 0847.65053

[99] Colella, P.; Woodward, P.R., The piecewise parabolic method (PPM) for gas-dynamical simulations, J. comput. phys., 54, 174-201, (1984) · Zbl 0531.76082

[100] Mellema, G.; Eulderink, F.; Icke, V., Hydrodynamical models of aspherical planetary nebulae, A&a, 252, 718-732, (1991)

[101] Mottura, L.; Vigevano, L.; Zaccanti, M., An evaluation of roe's scheme generalizations for equilibrium real gas flows, J. comput. phys., 138, 354-399, (1997) · Zbl 0903.76059

[102] Glaister, P., An approximate linearized Riemann solver for the Euler equations for real gases, J. comput. phys., 74, 382-408, (1988) · Zbl 0632.76079

[103] Quirk, J., A contribution to the great Riemann solver debate, Int. J. numer. methods fluids, 18, 555-574, (1994) · Zbl 0794.76061

[104] Smagorinsky, J.S., General circulation experiments with the primitive equations I. the basic experiment, Mon. weather rev.,

91, 99-164, (1963)

[105] Stone, J.M.; Mihalas, D.; Norman, M.L., ZEUS-2D: A radiation magnetohydrodynamics code for astrophysical flows in two space dimensions. III. the radiation hydrodynamic algorithms and tests, Apjs, 80, 819-845, (1992)

[106] Höfner, S.; Feuchtinger, M.U.; Dorfi, E.A., Dust formation in winds of long-period variables. III. dynamical models and confirmation of a dust-induced \textit{ϰ}-mechanism, A&a, 297, 815-827, (1995)

[107] Höfner, S.; Gautschy-Loidl, R.; Aringer, B.; Jørgensen, U.G., Dynamic model atmospheres of AGB stars. III. effects of frequency-dependent radiative transfer, A&a, 399, 589-601, (2003)

[108] H.-G. Ludwig, Non-gray Radiation Transport in Numerical Simulations of Stellar Convection, Ph.D. Thesis, University of Kiel, 1992.

[109] Ludwig, H.-G.; Jordan, S.; Steffen, M., Numerical simulations of convection at the surface of a ZZ ceti white dwarf, A&a, 284, 105-117, (1994)

[110] Vögler, A., Effects of non-grey radiative transfer on 3D simulations of solar magneto-convection, A&a, 421, 755-762, (2004)

[111] Davis, P.J.; Polonsky, I., Numerical interpolation, differentiation and integration, (), 877-924

[112] Steffen, M., A simple method for monotonic interpolation in one dimension, A&a, 239, 443-450, (1990)

[113] Feautrier, P., Sur la résolution numérique de l'équation de transfert, C.R. acad. sci., 258, 3189-3194, (1964)

[114] Cannon, C.J., Line transfer in two dimensions, Apj, 161, 255-264, (1970)

[115] Avrett, E.H.; Loeser, R., Radiative transfer in two-component stellar atmospheres, J. quant. spectrosc. radiat. transfer, 11, 559-571, (1971)

[116] Jones, H.P.; Skumanich, A., The formation of resonance lines in multidimensional media. II. radiation operators and their numerical representation, Apj, 185, 167-182, (1973)

[117] Jones, H.P., The formation of resonance lines in multidimensional media. III. interpolation functions, accuracy, and stability, Apj, 185, 183-196, (1973)

[118] Mihalas, D.; Auer, L.H.; Mihalas, B.R., Two-dimensional radiative transfer. I. planar geometry, Apj, 220, 1001-1023, (1978)

[119] Kunasz, P.; Auer, L.H., Short characteristic integration of radiative transfer problems – formal solution in two-dimensional slabs, J. quant. spectrosc. radiat. transfer, 39, 67-79, (1988)

[120] Brackbill, J.U.; Barnes, D.C., The effect of nonzero product of magnetic gradient and \textit{B} on the numerical solution of the magnetohydrodynamic equations, J. comput. phys., 35, 426-430, (1980) · Zbl 0429.76079

[121] Gombosi, T.I.; Powell, K.G.; de Zeeuw, D.L., Axisymmetric modeling of cometary mass loading on an adaptively refined grid: MHD results, J. geophys. res., 99, 21525-21539, (1994)

[122] K.G. Powell, An approximate Riemann solver for magnetohydrodynamics (that works in more than one dimension), Technical Report, ICASE-Report 94-24 (NASA CR-194902), NASA Langley Research Center, Hampton, VA 23681-0001, 1994.

[123] Evans, C.R.; Hawley, J.F., Simulation of magnetohydrodynamic flows – a constrained transport method, Apj, 332, 659-677, (1988)

[124] Tóth, G., The ⊠·\textit{B}=0 constraint in shock-capturing magnetohydrodynamics codes, J. comput. phys., 161, 605-652, (2000) · Zbl 0980.76051

[125] Balsara, D.S.; Spicer, D., Maintaining pressure positivity in magnetohydrodynamic simulations, J. comput. phys., 148, 133-148, (1999) · Zbl 0930.76050

[126] Janhunen, P., A positive conservative method for magnetohydrodynamics based on HLL and roe methods, J. comput. phys., 160, 649-661, (2000) · Zbl 0967.76061

[127] van Leer, B., On the relation between the upwind-differencing schemes of Godunov, enquist-osher and roe, SIAM J. sci. stat. comput., 5, 1-20, (1984) · Zbl 0547.65065

[128] Toro, E.F., Riemann solvers and numerical methods for fluid dynamics, A practical introduction, (2009), Springer · Zbl 1227.76006

[129] Gottlieb, S.; Shu, C.W., Total variation diminishing Runge-Kutta schemes, Math. comput., 67, 73-85, (1998) · Zbl 0897.65058

[130] Harten, A.; Lax, P.D.; van Leer, B., On upstream differencing and Godunov-type schemes for hyperbolic conservation laws, SIAM rev., 25, 35-61, (1983) · Zbl 0565.65051

[131] Einfeldt, B.; Roe, P.L.; Munz, C.D.; Sjogreen, B., On Godunov-type methods near low densities, J. comput. phys., 92, 273-295, (1991) · Zbl 0709.76102

[132] Balsara, D.S.; Spicer, D.S., A staggered mesh algorithm using high order Godunov fluxes to ensure solenoidal magnetic fields in magnetohydrodynamic simulations, J. comput. phys., 149, 270-292, (1999) · Zbl 0936.76051

[133] Rempel, M.; Schüssler, M.; Knölker, M., Radiative magnetohydrodynamic simulation of sunspot structure, Apj, 691, 640-649, (2009)

[134] Stone, J.M.; Pringle, J.E., Magnetohydrodynamical non-radiative accretion flows in two dimensions, Mnras, 322, 461-472, (2001)

[135] Wedemeyer-Böhm, S.; Kamp, I.; Bruls, J.; Freytag, B., Carbon monoxide in the solar atmosphere. I. numerical method and two-dimensional models, A&a, 438, 1043-1057, (2005)

[136] Brown, P.; Byrne, G.; Hindmarsh, A., VODE: a variable-coefficient ODE solver, SIAM J. sci. stat. comp., 10, 1038-1051, (1989) · Zbl 0677.65075

[137] Wedemeyer-Böhm, S.; Steffen, M., Carbon monoxide in the solar atmosphere. II. radiative cooling by CO lines, A&a, 462, L31-L35, (2007)

[138] Steffen, M.; Muchmore, D., Can granular fluctuations in the solar photosphere produce temperature inhomogeneities at the height of the temperature minimum?, A&a, 193, 281-290, (1988)

[139] E. Sollum, Hydrogen Ionization in the Solar Atmosphere: Exact and Simplified Treatments, Master's Thesis, University of Oslo, 1999.

[140] Carlsson, M.; Stein, R.F., Dynamic hydrogen ionization, Apj, 572, 626-635, (2002)

[141] Leenaarts, J.; Wedemeyer-Böhm, S., Time-dependent hydrogen ionisation in 3D simulations of the solar chromosphere. methods and first results, A&a, 460, 301-307, (2006)

[142] Helling, C.; Oevermann, M.; Lüttke, M.J.H.; Klein, R.; Sedlmayr, E., Dust in Brown dwarfs. I. dust formation under turbulent conditions on microscopic scales, A&a, 376, 194-212, (2001)

[143] Woitke, P.; Helling, C., Dust in Brown dwarfs. II. the coupled problem of dust formation and sedimentation, A&a, 399, 297-313, (2003)

[144] Freytag, B.; Höfner, S., Three-dimensional simulations of the atmosphere of an AGB star, A&a, 483, 571-583, (2008)

[145] Gail, H.-P.; Sedlmayr, E., Dust formation in stellar winds. IV. heteromolecular carbon grain formation and growth, A&a, 206, 153-168, (1988)

[146] Gauger, A.; Sedlmayr, E.; Gail, H.-P.; formation, Dust, Growth and evaporation in a cool pulsating circumstellar shell, A&a, 235, 345-361, (1990)

[147] Witte, S.; Helling, C.; Hauschildt, P.H., Dust in Brown dwarfs and extra-solar planets. II. cloud formation for cosmologically evolving abundances, A&a, 506, 1367-1380, (2009)

[148] Rossow, W.B., Cloud microphysics – analysis of the clouds of Earth, venus, Mars, and Jupiter, Icarus, 36, 1-50, (1978)

[149] Stein, R.F.; Nordlund, Å., Solar small-scale magnetoconvection, Apj, 642, 1246-1255, (2006)

[150] A. Vögler, Three-dimensional Simulations of Magneto-Convection in the Solar Photosphere, Ph.D. Thesis, Göttingen University, 2003.

[151] Kiselman, D., Solar 3D models versus observations – a few comments, Phst, 133, 014016, (2008)

[152] Steffen, M., Radiative hydrodynamics models of stellar convection, (), 36-43

[153] Wedemeyer-Böhm, S.; Rouppe van der Voort, L., On the continuum intensity distribution of the solar photosphere, A&a, 503, 225-239, (2009)

[154] Tsuneta, S.; Ichimoto, K.; Katsukawa, Y.; Nagata, S.; Otsubo, M.; Shimizu, T.; Suematsu, Y.; Nakagiri, M.; Noguchi, M.; Tarbell, T.; Title, A.; Shine, R.; Rosenberg, W.; Hoffmann, C.; Jurcevich, B.; Kushner, G.; Levay, M.; Lites, B.; Elmore, D.; Matsushita, T.; Kawaguchi, N.; Saito, H.; Mikami, I.; Hill, L.D.; Owens, J.K., The solar optical telescope for the hinode mission: an overview, Sol. phys., 249, 167-196, (2008)

[155] Hirzberger, J.; Feller, A.; Riethmüller, T.L.; Schüssler, M.; Borrero, J.M.; Afram, N.; Unruh, Y.C.; Berdyugina, S.V.; Gandorfer, A.; Solanki, S.K.; Barthol, P.; Bonet, J.A.; Martínez Pillet, V.; Berkefeld, T.; Knölker, M.; Schmidt, W.; Title, A.M., Quiet-Sun intensity contrasts in the near-ultraviolet as measured from SUNRISE, Apjl, 723, L154-L158, (2010)

[156] Ludwig, H.-G.; Caffau, E.; Steffen, M.; Freytag, B.; Bonifacio, P.; Kučinskas, A., The CIFIST 3D model atmosphere grid, Mem. soc. astron. italiana, 80, 711-714, (2009)

[157] Wende, S.; Reiners, A.; Ludwig, H.-G., 3D simulations of M star atmosphere velocities and their influence on molecular feh lines, A&a, 508, 1429-1442, (2009)

[158] Freytag, B.; Steffen, M.; Dorch, B., Spots on the surface of betelgeuse – results from new 3D stellar convection models, Astron. nachr., 323, 213-219, (2002)

[159] Chiavassa, A.; Plez, B.; Josselin, E.; Freytag, B., Radiative hydrodynamics simulations of red supergiant stars. I. interpretation of interferometric observations, A&a, 506, 1351-1365, (2009)

[160] Chiavassa, A.; Haubois, X.; Young, J.S.; Plez, B.; Josselin, E.; Perrin, G.; Freytag, B., Radiative hydrodynamics simulations of red supergiant stars. II. simulations of convection on betelgeuse match interferometric observations, A&a, 515, A12, (2010)

[161] M. Steffen, H.-G. Ludwig, S. Wedemeyer-Böhm, Linfor3D User Manual. <http://www.aip.de/⊠mst/Linfor3D/linfor_3D_manual.pdf>, 2010.

[162] Asplund, M.; Nordlund, Å.; Trampedach, R.; Stein, R.F., 3D hydrodynamical model atmospheres of metal-poor stars. evidence for a low primordial Li abundance, A&a, 346, L17-L20, (1999)

[163] Asplund, M.; Nordlund, Å.; Trampedach, R.; Stein, R.F., Line formation in solar granulation. II. the photospheric fe abundance, A&a, 359, 743-754, (2000)

[164] Caffau, E.; Sbordone, L.; Ludwig, H.-G.; Bonifacio, P.; Spite, M., Sulphur abundances in halo stars from multiplet 3 at 1045nm, Astron. nachr., 331, 725-730, (2010)

[165] Bonifacio, P.; Caffau, E.; Ludwig, H.-G., Cu I resonance lines in turn-off stars of NGC 6752 and NGC 6397. effects of granulation from CO5BOLD models, A&a, 524, A96, (2010)

[166] González Hernández, J.I.; Bonifacio, P.; Ludwig, H.-G.; Caffau, E.; Behara, N.T.; Freytag, B., Galactic evolution of oxygen. OH lines in 3D hydrodynamical model atmospheres, A&a, 519, A46, (2010)

[167] Behara, N.T.; Bonifacio, P.; Ludwig, H.-G.; Sbordone, L.; González Hernández, J.I.; Caffau, E., Three carbon-enhanced metal-poor dwarf stars from the SDSS. chemical abundances from CO^{5}BOLD 3D hydrodynamical model atmospheres, A&a, 513, A72, (2010)

[168] González Hernández, J.I.; Bonifacio, P.; Ludwig, H.-G.; Caffau, E.; Spite, M.; Spite, F.; Cayrel, R.; Molaro, P.; Hill, V.; François, P.; Plez, B.; Beers, T.C.; Sivarani, T.; Andersen, J.; Barbuy, B.; Depagne, E.; Nordström, B.; Primas, F., First stars. XI. chemical composition of the extremely metal-poor dwarfs in the binary CS 22876-032, A&a, 480, 233-246, (2008)

[169] Sbordone, L.; Bonifacio, P.; Caffau, E.; Ludwig, H.-G.; Behara, N.T.; González Hernández, J.I.; Steffen, M.; Cayrel, R.; Freytag, B.; van't Veer, C.; Molaro, P.; Plez, B.; Sivarani, T.; Spite, M.; Spite, F.; Beers, T.C.; Christlieb, N.; François, P.; Hill, V., The metal-poor end of the spite plateau. I. stellar parameters, metallicities, and lithium abundances, A&a, 522, A26, (2010)

[170] González Hernández, J.I.; Bonifacio, P.; Caffau, E.; Steffen, M.; Ludwig, H.-G.; Behara, N.T.; Sbordone, L.; Cayrel, R.; Zaggia, S., Lithium in the globular cluster NGC 6397. evidence for dependence on evolutionary status, A&a, 505, L13-L16, (2009)

[171] Steffen, M.; Cayrel, R.; Bonifacio, P.; Ludwig, H.-G.; Caffau, E., Convection and ^{6}Li in the atmospheres of metal-poor halo stars, (), 215-220

[172] Kučinskas, A.; Dobrovolskas, V.; Ivanauskas, A.; Ludwig, H.-G.; Caffau, E.; Blaževičius, K.; Klevas, J.; Prakapavičius, D., Can we trust elemental abundances derived in late-type giants with the classical 1D stellar atmosphere models?, (), 209-210

[173] V. Dobrovolskas, A. Kučinskas, H.G. Ludwig, E. Caffau, J. Klevas, D. Prakapavicius, Chemical abundances in metal-poor giants: limitations imposed by the use of classical 1D stellar atmosphere models, in: 11th Symposium on Nuclei in the Cosmos, PoS(NIC XI), vol. 288, Proceedings of Science, 2010.

[174] A. Ivanauskas, A. Kučinskas, H.G. Ludwig, E. Caffau, 3D hydrodynamical CO5BOLD model atmospheres of late-type giants: stellar abundances from molecular lines, in: 11th Symposium on Nuclei in the Cosmos, PoS(NIC XI), vol. 290, Proceedings of Science, 2010.

[175] Steffen, M.; Ludwig, H.-G.; Caffau, E., Micro- and macroturbulence derived from 3D hydrodynamical stellar atmospheres, Mem. soc. astron. italiana, 80, 731-734, (2009)

[176] Ludwig, H.-G.; Behara, N.T.; Steffen, M.; Bonifacio, P., Impact of granulation effects on the use of balmer lines as temperature indicators, A&a, 502, L1-L4, (2009) · Zbl 1177.85015

[177] Wedemeyer-Böhm, S.; Lagg, A.; Nordlund, Å., Coupling from the photosphere to the chromosphere and the corona, Space sci. rev., 144, 317-350, (2009)

[178] Grossmann-Doerth, U.; Schüssler, M.; Steiner, O., Convective intensification of solar surface magnetic fields: results of numerical experiments, A&a, 337, 928-939, (1998)

[179] Lites, B.W.; Kubo, M.; Socas-Navarro, H.; Berger, T.; Frank, Z.; Shine, R.; Tarbell, T.; Title, A.; Ichimoto, K.; Katsukawa, Y.; Tsuneta, S.; Suematsu, Y.; Shimizu, T.; Nagata, S., The horizontal magnetic flux of the quiet-Sun internetwork as observed with the hinode spectro-polarimeter, Apj, 672, 1237-1253, (2008)

[180] Schüssler, M.; Vögler, A., Strong horizontal photospheric magnetic field in a surface dynamo simulation, A&a, 481, L5-L8, (2008)

[181] Steiner, O.; Rezaei, R.; Schaffenberger, W.; Wedemeyer-Böhm, S., The horizontal internetwork magnetic field: numerical simulations in comparison to observations with hinode, Apjl, 680, L85-L88, (2008)

[182] O. Steiner, R. Rezaei, R. Schlichenmaier, W. Schaffenberger, S. Wedemeyer-Böhm, The horizontal magnetic field of the quiet Sun: numerical simulations in comparison to observations with Hinode, in: B. Lites, M. Cheung, T. Magara, J. Mariska, K. Reeves, (Eds.), The Second Hinode Science Meeting, Astronomical Society of the Pacific Conference Series, vol. 415, 2009, pp. 67-70.

[183] W. Schaffenberger, S. Wedemeyer-Böhm, O. Steiner, B. Freytag, Holistic MHD-simulation from the convection zone to the chromosphere, in: J. Leibacher, R.F. Stein, H. Uitenbroek, (Eds.), Solar MHD Theory and Observations: A High Spatial Resolution Perspective, Astronomical Society of the Pacific Conference Series, vol. 354, 2006, pp. 345-350.

[184] Rezaei, R.; Steiner, O.; Wedemeyer-Böhm, S.; Schlichenmaier, R.; Schmidt, W.; Lites, B.W., Hinode observations reveal boundary layers of magnetic elements in the solar photosphere, A&a, 476, L33-L36, (2007)

[185] Steiner, O.; Vigeesh, G.; Krieger, L.; Wedemeyer-Böhm, S.; Schaffenberger, W.; Freytag, B., First local helioseismic experiments with CO5BOLD, Astron. nachr., 328, 323-328, (2007)

[186] Nutto, C.; Steiner, O.; Roth, M., Magneto-acoustic wave propagation and mode conversion in a magnetic solar atmosphere: comparing results from the CO5BOLD code with ray theory, Astron. nachr., 331, 915-919, (2010)

[187] C. Nutto, O. Steiner, W. Schaffenberger, M. Roth, Modification of wave propagation and wave travel-time through the presence of magnetic fields in the solar network atmosphere, A&A, in press.

[188] Kato, Y.; Steiner, O.; Steffen, M.; Suematsu, Y., Excitation of slow modes in network magnetic elements through magnetic pumping, Apjl, 730, L24-L28, (2011)

[189] Petrović, D.; Vranjes, J.; Poedts, S., Analysis of the effect of neutral flow on the waves in the solar photosphere, A&a, 461, 277-284, (2007) · Zbl 1124.85003

[190] Singh, K.A.P.; Krishan, V., Alfvén-like mode in partially ionized solar atmosphere, New astron., 15, 119-125, (2010)

[191] Cattaneo, F., On the origin of magnetic fields in the quiet photosphere, Apjl, 515, L39-L42, (1999)

[192] Tobias, S.M.; Brummell, N.H.; Clune, T.L.; Toomre, J., Pumping of magnetic fields by turbulent penetrative convection, Apjl, 502, L177-L180, (1998)

[193] Vögler, A.; Schüssler, M., A solar surface dynamo, A&a, 465, L43-L46, (2007)

[194] Moll, R.; Pietarila Graham, J.; Pratt, J.; Cameron, R.H.; Müller, W.-C.; Schüssler, M., Universality of the small-scale dynamo mechanism, Apj, 736, 36-45, (2011)

[195] R.F. Stein, Magneto-convection, Philos. Trans. R. Soc. A, in press.

[196] Leenaarts, J.; Carlsson, M.; Hansteen, V.; Rutten, R.J., Non-equilibrium hydrogen ionization in 2D simulations of the solar atmosphere, A&a, 473, 625-632, (2007)

[197] S. Wedemeyer-Böhm, I. Kamp, B. Freytag, J. Bruls, M. Steffen, A first three-dimensional model for the carbon monoxide concentration in the solar atmosphere, in: J. Leibacher, R.F. Stein, H. Uitenbroek, (Eds.), Solar MHD Theory and Observations: A High Spatial Resolution Perspective, Astronomical Society of the Pacific Conference Series, vol. 354, 2006, pp. 301-305.

[198] Carlsson, M.; Stein, R.F., Radiation shock dynamics in the solar chromosphere – results of numerical simulations, (), 47-77

[199] Carlsson, M.; Stein, R.F., Does a nonmagnetic solar chromosphere exist?, Apjl, 440, L29-L32, (1995)

[200] Ulmschneider, P.; Nowak, T.; Bohn, U.; Kalkofen, W., Acoustic waves in the solar atmosphere. I. the hydrodynamic code, A&a, 54, 61-70, (1977)

[201] Skartlien, R.; Stein, R.F.; Nordlund, Å., Excitation of chromospheric wave transients by collapsing granules, Apj, 541, 468-488, (2000)

[202] S. Wedemeyer-Böhm, W. Schaffenberger, O. Steiner, M. Steffen, B. Freytag, I. Kamp, Simulations of magnetohydrodynamics and CO formation from the convection zone to the chromosphere, in: D.E. Innes, A. Lagg, S.A. Solanki, (Eds.), Chromospheric and Coronal Magnetic Fields, ESA Special Publication, vol. 596, 2005, p. 16.

[203] Gudiksen, B.V.; Nordlund, Å., Bulk heating and slender magnetic loops in the solar corona, Apjl, 572, L113-L116, (2002)

[204] Gudiksen, B.V.; Nordlund, Å., An ab initio approach to solar coronal loops, Apj, 618, 1031-1038, (2005)

[205] V.H. Hansteen, Numerical simulations of the chromosphere, in: AAS Meeting 216, Bulletin of the American Astronomical Society, vol. 42, 2010, p. 305.05.

[206] Cauzzi, G.; Reardon, K.P.; Uitenbroek, H.; Cavallini, F.; Falchi, A.; Falciani, R.; Janssen, K.; Rimmele, T.; Vecchio, A.; Wöger, F., The solar chromosphere at high resolution with IBIS. I. new insights from the ca II 854.2 nm line, A&a, 480, 515-526, (2008)

[207] Wöger, F.; Wedemeyer-Böhm, S.; Schmidt, W.; von der Lühe, O., Observation of a short-lived pattern in the solar chromosphere, A&a, 459, L9-L12, (2006) · Zbl 1101.85316

[208] Rosenthal, C.S.; Bogdan, T.J.; Carlsson, M.; Dorch, S.B.F.; Hansteen, V.; McIntosh, S.W.; McMurry, A.; Nordlund, Å.; Stein, R.F., Waves in the magnetized solar atmosphere. I. basic processes and internetwork oscillations, Apj, 564, 508-524, (2002) · Zbl 1008.76533

[209] Bogdan, T.J.; Carlsson, M.; Hansteen, V.H.; McMurry, A.; Rosenthal, C.S.; Johnson, M.; Petty-Powell, S.; Zita, E.J.; Stein, R.F.; McIntosh, S.W.; Nordlund, Å., Waves in the magnetized solar atmosphere. II. waves from localized sources in magnetic flux concentrations, Apj, 599, 626-660, (2003)

[210] Cally, P.S., What to look for in the seismology of solar active regions, Astron. nachr., 328, 286-291, (2007)

[211] Freytag, B.; Steffen, M., Numerical simulations of convection in \textit{A}-stars, (), 139-147

[212] M. Steffen, B. Freytag, H.-G. Ludwig, 3D simulation of convection and spectral line formation in \textit{A}-type stars, in: F. Favata, G.A.J. Hussain, B. Battrick (Eds.), 13th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, ESA Special Publication, vol. 560, 2005, pp. 985-988.

[213] Kochukhov, O.; Freytag, B.; Piskunov, N.; Steffen, M., 3-D hydrodynamic simulations of convection in \textit{A} stars, (), 68-70

[214] Viallet, M.; Baraffe, I.; Walder, R., Towards a new generation of multi-dimensional stellar evolution models: development of an implicit hydrodynamic code, A&a, 531, A86, (2011)

[215] Freytag, B.; Holweger, H.; Steffen, M.; Ludwig, H.-G., On the scale of photospheric convection, (), 316

[216] Ludwig, H.-G.; Allard, F.; Hauschildt, P.H., Numerical simulations of surface convection in a late \textit{M}-dwarf, A&a, 395, 99-115, (2002)

[217] Ludwig, H.-G.; Allard, F.; Hauschildt, P.H., Energy transport, overshoot, and mixing in the atmospheres of \textit{M}-type main- and pre-main-sequence objects, A&a, 459, 599-612, (2006)

[218] Stein, R.F.; Nordlund, Å., Simulations of solar granulation. I. general properties, Apj, 499, 914-933, (1998)

[219] Tremblay, P.-E.; Ludwig, H.-G.; Steffen, M.; Bergeron, P.; Freytag, B., Solution to the problem of the surface gravity distribution of cool DA white dwarfs from improved 3D model atmospheres, A&a, 531, L19+, (2011)

[220] Steffen, M.; Ludwig, H.-G.; Freytag, B., Synthetic spectra computed from hydrodynamical model atmospheres of DA white dwarfs, A&a, 300, 473-480, (1995)

[221] Gautschy, A.; Ludwig, H.-G.; Freytag, B., Overtures to the pulsational instability of ZZ ceti variables, A&a, 311, 493-508, (1996)

[222] Stothers, R.; Leung, K.-C., Luminosities, masses and periodicities of massive red supergiants, A&a, 10, 290-300, (1971)

[223] Schwarzschild, M., On the scale of photospheric convection in red giants and supergiants, Apj, 195, 137-144, (1975)

[224] Buscher, D.F.; Baldwin, J.E.; Warner, P.J.; Haniff, C.A., Detection of a bright feature on the surface of betelgeuse, Mnras, 245, 7-11, (1990)

[225] Chiavassa, A.; Lacour, S.; Millour, F.; Driebe, T.; Wittkowski, M.; Plez, B.; Thiébaut, E.; Josselin, E.; Freytag, B.; Scholz, M.; Haubois, X., VLTI/AMBER spectro-interferometric imaging of VX sagittarii's inhomogenous outer atmosphere, A&a, 511, A51, (2010)