1 Executive summary

The meeting brought together a number of distinguished computational astrophysicists from three major areas of research, namely, cosmic structure formation, star formation and planet formation. The group of people selected were nearly evenly distributed between those who develop and use Lagrangian particle-based techniques to model the equations of fluid dynamics and those who design and employ Eulerian techniques. These are the primary computational tools of fluid dynamicists who are tackling a broad spectrum of applications. In addition, several computational fluid dynamicists with an engineering background were also present and they enriched the intellectual debate considerably by proposing their quite different perspective on numerical techniques and on how to judge them. In particular, most of the intervening people were experts of either smoothed particle hydrodynamics (SPH) or adaptive mesh refinement (AMR) codes. In total 12 different numerical codes were presented and highlights of the scientific results obtained with them were discussed in the context of all three different areas of investigation.

We designed the program such that the presentations in the morning were followed by focused discussion in the afternoon. These discussion sessions were also used to cover the topics of code comparisons and problems related to algorithmic design. The evenings were kept free for hands on computing.

Both SPH and AMR codes are in principle ideally suited to tackle the enormous dynamic range of astrophysical problems but the advantages and disadvantages of both techniques, though frequently mentioned in meetings and articles, have never been analysed in a sufficiently quantitative and general way. This meeting made a step forward in this direction by asking all participants to carry out several test problems that were designed by the organisers and incorporating suggestions by several of the participants. The aim was to start a serious computational astrophysics code comparison using well defined control problems that "stress" different techniques in different ways. These tests include situations which are common in any of the three areas of investigation targeted by the meeting, and they involve not only pure hydrodynamical problems but also cases in which hydrodynamics is coupled with self–gravity. The organisers provided the initial conditions before the meeting for both SPH and grid codes. The tests were performed by the participants before and during the meeting.

The organisers brought a prototype "portable" parallel computer with 8 AMD-Opteron processors to the conference hotel which was made accessible to all participants via a local wireless LAN. Evenings were spent helping participants run the tests, exploring parameters in codes and general real–time hacking of codes to understand comparative performances. The small parallel computer was also equipped with software for analysis and visualisation of the simulations. This gave us the opportunity to start the analysis at the meeting, obtaining the first qualitative results. On site work was extremely successful, with everyone being actively involved in discussing and analysing the tests from the end of the daily talks though the afternoon and on until late into the night.

The close interaction between the various participants has allowed us to efficiently overcome several practical problems that usually represents a big obstacle for attempts to carry out such code comparisons; amongst this is finding a common platform for exchange of data formats and analysis tools. On-sight programming with the participants allowed us to refine the design of the tests themselves in order to bring specific issues into sharper focus. In addition, feedback from the participants was remarkable, including different ways of analysing results and suggestions of several new interesting test problems. One extremely positive outcome of the meeting is indeed that the code comparison is continuing; currently five tests run by 12 different codes are being analysed, with the aim of producing not just one but a series of research papers that should become the definitive guide for comparison of techniques in computational astrophysics.

During the discussions the following themes were extensively explored and debated in the context of the key scientific areas;

- the reliability of current astrophysics codes; are our methods really capable of modelling the physical situations that we desire, even in cases were several simplifying assumptions are made? How do numerical artifacts manifest themselves in the final state?
- the completeness of current astrophysics codes; are we simplifying too much, are too many mechanisms missing in our computer models to be considered faithful representations of reality? For example, many codes do not include important effects such as radiative transfer and magnetic fields.
- how to include sub-grid physical processes that can not be resolved at the same time as the global structure under study? A commonly discussed example is star-formation and supernovae feedback - an unresolved process that can play a very important role.
- the impact of algorithms in astrophysics; is one particular algorithm superior to any other in astrophysics? What algorithm might be best suited to tackle the most challenging problems in galaxy, star and planet formation?

  These four issues were discussed with the aim of trying to identify the directions for the future and the best strategy to design new astrophysical gravitational-magneto-hydrodynamics codes.

2 Scientific Content

The most challenging goals faced by astrophysicists is to understand the origin of structure in the Universe, from galaxies and clusters on large scales, to star and planet formation on small scales. Computational techniques are leading the way in helping astronomers understand these problems, this being the scientific focus of the meeting. The extensive discussions revolved around the correct modelling of the appropriate physical phenomenon that are important for each problem and for each relevant scale.

The meeting began with a session on star formation. Nordlund gave a review of current models of star formation emphasising the role of interstellar turbulence in driving high local densities in the interstellar medium. Such high density regions can rapidly collapse via self–gravity giving rise to stars and star clusters. Although the generation mechanism for turbulence is still not known, two possibilities seem equally likely; one is the generation of purely hydrodynamical turbulence from supernovae explosions, the other one is magneto-hydrodynamical turbulence. AMR simulations of both kinds of turbulence were described. Some of these simulations can show that fragments produced by the interplay between gravity and turbulence can reproduce the initial mass function of stars.

Klessen showed results of SPH simulations that describe the same process. Comparisons between SPH and high-resolution grid simulations were presented showing good agreement between the two techniques. However, comparison of the outcomes from the two methods remains non–trivial since initial conditions are generated differently for each and no simple definition of what constitutes an equivalent resolution exists. The “sink particle” technique was discussed as a way to prolong the calculations by effectively giving up on resolving the detailed physics within the inner regions of forming star clusters. Boundary conditions for the sinks and how local fluid behaviour is influenced by their sudden appearance in hydrodynamical calculations were highlighted among the open questions regarding this approach.

Bate presented new results on smaller scale calculations in which the formation of a single star cluster at high resolution is followed using purely hydrodynamical turbulence and simple equations of state for the interstellar medium (i.e. isothermal). He showed that star clusters with a Salpeter mass function are easily produced as a result of the fragmentation process driven by turbulence, and that a large number of brown dwarfs are produced out of each individual collapsing "star". Sinks are also used in such calculations and one big limitation is the simplified radiation physics; currently radiative transfer is applied only on the outputs of the simulation with the aim of producing spectral energy distributions that can be compared with observations.

Stone discussed the status of Eulerian simulations of accretion disks in astrophysics, both 2D and 3D, focusing in particular on local calculations that adopt shearing periodic boxes. Such calculations also include MHD and show that the magneto-rotational instability can be a very efficient way of shedding angular momentum for disk formation. It might be an important source of "viscosity" for accretion disks, namely a driver of their evolution. Missing from these calculations are of course global effects, especially those related to self-gravity (which is indeed often neglected in the first place). The generation and modelling of jets as well as more idealised problems regarding modelling of shocks and fluid instabilities was also presented.

Cottet and Kassinos discussed direct numerical simulations (DNS) of incompressible turbulence in computational fluid dynamics and their comparison with other approaches to model turbulence; Eulerian as well as particle based techniques to model vortices (using a potential dependent on velocity in place of the gravitational potential used in astrophysics were presented, and the concept of remeshing the particles on a grid to regularise the physical fields mapped through the particles was introduced. The issue of how relevant are such calculations to astrophysical situations were turbulence is typically compressible (e.g. star formation) was raised.

A session on planet formation took place during part of the first and the second day. Hal Levison reviewed the current status of N-Body algorithms designed to follow the gravitational accumulation of kilometre sized planetesimals into terrestrial planets and cores of giant planets. He discussed the issue of time integration in detail, focusing on symplectic algorithms. Among the scientific issues discussed was the difficulty of obtaining a system of terrestrial planets with low eccentricity and inclinations as those of the Solar System planets.

Willy Benz discussed the modelling of the very first stage of planet formation, from the accumulation of interstellar size grains to the detailed dynamics of collisions of small bodies of meters up to kilometre sizes. He showed how particle based techniques like SPH can be used to study collisions and investigate the main issue, namely in which conditions planetesimals stick together and which they do not. This involves knowledge of the properties of materials, in particular if their reaction to stresses of any sort, and it is usually incorporated using a complex SPH equation of state, illustrating one of the strengths of this computational method.

Proto-planetary disks, their evolution and how to model them were the subject of the remaining talks. In particular, Willy Kley covered the area of planet migration, showing the result of the latest 2D and 3D hydrodynamical and magneto-hydrodynamical calculations of the interaction between a planet and the surrounding proto-planetary disk. He showed results of both SPH and grid codes and discussed how the correct modelling of disk viscosity is crucial in these type of problems. Planets do in fact migrate because of gravitational torques triggered by the interaction with the disk and because of viscosity once they open a gap. SPH might be not well suited for this type of problem because artificial viscosity might drive spurious evolution on timescales similar to those of the actual physical viscosity sources (including gravity), unless a high resolution is used.

Durisen and Mayer discussed the latest numerical simulations of gravitational instability in protoplanetary disks in, respectively, grid and SPH codes. They remarked that the two main issues in this area are the modelling of thermodynamics, namely how realistic is the balance of heating and cooling in the simulations, and the dependence of the fragmentation process on numerical resolution and technique used. The latter issue is of general interest also for star formation (see above). Tests on the spreading of viscous rings were proposed by Kley.

The last day of the workshop was mostly dedicated to cosmology and structure formation simulations. The state of the art in simulations of the formation of cold dark matter haloes was reviewed (Diemand) as well as the largest cold dark matter simulation ever carried out using ten billion particles (Springel). For the latter issues of data formats and data managing were also highlighted. Pearce covered the role of hydrodynamics in structure formation, discussing numerical effects like spurious heating due to two-body effects and dependence of the survival of structures on softening in SPH simulations. Quilis and Tessyer described two new adaptive mesh refinement (AMR) codes designed to perform cosmological simulations with hydrodynamics.

A great deal of debate ensued on the suitable of the different approaches in modelling fluid flows. For example, the grid based codes can diffuse material across cell-boundaries, particle based codes could not treat turbulence as effectively. The first comparisons between the test problems were showed by the participants which demonstrated a general agreement between techniques, but some fascinating differences when a detailed comparison was made.

Ciardi covered the area of radiative transfer modelling in cosmological simulations, which is particularly important at high redshift during reionisation since it affects the formation of stars and galaxies throughout the evolution of the universe. Wadsley showed tests of SPH versus AMR codes (in particular GASOLINE and FLASH) on problems common in galaxy cluster simulations, such as gas clouds moving in a background fluid. He showed how in certain situations AMR can be more diffusive than SPH contrary to common belief; similar behaviour is obtained by including an additional conduction term in the SPH energy equation. Borgani described the current status of SPH simulations of galaxy clusters, describing also additional mechanisms that are now being included like thermal conduction and metalicity evolution.

Monaghan gave an overview of SPH, and especially its more advanced implementations capable of treating MHD problems, 3D radiative transfer and thermal conduction. He discussed the role that proper initial condition generation has in SPH (also discussed by Pearce) and showed examples of well posed problems where SPH performs extremely well compared to analytical solutions. He emphasised how it is important to design problems that respect the nature of the technique chosen to solve them and how forgetting this can lead to spurious comparisons.

Finally, Komoutsakos gave a perspective of the workshop from the experience of a computational fluid dynamicist with a broad experience in different fields from engineering to chemistry. He talked about particle based methods in turbulence modelling and described algorithms to remesh particles. Although the examples shown were mostly taken from the realm of incompressible fluids, they triggered an extremely lively discussion on how to use them to design new types of astrophysical "hybrid" codes that couple the flexibility and adaptivity of particles with the formal superiority and more accurate solutions of high order grid methods.

3 Outcome

The meeting successfully achieved the following goals;

1) it provided an overview of the most challenging problems in three cutting edge areas of astrophysics embracing all scales of astrophysics;

2) it fostered the discussion on the major algorithms used in astrophysics today;

2) it initiated a fruitful interaction between scientists in the different areas and also with computational fluid dynamicists;

3) above all, it officially started a code comparison relevant to all major techniques currently adopted, including as much as 12 different codes. Some of the test problems are already becoming a reference for researchers and are now being performed even by several other groups who were not present at the meeting.

Finally, we discussed further actions that could be taken. It was agreed by all the participants that bringing together the entire community of computational astrophysicists would be of enormous benefit to the European research arena. The EU research and training networks were considered too small and specialised for a platform to continue these discussions. It was unanimously agreed that the ESF programs provided the ideal basis for strengthening this active field and continuing this cross disciplinary activity. Moore has since contacted over a sixty European institutes with active researchers in computational astrophysics and has submitted a proposal for an ESF program, ASTROSIM. Our aims are to strengthen the existing European activities in computational astrophysics, avoiding fragmentation as this field grows in strength and to exchange expertise through an active program of conferences, workshops, training schools and exchange visits. Our scientific objectives are to refine our computational techniques and multi-scale modelling in order to develop and test theories of structure formation in readiness for the grand challenge European projects planned by ESO and ESA over the coming decades.

Final program and presentations are all available on the workshop webpage

www-theorie.physik.unizh.ch/ moore/wengen

Final Participant list

Prof. Stefano Borgani, Dipartimento di Astronomia, Universit di Trieste, via Tiepolo 11, I-34131 Trieste, Italy borgani@ts.astro.it

Prof. Richard H. Durisen, Department of Astronomy, Indiana University, 727 East 3rd Street, Swain West 319, Bloomington, IN 47405-7105, USA durisen@astro.indiana.edu

James M. Stone, Department of Astrophysical Sciences, Peyton Hall, Ivy Lane, Princeton, NJ 08544-1001, USA jstone@astro.princeton.edu

Dr. Frazer Pearce, School of Physics and Astronomy, University of Nottingham, University Park, Nottingham, NG7 2RD, England Frazer.Pearce@Nottingham.ac.uk

Dr. James Wadsley, Department of Physics and Astronomy, ABB-241, McMaster University, Hamilton, ON L8S 4M1, Canada wadsley@mcmaster.ca

Prof. Harold F. Levison, Department of Space Sciences, Southwest Research Institute, 1050 Walnut St., Suite 429, Boulder, CO 80302, USA hal@gort.boulder.swri.edu

Dr. Benedetta Ciardi, MPA, Garching, Karl-Schwarzschild-Str. 1, Postfach 1317, D-85741 Garching, Germany ciardi@mpa-garching.mpg.de

Prof. Ake Nordlund, Niels Bohr Institute for Astronomy, Juliane Maries Vej 30, DK-2100 Copenhagen , Denmark aake@astro.ku.dk

Prof. Willy Benz, Institut de physique, Universitt Bern, Sidlerstrasse 5, Bern, Switzerland willy.benz@phim.unibe.ch

Dr. Vicent Quilis, Departament d'Astronomia i Astrofsica, Universitat de Valncia, c/ Dr. Moliner no 50, E46100 - Burjassot (Valencia), Spain Vicent.Quilis@uv.es

Prof. Matthew Bate, School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, United Kingdom mbate@astro.ex.ac.uk

Prof. Ralph Klessen, Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany rklessen@aip.de

Prof. Willy Kley, Universitt Tbingen, Institut fr Astronomie and Astrophysik, Abt. Computational Physics, Auf der Morgenstelle 10, D-72076 Tbingen, Germany kley@tat.physik.uni-tuebingen.de

Dr. Lucio Mayer, Institute for Theoretical Physics, University of Zurich, Winterthurerstrasse 190, Zurich Switzerland lucio@physik.unizh.ch

Prof. Ben Moore, Institute for Theoretical Physics, University of Zurich, Winterthurerstrasse 190, Zurich, Switzerland moore@physik.unizh.ch

Prof. Joe Monaghan, Centre for stellar and planetary astrophysics, Monash University, Australia joe.monaghan@sci.monash.edu

Dr. Volker Springel, Max-Planck-Institute for Astrophysics, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany volker@mpa-garching.mpg.de

Dr. Joachim Stadel, Institute for Theoretical Physics, University of Zurich, Winterthurerstrasse 190, Zurich, Switzerland stadel@physik.unizh.ch

Prof. Petros Koumoutsakos, Institute of Computational Science, HRS H 12, Hirschengraben 84, 8092 Zurich, Switzerland petros@inf.ethz.ch

Prof. Georges-Henri Cottet, Professeur de Mathmatiques, LMC-IMAG, Universit Joseph Fourier, 38041 Grenoble Cedex 9, France Georges-Henri.Cottet@imag.fr

Prof. Stavros Kassinos, Department of Mechanical Engineering, University of Cyprus, 75 Kallipoleos St., P. O. Box 20537, 1678 Nicosia, CYPRUS kassinos@ucy.ac.cy

Dr. Markus Wetzstein, Institute of Astronomy and Astrophysics, Ludwig-Maximilian University, Wendelstein Observatory, Scheinerstr. 1, D-81679 Munich, Germany mwetz@usm.uni-muenchen.de

Dr. Romain Teyssier, Service d'Astrophysique, DSM/DAPNIA/CEA F-91191 Gif-sur Yvette Cedex, Saclay, France Romain.Teyssier@cea.fr

Dr. Elizabeth Tasker, Astrophysics, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH UK ejt@astro.ox.ac.uk

Dr. Juerg Diemand, Institute for Theoretical Physics, University of Zurich, Winterthurerstrasse 190, Zurich, Switzerland diemand@physik.unizh.ch

Mr Tobias Kaufmann, Institute for Theoretical Physics, University of Zurich, Winterthurerstrasse 190, Zurich, Switzerland tkaufmann@physik.unizh.ch

Mr Massimo Dotti Universit degli Studi di Milano-Bicocca dell'Ateneo Nuovo, 1 - 20126, Milano Italy Massimo.Dotti@mib.infn.it

Age and nationality

The participants spanned the age bracket from 25 years (two PhD students attended) to 55 years. The ration of male to female researchers in this field is dissapointingly low and is apparent in the gender ratio of the participants.

Nationalities, Swiss (3), English (4), French (2), Italian (3), German (4), Danish (1), American (3), Canadian (1), Australian (1), Spanish (1), Greek (1), Cypriot (1)

Sunday September 26, 2004

Arrival

Meeting point: 6 pm by the reception for drinks and then dinner together

Monday 27 September

9:00-9:40 Introduction by **Ben Moore** and short presentation of the European Science Foundation (ESF)

Session 1: Star formation

9:40-10:20 **Ake Nordlund** "Modeling interstellar turbulence and star formation"

10:20-10:50 *Coffee Break*

10:50-11:30 **Ralph Klessen** " Gravoturbulent fragmentation of molecular clouds"

11:30:12:10 **Matthew Bate** "Star Formation: Hydrodynamics and Radiation Hydrodynamics"

12:10-12:50 **George-Henri Cottet** "Numerical modeling of vorticity in fluid systems"

12:50-14:30 lunch break

Session 2 : Planet formation/astrophysical disks

14:30-15:10 **James M. Stone** "MHD simulations of accretion disks and outflows

15:10-15:50 **Hal Levison** "N-Body simulations of planet formation:successes and challenges"

15:50-16:30 **Willy Benz** "Planetary accretion: are planetesimals sticking or not?"

16:30-17:00 *Coffee Break*

17:00-19:00 Discussion + Tests

19:00-20:30 *Dinner*

Tuesday 28 September

Session 2 (continued)

9-9:40 **Richard H. Durisen** "Radiative Cooling in Gravitationally Unstable Protoplanetary Disks"

9:40-10:00 **Joachim Stadel** "PKDGRAV+GASOLINE: a multi-purpose parallel N-Body+SPH code"

10:00-10:20 **Lucio Mayer** "SPH simulations of gravitational instability in protoplanetary disks with GASOLINE"

10:20-10:50 *Coffee Break*

10:50-11:30 **Willy Kley** "Simulations of disk-planet interaction"

11:30-12:10 **Stavros Kassinos** "DNS and Structure-based Turbulence Modeling of Rotated Shear Flows: Implications for Accretion Disks?"

Session 3: Galaxy/structure formation

12:10-12:30 **Jurge Diemand** "N-Body simulations of cosmological structure formation"

12:30-14:30 *Lunch break*

14:30-15:10 **Frazer Pearce** ”Current challenges in numerical modeling of gasdynamics in structure formation”

15:10-15:50 **Volker Springel** ”SPH modeling of galaxy formation:Looking under the Hood of Gadget-2”

15:50-16:10 **Tobias Kaufmann** ”Numerical issues in SPH simulations of disk galaxy formation”

16:10-16:40 *Coffee Break*

16:40-19:00 Discussion + Tests

19:00-20:30 *Dinner*

Wednesday 29 September

Session 3 (continued)

9:9-40 **Romain Teyssier** ”RAMSES; and adaptive mesh refinement code for galaxy formation”

9:40-10:20 **Benedetta Ciardi** ”Numerical modeling of radiative transfer in early structure formation”

10:20-10:50 *Coffee Break*

10:50-11:30 **Stefano Borgani** ”SPH Simulations of the Intra-Cluster Medium”

11:30-12:10 **James Wadsley** ”SPH and AMR: Gasoline, FLASH and Galaxy Clusters”

12:10-12:50 **Vicent Quilis** ”MASCLET: a new AMR hydro+gravity cosmological code”

12:50-14:30 *Lunch break*

Session 4

14:30-15:10 **Joe Monaghan** ”New developments (especially Lagrangian Turbulence and MHD) and the future of SPH”

15:10-15:50 **Petros Komoutsakos** ”Critical summary; the status of computational astrophysics from the perspective of computational fluid dynamics”

15:50-16:30 Discussion + Tests

16:30-17:00 *Coffee break*

17:00-19:00 discussion + Tests (continued)

19:00-20:30 *dinner*

Thursday 30 September

Morning

8:55-12:15 Excursion to the observatory near the summit of the Jungfrau

12:15-14:00 lunch at the summit or departure depending on individual schedule

Afternoon Departure