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AstroMD, a tool for Stereographic Visualization and data analysis for astrophysical data

U. Becciani[1], C. Gheller[2],
V. Antonuccio[1], D. Ferro[3] and M. Melotti[2]

[1] INAF - Osservatorio Astrofisico di Catania via S. Sofia 78, 95123 Catania, Italy e-mail: `ube@sunct.ct.astro.it`

[2] CINECA, via Magnanelli 6/3, 40033 Casalecchio di Reno (BO), Italy

[3] Dipartimento di Fisica e Astronomia, Universitá di Catania, via S. Sofia 78 , 95123 Catania, Italy

Abstract. Over the past few years, the role of visualization for scientific purposes has increased enormously. In Astronomy the visualization techniques are so frequently applied to analyze data that they now represent a fundamental part of the modern researches in Astronomy. Since the evolution of high performance computers, the models and the simulations based on particle methods, have assumed a great role in the scientific investigation, allowing the user to run simulations with higher and higher numbers of particles. Data produced is often a multi-dimensional data set with several physical quantities, that is not simple to manage and to analyze. The cosmological astrophysical data obtained with computational astrophysics are different from data obtained with other kind of simulations or experiment and the data analysis they require cannot be easily provided by the available software. AstroMD, a project funded by the EC and the CNAA, is a tool for data analysis and visualization for simulation based on particle methods and manages different physical quantities and multi-dimensional data sets. The tool can use the virtual reality techniques where the user has the impression of travelling through a computer-based multi-dimensional model.

Key words. Scientific Visualization – Data analysis – Virtual Reality

1. Introduction

Since the beginning of modern astronomy, the scientific community has expressed a great interest in scientific visualization tools. A great improvement in this direction was determined by the introduction of modern CCD detectors to collect observational data in a digital format. Today, almost all the standard measures have a digital form and each measure can be generally considered as a collection of images forming a multi-dimensional data set. In many

Send offprint requests to: U. Becciani
Correspondence to: via S. Sofia 78 , 95123 Catania

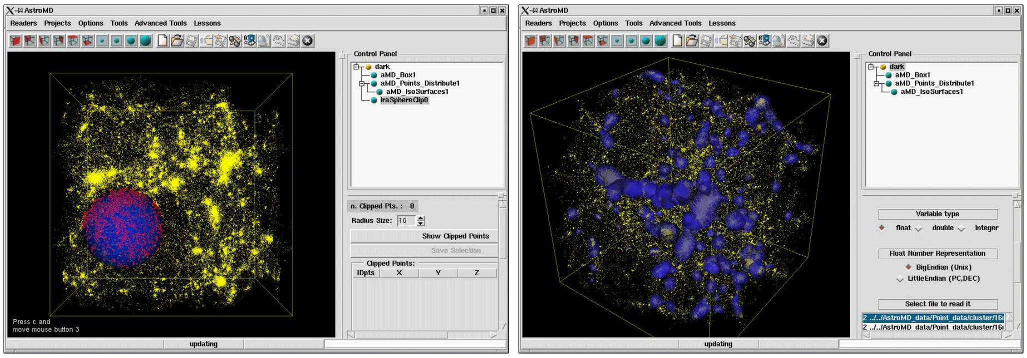

Fig. 1. Left panel: The main GUI of AstroMD allows the user to visualize data (Render Window), to define variables and projects, to control variables and filters and to save results. Right panel:Formation of clusters of galaxies in the universe, with overdensity of 200 compared to the average density, during the evolution of a sample of 150000 particles in a region of 50 Mpc.

cases extensive image processing is required to obtain meaningful images. The improvement of technology and the availability of supercomputing systems, has led to a dramatic increase in the volume of data coming from numerical simulations. Nowadays, astrophysical simulations produce many gigabytes of data which have to be efficiently visualized and analyzed. Visualization is the most intuitive approach to data and basic information can be obtained just "at a glance". Then the possibility of moving inside the data allows the scientist to focus a region of interest and to perform quantitative calculations. Therefore image processing tools play a fundamental role in astronomy.
AstroMD is a data visualization and analysis software specifically designed to deal with astrophysical data; it can powerfully handle large datasets allowing both their graphical representation and analysis, corresponding to the requirements proposed by several research fields. The basic application of this new tool is focuses on the dataset obtained from cosmological simulations, on data of observational galaxy catalogues and on data coming from observations of extragalactic radio sources. Although these fields do not cover all the requirements of astronomy, they pose many typical problems that we expect to be solved by AstroMD. The solution to these problems was implemented following the suggestions and the indications of the research groups involved in the project and of a User Interest group.
Astrophysical data have peculiarities that make them different from data coming from any other kind of simulation or experiment, therefore they require a specific treatment. For example, cosmological simulations consider both baryonic matter (described by fluidodynamics) and dark matter (described by N-body algorithms). Further components, like stars or different chemical species, can be introduced and followed in a specific way. These different species require different types of visualization: dark matter needs particles position or velocity rendering while baryons require mesh based visualization. Furthermore particle associated quantities, like mass density or gravitational potential, require their calculation and visualization on a mesh. Then simulated structures have a fully three-dimensional distribution. Therefore it is necessary to have a clear 3D representation, efficient and fast tools of navigation, selection, zoom and the possibility of improving the resolution and the accuracy in specific user-selected re-

gions. Moreover evolution can dramatically change the properties of the simulated objects and the information that can be retrieved, therefore it is important to efficiently control sequences of time-frames.
AstroMD is a on-the-fly data analysis tool that makes use of the scientific visualization to well address the sub-regions of principal interest for the researcher, that would analyze an N-Body or a fluidodynamic simulation.
In Section 2 we will describe the basic functionalities of AstroMD where the main GUI and the generic visualization features will be described. In Section 3 we will show the built-in-tools that allow the user to perform a data analysis using a selected frame of an N-Body simulation: the correlation function, the power spectrum the Minkowski functional and the friend-of-friend algorithm will be discussed. Section 4 shortly describes the visualization of catalogue capabilities of AstroMD, Section 5 describes the Cosmo.Lab project fundamental workplan and the participants involved in the project, and finally in Section 6 we report our conclusions.

2. AstroMD Basic Functionalities

In order to build a widely used product it was chosen to use a low cost software portable on a number of different platforms, the Visualization Toolkit (VTK) by Kitware (4; 11). VTK is an open source, freely available software system for 3D computer graphics, image processing, and visualization. It includes a C++ class library and several interpreted interface layers. VTK is available for nearly every Unix-based platform (e.g. Linux or IRIX) and PC's (Windows 2000 and Windows XP). The design and implementation of the library is based on the object-oriented paradigm. The graphical model in VTK is at a higher level of abstraction than rendering libraries like OpenGL or PEX. This means it is much easier to create useful graphics and visualization applications. In VTK applications can be written directly in C++, Tcl, Java, or Python. Using these languages it is possible to build powerful, fast and portable applications. The built-in functionalities are controlled by a specific Graphic User Interface (Fig. 1,(5)), written in incrTcl/Tk (16) that supports the object-oriented programming structure, allowing an easy way to add more and more powerful data analysis and visualization packages. AstroMD objects can represent a reader, that allows the user to read data from a file or from a database, a filter, that allows the user to manipulate data, and a viewer, to visualize the results. VTK supports a wide variety of visualization algorithms including scalar, vector, tensor, texture, and volumetric methods and advanced modelling techniques. It supports stereographic rendering and can be used for virtual reality visualization. Furthermore, being easily extensible, the system allows ad hoc implementation of specific modules. Furthermore efficient manipulation and analysis tools, like smoothing of the particle masses on a mesh or calculation of the power spectrum and correlation functions, are parts of the basic functionalities (1; 3).
AstroMD has also stereographic rendering capabilities, which makes it usable for immersive visualization, presently implemented at the Virtual Theatre of CINECA (15). The display of data gives the illusion of a surrounding medium into which the user is immersed. The result is that the user has the impression of travelling through a computer-based multi-dimensional model which could be directly hand-manipulated. In this sense, the virtual reality is a progressive lowering of the barrier which separates users from their data (10).
Nevertheless this tool is exploited on different platforms, from the very sophisticated virtual theatre, to the personal computer. AstroMD, in fact, is developed with particular care to the portability issues in order to make it usable on many different platforms and to allow a large diffusion and usage inside the scientific community and educational institutions.

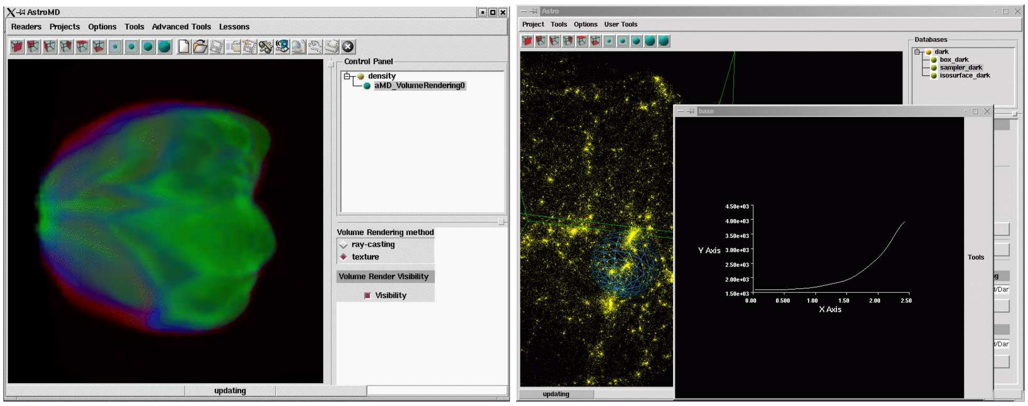

Fig. 2. Left panel: Volume Rendering displays visual images directly from volume data, enabling the viewer to fully reveal the internal structure of 3-D data. Right panel:Power Spectrum of the ΛCDM simulation sample.

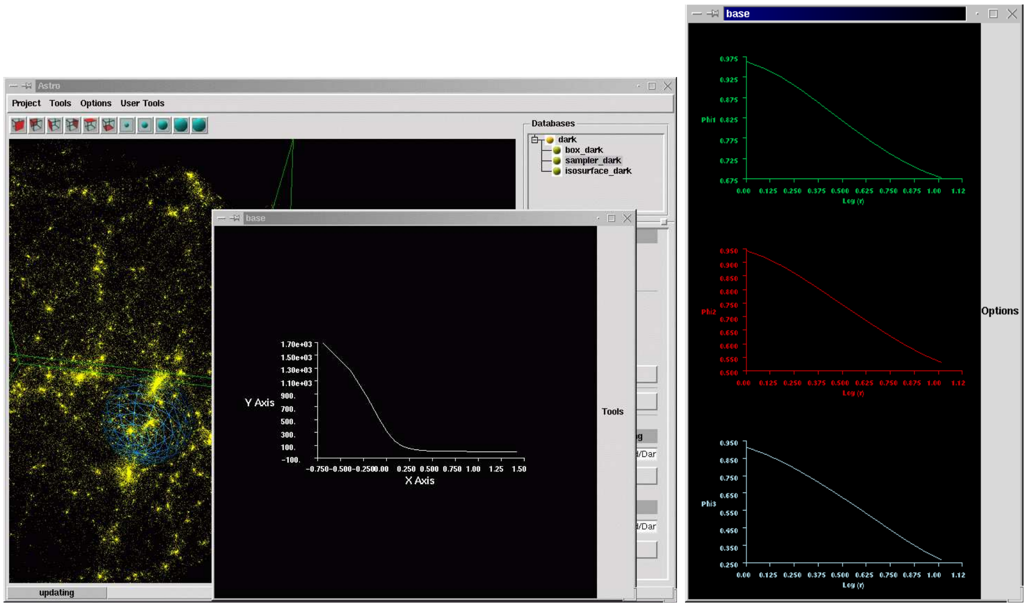

Fig. 3. Left panel: Correlation Function of the ΛCDM simulation sample. Right panel:Minkowski Functionals of a ΛCDM simulation.

2.1. Data Input and Manipulation

Data must be written as sequences of a 3D coordinates in the case of particles and as sequences of scalar values (fortran or C order) in the case of meshes. The input data formats presently accepted by AstroMD are the common unformatted C standard, the Raw Format, the TIPSY (13) and the FITS (12) Formats. Raw files are simply dump of the memory, written in a continuous sequence of x, y, z coordinates. TIPSY is a visualization toolkit specifically designed to quickly display and analyze the results of N-body simulations.

Tipsy requires a specific data format to work with, supported also by AstroMD. The basic data structure is an array of particle structures in three separate arrays for each type of particle used in the simulations: collisionless particles, SPH particles, star particles and their characteristic properties, such as potential energy and temperature. Binary and ASCII files can be read. Data are visualized with respect to a box which describes the computational region. A cubic or spherical sub-region can be selected interactively inside the parent box with a different spatial resolution, in order to focus on the most interesting regions. Data inside the sampler can be analyzed with the embedded tools or can be saved in specific files for an off-line analysis. Boxes can be translated, rotated, zoomed in and out with respect to selected positions. Colours and luminosities can be chosen by the user. Images of different evolutionary stages can be combined in order to obtain a dynamic view of the behaviour of the system. The opacity of the particles can be increased, so that low density regions are more easily detectable, or decreased, so that the details of the high density regions substructures are shown. Different particles species (e.g. dark matter and baryons) can be visualized at the same time using different colours. Other particles related to continuous quantities, like density fields, can be calculated as typical grid based fields and visualized as isosurfaces or volumes. Scalar fields can be visualized by isosurfaces or by volume rendering. The value of the isosurface can be selected on the user interface (Fig. 1,(5)). The volume rendering can be calculated using both the texture mapping and the ray tracing technique (Fig. 2). Different time frames can be shown in a sequence. When the system evolves, the particles positions can be interpolated between two time-steps. This improves the quality of the animation giving a fluidity otherwise unachievable. Both the single images and the whole sequence can be saved in bitmap or jpeg format to prepare an animation of the evolution. Activating the steady-cam, the system can be rotated in Azimuth and Elevation during its evolution. Zoom-in and zoom-out possibilities are also offered. The whole set of particles can be visualized but it is also possible to use a sub-sample of the data, in order to get a faster and easier visualization: AstroMD includes a randomize tool allowing the user to select a random subsample of data, without systematic errors in the selection procedure.

3. N-body Simulation and data analysis tools

Some built-in-tools, specifically directed to cosmological results of simulation, were implemented to allow an efficient manipulation and analysis of the data. At present the main following functionality are implemented.

3.1. Particles mass density

The mass density field associated to the particle distribution is calculated distributing the mass of each particle over the computational mesh by an eight-point Cloud-in-Cell smoothing algorithm (7). The computation can be done with the maximum accuracy using all the particles over a uniform high resolution mesh, but AstroMD allows the user to use only a sample of the whole set of particles, and the final result can be extrapolated to all particles of the simulation, reducing the CPU time consuming and the memory request. The smoothing of the masses can be performed generally using a coarse grid, that can be refined where high resolution is necessary.
The same tool can be used to calculate other fields related to quantities possibly associated to the particles, like, for example, the thermal energy density field or the X-ray luminosity field.

3.2. Gravitational field calculation

Considering the mass density $\rho(x)$ defined over the computational mesh as above, the gravitational field can be calculated solving the Poisson equation

$$\rho(\boldsymbol{x}) \propto \nabla^2 \phi(\boldsymbol{x}), \quad (1)$$

where $\phi(\boldsymbol{x})$ is the gravitational potential, by a Fourier Transform procedure. The Poisson equation is transformed in its momentum space image using a FFT VTK built-in function (9). This reduces the equation to a much simpler algebraic operation

$$\phi(\boldsymbol{k}) \propto \frac{1}{|\boldsymbol{k}^2|}\rho(\boldsymbol{k}), \quad (2)$$

where $\phi(\boldsymbol{k})$ and $\rho(\boldsymbol{k})$ are the Fourier images of the potential and of the density and $|\boldsymbol{k}|^2$ is the square module of the wavenumber. Finally, the potential is transformed to the physical space using an inverse FFT.

3.3. Fourier decomposition, Power Spectrum and Correlation Function

The quantity $\rho(\boldsymbol{k})$ is used to calculate the Power Spectrum $P(k)$ of the matter distribution, which is defined as the average value of the square norm of $\rho(\boldsymbol{k})$:

$$P(k) = \langle|\rho(\boldsymbol{k})|^2\rangle. \quad (3)$$

The Power Spectrum expresses the weight of each of the Fourier components of the mass distribution between k_{min} and k_{max} which represents the inverse of the size of the computational mesh and the Nyquist frequency (3). The Power Spectrum is a powerful measure of the statistical properties of the distribution (Fig. 2,(5)), together with the associated Correlation Function $\xi(r)$, which is its Fourier Transform (Fig. 3,(5)). The two-point Correlation Function indicates the probability to find a particle at a distance r from any other particle, and is usually used to analyze the clustering properties of a sample of discrete objects (particle, galaxies, galaxy clusters, etc) (1). Peebles and Hauser estimator (2) was used, that is preferable at large scale, for samples with non uniform density. The 2-D plots are shown in a separate window and can be executed on a selected region or on all the visualized domain.

3.4. Minkowski Functionals

The Minkowski Functionals provide a tool to characterize the large-scale distribution in the Universe (6). They describe the Geometry, the Curvature and the Topology of a point set. Considering the set of points in 3D space, supplied by galaxies of a cluster of galaxies, and decorating each point with a ball of radius r, the tool measures the size, shape and connectivity of the spatial pattern formed by the union set of these balls. These characteristics change with the radius r, which may be employed as a diagnostic parameter (Fig. 3,(5)).

3.5. Friend of Friend Algorithm

A group finder was inserted, known as Friends-of-Friends (14; 8). A particle belongs to a FoF group if it is within some linking length of any other particle in the group. After all such groups are found, those with less than a specified minimum number of group members are rejected. The user sets two parameters: the maximum distance among particles forming a cluster, the minimum number of clustered particles. The computation of the centre of mass of each group, the number of components and the radius of each group have been performed. The graphical output shows the particles in the groups. The centre of mass of each group is identified by a ball with radius as clustered group radius. In a separate window the plot of the fraction of grouped particles versus the number of components of the groups is displayed (Fig. 4,(5)).

4. Visualization of catalogues

A Catalog Manager (CM) is included in AstroMD, providing a powerful system to

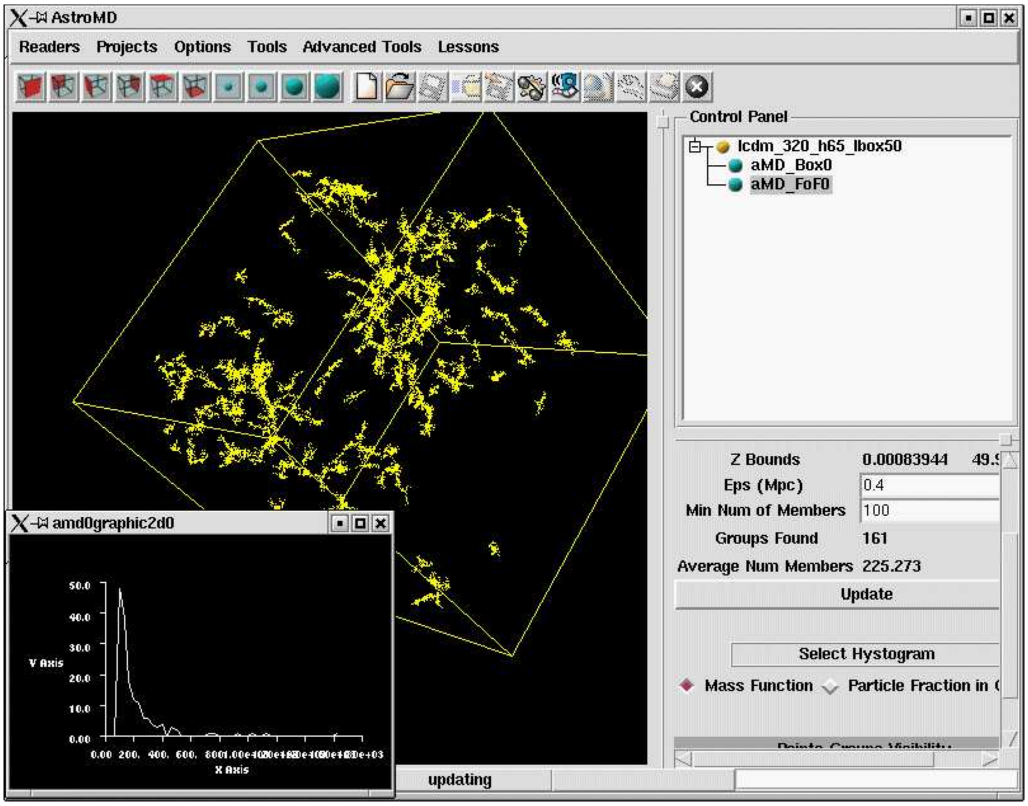

Fig. 4. Displaying groups from ΛCDM simulation results.

read astronomical catalogues in the most common data formats, which are ASCII files and FITS files. The CM of AstroMD uses ODBC (*Object Database Connectivity*) developed by Microsoft but available also for the most common Unix platforms and Linux. The ODBC allows the user to read data from any remote DBMS and use the SQL to retrieve data from it. The CM provides an useful tool to select the table in the database and write a selection query of table just in easier way. The CM main window (Fig. 5) on the left shows the buttons that allow the user to load or to save ASCII and FITS file and to connect to a remote database. The preview button shows a separate window where data is displayed. On the right side of the CM window, a tagged window where all the information, row by row, of the selected catalogue are displayed. The user can select every row and can assign an *Attribute* to the rows. To obtain a 3D plot of data in the catalogue the user must choose the X, Y and Z attributes from the three row of the tagged window, than setting the COLOR attribute to another field (i.e. the TYPE row in Fig. 5). The points can be visualized in a preview window and loaded in the AstroMD main window where the plot can be analyzed using the AstroMD analysis tools.

5. The Cosmo.Lab project

AstroMD is a visualization package developed in the Cosmo.Lab framework with the specific object of supporting visualization and analysis of astrophysical three dimensional structures. The Cosmo.Lab project (15) is financed by the European

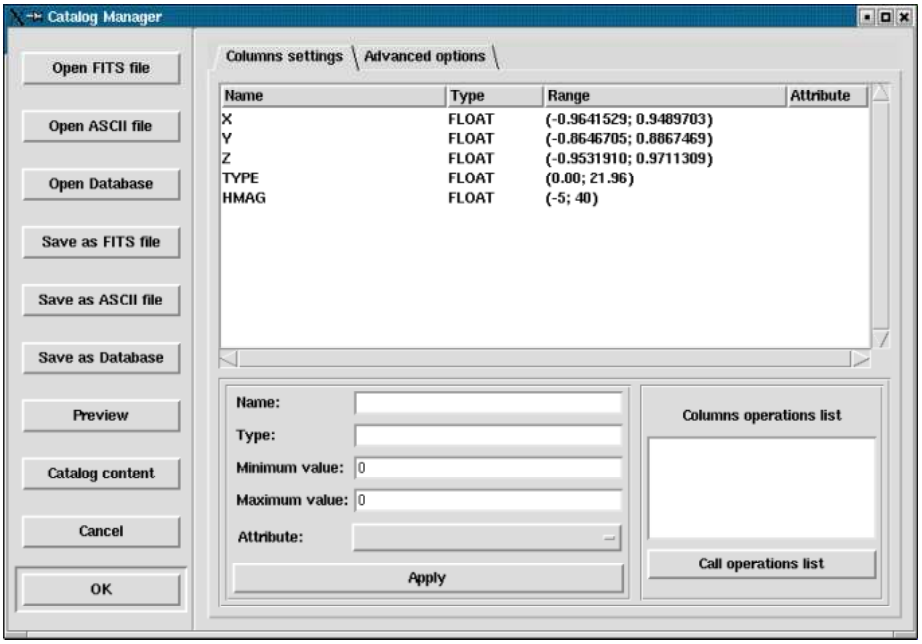

Fig. 5. Catalogue Manager main window.

Community and at the end of the project (October 2003) the software will be freely distributed. The project has also an educational goal, based on the 3D capabilities of AstroMD. This feature will be exploited on different platforms, from the very sophisticated virtual theatre, to the personal computer. The participant involved in the project are:

- the *Cineca* with the role of management, technical coordination, assessment and requirements analysis
- the *INAF - Astrophysical Observatory of Catania* for the development of tools for cosmological simulations, test and validation
- the *Institute of RadioAstronomy* of the Italian National Research Council, for the educational and dissemination aspects
- the *Cosmic Physics Institute "G.Occhialini"* of the Italian National Research Council, for the development of tools for galaxy catalogues
- the *Netherlands Foundation for Research in Astronomy* for the development of tools for radio sources

A group of interest is also established. It is composed by researchers in astrophysics who test the AstroMD tool, and give the developers their impressions and suggestions for the future development. The first meeting was held at CINECA on June 3rd 2002. At present the group involves people from the following institutions: INAF Observatory of Arcetri, Catania, Padova, Torino and Trieste, University of Roma, Washington and Zurich, TAC of Copenhagen, INFM Milano and Roma.

6. Conclusions

AstroMD represents the first experience of a tool of immersive visualisation and data analysis in astrophysics. It will be a valuable tool for scientific groups, able to interact efficiently with large amount of data, easily navigating inside them, analysing their properties, calculating their statistical properties and reconstructing their three dimensional shapes and features. This will lead to a deeper understanding of scientific problems and to their easier solution. The software developers and visualization experts will have the possibility of strongly improving their knowledge in the involved techniques and their experience on the possible applications of 3D visualization and immersive technology in scientific research applications. Finally, the use of AstroMD for educational purposes will be a very effective tool for teaching astronomy to students, giving the possibility of observing objects and structures from a privileged and personalised point of view.

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