Research Project: Astrophysical Processes, their Simulation and Related Nuclear Physics Issues

First Year Report for Swiss National Science Foundation Grant 200020-132816/1 (October 2010 - September 2012)

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The Theoretical, Computational and Nuclear Astrophyiscs group is part of the Astroparticle Physics focus within the Department of Physics at the Univerity of Basel, also participating in the EU FP7 Research Program ENSAR/THEXO (Theory of Exotic Nuclei within the European Nuclear Physics effort in Large Scale Facilities), the ESF Network "The New Physics of Compact Stars", the ESF Research Program "Eurogenesis: Origin and Evolution of the Elements in the Universe", as well as the SCOPES Project "Synthesis of Heavy Elements in Core Collapse Supernova and their Imprint on Galactic Chemical Evolution", and the HP2C Project "Supernova".

0 Summary

The quality of simulations for astrophysical objects relies on a consistent treatment of (magneto-)hydrodynamic modeling and the required microphysics. In case of the big bang and stellar objects (from stellar evolution to explosions) the latter includes nuclear/particle physics (from reactions to nuclear properties in general and the equation of state) as well as radiation transport (including neutrino transport). Thus, besides the numerical/hydro modeling, the quality of the employed nuclear and particle physics input matters highly with respect to energy generation and transport and as well as nucleosynthesis. The latter, describing nuclear burning and the resulting abundance patterns, provides a unique tool to test models by comparison with (spectral) observations of indivudual objects and links them also to the integrated (chemical) evolution of galaxies. The Basel nuclear astrophysics group combines strength in all these fields and achieved major advances. (i) New compilations of reaction rates were provided to the astrophysical community (thermonuclear reaction rates, based either mostly on experiments, statistical model rates for nuclei with high level densities, and shell model resonance properties for reactions with small level densities, specifically also including now fission channels of the heaviest nuclei). High density equations of state were developed, which cover the transition from nuclear to quark matter. (ii) Nuclear networks for hydrostatic and explosive nucleosynthesis (including treatments for chemical equilibria) were developed which incorporate all weak and strong interaction rates (including neutrino interactions and fission) and can be applied to nucleosynthesis

and energy generation in stellar evolution and explosions, covering especially nucleosynthesis processes like the r-, rp, p- and νp-process. (iii) Major advances were made in the past years in applications of the microphysics and nuclear burning tools mentioned above to (a) stellar evolution of massive stars with rotation, (b) self-consistent general relativistic modeling of core-collapse supernovae for extended periods after bounce with a full neutrino transport treatment, (c) tests of such core-collapse models with respect to the influcence of the equation of state (e.g. QCD-phase transition caused explosions), (d) tests of such models with respect to the influence of rotation and magnetic fields and the production of polar jets, (e) type Ia supernova nucleosynthesis in multi-dimensional simulations of the burning front propagation, (f) spherically symmetric X-ray burst simulations on neutron stars with complete rp-process modeling, (g) relativistic 3D simulations of neutron star mergers and their gravitational wave signal and related r-process calculations, as well as (h) early (inhomgeneous) galactic evolution modeling, making use of the composition of events (a)-(g).

a) Research Group, Scientific Projects, Major Results, Activities

1 Personnel and Equipment

1.1 Personnel

Investigators:

F.-K. Thielemann, M. Liebendörfer*, M. Pignatari**, PD T. Rauscher.

Postdocs:

A. Arcones*, R. Cabezon***, M. Hempel*, N. Nishimura*, I. Panov* [-3755] (1.4.-31.6.11; 1.4.-30.5.12), N. Vasset***.

PhD Students:

U. Battoni*, K. Ebinger*, M. Eichler*, S. Fehlmann*, M. Frensel,

finished their thesis in 2011: U. Frischknecht*, R. Käppeli*, A. Perego*, C. Winteler*.

Master Students:

O. Heinimann, J. Reichert, B. Wehmeyer,

finished in 2012: M. Eichler, K. Ebinger, M. Ruch.

Sekretary:

Francois Erkadoo (Secretary) [3750]

personnel marked with a * is financed by the SNF, two stars ** indicate the SNF Ambizione fellow M. Pignatari, three stars * * * indicate HP2C personnel, A. Arcones is partially also funded by a Feodor Lynen stipend of the Humboldt Foundation.

1.2 Personnel Changes and Honors

I. Cherchneff joined the group initially with an SNF Marie-Heim-Vögtlin stipend, was the paid by this SNF grant, and has now a university position

A. Arcones joined the group with a Feodor Lynen stipend of the Alexander von Humboldt Foundation

The collaboration with I. Panov and his group at ITEP Moscow is financed via a SCOPES Grant of the SNF

S. Scheidegger resumed a position with Credit Swiss in Zurich, followed by a postdoc at ETHZ (economics), R. Käppeli resumed a postdoc position at ETHZ (num. Mathematics), A. Perego a postdoc position at TU Darmstadt (nucl. astrophysics), C. Winteler a teaching position at FHNW, and U. Frischknecht went to industry.

1.3 Computer Access

We perform our computational modeling with the aid of our local linux workstation cluster. In addition, there is extended access to the IBM-SP4 MPP parrallel computer and a CRAY XT3 of the SWiss Supercomputer Center CSCS Manno (Ticino), via one of the 11 HP2C grants (High Performance and High Producticity Computing) given out to research groups in Switzerland.

2 Guests

We received short research visits by: G, Anton, U. Erlangen; S. Antusch, MPI München; E. Baron, U. of Oklahoma; M. Beard, U, of Notre Dame; K. Blaum, MPIK Heidelberg; C. Chiappini, U. of Geneva; P. Egelhof, GSI Darmstadt; M. Falanga, ISSI Bern; A. Fässler, Tübingen; K. Farouqi, MPI Mainz; C. Fröhlich, North Carolina State; C. Hanhart, FZ Jülich; P. Heck, Chicago Field Museum; R. Hirschi, U. of Keele; A. Hujeirat, U. of Heidelberg; T. Hurth, CERN Geneva; H. Jerjen, ANU Canberra; A. Kelic, GSI Darmstadt; I. Korneev, ITEP Moscow; K. Kotake, NAO Tokyo; K.-L. Kratz, Mainz; S. Lucatello, Obs. Padova; C. Lunardini, Tempe, AZ; G. Martinez-Pinedo, GSI Darmstadt; G. Meynet, U. of Geneva; M. Oertel, Obs. de Paris; I. Panov, ITEP Moscow; M. Pohl, U. of Geneva; J. Schaffner-Bielich, U. of Heidelberg; P. Serpico, Annecy; M. Steinmetz, AIP Potsdam; I. Tamborra, MPI München.

3 Teaching, Committee Memberships

3.1 Teaching

In 2010-2011 the following courses were taught regularly by members of the research group: B. Binggeli, F.-K. Thielemann: Astronomisches Proseminar; I. Cherchneff: Physics and Chemistry of the Interstellar Medium; A. Hujeirat: Relativistic Astrophysics; A. Hujeirat, F.-K. Thielemann: Proseminar in Computational Astrophysics; M. Liebendörfer: Computer, Kompakte Sterne und Schwarze Löcher; Strahlungstransport in Sternen und seine numerische Behandlung; In 2010-2011 the following courses were taught regularly by members of the research group:

B. Binggeli, F.-K. Thielemann: Astronomisches Proseminar; I. Cherchneff: Physics and Chemistry of the Interstellar Medium; M. Falanga, F.-K.Thielemann: Compact Objects in Binary Systems; A. Hujeirat: Relativistic Astrophysics; A. Hujeirat, F.-K. Thielemann: Proseminar in Computational Astrophysics; Numerical Methods in Astrophysical Fluid Dynamics; M. Liebendörfer: Computer, Kompakte Sterne und Schwarze Löcher; Strahlungstransport in Sternen und seine numerische Behandlung; Hydrodynamik: Einführung in das Programmieren paralleler Computer in Fortran; Introduction to Astrophysical Plasmas; M. Liebendörfer, F.-K. Thielemann: Proseminar in Theoretischer Physik; T. Rauscher: Nukleare Astrophysik I+II; F.-K. Thielemann: Analytische Mechanik, Klassische Electrodynamik, Thermodynamik und Stat. Mechanik, Höhere Quantenmechaniki; In addition, specialized schools take place for the graduate students within the ESF network "The New Physics of Compact Stars".

3.2 Committees

Liebendörfer and Thielemann: Members of the ESF CompStar Network and board.

Rauscher: Member of the n_TOF Kollaboration at CERN; External expert for written and oral Matura exams at Gymnasium Liestal, BL.

Thielemann: Associate Editor of Nuclear Physics A; Associate Editor for Astrophysics of Reviews of Modern Physics; Member of the Swiss Commission for Astronomy SCFA (2007-); Member and Head of the Board, Competence Center in Computational Sciences, Univ. Basel (since 2009/2011); Member of Program Advisory Committee, RIKEN Radioative Beam Facility, Wako, Japan; Member of Advisory Committee, EMMI (ExtreMe Matter Institute) of the Helmholtz Foundation

4 Research Projects

4.1 Stellar Evolution and Supernovae

Evolution and Death of Massive Stars

The Evolution of intermediate mass and massive stars with large-scale nuclear reaction networks (including s- and p-process) and with the aid of reaction rates for the strong, electromagnetic and weak interaction developed in Basel (capture of nucleons and nuclei, electron capture and beta-decay, neutrino scattering on nuclei). Evolution of stars to the final stages of Fe-core collapse (one of the very few world-wide efforts); stellar evolution including rotation, mass loss and magnetic fields; estimates of black hole formation and gamma-ray burst progenitors from such evolution calculations as a function of stellar metallicity.
Major achievements: Predicting s- and p-process abundances from a fully consistent treatment with large nucleosynthesis networks throughout stellar evolution and the supernova explosion; stellar evolution of massive stars with rotation (s-process via primary ^{22}Ne at lowest metallicities, pre-supernova models, predicting black hole formation and gamma-ray burst rate as a function of metallicity). (U. Battino, K. Ebinger, U. Frischknecht, R. Hirschi, M. Pignatari, T. Rauscher, F.-K. Thielemann)

Supernovae and their Nucleosynthesis

Self-consistent core-collapse supernova calculations with general relativistic radiation hydrodynamic and complete neutrino transport of all flavors, solving the Boltzmann transport equation; long-term neutrino wind simulations and resulting nucleosynthesis; tests of core-collapse supernova models with different nuclear equations of state and QCD-phase transition caused explosions; 3D simulation with isotropic diffusion approximation for neutrino transport: first modeling of core collapse with MHD and rotation; analysis of the resulting burning products from the innermost ejected zones, like ^{44}Ti, ^{56}Ni as well as the element ratios Mn, Cr, Co, V, Sc, Cu, Zn/Fe; analysis of the abundances of Sr, Y, Zr and the light p-process elements Mo and Ru as a function of the neutrino and anti neutrino flux (νp-process); r-process calculations for the neutrino wind in the late phases of a supernova; gravitational wave emission, testing of jet explosion models with rotation and magnetic fields; nucleosynthesis in self-consistent 3D Type Ia supernova models, including the inner zonen which produce neutron-rich Fe-group nuclei and are strongly affected by electron capture on protons and nuclei.
Major achievements: First detailed nucleosynthesis results from 3D type Ia supernova models; discovery of a proton-rich environment in the innermost core-collape supernova ejecta due to the influence of neutrino and anti-neutrino irradiation and its influence on the production of Cu and Zn as well Sr, Y, Zr and light p-process elements (νp-process); nucleosynthesis and weak r-process in QCD-phase transition caused supernova explosions; r-process in jet ejecta from core collapse with rotation and magnetic fields. (A. Arcones, M. Eichler, R. Käppeli, M. Liebendörfer, N. Nishimura, T. Rauscher, F.-K. Thielemann, C. Winteler)

4.2 Compact Stars in Binary Systems

Nuclear Burning in Accreting White Dwarfs and Neutron Stars

Hydrogen accretion onto white dwarfs and test for He-shell flashes (like in AGB stars) which could produce a highly s-processed initial composition for later type Ia supernova

explosions; hydrogen accretion onto white dwarfs or neutron stars with either stable hydrostatic burning or thermonuclear ignition (novae or X-ray bursts), including the modeling of resulting energy generation and composition changes; surface composition of possible ejecta; dependence of explosive burning on nuclear uncertainties far from stability at the proton drip-line (proton capture rates, beta-decay rates, nuclear masses); inclusion of deeper layers of the neutron star to test the influence of partially burned matter (from previous bursts) to analyse the cause of so called superbursts.
Major achievements: Preparing typa Ia supernova progenitor models; Predicting the upper end of the rp-process in realistic X-ray burst models, explaining observed X-ray burst lightcurves with multiple peaks as a result of nuclear waiting points in the rp-process path. (U. Battino, S. Fehlmann, A. Hujeirat, M. Pignatari, T. Rauscher, F.-K. Thielemann, C. Winteler)

Neutron Star-Mergers

Modeling neutron star mergers in binary stellar systems via smooth particle hydrodynamics (SPH) in 3D; implementation of sophisticated neutrino leakage schemes; including the feedback of nuclear energy generation consistantly into the hydrodynamic modeling; variations of the nuclear equation of state and predictions of gravitational waves as well as the mass of ejecta (possible r-process source?).
Major achievements: gravitational wave signal differences for equations of state with and without the quark-hadron phase transition; explanation of lightcurves due to continuous (r-process) energy generation in ejecta and fallback. (A. Arcones, M. Eichler, I. Panov, A. Perego, T. Rauscher, F.-K. Thielemann, C. Winteler)

4.3 Chemical Evolution of Galaxies

Evolution of element abundandances in our Galaxy as a function of metallicity with the aid of chemical evolution models as a constraint for ejecta abundances of core-collapse and Type Ia Supernovae as well as neutron star mergers; very early galactic evolution and mixing of stellar winds and explosive ejecta in order to understand LEPP, p-process and νp-process contributions; analysis of abundance variations in (very) low metallicity stars; interpretation of the results with respect to Fe-group ejecta from type II supernovae as a function of progenitor mass; test for the origin of r-process nuclei via the r/Fe scatter as a function of metallicity (supernovae - including jet ejecta - vs. neutron star mergers).
Major achievements: explaining features in very early galactic evolution via wind ejecta of rotating low-metallicity stars; understanding p-process and νp-process contributions to LEPP abundances; finding an r-process source with rotating core collapse supernova models and high magnetic fields which can explain very low metallcity r-process observations. (U, Frischknecht, R. Käppeli, I. Panov, M. Pignatari, T. Rauscher, F.-K. Thielemann, C. Winteler)

4.4 Nuclear Properties for Astrophysical Applications

Nuclear Reactions and Nuclear Structure

Calculations of nuclear cross sections for stable and unstable targets with neutrons, protons, α-particles and nucleus projectiles, applying the statistical model for compound nucleus reactions or the direct reaction mechanisms; prediction of nuclear properties which are needed for such calculations, e.g. the level density of excited states, their corresponding parity distributions, optical potentials, energy and width of giant resonances ..; test of optical potentials with experimentally determined strength functions for neutrons, protons and α-particles; introduction of consistent methods to describe isospin mixing; investigations of nuclear fission rates and the chance to produce superheavy nuclei; employing mass models with correlations for nuclei far from stability.
Major achievments: Involvement and theoretical analysis of neutron-induced reactions from the N-ToF experiment at CERN, s- and p-process reactions, applying a parity-dependent level density treatment and microscopic descriptions of low-lying giant dipole

resonance strength; the prediction of neutron-induced fission for a large set of nuclei in r-process applications. (M. Eichler, I. Panov, T. Rauscher, F.-K. Thielemann, C. Winteler)

Nuclear Equation of State

Constraining with the recent observation of the pulsar PSR J1614-2230 with a mass of 1.97 ± 0.04 $M_\odot$ gives the quark and nuclear matter equations of state (EoS); taking into account effects from the strong coupling constant and color-superconductivity; hybrid stars, i.e. compact stars with a quark matter core and a hadronic outer layer: utilizing chemical equilibrium abundance distributions for the nuclear part of the EoS and testing the effect on electron captures during core collapse,
Major achievement: Prediction of high density EoS properties for test in core collapse supernovae and the influence of electron captures on an equilibrium sample of nuclei (rather than one average nucleus as generally used). (M. Hempel, M. Liebendörfer, F.-K. Thielemann)

Nuclei far from β-Stability and the rp- and r-Process

Nuclear properties (nuclear structure, masses, decay properties, fission) of unstable nuclei, which are either very neutron or proton-rich; utilization of these properties in nucleosynthesis calculations for the production of heavy elements via rapid neutron capture (r-process); the effect of neutron-induced fission and beta-delayed neutron emission on r-process abundances: solar abundances as a test for nuclear structure far from stability; tests for the quenching of shell closures far from stability; application of the properties of proton-rich nuclei in the νp-process of core collapse supernovae; application of the properties of proton-rich nuclei for explosive hydrogen burning (rapid proton capture, i.e. rp-process) in novae and X-ray bursts after the accretion of hydrogen envelopes onto white dwarfs or neutron stars in binary stellar systems.
Major achievements: Modeling the νp-process in realistic core collapse environments and its sensitivity to nuclear properties far from stability; modeling the r-process in realistic neutrino wind environments and jet ejecta or core collapse supernova and the inclusion of neutrino-induced reactions. (I. Panov, T. Rauscher, F.-K. Thielemann, C. Winteler)

5 Master Theses, Dissertations, Habilitations

5.1 Master Theses

completed:

M. Eichler: r-Process in Supernova Neutrino Winds;
K. Ebinger: Induced Supernova Explosions;
S. Fehlmann: Magneto-rotational instabilities M. Ruch: Optical Potentials for Heavy Nuclei.

ongoing:

O. Heinimann: The Equation of State of Neutron Stars;
J. Reichert: Minimum Nuclear Networks for X-ray Bursts;
B. Wehmeyer: The r-Process in Chemical Evolution of Galaxies.

5.2 Dissertations

completed:

U. Frischknecht: The s-Process in Core He-Burning of Massive Stars;
R. Käppeli: Jets in rotating Supernovae;
S. Scheidegger: Gravitational wave emission from core collapse supernovae
C. Winteler: r-Process in Supernovae.

ongoing:

U. Battino: Type Ia Supernova Progenitors from White Dwarfs Accretion Models;
K. Ebinger: Core Collapse Supernovae in 3D;
M. Eichler: r-Process in Neutron Star Mergers and Polar Jets;
S. Fehlmann: Accretion onto Neutron Stars;
M. Frensel: Collective Neutrino Oscillations in Supernovae;
A. Perego: Neutron star mergers;

6 Organized Conferences, Joint Research Projects with Outside Groups

6.1 Conferences, Workshops, Cooperations

see output data

6.2 Research Projects and Collaborations with Outside Groups

The research projects of section 4 are carried out in collaboration with the following research groups and individuals:

- 4.1: T. Foglizzo (CEA, Saclay), C. Fröhlich (U. of North Carolina), R. Hirschi (U. of Keele), R. Hix (Oak Ridge National Lab.), R. Hoffman (Livermore Natl. Lab.), K. Kotake (Waseda University), G. Martinez-Pinedo, K. Langanke (GSI Darmstadt), G. Meynet (Observatoire de Genève), A. Mezzacappa (Oak Ridge National Lab.), K. Nomoto (U. of Tokyo), U.-L. Pen (CITA, Toronto), A. Perez-Garcia (University of Salamanca), S. Rosswog (Jacobs University Bremen), J. Schaffner-Bielich (U. of Heidelberg), C. Thompson (CITA, Toronto).

- 4.2: D. Blaschke (University of Wroclaw), J. Fisker (Livermore National Laboratory), I. Panov (ITEP Moscow), S. Rosswog (Jacobs University Bremen) J. Schaffner-Bielich (U. of Heidelberg), H. Schatz (Michigan State Univ.),

- 4.3: J.J. Cowan (U. of Oklahoma), R. Qian (U. of Minnesota), J.W. Truran (U. Chicago), C. Vockenhuber (ETH Zürich), A. Wallner (U. Wien).

- 4.4: Y. Alhassid (Yale Univ.), J. Görres (U. of Notre Dame), F. Käppeler (FZ Karlsruhe), P. Koehler (Oak Ridge National Lab.), I. Korneev (ITEP Moscow), K.-L. Kratz (U. Mainz), K. Langanke, G. Martinez-Pinedo (GSI Darmstadt), N. Özkan, (U. Kocaeli), I. Panov (ITEP Moscow), B. Pfeiffer (U. Mainz), E. Somorjai (Atomki Debrecen), S. Typel (GSI Darmstadt), M. Wiescher (U. of Notre Dame)

In addition there exist larger research cooperations which are listed in section 7.3.

7 Contributions to Conferences and Colloquia, Membership in Cooperations

7.1 Conferences and Workshops

7.2 Colloquia and Seminar Talks

see output data

7.3 Cooperations

T. Rauscher is Member of the n-TOF Collaboration at CERN (PS-213)

EXL The research group Nuclear Astrophysics is Member (node) in the EU research network EURONS/EXL within the 6th European Framework program.

CARINA The research group Nuclear Astrophysics is Member (node) in the EU research network EURONS/CARINA within the 6th European Framework program.

THEXO The research group Nuclear Astrophysics is Member (node) in the EU research network ENSAR/THEXO within the 7th European Framework program.

SCOPES, The research group Nuclear Astrophysics undertakes investigations jointly with the Observatoire de Geneve, the Institute for Experimental and Theoretical Physics (ITEP) in Moscow, and the Astronomical Institute of the University of Odessa within the framework of the SCOPES Program of the SNF (Project “The Role of Neutrons and Neutrinos in Supernovae”).

The research group Nuclear Astrophysics is a Participating Research Institution within the Joint Institute for Nuclear Astrophysics (JINA, funded by the US NSF).

ESF Research Network “The New Physics of Compact Stars”, this network was selected in February 2008 by the ESF (until 2013). The Basel reseach groups are contributing in a prominent way.

ESF Research Program ”EuroGENESIS: Origin and Evolution of the Elements in the Universe”. The research group Nuclear Astrophysics is represented by two project leaders of collaborative research projects: I. Cherchneff (CoDustMas), F.-K. Thielemann (MASCHE)

b) Results published and c) Results in press

8 Publications

8.1 in Journals

published:

8.2 Conference Proceedings

published:

8.3 Popular and other Publications

see output data

9 Miscellaneous

M. Liebendörfer obtained an offer for a full professorship at the University of Frankfurt

I. Cherchneff an T. Rauscher received the ”Goldene Kreide” for their teaching by the students of the Department in the fall terms 2010/2011

S. Scheidegger received the faculty prize 2011 for best thesis of the Natural Sciences Faculty in 2010

A. Arcones received a Helmholtz Young Investigator Award and will start her own research group at the University of Darmstadt in 2012

F. Thielemann received the Lise Meitner Prize of the European Physical Society in 2012

Friedrich-Karl Thielemann, Matthias Liebendörfer, M. Pignatari, Thomas Rauscher