Chapter 1

Theory Part II (need to rename)

1.1 The 'Omega' model

OMEGA stands for 'One-zone Model of the Evolution of Galaxies' and evolves the isotopic content of a galaxy. The model is a one-zone model, which means that the entire galaxy is simplified to a single point. A zero-space-dimensional galaxy model seems unrealistic, but it can be imagined as the mean value for a three-space-dimensional galaxy model. Add reference to cote-paper

1.1.1 Process

The 'Omega' model emulates the chemical evolution of a galaxy by representing the initial primordial gas. A simple stellar population is created by integrating the star formation rate in time. The star formation rate is calculated either by using a constant star formation rate, the Kennicut-Schmidt law, or by using an input star formation rate and interpolate over those values.

The stellar populations represent a cluster of stars, with a total mass, initial mass distribution, and initial metallicity distribution. The initial mass distributions are given as one of the standard distributions, Salpeter, Kroupa, Chabrier, or a power-law, all between some minimum and maximum mass limit. The initial metallicity distribution is the mass of each single isotope tracked, then scaled to one to get the relative amount of each isotope.

Stellar evolution codes calculate the amount of ejected material, for each isotope, for a star with a given initial metallicity and initial mass. These codes are used to create **yield tables** for certain kind of stars with different initial mass and metallicity.

In the simple stellar population in the galactic chemical evolution model, these yield tables are used to calculate the chemical composition and mass of ejecta from a group of stars. The ejecta are disspersed back into the interstellar medium (gas of the galaxy model) at delay-times appropriate for each mass of star. E.g. For a given mass-bin the total mass of stars, number, and age of stars, with initial mass in that bin, are calculated using the total mass of the total stellar mass and mass function chosen. By choosing the yield tables closest in initial mass and initial metallicity the total ejecta composition is calculated and added to the interstellar medium at the age where those stars would have gone supernova. The material that is not ejected is left as remnants and total mass and number of remnants are also

added to the simulation at the time these stars would have gone supernova.

In 'Omega' the creation and treatment of simple stellar population is done by another python-program called |SYGMA—.

Another key effect that dictates chemical evolution is outflow and inflow. Outflow created from supernova feedback, active galactic nucleus, stellar kick or similar, and inflow from matter outside the galaxy into "box" that is our model. To describe the chemical evolution one needs to know the total content of the galaxy (or box) and the distribution. In other words, how much of the total mass is stored as each isotope. Material with the same composition as the box is ejected from the box, and material with another composition falls into the box.

The 'Omega' model is a *one-zone* model, meaning that everything inside the box has been enriched from stellar lifecycles. Everything outside the box is untouched since "it's creation", and has the same composition as the material inside the box had to start with. This composition is called the primordial composition (three parts hydrogen, one part helium and trace amounts of lithium and beryllium), and is derived from the big bang nucleosynthesis (add reference here or in theory part 1) . More on outflow/inflow

1.1.2 Uncertainty of parameters

uncertainty of parameters and summary of article (cote16a)

Galaxies consist of many different, widely varying, scales for both spatial and temporal resolution. Galaxies span hydrodynamical evolution on many kpcs and Gyrs, while their stars and supernovae span scales closer to seconds and meters. The nuclear processes within stars span nanometer and millisecond timescales, even though stars can last for billion years(with short timescale bursts in between). Simulations cannot cover all these scales at once, that is when subgrid methods are used. Stellar evolution simulations predict the fate and output from a stellar life based on input parameters. These solutions are then simplified and applied to more complex galaxy simulations. Output from stars are "looked up in a table" and applied to the nearby interstellar medium. All these methods and linked applications create some uncertainties, both physical and numerical, and these uncertainties are inherited through all methods based on applications of these models. In order to probe how these uncertainties manifest through the resulting galaxy evolution, this article presents a simple one-zone, closed-box model of galaxy evolution, called 'Omega'.

SYGMA creates the simplified stellar populations(mass function, total mass, lifetime distribution, initial metallicity). OMEGA combines several stellar populations to emulate a galaxy evolution.

Stellar yields are tables from stellar evolution simulations. The tables used in OMEGA are taken from NuGrid and include AGB stars between 1 and 7 msol, massive stars between 12 and 25 msol, all with metallicities at 0.02, 0.01, 0.006, 0.001, 0.0001. These tables contain many isotopes between hydrogen and bismuth.

The stellar evolution was calculated with MESA, post-processing was done with MPPNP, the same nuclear reaction rates were used in all calculations, explosive nucleosynthesis was done with semi-analytical models. Yields are complemeted with SN1a yields from Thielemann and population III yields from Heger&Woosley.

The probability distribution functions are created from values and uncertainties in the literature. Methodologically there are, for each input parameter, gathered a list of literature values and uncertainties. The errors are considered gaussian in nature and distributions are created thereafter, all the distributions are then averaged to a single distribution. Then a single gaussian is fitted atop the "average of gaussians from the literature", and the median and standard deviation from the final fit is used as value and uncertainty for the input parameter in question.

The parameter space was sampled by running 300 simulations where each parameter was varied within their gaussian probability distribution. Then a set of 700 simulations where run with all parameters sampled randomly from their gaussian probability distribution. A final set of 300 simulations where also run with varying final stellar and gas mass.

The mass limits of the IMF generate little uncertainty.

Modifying final stellar-gas ratio, the uncertainty is manifested in low [Fe/H] values, because more stars produce more iron and and more gas means more hydrogen. However the relative ratio of ejecta is unchanged, meaning [X/Fe] are not affected. In the grand scheme, uncertainties from final stellar mass and gas mass are not significant.

Uncertainty in number of type 1a supernovae does not manifest as uncertainty in abundance until after delay time of those supernovae. The abundance has no uncertainty until [Fe/H] -1.5 associated with 150 Myr. The unusual low iron abundance (milky way is believed to have type 1a supernovae onset at [Fe/H] 1) is due to the closed-box approximation. Type 1a supernovae add mostly iron to the interstellar abundance, increasing [Fe/H],

decreasing [X/Fe]. CNO-elements that are not produced much in SN1a are most affected.

Slope of the IMF has the most effect, increasing it allows for more massive stars with quick and much ejecta. These stars quickly enrich the surounding gas.

Overall uncertainty is calculated by varying all parameters simultaneously. Since the previous analysis depended on the uncertainty of a single variable, while keeping the other parameters constant, this becomes only an estimate of the uncertainty. However it will grant some valueble insight into which parameter affects the uncertainty the most.

Parameters with the most impact: Slope of the IMF, total number of type 1a supernovae and final gas mass of galaxy.

Varying seven input parameters stochastichally and in a monte carlo type fashion. The main conclusions are:

1. Overall uncertainties between 0 and 0.6 dex. Metaliccity dependant uncertainties.

2. Mass of gas and stars affect the uncertainties below [Fe/H] -2, with the delay-time distribution and number of type 1a supernovae affect the uncertainties above [Fe/H] -1.5, slope of the IMF affects uncertainty at all metallicities.

3. Slope of IMF and number of type 1a supernovae affect uncertainty the most when plotting against metallicity. Uncertainty is greatest when cosidered element and reference element is not the same.

4. Features in [X/Fe]-[Fe/H] and [X/Mg]-[Mg/H] share the same characteristics. Such variations are mostly caused by stellar yields, type of galaxy and star formation history.

1.1.3 Relevant parameters

'Omega' has many input parameters, both numerical and physical in nature[1], to guide the evolution of the galaxy.

This section will describe the most relevant ones.

[1] A physical input parameters are model parameters, while a numerical parameter decides on which calculations to choose from and where to get data. E.g initial gas of galaxy is considered physical, while the boolean switch to turn on neutron star mergers are considered numerical.

galaxy This string option chooses predefined parameters to best match a certain galaxy on record. The relevant options are:

None No parameters determined.

milky_way_cte Set present dark matter mass to $10^{12} M_{\odot}$ and present stellar mass to $5 \times 10^{10} M_{\odot}$, and use a constant star formation rate of $1 \frac{M_{\odot}}{yr}$

milky_way Set present dark matter mass to $10^{12} M_{\odot}$ and present stellar mass to $5 \times 10^{10} M_{\odot}$, and use the star formation rate from Chiappini et al. (2001) add proper reference

dt Length of first timestep (in yrs)

special_timesteps Number of logarithmic timesteps

tend Final point in time (in yrs)

mgal Initial mass of gas (if not calculated by other means), defaults to $10^{10} M_{\odot}$

imf_type Which form to use for the initial mass function explain this somewhere .

sfh_array Two one-dimensional arrays, time and star formation rate, that `'Omega'`will interpolate over in order to find the star formation rate at a given time.

in_out_control Boolean switch to turn on or off inflow and outflow.

inflow_rate Constant inflow rate in $\frac{M_{\odot}}{yr}$. Gas with primordial composition (reference to BBN?) flows into the galaxy.

outflow_rate remove this? Constant outflow rate in $\frac{M_{\odot}}{yr}$. Enriched gas from the interstellar medium is removed from the galaxy.

mass_loading Fraction of solar masses ejected per solar mass created as star. A different way of calculating outflow based on star formation rate.

out_follows_E_rate Adds a time-delay to outflow with mass_loading such that outflow follows supernova rate.

transitionmass=8 Mass-limit that separates the AGB stars from the massive stars explain these stars somewhere . Defaults to $8M_{\odot}$

popIII_on Boolean switch that turn on or off the use of Population III stars

pop3_table Yield tables for population III stars

imf_bdys_pop3 The boundaries of the initial mass function of population III stars.

sn1a_on Boolean switch that turn on or off the use of type 1a supernovae.

nb_1a_per_m The number of type 1a supernovae per solar mass formed. Used to calculate the number of type 1a supernovae from star formation rate.

sn1a_table Yield table for type 1a supernovae

sn1a_rate This string option chooses which distribution to calculate the rate of type 1a supernovaefrom. Options are powerlaw, gaussian, and exponential distribution.

- **beta_pow** Set the power of the power law distribution if 'sn1a_rate' is "power_law"
- **gauss_dtd** Set the mean and standard deviation of the gaussian distribution if 'sn1a_rate' is "gauss"
- **exp_dtd** Set the e-folding time of the exponential distribution if 'sn1a_rate' is "exp"

ns_merger_on Boolean switch to turn on or off binary neutron star mergers

bhns_merger_on Boolean switch to turn on or off black hole neutron star mergers

nsmerger_table Yield table of binary neutron star mergers

nb_nsm_per_m Set the number of neutron star mergers per solar mass formed as stars.

t_nsm_coal Set the time after which all neutron stars collide/merge

nsm_dtd_power Set the powerlaw distribution of the neutron star merger delay-time distribution explain this somewhere .

f_merger Fraction of binary systems that eventually merge. All systems are considered binary. This is instead of 'nb_nsm_per_m'

m_ej_nsm solar masses ejected per neutron star merger.

1.2 Smooth particle hydrodynamics

Particle physics can be simulated by calculating the forces acting on each particle, then using newtons second law to get the acceleration of each particle. By integrating in time, with a large variety of numerical methods, the acceleration will give correction to the velocity in the next timestep. In a similar fashion the velocity of each particle will give the position in the next timestep. Examples of such numerical methods are Euler's method, Euler-Cromer's method, Velocity Verlet, Runge-Kutta 4. Numerical particle physics approximates all matter to discrete points in time and space. Due to limited numerical capabilities, and the sheer scale of astronomical dimensions it will not be able to resolve an entire galaxy.

Alternatively to representing a galaxy by many discrete points, is representing a galaxy as a meshgrid of average physical properties. This meshgrid holds physical properties like density, pressure, velocity and internal energy. Flow of mass and energy between the gridspaces is done according to hydrodynamics.

Smoothed particle hydrodynamics represent an effort to combine the two different approaches. Point particles representing a sphere of gas/stars/dark matter with a kernel function to extend the sphere around the point particle. The kernel function is historically represented by a gaussian, but for numerical ease modern methods use a spline-function that is zero outside a given range. Hydrodynamical effects on a particle from another nearby particle is given by the overlapping kernel functions, which represent a higher density/pressure/internal energy region. The hydrodynamical equations then govern change in velocity and temperature.

Tree-structure method:

If a group of bodies is far away from an observer, the sum force of each body is similar to force to the mass-center with a mass equal to the sum of indivdual masses. This is exploited numerically by splitting the point particles into "trees" where the force on one body from a group of smaller bodies far away is given by the distance to the mass-center of said group and the sum of masses. Numerically this is done by calculating the mass-center of all bodies, then splitting the simulation in two sections with equal number of particles and calculate the mass-center of these two sections. This process is repeated iteratively until a single body/point particle is left. In other words; the "tree" tretches into many "branches" with a single particle at the end of each branch. Nearby particles are also grouped together into "leaves". When

calculating the force acting on a single particle one calculates the force from each neighbour, but as the distance increases the mass-center for a large "branch" is used instead of all individual "leaves".

Gasoline:

Gasoline is a parallelized tree-smoothed-particle-hydrodynamics code that is designed to be modular and easy to apply to many different systems. "Astrophysicist have always been keen to exploit technology to better understand the universe."(add citation). Gasoline tracks particles with a selfgravitating sphere of density, represented by a kernel function around the particle, extending a certain distance from the particle. The code builds a tree to connect all the particles, in order to calculate gravitational forces more efficiently. The tree is also reproduced to calculate periodic boundary conditions more efficiently.

The simulation consists of four separate layers; the master layer, the processor set tree, the machine dependant layer, and the parallel K-D layer. The Master layer handles all code and processors, the processor set tree handles processes and information flow. The machine dependant layer is a short piece of code to handle function calls and memeory sharing for various machine setups. The last layer is where all the interactions and calculations are made. This means that the simulation is easy to modify for different machine architectures and can take many different physical effects into account without diving deeply into the entire workings of the code.

Particle hydrodynamics is only relevant when two smoothing kernels (representing the extension of gas) overlap. When the edges of two kernels start overlapping, the density and pressure the kernel represent increase causing a repulsive force from the hydrodynamical equations of motion and continuity.

Cooling in gasoline Energy transport in Gasoline can follow a wide range of procedures, like adiabatic and isothermal cooling processes, hydrogen/helium cooling processes with ionization fractions in addition to ultraviolet feedback from star formation and cosmic background.

Timestepping in gasoline With many different timescales originating from the large density variations, as well as different processes. Using a constant timestep in the integration, the velocity and other hydrodynamical quantities are updated within half of this timestep. The position on the other hand is updated to one full timestep while the the rest of qunatities are integrated for another half-step to catch up. This process of splitting up steps is repeated if necessary in the so-called Kick-Drift-Kick timestep scheme.

1.3 'Eris'simulation

'Eris' is a N-body/smooth particle hydrodynamics simulation of a galaxy forming in ΛCDM cosmology. The simulation consist of dark matter particles and baryonic gas particles. Star particles are created when the number density passes 5 atoms cm^{-}3. Feedback from an active galactic nucleus is neglected, but supernova-feeback is considered along with cosmic UV background and radiative cooling.

Some properties of the simulated galaxy:

- rotaional disk with scale length $R_d = 2.5kpc$
- "gentle" rotation curve with circular velocities at 2.2 scale lengths
- i-band (infrared wavelength 806 nm, bandwidth 149 nm) bulge-to-disk-ratio of $B/D = 0.35$
- baryonic mass fraction inside halo is 30% lower then cosmic average
- thin disk with typical HI-stellar mass-ratio
- disk is forming stars in $\Sigma_{sfr} - \Sigma_{HI}$ plane
- disk falls on photometric Tully-Fisher relation and stellar mass - halo virial mass relation
- structural properties, mass budget, and scaling relations between mass and luminosity matches several observational constraints

In galactic simulations there is an "angular momentum problem". This refers to baryonic components having much less rotaional spin in simulations than real observations. This failure was believed to arise from friction moving angular momentum from sub-structures to outer halo when these sub-structures merge causing the cold clumps of gas to fall to the center. In newer times this problem have been attempted solved with energy injected from supernovae, meaning evolving stars from the gas content to decrease the effect of cooling and removing angular moment from the center of the galaxy. Star formation in the disk comes from inflow of cold baryonic gas that was never shock heated to virial temperature. INSERT S0...-GALAXY-SHEET.

Yet the simulated galaxies have more centered baryon components and reproduce only S0 and Sa type galaxies. With two major exceptions there

are no simulations of type Sb and Sc, one exception with low star formation and another with low mass.

This paper presents a realistic simulation of a Milky Way type galaxy using a new smotth particle hydrodynamic cosmological simulation. It includes radiative cooling, cosmic UV heating, supernova feedback, and high-density star formation requirement(which is believed to be a key ingridient.

The high threshold for star formation is important to create non-centered galaxies

In Shen 15 (insert proper citation) the simulation data from 'Eris' is post-processed to include, not only oxygen adn iron, but also europium from neutron star mergers.

By using the 'Eris' simulation**?**, the chemical evolution of the milky way is studied. 'Eris' traces oxygen and iron from supernovae and in this work, postproduction traces neutron star mergers and the europium ejected from them post-merger. r-process abundance is traced in the milky way proxy by the [Eu/Fe]-ratio. The study shows that the heavy products of neutron star mergers can be incorporated into early stars, even if the shortest neutron star mergers is 100 Myr.

The conclusion of the study does not vary much with delay-time and merger rate and an argument is made for neutron star mergers being the dominant r-process source in the galaxy.

Looking at very metal poor stars in our Galaxy, which have been around for a long time. r-process abundances can be found. Meaning that the source of r-process has been around for a long time, and in a robust manner. However, the large variations show that the process was unhomogenous for early times, while it is moore smoothed after many Galactic rotations and repeated events. The two main regions of producing these heavy r-process elements are in the merger of two neutron stars (or the merger between a neutron star and a black hole) or in a heavy core collapse supernova. The production yields are much larger for neutron star mergers, but they are also much more rare. (Important citations Takashi94 and Woosley94 for SNII; Lattimer 77 and Freiburghaus 99 for NSM)

The neutron star mergers are described by delay-time distribution, merger rate, yield of r-process elements, the spatial distribution of events. The delay-time distribution is modelled by a power-law, $P(t) \propto t^{-n}$, from some minimum timescale to the hubble-time(end of simulation). Each neutron star merger is assumed to created some mass of r-process material, only a fraction of this material will be europium(which is used as the tracer). The

ratio of europium to r-process material is assumed to be solar(Sneden 2008), while the merger rate is calculated from scaling the star formation integral until europium-oxygen ratio equals solar ratio.

The neutron star merger events are set to occur near the stellar distribution, and since the kinetic energy outout is not large compared to supernovae the gas dynamics is unaffected. In simple terms, the neutron star mergers are injected in stellar regions and therefor drown in the bright, explosive environment of larger supernovae.

Using the time evolution of the star formation rate, the neutron star merger events are injected at random star-particles (simple stellar populations).

At redshift zero the oxygen-iron abundances can be split into two main regions. One primarily enriched by type II supernovae, which are more rich in oxygen, leading to higher (supersolar) ratios. Another which are primarily enriched by type Ia supernovae, leading to more iron than oxygen.

There are two main implementations involved, one without any mixing, and another with mixing of metals between gas particles. For both oxygen-iron ratios and europium-iron ratios one sees that mixing gives less variation between "upper" and "lower" sigma-bands.

Populating some star particles with neutron star mergers and have them enrich the nearby gas particles, and subsequentually the new star particles, gives a more complete abundance-pattern to trace. The abundances traced are hydrogen, oxygen (which primarily follows type II supernovae), iron (produced more abundently in type Ia supernovae) and europium (produced in neutron star mergers only). The europium-iron ratio varies widely, even for early times.

r-process nucleosynthesis requires neutron heavy isotopes, and the two leading theories are neutron star mergers and type II supernovae (see references Burbridge 1957, Roberts 2010, Lattimer 1977). Even though the conditions of the neutron star environment are somewhat uncertain, estimates are promising for the neutron star mergers to produce heavy isotopes in r-process distributions. These two processes, neutron star mergers and type II supernovae are quite different in frequency and yields, meaning that galactic chemical evolution models should be able to predict which of the models are most likely.

The chemical enrichment is closely tied to the star formation rate/history/birth/death, and thereby makes the 'Eris' simulation a good approximation for the Milky Way Galaxy. This study (shen15 'Eris' rncp post-production) finds that

neutron star mergers are capable of enriching the surrounding medium, even with a minimum delay-time of 100 Myr.

The dispersion/variantion of [Eu/Fe] is great enough, even at low metallicities. The results changing the parameters in the fiducial model is obvious, and I've elaborated on this before. The conclusion is that variations of the model parameters do not significantly alter the result. The mixing level affects the abundance of europium, but it is hard to compare to observations becasue spectroscopic abundance of many stars are unknown.

Galactic chemical evolution models are single points in space with mass resolution and time-integration. These models are simple way of calculating the mean amount of elements in the galaxy based on a star formation history, yield tables and initial composition. These models do not replicate the inhomogeneities and variations in metal-distributions. An attempt is made in this study to reproduce the results with a 1D-model based on the parameters used in Eris. At late times model agrees well with the average of all of Eris, however it does not agree well with the early results of Eris, nor does it replicate the large variations in spectroscopic abundance during early times.

1.4 Methodology

divide this section into more logical subsections?

In this thesis the goal is to examine the influence of uncertainty in models and parameters with regards to r-process nucleosynthesis. This will be done by comparing simple galactic chemical evolution models to high resolution smoothed particle hydrodynamics simulations.

The chemical evolution used is `'Omega'`, due to it's simplicity and versatility in executing. `'Omega'` also demonstrates a much larger resolution in mass, resolving the mass into many different isotopes. The smoothed particle hydrodynamics simulation `'Eris'` is a highresoltuion simulation that resembles the Milky Way Galaxy in many aspects, and is therefor a great candidate for a Milky Way Proxy. Assuming that the evolution of `'Eris'`also resembles the evolution of the Milky Way allows us to use the star formation history and baryonic content data from `'Eris'` in order to match the generated data from `'Omega'`.

The first step is to find the parameters for `'Omega'`that best reproduce the results from `'Eris'`?. This is done stepwise, and explained further in section point to correct section in results . To fit the `'Omega'` model to `'Eris'`, the star formation rate calculated for each timestep is used as the star formation history in `'Omega'`. This ensures that for sufficiently large timesteps `'Omega'`will use the same star formation rate as `'Eris'`. Otherwise, the parameters of `'Omega'`are probed in order to best reproduce the total baryonic content of the simulation, as well as the spectroscopic abundance of [O/H], [Fe/H], and [Eu/H].

Attempting to probe the uncertainties of nuclear observables is difficult, because both `'Eris'` and `'Omega'` both use the observed r-process abundance from the Solar system as the yield tables for all r-process events (neutron star mergers). This mean that all r-process events assume to generate the same distribution of heavy metals, and that distribution is the same as the component measured in the Solar system. In order to vary these values in `'Omega'` a single isotope is chosen, along with a factor that applies to the yield of that isotope. When using `'Omega'`, all yield tables will multiply with this factor for that specific isotope alone. E.g. ('C-14', 1.3) would mean that the yields for $^{14}_{6}$C will be multiplied with 1.3 in all yield tables. This method does not only probe the nuclear uncertianties, varying the yield-tables of a chemical evolution code finds the effect of the accumulated uncertainty of the stellar evolution applied to chemical evolution methods. add more details

of stellar evolution codes in theory part I

There are many parameters that affect r-process production alone. Ejecta distribution and size from neutron star mergerand type II supernovae, and the ratio of ejecta and frequency between the two. Even in relatively simple galactic chemical evolution models, these parameters can interact in unpredictable ways. In order to get a complete picture of errors and uncertainty in numerical models, a common approach has been Monte Carlo style simulation do I need a reference for this? . Each parameter is randomly drawn from a distribution correspondin g to their "determined" uncertainty (usually the chosen distributions are gaussian), and after many repetitions of randomly drawing, the result can be viewed statistically in order to determine uncertainty behavior. This thesis will such an experiment with list parameters here and see how the uncertainties of the r-process affect the uncertainty of the Re-Os dating method.

Bibliography