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).

1.1.2 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.

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 $1\frac{M_\odot}{yr}$

[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.

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.

'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.

Bibliography