



# CompOSE

## A repository of equations of state for astrophysical applications

Stefan Typel<sup>1,2,a</sup>

<sup>1</sup> Institut für Kernphysik, Technische Universität Darmstadt, Fachbereich Physik, Darmstadt, Germany

<sup>2</sup> GSI Helmholtzzentrum für Schwerionenforschung GmbH, Theorie, Darmstadt, Germany

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**Abstract** CompOSE is a data base of equations of state (EoS) with detailed information on the thermodynamic, compositional and microscopic properties of dense matter that can be used in astrophysical simulations. It is available online and hosted by the Observatoire de Paris at Meudon. The development and main features of CompOSE are presented in this overview. Besides the furnishing of data tables in various EoS categories using a specific, flexible format, computational tools are provided to extract and manipulate the stored data either by employing codes for download or through a web interface. Comprehensive documentations of the EoS models with links to the original literature and an extensive manual are available. Prospects for the future development are indicated.

### 1 Introduction

The evolution and fate of heavy stars with masses above 8–10 solar masses is a challenging problem in numerical astrophysical simulations, see, e.g., [1–14]. These model calculations rely on the knowledge of several branches in physics, in particular the microphysics of strongly interacting matter. A detailed description of core-collapse supernovae, the formation of compact stars and their merger in binary systems requires information on the thermodynamic properties and chemical composition of matter, on microscopic quantities such as potentials of particles, transport properties and potentially reaction rates in these dynamical processes. The expression ‘equation of state’ (EoS) is commonly used to denote such a collection of thermodynamic data and thus not in the strict thermodynamic sense.

The main challenge of constructing models for the EoS is to cover a broad range of primary variables, in particu-

lar densities and temperatures, using appropriate degrees of freedom and interactions. Temperatures and densities vary over several orders of magnitude and the composition of matter changes considerably, possibly with phase transitions. Values of temperature  $T$  and baryon density  $n_b$  typically lie in the intervals  $0 \text{ MeV} \leq T \lesssim 100 \text{ MeV}$  and  $10^{-14} \text{ fm}^{-3} \lesssim n_b \lesssim 10 \text{ fm}^{-3}$ , respectively. Also the isospin asymmetry of the system can vary within certain limits. This is often specified by the electron fraction  $Y_e$  that usually assumes values between 0 and approximately 0.6. Thus global, multi-purpose EoS are needed in astrophysical applications. In most cases, phenomenological approaches in the framework of density functionals are used in the development of EoS models that are guided by experience and information from theory and experiment. For a detailed discussion of EoS for astrophysical applications see, e.g., the review [15] and contributions in this topical issue.

For many years, astrophysical simulations utilized EoS data from only a small set of models that were available at that time. These EoS were provided in tabular form or as computer code and gave the basic thermodynamic and compositional data needed in the applications. Most well known are the early EoS by Hillebrandt, Nomoto and Wolff [16], the EoS by Lattimer and Swesty [17] with an option to select the stiffness of nuclear matter, and the tables by Shen, Toki, Oyamatsu and Sumiyoshi [18, 19]. In the subsequent years many new models for the EoS were developed with considerable improvements in the physical description, the number of provided quantities, and the resolution and extend of the tables. However, the data were distributed over many places in different formats that made a direct and easy usage difficult, e.g., for comparative studies. It became clear that a coordinated effort of the community was inevitable to establish a central EoS repository.

In this contribution to the topical issue on CompOSE the main features of the EoS repository will be described. The

<sup>a</sup> e-mail: [stypel@ikp.tu-darmstadt.de](mailto:stypel@ikp.tu-darmstadt.de) (corresponding author)

presentation starts with a short historic overview in Sect. 2. The following Sect. 3 gives details on the tabulation scheme, the stored quantities and data files that accompany each EoS. Computational tools to handle, customize and extract data for personal use are summarized in Sect. 4. The online tools and services are depicted in Sect. 5 together with the provided means of documentation. Finally, a summary and outlook to future developments are given in Sect. 6.

## 2 History of CompOSE

First developments of a centrally managed data base for EoS were substantially facilitated by the Research Networking Programme ‘The New Physics of Compact Stars’ (CompStar) funded by the European Science Foundation (ESF) from February 2008 to February 2013 [20]. Following the suggestion of the CompStar founding members David Blaschke and Luciano Rezzolla, a project with an initial group of interested people was established with Micaela Oertel, Thomas Klähn and the author as core team and David Blaschke, Tobias Fischer, Matthias Hempel and Daniel Zablocki as support team. The format of the data tables and their usage with a specially designed computer code were discussed and specified. A first website was developed for the public access to the data, originally hosted at the Institute of Theoretical Physics at the University of Wrocław. The project became known as **CompOSE = CompStar Online Supernovae Equations of State**. The status and development was reported at several workshops, e.g., at Caen, Darmstadt, Rostock. A first manual with all details on the EoS tables and their usage was prepared in 2013 and finally published [21].

The CompOSE project received further support for development from the COST Action MP1304 ‘Exploring fundamental physics with compact stars’ (NewCompStar) within the European Union framework program [22,23] that officially started in November 2013 and ended four years later. The support of CompOSE with dedicated working groups and workshops continued with the subsequent COST Action PHAROS (CA16214) ‘The multi-messenger physics and astrophysics of neutron stars’ [24,25] that began in November 2017 and will finish in May 2022. The website [26] moved to the Laboratoire Univers et Théories (LUTH) [27] at the Observatoire de Paris, Meudon (OBSPM) [28] as permanent host and the number of entries in the EoS repository substantially increased. The EOSDB project by Chikako Ishizuka was incorporated and further functionalities were added with the help of Jérôme Novak, Marco Mancini, Jean-Yves Giot, and Mathieu Servillat. It is now possible to calculate user-defined EoS tables online and to view and manipulate diagrams that depict the dependence of selected quantities.

## 3 Repository of EoS data

The CompOSE data base [26] comprises EoS tables of different type using a flexible scheme to store a large variety of quantities. It was developed to allow future extensions without the need of complete revisions. The main focus is on global, general purpose EoS tables that can be used in the simulation of dynamical scenarios such as core-collapse supernovae and neutron-star mergers. Furthermore, less extensive tables of lower dimension are provided for cold matter, pure neutron matter and neutron star matter. These are partly subsets of global tables for specific conditions, e.g., zero temperature, charge neutrality, or  $\beta$  equilibrium.

There is no limitation on the theoretical models that can be employed to construct EoS tables for the CompOSE repository. However, some models are only applicable in limited ranges of the primary variables and not all types of EoS tables can be provided by them. There is a clear difference between simple parametrizations, e.g., of polynomial form for thermodynamic quantities, and truly microscopic models which can give much more detailed information on various properties of the system.

The details of every EoS are stored in dedicated tables with a defined structure, on the one hand related to the discretization scheme and on the other hand related to the type of quantities that can be calculated in the selected EoS model. Here only the main characteristics of the tables are discussed. Their exact structure is given in the CompOSE manual available from the web site [26].

The format of the EoS tables for cold neutron star matter can be used directly to construct neutron star models with LORENE (Langage Objet pour la Relativité Numérique) [29], which was developed to solve problems in numerical astrophysics, using the new C++ class eos\_compose.

In the most general case, there are three quantities in the space of variables that define a point in an EoS. They are chosen as the most commonly used quantities: the temperature  $T$ , the baryon density  $n_b$  and the hadronic charge fraction  $Y_q$ , which is the ratio of the charge density  $n_q$  of the hadronic component of the system to the baryon density  $n_b$ . In contrast to the electron fraction  $Y_e = n_e/n_b$  with the net electron density  $n_e$ ,  $Y_q$  is also available in systems without electrons, e.g., nuclear matter. The actual values of the three variables are stored in three files: eos.t, eos.nb, and eos.yq for  $T$ ,  $n_b$ , and  $Y_q$ , respectively. They are referenced by integer numbers  $i_T$ ,  $i_{n_b}$ , and  $i_{Y_q}$  that serve as indices to define the discretization grid and appear again in the files that contain the actual EoS data. The variables are given in the usual units as used in nuclear physics, i.e., MeV and  $\text{fm}^{-3}$  for  $T$  and  $n_b$ , respectively. The hadronic charge fraction  $Y_q$  is dimensionless by definition.

All EoS data are collected in up to three separate files eos.thermo, eos.compo, and eos.micro. The main

principle of the data format is that each row in these files gives the information of a single point in the space of primary variables. Correspondingly, the first three entries in a row are the indices for  $T$ ,  $n_b$ , and  $Y_q$  followed by the actual EoS data. Only the first row in `eos.thermo` has a different form containing some general information, i.e., neutron and proton masses, and information whether charged leptons are included in the calculation or not.

For all EoS models only the file `eos.thermo` is mandatory. It contains the minimal thermodynamic information of an EoS given by seven quantities:

- the pressure-baryon density ratio  $Q_1 = P/n_b$ ;
- the entropy per baryon  $Q_2 = s/n_b$  with the entropy density  $s$ ;
- the scaled and shifted baryon chemical potential  $Q_3 = \mu_b/m_n - 1$  with the neutron mass  $m_n$ ;
- the scaled charge chemical potential  $Q_4 = \mu_q/m_n$ ;
- the scaled lepton chemical potential  $Q_5 = \mu_l/m_n$ ;
- the scaled and shifted free energy per baryon  $Q_6 = f/(n_b m_n) - 1$  with the free energy density  $f$ ;
- the scaled and shifted internal energy per baryon  $Q_7 = e/(n_b m_n) - 1$  with the internal energy density  $e$ .

Further thermodynamic data can be added if required. Quantities  $Q_2$  to  $Q_7$  are dimensionless and the ratio  $Q_1$  is just the temperature if the EoS is that of an ideal gas.

Information on the chemical composition of matter is given in the optional file `eos.compo` that can only be provided by models that consider individual degrees of freedom, e.g., nucleons, hyperons, nuclei, electrons and muons, explicitly. The data storage follows again a specific scheme. In models with phase transitions, the different phases can be identified with a corresponding index. For each particle species a pair of two numbers is given: (1) an index that identifies the particle, see the manual with the corresponding table of definitions, and (2) the density fraction  $Y_i = n_i/n_b$  with the particle number density  $n_i$ . For systems at finite temperature,  $n_i$  is usually the net particle density, i.e., the difference of particle and antiparticle densities. For sets of particles, e.g., a group of nuclei, also average quantities can be stored. Here a quadruple of numbers is given: (1) an index defining the set, (2) the average mass number, (3) the average charge number, and (4) the density fraction. The precise definition of these quantities can be found in the manual.

Microscopic data of a specific EoS model are collected in the optional file `eos.micro`. Here a variety of quantities can be stored. Most common are effective masses and various types of potentials for individual particles. In each case a pair of two numbers is given. The first is an index that combines the identification of the particle with that of the quantity. The second is the actual value of the quantity.

Besides the files defining the grid of variables and that containing the numerical data, a PDF file `eos.pdf` is available

for each EoS. It includes a short description of the model, characteristic nuclear matter parameters, neutron star properties if available, a list of references and further information that is needed to interpret the stored data. All files mentioned above are collected in a single archive file `eos.zip` that can be downloaded easily from the CompOSE website [26].

#### 4 Tools for data handling

The EoS tables can be downloaded and used as stored in the repository and every user can extract herself/himself the data relevant for applications in her/his project. However, it is possible to customize the data for personal use with the help of computational tools either by using the available FORTRAN90 routines or by running the software online via a web interface. The original EoS tables are usually large and require considerable memory space. All information is not always needed and tables of smaller size are often sufficient. The range of the variables  $T$ ,  $n_b$ , and  $Y_q$  can be adjusted as well as the resolution of the grid by interpolating the data using different orders, i.e., continuous in the data or their first or second derivatives. Selected quantities from the tables can be extracted or additional derived quantities, e.g., the adiabatic index or the speed of sound, can be calculated from the original data. A tabulation as function of the temperature can be replaced by one as function of the entropy per baryon within the limits given by the original data. Also the EoS under the condition of  $\beta$  equilibrium can be extracted from global, multi-purpose tables.

The FORTRAN90 code together with subroutines and modules as well as a makefile are combined in an archive file `code.zip`. After unpacking and compilation using, e.g., the GNU compiler `gfortran` and the GNU Make utility [30], the program `compose` can be used directly when the EoS data files are included in the same directory. There is an option to switch from the standard ASCII format of the output files to a HDF5 format. The actual calculation of the customized EoS table proceeds in three steps. In a first run of `compose` the data tables are analyzed, the extracted information is stored in auxiliary files, e.g., `eos.init`, and the desired output quantities can be selected by the user. A second run of `compose` allows to define the range and discretization scheme of the variables and the interpolation order. Information on the output quantities and tabulation scheme are stored in the files `eos.quantities` and `eos.parameters`, respectively. They can be modified by the user according to her/his wish. A final run of `compose` generates the customized EoS table with file name `eos.table` for further usage. If possible, a file `eos.beta` is created with data needed to calculate the mass-radius relation of neutron stars. Additional information of the model properties, e.g., on nuclear matter parameters, can be found in the file `eos.report`.

Instead of calculating an EoS table with the `compose` code locally on a computer of the user, it is possible to generate such a table online with the CompOSE web interface and download the data afterwards from the server at the host institution in Meudon. This tool can be accessed directly from the specific detail page of every EoS in the catalogue by a simple click. However, the access is restricted and a login of the user is required. An account is easily obtained by sending an email with the request to `develop.compose@obspm.fr`. A password will be sent in reply. The input for the calculation can be specified by entering the required data in a web form. The dependence of quantities on the primary variables or other quantities can be visualized online with the possibility to adjust the graphical display.

## 5 Website and documentation

The CompOSE website [26] shows a clear and well-arranged structure when starting at the home page. The main panel gives some general introduction and asks to acknowledge CompOSE properly when used in studies. Links to specific detail pages via fold-out menus are given in the left margin. The following items are available there:

- an EoS section with an overview and a list of various EoS, which are classified in four families, i.e., cold neutron star EoS, cold matter EoS, neutron matter EoS, and general purpose EoS;
- a bibliography of the relevant literature with search function and links to the original publications and the corresponding EoS tables in the CompOSE data base;
- a section to download software and the manual;
- info on the subscription of a newsletter after joining the CompOSE mailing list;
- a collection of external links to other web sites with EoS data and software;
- information on how to contact the team of developers of CompOSE;
- a list of institutional supporters of CompOSE;
- access to accounts via login and the option to change the password;
- a list of jobs for generating EoS tables that were submitted via the web interface by the user (if logged in).

The navigation through the CompOSE web pages is easily accomplished by a few clicks.

Each EoS in the data base is accompanied by an extensive documentation. The web page of a specific EoS contains information on the grid, an abstract of the theoretical model, links to references with original works, a data sheet, all data files, a plot of the neutron star mass-radius relation (if available) and a button for online computations. A `LATeX` file of the data sheet with basic information can be created with the

dedicated C++ program `eosform.cpp` by every supplier of EoS tables.

All information with details on the structure of the EoS data files, the indexing method and the calculation procedures is collected in the CompOSE manual with more than 80 pages in its second version. It also contains values of physical constants and general remarks on the definition of various thermodynamic quantities and their relations. The manual is available as a PDF file for free download from the website [26].

The online bibliography serves as a valuable source of information linking particular EoS tables and models to the original publications.

## 6 Summary and outlook

The CompOSE repository of EoS tables for astrophysical applications is the result of a collective endeavor by the community of nuclear physicists and astrophysicists to establish a central web-based storage place of EoS data with easy access and practical tools to manipulate and analyze them. It was developed with ideas and contributions from many people and grew substantially in recent years with presently almost twohundred EoS entries of various type and scope. These are grouped into four major categories: cold matter EoS, cold neutron-star EoS, neutron matter EoS and general-purpose EoS.

A flexible data format was introduced for the storage of thermodynamic quantities, information on the composition of the system and microphysical data in corresponding data files. They can be downloaded from the CompOSE website and used as such or customized with the available routines or online tools. A detailed documentation is available for every EoS and access to the original publications is made possible via an extensive bibliography. All details on the use of CompOSE are documented in a comprehensive manual.

CompOSE is under continuous maintenance and development. Many improvements can be conceived. It is planned to widen the scope of the data base and to add more functionalities of the computer codes and web tools. New categories, e.g., ‘unified’ EoS, can be introduced and additional data, e.g., on transport properties and opacities, will be included since they are needed in various studies of compact stars and their evolution. EoS data from more diverse theoretical approaches have to be added. For an easier referencing of EoS tables, a unique scheme for the EoS names will be established. The computer code will be updated and more options for the extraction and handling of data will be added, e.g., by allowing certain cuts through the space of variables depending on pre-defined conditions. The interpolation scheme will be revised to avoid certain problems for rapidly varying quantities. An alternative representation of EoS data will be considered that

replaces tabulations on a grid by analytic functions which can accelerate the speed of calculations in numerical simulations. Suitable parametrisations for this dependence have to be designed. This approach requires the development of new computer programs that will be made available via the CompOSE web pages. The web site will offer more options to classify and select EoS that satisfy certain constraints, e.g., in regard to characteristic nuclear matter parameters or compact star properties. All modifications will be incorporated in future updates of the comprehensive manual. For suppliers and users of EoS data, more focused quick guides for the usage of CompOSE will be prepared. It can be expected that the CompOSE data base will be a helpful tool for many branches of nuclear physics and astrophysics in the future.

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