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The Grand Challenge Problem Cosmology

Presentation for
High Performance Computing in Physics
by

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26 February 1999

This presentation is based on the Internet pages of the GC3:
`http://zeus.ncsa.uiuc.edu:8080/GC3Home.html`

1 Aplication area

The *Grand Challenge Cosmology Consortium (GC3)* works on the elucidation of the process forming the large scale structures found in the universe.

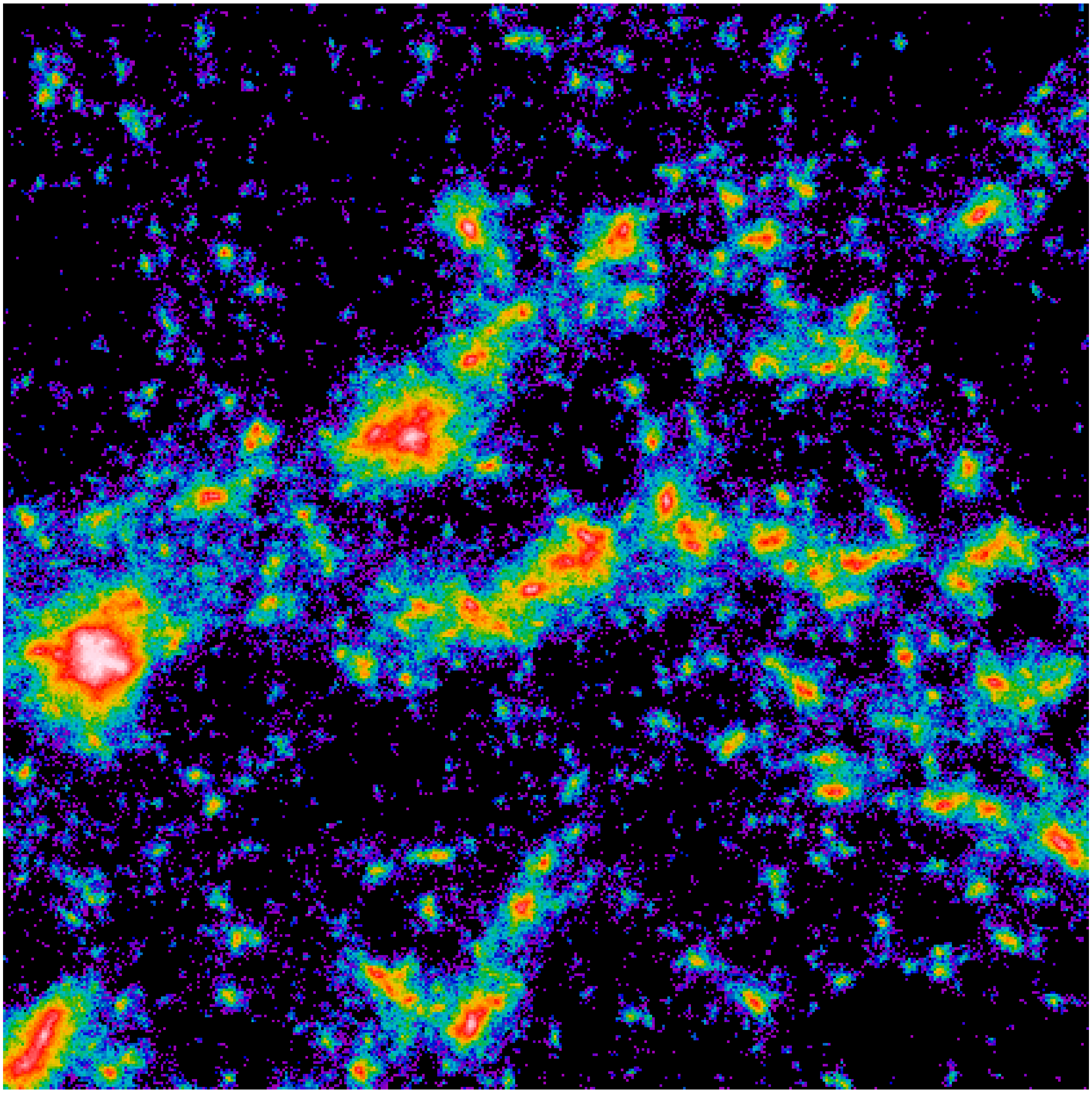

Figure 1: Simulation of gravitational clustering of dark matter in a scale-free (n=-2) Einstein-deSitter universe using the NCSA Connection Machine-5.

Several topics have been investigated

- Formation of galaxies and large scale structure
- Computing the universe: x-ray clusters in a cold and hot dark matter uni-

verse — X-ray telescopes orbiting the Earth have discovered that clusters of galaxies are immersed in halos of million degree gas. This hot gas is a byproduct of the galaxy formation process and emits large amounts of energy in the form of X-rays.

- Star formation during galaxy mergers
  - The merging of two equal mass disk galaxies.
  - A small dwarf companion galaxy is accreted by a disk galaxy.
- The metamorphosis of the local group — Collision of galaxies due to gravitational attraction.
- Galactic dynamics of cluster formation

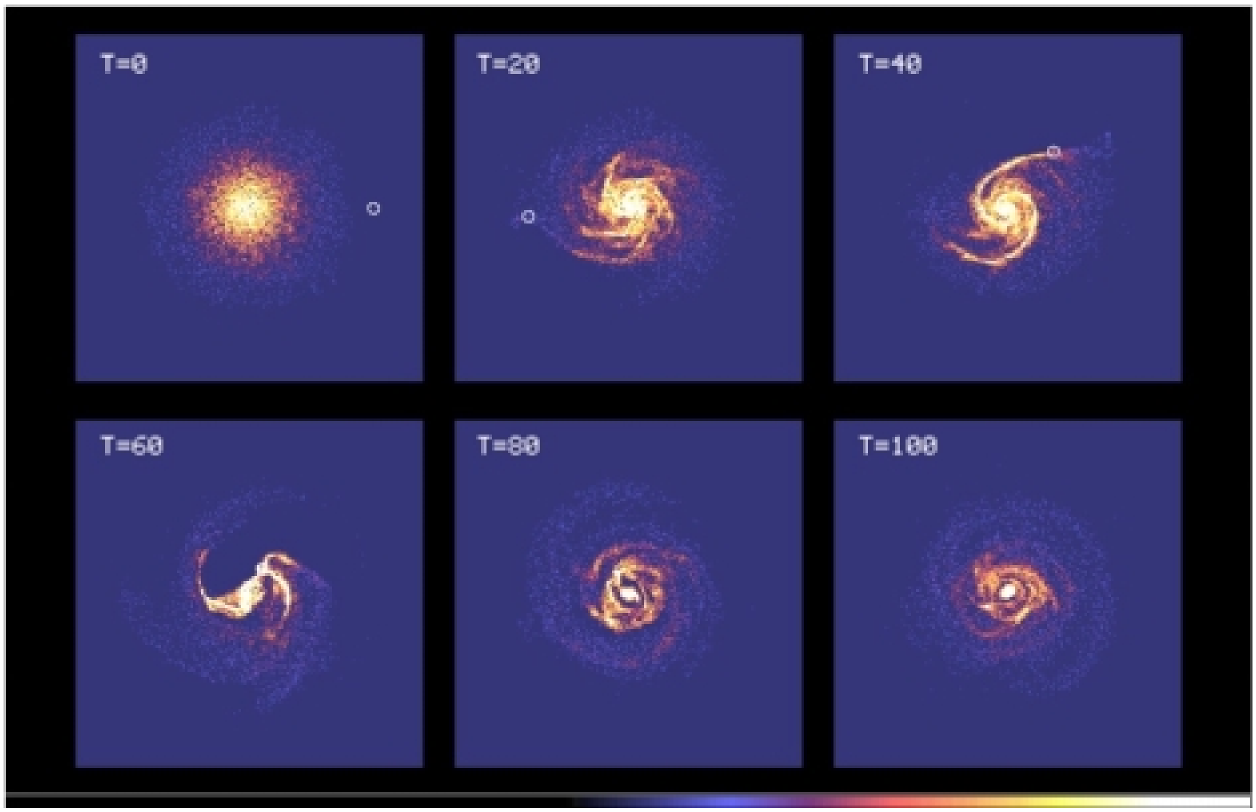

Figure 2: This sequence shows star formation in a disk galaxy accreting a small dwarf companion galaxy (shown as a white circle). Time is shown in the upper left corner of each frame, with unit time corresponding to 13 million years. As the companion falls into the disk galaxy, it triggers a stong inflow of gas and ensuing burst of star formation in the central kiloparsec of the disk. These types of mergers are thought to be common events in the life of many disk galaxies, and may explain the formation of many starburst galaxies and active galactic nuclei.

2 Algorithms and Techniques

To cope with the difficulties that emerge from the multiscalar approach complex data structures and algorithms are employed. The GC3 utilizes following methods to discretize the universe

- Grid based
- Particel based
  - Particle — Particle
    - Accumulate forces by finding the force $F(i,j)$ of particle j on particle i
    - Integrate the equations of motion
    - Update time counter
  - etc.
- Hybrid, a combination of both
  - Particle — Mesh
    - Assign "charge" to the mesh ("particle mass" becomes "grid density")
    - Solve the field potiential equation (e.g. Poisson's) on the mesh
    - Calculate the force field from the mesh-defined potential
    - Interpolate the force on the grid to find forces on the particles
    - Now like the Particle — Particle: integrate the forces to get particle positions and velocities
    - Update the time counter
  - etc.

The universe is simulated over a long period of time. The simulation starts with an expanding homogenous universe. This starting point is set by the hypothesis of the *Big Bang*. One of the goals of the project is to show how large scale structures condense out of this primordial gas. Due to the large changes in the density of matter and therefore in the work that has to be done for a certain region of the simulated volume a dynamic load balancing is necessary to achieve efficiency. The GC3 uses two strategies to do this

- Adaptive mesh refinement

- Hierarchical tree

The programs use following programming models

- Data parallel
- Object parallel
- SPMD (Single Program Multiple Data)

3 Why is HPC needed?

The simulation of the universe is clearly one of the most demanding problems one can imagine. The complexity of the simulation arises from the need to work on a large range of length scales. The Figure shows the relative sizes of the simulated length scales.

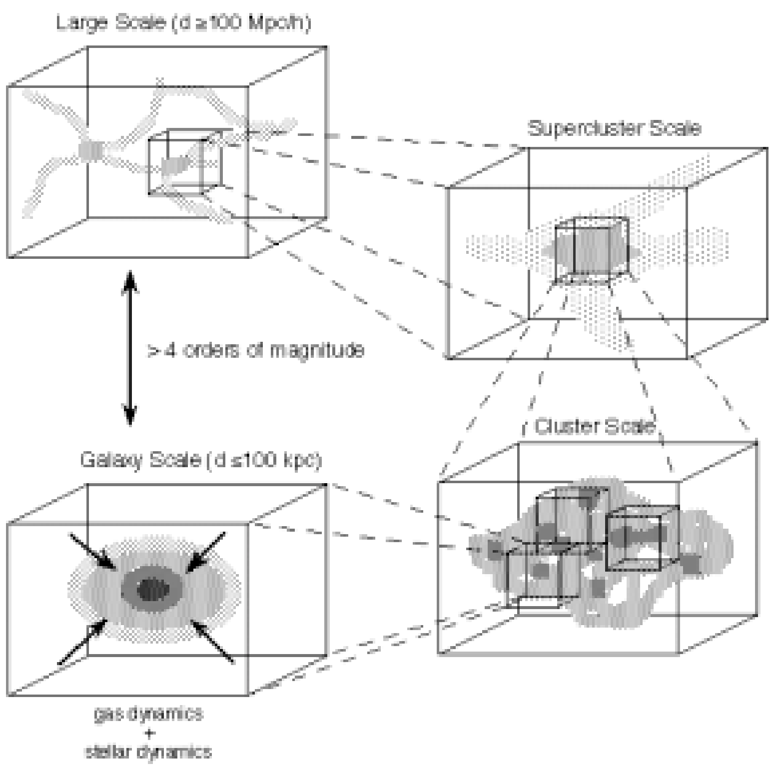

Figure 3: Length scales in the cosmology project

Simulations that have been carried out usually comprise of tens of millions of particles. This vast amount of particles is needed to be able to observe typical structures found in our universe, for example the red and white spots in the first figure are so-called galaxy halos.

4 High Performance Computers available to the Cosmology Consortium

- TMC (Thinking Machines Corporation)
- CM-5 (Connection Machine)
- Intel PARAGON
- Cray T3D
- Convex MPP

5 Spin-offs

The cosmology project deals predominantly with pure science. In spite of this applications exist. The main influence of GC3 is on the parallel programming languages harnessed. These are *High Performance FORTRAN (HPF)*, *parallel C++ (pC++)*.

The GC3 has improved *pC++* extremely to make it suitable to their needs. Several programming codes shall be ported to *HPF*. Therefore a similar development is expected to happen to *HPF*.

There were many practical and efficient strategies devoloped to store, visualize and analyse massive numerical data sets. These strategies may be used for other HPCC applications.