Modelling interacting galaxies

(Christian Theis, Vienna)

- Motivation
- Modelling of galaxies
- MINGA: Genetic Algorithm approach
- Examples
- Summary & future prospects

M51: a prototype for an interaction
The Antennae Galaxies

What can we learn from galaxy interactions?

- kinematical history of galaxies
- test bed for galaxy evolution:
  - strength, mode and timing of perturbation
  - dynamical stability of galaxies
  - induced structural changes (mass flows, bars and spiral structure, mergers)
- reaction of ISM
  - star formation
  - chemical evolution
  - nuclear activity and mass loss
- properties of the dark matter halo

(Cristian Theis, Vienna)
Influence of dark matter halos on galaxy interactions

- **Why interacting systems?**
  - Tidal tails can trace outer galaxy
  - Tidal tails can probe off-plane regions
  - Tidal features sensitive to DM halo properties (Dubinski et al. 1999, Springel & White 1999)

- **Halo parameters:**
  - Mass
  - Extension
  - Flattening (?)
  - (Rotation)

Halos act like softened gravitational forces

---

Modelling Galaxies

- **Components:**
  - Stars and stellar remnants
  - Interstellar medium (molecular clouds, diffuse gas, dust)
  - Dark matter
  - Black Holes

- **Processes:**
  - Dynamics:
    - Gravitational N-body problem
    - Hydrodynamics
  - Galactic microphysics:
    - Phase transitions (star formation, stellar death etc.)
    - Processes within a phase (e.g. cooling)
    - Interactions between phases (e.g. stellar heating)
Restricted N-body simulations

- **Idea** (Pfleiderer & Siedentopf 1961, Toomre & Toomre 1972)

- **Basic assumption:**
  - Galaxies follow Keplerian orbits
  - Stars are treated as test particles
  - Fast integration (~ 1 CPU sec on modern PC)
  - High spatial resolution in regions of interest

- **BUT:** not self-consistent (e.g. no merging)

Self-consistent simulations

- include self-gravity of stars, gas and dark matter
- main problem: \(N^2\)-bottleneck
- simulation methods:
  1. **TREE-codes** \((\sim N \log N, \sim N)\) (e.g. Barnes & Hut 1986, Dehnen 2000)
  2. **grid-based schemes** \((\sim N)\) (e.g. Sellwood 1982)
  3. **expansion methods**, \((\sim N)\) (e.g. SCF Hernquist & Ostriker 1992)
  4. **special purpose computer**, GRAPE \((\sim N^2)\) (Tokyo group [Makino, Sugimoto et al.] since 1990)

- **BUT:**
  - no trivial stable initial configurations
  - low resolution in low-density regions
  - computationally expensive
Gas dynamics in galaxy models...

- **Single component ISM**
  - hydrodynamical models:
    - grid codes
    - smoothed particle hydrodynamics (SPH)
  - phenomenological models:
    - sticky particles (for gas clumps, clouds)

- **Multi-component ISM**
  - often: sub-grid models
  - high-resolution hydrodynamical models (SPH, grid)
  - hybrid codes

Chemo-dynamics: towards a complete model...

diffuse gas \[\rightarrow\] stars \[\rightarrow\] clouds \[\rightarrow\] diffuse gas

- dissipation
- feedback
- star - formation
- condensation & evaporation
- gravity
- dissipation
- dark halo
How can we learn from interactions: parameter space

**Goals:**
- Finding a solution
- Uniqueness of a solution

**Problems:**
- Extended parameter space
- Trapping by local optima

**Optimization problem:**

Fitness function:

\[ f = \frac{1}{1 + \delta}; \delta = \sum_{i=0}^{\text{max}} |l_{i_{\text{ref}}} - l_{\text{max}}| \]

**Fitness landscapes**

- **Smooth landscape:**
- **Multi-peaked landscape:**
**Parameter space**

- **Parameters:**
  - two-body parameters (orbital plane, eccentricity, pericenter, masses...)
  - characteristics of galaxies (orientation of disk, scalelength,..., halo...)

- **Example:**
  - Disk+point-like perturber: 7 parameters
  - grid with 5 pts./dimension: 78125 models or
  - ~3.5 years GRAPE6 CPU time

Fast N-body technique and efficient search strategy required!

---

**Genetic algorithm**

- **IDEA:** imitate evolutionary optimization, i.e. adaptation of a population by "survival" of the fittest solution
  (Holland 1975, Goldberg 1989)

1. Start with a random population, i.e. \( N_p \) points in parameter space
2. Apply iteratively reproduction operators
How do genetic algorithms work?

Population:

Individual:
- orb. incl. $[0^\circ,180^\circ]$: 55°
- map in $[0,1]$
- 0.3055
- on chromosome
- ... 3 0 5 5 ...
- gene

Parameter set

Evaluate fitness by comparison with reference map

N-body simulation

Evaluate fitness by comparison with reference map
How do genetic algorithms work - 2

- Select according to fitness
- Cross-over
- Mutation

Generation i
- Parents
- Cross-over mutation
- Children

Generation i+1

Cross-over position

A test example...

\[
 f(x,y) = \cos^2(n\pi r) \exp(-r^2/\sigma^2) \\
 r^2 = (x-0.5)^2 + (y-0.5)^2 \\
 n = 9 \quad \sigma^2 = 0.15
\]

Later stage of GA run:

(provided by P. Charbonneau)
Example 1: a model for NGC 4449

MINGA reproduces parameters to better than 10-20%, some even better than 1%!  
(Theis & Kohle 2001)

Comparison of parameters

MINGA reproduces parameters to better than 10-20%, some even better than 1%!  
(Theis & Kohle 2001)
Example 2: M51

- M51 restricted N-body simulation

- GA models fits intensity map
- parameters are close to Salo & Laurikainen’s (2000) “two disk passages”-model
- (interaction induced grand design spiral)

Example 2: snapshots of the GA model for M51
Example: influence of a dark halo on a small group of galaxies

without a halo: (point mass)  including a halo:

modified restricted-N-body-code is rather sensitive for halo parameters!

Example 3: MINGA-Fit of a small group of galaxies

MINGA-Fit for a small group of galaxies:

Small groups can be modelled by MINGA!
Example 4: The Magellanic System

The Magellanic System in HI

(Lund observatory)

(Brüns et al. 2005)
A Genetic Algorithm model...

Observational data cube:

Smoothed data cube: (used in GA)

(Ruzicka, Palous & Theis 2007)

A Genetic Algorithm model...

Observed intensity map

Intensity map (model A seq.)

(Ruzicka, Palous & Theis 2007)
A Genetic Algorithm model...

- 3D LMC-SMC column density data-cube used
- actual resolution of 16” x 16” x 7km/s

Results:

- MW dark matter halo close to spherical, probably slightly oblate
- Preferred model class A:
  - MW halo flattening: q~0.84
  - Clouds only recently close together
  - Material in the Stream stems from both Clouds
Summary

- **MINGA can model interacting galaxies:**
  - Automatic analysis of observational data
  - Uniqueness tests

- **Included Features:**
  - Spherical DM halos consistently included
  - Extended to small galaxy groups
  - Applied to Magellanic System

- **Easy to parallelize**

- **Remark:** GA models are just a first step, further detailed self-consistent models necessary

Multimethod Modelling

- **Step 1:** GA-based analysis of parameter space
- **Step 2:** Dynamically self-consistent modelling
  - Pure stellar dynamics
  - Gas dynamics

- **Step 3:** Self-consistent multi-component modelling, i.e. chemo-dynamical modelling (including SF, feedback, etc.)
Collaborators

- Stefan Harfst (Rochester)
- Simone Recchi (Trieste), Gerhard Hensler (Vienna), Pavel Kroupa (Bonn)
- Christian Boily (Strasbourg), Thorsten Naab (Munich)
- Lia Athanassoula, Albert Bosma (Marseille)
- Christian Brüns, Nikolaus Neininger, Uli Klein, Sven Kohle (Bonn)
- Adam Ruzicka, Jan Palous (Praha)
- Helmut Meusinger (Tautenburg)
- Jay Gallagher, Linda Sparke (Madison)
- Werner Zeilinger (Vienna), Giovanna Temporin (Milano)
- Christoph Gerds, Christian Spinneker (Kiel)
- Gerald Jungwirth, Harald Leibinger, Armin Liebhart, Hanns Petsch, Julia Weniger (Wien)